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Blockchain in Energy Sector

Master's Thesis

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Declaration

I declare that this Master's thesis has been composed entirely by myself and that all the used resources are noted and provided in the list of references.

In Hradec Králové, 13th May 2021.

Spahić Sara

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Abstrakt

Název: Technologie Blockchain v energetickém sektoru

Blockchain je rozvíjející se technologie zaměřená na decentralizované a transparentní transakce, které získávají na významu v energetickém sektoru. Tato práce představuje koncept technologie blockchain a zkoumá možné případy užití v energetickém sektoru s cílem je identifikovat, klasifikovat a ohodnotit je. Existuje již celá řada implementací technologie blockchain, každá s různými funkcemi, jako jsou přístupová práva a konsensuální protokoly, které ovlivňují jejich použitelnost v energetickém sektoru. V práci jsou podrobně zkoumány aplikace technologie blockchain v oblastech správy energetické sítě, obchodování s elektřinou, elektrických vozidel, zlepšování transakcí a plateb, správy obchodovatelných aktiv a v ropném a plynárenském průmyslu. Práce zkoumá jak teoretické modely a simulace prezentované v akademických výzkumných pracích, tak společnosti a start-upy, které se věnují praktickým implementacím. Dále práce diskutuje použitelnost technologií blockchain pro vybrané případy užití a analyzuje hlavní výzvy a překážky z širšího hlediska. Výstupy práce lze použít k vyhodnocení potenciálních obchodních případů a také jako vodítko pro další výzkum.

Klíčová slova: blockchain, decentralizace energie, energetický internet, energetický sektor, obchodní modely, případy užití

Abstract

Blockchain is an emerging technology focusing on decentralized and transparent transactions gaining significance in the energy sector. This thesis introduces the concept of blockchain technology and explores possible use cases in the energy sector intending to identify, classify, and evaluate them. There already exists a large variety of blockchain implementations, each with different features such as access rights and consensus protocols, which affect their applicability to the energy sector. Blockchain applications in the areas of power grid management, electricity trading, electric vehicles, improving transactions and payments, tradable asset management, and in the oil and gas industry are thoroughly examined. The thesis explores both theoretical models and simulations presented in academic research papers as well as companies and start-ups working on practical implementations. The applicability of blockchain technologies for selected use cases is discussed and the main challenges and obstacles for widespread adoption are analyzed. The information presented in this work can be used to evaluate potential business cases and also to provide guidance for potential further research.

Keywords: Blockchain, Business models, Energy decentralization, Energy Internet, Energy sector, Use cases

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List of Abbreviations

CEBN – Clean Energy Blockchain Network

D3A – Decentralized Autonomous Area Agent

DENA – Deutsche Energie-Agentur, The German Energy Agency

DLPS – Distributed Ledger Performance Scan

DLS – Distributed Ledger Systems

DLT – Distributed Ledger Technology

DPoS – Delegated Proof of Stake

DSO – Distribution System Operator

EAC – Energy Attribute Certificate

EEA – European Environment Agency

EU – European Union

EW – Energy Web

EW-DOS – Energy Web Decentralized Operating System

GDPR – General Data Protection Regulation

IoE – Internet of Energy, the Energy Internet

IoT – Internet of Things

IoV – Internet of Vehicles

LCFS – Low Carbon Fuel Standard

P2P – Peer-to-peer

PBFT – Practical Byzantine Fault Tolerance

PoAu – Proof-of-Authority

PoS – Proof-of-Stake

PoW – Proof-of-Work

UN – United Nations

VPP – Virtual Power Plant

1 Introduction

Energy is the driving force of modern society. It is an essential resource for the development of all other industries as well as sustaining everyday life. As a result, the energy sector is a crucial element of every nation's success and a major driver of global market shifts. It is hard to overestimate the importance of energy for the functioning of our society and the global energy consumption is steadily growing. In 2019, primary energy consumption has increased by 1.3% compared to the previous year [1]. Even though energy production and consumption facilitate humanity's accelerated growth, the current system has some shortcomings. According to the European Environment Agency (EEA), the most significant contributors to greenhouse gases emission are energy supply and domestic transport [2]. Thus, there is a large effort in the energy sector for innovative solutions which can help reduce the carbon footprint of energy production and consumption. Most of the world's primary energy needs, more than 33% in 2019 are fulfilled by oil, with coal and gas following with 27% and 24%, respectively. Renewable energy sources such as solar, wind, and biofuels, have contributed to only 5.0% of the primary energy consumption in 2019, and hydropower contributed to another 6.4% percent, as shown in Figure 1. However, even though the percentage of renewables in terms of total power is still small, there is a high growth trend present, and renewables contribute the most to the increase in the energy demand [1].

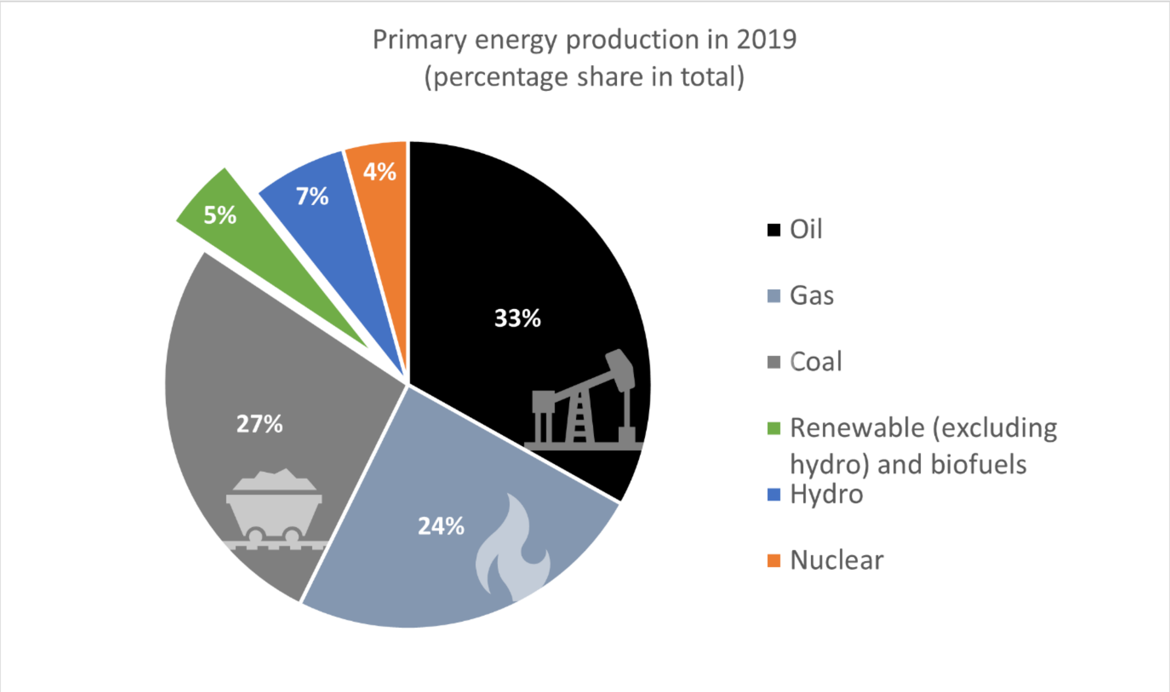

Figure 1 Primary energy production in 2019. Source: Adapted from [1].

In the last five years, the demand for energy from renewable sources grew three times faster than the demand for fossil fuels and nuclear energy [3]. This rapid increase in demand for renewable energy brings new challenges to the energy sector, exacerbated by the pressure from governments, international organizations, and the public for a shift towards more climate-friendly energy production, distribution, and use. These challenges are driving forth innovations in the energy sector and are enabling new technologies to enter the field. In recent years, we have seen big data, machine learning and artificial intelligence, the Internet of Things, and cloud technologies make a significant impact [4]. Besides these technologies, blockchain is also gaining significant attention and becoming an important topic in the energy sector.

Blockchain has evolved rapidly in the last decade and it has presented itself as a potential candidate for application in many areas of the energy sector. According to reports by the German Energy Agency (DENA) from 2016, industry experts agree that blockchain technology is in alignment with the goals of building cost-effective, trustworthy, and sustainable energy systems [5]. Judging by the current trends and development of the markets, it is certain that blockchain will play a role in the future of the energy sector [6]. According to the Renewables 2020 Global Status Report, distributed renewable energy systems have considerable potential for electrification of remote communities, and technologies like virtual power plants can help manage the processes needed to add flexibility to the grid [3]. These are some of the areas in which blockchain can be used and overall, there are plenty of possible applications which can successfully utilize this technology. However, in all possible use cases, there are many questions to be answered, such as determining the best blockchain technology to use and evaluating the impact of the new business models on the energy sector as a whole. Additionally, not all possible applications which are explored in theoretical models and pilot projects will be successful when implemented in enterprise-grade, large-scale projects.

This thesis aims to give an overview of the potential use cases for blockchain in the energy sector, to provide an understanding of how this technology can be used to improve it, and to evaluate the potential applications according to their current impact and feasibility. After the introduction, the thesis is organized as follows. Section 2 outlines the research done in the classification of use cases in the energy domain and Section 3 presents the objectives of the work and the methodologies used to construct the thesis. In Section 4, blockchain technology is introduced and the specificities of its technical implementations, the main applications, and the motivation to implement it in the energy sector are described. In Section 5, the exploration of possible use cases for blockchain in the energy domain is given and the main arguments for their implementation are presented. In Section 6, possible drawbacks and challenges for the given applications are explained and finally, in Section 7, the main observations and outcomes of the thesis are discussed.

2 Related Research

There have not been many comprehensive overviews of the possible use cases of blockchain in the energy domain since the technology is still relatively new. Andoni et al. [7] published one of the first works to systematically study blockchain technologies in the energy sector in 2019. They looked at 140 commercial and academic blockchain projects in this space and categorized them based on their use cases. Their paper suggests the following classification:

- billing and security,
- cryptocurrencies, tokens, and investment,
- decentralized energy trading,
- green certificates and carbon trading,
- grid management,
- Internet of Things (IoT), automation, and smart devices,
- e-mobility, and
- general-purpose initiatives [7].

Bürer et al. [5] have also explored possible use cases for blockchain in the energy sector. They have divided the use cases into ones pursued by incumbents – utilities and large energy companies which are already established in the sector, and use cases among start-ups, new companies, and small and medium enterprises. This is an interesting categorization since most of the innovation in blockchain development for uses in the energy sector is driven by start-ups [6], while the utilities and incumbents are trying to stay relevant by participating in pilot projects and exploring the possibilities for their involvement. For use among incumbents, Bürer et al. recognize three categories of use-cases:

- peer-to-peer energy trading,
- real-time supply and demand management,
- and electric vehicle charging improvements.

For new entrants to the market, the use cases identified by Bürer et al. are:

- trading energy, renewable energy certificates, or carbon emissions,
- enabling peer-to-peer power generation and distribution and models to increase energy access in developing countries,

- using blockchain for microgrids, and
- using blockchain for financing social action [5].

Wu and Tran [8] gave an overview of the possible applications for blockchain in the energy system with a focus on the sustainability of the proposed frameworks. Mainly they explored the possible use-cases in terms of blockchain integration with the Energy Internet. Their research summarizes the use cases in the following categories:

- peer-to-peer energy transactions,
- electric vehicles,
- physical information security,
- carbon credits certification and trading,
- virtual power plants,
- multi-energy systems, and
- demand-side response [8].

In 2019, Brilliantova and Thurner [6] have conducted their analysis of the future of blockchain in the energy sector by reviewing the available literature and conducting interviews with industry experts, academicians, and relevant start-up founders and managers. They have also compared the possibilities of blockchain implementations in South Africa and Russia. Their findings give an insight into the industry's perspective regarding blockchain, and they conclude that there is a large potential for successful implementations, especially in remote communities, but that a joint effort must be made from all stakeholders to achieve the optimal results [6].

3 Objective and Methodology

This thesis utilized a qualitative methodology, primarily based on an exploratory review of the academic literature and publicly available information. The topic of blockchain has been explored in depth in academic resources and the various applications of blockchain in the energy sector have been studied in numerous research projects. Most of the literature on the topic of blockchain use in the energy sector dates from 2016 onwards, with the most impactful research being performed in the last three years. The academic resources for this thesis were gathered through searches of established academic databases and search engines including Google Scholar, Web of Science, JSTOR, and Science Direct. Additionally, citation tracking and reference checking for potential additional use cases and reviews were performed.

One of the difficulties in researching a novel and rapidly developing technology like blockchain is that academic resources are often not enough for forming the right picture of the topic. There are two ways in which these resources might be lacking. Firstly, the information stated can be outdated, and secondly, the newest information might not yet be recorded in the academic resources. This is especially true when talking about practical implementations, new projects, and start-up companies. Thus, in addition to peer-reviewed articles, an assortment of available grey literature in the form of reports, white papers, and government documents have been considered in the exploration of the thesis.

Besides the published literature, for the efficient analysis of the effectiveness of use cases presented in this thesis, it is important to consider other available information on the companies and implemented pilot projects. Start-up companies, in general, are much more likely to fail than to succeed [9], which means that companies that were relevant for energy blockchain a couple of years ago may now be shut down, and new ones might have emerged in the meantime. For this reason, besides the thorough research of scientific libraries, a selection of other resources such as news and magazine articles, company websites, and social media have been used for this work.

This methodology approach that includes a broad range of considered resources, provides a clear overview of the research matter, and allows for the observation of the topic’s development over time. Additionally, including non-academic sources allows for the tracking of new and emerging use cases that might not have been described in the literature yet.

Moreover, it enables the assessment of present information about the practical implementations of the use cases and their reception by the industry experts and potential consumers.

Limitations of this approach are that for some of the resources used, information such as the publishing date or the authors is missing. Moreover, due to the lack of proper classification and permanent storage repositories, the information found on online-published resources might become unavailable if the hyperlinks which are functional at the time of writing the thesis might become inoperative in the future. And finally, with grey literature, additional attention must be given to the verification of the credibility of the presented information and the elimination of potential biases of the resource's authors. Despite these limitations, the need to have up-to-date information on the current state of blockchain projects in the energy sector justifies the use of this variety of resources.

With the methodology described above, this thesis aims to:

- provide an overview of blockchain technology for energy industry professionals,
- collect, describe, and evaluate the use cases for blockchain in the energy sector, and
- give prospects for the potential of this technology to impact the future of the energy domain.

4 Blockchain Technology

The conceptualization of blockchain technology is attributed to an author known under the pseudonym Satoshi Nakamoto, in their work “Bitcoin: A Peer-to-Peer Electronic Cash System”, published in 2008 [10]. This paper explains the inner workings of the world’s first cryptocurrency, Bitcoin. Cryptocurrency is a type of digital currency where instead of relying on a central authority such as a national bank, the currency relies on cryptographic challenges for its security of transactions [11]. Even though the initial thought behind blockchain was to provide a means for financial transactions, today there are many different applications of this technology.

4.1 Technical Description of Blockchain

Blockchain is often described as a distributed ledger of transactions [12], as depicted in Figure 2. It is enabling safe interactions between two parties, without the mediation of a trusted authority [6]. The challenge with this approach is the establishment of trust between unknown

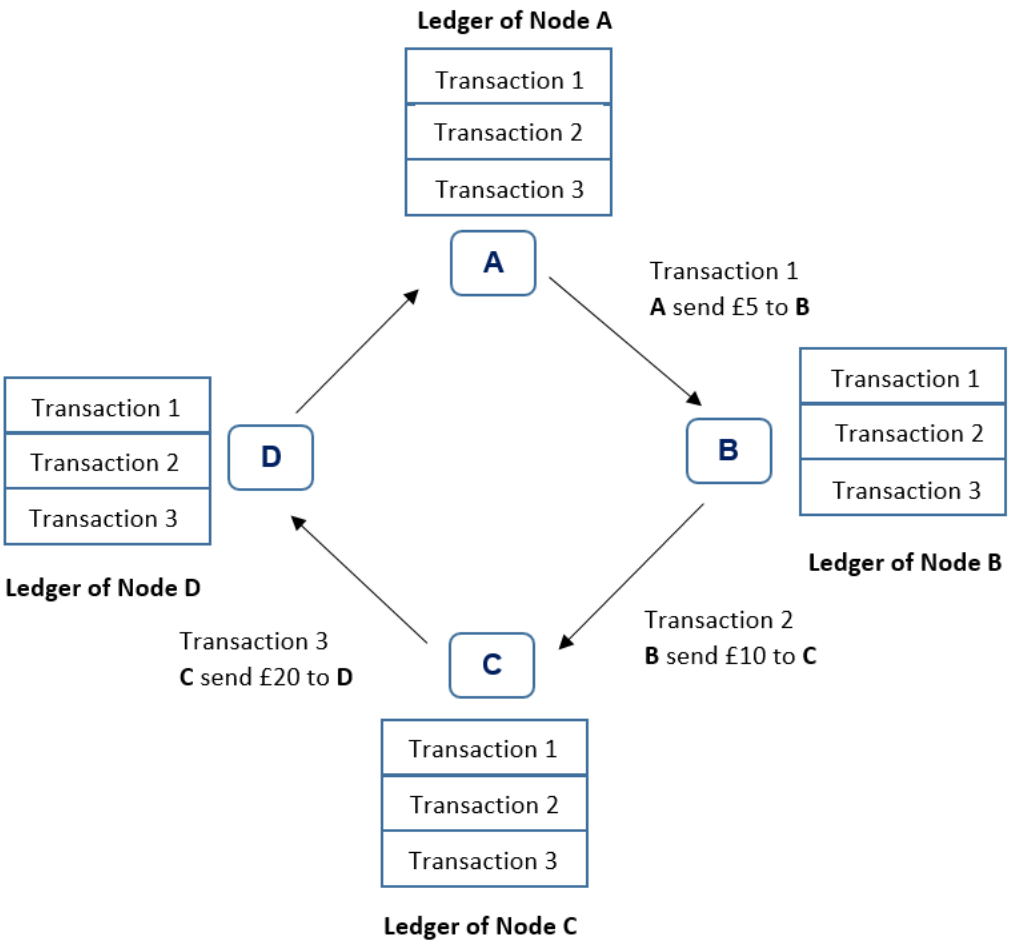

Figure 2 Simple representation of a distributed ledger. Source: [12, p. 4], *Copyright © 2018 MECS.*

parties. The way this is achieved is by the distribution of the transaction recorders across several parties, typically called nodes. Each node stores a copy of the whole record of transactions.

When new data needs to be added to the ledger, it is bundled into blocks. To add a new block to the list of already existing transactions, a verification process occurs. This is performed in different ways, called consensus protocols, explained in Section 4.1.2. If the block of data is deemed trustworthy, all nodes add it to their existing ledger. This resulting ledger is what is known as the blockchain. An important feature of the blockchain is that besides the data about new transactions, each new block contains a summarization of all blocks that come before it in the form of a hash code in its header [6]. This hashed value contains an encrypted summarization of the whole blockchain, and it is a mechanism that ensures the integrity of the data written on the blockchain. A simplified structure of the blockchain can be seen in Figure 3.

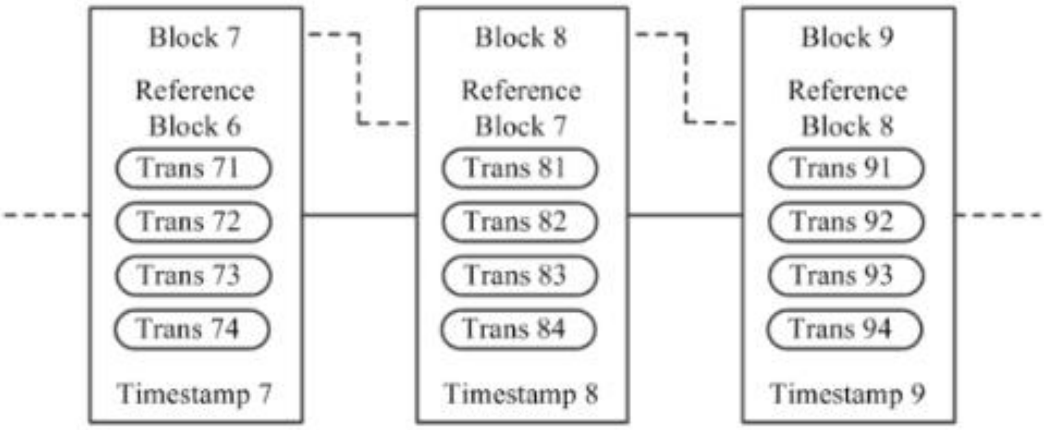

Figure 3 Blockchain structure. Source: [8, p. 4].

Blockchain is a technology with unique properties that can be applied to a variety of industries. It must be noted, however, that this basic definition of a distributed ledger can be implemented in a variety of ways, resulting in the development of widely different blockchains, each with its own set of characteristics. These systems are also referred to as Distributed Ledger Technology (DLT) [6], or Distributed Ledger Systems (DLS), and these terms might include non-blockchain-based frameworks as well [13]. The main characteristics of the blockchain protocol are shared with other DLTs and in the energy sector these terms are sometimes used interchangeably in the literature.

Some important characteristics of the blockchain protocol are (Figure 4):

- Decentralization. The blockchain should be distributed and function properly without a central authority to manage it [14]. The nodes participating in the blockchain have an equal role in the networking system and the blockchain should be able to establish trust between them [8].
- Immutability. This property is often cited in the literature as blockchain being tamper-proof. To be more specific, for a well-constructed blockchain, any attempt to modify the data already stored in the blockchain could be easily detected [15]. Since each new block of data contains a hashed summary of all the previous blocks, to make a change in one already verified block, all the blocks that have been added afterward would have to be recalculated and added again, essentially resulting in a new blockchain.
- Irreversibility. Once an action is recorded on the blockchain, it should not be possible to reverse it [14]. In addition to the records being permanently kept on the blockchain, the complete transfer path for the transactions should be fully traceable [8].
- Transparency. The rules of the blockchain's operation, the status of the nodes, and their interactions are all open and transparent. The private data about the nodes or transactions can be encrypted to preserve privacy [8].

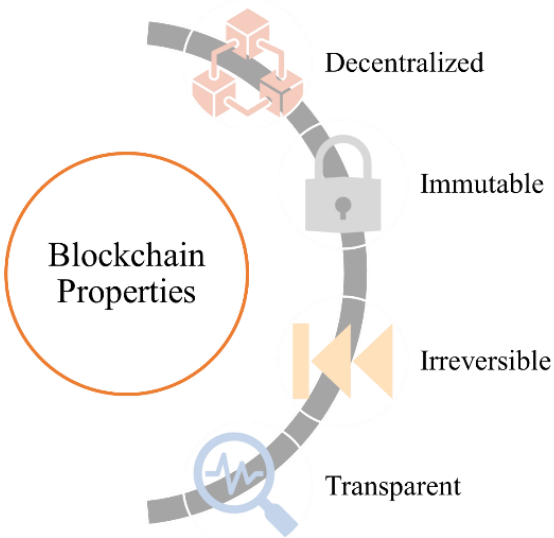

Figure 4 Main blockchain properties. Source: Author's elaboration.

Another characteristic that is often stated in the academic literature as a blockchain property is anonymity. Although the blockchain can be anonymous, this is not true for most implementations today. Even though there is not a central authority keeping records of the identities of the users, the participants in the blockchain and their transactions are transparent and possible to be viewed by others. For public blockchains, this means that the information is visible to everyone, and for private and consortium blockchains it will be visible to authorized members of the network. If the identity of the blockchain participant can be in any way related to their real identity, such as when using a cryptocurrency exchange, their anonymity on the blockchain is compromised. Thus, we can say that at best, blockchain is pseudo-anonymous since the participants and their transactions can be viewed by everyone who has access to the blockchain and the anonymity property of the blockchain holds only if the identities of the blockchain participants cannot be in any way related to the identity of a real person or organization [16]. The issue of anonymity on the blockchain is still being researched and new ways to have anonymous blockchain applications are being developed. Depending on the specific blockchain there are different solutions to preserve the anonymity of participants. For example, mixing and grouping of transactions can be used to disrupt the usage patterns and the employment of zero-knowledge proofs enables completely anonymous transactions [17].

For the most important properties of the blockchain, the specific implementation and scale of the network must be considered. Properties such as immutability and resilience to attacks are not inherent to the blockchain structure itself, but they emerge from it being used in a decentralized ledger system, and for these features to hold in a practical setting, the blockchain itself must be well constructed [15]. These properties shall be considered valid for all blockchain applications described in this thesis, but with the decentralization and proper implementation of the blockchain's structure in mind. In addition to the main idea of the distributed ledger, other technologies are contributing to the blockchain's applicability in a wide number of use-cases such as its consensus mechanisms, encryption algorithms, and distributed data storage [8].

Another important feature of the blockchain is the ability to execute smart contracts. This technology is not possible on every blockchain, but it is certainly an important piece of the puzzle for enterprise-grade blockchain applications. This functionality was firstly implemented on the Ethereum blockchain in 2015 [18]. To enable the blockchain to be able to successfully handle a wide range of use cases and more complex transactions, the creator of Ethereum Vitalik Buterin, added to the blockchain the possibility to use smart contracts. Smart contracts are defined as executable pieces of code permanently stored on the blockchain which enable automatic execution of transactions [6]. After Ethereum, the idea of smart contracts has been embraced and implemented with many other blockchain technologies.

The addition of smart contracts has made a great difference and led to the blockchain having much more potential and variability in possible use cases.

4.1.1 Permissionless and Permissioned Blockchain

There are two types of blockchains in terms of access rights: permissionless, or public, and permissioned, which is usually further classified into private and consortium [19]. The following paragraphs provide a summary of the key features, use-cases, benefits, and drawbacks of these different types of blockchain.

A permissionless blockchain is a distributed ledger in which everyone can participate and be a validator node. The data stored on a public blockchain is easily accessible and even though it might be encrypted, it can still be publicly viewed. Most cryptocurrencies are implemented on a public blockchain with the most well-known ones being Bitcoin and Ethereum [8]. Public blockchains typically have higher levels of distribution since there is no entry barrier to participate in the validation of blocks [7]. For industry applications, however, public blockchains have a few problems. Processing personal data on a public blockchain can be a problem due to the transparency and immutability properties of the blockchain [20]. This can bring issues for companies that want to comply with personal data protection regulations such as GDPR in European Union [21]. In the case of public blockchain use, the sensitive data must either be carefully encrypted or not stored on the blockchain at all.

Permissioned blockchain requires access rights to be granted to a node before it can participate in the blockchain. Typically, there are two types of permissioned blockchain differentiated in the literature: private blockchains and consortium blockchains [19]. Private blockchains are typically run by a single organization and the rules of the blockchain’s setup and operation are set by the owner. The decentralization of this type of blockchain is often questionable since a single entity has full control over the blockchain. Consortium blockchain also requires access rights but it enables multiple entities to participate, each with the same degree of control over the blockchain's activities [22]. This type of blockchain is very convenient for applications that span multiple companies and organizations in one industry, and it enables fair participation for everyone. A consortium blockchain is often used in the energy sector for integrated and safe peer-to-peer energy trading in microgrids and electric vehicle-to-grid networks [6]. Both private and consortium blockchains can achieve higher efficiency and better transaction than public blockchains [7], at the cost of full decentralization and transparency.

4.1.2 Consensus Protocols

For a block of data to be accepted and added to the blockchain and all transactions to be finalized, there must be a system in place which ensures the trustworthiness of the data in question. This process of establishing trust between different participants in the blockchain system is called the consensus protocol, or consensus mechanism. Consensus mechanisms are especially important in permissionless blockchains [23] where anyone can participate as a node, although some form of consensus protocol is typically employed in permissioned blockchains as well. The need to establish trust between distributed nodes is sometimes also referred to as a need to establish Byzantine fault tolerance in a blockchain [23].

Different blockchains rely on different systems to reach consensus, and the type of consensus protocol used can greatly affect the efficiency, transaction speed, and scalability of the blockchain [7]. Not only that, but the consensus protocol is crucial to the blockchain's security because it is the mechanism that protects the blockchain and ensures that all blocks of data are trustworthy. Some common consensus protocols which are often used in blockchain applications for the energy market are explained in the following paragraphs. A summarization of their main properties is presented in Table 1.

Proof-of-Work (PoW), sometimes also called Nakamoto consensus protocol in literature [24], is the consensus protocol suggested for use in the Bitcoin whitepaper by Satoshi Nakamoto [10]. However, the concept of PoW is much older, and it is usually credited to Dwork and Naor, who proposed using computational power to control access to resources in 1993 [25]. With PoW, nodes in the network use their computational resources to compete in solving cryptographic puzzles [7]. The block with the correct solution is added to the chain and accepted by other nodes. An incentive must be given to the winning node for PoW to be effective. This is usually a built-in tipping method for successfully completed transactions. This means that nodes profit economically from behaving honestly rather than trying to deviate from the protocol [26]. The process of validating the nodes and receiving a financial reward is often called mining, especially when talking about cryptocurrencies [7]. PoW is widely used for reaching consensus for cryptocurrencies, with Bitcoin, Litecoin, Ethereum, and many others currently relying on it for security. Thus, PoW is generally regarded as being very secure and although the initial work on solving cryptographic puzzles is quite challenging in terms of processing power, the verification process is quick and simple [27]. The biggest threat to the security of PoW protocol is the 51% attack, which represents the situation in which a malicious node holds more than half the computing power in a distributed network. If this happens, the trustworthiness of the blockchain is compromised since a single node has the potential to control the validity of blocks written to the blockchain [10]. This problem is especially dangerous for networks with a small number of nodes. PoW is also criticized for its high electricity usage and low transaction speeds [7].

Proof-of-Stake (PoS) is a consensus protocol in which a node's staked wealth decides how many votes it has when deciding the validity of a block data. The stake is usually represented by the ownership of some form of cryptocurrency. A node is chosen at random to validate a block of data, with the probability of being chosen directly proportional to the staked wealth [7]. Delegated Proof of Stake (DPoS) is a more cost-efficient version of PoS where the stakeholders do not directly create blocks, but rather use their stakes as a voting power to democratically delegate block verifier nodes [28]. According to Di Silvestre et al., the PoS consensus protocol is favored for use in energy blockchains since the power consumption for blockchain usage in microgrids is in this way reduced [29]. PoS and DPoS are also vulnerable to the 51% attack, but instead of nodes having control in terms of the processing power, it refers to the possibility that a node has more than half of the whole staked balance.

Practical Byzantine Fault Tolerance (PBFT) is a consensus protocol that originates from a paper written by Castro and Liskov in 1999 [30]. Rather than being used in permissionless blockchains like PoW and PoS, PBFT is typically aimed at use in permissioned blockchains. Nodes in the blockchain are divided into primary and backup nodes. A big advantage of PBFT is that it is not directly dependent on cryptocurrency for a reward mechanism [30].

Proof-of-Authority (PoAu) is a consensus protocol in which validator nodes are individually selected being as being trusted entities and are pre-authorized to participate in the validating process. The nodes do not compete to verify the block, but instead, a block is considered legitimate if most approved nodes sign it [7]. The PoAu blockchains rely on the participants' reputation instead of computing power or cryptocurrency stakes [27]. PoAu blockchains are said to be highly scalable, have better transaction speeds and capacity, and lower electricity consumption than protocols used in public blockchains [31]. To add a new validator node to the blockchain, a standardized method should be employed such as a voting system. With high performance efficiency and a high level of centralization and control over who can participate in the blockchain, this consensus protocol is popular for use in the energy sector [7]. However, the most common critic of PoAu is that it does not have a high enough level of decentralization and that reputation alone is not enough to safeguard from nodes that would want to compromise the security of the blockchain [27].

Consensus protocol	**Permissionless /permissioned**	**Number of nodes**	**Power consumption**	**Scalability**	**Latency**	**Transaction throughput**
PoW	Permissionless	Unlimited	High	High	High	Low
PoS	Both	Unlimited	Low	High	High	Low
DPoS	Both	Unlimited	Low	High	Low	High
PBFT	Permissioned	Limited	Low	Low	Low	High
PoAu	Permissioned	Unlimited	Low	High	Low	Low

Table 1 Comparison of selected consensus mechanisms.
Source: Adapted from [19], [28], [30].

Besides the above-mentioned ones, common consensus protocols are Proof-of-Capacity (PoC), Proof-of-Burn (PoB), Proof-of-Elapsed-Time (PoET), Proof-of-Activity (PoAc) [7], and hybrid protocols such as Snow White, or Algorand [26]. An overview of consensus protocols currently in use for several big permissioned blockchain projects has been given by Cachin and Vukolić in their 2017 work "Blockchain consensus protocols in the wild" [23]. New consensus protocols are still being developed jointly with other improvements in blockchain technology [30]. While most have not yet achieved market-wide adoption, they do provide creative new perspectives on how trust can be established for participants in the blockchain. Some recently emerged consensus protocols are Proof-of-Person [32], Proof-of-Sincerity, and Proof-of-Play [30].

4.1.3 Blockchain Technologies Used in the Energy Sector

This section provides an overview of technologies that are popular for use in the energy sector and explains their main characteristics. The technologies which are discussed are Ethereum, Energy Web Chain, Quorum, Hyperledger, BitcoinJ library, Corda, and Microsoft Azure blockchain framework.

The majority of blockchain projects in the energy sector are built on the Ethereum blockchain or one of its derivatives [7]. Aside from serving as a platform for the Ethereum cryptocurrency, this blockchain facilitates the use of smart contracts, which enable developers to create blockchain-based applications with self-executing code. A special custom-developed programming language, Solidity, is used to build blockchain applications on Ethereum [33]. Due to the use of the PoW consensus protocol and the network's high congestion, Ethereum is often criticized for its high transaction fees. As a result, Ethereum’s core blockchain technology is gradually migrating to the PoS consensus protocol [7].

Energy Web Chain is a blockchain based on Ethereum that is intended specifically for use in the energy field. Several updates to the original Ethereum blockchains have been made to increase scalability and transaction speed. One of the most significant changes is the adoption of the PoAu consensus protocol to improve the scalability and power effectiveness of the blockchain [31]. According to research by Andoni et al., Energy Web Chain is used by around 10% of projects that have revealed details on the technology they utilize for use-cases in the energy blockchain [7].

Quorum is an Ethereum-based open-source blockchain framework constructed for use specifically in enterprise permissioned blockchain implementations. Quorum was built by J.P. Morgan, but it was acquired by the blockchain company ConsenSys in 2020. The platform offers the possibility to develop enterprise-grade solutions on the blockchain. The majority of the platform relies on the GoQuorum client interface for the Ethereum blockchain written in Go language [34].

Hyperledger is a Linux Foundation-led open-source collaboration project that aims to provide a blockchain development platform for innovative business applications. IBM, an American technology corporation, is one of the project's supporters, and their blockchain solutions often use Hyperledger technology [7]. Under the Hyperledger umbrella, there are a variety of frameworks, with Hyperledger Fabric being mostly used in the energy sector applications. The consensus protocol for use in Hyperledger blockchains is PBFT [30], although others such as PoET are also being explored [7].

Corda is an enterprise-grade permissioned blockchain platform developed by the American company R3. Corda is aimed at providing businesses with ready-made blockchain solutions for secure and private transactions using smart contracts. Corda is well suited for applications in the energy sector due to its ability to scale and adapt to a large number of transactions while still maintaining the privacy and security of the blockchain. In October 2020, Corda and Energy Web have announced a strategic partnership and service integration to improve decentralized balance settlement for the Energy Web Chain ecosystem [35].

Several theoretical models for blockchain applications in the energy sector have been built with the help of the BitcoinJ library. This library enables easy implementation of a Bitcoin-like blockchain and provides basic functionalities such as creating a wallet and sending transactions. Although the library is written in Java, it can also be used with other programming languages including Phyton and JavaScript. This method is useful for quickly developing proof-of-concept theoretical models and exploring possible blockchain use cases, but it has drawbacks that make it unsuitable for large-scale implementations. Apart from using the PoW consensus protocol, which has performance problems, the BitcoinJ library has many security and privacy issues, rendering it unsuitable for use in enterprise applications [36].

Azure Blockchain Workbench is a Blockchain-as-a-Service platform launched by Microsoft as a part of their Azure framework [8]. The service can be used to easily build prototype blockchain applications on the cloud using several different ledger technologies, including Ethereum, Hyperledger, Quorum, and Corda. The platform enables easy deployment and testing of smart contract decentralized applications. Azure Blockchain Workbench is aimed at quick and easy development of proof-of-concept projects and enables the exploration of multiple use cases in a short period [37]. Thus, it has been valuable in the exploration of potential use cases in the energy sector, and it has been used by multiple energy-focused blockchain initiatives.

4.2 Applications of Blockchain Technology

After its introduction in 2008 as a technology for electronic currency, blockchain has expanded into a wide range of fields and found numerous business applications. Financial applications, e-Government, healthcare, and supply chain monitoring are only some of the potential applications for this emerging technology [38]. According to a study conducted among business managers in technology positions in 2018, financial services, industrial goods production, energy and utilities, and healthcare are the most advanced industries in developing blockchain. Other notable sectors include government applications, as well as uses in retail and consumer services [21].

The most significant application fields for blockchain are cryptocurrencies and related decentralized finance use cases [38]. The idea of electronic cash systems has been explored before Nakamoto's Bitcoin, but earlier proposals have not managed to efficiently solve the double-spending problem associated with digital assets [13]. After the initial cryptocurrency Bitcoin was established, thousands of other different cryptocurrencies have been created. Many of them have struggled with widespread adoption and a lot of projects have become abandoned, but a considerable number succeeded in offering solutions to specific use cases in the financial world [5].

Blockchain is a great technology for e-government applications because of its immutability and transparency features, particularly where open governance is advocated to encourage trust between citizens and the government. Electronic voting systems on the blockchain can provide a transparent and secure voting process [38]. Similarly, there is a use case for blockchain in providing a platform for a transparent public procurement process. This technology has already been implemented in a few smaller government projects [8]. There have also been several projects aiming to implement digital citizen identity on the blockchain [38]. In the United States, the government in the state of Vermont has considered using blockchain to help simplify public record keeping. The Vermont State Archives and Records Administration Office looked at the possibility of putting land ownership records on the blockchain to save time and effort while maintaining data integrity, but their results did not strongly support the use of blockchain in this case [39]. However, there is a strong case for using blockchain for asset management in general, with some projects in the space being oriented towards tokenized income-producing securities ownership [21]. Blockchain technology can also provide a good alternative to lengthy intellectual property protection processes [19].

Several use cases for blockchain in health care have also been implemented, such as storing the patient’s medical data securely and privately and transferring the medical records easily. In addition, blockchain may be used to monitor medical products in the pharmaceutical supply chain [38]. Because of its ability to store data transparently and efficiently, blockchain has found application in supply chain management and logistics for many different industries. The blockchain's ability to maintain data integrity allows a stable way to create trust between parties, particularly in larger supply chains involving multiple large organizations. This use case is explored in the context of the energy sector in Section 5.6 where the possibility for oil and gas supply chain management through blockchain is presented.

4.3 Motivation to Use Blockchain in the Energy Markets

Several global trends create an environment in which blockchain applications for the energy market can thrive, such as an increase in decentralization and localization, the rise in renewable energy generation, and increased use of smart energy metering devices and the Internet of Things, as illustrated in Figure 5. Most of these trends align with the Sustainable Development Goals of the United Nations (UN), and blockchain has been recognized by the UN as a technology that has the potential to contribute to more sustainable infrastructure and empowered communities [40]. The following sections explore the arguments which make blockchain technology a potential candidate for the implementation of projects in the energy sector.

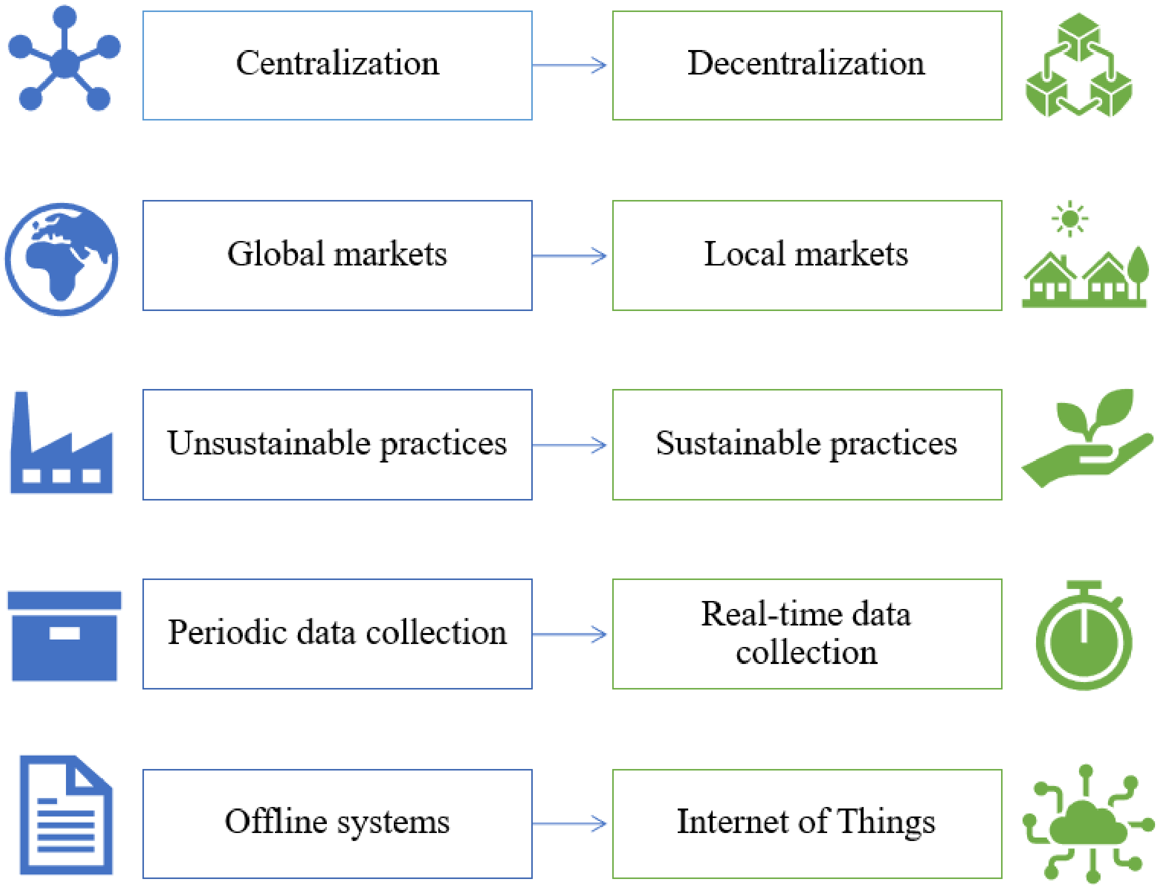

Figure 5 Paradigm shifts facilitating the use of blockchain in the energy sector.
Source: Author's elaboration.

4.3.1 Decentralization and Localization

The energy sector has preserved a high level of centralization throughout the years, especially on a national level where one or a few utility companies have control over the energy market and the market entry barriers are high [5]. This high degree of centralization can lead to several problems. Most notably, there is a single point of failure for system stability and performance which puts the power supply at risk [41], [42]. Centralized systems can also have issues with low privacy and anonymity, which is especially significant when dealing with the personal data of prosumers and consumers. The privacy of consumers can be breached by middlemen who can track patterns of daily activities of consumers, or by malicious access to the centralized database, in which case the whole system is compromised [41], [43].

Besides the general disadvantages of a centralized system, when talking about the energy sector, a few other specific issues arise. With an increase in small local renewable energy producers - prosumers, and a general shift towards local markets [5], new challenges for the energy sector emerge. These are mostly the issues of smart grid management which require innovative decentralized solutions [41]. Both large utility companies and grid operators, as well as small prosumers and customers, could gain from the benefits that blockchain will provide by decentralizing the field. For the utilities and grid operators, the possibility to handle peak demand and grid balancing through decentralized demand/supply load control can lower operating costs and increase energy efficiency [41]. This provides an incentive for them to support blockchain projects since they can integrate the volatile energy created from renewable sources to the grid while keeping the costs low. Consumers, on the other hand, benefit from getting more flexibility in selecting which price to pay for energy in decentralized structures rather than having to stick to government and energy company-determined rates [44].

4.3.2 Sustainability and Social Fairness

The use of renewable energy resources in the world is increasing [44] and it should continue to do so in the following decades to reach independence from fossil fuels. This, however, brings several challenges to the whole energy sector. With the emergence of many distributed energy prosumers, conventional models are struggling to scale up [41]. Due to the unpredictable and variable nature of renewable energy generation [41], more flexible management solutions are needed for the grid [5]. Distribution system operators are often forced to reduce energy production to avoid putting the grid system at risk. This is not the best approach since it impacts the aims of increasing renewable energy integration and lowering emission targets [41]. Blockchain can provide ways to solve problems related to the variable energy output from renewable sources.

Some authors claim that the current business model of the energy sector is encouraging unsustainable practices [5] and they are related to not only the use of fossil fuels but also low transparency and credibility [43], [45]. With the implementation of blockchain, the transparency of the transactions is increased, which enforces the accountability of participants for any disreputable activities. Some blockchain applications are aimed at the improvement of energy access in developing countries and minimization of fuel poverty by reducing energy prices and introducing demand-side management [5]. In these geographical areas where the traditional centralized grids are not fully developed, blockchain solutions might have a big impact in establishing the electricity network [6]. Additionally, through the implementation of new sustainable business models and innovation in the energy domain, further reduction of carbon emissions will be possible [5].

4.3.3 Real-time Data Management and Internet of Things

The time for making critical decisions based on real-time supply and demand has decreased in the energy sector, as it has in other industries [41]. The importance of having the right data at every moment is now higher than ever. The added amount of data and digital capital generated in the energy sector requires precise, reliable, and transparent storage. Additionally, a direct and cost-effective transfer of information without the need for costly intervention of third parties is needed [6]. Blockchain solutions can, in theory, provide more efficient monitoring, maintenance, and better response times in critical situations by using automatic smart contract execution [5]. They can also aid in the detection of any disturbances that could threaten grid stability [41]. This need for real-time data management is also closely related to the trend of the Internet of Things (IoT). Smart metering of energy flow is being implemented throughout the grid [41]. A new area in IoT research, named Internet of Energy (IoE), or the Energy Internet has emerged as the next level evolution of the smart grid, which incorporates integrated data flow and communication between different elements of the grid [46]. However, due to the limitations of IoT devices, IoT systems can sometimes struggle with the massive data traffic needed [47], and this is another problem for which blockchain solutions can be developed.

5 Use Cases of Blockchain in Energy Domain

According to research by Andoni et al. from 2019, more than a third of companies and start-ups using blockchain in the energy domain have been focused on decentralized energy trading. Other prominently represented areas are cryptocurrencies and tokens, the Internet of Things, security, and grid management [7]. For some application areas in the energy industry, there is not a large difference in the operation of blockchain and other technological solutions. These applications can be implemented in a decentralized manner, but industry experts claim that they are not as necessary or impactful as more innovative use cases. One example of such a use case is the possibility to perform automatic billing for consumed electricity on the blockchain [6].

For a lot of projects and initiatives involving blockchain in the energy domain, it is difficult to provide a clear classification and distinction between use cases. Many companies combine multiple applications in their projects and provide solutions that span multiple use cases [6]. For this thesis, the projects and initiatives are classified according to their most significant use case and the area where the project is most influential. It should be noted, however, that many of the blockchain applications mentioned can serve several use cases at the same time, and they can also be integrated with other frameworks to have a greater impact. Based upon the classifications of use cases proposed by Andoni et al.[7], Bürer et al.[5], Brilliantova and Thurner [6], and Wu and Tran [8], which are presented in Section 2, the following classification is used in this thesis (Figure 6):

- Energy Internet and smart grid management – use cases in the stabilization of the grid, IoT devices, and virtual power plants,
- Peer-to-peer energy trading – use cases for microgrid peer-to-peer trading,
- E-mobility – use cases in electric vehicle charging and vehicular networks,
- Transactions and payments – cryptocurrencies and tokens used for energy market transactions,
- Renewable energy certificates and carbon credits, and
- Use cases in the oil and gas industry.

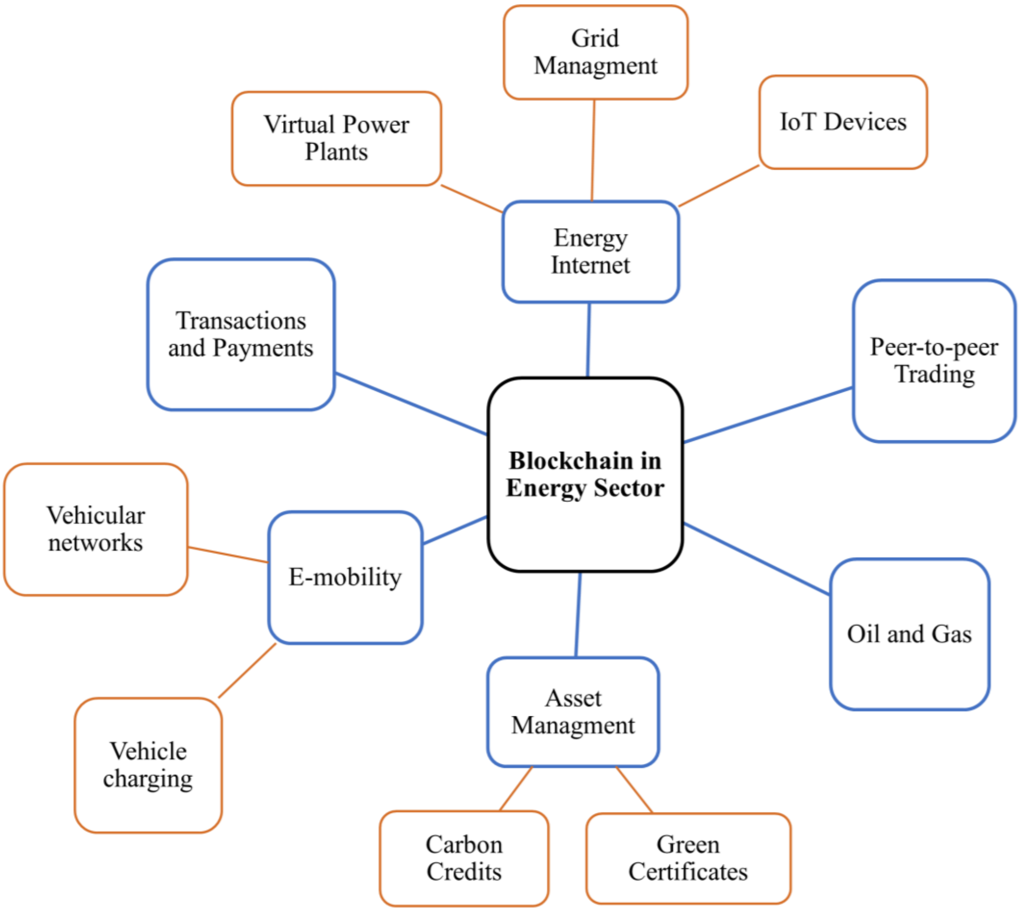

Figure 6 Use cases for blockchain in the energy sector. Source: Author's elaboration.

In the next subsections, the overview of the selected use cases is presented, relevant theoretical research and simulation models are described, and important pilot projects, start-ups, and companies are listed.

5.1 Energy Internet and Smart Grid Management

A large number of blockchain applications in the energy sector are related to the concept of the Energy Internet. This new frontier in the energy sector has emerged in the last decade and it represents an energy network with the aim of connecting all electricity system components and enabling communication and sharing of both energy and information between them. Components of the Energy Internet network can be microgrids, distributed energy producers, consumers, and private and governmental energy girds. Energy Internet relies on advanced sensors, smart meters, and control methods of the smart grid but offers much more than that. It is a robust, open, and competitive network for energy generation, distribution, and consumption [48]. Energy Internet is an appealing concept for both industry and academia to explore, but there are still several challenges to address before the technology can be widely adopted. Efficient management of distributed renewable energy sources is one of them. One of the technologies which could contribute to the efficient implementation of the Energy Internet is blockchain [8].

The concept of the Energy Internet can be implemented in many ways, not only using blockchain solutions. However, it is necessary to have the data transferred through the network transparently and safely. In a traditional centralized solution, this would mean that there needs to exist a trusted organization in charge of this data and transactions which should control and manage it effectively and transparently, which might present a challenge. Additionally, a large number of producers, prosumers, and consumers of energy incur larger operating costs for this centralized entity, which opens up the possibility of deploying decentralized solutions. Wu and Tran have found that the blockchain is aligned with the Energy Internet in four different aspects: decentralization, interconnected autonomy, openness, and intelligence. They have concluded that due to the possibility to solve bottlenecks in the Energy Internet like distributed decision-making with blockchain, it is a feasible technology for this implementation [8].

One of the use-cases where blockchain can provide benefits to the Energy Internet is in multi-energy systems. These systems combine multiple different energy sources such as electricity, heat, natural gas, and others and enable energy conversion between them and maximize the efficiency of energy consumption. Several authors have explored the possibility to manage these multi-energy systems through blockchain, which would enable real-time pricing and energy cost settlements performed through smart contracts [8].

Blockchain can also be utilized in the creation of Virtual Power Plants (VPP) [6], which are an important aspect of the Energy Internet and typically used for management and aggregation of distributed power resources. Decentralization and reliability make the blockchain a suitable choice for building VPP with low cost of transactions between users and the VPP [8]. Mnatsakanyan et al. have created such a framework that uses blockchain to manage transactions on the VPP, providing transparency to the system. The blockchain-based VPP system contributes to power grid digitalization and enables easier participation of distributed energy resources. Their blockchain implementation avoids the possible transparency issues and disputes between distributed asset owners and energy aggregators or grid operators [49]. A similar system was developed by Wei and Yue with increased information security offered by the blockchain platform [8]. The city of Busan in South Korea has already launched a blockchain-based VPP project in partnership with Busan City Gas company. The platform is claimed to provide more efficient operation and better adapt to energy consumption demands [50]. The concept of VPPs on the blockchain has also been explored by Japanese Kyocera in cooperation with LO3 Energy. In 2019, they have announced a project which incorporates Kyocera's solar modules and batters with LO3 Energy's blockchain platform. The energy is traded in a microgrid with the transactions recorded and verified on the blockchain. The long-term vision of the project is to enable external participants to use the platform to manage their controllable load. With the changes in the Japanese retail energy market which are expected in the future, the virtual power plant could participate in the wholesale market and support more solar power use. The test phase of the project is expected to last until 2021 with the possibility to be extended further [51].

Compared to the traditional VPPs, blockchain solutions are claimed to provide lower transaction costs and higher security. The comparison of the two approaches can be found in Table 2.

Feature	**Conventional VPP**	**Blockchain-based VPP**
Information security	Low	High
Transparency	Low	High
Transaction costs	High	Low
Real-time data affordability	Low	High

Table 2 Comparison of conventional and blockchain-based VPPs.

Source: Adapted from [8], [52].

Wu and Tran suggest that one of the main arguments for use of blockchain in the Energy Internet is that it can improve the information security for power grid companies. Instead of relying on dedicated line transmission systems or using vulnerable public networks, they suggest that energy systems could rely on blockchain for the solution to the security issues in the energy sector [8]. Energy Internet relies on smart grid technology which enables utility companies and their consumers to have better communication and offers more flexibility for users to optimize their electricity usage. In this communication, the sensitive data is usually sent through the internet, which can be compromised and lead to unfair billing of the consumer by the utility company [53]. Several authors have explored the possibility of solving data integrity issues for smart grids by using blockchain.

Gao et al. have developed a system named GridMonitoring which focuses on secure communication between consumers and utility companies. This system relies on the transparency, provenance, and immutability properties of the blockchain. The proposed framework is built with the following flow of processes: a registration and authentication layer that allows users to request and obtain access to electricity, a smart meter that can monitor electricity and gas flow in real-time and transmit the readings to the blockchain network, and data processing on the smart grid network performed by processing and consensus nodes. The whole process is governed by smart contracts [53].

Besides information integrity, blockchain can be utilized in smart grid solutions to help match the demand to the available energy supply. Pop and al. have suggested a system that aims to balance energy demand with output by encouraging distributed energy producers to shed or change their energy demand to cope with peak load times for energy storage. Usage data from smart meters is stored on the blockchain and the expected energy flexibility is determined by smart contracts. Rewards and penalties are distributed to prosumers based on whether they match their energy demand and production to the required smart grid level. Their system was developed on the Ethereum blockchain in the Solidity programming language. The results of a smart grid simulation involving twelve distributed energy producers showed positive results, with near-real-time changes to energy demand [41].

In parallel, Danalakshmi et al. have created a blockchain platform for reactive power optimization and price management. Their research suggests that conventional energy pricing methods are restrictive and not transparent. They have proposed a microgrid architecture for generators, users, and prosumers, in which the distribution system operator acts as the network manager and is responsible for loss computation, voltage point balancing using an optimization algorithm, and network maintenance. Smart meters are used to calculate the actual power demand, and a self-balanced differential evolution algorithm is used to optimize it. The service providers are chosen based on customer demand, minimal system loss, price, and service quality criteria. The energy is transmitted by the power distribution and the relevant information is provided to the DSOs once a suitable service provider has been selected. Excess power is made available on the agents' blockchain accounts. The system is said to provide improved efficiency, accountability, and security, as well as better utilization of computational resources, optimal reactive power dispatch, and power flow minimization [44].

When considering practical blockchain implementations in smart grid management and Energy Internet, one project stands out as particularly important. The Energy Web Foundation is a project created by Grid Singularity, a German green blockchain technology business, with funding from Rocky Mountain Institute, a United Sates organization that supports sustainable energy solutions [5]. The Energy Web Foundation aims to give individuals and businesses the resources they need to create scalable, open-source blockchain systems that are customized to the needs of the energy sector. They provide tools that are catered to creating energy-efficient solutions on their Energy Web Chain platform launched in June 2019. Energy Web Chain is a blockchain based on Ethereum but utilizing the PoAu consensus mechanism for its better performance characteristics. They have developed three different software development toolkits for blockchain:

- EW Origin (a modular framework for developing decentralized applications to issue, exchange, monitor, and report information in renewable energy systems),
- EW Link (for integrating physical devices to the blockchain in a safe manner),
- and D3A (grid management and decentralized energy trading modeling platform) [31].

A platform named Energy Web Decentralized Operating System EW-DOS encompasses the entire system developed by the Energy Web Foundation, including the above-mentioned software development kits, Energy Web Chain, and all middleware services [54]. This infrastructure can be used for various use cases in the energy blockchain domain.

Another significant implementation case for blockchain in grid management is the grid balancing needed to handle energy production peaks. This issue is critical in countries where a high percentage of energy is derived from renewable sources since the grid may be harmed by excessive renewable energy output. In Germany, for example, offshore wind farms in the country's north provide more electricity than can be consumed. As a result, they were occasionally cut off from the power grid [41]. This is a problem that was addressed by TenneT, a German transmission system operator, in collaboration with Sonnen, an energy storage producer, who designed a system for storing the excess power generated by windfarms in home and electric car batteries. The blockchain implementation is based on Hyperledger Fabric and the development was carried out by IBM. The preliminary results of a 2017 pilot study showed that small decentralized flexible units such as home batteries were able to effectively stabilize the electricity system. Sonnen has in total launched three virtual power plants for balancing renewable energy using their home batteries with the most recent one announced in March 2020. Their latest project relies on the blockchain technology from Energy Web Foundation and the free storage capacity is traded on the EW Origin digital exchange. When the grid operator predicts a possible bottleneck in the system due to excessive generation of power, the demand for storage is announced via the platform. Origin's software then matches this request with the available storage capacity in Sonnen's virtual power plant. All transactions are written on the blockchain using smart contracts and the payments for storage are transferred automatically from the grid operator to Sonnen [55].

The problem of handling the variable outputs of energy from renewable sources will still be present in the upcoming years for Germany [56], [57], especially with the EU's current goal of climate-neutral Europe by 2050 [58]. Non-battery storage (such as hydrogen, seawater, and aluminum storage), cross-border exchange through smart transition networks [5], and different electricity price zones that would incentivize high electricity customers to switch closer to renewable energy sources are other potential solutions to the problem currently researched [56]. Each approach to managing this issue has its shortcomings, which are especially apparent in inter-seasonal renewable energy variation cycles. For this reason, industry experts suggest that a combination of more than one solution should be considered [59]. A summarization of the possible approaches can be seen in Figure *7*.

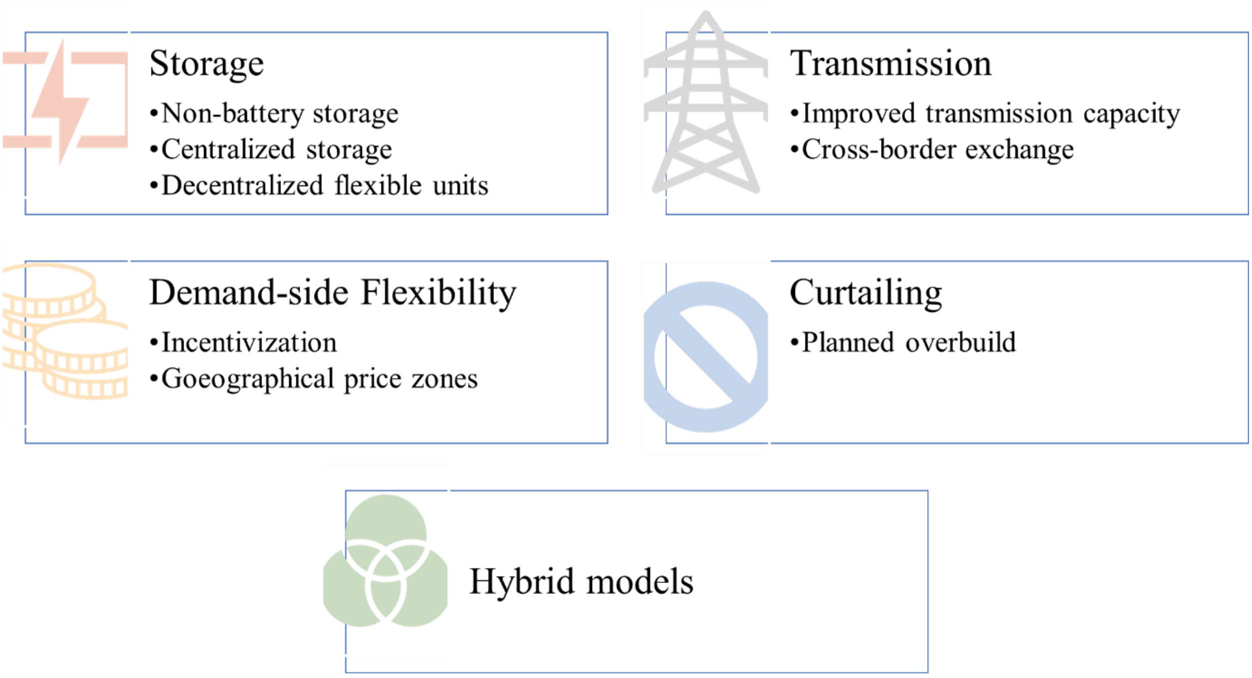

Figure 7 *Surplus renewable energy management approaches.*

Source: Adapted from[5], [56], [59].

Blockchain can have an important role in several of these solutions, especially in decentralized battery storage and energy demand management.

5.2 Peer-to-peer Energy Trading

One of the most researched areas of blockchain application to the energy sector is peer-to-peer energy trading. Even though it is an important aspect of the Energy Internet, this use-case can be explored independently since it can be implemented in less complex approaches as well. Microgrids, energy harvesting networks, and networks using electric vehicles as energy storage systems are the three major peer-to-peer energy trading scenarios [60]. The impacts and possibilities of using electric vehicles in this manner are discussed in more detail in Section 5.3 and this section focuses on peer-to-peer trading in microgrids.

When talking about energy trading systems, we can differentiate three implementations with varying levels of centralization and control: centralized, decentralized, and distributed energy trading. These implementations refer to the relationship between the energy consumers, prosumers, and the utility grid. A simple graphical representation of the three different systems is shown in Figure 8.

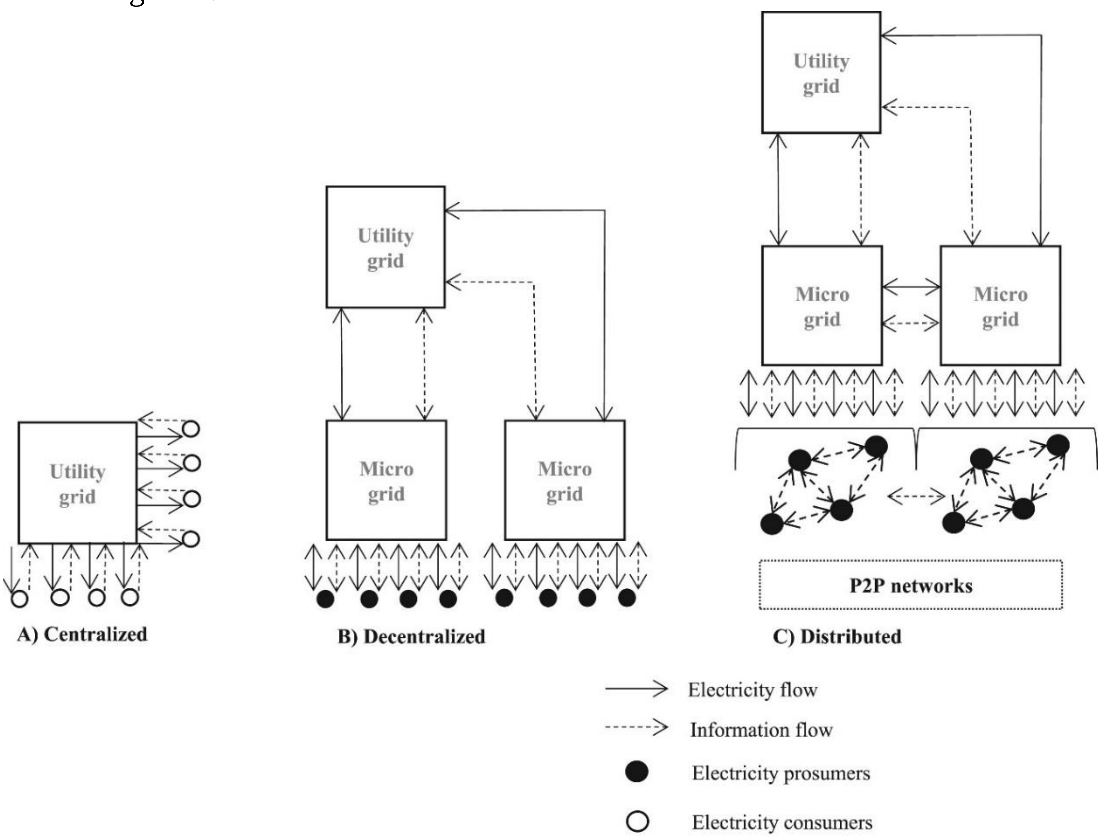

Figure 8 Centralized, decentralized, and distributed energy trading. Source: [61, p. 2].

The traditional centralized system enables the energy flow from the utility grid to energy consumers. With the increased number of energy prosumers who both generate their own renewable energy and consume the energy from the utility grid, it is necessary to implement decentralized solutions to allow them to participate in the grid effectively. However, blockchain solutions can go a step further and offer a distributed peer-to-peer energy trading between participants of the microgrid [61]. The terms decentralized and distributed sometimes appear interchangeably in research and practice since they can both describe certain blockchain applications and technologies. In this section, the possibilities of energy trading in small local grids where small distributed renewable energy producers interact with their neighboring consumers on a peer-to-peer basis are explored.

In peer-to-peer networks, important information such as grid conditions, current energy cost, power supply and demand, should be available to the nodes in real time. In blockchain-based solutions for peer-to-peer trading, a big advantage is that the transactions and billing can be executed automatically using smart contracts and payments could be facilitated through cryptocurrency based on the data from the smart meters. Participants in the network can affect the prices by participating in auction mechanisms [61].

Implementation of peer-to-peer energy trading on the blockchain has great potential in less developed countries where there are communities that are not connected to the electricity grid yet. For example, in South Africa, there is a great potential to create distributed peer-to-peer trading in microgrids. Blockchain applications, combined with shared ownership of energy equipment, have the potential to electrify whole communities while leapfrogging the implementation of the traditional centralized grid completely [6].

Energy trading in microgrids using blockchain has been extensively explored in the academic literature with multiple authors suggesting frameworks for distributed peer-to-peer trading. Li et al. have developed a system for secure energy trading on the blockchain focused on the industrial Internet of Things. The arguments for developing such a system are improved security, transparency, and privacy for decentralized energy trading. Their energy trading framework is designed with three main properties:

- unified consortium blockchain which caters to all three typical energy trading scenarios (microgrids, energy harvesting networks, and vehicle-to-grid networks),
- credit-based payment scheme which enables faster and more frequent transactions through coin loans, and

- pricing using Stackelberg game mechanics which maximizes the economic benefits of coin creditors.

The model was tested for security and performance and showed promising results [60].

Aitzhan and Svetinovic have created PriWatt, a token-based decentralized energy platform that allows smart grid participants to set energy prices anonymously and conduct secure trading transactions. The blockchain is implemented similarly to Bitcoin, with Python 2.7 as the programming language and the assistance of many libraries, including BitcoinJ. An interesting feature of PriWatt which makes it especially interesting is that it can operate as a decentralized network with no centralized authority, or it can be designed so that distribution system operators (DSOs) act as mediators in trading transactions. The framework has several drawbacks, including scalability problems and transaction speed issues which are inherent in Bitcoin-based blockchains [42]. Another interesting topic for energy trading in microgrids is the role of batteries and their contribution to the system's stability, which was explored by Lüth et al. [62].

Han et al. have devised a comprehensive energy trading system based on smart contracts. They concentrated their efforts on the retail electricity sector and developed a mechanism that represents market quotes, balances player earnings, and encourages the use of renewables. They suggest a three-dimensional structure for the framework. The Ethereum blockchain was chosen as the technology of choice for their project because it easily facilitates the development of decentralized applications and supports smart contracts. The project was created using the Remix integrated development environment and the Go Ethereum implementation in Solidity programming language. Proof of Stake was the consensus protocol of choice [43]. Monroe et al. proposed a blockchain peer-to-peer trading framework based on an agent-based model. The framework is based on the Power Ledger blockchain platform for exchanging renewable energy. Data from the RENeW Nexus trial system in Perth, Australia, where a peer-to-peer energy sharing project was piloted, was used to validate the system [63].

Several authors have focused on constructing the best strategies for matching peers in the energy trading process. Yu et al. have developed a method that uses Bayesian correction to predict bidding strategies. Their scheme encourages local transactions by arranging the agents in a hierarchical order. Hyperledger technology was used as a basis for blockchain implementation [64]. Zhang and Shi have worked on an intelligent transaction model on the blockchain which improves the power matching decision-making process. They claim to have achieved a system that enhances transparency and security using smart contracts [45]. Horta et al. have criticized the double auction mechanism suggested in several other papers and have instead developed a proof-of-concept working on locally balancing renewable energy production and flexible demand [65].

When considering the practical implementations, one of the most important projects in blockchain peer-to-peer energy trading is Decentralized Autonomous Area Agent (D3A) developed by Grid Singularity and Energy Web Foundation [5], [7]. Anyone can use this open-source software to create virtual grids to simulate energy exchange. The goal of the developers of D3A is to provide blockchain solutions that will reduce energy costs, promote the use of renewable energy, and create a place for DSOs to participate in the system with reduced resources and smaller operating costs. The platform aims to include tools for energy data analysis, benchmarking, smart grid management, green certificate trading, and investment decisions in addition to energy exchange [66].

A blockchain-based renewable energy trading network has already been introduced and it is being used by the Lithuanian company WePower. Their business model is based on the fact that blockchain allows for more liquid energy trading, enabling project developers to raise funds by selling power contracts at below-market rates. Renewable energy contracts are liquidated on the wholesale market or sold and purchased on the blockchain. Since the energy comes directly from the manufacturer rather than through wholesale market processes, lower prices are possible [67].

A famous example of peer-to-peer energy trading through blockchain is TransActive Grid, a pilot project carried out in 2016 on a microgrid in Brooklyn, New York. This project was carried out by LO3 Energy in cooperation with the blockchain company Consensus Systems [8]. The implementation of the project was based on the Ethereum blockchain. The platform received a lot of support from big technology companies, including Siemens [5]. Ten neighboring households have participated in the pilot project and they have used blockchain to trade renewable energy created from solar power panels installed on the house roofs [8]. The project has remained active and is continuing to exist as the Brooklyn Microgrid community microgrid initiative [68]. In December 2019, the Brooklyn Microgrid has received a green light for the creation of a regulatory sandbox environment which enabled them to expand the project to more than two hundred participants. The regulatory sandbox was required to allow prosumers to sell energy directly to their neighbors since the current state regulations in New York only allow registered electric utilities and approved retailers to sell electric energy [69].

Following the success of the Brooklyn Microgrid, LO3 Energy has become very active in developing microgrid peer-to-peer trading solutions on the blockchain with their cloud platform Pando being tested for commercial applications across the United States, Europe, and Japan. Pando is targeted towards utility companies and retail electricity providers which would like to better incorporate distributed energy producers and support their participation in the energy markets. The company is actively working on the platform enhancement and has secured additional investment from Shell Ventures and Shikoku Electric Power at the beginning of 2021 to help support the development [70]. LO3 Energy is quite involved in the field of energy blockchain, cooperating with multiple other companies such as the European electricity exchange EPEX Spot in 2017 [71] and Energy Web Foundation in 2018 [72].

In the Perth neighborhood of Australia, a blockchain energy trading platform Power Ledger was piloted in 2016 [5]. Since then, Power Ledger has been a significant player in the energy blockchain arena, and they have made significant progress in developing and implementing peer-to-peer energy trading projects in microgrids. The Power Ledger Platform relies on the use of the Power Ledger Token (POWR) and an “exchangeable frictionless energy trading token”, Sparkz [73, p. 11]. The platform is operating in several technology layers, including the Ethereum blockchain for third-party transactions and their own PoS based and private EcoChain which can handle energy transactions at a low cost [73]. The company has already successfully implemented projects in countries all over the world, including Australia [74], Japan, France, and the United States [75]. Most recently, Power Ledger has established cooperation with Indian power distribution utility Tata Power DDL to bring peer-to-peer trading of solar power between 140 sites in Delhi. Using the platform, consumers can select which seller to buy energy from and the transactions are settled automatically and transparently stored on the blockchain [76]. Besides peer-to-peer energy trading, Power Ledger is also offering solutions for the wholesale energy market, electric vehicle charging, and carbon trading [73].

On the European market, German company Ponton company created the Enerchain network for regional microgrids and wholesale energy trading. They developed WRMHL, a custom, application-agnostic blockchain platform written in the Java programming language.

The system allows for market-based control of energy demand and supply [77]. One big benefit of peer-to-peer energy trading is the possibility to easily match energy demand with available supply. Electron, a flexible marketplace in the United Kingdom, was introduced to tackle this issue and try to balance power demand and supply. With blockchain-based asset registers, the platform was dubbed "energy eBay." Consumers who have reduced their energy consumption to balance the existing supply are rewarded [7]. Several non-blockchain implementations of the peer-to-peer energy market are also live, such as Piclo in UK and Vandebron in the Netherlands [43], [78].

5.3 E-mobility

The use of electric cars worldwide is increasing with more than 4.7 million electric vehicles in operation in 2019 [79]. The cost-effectiveness and battery storage of produced vehicles have increased greatly over the last few years, but the charging infrastructure is still lacking, and it is currently the largest barrier to mass-market adoption of electric vehicles. There is a lack of uniformity and standardization for the charging station which can lead to inconveniences for users [8].

An increase in the use of electric cars has led to the emergence of a new field of Internet of Things research, coined as the Internet of Vehicles (IoV) and also known in the literature as vehicular networks. Research and new proposed frameworks in this field are split into several focus areas, including peer-to-peer energy trading between vehicles, data credibility for communication in vehicular networks, and improvements to charging infrastructure. According to Brilliantova and Thurner, the use of blockchain in the domain of e-mobility has the greatest potential to have a large effect in the near future compared to all the other currently explored use-cases [6]. Electric vehicles can have a great impact if utilized in grid balancing and energy storage solutions. Some industry experts suggest that the impact that electric vehicles could have in this aspect is so big that the cars could be possibly distributed free of charge if their owners participated in this new business model and lent the vehicle’s battery for use in grid balancing and energy storage overnight, for example [6].

There have been several research papers tackling the topic of blockchain for electric vehicle networks. Kang et al. have developed a localized peer-to-peer trading system for plug-in hybrid electric vehicles named PETCON. Their model incentivizes the owners of such electric vehicles to discharge their vehicles to balance local electricity demand in local markets. The model is based on consortium blockchain which employs local aggregator nodes.

For transactions between charging and discharging vehicles, the authors propose the use of a cryptocurrency. The details about the transaction are encrypted and signed with digital signatures before being stored on the blockchain, and pseudonyms are used to preserve the privacy of participating vehicles. An iterative double auction mechanism is proposed for optimizing electricity prices and the volume of exchanged electricity. PETCON's numerical results in a simulated environment revealed that it had maximized social welfare while also performing well in terms of electricity utilization and efficiency [22].

Asfia et al. have proposed a framework for handling interactions between charging systems and electric vehicles through permissioned blockchain and smart contracts. The framework aims to solve trust issues between the two parties and provide a smart contract algorithm that meets the individual energy usage preferences of electric vehicles and optimizes the operator's utility. Thanks to the decentralization properties of blockchain, the system framework is said to significantly improve the trading mechanism and mitigate security risks. However, it currently lacks empirical evidence or simulation studies to support that claim [80].

Aside from electric vehicle charging, a few authors have looked at using blockchain to improve electric vehicle communication in IoT systems. While this aspect of vehicular networks is not technically a part of the energy market, it is fitting to include it in this thesis since it represents a significant innovation in the field of e-mobility. Li et al. have developed CreditCoin, a blockchain-based privacy-preserving announcement network that aims to enhance vehicle communication in IoV networks. The model is built in Java using the BitcoinJ library. CreditCoin incentivizes users to exchange traffic details such as current accidents, traffic queues, and road construction. Reputable information generates cryptocurrency coins and improves the credibility of the vehicle in the network. Experimental results have shown that CreditCoin is effective and realistic in smart transportation simulations [81].

Yang et al. have also created a blockchain-based reputation framework for data integrity evaluation in vehicular networks. Four types of entities participate in the system: a trusted authority, an ordinary vehicle, a malicious vehicle, and miners. When a message about the traffic environment is broadcast by a vehicle on the network, other participants measure the sender's reputation and assess the message's credibility using ratings stored in the blockchain. Ratings are a representation of a vehicle's past behavior, which must be modified regularly. The framework's goal is to prevent malicious vehicles from broadcasting fake messages with the purpose to degrade traffic security or quality, or from broadcasting fake ratings which can degrade the reputation system's reliability. Additionally, the trusted authority can use the ratings to award reputable vehicles with benefits such as lower road toll fees or insurance premiums. Simulation results comparing the blockchain-based system and a system where each vehicle individually detects and stores ratings have shown that the blockchain-based framework outperforms the individually-detect one, given that there is a small percentage of malicious agents [82].

Even though there are not many ongoing blockchain initiatives for e-mobility, several major pilot projects have been completed. In 2016, a cooperation between German energy company RWE and an innovative blockchain company Slock.it has led to the foundation of BlockCharge – a framework for electric vehicle charging with transactions managed on the blockchain. The company's business use case is based on the premise that the current charging model's price differences between different charging stations are detrimental to consumers. Additionally, they claim that electric vehicle adoption is hampered by a lack of interoperability and transparency in the current charging infrastructure. BlockCharge aims to solve this problem with the use of smart plugs and a smartphone application. Smart plugs are physical devices that would enable the charging of the electric vehicle at any electric charging point plug and the transactions will be handled by blockchain using a smartphone application as an interface. The benefit of using the blockchain would be in finding the best price for consumers. The company would profit from the one-time purchase of the smart plug and a microtransaction fee for the charging process [83]. However, BlockCharge received criticism for relying on the Ethereum blockchain as the main technology since the high transaction fees on Ethereum make the model financially unfeasible [84].

Share&Charge is a German company that provides an interface for sharing electric vehicle charging stations with payments executed through blockchain. Owners of electric charging stations can use the platform to rent out their stations in specified periods to interested buyers of electricity. Electric vehicle drivers, on the other hand, can use the Share&Charge application to find available charging stations in their surroundings. In 2017, the application supported more than a thousand charging stations in Germany [85]. Through a partnership with an electric vehicle infrastructure company from California, eMotorWerks, the platform was introduced to the North American market through an application named JuiceNet [8]. With the help of this platform, electric charging companies aim to reduce the anxiety of electric vehicle users about the lack of charging stations. On the other hand, they also provide a monetary benefit for owners of electric vehicle charging stations and incentivize them to provide charging services [85]. In November 2017, Share&Charge participated in the Oslo2Rome initiative which gathered multiple companies and created a network of cross-border charging points throughout Europe. The idea of the project was to create a pan-European electric vehicle charging network powered by blockchain and to suggests that a blockchain implementation can solve the roaming problems the electric vehicle charging network in Europe is currently facing [86]. In 2020, Share&Charge launched their open-source platform Open Charging Network, which integrates with the Energy Web Chain and enables information exchange for participants of the charging system. The first version of the software was released in October 2020 and active improvement and development of the Open Charging Network is still ongoing [87].

5.4 Transactions and Payments

Rather than reimagining the business model of energy production and delivery, many ventures in the energy market used blockchain to improve the process of transactions and payments for energy using cryptocurrency. The majority of solutions in this field are empirical and practical projects with few theoretical explorations and academic research studies.

SolarCoin, advertised as a cryptocurrency backed by sunlight, is one of the most well-known projects in this sector. SolarCoin can be earned by owners of solar photovoltaic installations in 17 countries [5]. This project functions similarly to green electricity attribute certificates, but it raises the issue of double-counting if the produced renewable energy is rewarded with both SolarCoin and another green certificate trading scheme. Thus, it is suitable for use by small renewable energy producers but might face issues if implemented for large-scale operations. M-PAYG, a company from Denmark, has developed a system that uses cryptocurrency to monitor solar power output in real time and provides prepaid solar energy systems to people living in poverty [7]. Small solar energy prosumers can now tap into new revenue sources thanks to this framework. The company has already implemented this system in Tanzania with plans to expand to Uganda and Malawi [5].

Coinfy specializes in blockchain-based cross-border payments [5] and Bankymoon, based in South Africa, facilitates financial transactions on the blockchain to help developing countries gain access to electricity [5]. Bankymoon employs Bitcoin-compatible smart meters that only release power after a cryptocurrency top-up has been made [7]. This gives potential donors the option of donating cryptocurrency for the use of electricity in a specific place such as a school. The transactions are automatic and transparent. Usizo, a crowdfunding platform that allows donations to smart meters in schools, has also been launched [88]. SunExchange is a project that seeks to close the funding gap for African commercial solar projects by allowing everyone in the world to buy solar cells placed in Africa and generate income from them [5]. Other notable projects regarding transactions and payment use cases are ImpactPPA and EcoKraft [5].

5.5 Renewable Energy Certificates and Carbon Credits

Renewable energy certificates are commodities that signify that a certain amount of electric power was created from renewable energy sources such as solar or wind. Different terminology is used in literature to describe these commodities depending on the region and specific implementation, and they can be labeled as renewable energy credits [89], green certificates [90], guarantees of origin [91], or Energy Attribute Certificates (EACs) [92]. These certificates are typically verified and issued by a national registry to renewable energy producers, and they can be traded between parties [90]. However, the current implementation of green certificates does not suit the small prosumers of renewable energy in microgrids. They are unable to participate in the issuance of green certificates due to the high costs associated with the process, and they are searching for other ways to monetize their renewable energy output [7]. According to Imbault et al., another problem that can be considered when talking about the current green certificate energy system is the issue of trust in the current centralized mechanisms which prevent double counting of generated renewable energy [90].

Several attempts have been made by academics, businesses, and start-ups to provide blockchain-based solutions to these issues. Imbault et al. investigated the possibility of developing a green certificate issuing and trading system that was incorporated with the Predix industrial IoT system. They created a proof-of-concept model and tested it in a local eco-community in the French district of Rueil-Malmaison. The proof-of-concept was created with the help of enterprise blockchain application development platform Corda, however, the authors suggested that a custom blockchain solution would be needed for large-scale implementation. They concluded that, while much more research and testing is required in this field, blockchain has the potential to be used for trusted assessment and tracking of energy-related assets such as green certificates [90].

Regarding the practical implementation of blockchain-based green energy certificates, LO3 Energy has been successful in implementing a pilot project in cooperation with Green Mountain Power utility company in Vermont in 2019. The pilot project focuses on delivering renewable energy credits to businesses that want to use green energy sources. The energy is generated primarily by households owning solar panels. The prices on the market are determined via the auction platform developed by LO3 Energy. Each day, the businesses request the required number of certificates and indicate the maximum price. The trades are settled automatically once a day for renewable energy generated the previous day and all transactions are transparent to the participants. The billing process and compensation to the households are handled by the utility company, which takes a 5% transaction fee to cover the operating costs. The utility also provides any additional green energy which could not be supplied by the households. The benefit of the platform compared to other renewable energy credit options is that the businesses can be certain of the exact location and origin of the produced energy. Additionally, instead of a typical six-month lag for renewable energy credit sales in this area, the trades on the blockchain platform happen daily [93].

KWHCoin project has suggested an alternative approach to renewable energy counting by creating a cryptocurrency that is awarded for the generation of units of clean energy. The value of the KWHCoin is that it represents active renewable energy generation and distribution. To avoid issues with duplicate counting of renewable energy, KWHCoin is focusing on the edges of the grid where smaller distributed energy resources such as residential market solar panels are located [5]. A similar approach has been taken up by Veridium with their Ethereum-based token TRG [7]. Other initiatives have sought to improve the conventional way of issuing and trading green certificates by implementing them on the blockchain. Examples of such companies are Nasdaq [7], Volt Markets (built on Ethereum) [5], and Spanish FlexiDAO [94].

Besides renewable energy certificates, blockchain can be used in similar ways to manage carbon credits trading. These credits are traded in a similar way to renewable energy certificates, but instead of referring to clean electrical energy, they guarantee lower carbon emissions, usually amounting to one metric ton of avoided CO_2-equivalent emissions [89]. The carbon credits market is currently experiencing issues such as a high volume of requested emissions certifications, and complexity in the tracking of transactions. With a blockchain solution, the issuing of carbon credits and their trading could be performed automatically through smart contracts which would prevent tampering, reduce information asymmetry, and cut operating costs [8].

In 2019, Hartmann and Thomas have explored the possibility of applying blockchain to carbon trading in Australia. They have constructed guidelines for the development of a custom blockchain which are based on previous research in blockchain use for carbon trading. The proposed model is developed with regard to the current regulations and institutions participating in the Australian carbon market. They advocate the use of partial decentralization on a private blockchain utilizing PoAu consensus protocol and enabled smart contracts. This model should provide transparent, effective, and financially feasible carbon trading on the blockchain [95].

In 2017, IBM and China's Energy Blockchain Labs collaborated on a project that resulted in the creation of the world's first platform for green asset management utilizing blockchain. Using the platform will significantly accelerate the production of carbon credits and development costs will be reduced by at least 20% [8]. American initiative Clean Energy Blockchain Network (CEBN) has also launched a project to promote clean fuel production by awarding Low Carbon Fuel Standard (LCFS) credits to clean fuel providers such as electric vehicle charging station owners [89]. They have developed the platform in cooperation with Power Ledger and Silicon Valley Power [96]. Other companies with similar projects launched are Greenium, Inuk, Veridium, Poseidon, DAO IPCI, and CarbonX [7].

5.6 Use Cases in the Oil and Gas Industry

Oil and natural gas are energy resources that currently dominate the global energy market and are expected to do so for the next few decades [19]. Thus, when talking about blockchain in energy markets, it is essential to consider the applications in this industry as well. However, relative to the electricity sector, there are substantially fewer initiatives investigating blockchain usage in the oil and gas sector, which can be due to higher entry barriers to the market and a lower potential for blockchain involvement in the industry's primary activities [6].

There have been a few attempts in the current literature to summarize the potential applications of blockchain in the oil and gas sector. Lu et al. have listed the following aspects in which blockchain technology can be implemented for the oil and gas industry: trading, management and decision making, supervision, and cybersecurity [19]. Similarly, Mingaleva et al. have divided the use cases of blockchain in the oil and gas industry into the following areas: workflow management; improving the efficiency of equipment usage, logistics and IoT technology, hydrocarbons market, and information security [97]. In general, Brilliantova and Thurner have concluded that most blockchain applications in the oil and gas sector concern the optimization of the existing business processes and reduction of operating costs, rather than energy-specific activities [6]. A summarization of possible applications for blockchain in the oil and gas industry is in Figure 9.

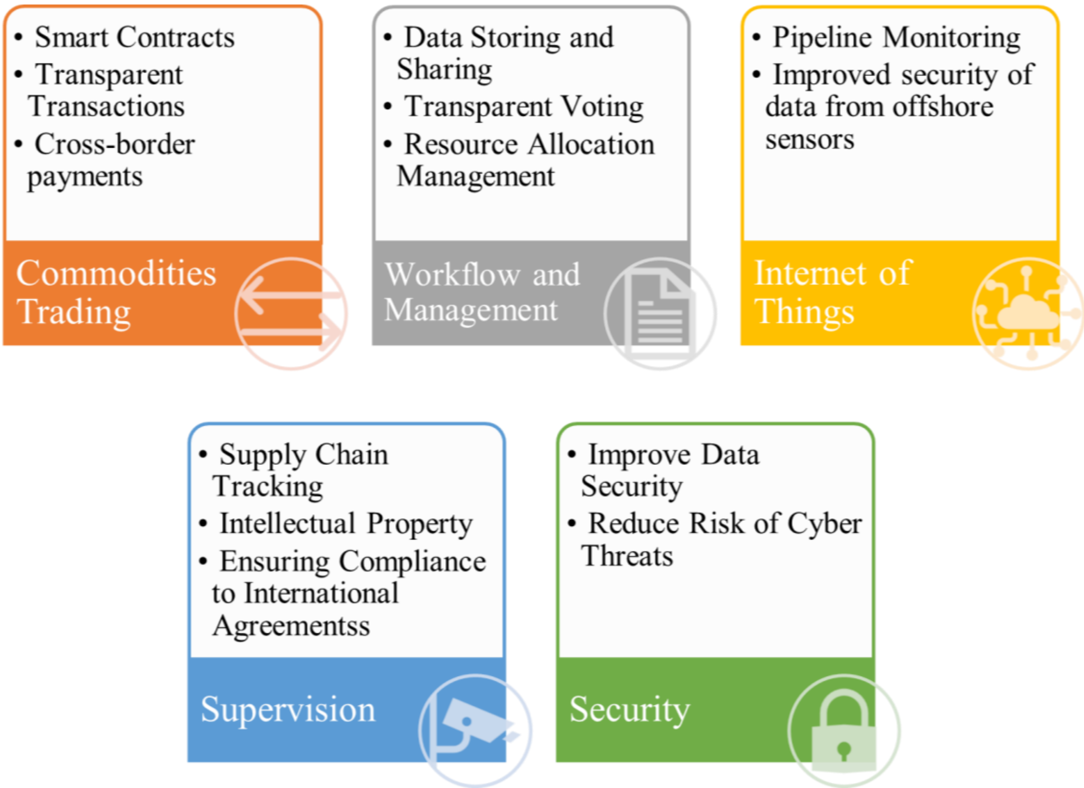

Figure 9 Applications for blockchain in the oil and gas industry.

Source: Adapted from [6], [19], [97].

Supply chain tracking has been identified as the most critical problem in the oil and gas industry that blockchain could solve [19]. Because data security is a major concern in the oil and gas industry [97], blockchain applications for oil and gas tracking must be carefully crafted to preserve the integrity and privacy of sensitive data. Many major oil and gas companies have already expressed interest in working with large technology companies to create blockchain-based systems for tracking resources from extraction to final consumers [19]. The following growth developments for blockchain technology in the oil and gas industry have been proposed by Lu et al.: hybrid blockchain architecture, collaboration with other technologies, cross-chain and high-performance blockchain development, hybrid consensus mechanisms, and increased participation of interdisciplinary professionals [19].

Regarding the practical implementation of blockchain in the oil and gas sector, Lu et al. have analyzed twelve major oil and gas industry blockchain projects active in 2018, out of which most were implemented in Europe and Asia [19]. The American multinational technology company IBM has launched several blockchain projects for the oil and gas industry. Together with the oil trading company Trafigura and French bank Natixis, IBM worked on a blockchain platform for trading crude oil in the United States. The application allowed for real-time sharing of relevant payment, distribution, and delivery data. This reduced the need for complex paper procedures. The blockchain technology used for the project is Hyperledger Fabric [98]. Another IBM project, named Vertrax Blockchain, was developed in collaboration with Chateaux Software and it aims to avoid supply chain disruptions. The project was announced in 2019 and the development is still in progress, according to the company's website [99]. When completed, it will include a multicloud blockchain solution for supply chain management, allowing total asset visibility and lowering supply chain costs significantly. IBM has also partnered with ADNOC, Abu Dhabi's National Oil Company, to develop a blockchain solution for electronic transactions and accounting services for the trading of petroleum products [19].

Sinochem Group from China has shown a lot of interest in blockchain technology and has implemented several test projects and prototypes for different use cases during the last three years. Firstly, in 2018, they tested the possible applications of blockchain for export business by simulating gasoline shipments from Quanzhou in China to Singapore [100]. In 2018, they have announced a cooperation with Royal Dutch Shell and Macquarie Group on a blockchain platform for trading crude oil. The cooperation platform named Gateway aims to reduce trade and settlement inefficiencies, increase transparency between parties, and reduce fraud risk [101]. Finally, in 2020, they have launched a project to digitally monitor warehouse products using blockchain receipts. This is another use case in which the application's main purpose is to avoid theft and tampering with confidential data [102].

In 2017, The Swiss company Mercuria Energy Group has developed the Easy Trading Connect platform for documenting trades on the blockchain in collaboration with the French bank Société Générale and the Dutch ING Group. The platform was used to manage the supply of crude oil from Africa to China, cutting the trade operations time from several hours to just 25 minutes. The success of this platform has led to the creation of the OOC Oil & Gas Blockchain Consortium [97], now rebranded as Blockchain for Energy [103]. This consortium brings together the world's leading energy firms and banks to explore how blockchain can be used in trading operations to improve performance and traceability [97]. One of the biggest currently active projects using blockchain in the field of physical commodities trading is the Vakt platform. The project is backed by several major energy companies and banks. Vakt is currently active in the North Sea crude oil market where it offers easy and low-cost trading for all stakeholders. The software for the blockchain platform was developed by the technology company ThoughtWorks, and it is claimed to be the world's first enterprise-level blockchain platform [104].

In the area of improving the performance of equipment and processes in the oil and gas sector, the company Quisitive completed an interesting proof-of-concept project in 2018 focusing on pipeline monitoring and data collection using Microsoft's Azure Blockchain Workbench. The Blockchain Oil Pipeline project aimed to store precise crude oil purity measurements on the blockchain and make them available to organizations enforcing purity standards as well as other interested parties [97]. According to the author’s research, the project has not progressed beyond the proof-of-concept level, and there is no evidence of effective large-scale implementation.

6 Challenges for Blockchain Applications in the Energy Sector

The advantages and drawbacks of future implementations of blockchain technology must be carefully considered, as with any modern technical advancement. Even though there are multiple arguments in support of using blockchain in the energy field, the challenges and disadvantages should be acknowledged as well. The key drawbacks and potential problems with blockchain implementations in the energy sector are addressed in this section.

Several authors have previously classified these issues. Wu and Tran have identified the following challenges related to blockchain technology applications in the energy sector:

- bottlenecks, including scalability and energy consumption issues,
- reliability and security,
- lack of standardization and supervision, and
- talent shortage [8].

Based on the interviews of industry experts, the following issues for blockchain applications in the energy sector should be highlighted:

- issue of the running cost distribution in decentralized solutions,
- lack of digital identity management standards,
- lack of anonymity and data deletion,
- blockchain performance issues,
- integration challenges,
- skill requirements for operating blockchain interfaces,
- high operating costs, and
- lack of regulatory framework [6].

When talking about risks related to blockchain applications in the oil and gas industry, Lu et al. have divided them into three segments: operational risks, cyber risks, and legal risks [19]

In this section, a summarization of potential challenges and drawbacks for the implementation of blockchain in the energy sector is presented. The challenges are classified into three categories: limitations related to the current energy market and grid infrastructure, problems with the blockchain technology itself, and concerns for investors. This classification is chosen to establish a clear distinction between problems that can be addressed by the stakeholders in the energy sector, the blockchain development and research community, and by investors and regulators.

6.1 Energy Market and Grid Infrastructure Limitations

Since blockchain implementations in the energy sector have only been explored significantly in the last five years, there are many barriers that the existing energy sector currently presents to this new technology, and there has not been enough time for large-scale infrastructure improvements to occur and adjust to rapid technological advancements. Applications of blockchain in the energy sector are specific since, in addition to the value exchange happening on the blockchain, there is physical energy transmitted through the grid for most of the use cases. This physical energy transmission needs to be accurately mapped to the digital transactions [8]. Besides that, there are some infrastructural challenges for blockchain integration with the current electricity grid. The presumption in recent blockchain research in the energy sector is that the physical grid system will support successful integration with blockchain applications, however, this might not be the case in all countries. Increased power exchange due to peer-to-peer energy trading can affect power flow, voltage and frequency levels, and grid harmonics, among other things [5]. Bürer et al. consider the management of the complex grid architecture in a decentralized manner as the biggest challenge for blockchain energy trading applications [5]. These infrastructural problems can bring the security of the grid into question, if not addressed properly by the grid operators and relevant experts from the field of electrical engineering [6].

Another issue is that the current system is rigid and slow to adapt. The utilities and grid operators must be involved in innovative blockchain applications as central stakeholders [5]. The progress of the small start-up is often dependent on the willingness of grid operators to participate in the project. This is further enhanced by the constraints such as monopoly over the power metering market [5]. In decentralized energy markets, the issue of the distribution of costs for blockchain applications is also relevant and it might pose a challenge for some practical implementations, according to industry experts [6]. Another limitation that is specific to the energy market is that there are strict standards related to energy production, trading, and consumption to which all new frameworks must adhere [8].

6.2 Problems with Blockchain Technology

Along with the obstacles that the energy sector presents, blockchain implementations in this area are also confronted with challenges that are intrinsic to blockchain technology. The first concern is the participants' privacy. All information about potential users and transactions is stored indefinitely and is available for public viewing, particularly with implementations on public blockchains. New ways of protecting privacy must be invented if blockchain applications are to use public blockchains in the energy domain. Some solutions to this problem are to use private or consortium blockchains which offer a higher level of control over the privacy of the data and to employ zero-knowledge proofs to store encrypted data on the blockchain but with its integrity maintained [41].

Blockchain, like any other technology, has security issues that are inherent in its design. Ferrag et al. have identified the main security vulnerabilities of the blockchain protocol and classified them in the following way: private key leakage, double spending, transaction privacy leakage, 51% vulnerability (also referred to as a type of Sybil attack [15]), and selfish and reputation-based behaviors. These vulnerabilities can be exploited in multiple attack models, which can be grouped into identity-based attacks, manipulation-based attacks, cryptanalytic attacks, reputation-based attacks, and service-based attacks [47]. Consensus protocols are a particularly vulnerable element of blockchain implementation. If the consensus protocol's integrity is compromised, the entire blockchain architecture is vulnerable to attacks. The 51% weakness of the PoW consensus protocol is a well-known example of consensus protocol security danger, which means that if a node or group of nodes has more than half of the computational power engaged in block verification, they may write any information to the blockchain. Other consensus protocols have similar vulnerabilities and ensuring that there is high dispersion of power is critical to ensure that the blockchain's security is not jeopardized in this way [30]. Scalability and transaction speed can also be a problem for blockchain applications; however, they do vary greatly with different implementations.

Another problem with which many blockchains are struggling is the environmental impact of the technology. Some blockchains, especially the ones utilizing PoW consensus protocol, like Bitcoin, require a lot of electricity to perform the mining operation [40]. Due to the diversity of technological implementations, the environmental impact of blockchains as a whole is hard to determine. Scientific studies have shown different results and there is no consensus on how energy efficient the blockchain is [5]. For a blockchain to be sustainably used in the energy domain, energy-efficient consensus protocols must be utilized.

There are also other alternative approaches to reduce the environmental impact of blockchain, such as utilizing the excess energy power which is generated by renewables and which cannot be absorbed by the grid for the electricity-intensive operations on the blockchain [40].

Aside from the fact that certain blockchains are not cost-effective due to their energy consumption, there are concerns that the cost savings achieved in simulations are highly dependent on certain factors such as network size [63]. In general, storing data on the blockchain can be very costly [5], and applications on the blockchain need to be carefully designed to save resources and store or process only necessary information. Every transaction typically incurs some cost in terms of energy and power [7], and especially on public blockchains due to the congestion of the network, these costs can be very high [19]. Aside from the financial impacts, there are still several technical obstacles to real-world blockchain implementation. Real-time energy tracking, for example, is required for issuing bills and settling accounts on the blockchain. This requires specific measuring equipment to be installed in the grid before the blockchain application can be effective.

6.3 Concerns for Investors

There is some risk for potential investors who want to endorse the growth of blockchain applications in the energy sector because of the novelty of blockchain technology. Due to the high level of decentralization in blockchain applications, issues may arise if the legal and technical liability for any potential problems is not clearly defined [94]. To begin with, there is still a lack of regulation in the energy sector for such applications [8]. Typically, energy companies wait for emerging technology to be regulated by government bodies before investing. However, due to the rapid growth of blockchain, regulatory bodies do not yet have a complete overview of the technical potential and ramifications of these applications, preventing the development of new guidelines and regulations [5]. Another danger is that new blockchain technology legislation will differ greatly between countries, increasing the regulatory risk for potential investors. For the successful development of the energy blockchain, consulting services will be needed for both businesses and regulatory agencies [5]. Even though there is interest from government bodies to learn and understand blockchain technology [94], rigid regulatory frameworks remain the most significant barrier to blockchain adoption in primary energy sector activities [6].

Regardless of regulatory bodies' positions on blockchain implementations, there is inherent technical uncertainty about this relatively new technology, which poses a danger to investors.

This high level of technical uncertainty is causing business uncertainty, which organizations are finding difficult to handle. The disruption of the energy sector's already well-established structure could result in increased risk and a loss of credibility for the companies that currently dominate the market. There are also risks for investors' current investments in distribution and transmission networks, which could become redundant because of a major technological shift, and any drastic changes in the sector may disrupt conventional energy power stakeholder relationships. If an investor chooses to invest in new and future blockchain applications, there is a chance of technical problems arising with these early applications, which could have substantial implications [5].

7 Results and Discussions

This analysis has shown that there is an argument for using blockchain in the energy sector, both from the academic and business perspective. Blockchain technology is not only emerging for use as a digital currency but there is an active development of enterprise-grade solutions for decentralized applications in various industries, including the energy sector. Blockchain offers solutions to many problems the current centralized energy markets are facing, especially with distributed renewable energy producers. However, the variety of blockchain implementations and properties cater to a multitude of different use cases. For each use case, the applicability of blockchain and its value-added must be carefully analyzed. As determined by Brilliantova and Thurner, the experts from the energy sector consider the applicability analysis and the exact business the most important information about a blockchain project [6].

An important thing to note is that in an ideal use case for the blockchain in the energy sector, its unique property of being able to achieve trust in a decentralized environment should be fully utilized. This means that applications that simply employ the blockchain as a database or messaging system without fully embracing the technology will likely not realize the full benefits of the blockchain. In most cases, the business processes and the energy markets need to be reimagined as a whole and redesigned with the desired technology in mind to achieve the optimal results with blockchain. Along with the business and market processes, the roles and concerns of the stakeholders might be drastically changed to accommodate the new technology architecture [54].

Several implemented projects have shown that the existing blockchain technology is indeed capable of serving enterprise-grade applications if they are designed properly. The possible issues of scalability, transaction costs, and data privacy for enterprise blockchain applications can all be overcome with thoughtful application design and proper implementation [54]. Projects such as Vakt for commodity trading and WRMHL for business-to-business integration claim that they have managed to produce enterprise-ready solutions on the blockchain [77], [104].

As more large companies and energy utilities are showing interest in blockchain solutions, a need for proper performance and scalability which can help guide companies into finding the right blockchain technology for their use case is emerging. To help measure the effectiveness of existing blockchain technologies, a benchmarking tool named Distributed

Ledger Performance Scan (DLPS) has been developed by Sedlmeir et al. This tool allows the measurement of performance metrics such as latency and throughput for different blockchains and different sizes of networks. DLPS already supports the comparison of performance between industry leaders such as Hyperledger Fabric, Ethereum, and Quorum [105]. This availability of such benchmarking tools will certainly aid in accelerating the development of blockchain applications for the energy sector.

One of the biggest implications that blockchain technology could bring if implemented for peer-to-peer energy trading is diminishing the role of middlemen between energy generation and energy consumption. This would indicate that utility companies and electricity retailers would have less involvement in energy trading which can ultimately cut energy costs for final consumers. Lowering the cost of electricity would possibly have an impact on other markets as well, such as real estate [6]. However, that leaves the question of the role of the utilities and retailers in this new energy market open for discussion.

Even though significant progress has been made in the research and development of blockchain technology for the energy sector, further work remains to be done to address open research questions and business concerns. Ahl et al. have proposed an analytical framework TESEI, encompassing technical, economic, social, environmental, and institutional dimensions in exploring the impact of blockchain on energy markets [61]. For better effectiveness of blockchain technologies in use for IoT, Ferrag et al. [47] have identified the following open research questions and focus areas: resilience against combined attacks, dynamic and adaptable security framework, energy-efficient mining, social networks and trust management, blockchain-specific infrastructure, vehicular cloud advertisement dissemination, and skyline query processing.

Aside from the complexities of technical implementation of the suggested solution, the effects of blockchain technology advancement on the energy sector environment should be closely studied as well. The impact of blockchain technologies in the energy sector on issues like meeting climate change goals and energy transition targets should also be closely monitored and assessed [5]. One of the most important open research questions for blockchain is the energy consumption of this new technology and there is currently a lack of large-scale empirical studies in this area that consider the distributed nature of blockchain computing and power consumption [5].

The socio-economic impact of blockchain integration into the energy sector and its successful integration with the current system is an important area for further research. Another challenge for the industry is developing regulations proactively to ensure consumer protection and a safe and reliable supply of energy when using blockchain applications [5]. This indicates that new institutions might be needed for governing this sector and helping integrate the innovations with the current systems [5]

Blockchain technology itself is only a part of the solution for the future of the energy sector. Blockchain applications should not be considered as a replacement for existing technology used in the energy sector, but rather they should integrate with it and enhance its possibilities. In addition to that, other decentralized technologies specialized for legacy technology integration, fast messaging, and distributed data storage can be employed to achieve the full transition to a new decentralized energy paradigm [54]. Blockchain technology can also be combined with other innovative concepts to further improve the efficiency of decentralized applications. Researchers in this field are proposing various technology combinations to find the best solutions to the existing energy problems. For example, multiple game theory models could be used for a better understanding of the optimal strategies for reducing energy consumption bills in households using distributed market mechanisms [65]. Additionally, artificial intelligence algorithms and multi-cloud architectures have the potential to make blockchain applications in the energy sector more impactful [19].

8 Conclusions

Blockchain is the technology providing the establishment of trust in a distributed environment with no central authority. Besides being successful in facilitating financial transactions, recent developments in the area of blockchain have enabled multiple different applications for this technology in various industries, including the energy sector. This thesis introduces the main characteristics of blockchain technology, enumerates and evaluates the possible use cases for blockchain in the energy domain, and discusses the possible challenges for blockchain applications in this sector.

When talking about comparisons between blockchain projects and the currently implemented systems, it is hard to make generalized conclusions since each use-case is unique. Additionally, even though blockchain technologies share some common features, there is still a lot of versatility in the implementation. Still, it is possible to identify some main features which successful projects in the energy sector are sharing. Firstly, blockchains that have smart contracts enabled have a lot more potential to have a significant impact. Furthermore, consortium and private blockchains seem to be more appropriate for use in enterprise-grade applications the energy sector requires than public blockchains. In addition, energy-efficient consensus protocols with high transaction throughput and low costs such as PoS and PoAu seem to be preferred. Most of the currently running pilot projects with promising results are focused on the incorporation of blockchain in the Energy Internet paradigm, and especially in decentralized energy trading and e-mobility. Additionally, the use of blockchain for asset management in the energy sector such as with green certificates or carbon credits trading has been extensively developed, while in the oil and gas industry supply chain management and workflow improvements on the blockchain have gained the most interest.

The collection of use cases gathered in this thesis, although diverse and extensive, is not exhaustive and, in the future, more potential use cases will certainly emerge. Innovative thoughts, start-ups, and pilot projects for various blockchain applications in the energy industry are plentiful. Not all of them will be successful, but this test-and-error approach will facilitate the identification and widespread adoption of the most effective applications that can have a greater impact on the energy sector as a whole. For this reason, even more innovative business models and research in the blockchain would be beneficial for the energy sector.

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Work topic: Technologie Blockchain v energetickém sektoru
Work topic in English: Blockchain in Energy Sector

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Theses guidelines:

This Master's thesis aims to explore the use cases of blockchain technology in the energy markets, more specifically in specialized software supporting the business processes related to operation of electricity grid. This includes variety of business processes of Transmission System Operators (TSOs), Distribution System Operators (DSOs) and related companies.
The thesis shall contain following parts:

- Introduction
- Objective and Methodology
- Blockchain Technology
- Use Cases of Blockchain in Energy Domain
- Suitability of Blockchain Technology for Selected Use Cases
- Results and Discussion
- Conclusion
- Bibliography
- Appendices

Recommended resources:

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