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Applications of the Blockchain Technology in the Energy Sector: The Case of Greek Islands' Microgrid

Stefanos Bompolakis

S.C.: MEN18041

Supervising Professor: Dr. Athanasios Dagoumas

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Abstract

Energy systems around the globe nowadays are undergoing a rapid transformation in their conventional structures that are vital from an environmental, economic, and social perspective. The driving forces behind the shift to the new era of the energy, also known as Energy 4.0, are the so-called 3 D's: Decarbonization, Digitalization, and Decentralization.

The blockchain technology, which comes as a result of digitalization, is considered by many experts a transformative force for the energy sector. More specifically, it is believed that it can be a direct driver for the decentralization of energy systems as well as an indirect one for their decarbonization and further digitalization. This is due to the technology's most prominent technical capacities, namely, transparency, security, and decentralization. All these combined have provided practical use cases, with the most widely-known being peer-to-peer power trading. On this occasion, consumers are enabled to trade the surplus amount of the energy they produce (e.g. with photovoltaics) with other consumers in decentralized energy networks. Such a solution can contribute to the decentralization of energy systems and make them more democratic and inclusive.

Most of the blockchain applications in the energy sector today have been directed towards the electric power industry, with more than half of blockchain use cases focusing on decentralized energy trading and energy projects financing. In contrast, the application of blockchain in the petroleum industry is still in its infancy. In the oil and gas sector, new technologies have to pass through several phases before mass adoption occurs, due to high costs and increased probability of component failures. Another deterrent is the particular nature of operations in the industry. For instance, oil is traded as a commodity on a global level and is impacted by external factors such as geopolitics, while electricity is specific to a regional level. Despite the sluggish adaptability of the industry, more recently, a number of blockchain initiatives from oil and gas majors have been launched.

Regardless of those advances and the fact that there is a growing number of startup companies developing similar solutions, blockchain is still in an exploratory phase of development. That is the main reason for it not being widely adopted by large industry players or in large-scale applications, which could otherwise help it grow faster and be established as a standard technology for particular applications. It will only become apparent in the next five to ten years, at a time when blockchain is expected to reach maturity from a technical standpoint, whether it will be a revolutionary technology that will bring about a revolution in the structure and processes of the energy industry.

This thesis aims at reviewing the main characteristics of blockchain technology, and based on its technical advantages, analyze the role it has played up to this day in the transformation of the energy industry and, more specifically, in the electric power and oil & gas sectors. In addition, a case study is presented that aims at showing how blockchain can provide solutions for the Greek energy ecosystem.

Contents

List of Abbreviations and Acronyms

ADNOC	Abu Dhabi National Oil Company
AI	Artificial Intelligence
B2B	Business to Business
CO2e	Carbon dioxide equivalent
DCS	Distributed Control System
EV	Electric Vehicle
DER	Distributed Energy Resources
DLT	Distributed Ledger Technology
ETRM	Energy Trade and Risk Management
EV	Electric Vehicle
GHG	Green House Gas
Gt	Gigatonnes
GW	Gigawatt
IBM	International Business Machines Corporation
ICT	Information and Communications Technology
ID	Identity
IEA	International Energy Agency
IOC	International Oil Company
IoT	Internet of Things
IIoT	Industrial Internet of Things
LNG	Liquefied Natural Gas
Mb/d	Millions of Barrels per Day
Mboe/d	Thousand Barrels of Oil Equivalent per Day
Mt	Million tonnes
O&G	Oil & Gas
OOC	Offshore Operators Committee
P.A.	Per Annum
P2P	Peer-to-Peer
PoS	Proof of Stake
PoW	Proof of Work
PV	Photovoltaic
PBFT	Practical Byzantine Fault Tolerance
RES	Renewable Energy Sources
SCADA	Supervisory Control and Data Acquisition
TSO	Transmission System Operator
USD	United States Dollar
VRE	Variable Renewable Energy

Glossary of Terms

Bitcoin	A digital currency introduced in 2009 that utilizes a peer-to-peer network to fulfil token transactions between participants without the intervention of intermediaries.
Blockchain	A list of interlinked transactions that consists of a peer-to-peer network and a distributed database.
Critical Energy Infrastructure	Assets of a power system that are of particular importance for the operation and development of the society and the economy.
Cyberattack	An assault aiming at harming the integrity of computer systems and networks or compromise data.
Cybersecurity	The methods used to protect digital systems and their data from cyber threats.
Distributed Ledger	A geographically spread database without a central operator used for recording digital transactions.
Ethereum	A decentralized, blockchain-based platform founded in 2015, which is used for electronic payments and smart contract development/execution.
Fourth Industrial Revolution	The Fourth Industrial Revolution describes the situation where today's systems, which derived from the three previous Industrial Revolutions, are continuously upgraded and transformed by the driving force of emerging technologies.
Microgrid	A microgrid is an autonomous power system that is connected to the macrogrid and is comprised of distributed resources, storage solutions and control devices. The main difference between microgrids and mini-grids is that while the former usually operates connected to the main grid (but can disconnect in cases of disturbances), the latter is an off-grid distribution network that always operates in "island mode" (usually in remote or rural areas where transmission from centralized generation is not feasible due to the power loss -up to 30%- during delivery).
Node	Any digital device connected to a network that actively receives or transmits data across the network.
Paris Agreement	An agreement aimed at reducing worldwide greenhouse gas emissions and keeping global warming below 2°C during the 21st century. The agreement came into effect in 2016, and since it has been signed by 195 member countries of the United Nations Framework Convention on Climate Change.
Smart Grid	A smart grid is a modernized version of conventional grids which is controlled through digital and intelligent means and can enable bidirectional flows of energy and information.

1. Introduction

Nowadays, the ongoing effort for the transformation of energy systems around the globe, which are highly dependent on polluting fossil fuels, has become a matter of utmost importance from an economic, social, and environmental perspective. This dependence on greenhouse gas-emitting resources is the result of the previous industrial revolutions, while the current "reshaping" of the energy industry is mainly based on the Fourth Industrial Revolution and the trends that accompany it. In particular, digitalization and technological developments constitute the driving forces behind the shift to the new era of the energy industry – also known as Energy 4.0.

The constant energy transition to digitalized and non-fossil fuel dependent energy systems takes advantage of the new and emerging technologies to accelerate the whole transformation process, increase security, and significantly reduce costs. The transition is driven by the so-called 3 D's: Decarbonization, Digitalization and Decentralization. It mainly aims at:

- Mitigating the adverse effects of climate change,
- Tackle energy poverty by making energy affordable and accessible around the globe and for all income levels,
- Diversifying the global energy mix based on the penetration of renewable energy and
- Creating new business models

The blockchain technology is considered by many experts a transformative force for the energy sector and an important direct driver for the decentralization of energy systems as well as an indirect one for their digitalization and decarbonization. This is thanks to the technology's most important abilities:

i. To enable consumers to self-produce (e.g. with photovoltaic panels) the energy they use and trade the surplus amount with other consumers in decentralized energy networks – a trend that recently has been characterized as "prosuming". This trend can help in the decentralization of energy systems and make them more democratic and inclusive.

ii. To assist in the decarbonization of the energy sector by improving the integration of RES. This can be accomplished by the use of decentralized energy trading (especially in microgrids) where companies and prosumers can sell their power surplus and help contribute to load balancing. Consequently, this can allow for greater penetration of renewables.

iii. To optimize the security of energy networks. Thanks to its characteristics, blockchain can also be viewed as a digital securitization tool, as it can provide solutions for access management to private networks, secure interconnectivity of devices within a network, and data privacy. This can increase the confidence in such digital tools and accordingly help in the digitalization process of the energy sector.

iv. To further promote digitalization of processes that have remained widely manual until today. In the case of the electric power industry, this can be mainly achieved by supporting through its underlying capabilities innovative business models that utilize a range of new technologies, while in the oil and gas industry by introducing solutions to digitally transform operations such as trading, resource management, and regulatory affairs.

Today there is a growing need to determine the technologies that have the highest potential to transform the energy industry. Of course, for certain new technologies that are not yet well established or widely tested, this can be an unfair trial since they possibly have not revealed their true potential. The blockchain technology is one such case.

Blockchain gained popularity back in 2008 when it was firstly used in the Bitcoin network. This constituted the first generation of the blockchain where the technology was only used by digital currencies – the so-called “Blockchain 1.0”. After 2012 the first use-cases of the technology in a commercial context began taking place, while with the introduction of the Ethereum network and smart contracts in 2015, blockchain gained even more significant potential for business applications and, therefore, a higher adoption rate. This phase of development is known as “Blockchain 2.0” and it lasts as of today. However, as we mentioned before, blockchain is still in a relatively early stage of development and a “dominant design” has yet to emerge. As a result, the technology is expected to provide comprehensive commercial solutions after 2025 (Tasca, 2017). Similarly, in the electric power and oil & gas industries, blockchain is still in an early adoption and development stage, and it is anticipated to reach maturity in 5 to 10 years, as we will see in chapters 4.1 and 4.2.

The objectives of this research are to determine what the needs of the electric power and oil & gas industries are today and whether blockchain can support their transformation based on its current capabilities. More specifically, the following questions are addressed throughout the thesis:

I. What are the characteristics of blockchain technology? How can they be applied in the energy industry? Which are the pros and cons? These will help us to gain insight into the nature of the blockchain technology and the solutions it can provide to the energy sector.

II. Which trends are prevalent in the electric power and oil & gas industries today? Which are the challenges that stem from those trends? By answering these questions, we will be able to better understand the solutions provided by blockchain technology in those industries.

III. Which are the applications of blockchain in the electric power and oil & gas industry as of today? This review helps us identify how blockchain manages to address the challenges of the industry discussed previously.

IV. Based on those blockchain solutions, we will analyse in the last chapter through a business plan how the blockchain technology can help resolve a major problem for the Greek energy sector: the electrification of Greek islands not interconnected to the mainland country with affordable and clean energy.

1.1 Organization of the dissertation

As mentioned before, the scope of this dissertation is to examine the potential of blockchain and other underlying technologies like smart contracts in the energy sector as well as to address how relevant use cases can go from theory to practice. To achieve this result, it was deemed appropriate to begin by presenting the basics of the technology from a technical but approachable standpoint. The second chapter constitutes this preface to the blockchain technology and its characteristics along with other topics such as its types, transactions on blockchain networks, the role of consensus mechanisms, its advantages and limitations, and based on them, possible use cases for the energy sector.

At this point and as a short introduction to the benefits of the technology for the field of interest has been made, an overview of the current trends and challenges in the energy industry is given in chapter three. This can be considered as a “step back” which aims to showcase the emerging trends in the sector, such as environmental concerns, penetration of renewables, decentralization of power systems, and digitalization. Accordingly, these trends form a growing number of challenges, namely changing business environment, renewables integration barriers, increasing operational complexity, and cybersecurity concerns. These impede the further development of the energy industry and thus need to be resolved, particularly with the assistance of new technologies.

Blockchain is included in the innovative new technologies that can enable industries such as the electric power or the oil and gas ones to resolve sector-specific issues, help in the optimization of their processes and securitize their digital systems. The fourth chapter is a review of most use-cases that have been applied in the energy sector as of today and practically seek to provide solutions to the issues mentioned earlier. Essentially, these constitute solutions to the energy trilemma as they:

- Enhance the reliability of energy infrastructure by providing cybersecurity tools (energy security),
- Enable more people around the globe and primarily in developing countries to get access to clean and affordable energy by using renewable energy systems combined with blockchain-based applications (energy equity), and
- Promote the use and integration of renewable energy sources (environmental sustainability).

It needs to be addressed that the purpose of this dissertation is to investigate the main characteristics of blockchain technology, and based on its technical advantages, analyze the role it has played up to this day in the transformation of the energy industry. To enable the connection between theory and practice, a case study is also presented that aims at showing how blockchain can provide solutions for the Greek energy ecosystem. More specifically, in the fifth chapter, the theory discussed previously helps us to form a practical scenario that shows how the actual implementation of blockchain could help the non-interconnected Greek islands produce and exchange clean and affordable energy, promote energy communities, cope with energy poverty and even manage to be completely energy independent from the central system.

2. What blockchain is

The technology of blockchain was made popular in 2008 as the basis for Bitcoin network[1], and since then, it has been utilized in a large number of blockchain applications that are based on different architectures (Prieto, et al., 2020). Bitcoin is a decentralized digital currency that utilizes a peer-to-peer network to fulfil token transactions between participants without the intervention of third-party intermediaries or financial institutions (Nakamoto, 2008). Typically, such an intermediary would be needed to ensure the integrity of the network's content and that the tokens are not spent more than once (Andoni, et al., 2018). Consequently, Bitcoin solves the problems of double-spending and the so-called Byzantine Generals' Problem (keeping the system reliable even in case of a failure in a number of its components). This way, it manages to replace the intermediary by cryptographic proof as described below (Lamport, et al., 1982).

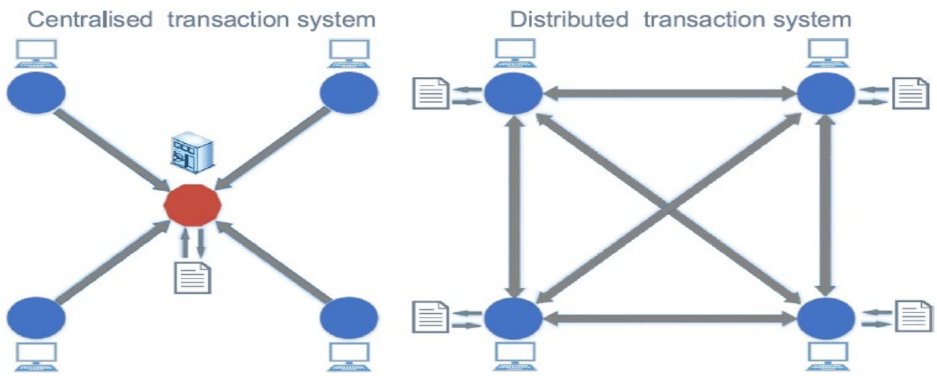

Figure 1: The two types of transaction systems. In the centralized, an intermediary receives transaction data and manages the network, while in the distributed, participants individually fulfil transactions and manage the network (Andoni, et al., 2018).

The technology of blockchain can be described as a digital and decentralized ledger of transactions which consists of a peer-to-peer network and a distributed database (Nakamoto, 2008) (Prieto, et al., 2020). The blockchain database collects an increasingly growing log of transactions and adds them in "groups", which are called blocks. These blocks are time-stamped and cryptographical linked with previous blocks in a way that they form a "chain" of records (Nakamoto, 2008). Copies of those transactions are then stored in all the geographically-distributed participating computers, known as "nodes" (PwC, 2018). Therefore, the blockchain system in this context is operated in a decentralized manner and without the control of a central authority. In order to facilitate the confirmation, execution, and recording of those transactions, blockchain utilizes data management systems, cryptography[2], networking, and incentive mechanisms for the nodes that participate in the transaction's processing[3] (Xu, et al., 2019).

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[1] The Bitcoin network is often mistakenly linked to the invention of blockchain technology. While Bitcoin's white paper (Nakamoto, 2008) makes references to relevant phrases such as "blocks are chained" or "chain of blocks" (does not verbatim cite the word blockchain though) the general idea of data verification by time stamping is connected to 1991 paper "How to Time-Stamp a Digital Document" (Haber & Stornetta, 1991). The term "block chaining" stretches even further back to 1976, cited in the IBM patent document "Message verification and transmission error detection by block chaining" (Ehrsam, et al., 1976).

[2] Cryptography is used in the blockchain networks as a means of identification of the participating parties (Xu, et al., 2019).

[3] Those incentives are offered to the participating nodes as a motive for honest behaviour and as compensation for the computing power and electricity that they expend to validate the blockchain transactions (Nakamoto, 2008). Incentives can take the form of financial rewards (e.g. direct token assignment to the user) for honest behaviour

The average confirmation time of the transactions ranges between different blockchain networks. While in the Ethereum network a transaction takes only about 15 seconds to be confirmed, the Bitcoin network has a processing time of up to 10 minutes[4] (Swan, 2015). This is mostly related to the type of blockchain and the consensus algorithm used by each network, but transaction volumes and block sizes play a significant role as well (Luke, et al., 2018).

2.1 Main types of blockchain systems

Based on the development purpose and use case of blockchain systems (e.g. cryptocurrency, application in industry etc.), a variety of system architectures can be followed. Blockchain architectures can be classified based on the access rights they grant (public and private) and on their governance rules (open- and closed-source) (Atlam & Wills, 2018).

2.1.1 Permissioned and permissionless blockchains

Blockchains can be divided into permissioned and permissionless (or non-permissioned) according to their openness. While all blockchains were permissionless (open) at their initial state, the permissioned (closed) type evolved later on and constituted a superior use case for internal business processes and applications within an enterprise context (Dob, 2018).

Most digital currencies utilize the permissionless blockchain type. It allows anyone to enter the network and interact with it without prior approval from an entity or third parties (Xu, et al., 2019). Participants, based on the computing power they wish to commit, can choose either to simply run a node within the network and perform different actions (e.g. “full nodes” confirm transactions in Bitcoin) or validate blocks (e.g. “mining nodes” in the case of Bitcoin) (Dob, 2018).

Permissioned blockchains can ensure a more controlled environment for the network operator. This is achieved by allowing users to join the network only after verification of their identities (Andoni, et al., 2018). To perform different functions within the network (e.g. initiate transactions, validate blocks), participants need to gain special permissions from the network operator as well. These include the permission to:

- Read (access the ledger and the history of transactions),
- Write (initiate transactions) and
- Commit (validate blocks and update the state of the ledger) (Hileman & Rauchs, 2017).

2.1.2 Public, private and consortium blockchains

Ledgers can be separated in public, private, or consortium according to their access control. Bitcoin and Ethereum networks are both public and permissionless, which means that they are open to anyone to join without any permission required (Treiblmaier & Beck, 2019). Thanks to the free access policy, public networks are decentralized and the nodes that are participating in the network are responsible for providing computational power and verifying new data (blocks, transactions). Due to the costly nature of consensus in public blockchain networks, incentive mechanisms are provided to the validating nodes (Christidis & Devetsikiotis, 2016). In most instances, the members of a public and permissionless blockchain are only represented by a random ID, and no personal information is provided to the rest of the network.

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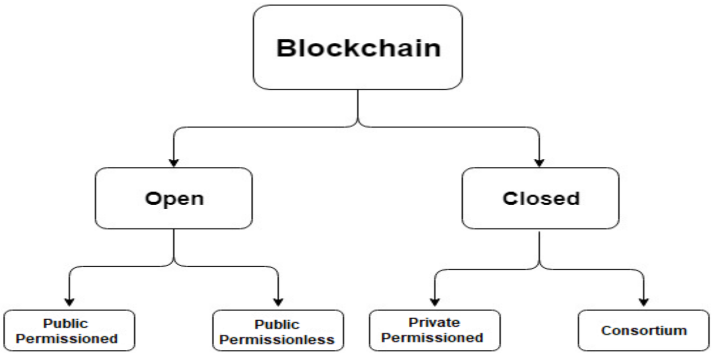
during the transaction verification process or the form of punishment (e.g. confiscation of tokens) as a countermeasure and dishonest behaviour prevention (Andoni, et al., 2018).

[4] The Bitcoin network currently can support up to 7 transactions per second (Prieto, et al., 2020).

In contrast, private blockchain networks are open to join or contribute computational power only after special permission has been received by the governing body. The personal details of the participants are known to the governing body as well.

Consortium blockchains are hybrid ledgers that have both public and private characteristics but are primarily considered semi-private as only verified users are allowed to participate in block validation (Xu, et al., 2019). Their governing body is usually a group of companies and they offer a range of incentives for implementation in the energy market, namely: privacy, scalability, and performance (Atlam & Wills, 2018) (Treiblmaier & Beck, 2019).



On the one hand, private blockchains provide better overall performance[5] and attributes such as user authentication processes. This, in turn, offers optimal privacy, which better corresponds to the requirements of the corporate world and especially to highly regulated industries such as the energy one (Xu, et al., 2019).

Blockchain Permission Control			Read	Write	Commit	Example	Properties	
	Open	***Public Permissionless***	Open to Anyone	Anyone	Anyone	Bitcoin, Ethereum	Immutability Transparency Performance Cost efficiency	+ + + + + + +
	Open	***Public Permissioned***	Open to Anyone	Authorized Participants	All (or subset) of authorized participants	Hyperledger Indy	Immutability Transparency Performance Cost efficiency	+ + + + + + + +
	Closed	***Private Permissioned***	Fully Private	Network Operator Only	Network Operator Only	An internal blockchain network operated by a single enterprise and its subsidiaries	Immutability Transparency Performance Cost efficiency	+ + + + + + + +
	Closed	***Consortium***	Authorized Participants	Authorized Participants	All (or subset) of authorized participants	A consortium of enterprises operating a shared blockchain network	Immutability Transparency Performance Cost efficiency	+ + + + + + +

+ + + More favourable
+ + Neutral
+ Less favourable

Figure 2: Types of blockchains according to permission control (Xu, et al., 2019), (edited by the author).

On the other hand, public blockchains are naturally available to a broader audience to join, which can promote innovation and productivity. Moreover, they are less vulnerable to attacks thanks to their decentralized nature, contrary to the private networks which have a central authority and, therefore, a single point of failure (Gates, 2017).

[5] The number of participating nodes in a private blockchain network is significantly smaller than in a public one, and thus the verification of transactions needs less computational power and time (Atlam & Wills, 2018).

2.1.3 Open- and closed-source blockchains

Blockchain architectures can be classified according to their governance status into open- and closed-source. Open-source blockchains are publicly available to all the network members for review and community decision-making (e.g. decisions on matters of technical improvements, software selection etc.) (Andoni, et al., 2018). The most prominent open-source blockchain projects are Bitcoin and Ethereum[6].

By comparison, any alterations in the system governance or the system operation rules are privately decided in closed-source blockchains, whilst their source code is managed by an organization or a consortium of institutions and is not publicly shared (Gates, 2017). Ripple is a well-known closed-source blockchain platform, used mostly by financial institutions to facilitate cross-border payments.

2.2 Distributed consensus algorithms

As consensus algorithm we can describe the mechanism that is used by a blockchain network to ensure that all the nodes approve the contents of the ledger and achieve transaction finality (reach consensus) (Singhal, et al., 2018) (Atlam & Wills, 2018) (Christidis & Devetsikiotis, 2016). It is considered to be a blockchain network's core element as both the security of the whole system and the integrity of transactions depend upon this layer (Arun, et al., 2019).

More specifically, the five steps that are followed to reach consensus within a typical blockchain network are the following (Froystad & Holm, 2016) (Nakamoto, 2008):

1. A transaction that includes the receiver's public address, the transaction's value, and an encrypted digital signature is transmitted in the network by a sender.
2. Once the transaction is received by the participating computers (nodes) of the network, the authentication process initiates. This is done by the decryption and verification of the digital signature of the sender. The verified transaction receives a unique "hash" and is then placed in a "pool" together with other pending transactions.
3. A node of the network combines all the pending transactions into a block and transmits it to the rest of the network for validation.
4. The block is received by the nodes of the network, which validate it by a specific validation process[7]. For the block to be validated, a consensus from the majority of the network is required.
5. If all transactions within the block are validated, the newly created block is permanently added to the blockchain and then communicated to the network.

[6] Bitcoin is the largest cryptocurrency by market capitalization (over USD 148 billion) and Ethereum the second largest with a market capitalization of over USD 17 billion as of September 2019 (Coin Market Cap, 2019).

[7] The validation process varies between different blockchain networks.

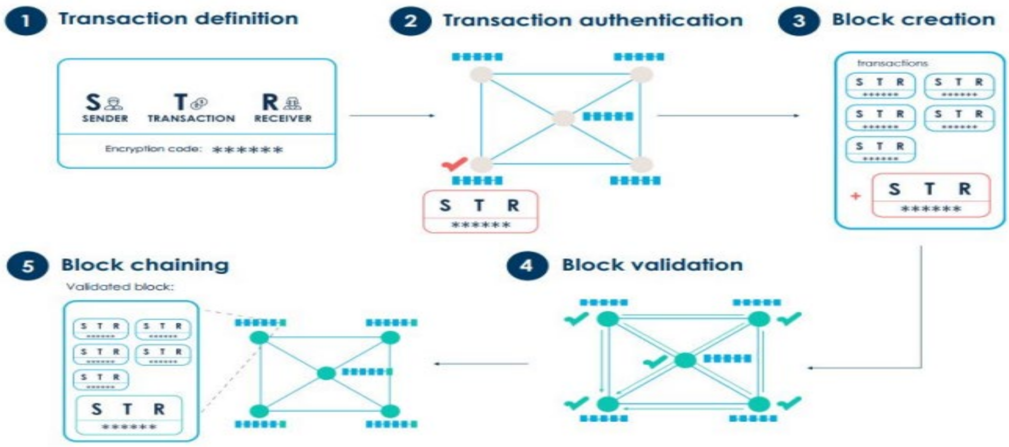


Figure 3: The main procedure of a blockchain transaction (Froystad & Holm, 2016).

The main approaches of consensus mechanisms include the Nakamoto consensus and variations of the Byzantine Fault Tolerance (BFT) algorithm. In the case of Nakamoto consensus, a lottery-based[8] protocol, the primary rules followed are those of the "longest chain"[9] and Proof of Work (PoW) (Xiao, et al., 2019b). The majority of public blockchains utilize the Nakamoto consensus, with the most known being the Bitcoin network (Xu, et al., 2019). BFT-based consensus protocols follow the concept of keeping proper function in a distributed computer network, despite a possible malfunction in system processes or malicious action against it (Lamport, et al., 1982). A common point of the two consensus mechanisms is that they both have as an objective to ensure that there is agreement among the participants about the history of the blocks (Xiao, et al., 2019a).

From an economic point of view, consensus algorithms have a direct impact on the computational costs and the overall amount of investment in a blockchain system. On the technical side of the equation, they determine many performance characteristics of the network, such as security, scalability, and transaction speed (Andoni, et al., 2018). Therefore, if a blockchain solution is to be integrated into the corporate world, the different aspects of each algorithm need to be taken into account (Arun, et al., 2019). This can help businesses to implement the optimal consensus algorithm for the use case they are planning.

There are many variants of consensus models applied in different blockchain platforms, with the most known being: Proof of Work (PoW), Proof of Stake (PoS), and Practical Byzantine Fault Tolerance (PBFT).

2.2.1 Proof of Work (PoW)

Initially used by the Bitcoin network, Proof of Work is a consensus mechanism that relies on validating nodes (on this occasion called "miners"), which compete to solve a cryptographic mathematical problem (Andoni, et al., 2018). The solution to this problem is called "hash". Mining nodes test random numbers, also known as "nonce" through a trial and error process until they produce a nonce that delivers the requested hash value (Nakamoto, 2008) (Christidis & Devetsikiotis, 2016). The miner that finds it first wins the round and links a new block to the

[8] The term lottery-based is used to describe the process of block validation. For a block to be validated and added to the blockchain, a cryptographic math problem needs to be solved by the mining nodes of the network – a process also known as Proof of Work (see 2.2.1) (Andoni, et al., 2018).

[9] The "longest chain" rule refers to the fact that the participating nodes always recognize the chain with the greatest length (which translates to the most computing effort invested in it) as the true chain. The mining process of the network should always extend the specific chain (Nakamoto, 2008) (Xiao, et al., 2019b).

existing blocks in front of it (Mingxiao, et al., 2017). They also receive rewards defined by the incentive structure of the network for their computational usage.

Thanks to its design, PoW is resistant against a range of cyberattacks, including DoS attacks, which overload a networks' servers to make it unavailable to its users (Back, 2002). Moreover, it is a mechanism that can be scaled and support a large number of users (Andoni, et al., 2018).

The most significant drawback of PoW is that the mining process requires immense amounts of energy and computational expense and that it suffers from slower transaction speeds compared to other consensus mechanisms (Eurelectric, 2018) (Andoni, et al., 2018). Additionally, it can be prone to 51% attacks, meaning a single entity (or a group of entities) to acquire the majority of the computational – "mining" power of the network and use it to monopolize the mining of the blocks or alter the order of blocks, leading to a double-spending problem (Deirmentzoglou, et al., 2019) (Baliga, 2017).

2.2.2 Proof of Stake (PoS)

Proof of Stake is a consensus mechanism that replaces the need to mine blocks with a voting-based system that depends on the validator's wealth. Thereby, the probability for a validating node to add a block to the chain is directly related to the node's possession of the native token of the network (e.g. ether in the case of the Ethereum network) (Xu, et al., 2019).

PoS is considered to be a faster and more cost-efficient alternative to PoW for public blockchains (GitHub, 2019b). Furthermore, its stake-dependent voting mechanism can be used as a way to prevent centralization and 51% attacks, since participants do not have an incentive to accumulate significant computing power or form mining pools (Deirmentzoglou, et al., 2019). Ethereum is the most known blockchain network that considers moving from PoW solutions to PoS.

Although PoS is less vulnerable to 51% attacks, a problem known as "nothing at stake"[10] is prominent in PoS networks (Andoni, et al., 2018). In addition, its capabilities and vulnerabilities have not been widely exposed as it has been less implemented than PoW (Xu, et al., 2019).

2.2.3 Practical Byzantine Fault Tolerance (PBFT)

PBFT is one of the most widely known BFT-based consensus protocols. PBFT is more suitable to be used in permissioned blockchains rather than in public permissionless ones (Xu, et al., 2019). This is due to PBFT being a voting-based consensus algorithm where a leading node is chosen by the network only if it has been approved by at least 2/3 of all nodes[11], and therefore every participant should be known to the rest of the network (Andoni, et al., 2018). The leader is responsible to select the blocks that will be added to the network[12] and is replaced in each round[13] of the process (Zheng, et al., 2017).

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[10] The "nothing at stake" problem refers to validating nodes working on multiple chains (instead, they should participate in the longest one alone), an action that prevents consensus from being reached and possibly leads to a double-spending problem as well (Deirmentzoglou, et al., 2019).

[11] In order to perform typically, a PBFT network requires less than 1/3 of the nodes to be faulty (e.g. faulty nodes may be caused by software errors, malicious attacks etc.) (Castro & Liskov, 1999).

[12] This process replaces the need for block mining, which is encountered in PoW systems (Castro & Liskov, 1999).

[13] Each round consists of a three-phase protocol which includes: pre-prepared (the leader broadcasts a new block to a consortium of peer nodes), prepared (nodes coming to an agreement) and commit (adding the accepted block to the blockchain) (Mingxiao, et al., 2017).

A significant advantage of the PBFT protocol is that, compared to PoW, it is significantly less computationally intensive, which translates to reduced electrical energy consumption. Another important benefit of the particular consensus mechanism is its lower latency time (the time needed to validate a block and add it in the chain) in comparison to PoW (Xiao, et al., 2019b).

Disadvantages of the PBFT include its capacity to support only a small number of participants, and its vulnerability to Sybil attacks[14] due to its voting-based algorithm (Curran, 2018) (Xu, et al., 2019).

2.3 Developing stages of blockchain technology

Since its conception in 2009, a number of new characteristics and capabilities have been added to the blockchain technology. Thus, a categorization into three stages, each with a different purpose of development, can be made according to its degree of complexity:

- Stage I – "Blockchain 1.0": The first developing stage of blockchain is connected to cryptocurrencies and the networks that support them. This is thanks to Bitcoin, as it was the first use case that utilized the technology to build a solution to a practical issue: the execution of secure transactions within an untrusted, anonymous environment without the need for a trusted third-party intermediary (Swan, 2015).
- Stage II – "Blockchain 2.0": The second phase of blockchain development represents smart contracts, a form of digital contracts that practically derived from the generalization of the "trustless payments" of the first stage. The Ethereum network was the first platform that realized the development and deployment of smart contracts in 2015 (Buterin, 2013).
- Stage III – "Blockchain 3.0": The implementation of blockchain technology in different industries constitutes the third and final developing phase of blockchain. For the time being, relevant large-scale applications are limited. In the future and once the software environment further develops, blockchain can enable new business models and provide solutions to automate and accelerate processes in several industries, including energy (Eurelectric, 2018) (PwC, 2018).

2.4 Characteristics of blockchain technology

As previously stated, blockchain technology ensures that its users can safely fulfil transactions between each other, without the need of an intermediary who controls the integrity of those transactions. In this section, a more detailed description of the advantages and limitations of the technology is presented, as well as the possible benefits that it could bring to the energy industry as a whole.

2.4.1 Advantages

With the constant emerging of new technologies and the complexity of digital systems growing ever larger, companies and organizations seek innovative ways to enhance the security and optimization of their operations. One of the most discussed technologies in the context of the

[14] A Sybil attack occurs when a single participant of a peer-to-peer network creates or manages to manipulate a large number of identities (participating nodes). In the case of PBFT, such an entity can receive multiple votes from those pseudo or "controlled" identities and gain disproportionately large influence of the network (Christidis & Devetsikiotis, 2016) (Curran, 2018).

so-called Fourth Industrial Revolution is the distributed ledgers technology and the potential it holds to transform the way we conduct transactions today.

In particular, applications of blockchain technology within an industry context can empower corporations with the following benefits:

I. **Security**: Blockchain systems are considered less susceptible to cyber threats and malicious actions than conventional record-keeping systems. Transactions within a blockchain system are cryptographically secured in a tamper-proof way and the only approach a dishonest participant can follow to alter the history of transactions for their benefit is to control the majority of the computing power of the network (Arun, et al., 2019).

   Additionally, the security of transactions is reinforced by digital signatures: For users to be capable of signing, and therefore fulfil transactions, they need to possess private keys that ensure that a valid user has initiated a given transaction and no malicious actors have tampered with it. As a result, significant importance should be paid to the management of private keys, as any unauthorized entity that gets access to a user's private keys can also have to their account (Hileman & Rauchs, 2017).

   Thanks to their decentralized architecture, blockchain systems do not have a single point of failure. Thus, a maliciously affected node alone is not capable of threatening their operational stability, which makes them less prone to cyber threats, contrary to other traditional networks (Eurelectric, 2018) (Hongfang, et al., 2019).

   While distributed ledgers offer a great variety of security benefits compared to many conventional systems, there exist several concerns related to security, which are discussed in more detail in 2.4.2.

II. **Transparency**: Compared to traditional methods of recordkeeping and auditing for transactions that involve multiple entities, blockchain systems provide greater transparency and safeguard against any arbitrary actions of the engaging parties. All the participants of the network have the same copy of transaction history (this depends on the type of blockchain and the permissions of each participant) and agree to write new transactions only through mutual consent (Arun, et al., 2019). The whole process happens in a real-time manner that optimizes transparency, while all the data entered onto the blockchain are immutable (Gates, 2017).

III. **Smart Contracts**: The term "smart contract" was firstly introduced by Nick Zambo in 1994, describing a computerized transaction protocol that executes the terms of a contract by using computer language instead of legal language (Zambo, 1994) (Hongfang, et al., 2019). The primary objective of smart contracts is to fulfil transactions defined by contractual conditions, with guaranteed execution and payments, and without the need for arbitration from a central authority or legal system (Arun, et al., 2019) (MIT Sloan Management Review, 2017).

   Smart contracts were integrated into blockchain by the Ethereum network in 2013. In this context, they were described as computer programs that are built on a programming language, and which could be deployed and run on the blockchain system. More specifically, the procedure is as follows: After an agreement is established between the parties, the terms are passed on to the smart contract. For it to be executed, certain conditions should be met, such as the initiation of a predetermined payment among the two parties (Buterin, 2013). Following the fulfilment of conditions, the execution of transactions commences and the assets are automatically transferred to the accounts of their new beneficiaries[15]. Lastly, all the data concerning the transaction are written on the blockchain.

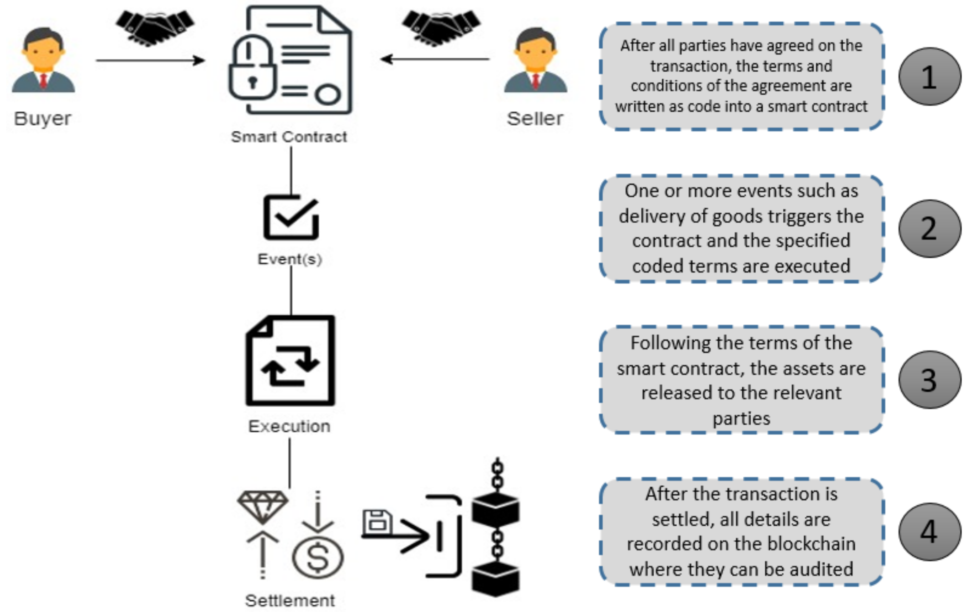

Figure 4: The process of a smart contract transaction (edited by the author)

In the case of the Ethereum, a smart contract is written only in specific programming languages like Solidity. Transactions in the particular network follow similar steps as above, with the only exception being the fee that needs to be paid to the network by the party that initiates the smart contract. This is due to smart contracts being executed by all the miners of the Ethereum network who consume computing power. Hence, the fee, also known as "gas", works as a compensation for the mining nodes and is proportional to the computing power required for the contract execution (Xu, et al., 2019).

IV. **Decentralization**: The decentralized nature of blockchain networks is one of the essential characteristics of the technology. In contrast to centralized systems, where a single entity is making decisions, blockchain networks are operated by its participants, and transaction records are copied to every participating node in a decentralized manner. This helps to avoid data losses or alterations and makes the networks less immutable to malicious actions (Gates, 2017).

Transactions can be less costly and significantly accelerated by utilizing shared ledgers, as all participants of the network share an identical version of transaction requirements and history, and it is not required from them to keep separate records. The state of the transaction (e.g. completed, unconfirmed, rejected) is updated automatically on the shared ledger once consensus is reached among the participants or, in the case of smart contracts, if it fulfils specific criteria (e.g. correct amount of funds sent to the contract by the buyer and correct amount/type of products sent by the seller). These automated methods can be used by businesses who wish to abolish

[15] The automatic transfer occurs only in the case of digital assets. For assets represented off-chain (e.g. commodities, stocks, real estate), the changes on the participating accounts will follow the off-chain settlement instructions.

relevant manual procedures to reduce complexity and minimize error rates (Tijan, et al., 2019).

2.4.2 Limitations

Apart from its positive effects, blockchain technology comes with a number of challenges, which for the time being, can be considered accountable for the slow adoption of the technology by the corporate world. For blockchain to achieve its highest potential, those issues should be addressed and resolved with an appropriate tactic so as not to cause new vulnerabilities thereafter.

It needs to be mentioned that a key issue of concern to the blockchain world nowadays is the so-called "scalability trilemma": in fact, while a blockchain system would require to be characterized by all three features of decentralization, scalability, and security for it to be flawless, with the current design a system can have only two of those (GitHub, 2019a).

In further detail, the current drawbacks of the blockchain technology can be considered the following:

A. **Scalability**: By the term scalability in this context is meant how well a system can adapt and perform well under expanding conditions. Since the Bitcoin network began to grow considerably, the number of transactions also spiked from around 10.000 per month in 2010 to 10.000.000 per month in 2017. Nevertheless, while there is a need for a substantial rise in the throughput capacity of the network, this is something difficult to achieve because of the predefined block size (i.e. how many transactions can fit into a block or in other words to be processed). Overall this has caused network transactions to be significantly slower (2.000 transactions every 10 minutes) than other payment systems like VISA (1.700 transactions per second) (Xu, et al., 2019).

Several solutions, such as storage optimization and redesigns of network consensus mechanisms and processing methods, have been proposed to improve blockchain characteristics connected to scalability. Nevertheless, it should be emphasized that the scalability issues constitute a significant obstacle for the adoption of the technology, especially in industrial use cases that require high throughput rates (Drescher, 2017). For blockchain to reach a more comprehensive corporate audience, it needs to be able to compete with the high-capacity payment systems that exist today (Croman, et al., 2016).

B. **Security concerns**: Distributed ledgers might offer a highly safe environment for transactions compared to many conventional systems but they also suffer from potential security flaws which are very relevant nowadays and need to be addressed appropriately. The issue of a 51% attack is the most well-known of them, as it has been linked to the integrity of the Bitcoin network. As the difficulty of block mining in the network becomes more and more difficult, it also gets more challenging for individual participants with the average computational capacity to compete in the process.

This has led to the formation of "mining pools", meaning the cooperation of many individual nodes, which later transformed into organizations that possessed a large number of specially designed computers competing in block mining. These organisations assembled enough computational power that made a 51% attack in the Bitcoin network possible. As a result, the integrity of the Bitcoin network and the blockchain technology as a whole has come into question ever since, and alternative consensus algorithms that solve the 51% problem have been developed. Nevertheless, these come with relevant issues and possibilities of network attacks as well, namely Sybil attacks, Long-Range attacks, and Distributed Denial-of-Service attacks (Sayeed & Gisbert, 2019).

Another relevant issue that blockchain poses is the private key storage. As previously noted, the private key is the only way of authentication through which a user can enter their account, and if lost or forgotten[16], there is no method to restore it. If a third party gets access to a user's private keys, they will also get to their account and funds, and as transactions are irreversible, the legitimate user will not be able to cancel an unauthorized transaction. This has led to users storing their private keys on wallets held privately by third-party companies. However, a possible leak of private keys to unauthorized parties is still possible in the case that the website that hosts them is maliciously attacked (Gates, 2017).

C. **Cost**: The PoW consensus mechanism requires a large amount of computing effort as an expense for block validation. Of course, this translates to high energy consumption and waste of resources[17], which become more and more severe as the difficulty of mining increases[18]. This issue can be partially addressed by using other consensus mechanisms apart from PoW or by making the network completely private where the identities of participants are known, and there is no need for costly consensus methods (Christidis & Devetsikiotis, 2016). Finally, it is apparent that for any corporate project to be realized, the benefits of blockchain systems should outweigh their currently high costs required in ICT hardware and software infrastructure (Andoni, et al., 2018).

D. **Regulations**: Due to the decentralized nature of the technology, a blockchain system can be distributed across many countries with different regulatory jurisdictions, making its classification under a specific legal regime a challenging process for lawmakers. This concern extends to liability issues, meaning that it is often unclear who is to be held responsible for any losses or security breaches of blockchain networks (Eurelectric, 2018).

Until a clear regulatory framework is established, enterprises will be more hesitant to apply the technology in large-scale applications. Especially the energy industry that is characterized by strict regulations will be plodding to adopt blockchain for the most promising solutions like P2P energy trading and specific applications of smart contracts, due to consumer data protection laws. For the relevant regulations to adapt to the changing environment, the regulators should first understand how these technologies work and how they can impact the energy industry as a whole (Deloitte, 2016).

2.4.3 Advantages for application in the energy sector

Based on the characteristics described above, we can define potential use cases of the blockchain technology that correspond to the needs of today's energy systems worldwide:

I. **Security of energy systems**: In an industry context, businesses that manage sensitive data need to be increasingly aware of digital threats, and continuously

[16] The private key is a sequence of random numbers and letters, in the range 0-9 and A-F, and therefore challenging to memorize.

[17] When nodes compete to mine a node, but they do not manage to do so, the resources that they spent are practically wasted.

[18] In the Bitcoin network, the consumption of electricity for block mining activities rose from 9,5 TWh per year in early 2017 to 73,1 TWh per year in late 2019, with a carbon footprint of 34,7 Mt of CO_2 equivalent (Digiconomist, 2019).

improve their cybersecurity defenses and means of transmitting such information. The need for such measures is becoming more eminent by the rapid expansion and vulnerabilities of digital systems. Blockchain can offer valuable solutions and assist companies in safeguarding their data transmissions and a variety of their transactions (Hooper, 2018).

The security of systems and data has been a headache for energy companies, especially in the course of the last decade. During this time, about 70% of the systems of energy companies have been breached globally, with the most prominent being the cyberattack against Saudi Aramco in 2012 (IEA, 2017). Such phenomena can further escalate to threat national power grids or other Critical Energy Infrastructures (CEI). Consequently, it is considered essential that energy corporations continue to safeguard their operations by software or hardware updates and by investing in secure solutions, including blockchain.

Applications in the oil and gas industry, which is the second more prone to cyber threats and generally suffers from complex systems, have evolved to include the secure storage of sensitive data in a distributed manner (Deloitte University Press, 2017) (Hongfang, et al., 2019).

Relevant use cases have been demonstrated in the electric power sector as well. These focus on securing the supply chains and assets of CEIs, as well as increasing the protection of essential data exchanged among energy management and energy delivery systems (Roeder, 2019).

II. **<u>Transparency in operations</u>**: In cases of industries such as the oil and gas, which are characterized by a complex supply chain, blockchain solutions can enable more transparent transactions and allow all the involved parties to track payments and delivery of products in real-time (Vakt, 2019) (Morabito, 2017). For instance, a potential application in the downstream B2B oil supply chain is a blockchain-powered platform, managed by its participants – an oil distribution company (seller), an industrial customer (buyer), and their respective banks – who have access to the same data concerning a given transaction. After the two parties have agreed on the terms of the contract, the information is shared on the platform and is updated in real-time when transactions are executed. This can offer participants the opportunity to automate such operations and replace traditional labor-intensive back-office processes that include many phases of reviews, confirmations, and exchanges of paperwork (Mashreq, 2019) (Deloitte, 2016).

Additionally, they can be utilized for certification purposes of green energy products: for example, an increasing number of consumers nowadays tend to prefer electricity from renewable or environmentally friendly sources. Blockchain can be used to develop solutions that will inform the consumer about the origins and methods of production of the energy they are purchasing (Burger, et al., 2016).

Another potential that distributed ledgers have is to increase transparency in energy regulation matters, by simplifying regulatory processes and providing real-time data to regulators (World Energy Council, 2017).

III. **<u>Decentralization of energy systems and business procedures</u>**: As energy systems grow, they tend to become more decentralized and, therefore, communication and exchange of data among their distributed parts become more complex as well (Andoni, et al., 2018).

Such a case is that of electrical grids, which have been greatly impacted by the penetration of renewables in recent years. Dependency on renewable energy sources for power generation is expected to further increase during the next decades[19], amid the Paris Agreement and the reduction of relevant costs (IEA, 2018). This could translate into greater decentralization and expansion of smart grids. But at the same time, the management of such a decentralized system is expected to be particularly complicated under current standards, and as a solution, it is suggested that a combination of new technologies are utilized, including blockchain (see 4.1).

From a consumer's perspective, the technology can enable peer-to-peer energy markets[20], simplify contracts with utilities, and empower consumers with automated billing. Furthermore, blockchain-based solutions can enable consumers to participate in fund-raising for energy projects where they can enjoy partial ownership of the project's assets (Wang, et al., 2019).

In a commercial context, blockchain can offer a wide range of benefits, such as decentralized wholesale power trading, enhance the grid's security, and enable new business models. Utility companies can also expect to substantially automate grid management and relevant operations such as energy balancing, metering, and billing to customers. Last but not least, through this decentralized model, the overall capacity of the network can be optimized and transmission losses to be reduced, as a result of the smaller yet numerous distributed generation units (WEF, 2017b).

IV. **Smart Contracts**: A major part of the use cases mentioned before requiring at least some contribution from smart contracts in order to reach their full potential in an energy industry environment, and some are even entirely based on them. The P2P electricity market is the most representative example: smart contracts[21], employed here to control transactions including energy trading and payments, is the driving force behind secure, fast, and cost-effective energy transactions between consumers (PwC, 2018).

Another relevant application is a blockchain and smart contracts powered platform, which includes energy utility companies and power plants apart from final consumers only (like in the P2P market case). All participants are required to have a smart metering device installed within their premises, and can fulfil power trading within a micro-grid system (Xia, et al., 2019).

Lastly, the most crucial application of smart contracts in the oil and gas industry is commodities trading. The majority of the blockchain-based B2B platforms for oil & gas wholesale trading utilize smart contracts to automate the entire process: the two parties agree on the transaction and create a smart contract that binds the relevant information, the shipping commitments and the funds. Once certain criteria have been met, the contract automatically executes the payment, and the funds are sent to the seller (Hofmann, et al., 2018).

[19] According to IEA, electricity generation from renewable resources is projected to increase to 33% by 2040 in a Current Policies Scenario (i.e. there are no alterations to the policies existing today) (IEA, 2018).

[20] By the term peer-to-peer energy market is meant that the consumers apart from producing their own energy (in that case also referred to as "prosumers"), using PV panels or other means, can also choose to sell any excess amount of it to other consumers who participate in the local P2P market or, respectively, buy energy from them.

[21] In addition, blockchain applications and smart meters are needed in this case: the blockchain executes transactions and payments, while the smart metering devices are used to measure the energy produced by the installed sources of a household (PV panels, small wind turbines, etc.) along with the energy consumed.

3. Trends and challenges of today's energy sector

The advantages of the distributed ledger technology discussed in the previous chapter have come to the attention of both start-up companies and multinational corporations who see the potential of the technology to solve complex problems of today's energy systems. This phenomenon has been rising since 2017, when the investment in blockchain applications related to energy services reached $300 million (IEA, 2018).

To better understand the current but also potential future blockchain-based solutions for the energy sector, we need first to identify the emerging trends affecting the sector, and in particular, in the electric power industry (discussed in 3.1.1) and the oil & gas industry (discussed in 3.1.2). Subsequently, these trends shape a number of challenges for the two industries (discussed in 3.2.1 and 3.2.2 respectively), for which the blockchain technology can provide the respective solutions.

3.1 Current trends in the energy sector

Energy systems worldwide are currently undergoing radical developments in their conventional structures and operations, driven by decentralization, digitalization, and decarbonization efforts. Each of these dimensions comprises of several components such as climate initiatives and energy policies[22], which have emerged out of the need to respond to climate change and secure energy supplies amid the global energy demand growth.

This chapter reviews in more detail the current trends of the electric power industry and O&G, which constitute the leading force for the transition to cleaner and more robust energy systems.

3.1.1 Electric power industry trends

Traditionally, the electric power industry has been characterized by centralized power plants that relied mainly on fossil fuels for electricity generation, with the most predominant of them being coal (currently around 38% of the global generation). The centralized nature of those generating units meant that system operators were transmitting electricity in one direction, starting from the power plants, passing through substations (used for converting high voltage power to low voltage and inversely), and from there distributing it to individual consumers.

In the conventional grid, consumers were given little control of their energy systems, and thus their electricity use, while grid operators had limited real-time information about the network's conditions and performance, due to structural issues and unidirectional power flows. Other drawbacks included prolonged power outages and blackouts, substantial spending for infrastructure maintenance, transmission over long distances, and, most importantly, high levels of GHG emissions.

Countries across the globe need to take biding measures to modernize their grids in order to mitigate the adverse effects of climate change, reduce environmental pollution caused by electricity generation based on fossil fuels, and ultimately achieve the targets of the Paris Agreement. These efforts are being augmented by the current trends observed in the electric power sector:

[22] Energy policies can be divided into four categories depending on the objectives they pursue, namely: Addressing Climate Change Policy (ACCP) which is targeted to reducing GHG emissions, Renewable Energy Policy (REP) to promote development of RES solutions, Energy Efficiency Policy (EEP), and Building Energy Efficiency Policy (BEEP) to improve energy efficiency (IEA, 2019c).

- ***Grid decarbonization:*** As previously mentioned, large centralized power plants are fueled mostly by polluting fossil fuels, including coal and lignite, oil, natural gas, and in smaller scales, less-pollutant fuels such as nuclear. In addition, it is estimated that power generation globally accounts for 64% of coal use and 40% of natural gas use, while it is responsible for 38% of energy-related CO2 emissions. Therefore, it is clear that the electric power industry should gradually replace fossil fuels with cleaner forms of energy (IEA, 2018) (IEA, 2019a).
- ***Renewable sources penetration:*** Thanks to the need for cleaner methods of power generation, energy systems are currently experiencing a rise in the adoption of RES. Moreover, declining costs, in combination with aimed governmental support, have played a leading role in the adoption of renewables. As a result, solar PV and wind power surpassed fossil fuel additions in 2017 and reached 6% of electricity generation (IEA, 2018).
- ***Decentralization of power systems:*** The more flexible forms of RES, which include solar panels and small wind turbines are widely adopted during the last few years in decentralized applications (residential and commercial). As an increasing number of individuals install renewables in their properties, grid operators are facing emerging challenges because of the volatile and unpredictable power generation that depends on the weather. Most importantly, grid operators have to face the need for operational adjustments and RES integration within the central distribution and transmission system. Emerging decentralized grid systems like smart grids, microgrids, and mini-grids utilize new technologies to facilitate those adjustments and offer multiple additional benefits (IEA, 2015).
- ***Digitalization:*** The rising deployment of RES and the modernization of grids come alongside with the digitalization of the power sector. This means that operators utilize a growing number of new technologies to transform conventional grids and make them "smart". In 2016 investment in the digitalization of electric systems reached $47 million worldwide. These developments allow operators to receive real-time data about consumption and operation, provide resiliency to outages, and optimize grid stability. Consumers utilizing digital solutions are empowered with better management of their energy production and usage and can actively participate in the system by feeding in their excessive energy or completing P2P energy transactions (Livingston, et al., 2018).

Grid decarbonization

The First Assessment Report of Intergovernmental Panel on Climate Change (IPCC), published in 1990, initiated the discussions about the reduction of GHG emissions and provided the basis for the subsequent singing of the United Nations Framework Convention on Climate Change (UNFCCC) by 165 Member States in 1992.

As part of the UNFCCC, the Kyoto Protocol was signed in 1997 and came into effect in 2005. The protocol, which was ratified by 192 countries, extends the UNFCCC and specifies legally binding targets for the signatories to reduce their emissions. The measures included, amongst others, adoption of renewable forms of energy and limitation of emissions in energy production, transmission, and distribution (United Nations, 1998).

In 2015, during discussions about the proceedings after the end of the Protocol's second commitment period (2012-2020), the Paris Agreement emerged and was later signed in 2016. The Paris Agreement is an instrument of the UNFCCC that, contrary to the Kyoto Protocol, has a voluntary approach where the signatories are not bound by specific targets for emissions reduction (United Nations, 2015).

Overall, the Agreement is to be regarded as one of the main drivers for global cooperation in combating climate change. Current efforts are concentrated in the reduction of energy-related CO2 emissions, which are on the rise during the last decade and in 2018 reached a historic high of 33.1 Gt CO2 (IEA, 2019a).

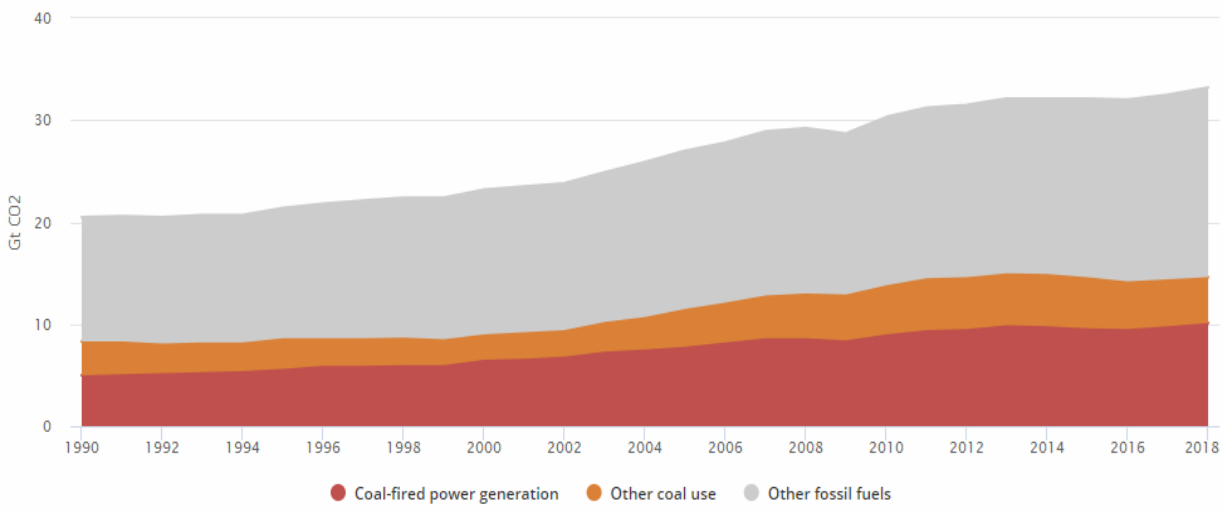

Figure 5: Global energy-related CO2 emissions by source (IEA, 2019a; IEA, 2019).

The power sector is considered the prime target for most GHG emissions mitigation strategies, mainly because of the challenges and costs arising from similar efforts in other sectors. In EU, utilities of Member States have committed to terminate construction of coal-fired power plants by 2020, among other measures, to achieve a domestic GHG emissions reduction of 40% by 2030, compared to 1990 levels (Amanatidis, 2019). Nevertheless, it is estimated that to achieve the decarbonization of the power sector in accordance with the targets of the Paris Agreement, RES generation should reach 85% globally by 2050 (IRENA, 2019).

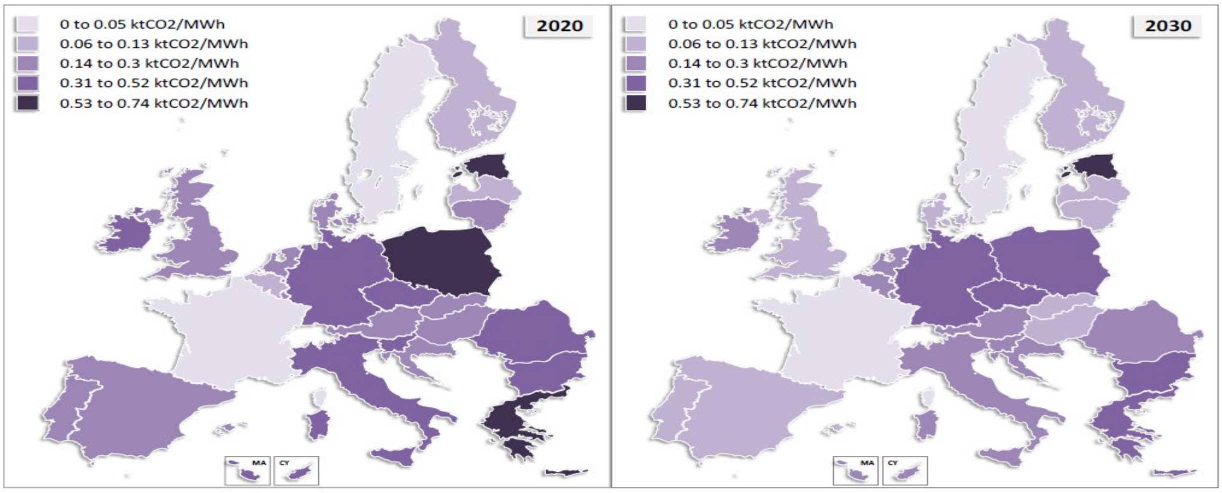

Figure 6: Carbon intensity of power generation in EU Member States in 2020 and 2030 (European Commission, 2016a).

Climate policies aiming at grid decarbonization utilize strategies such as increasing public tendering schemes for the installation of RES, offering higher feed-in tariffs[23] and setting higher carbon prices (Rottgers & Anderson, 2018).

In essence, the above policies set incentives for carbon-free power generation, reduce risk factors associated with renewable energy investments, and make electricity production based on fossil fuels more expensive for utilities. Ultimately, these developments compose a leading factor in the penetration of RES.

Renewables penetration

While renewable energy is not a recent phenomenon, the rate at which RES capacity has grown during the last decade, particularly due to the rising energy demand and general awareness of environmental problems, is substantial. Initiatives on climate change, such as those discussed earlier, are also forming climate policies based on current trends and are paving the way for clean energy production. Whereas many emission-free technologies exist, only a number of them have been widely adopted lately. This is especially true for certain renewables such as biofuels, which have not achieved technological maturity yet, and for nuclear power, which has become less popular, especially in the EU, after the Fukushima incident in 2011.

As a consequence, the installations of other RES, and especially of Variable Renewable Energy (VRE) that is defined as solar PV and wind, has increased manifold. VRE accounted for almost 50% of new capacity in the global power mix in 2017 and currently provides 6% of global electricity generation compared to just 0.2% in 2000. Apart from the policy and government financial support described before, additional factors that contributed to the rapid expansion of VRE were falling costs and technological improvements. Solar PV installation costs dropped nearly 70% between 2010 and 2018, with 97 GW of new additions in 2017. During the same period, costs for residential projects declined an average of 60%, allowing consumers to install greater capacities. Advances in wind power technology and overall efficiency provided incentives for offshore and onshore additions that reached 48 GW in 2017 (IEA, 2018) (IRENA, 2019).

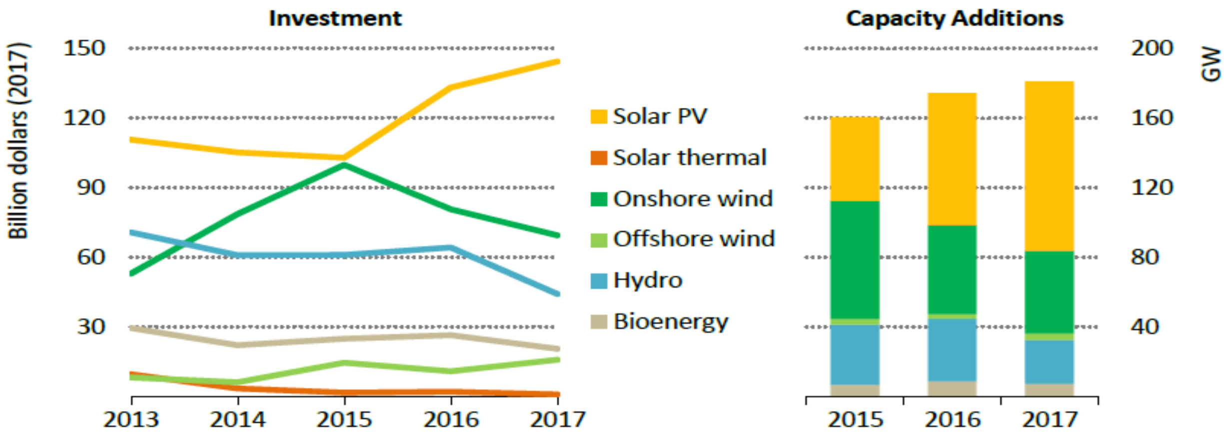

Figure 7: Renewable electricity investment (2013-2017) and capacity additions (2015-2017) (IEA, 2018).

Besides the environmental impacts of RES, these systems also offer advantages associated with:

[23] Feed-in tariffs are incentives offered by system operators to renewable energy producers by guaranteeing a stable price for each unit of electricity produced (Canton & Linden, 2010).

- Accessibility to clean and sustainable energy for both developed and developing countries
- Energy security by diversifying the energy mix
- Socio-economic development and
- Improvement of health factors by reducing health hazards found mostly in the atmosphere

Regardless of the benefits offered by these developments, particular emphasis should also be paid to the challenges arising from the increasing adoption of renewable energy for power generation, namely the integration of the resources to the central grids, the increasing operational complexity of the systems, and grid balancing issues.

Decentralization of power systems

The phenomenon of decentralization in energy systems is becoming increasingly apparent nowadays, as a result of the rapid deployment of Distributed Energy Resources (DER) and the rise of prosuming. These consist of renewable energy and storage solutions, as well as demand response management systems. The fundamental characteristic of a decentralized system is that the facilities for energy production are located close to where this energy is consumed, and therefore centralized power plants are substituted with small-scale generation units (Richter, et al., 2012).

Apart from minimizing carbon emissions and decreasing energy transmission losses, distributed generation empowers individuals and communities with better control of their electricity consumption and production, and reduces their dependence on external fuel prices. Moreover, if combined with the necessary digital tools, it can enable P2P or B2B decentralized energy trading, and as a consequence, decentralization is closely related to digitalization (Marnay, et al., 2015).

PV modules have been the main contributor to the decentralization of power systems, thanks to their flexibility for residential deployment apart from commercial. The total capacity of solar PV is projected to rise from 142 GW in the period 2012-2018 with 36% of it being distributed to over 317 GW during the years 2019-2024 with distributed additions reaching 45% (IEA, 2019b).

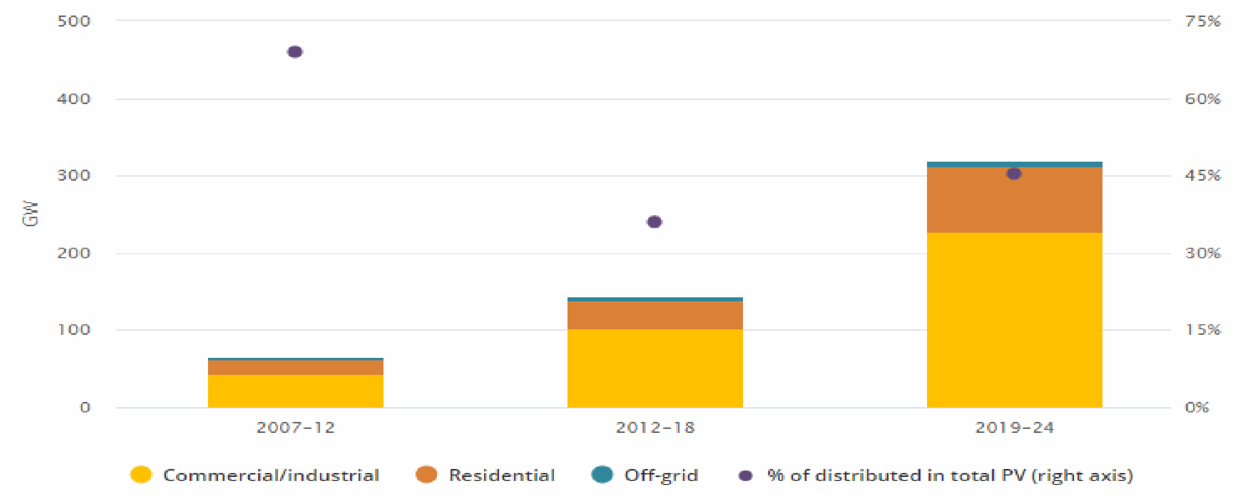

Figure 8: Solar PV growth by segment and distributed share of total (IEA, 2019b).

System operators will have to face new technical and economic challenges from the increasing number of assets connected to the grid and will need to adapt their role within the system as a result of the changing business environment. Furthermore, operational complexity will increase due to requirements for balancing across the extensive decentralized network and coordination of the multiple resources. Lastly, the volatile production of renewable resources necessitates additions of large-scale storage capacities, as well as technical adjustments (grid development, new substations) to facilitate bidirectional power flows.

Digitalization

In the past, the power industry has been a pioneer in the adoption of digital technologies for the management and operation of grids. In recent years, the growing number of DER requires system operators to facilitate the integration and balancing of those resources in the central network by utilizing the necessary digital technologies. Therefore, the digitalization of power systems comes primarily as a result of the increasing penetration of RES, but also from the general trend of adoption of emerging technologies. In addition, new digital tools and upgrades are the only methods for the transformation of conventional grids to smart grids, for which the investment in 2017 reached $13 billion (IEA, 2018).

Utilities and system operators can utilize digital technologies to improve asset efficiency, reduce operational costs, and optimize the management of transmission and distribution network by remote monitoring. Another important aspect of digitalization is that it can contribute to the grid balancing, which becomes more challenging as more RES are deployed into the system. This can be done by matching electricity demand with generation and not vice versa, according to the current practices[24]. System operators can inform consumers in real-time about supply conditions and help them to adjust their demand, respectively. Devices like smart meters are necessary for demand-response management to take place (Burger, et al., 2016).

At the consumer and prosumer level, smart meters offer additional benefits such as information on electricity market prices, based on which the consumer can match their consumption (e.g. in case of low prices use devices that require higher electricity consumption). The prosumer can either store the produced electricity (in case of low selling prices) or sell electricity (in case of high prices). They also give users the ability to communicate their consumption and production data to system operators who subsequently utilize them to improve the overall system configuration. Most importantly, if combined with blockchain technology solutions, these devices can be used to automate billing procedures or to facilitate P2P energy exchange.

Apart from the perks it provides, the digitalization of electricity systems can cause specific vulnerabilities. These include malicious attacks and other network breaches that can occur at different parts of the communication system of the smart grid, resulting in financial loss or theft of personal data. Another major issue arising from the increasing number of personal details recorded on digital devices is how this data can be protected, and the ways that exploitation or data theft can be avoided (Keyhani, 2019).

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[24] These flexible forms of power balancing are not supported in conventional grids or grids that do not utilize the required technologies, mostly due to lack of large-scale storage solutions and limited information on consumer demand. This results in system operators balancing the system by adjusting production in the centralized power plants of the grid in cooperation with the producers (Kabalci, 2019).

3.1.2 Oil and gas industry trends

In the past, the structure of the Oil and Gas industry was primarily affected by fluctuations in supply and demand, changes in regulations, and technological innovations, especially in the sector of exploration & production. In more recent decades, and particularly after the early 1990s, the increasing environmental concerns and emerging climate policies altered the operational procedures of O&G companies, forcing a lot of them to initiate operations in alternative sectors (many oil majors created renewable energy divisions), and constrained profit margins (Petrie, 1993) (Accenture, 2017).

Even more recently, technological advances have given rise to the exploration of unconventional resources, which are considered a solution to meet the future rising demand for oil and gas[25]. Moreover, the rise of IoT (or IIoT for industrial applications), big data, and blockchain have brought in a different form of digitalization from what the industry has been traditionally exposed to. All those trends are believed to play a major role in the shaping of the O&G industry in the future and affect its entire value chain, which can be divided into three sectors:

- ***The upstream***: This sector refers to the exploration of potential crude oil and natural gas reserves in on-shore or off-shore formations and the processes from which they can be extracted and produced. Entities that participate in upstream operations include National Oil Companies (owned by governments), Majors (the largest multinational companies of the O&G industry), Independents (companies that operate in the upstream segment alone), and Oilfield Services (companies that provide specialized services and equipment for upstream processes). The majority of upstream projects are carried out in partnerships as a means of risk mitigation (Inkpen & Moffett, 2011).
- ***The midstream***: After the extraction of hydrocarbons, storing, trading and transporting takes place. Those are part of the midstream sector, which involves the delivery of oil to refineries, by different means of transportation, for the final processing.
- ***The downstream***: Downstream includes the processing of oil into finished products, as well as their marketing and delivery to retail locations to be sold to end consumers. Involved entities in the downstream sector include the Integrated Companies (large firms with operations in both the upstream and downstream sector) and Independents (which do not have operations in the upstream sector) (Consensys, 2019a).

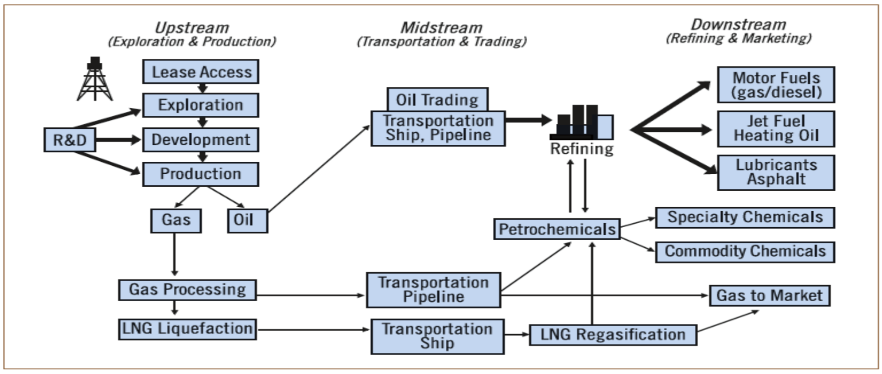

Figure 9: The oil and gas value chain (Inkpen & Moffett, 2011).

[25] This growing demand will mostly derive from developing nations in the future, while the majority of production will come from North America, whose reserves rose from 40 billion barrels in 1980 to over 210 billion barrels in 2018 (EIA, 2019).

The value chain of O&G will face an increasing number of challenges in the years to follow, driven by the current trends of the industry. Companies in the field need to strictly observe the following trends and adapt their strategic planning when necessary to maintain a steady market share.

- ***Growing demand:*** In the Asia Pacific region, demand for oil is projected to rise from 32 mb/d in 2018 to 39 mb/d in 2040, based on the current policies. On a global level, however, the adoption of cleaner forms of energy, environmental policies, and energy efficiency targets will set limits on oil demand growth. Natural gas, as a cleaner and less polluting type of fossil fuel, will be the most significant contributor in meeting future energy demand, growing by more than a third by 2040 (OPEC, 2017) (IEA, 2019e).
- ***Digitalization:*** With the demand for oil and gas on the rise and companies in the field seeking ways to improve profit margins, digitalization is a critical factor for the O&G industry to reduce costs and accelerate decision making. While the O&G industry has begun to adopt digital technologies already since 1980 (mainly to enhance productivity in E&P and for health and safety purposes), it has been less competent compared to other asset-intensive industries (Hongfang, et al., 2019). Thereby, it is essential for the industry nowadays to increase the rate of adoption of innovative technologies such as blockchain and IIoT that will help it to manage assets more efficiently, collect and utilize data, and optimize its supply chains, among other benefits (WEF, 2017a).
- ***Development of unconventional resources:*** Back in 2009 and as oil prices had plummeted below $40 per barrel, a phenomenon widely known as "shale boom"[26] began trending, enabled by technological advances. This refers to the unconventional resources of shale oil and gas, which were mostly developed in North America. Other factors that played an essential role in these developments were the challenging environments or remote locations of many conventional reservoirs (e.g. located in the Arctic, in deepwater reserves, or politically unstable countries) or the fact that they did not fulfil the properties for commercial exploitation. Despite the advantages they offer, unconventional resources face specific environmental challenges today, mainly due to the high water usage in the drilling processes (European Commission, 2016b).
- ***Environmental concerns:*** The increasing efforts to mitigate GHG emissions in recent years and the growing emphasis given to environmental protection, put restrictions on the use of fossil fuels and established an increasing demand for cleaner forms of energy. Many O&G companies followed those trends and have already launched significant investments in RES and biofuels. It needs to be kept in mind that these efforts have been intensified after the adoption of environmental regulations by the EU and the ratification of Paris Agreement, which is estimated that will cause a total revenue loss of $16.4 trillion for the crude oil industry alone (World Energy Council, 2016).

Growing demand

Back in 2000, Europe and North America accounted for more than 40% of primary energy demand, whereas developing nations in the Asia Pacific for less than 20%. At present, economic and demographic factors are key drivers that contribute to the overall growth in energy demand, particularly in developing countries. This trend will continue in the years to come, as global GDP growth is projected to grow by 3.6% p.a. (4.8% in developing countries)

[26] Many E&P companies moved into unconventional resources in the mid-2000s, but production soared after 2009.

while the global population grows at slower rates, compared to the past, with an average yearly increase of 0.77% by 2050 (IMF, 2019) (UN, 2004).

These trends will also give rise to the demand for oil and gas, which continue to cover more than half of energy consumption even after 2040. The demand for oil grows by 0.3% p.a., while natural gas rises at the much higher rate of 1.7% p.a., mainly thanks to its lower CO2 emissions, and surpasses coal by 2030 to become the second-largest source of energy (BP, 2019).

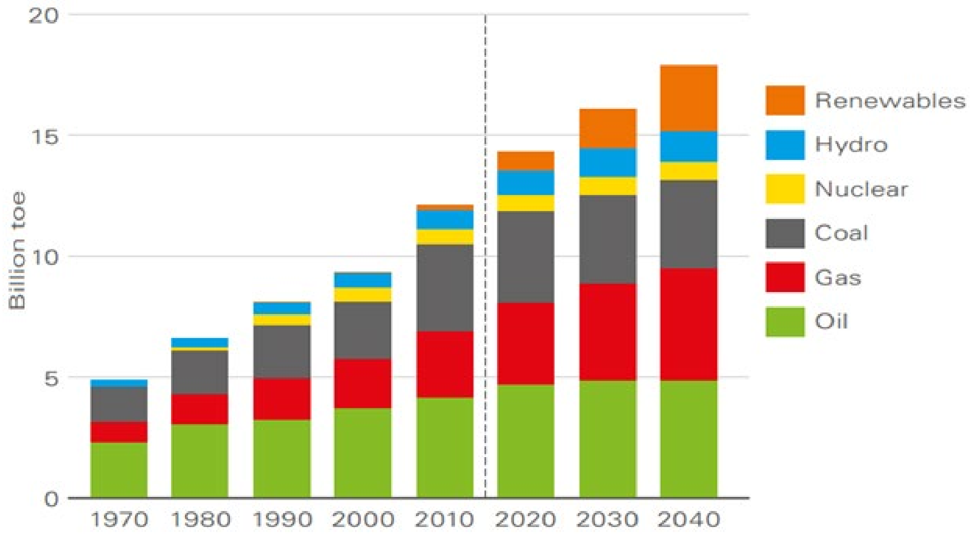

Figure 10: Primary energy consumption by fuel (BP, 2019).

The demand for liquid fuels gradually turns away from developed nations to developing ones, especially in the case of oil. In North America and Europe, oil demand falls by more than 20% between 2018 and 2040, whilst in the Asia Pacific and Africa expands by 27% during the same period. Natural gas, on the other hand, remains a priority for the energy mix of most regions, with its share growing to 36% in North America by 2040. China and India are projected to cover 14% and 8% of their energy needs with natural gas, respectively, while a particular focus turns to LNG, with more than 60% of demand coming from the two countries (IEA, 2018). In Europe, demand for gas falls from 617 bcm in 2018 down to 557 bcm in 2040. The region is today the largest importer of natural gas in the world and is expected to remain dependent on countries such as Russia to meet its energy needs, as domestic production falls by more than 30% during the next twenty years (IEA, 2019e).

The above trends describe short-term growth in the demand of oil that peaks around 2030 and long-term growth in natural gas demand, which keeps expanding even after 2040, but at a slower rate. The expansion of the hydrocarbons market will establish opportunities for revenue growth, but will also create several challenges that include increased complexity and riskier environment of operations. O&G companies need to respond to these challenges by leveraging innovative technologies that will help them enhance their performance management and optimize their operations.

Digitalization

In general, many O&G companies have been technologically advanced and have utilized a range of technologies, mainly in the upstream sector, to get better insights into reserves and to improve their marginal operational efficiency. Nevertheless, the industry as a whole has been rather slow in its digital transformation, and most of the new technologies were adopted without being integrated into existing systems and the different operational areas. At present, more than 30% of the enterprises in the field keep a risk-averse profile in their digitalization strategies and it's mostly majors that have achieved a high level of digital adoption (Hongfang, et al., 2019).

As new challenges like falling production and fluctuating prices arise in the O&G sector, companies will seek a growing number of ways to increase margins and optimize operations. In the meantime, Industry 4.0 becomes more prevalent, and its core technologies (IIoT, blockchain, big data, and cloud computing) are expected to play a crucial role in shaping tomorrows' digital O&G company. Apart from reducing production costs by an average of 10% to 20%, other benefits of the application of these technologies include (IEA, 2017):

- ***Operations optimization***: Emerging technologies today have the potential to optimize operational procedures to such an extent that savings for the O&G industry can reach $275 billion by 2025. The technologies that are expected to unlock the greatest value are blockchain, big data, and IIoT. Blockchain and smart contracts can offer greater operational transparency, accelerate procedures and facilitate real-time balancing of supply & demand, while big data and IIoT support real-time decision making (GE, 2016).
- ***Asset performance management***: Another advantage of the technologies mentioned above is the way they can contribute to the optimal management of assets. Blockchain solutions can be used from O&G companies to create asset management platforms, where equipment history and maintenance records will be stored. Moreover, by combining these platforms with predictive analytics and IIoT, companies can get better insights for particular pieces of equipment (e.g. receive notifications when maintenance is needed), enhancing thus their reliability and performance (GE, 2016).
- ***Benefits for society***: It is estimated that digital transformation in the O&G industry will benefit the broader society with more than $170 billion in cost savings for customers. Other societal benefits with an environmental impact are the savings of $30 billion from the lower water usage in operations, as well as the reduction of up to 900 million tonnes in CO_2e, which translates to $430 billion (in monetary equivalents) (WEF, 2017a).

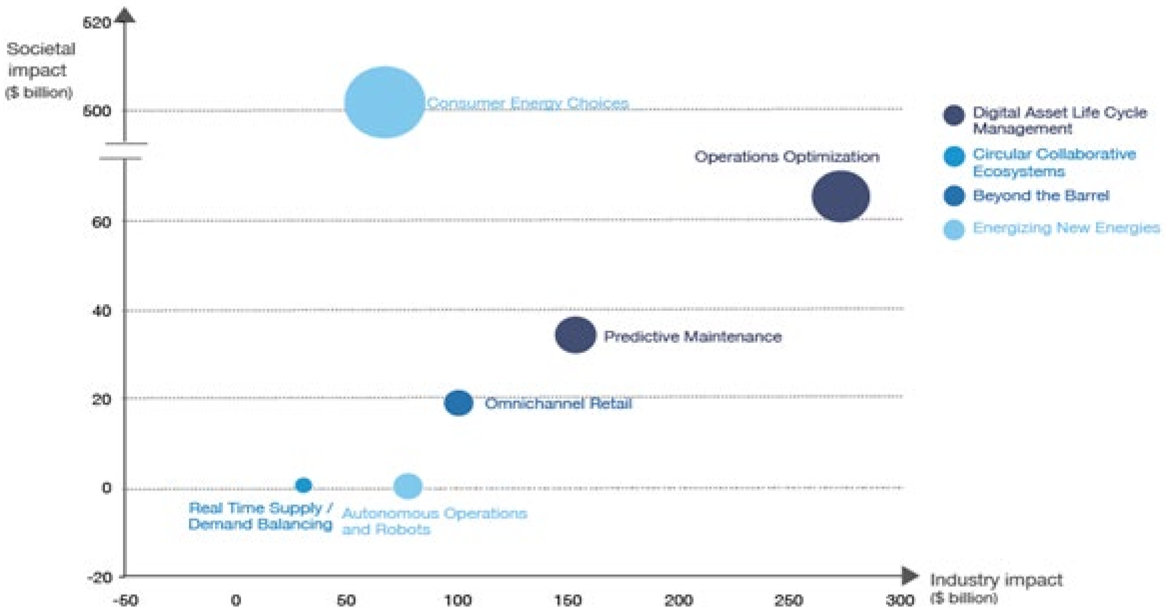

Figure 11: Potential impact of digital initiatives in Oil & Gas, for the industry and society, by 2025 (WEF, 2017a)

Besides the benefits described above, the petroleum industry should be aware of the risks that come with digital systems. As digitalization and interconnection of systems increases, so does their attack surface[27]. This means that sensitive data[28], as well as the integrity of the systems, will be more vulnerable and prone to sophisticated cyberattacks or systemic risks if companies in the field do not exploit the cybersecurity solutions that come with innovative digital systems (Deloitte, 2017b).

Unconventional resources development

By the term, "unconventional" resources are meant a number of different types of oil or gas that in the past have been too costly or technically challenging to extract. These can be extracted from shale formations, coal beds, and tight sands, amongst others, by following special techniques including horizontal drilling and hydraulic fracturing (Inkpen & Moffett, 2011) (Olaguer, 2016).

Unconventional resources are set to grow in significance in the near future, mainly due to projections of rising demand for fuels, particularly in the case of gas, and the rising scarcity of conventional reservoirs. In the past, shale gas rose from a mere 5% of total US dry gas production in 2005 to 58% in 2017. Despite not rising at precedent levels, shale gas production on a global level is estimated to rise at an average of 4% p.a. in the following years, compared to 1% for conventional gas (IEA, 2019e) (McKinsey, 2019).

Despite the positive outlook for demand and production, the viability of unconventional resources is closely related to global energy prices. The techniques involved in non-conventional drilling are coming with high costs[29] and a sharp drop in the prices of oil or gas could constitute production unprofitable. Additionally, the overall process of production entails the acquisition, shipping, storage, and management of large quantities of bulk material, which make the supply chain highly complex.

Another challenge comes with the large volumes of water used in the drilling operations (up to nineteen million litres) and other environmental concerns, because of which corporations face stricter rules for regulatory reporting. Therefore, companies in the field of unconventional production need to incorporate the necessary digital tools in their operations that will make operations more transparent, facilitate regulatory compliance, and also contribute to the improvement of efficiency in their supply chains (Accenture, 2013).

Environmental concerns

The operations involved across the value chain of oil and gas, and in particular the exploration, shipping, and refining of hydrocarbons, have been linked to a number of environmental issues in the past. Some of those include the emission of GHGs[30], oil spills in onshore and offshore locations, waste discharges, and other problems that are associated with climate change, disruption of ecosystems, and negative impacts on the health of local populations. Today,

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[27] An attack surface is the total number of different points (also known as "attack vectors") within a digital environment, that an unauthorized user can access to extract information or carry out a malicious act (Deloitte University Press, 2017).

[28] Given the immense amount of data produced, stored and shared by large O&G companies (just a seismic survey generates more than 6 terabytes of data within a day), and their value, in competitive terms, it is clear that the securitization of digital assets becomes a matter of utmost importance (Hajozadeh, 2019).

[29] Costs range between $5 to $10 million per well, with a great number of wells required compared to conventional production (Accenture, 2013).

[30] Energy-related CO2 emissions rose to 500 Mt in 2017, while oil and gas remain the second and third largest contributors in greenhouse gas emissions by 2040 (IEA, 2018).

these problems remain, and they make up some of the biggest challenges for the industry, but companies in the field have taken significant steps forward to achieve sustainability in their practices (Olaguer, 2016) (Grasso, 2019).

Moreover, the overall approach of major O&G companies towards climate change has been improved significantly during the last two decades. In the late years of 1980, the IPCC, which later played a leading role in climate discussions, was established. During the same period, a number of O&G, coal, and industrial companies formed the Global Climate Coalition that was promoting climate change skepticism. However, with climate movement initiatives on the rise and the publication of the first two IPCC Assessment Reports in 1991 and 1995, major contributors left GCC in 1996 (e.g. BP and Shell) and 2000 (e.g. ExxonMobil and Texaco), with the organization being dissolved in 2001.

Since then, the same companies and other large O&G firms have recognized climate change as a matter of great importance and have agreed on developing solutions to address it (Bach, 2017). In particular, they have adopted several measures to ensure the safety of operations, limit emissions, and reduce adverse effects on the environment and society. Most importantly, a growing number of them redefine their corporate strategies to be in line with sustainability goals. What remains to be done is closer cooperation between those firms, governments, and climate initiatives, but also a more targeted investment in R&D and broader use of innovative technologies to accelerate sustainable development processes (Mojarad, et al., 2018).

3.2 Challenges of today's energy sector

The trends discussed in the previous chapter play nowadays a leading role in the formation of energy networks, corporate strategies, and consumer behavior, but also establish particular challenges for the energy sector that companies need to be increasingly aware of.

In the electric power industry, those challenges are formed by the replacement of fossil fuels by RES in electricity generation and the decentralization in the system that this entails, as well as by the rapid adoption of digital technologies.

In the case of the O&G industry, growing demand in fuels, new methods of exploration and production, digitalization, and rising environmental awareness are the key shapers of today's industry challenges.

3.2.1 Electric power industry challenges

Electricity generation nowadays is characterized by increasing decentralization, decarbonization, and digitalization, as discussed in 3.1.1. In turn, these trends create several challenges for the electric power industry, namely:

- **Decarbonization of the grid** derives from a number of climate directives and leads the way for the deployment of RES and other carbon-free power generation methods. Ultimately, it disrupts the traditional business environment, and companies in the sector are required to adjust their strategic planning.
- The rising **penetration of RES,** on the one hand, supports countries to diversify their energy supply and reduce GHG emissions. On the other hand, it creates integration challenges into the pre-existing power networks and other issues like the balancing of power demand and supply that Transmission System Operators (TSOs) will have to find ways to solve.

- **Decentralization** of power systems is a result of the rapid penetration of RES and their increasing affordability for residential deployment[31]. This means that power is generated closer to where it is consumed instead of centralized power plants, which dramatically increases the operational complexity of power systems.
- **Digitalization** of the industry on both the business and consumer sides comes with certain drawbacks apart from the perks it offers. These include the cybersecurity vulnerabilities created by the increased attack surface and the cyberattacks on critical infrastructure.

Below are discussed in more detail the challenges that characterize the electric power industry nowadays.

Changing business environment

Digitalization along with the decarbonization of electricity systems worldwide are the main factors that shape the business environment of the electric power industry today. These trends are driven by advances in technology (e.g. that make RES more productive and economically viable), specific climate policies that require countries to decrease their GHG emissions from power generation, and by the changing habits of consumers. Therefore companies in the sector are currently required to adjust their business models to fit in this changing environment. Of course, this requires increased spending[32] for grid modernization, new technologies, storage solutions, and cybersecurity.

Apart from asset-based strategies, customer relations is another crucial aspect that utilities should also focus on. In many markets, the rapid penetration of RES and storage solutions will enable consumers to produce and store their own power, and thus load demand will start to decline. At the same time, a portion of the "traditional" customers (i.e. who are conservative or hesitant in the adoption of new technologies and RES) will remain but will demand much better customer service and faster response to their requests. Other potential types of customers that may arise are the "environmentally aware" that will choose utilities based on their environmental footprint or the "innovators" who will be open to new technologies and may require from utilities to provide innovative solutions for energy management and home automation (Kounelis, et al., 2017). Additionally, industrial or large commercial customers will require better control of their energy usage and will seek ways to reduce their costs, for example by installing a small number of RES in their properties to diversify their energy mix (PwC, 2016).

Utilities will need to respond to these requirements to keep or gain a viable market share. The problem lies within the nature of electricity as a product. Similarly to other commodities, electricity cannot be easily differentiated, and therefore utilities need to adjust their services to develop new streams of revenue. In some instances, like this of prosumers, utilities should alter their role from electricity providers to energy service providers (IRENA, 2019). Such services may include the installation and maintenance of PV panels and batteries or balancing services, solutions that are deemed necessary for any prosumer. For other consumer categories, they should try to differentiate their "final product" as much as possible[33], include

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[31] In the US the installed cost per watt for residential PV panels fall by 63% between 2010 and 2018 (Fu, et al., 2018).

[32] In 2018, investment in the power sector increased to $775 billion up from %750 billion in 2017, with most of it going towards renewables and network installations or upgrades, while the 50 largest utilities worldwide increased their capital expenditures by 14% (Deloitte, 2018) (IEA, 2019d).

[33] Ways to achieve this is by offering special tariffs on certain occasions (e.g. night time consumption) or offering fixed-priced electricity bills based on consumption range (also known as "Energy as a Service").

more RES in their energy mix and provide installation services for smart devices and smart home appliances. As for industrial customers, utilities can even provide energy consulting services that will help determine the necessary adjustments for optimal power usage or generation.

From the above, it becomes clear that in the years to follow, companies in the electric power industry will need to diversify their product base by offering a broad portfolio of products and services that correspond to consumer demands and, at the same time, shape a unique corporate identity. This will require not only strategic adjustments but also new business partnerships and increased investment in R&D and new technologies.

Increasing operational complexity

The decentralization of power systems that comes as a result of the rapid penetration of RES has contributed to the increasing operational complexity of those systems. Traditionally, electricity flows and communication were following a unidirectional flow, from the producing sites (usually large power plants) to the substations and from there to the final consumer. But nowadays, due to a large number of producers and the rise of prosuming in some regions, this system has the potential to reverse and the flows to become bidirectional. This means that prosumers, instead of just receiving electricity, may also sell the power they have produced in their properties to other consumers (Brilliantova & Thurner, 2019). The flow of information has also followed a similar path, thanks to smart meters and other smart devices, that can inform grid operators in real-time about conditions in different parts of the grid (e.g. in case of power outages).

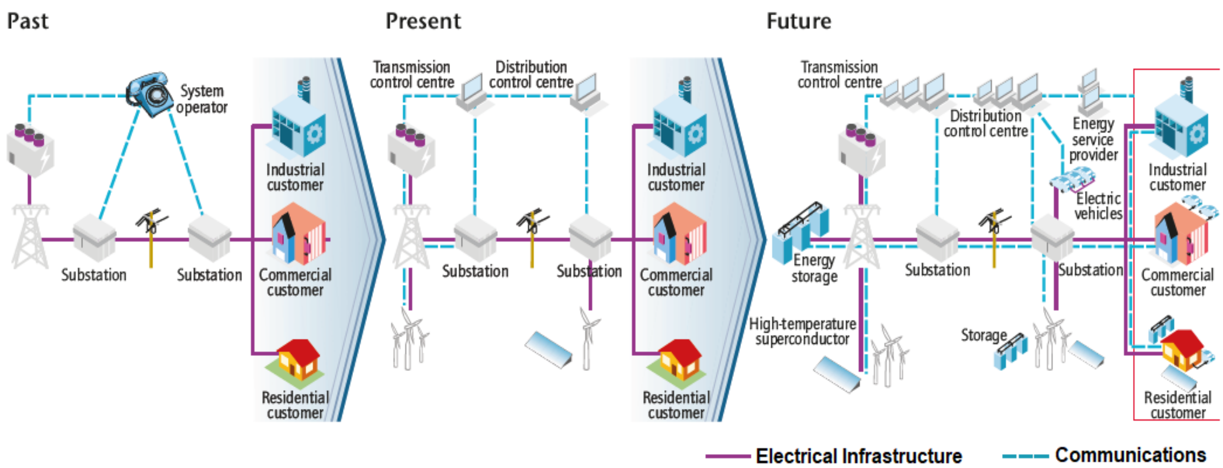

Figure 12: Evolution of electric power systems (IEA, 2015).

Another factor that adds to the overall complexity is the surplus that RES production creates at certain times of the day. For instance, during the day supply may exceed demand as a result of the producing PV panels, forcing grid operators to turn off large power plants, which comes at a high cost. This is a necessary action to prevent over-regeneration, which can damage the grid infrastructure. Therefore the grid operators ought to find ways to record production and consumption during different times of the day to coordinate the different sources and keep the system balanced (Andoni, et al., 2018).

These developments have significantly increased the operational complexity of power systems during the last few years and have created several challenges for grid operators, utilities and regulators. Apart from the continuous upgrading of the physical infrastructure and adaptation of market mechanisms, grid operators should also utilize new technologies to support the increasing flows of power and information and reduce the overall complexity of the systems. Blockchain can contribute to this effort by enabling peer-to-peer energy transactions, facilitate secure communication between smart devices, and utilize information collected by smart meters to optimally manage power flows (see 4.1).

Integration of Renewable Energy Sources

As indicated in the previous subchapter, RES (and especially the weather-dependent ones[34]), are characterized by volatile and uncertain production, which impacts supply and demand of electricity within a system. If power flows are not managed properly, they can also cause multiple problems in the distribution networks such as congestions, losses and quality issues. While more and more electricity is generated by such sources by both large and small-scale producers, the need to integrate them into the grid becomes apparent, but it also comes with certain challenges (Brunner, et al., 2019).

One of the most prominent challenges that TSOs have to face during RES integration is to keep the voltage within the predetermined operational limits to avoid damage in the grid and consumer infrastructure. Renewables can cause an increase in the voltage around the areas where they are connected in the main network, particularly in the case that supply exceeds demand (Dagoumas, et al., 2017).

Another issue that arises from the increase in power flows that integration of renewables causes is the system congestion. The aforementioned volatile nature of RES adds greatly to this problem, as TSOs are not able to forecast their exact generation levels in many cases. Demand becomes also challenging to predict as consumers take more and more energy efficiency measures. Currently, the issue of congestions is addressed with adjustments in the generation of centralized power plants and by infrastructure upgrades. Furthermore, RES may cause over-generation, which leads to grid losses if the excess energy is not stored or upgrades in the transmission lines (e.g. increase their capacity) do not take place. This can happen during night-time when demand for electricity is minimal but wind turbines can still produce (Sweco, 2015).

Each of the above issues arises in the various phases of RES integration within a system. This means that depending on the penetration of renewables and the impact they have in the particular system, there are diverse challenges which accordingly require different countermeasures to resolve, as shown in the graph below.

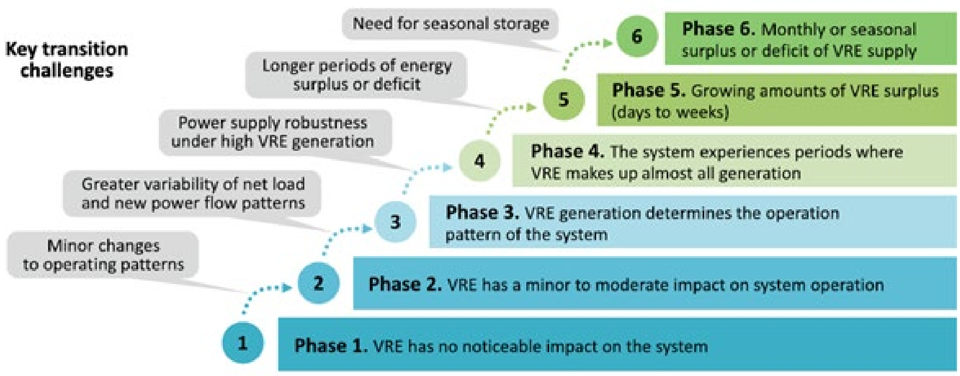

Figure 13: Challenges and characteristics of the different phases of renewables integration (IEA, 2018).

[34] From weather-dependent renewables, wind and wave power are the two most unpredictable, whereas solar PV has a predictable pattern and usually can still generate even in cloudy weather (IEA, 2011).

Most of the challenges described before arise after Phase 3, where renewables have a share of more than 10% in the system (or country). For instance, systems within Phases 3 to 5, having a high penetration of renewables, require flexibility in their power plants in terms of production adjustment (Dagoumas, et al., 2017). Additional measures in Phase 4, where RES are the major source of power for certain periods, are technical as well as regulatory adjustments. In Phase 5, renewables cover the total electricity demand in specific intervals, and measures of greater scale (e.g. electrification of energy-intense sectors such as transportation) need to take place. Lastly, in Phase 6, a number of storage solutions are required, in addition to the measures mentioned previously (IEA, 2018).

Apart from storage solutions, which constitute one of the most crucial technology for energy transition and RES integration, technologies such as blockchain in combination with IoT and smart meters also have significant potential and can contribute to the acceleration of the overall process. The primary way this can be done is by enabling surplus energy trading between prosumers and consumers on a P2P blockchain-based platform (see 4.1.2).

Cybersecurity concerns

With the rapid interconnection and deployment of digital technologies in the electric power industry that are required to facilitate the increasing complexity and the integration of renewables, the attack surface of the systems within the sector has grown exponentially. Moreover, as data continuously grow in quantity and importance, an increasing number of malicious data breaches occurs and thus, TSOs have to find ways to store them safely so as to avoid sensitive information leakage. These developments have placed at risk of digital threats critical infrastructures and particularly smart grids which are highly interconnected and dependent on ICT systems (Lund, et al., 2019).

While simple cyberattacks that target the integrity of smart grid infrastructure are not highly likely to cause a disturbance, well-coordinated attacks, even in small scale, can result in temporary disruptions in local power generation and distribution. In extreme case scenarios, wide-scale malicious acts may even lead to widespread outages or even blackouts and endanger the energy security of an entire country (Li, et al., 2019). To avoid such incidents, TSOs and utilities ought to take specific precautionary measures for the protection of their most vulnerable infrastructure that includes ICT of transmission and distribution systems.

- ***Transmission system ICT***: It incorporates all the systems necessary for the orderly electricity delivery and monitoring from the generation sites to the substations. The core component of those systems, especially in large-scale environments, is the SCADA. It is a tool utilized for the monitoring and controlling of the grid but also for the communication between the control center and remote devices. Due to its vulnerable nature[35] and importance in electric systems, it can be the key target for cyberattacks and, therefore, its protection should be a priority for any digital security architecture. Another highly used yet vulnerable ICT system that collects and analyses data from different devices for the optimal operation of the substation is the Substation Automation System (Rob, et al., 2016).
- ***Distribution system ICT***: Includes all the digital systems that are required for the monitoring and control of electric power to the end-users. The most important of these systems is the Advanced Metering Infrastructure which is comprised of a number of devices, including smart meters. These are installed on the consumer's premises and are utilized for recording and analyzing electricity consumption data. Their two-way

[35] SCADA systems are at least decade-old in most cases and not designed to withstand cyberattacks.

communication system makes them necessary for peer-to-peer electricity trading. Distribution Automation is another integral part of the electricity distribution system used mainly for monitoring purposes and remote control of devices (Sun, et al., 2018).

The above systems and the different stakeholders of electricity grids such as utilities and even customers are facing an increasing number of cyber threats that can have different objectives. These may involve attacks that have as their prime target to corrupt the communication between parts of the grid (attack on availability), to disrupt or manipulate device information (attack on integrity) and get access to confidential data (attack on confidentiality) (Mengidis, et al., 2019). Apart from the objective-based categorization, threats can be divided based on the infrastructure they target (Rob, et al., 2016):

- ***ICT systems***: Includes attacks that target the aforementioned transmission and distribution IT systems of utilities and grid operators. These attacks are currently the most common and can result in the disruption of digital communications and power control of the overall system.
- ***Generation sites***: The purpose of such attacks is to manipulate or damage the electricity generation infrastructure and cause power outages which without the necessary countermeasures from the TSO can eventually induce a blackout.
- ***Security systems***: These attacks are aimed toward interfering with protection systems and software such as firewalls so as to penetrate in other parts of the network. In general, they require special knowledge of the security systems utilized by the targeted entity and need to be better prepared and coordinated in comparison to previous attacks to have an impact.

The two most essential steps in grid security strategies are to classify the cyber threats according to the overall effects they can have if successfully deployed as well as to identify current weaknesses in the systems of the network. Based on these findings, the appropriate security systems to be used in a particular case can be identified. Security systems and techniques that are critical for any system include firewalls (for access control), cryptographic protection (to ensure the integrity of the data) and Intrusion Detection Systems (for monitoring of malicious acts).

Finally, blockchain can also offer some solutions for the securitization of electric power systems such as and cryptographic protection and registration of smart meters on blockchain platforms, automatic firmware updates of the systems by using smart contracts and identity control (see 4.1.5). (Mengidis, et al., 2019).

3.2.2 Oil and gas industry challenges

The trends analyzed in 3.1.2 are defining a number of challenges that companies in the O&G industry need to tackle. In particular:

- **Growing demand** for hydrocarbons is associated with added complexity and more costly operations across the O&G value chain (e.g. need of unconventional production to cover demand, shipments to distant locations, etc.). An additional issue is that the raised number of trading flows requires better tracking and quality control tools, whilst companies have to manage an increasing volume of data.
- **Digitalization** makes the digital systems of companies more vulnerable to cyberattacks and other cyber threats.

- **Development of unconventional resources** is linked to higher costs for exploration and production due to the more complex drilling and production process. Furthermore, the high water use in drilling operations and the increased risk of water aquifer contamination, have generated concerns about the environmental impacts of these resources.
- **Environmental concerns** and the overall growth in climate initiatives and regulations have put pressure on O&G companies to find ways to develop sustainable strategies.

Further analysis of the challenges that the upstream, midstream and downstream O&G industry faces nowadays is presented below.

3.2.2.1 Upstream

Two main challenges in the upstream segment, where blockchain can provide solutions, are the increasing costs in E&P as well as the optimal asset and resource management. Those are mainly formed by increases in demand and the rise of non-conventional production.

Upstream costs increase

Since the beginning of the 2000s, costs in exploration, development and production of hydrocarbons have more than tripled. In 2017 global upstream expenses were worth $450 billion. This number is projected to rise to $580 billion by 2025 and further to $740 billion in 2040 (IEA, 2018).

Increasing demand is a key determinant for the level of upstream expenses. Companies in the sector have been forced to develop reserves that fall into costly and more complex categories, such as:

- Non-conventional,
- Deepwater and ultra-deepwater
- Located in remote areas or at greater depths, which have lower yields and higher costs from conventional ones

Another method companies can utilize to increase production is to use new technologies for enhanced recovery from existing hydrocarbon fields.

All these production methods pose critical challenges for supply chain, planning, scheduling, risk and data management. Altogether they increase production costs and might not be viable in case of low prevailing oil prices. In total, it has been estimated that companies will have to spend $10 trillion in upstream investments by 2040 (IEA, 2018) (Inkpen & Moffett, 2011).

Until recently, companies in the E&P sector have generally been risk-averse and sceptical about adopting digital tools to a wider extent than other industries. As a result, they perform most of their operations with outdated and inefficient systems that slow down decision making and add additional burdens to the overall upstream costs. To reduce complexity and enhance collaboration among them, all involved parties (operators, contractors, suppliers) should explore new ways that will help them to drive down upstream costs and increase profit margins. If advanced digital technologies such as big data, AI, and blockchain were to be utilized for such purposes, they could deliver five times more value to the optimization of processes and operational improvement in the upstream O&G (Streubel & Ravishankar, 2017).

Asset and resources management

As upstream O&G operations increase in size and complexity, transparency across assets (e.g. oil fields, pipelines, remote platforms) declines, making their management more challenging. As a result, O&G companies need to seek solutions that will help them to better manage those assets. This chapter analyses the challenges that upstream firms have to face today regarding land rights and equipment management.

Land records management

The management of land sales and rights is one of the most critical aspects of the upstream segment. Without the proper records specifying the owner of a given land parcel and the resources found beneath[36], O&G companies cannot commence exploration and other upstream activities. This combined with the worldwide increase in competition for upstream assets (due to the growth in demand), means that companies should place special emphasis on ensuring that they keep a properly organized database of land records (Picton, 2009).

However, this is not a straightforward task as the process to determine land rights involves complex proceedings, and often there are multiple records of the same piece of land that contradict each other or even contract disputes. The blockchain technology can be used in this case to provide an indisputable database of land transactions (Hongfang, et al., 2019).

Equipment records management

Upstream equipment is used for conducting a range of operations that include drilling, well completion, production and abandonment of the well. The market of such equipment is projected to increase to $211 billion in 2022 from $172 billion in 2012, from which it becomes clear that O&G companies will have to inspect an unprecedentedly large amount of equipment (ITO, 2017) (Business Wire, 2018).

Keeping upstream devices functioning properly, is a practical way to optimize production and reduce overall E&P costs. Traditionally, the process of inspection and maintenance was performed manually and relevant records were stored in a centralized database that only the owning company had access to. Nowadays, upstream firms have the opportunity to utilize remote monitoring technologies and in combination with the blockchain technology to track and share with involved third parties (e.g. service companies) the maintenance records of their assets on a blockchain-based platform (see 4.2.1.1) (Infosys, 2018).

3.2.2.2 Midstream

As already mentioned, the rising demand for liquid fuels has brought a rapid increase in energy flows around the world, which has complicated trading to a large extent. Companies operating in the midstream sector need to utilize the right systems that will help them optimize their trading operations, reduce risks and drive down costs.

Highly complex trading operations

The surge in demand for hydrocarbons is partially caused by their ease of transport and the multiple means by which they can be transferred, such as pipelines, ships, railroads, and tank trucks. While trade of oil currently increases and peaks around 2030, LNG grows from 42% in 2017 to almost 60% by 2040 (Inkpen & Moffett, 2011). This translates into a significant

[36] For example, the US is one of the few countries that land ownership is closely related to ownership of the natural resources found below the surface, unless otherwise specified by contract (Inkpen & Moffett, 2011) (U.S. Department of the Interior, 2019).

increase in costs and complexity in the future, but trading can be already characterized as the most complicated operation in the midstream sector. The involvement of many stakeholders (e.g. regulators, O&G operators, royalty managers and financial institutions) in addition to the immense number of documents (e.g. invoices, shipping records, bank documents, etc.) means that companies are required to manage a particularly complex supply chain which adds extra burdens to the midstream costs (GuildOne, 2018b).

Other issues arising are contract disputes due to errors in documents or missing data. Many of the administrative proceedings are still manual and paper-based and it can take up to four months just for the preparation of trading. In recent years, there have been attempts of digitalization to a limited extent, with the use of digital documents. Still, this requires a relative trust among the involved parties (WEF, 2017a). A typical example is the digitization of the bill of lading, a receipt that entails all the goods transferred to a particular destination, which is signed by both the carrier and the receiver. Although the digitized bill of lading has already been applied in many sectors, the energy one is slow to adopt it because of the low trust among companies (Consensys, 2019b).

Many O&G companies are currently exploring possible applications of the DLT technology in hydrocarbons trading, with a number of majors having already successfully conducted such operations in customized blockchain-based platforms. The companies can most benefit from the transparency and optimal supply chain tracking that the technology provides. Other advantages include enhancement of transaction security, increase in the efficiency of back-office operations, and the overall savings (from reduced labour costs, reliance on fewer systems and faster settlements) that can reach up to 60% (see 4.2.1.2) (EY, 2017).

3.2.2.3 Downstream

As importantly, the trend of rising demand in the petroleum industry, and consequently, the increasing energy flows, have also created key challenges for the downstream sector. This relates to the overall management of the downstream supply chain and to the quality of the product (i.e. counterfeiting or difficulties in tracking original products).

Downstream supply chain management and product quality tracking

The downstream supply chain constitutes a crucial part of the O&G value chain, as it includes the manufacturing of petroleum products and their distribution to the end customer. By manufacturing is meant mainly the refinement of crude oil from which a wide range of products is produced. As these products are intended for completely different uses across an immense number of sectors (e.g. heavy industries, aviation, agriculture, electricity and many more), O&G companies need to put extra emphasis to achieve a comprehensive overview of their downstream supply chain and ensure that all processes and products comply with environmental regulations. This is a rather complicated task as it involves the collection, analysis and storage (usually in centralized databases that can be prone to attacks) of data from multiple sources.

The main issues that can arise from the inefficient tracking within the vast downstream supply chain are the counterfeiting of products delivered to the final consumer and the increase in erroneous shipments. Counterfeiting occurs most frequently in products like lubricants or gasoline additives (packaged) and it is estimated that it costs O&G firms billions of dollars every year and in certain cases, they may even face legal liabilities and defamation (Consensys, 2018b).

As a means to tackle such problems, O&G firms operating in the downstream sector run test labs to ensure optimal quality of refined products and apply Total Quality Management for certain processes. Beyond these methods, they may also utilize blockchain technology to ensure the optimal management of their supply chains and tracking of products (see 4.2.3).

3.2.2.4 Cybersecurity concerns

Aside from the issues in upstream, midstream and downstream sectors discussed before, the petroleum industry currently faces serious cyber threats and other digital vulnerabilities. These have grown in frequency and sophistication during the last few years, primarily as a result of two factors:

- Most of those systems were implemented one or even two decades ago, at a time when the operational needs of those enterprises were different and cyber threats were not as widespread as today. For example, many systems were designed so as to provide remote access for different purposes, which at present may constitute a vulnerable point[37] and puts operations at risk. This was done by Industrial Control Systems (ICS) like DCS and SCADA, which are utilized nowadays as well.

  Such systems are used across the value chain of O&G from the control of pipelines and refineries to manufacturing and product distribution, and by interconnecting them with digital networks, companies are able to share information or remotely operate control functions and complete maintenance tasks. Due to the operational and safety requirements of the industry[38], these systems in some instances can be accessed with minimal to none identification and are therefore more prone to attacks, with possible negative consequences on business processes, employee's health, corporate liability and the environmental issues (Stoddard, et al., 2005).

- On the other hand, recent technological additions can be much safer than the previously explained systems, but on this occasion, problems arise from elsewhere. Firstly, by interconnecting systems and digitizing processes that were previously manual, the attack surface of a digital environment widens, providing a higher number of intrusion points. Secondly, the rapid implementation of digital tools into a wide and complex ecosystem can outpace the advances in cybersecurity and make the overall system more vulnerable to cyberattacks (Deloitte University Press, 2017).

  More recently, a range of innovative technologies that enhance efficiency and accelerate workflow has been introduced in the petroleum industry. These include IIoT functions which are interconnected with a network of smart devices and can be used to track and store metrics of equipment performance or monitor operations. The total amount of smart devices in the O&G industry accounted for 1.8 million in 2018 and have an annual growth rate of 6.8%[39] (Smart Industry, 2019). Such devices are the smart sensors that are used to provide real-time information on the underwater conditions of oil rigs, wellhead monitoring and many more. The problem lies with the vast interconnection which expands the attack surface of the network, and in case an attacker finds a breach in one of the dozen devices, the whole system can be at risk (Deloitte, 2017a).

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[37] Retrofitting of those systems adds extra security layers, but on certain occasions, it can be highly costly and impact operations during the upgrading period.

[38] For example long and complex passwords may not be suitable, as in emergencies fast access to the ICS is needed, whereas firewalls may introduce significant latency to those systems (Deloitte University Press, 2017).

[39] These devices are not only geographically dispersed but may also be controlled by different stakeholders, such as engineering contractors, and have different security standards.

The systems and devices described above have applications across the value chain of the petroleum industry. However, each segment utilizes tools specialized to its operations and follows different processes, which means that it also faces completely different cyber threats. Below are listed several cybersecurity risks specific to the upstream and downstream sectors.

Upstream cybersecurity risks

Traditionally, the different parts of the upstream sector have been isolated from each other and less prone to outside threats. But as more real-time information about field conditions began to be needed for exploration and production, the interconnection of upstream systems was inevitable. Operations in the E&P segment include the exploration, development and production phases, which can face the following digital threats:

- The exploration phase commences with geological and seismic surveys which help the company to determine if the given site is suitable for commercial exploitation. The data collected during the surveys are sent from the field sites to the corporate offices for analysis, and it is decided whether or not the operation will proceed with exploratory and appraisal drilling[40].

  While data transmission in this stage used to be done with tapes and other physical means, it is currently conducted via digital networks, and therefore a higher level of security measures are required to avoid data leakage. Nevertheless, exploratory and appraisal drilling are more prone to cyber threats as they involve several devices and utilize SCADA systems for operational control (Nasir, et al., 2015).

- During the development phase, the so-called "development drilling" takes place. Some of the development drilling processes relate to those of exploratory drilling, but in this case, a more comprehensive range of critical systems that provide sensitive real-time data on well, equipment and geological conditions are involved and most operations are fully automated.

  In addition, a plethora of contractors like engineering firms, material suppliers and consultants participate, and as a result, different security protocols are followed and much more information needs to be shared among the parties. Another step included in the development phase is well completion, a process that prepares a well so it can commence production. Whereas it mostly involves installing of equipment, in recent years a number of digital tools such as real-time tracking of materials (e.g. fracking fluids, cement) and advanced analytics software are utilized to reduce completion time (Deloitte University Press, 2017).

- Production is the last phase of the upstream segment and the most vulnerable to cyber threats[41]. It includes the extraction of hydrocarbons from the subsurface reservoir and their preparation for transportation and sale. All the facilities involved in production not only are highly automated but also have been operational for more than one decade[42], and as a consequence were not designed to contend with today's sophisticated cyber

[40] Exploratory drilling is being conducted to collect rock and fluid samples from which the reservoir productivity and other characteristics can be identified. Usually, more than one exploratory well will need to be drilled to provide more information about the reservoir. Appraisal drilling involves mapping (evaluation of reservoir size), reservoir simulation and drilling of additional wells. It helps in estimating if the project is economically viable.

[41] An upstream cyber-attack incident occurred in 2013 in an offshore oil platform in Africa when hackers managed to obtain control of its stabilization systems which resulted in production being shut down for 19 days (Ridima, 2016).

[42] Around 42% of offshore facilities have been in operation for more than 15 years whereas only 9% are considered to be newly constructed (less than 5 years old) (Baker Hughes, 2016).

threats (e.g. malicious software can attack a system and go undetected for an average of 15 months) (Effendi & Davis, 2015).

On top of that, ICS which is used for controlling each well within a reservoir (majors operate more than 25,000 wells worldwide) are also interconnected with the ERP systems of most companies. ICS are highly vulnerable and in case they are threatened by a cyber-attack they can subsequently cause damage to all the other systems they are interconnected with (Deloitte University Press, 2017) (Nasir, et al., 2015).

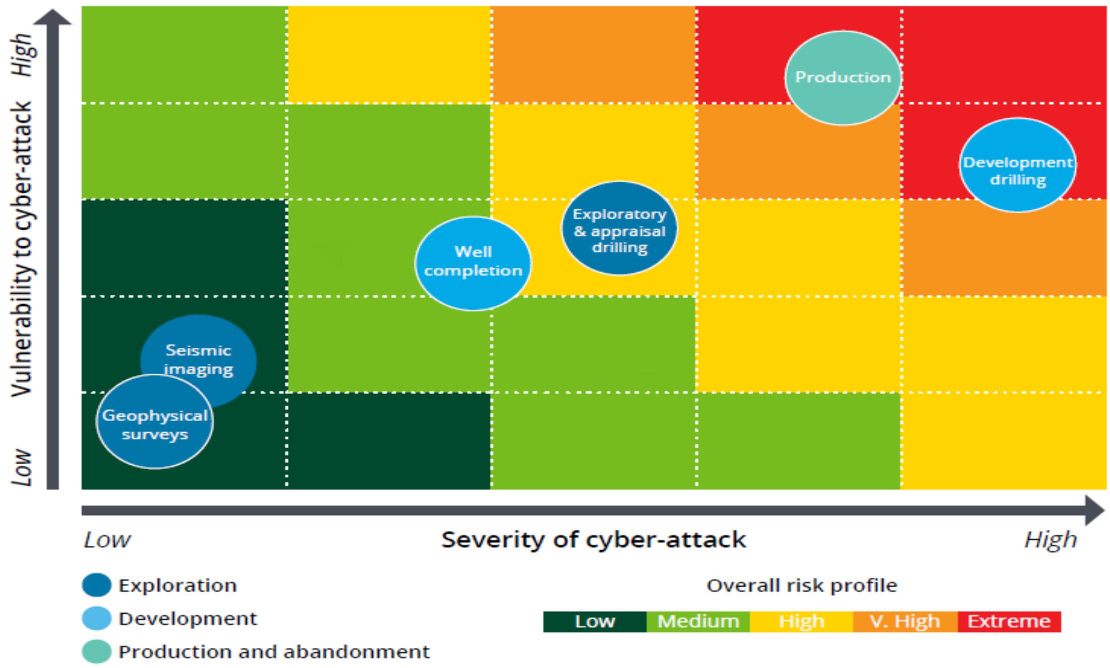


Figure 14: Cyber-attack vulnerability and severity by upstream operation (Deloitte University Press, 2017).

From the above, we conclude that the most vulnerable operations to cyber threats in the upstream segment are development drilling and production. A possible breach of these phases can result in severe health & safety, environmental, reputational and financial damage. It must be noted though that while upstream has a broader attack surface, the potential threats for this sector are relatively less compared to the midstream and downstream segments (Dragos, 2019) (BCG, 2016).

Midstream cybersecurity risks

Cyber threats in the midstream segment constitute a rising concern for O&G companies. The midstream sector involves the trading, transportation and storage of liquid fuels which can be impacted by cyber threats in the following ways:

- After production, hydrocarbons are transported mostly by pipelines and ships which have different vulnerable parts. More specifically, in the event of unauthorized access to the sensors[43] or control systems of pipelines, there is a high probability for an interruption in transmission or even spillage and environmental damage. In the US, cyberattacks on pipeline infrastructure have been so widespread (e.g. the trans-Alaska pipeline faces 22 million cyberattacks per day) that Homeland Security launched the Pipeline Cybersecurity Initiative in 2018 (DHS, 2018). Regarding shipping, a heavy

[43] Different types of sensors can be used for flow metering or to provide information on oil and gas temperatures, pipeline conditions and other metrics (Nasir, et al., 2015).

burden on cybersecurity is created by the lack of relevant frameworks and standards, in addition to the outdated security measures used by many operators (Nasir, et al., 2015) (Ridima, 2016).

- Trading and storing of liquid fuels is less susceptible to cyber threats but the increased demand, and therefore complexity, has introduced difficulties in the securitization of the systems involved. For instance, CTRM platforms used in back and front office trading processes, as well as inventory control systems, can be a possible target to cyberattacks with immediate financial consequences and disruption in the supply chain (PwC, 2017).

We can deduce from the above that while the midstream sector has a narrower attack surface compared to the upstream, the pipeline transportation system can be highly vulnerable to cyber threats. However, these threats cannot be compared to the number and severity of those in the downstream segment (BCG, 2016).

Downstream cybersecurity risks

The downstream segment involves the refining of crude oil and production of petrochemicals and other petroleum by-products. Moreover, it includes the marketing and distribution of those end products to industries, wholesale and commercial markets. Thus, private and sensitive data of customers are involved in these procedures. The risks related to this phase are the following:

- The refining and production of petroleum products involve equipment such as reboilers and pumps, which are the most sensitive parts of the refinery. Their monitoring for safety and efficiency reasons is being done by sensors and algorithms. Additionally, the supervision systems employed, including SCADA and DCS, are also prone to sophisticated cyber threats (Deloitte, 2017b).

  These include malware which can go undetected for long periods, gathering information on security traits and detecting possible system vulnerabilities. If enough data are collected, possible outcomes include the manipulation of the refinery's control systems, shutting down production or even causing emergency situations by interrupting the utilities of the refinery (e.g. electricity, cooling water etc.) (S&P Global Platts, 2018).

- During the operations of marketing and distribution, weak points include the extensive amount of digital devices and the logistics software due to access from third-party personnel. Trucks are less prone to cyber-attacks as they have few exposed parts like geolocation systems.

  Another sensitive spot is personal customer data (e.g. credit card or bank account information) which require safe environments to be stored since data leaks can result in regulatory or financial penalties and brand damage for the given company (Deloitte, 2017b).

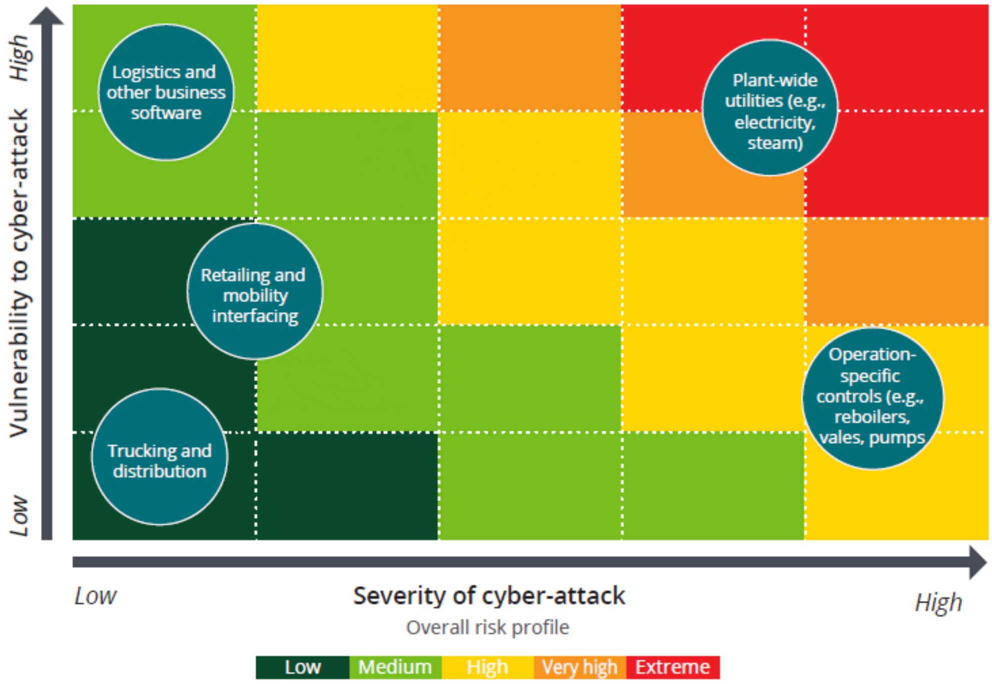


Figure 15: Cyber-attack vulnerability and severity by downstream operation (Deloitte, 2017b).

The vulnerability ranking of the downstream segment remains at the top compared to the other two, while the most likely target is refining, mostly due to the technical and classified data involved.

Companies operating across the value chain of the petroleum industry are increasingly aware of the vulnerabilities in their digital systems and the threats that they face from cybercrime. That is the reason that investments in cybersecurity strategies and practices, such as biometrics, are on the rise, yet there is considerable scope for improvement. The blockchain technology and smart contracts are other solutions that can also offer substantial advantages to the securitization of O&G systems, as discussed in 4.2.5.

4. Blockchain technology in the energy sector

The potential of blockchain applications in the energy sector can be distinguished by the ability of the technology to provide solutions towards the energy trilemma:

- ***Energy security**:* Provide additional security measures in terms of cybersecurity in today's increasingly complex and digitalized energy systems, and in terms of security of supply.
- ***Energy equity**:* Enable more people in developing countries and distant areas to get access to affordable and clean energy by combining RES and innovative methods of peer financing.
- ***Environmental sustainability**:* Assist in the promotion of renewable energy generation or other low-carbon solutions and promote the integration of RES. Additionally, support O&G companies in their sustainability strategies.

Most of the blockchain applications in the energy sector today have been directed towards the electricity sector, with more than half of the use cases focusing on the two following categories: decentralized energy trading (33%), and tokens & energy project financing (20%). Both of these categories can provide valuable solutions across the energy trilemma[44]. Additional cases include the "support services" category of smart devices and asset management (11%), while 9% are targeted in metering and security of energy systems (Andoni, et al., 2018).

It should be emphasized that the blockchain technology is mostly useful in cases that decentralization or transparency is needed (usually when more than one parties are involved). Especially in the context of a private company network, DLT is not always the optimal solution as traditional databases that offer better processing times can be utilized (see Appendix A) (Fernandez & Fraga, 2019).

As for the petroleum industry, blockchain applications have been limited. This is mostly related to the entry barriers and the different nature of operations of the sector[45]. Nevertheless, more recently, a number of initiatives from majors in the industry have been launched. These aim at testing DLT solutions in different use cases with a view to establish them in a greater degree (Brilliantova & Thurner, 2019).

This chapter examines the trends and challenges that the electric power industry and the oil & gas are facing nowadays and identifies the relevant solutions offered by the DLT through different use cases.

4.1 Blockchain-enabled solutions for the electric power industry

The earliest applications of blockchain in the electric power industry could be observed already since 2014 and were related to electricity transactions. In the years that followed and as more and more investments were attracted towards energy-related blockchain applications[46], the number of use cases grew to include peer-to-peer energy trading, wholesale markets, grid

[44] For instance, decentralized and P2P energy trading within a smart grid is environmentally sustainable (power is produced with RES) and also provides security of supply in the given network (in case of a temporary outage, prosumers can utilize and exchange their stored electricity).

[45] Oil and gas are traded as commodities on a global level and are impacted by external factors such as geopolitics, while electricity is specific to a regional level (IRENA, 2019b).

[46] Between the second quarter of 2017 and the first quarter of 2018, venture capital investment in blockchain energy projects amounted to more than $290 million (Luke, et al., 2018).

management, decentralized generation, payment facilitation and many more (Luke, et al., 2018). According to Accenture (Accenture, 2018), in 2018, there was a total of 80 blockchain-based energy projects in 24 countries with startups amounting to 122 worldwide.

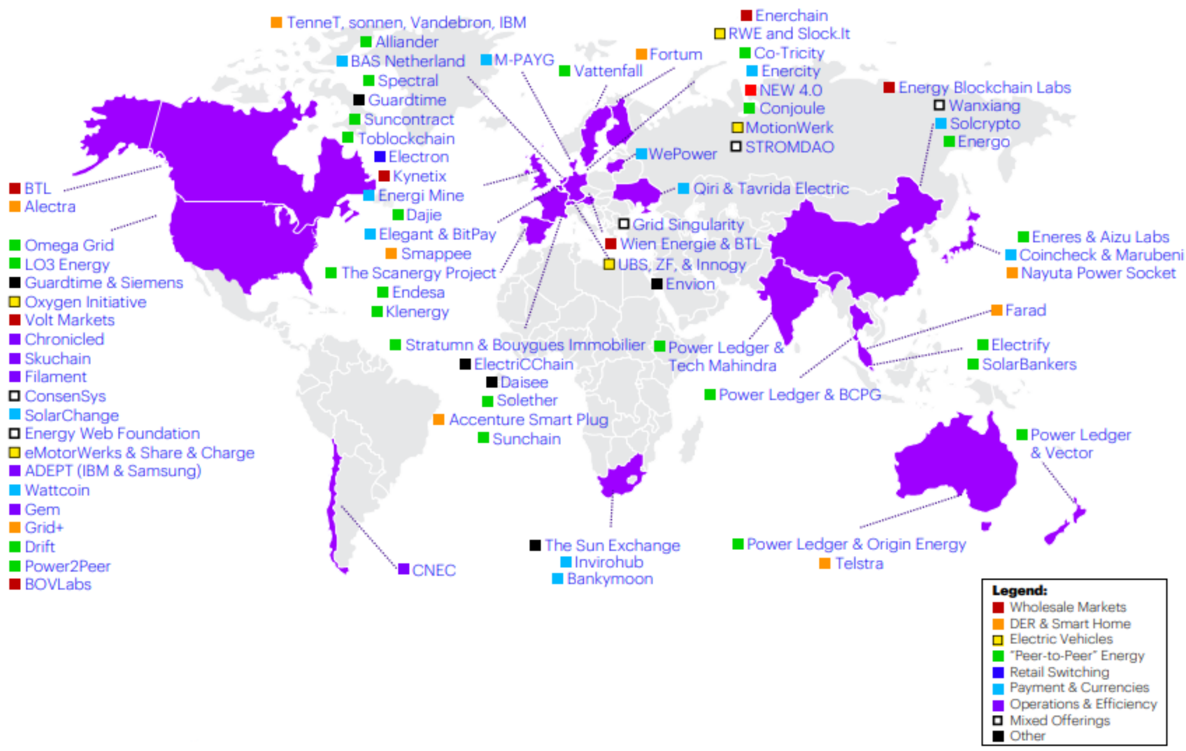


Figure 16: Blockchain projects in the electric power sector worldwide (Accenture, 2018).

Despite the growth in the number of entities engaged in the sector, blockchain in electricity is still in an exploratory stage, with limited practical applications. The primary reasons for this are sector-related as well as technically-related. Most companies in the sector follow a risk-averse business strategy and many technologically uncertain or least-applied technologies like blockchain are not ranking high in their investment agendas. From a technical standpoint, scalability is the main issue to be addressed for wide-scale applications in the sector, along with the speed of transaction and particular security challenges. Regulatory compliance is another issue in most countries, as the technology can change several procedures in a highly regulated environment like the electric power industry (Livingston, et al., 2018).

Blockchain applications in the electric power industry are predicted to reach maturity in 5 to 10 years (see Appendix B). Blockchain will deliver a number of solutions for the challenges faced by the industry (discussed in 3.2.1) and will assist TSOs with RES integration and better infrastructure management. Moreover, companies in the sector will be able to transform their business models and offer better services to customers by utilizing blockchain and the vast amount of data produced by smart devices. Finally, from a consumer point of view, the most prominent application enabled by the blockchain-IoT combination is peer-to-peer energy trading which will enable active participation in the energy markets and provide an environmentally and economically sustainable solution for consumers.

4.1.1 Changing business environment

As stated in 3.2.1, the decarbonization of the electric power industry, as well as Energy 4.0 have already begun to influence the traditional business environment. They are also projected to cause an even greater disruption in the years to follow. Utilities will see new markets to arise in the sector and their business models changing rapidly, while those that are slow to adapt will lose significant market shares which will impact their prospects negatively. Thanks to the new technology paradigms it will also be easier for new entrants to enter the emerging markets and compete, which poses another threat for traditional utilities.

Blockchain can contribute to the development of new products and in the promotion of new business models in the power sector. This, in turn, will support companies to find alternative ways of project financing, expand their market share and serve the ever-increasing needs of customers. More specifically, blockchain can contribute to the establishment of the following business models:

Community ownership and financing models: Accessing the required capital for a RES project financing can be a long and complicated process, especially for small and medium-sized enterprises. In the case of developing countries, while there is a high potential for the development of RES, high upfront costs in combination with political reasons and distrust from the financing sources can restrict the deployment of otherwise successful projects.

Blockchain can support companies to raise capital from innovative crowdsourcing models and contribute to the alleviation of energy poverty, a significant issue nowadays, especially in developing economies[47]. This can be done through blockchain platforms or token sales. In the first case, potential investors participate in the fund-raising platform that is powered by blockchain for optimal transparency.

A startup company that uses this model of crowdsourcing is called The Sun Exchange. The platform connects individuals or organizations that are interested in investing in solar power with companies that want to install solar PV panels on their premises. After a solar PV project is approved and added to the blockchain platform, users are able to finance it by buying virtual solar cells. When the financing round is completed, the funds are used for the installation of the PVs in the premises of the given company. The company can then produce its own power and lower its electricity bills, and in exchange, it pays a monthly allowance to the parties who crowdfunded the project (WEF, 2018). To date, the startup has funded through its platform 18 solar projects with a total capacity of more than 1700 kW (Sun Exchange, 2019).

Tokens, however, are currently the most used fund-raising model. Through Initial Coin Offerings (ICOs), companies can make a given number of digital tokens available for public purchase to fund a project or a part of it. The value of the tokens will increase as the number of successful projects rise and the network is used by more individuals interested in investing (IRENA, 2019a). Certain startups utilize fundraise platforms like the one described before, but the whole fundraising process is being done through sales of their native token instead of third-party cryptocurrencies or other means. Such cases are those of SolarGridX and WePower.

Tokens have also been used to incentivize clean energy production. The SolarCoin Foundation created a cryptocurrency back in 2014 to reward solar energy producers around the globe, through a rewarding system similar to that of Bitcoin with miners. For each MWh of energy produced, members of the platform are able to claim one SolarCoin which is then sent to their digital wallets and can be either spent at partner companies or exchanged for fiat money (SolarCoin, 2019).

Pay-as-you-go models: This model is currently offered by a small number of companies as an alternative to the traditional per unit charge for electricity use. Through PAYG, consumers can buy and install prepaid smart meters in their premises, and as they consume electricity,

[47] Globally, 1.2 billion people lack access to electricity, while in developing countries, more than 15% of the population suffer from energy poverty (IEA, 2017b).

their credits will be reduced. The smart meter will inform them after they have used most of their credits and they can pay a certain amount to recharge the meter in a model similar to that of mobile top-up.

As this payment model has not been widely used yet, there are only a few blockchain initiatives utilizing it. M-PAYG is a startup that combines project financing and pay-as-you-go services through a blockchain platform. After the company approves a project, it funds the installation of PV panels in the premises of the interested party and connects them to a smart meter. To use the panels to generate electricity, the interested party should top-up their smart meter "balance" through monthly payments. This process is repeated until the initial cost of the project is covered (Andoni, et al., 2018). ImpactPPA is another startup that utilizes a crowd funding model through its own token offerings to finance renewable energy projects in developing countries. After the project is completed, the consumer pays through a pay-as-you-go model to use the equipment (PV panels, small wind turbines, smart meter) and generate energy (ImpactPPA, 2018).

Energy-as-a-service models: According to the EaaS model, the consumers pay for their energy consumption on a subscription basis in contrast to the traditional "per unit" charge. Similarly, those who want to generate energy in their properties do not pay any upfront costs for the equipment or the installation rather than a subscription to the service provider or utility, which funds the project and "rents" it to the interested parties. For instance, if a commercial customer wishes to install PV panels in their premises, they can consult an EaaS provider who will plan and fund the purchase, installation, monitoring and maintenance of the necessary equipment. This will be done after an Energy Service Agreement[48] is signed by both parties (ACEEE, 2018). At present, this model is offered by a small number of multinational companies with their main target market being commercial and industrial consumers.

Apart from the above, the EaaS model incorporates services that in the future will be essential for small and large energy producers, such as demand management, energy storage services, Power Purchase Agreements and consulting services for energy portfolios. Moreover, in the EaaS model are included several platform services enabled by the blockchain technology like wholesale contracts, renewable energy certificate tracking and most importantly, P2P energy transactions (Deloitte, 2019).

Last but not least, another essential business model enabled by the blockchain technology is peer-to-peer and decentralized energy trading, which is described in more detail in the following subchapter.

4.1.2 Decentralized energy trading

The changing landscape of today's power systems as a result of the increasing deployment of RES and the rise of prosuming requires specific solutions that will help to facilitate the process to decentralized energy systems and address the challenges that will arise. One of the major challenges is the surplus in production that renewables create at certain times of the day. Currently, this problem is either solved by storing the excess energy in batteries solutions or by turning off large power plants, which is rather costly.

Blockchain technology enables prosumers with access to small-scale DER units such as PV panels and small wind turbines to cover the demand in the network with this energy surplus by trading it with other consumers. In essence, this changes the energy flows from

[48] This agreement guarantees that the client will stick to the contract for a period sufficient to cover the total costs of the project.

unidirectional to bidirectional (as described in 3.2.1) as consumers will also produce energy instead of consuming alone and thus will not be entirely dependent on centralized power plants.

Decentralized energy trading which includes P2P and wholesale (or B2B) trading, has attracted the most blockchain initiatives within the energy sector up to date.

Peer-to-peer energy trading

It is a specialized to the energy market form of P2P collaboration based on the notion of Collaborative Consumption, according to which consumers can directly transact resources or services among them, with little or no interference of other intermediaries (Botsman & Rogers, 2010). Despite being at an early stage, blockchain applications that concern peer-to-peer energy trading between consumers and prosumers are currently the most promising initiatives in decentralized energy trading.

The whole process concerns trading within microgrids connected to a central grid and is done through blockchain platforms, which are being combined with smart contracts that help in the implementation and recording of the transactions. To connect to a given platform, all participants will need to have an installed smart meter within their premises which will send updates about power flows, power generation and transactions to the operator and communicate with the blockchain network (Andoni, et al., 2018). The platforms may be enabled by government entities, grid operators, or private firms who will charge accordingly (e.g. with monthly/annual subscription plans or per-transaction fees) for these services. Cooperative communities might also create their individual projects and platforms to avoid charges by third parties (PwC, 2018).

Depending on the structure of a given P2P market, the participants and procedures will be defined accordingly. In one of the proposed models, the blockchain platform is used to create a pool of prosumers and consumers and match their offers through a bidding process (described in Appendix C). Therefore, in this case, the platform and its administrator merely acts as a facilitator of the trading process. In another case, prosumers sell their excess energy to the grid (or directly to a given platform) and the platform administrator is responsible for buying the necessary energy to cover the demand of their customers.

As a result, there is no bidding or a direct exchange of energy between individual prosumers and consumers in that case, as the platform acts as an intermediary (AGL, 2017). The involvement of other intermediaries such as banks that transact tokens for fiat currency depends upon each platform's conditions and technical capabilities. On both occasions, though, the participation of a grid operator, which will be responsible for the management of grid infrastructure and power delivery is deemed necessary.

In comparison to traditional electricity markets, P2P trading can benefit both the participating prosumers and consumers as well as the grid infrastructure. One of the essential aspects of P2P markets is that prosumers are given economic motives for selling their excess energy[49] whilst consumers can enjoy cheaper and greener energy and greater flexibility in their choices (e.g. choose the cheapest offer or buy from producers within close geographical proximity). For instance, by buying from local prosumers, they immediately minimize the distance that the electricity has to be transmitted, which subsequently reduces power losses and strain on the

[49] Even in comparison with net metering, revenues from selling in a peer-to-peer market can be significantly higher, as prosumers do not sell their energy to utilities at a fixed fee, which is usually low, but receive different spot prices or biddings each hour from individual consumers. Government subsidies can be another motive for prosumers to engage in P2P markets.

network and lowers the transmission costs (OECD, 2018). Moreover, prosumers can sell their energy during price peaks to maximize profits and store or use their energy when spot prices are lower[50]. Of course, this might create an imbalance in the system for which the TSO and the platform administrator must be aware of.

Since 2016, when the first pilot P2P energy trading projects began taking place, the number of startups that engage in the particular sector has grown significantly, but most of them remain in a proof-of-concept stage or an early market engagement with a small number of customers[51].

Brooklyn Microgrid, the first pilot project concerning peer-to-peer energy exchange took place in April 2016 in New York. The project that was developed from the startup LO3 Energy initially involved 5 prosumers with photovoltaic power generation and 5 consumers. All participants were required to have an installed smart meter in their properties and were able to transact electricity using a native token called Exergy. The exchanges were completed through a platform, and all the transaction information[52] recorder from the smart meters of transacting parties were added to the blockchain (Exergy, 2017). Results were positive as the participants managed to reduce their electricity bills by 6 to 12%. This led to the company seeking authorization from the responsible authorities to expand the project and allow more interested parties to engage in it, including local businesses (Business Insider, 2019).

A similar case, also developed in 2016, is that of Power Ledger. The Australia-based startup developed a vast number of projects from which the most prominent, the so-called xGrid platform, allows consumers and prosumers to engage in peer-to-peer energy exchange by using the “Sparkz” token.

[50] Spot prices are determined through a platform’s pricing mechanism which constantly receives signals from the participants’ smart meters to keep the supply and demand of the network updated (Tushar, et al., 2018).

[51] Their development and business scaling-up depend mostly on blockchain’s technical capacities (i.e. transaction rate, latency and security issues) and local regulations (which need to allow the exchange of electricity among individuals and not with private companies alone). Another important factor will be the consumers’ preferences and interest to engage in prosuming and peer-to-peer markets, which are expected to be reluctant during the first years of exposure to wide-scale P2P projects (except for the “innovators” and “early adopters” types of consumers) (Kounelis, et al., 2017).

[52] Transaction information included the amount of energy exchanged, the transacting parties (defined by smart meter ID) and the price at which the energy was sold (Exergy, 2017).

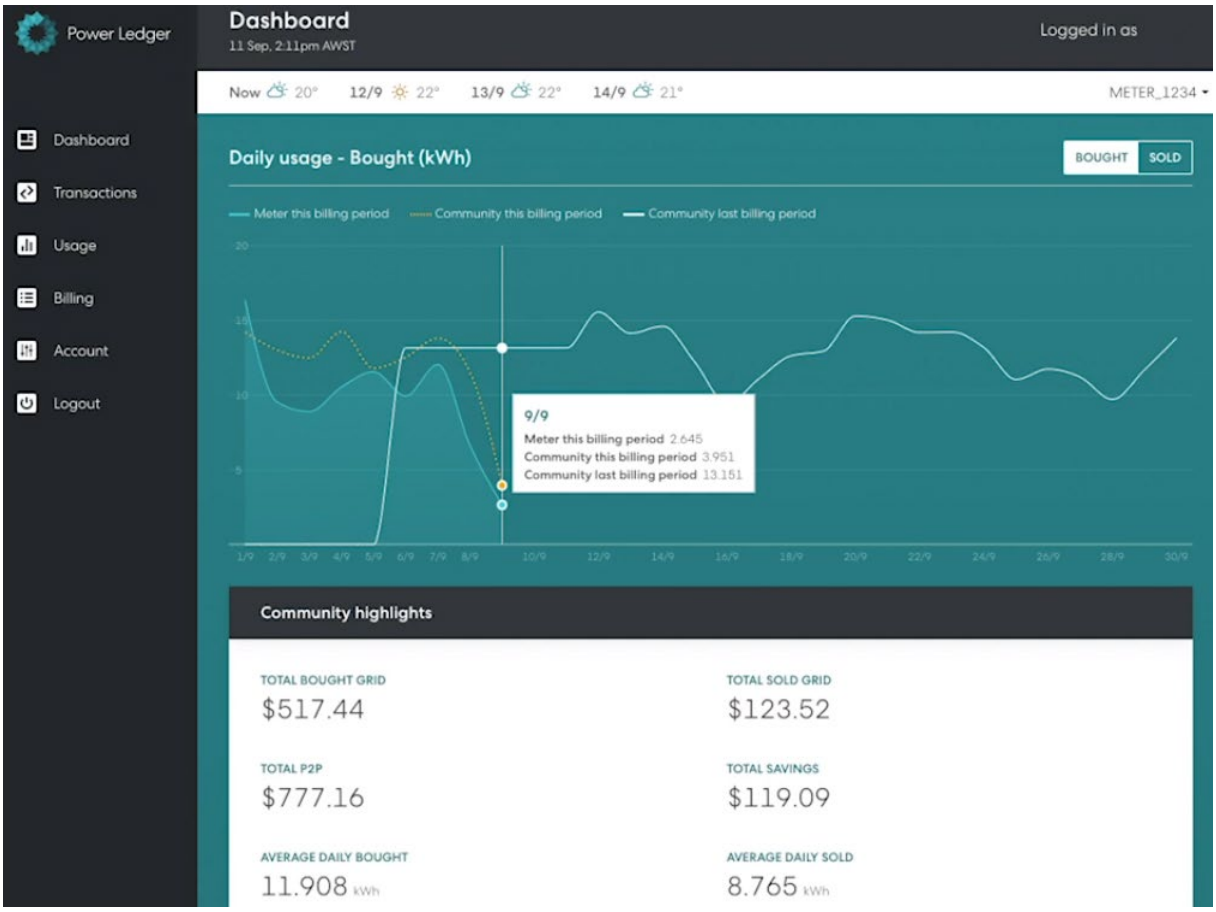


Figure 17: The dashboard of Power Ledger platform. Users are able to buy and sell energy and view the details of transactions and billing information (Power Ledger, 2019).

Up until now, the xGrid platform has been utilized in nine wide-scale projects of P2P solar energy trading (Power Ledger, 2019):

- Three of the projects are located in Japan (two of the cases includes 100 participating households each)
- Two in Australia (10 commercial sites and 40 households)
- One in Malaysia (5 commercial sites with 1.5 MW of installed PV capacity)
- One in Thailand (participants include 1 commercial site, 1 residential site and 2 public buildings)
- One in Austria (10 households)
- One in the U.S. (1 commercial site trading electricity P2P with local residents)

Most of the above projects are still in an early or pilot stage and they have the potential to include more significant numbers of participants in the near future.

Given the positive results of those experimental cases, there was a considerable increase in the number of initiatives in 2017. Spectral, a startup founded in 2015 in the Netherlands, managed to establish its own private and permissioned P2P blockchain platform in 2017, called “SPEX”. Participants are enabled to buy energy from local producers or sell their energy directly to their neighbours by using the platform’s token, without the need of a bank or other third-party to fulfil the transactions. After the user inputs their preferences (i.e. bid prices, amounts to be sold or bought) the platform automatically matches offers and sends the billing documents to the transacting parties (Spectral, 2019a). The company’s goal is to scale the project to allow users to purchase wholesale power and connect it to centralized balancing markets. Recently, the city of Groningen consulted the company, as it intends to create local peer-to-peer electricity markets in its neighbourhoods, and in a later phase, when conditions are favourable to expand it to other cities as well (Spectral, 2019b).

Other notable P2P energy initiatives in Europe include SunContract, a Slovenian-based startup that has managed to create within its platform a “pool” of prosumers and consumers that range from small households to large industries and are interested in trading peer-to-peer electricity. The Prosume Foundation, based in Italy, empowers prosumers and small plants to trade gas in addition to electricity on its mobile application, connected to a P2P platform (SunContract, 2017) (Prosume, 2019).

Finally, in developing parts of the world, Solarex provides PV panels and smart meters to local communities, which can cover their needs and trade the excess energy on the company’s P2P platform. Similarly, Solshare has managed to connect through its platform several villages with existing photovoltaic and smart meter infrastructure, thereby creating local microgrids that can disconnect from the main grid in case of disruptions and operate in island mode (Solarex, 2018) (Solshare, 2019).

Decentralized wholesale energy trading

Similarly to platforms providing users with peer-to-peer energy exchange services, several initiatives concerning wholesale energy trading have emerged. These not only allow consumers to access wholesale energy markets or power plants to directly sell their power to the final consumer without the need of an intermediary but also provide companies with B2B platforms where they can purchase energy at a reduced cost compared to traditional wholesale markets. Blockchain technology can also be utilized to provide a transparent environment for the processing of wholesale energy transactions and simplify the relevant procedures, which currently include complex paperwork exchange among the involved parties such as brokers, exchanges, trading agents and banks (Andoni, et al., 2018).

One of the first initiatives that completed a wholesale energy trade through a blockchain platform was that of Enerchain, developed by the German software company Ponton. The decentralized trade was completed in 2016 on the Enerchain application, which was at that time in a proof-of-concept stage with participants including 44 large utilities. In 2019 the consortium blockchain application went live, enabling all the participating companies to trade spot and forward electricity and gas contracts (Ponton, 2019).

Lition, a Germany-based startu,p enables its clients in 10 cities to gain access to power from local biomass power plants in addition to solar power (Lition, 2019). Producers that participate in the platform include:

- 19 biomass power plants that their capacity ranges from 0.4 MW to 4 MW and have a combined capacity of 28 MW
- 6 photovoltaic producers and solar farms with capacities from 0.1 MW to 0.75 MW and with a combined capacity of 2.8 MW

Companies that use blockchain-enabled platforms to provide their customers with access to wholesale electricity prices are also attracting attention lately. One such case is that of Grid+. Its customers can place their electricity orders on the platform in 15-minute intervals after they have bought the necessary amount of tokens. The company achieves the low rates of electricity prices by aggregating the orders of its customers and purchasing large amounts directly from the wholesale market (Livingston, et al., 2018). Another startup that uses an auction system where renewable energy producers place their offers and sell directly to customers is WePower. The platform is at present accessible only by corporate consumers and is thereby a B2B marketplace (WePower, 2019).

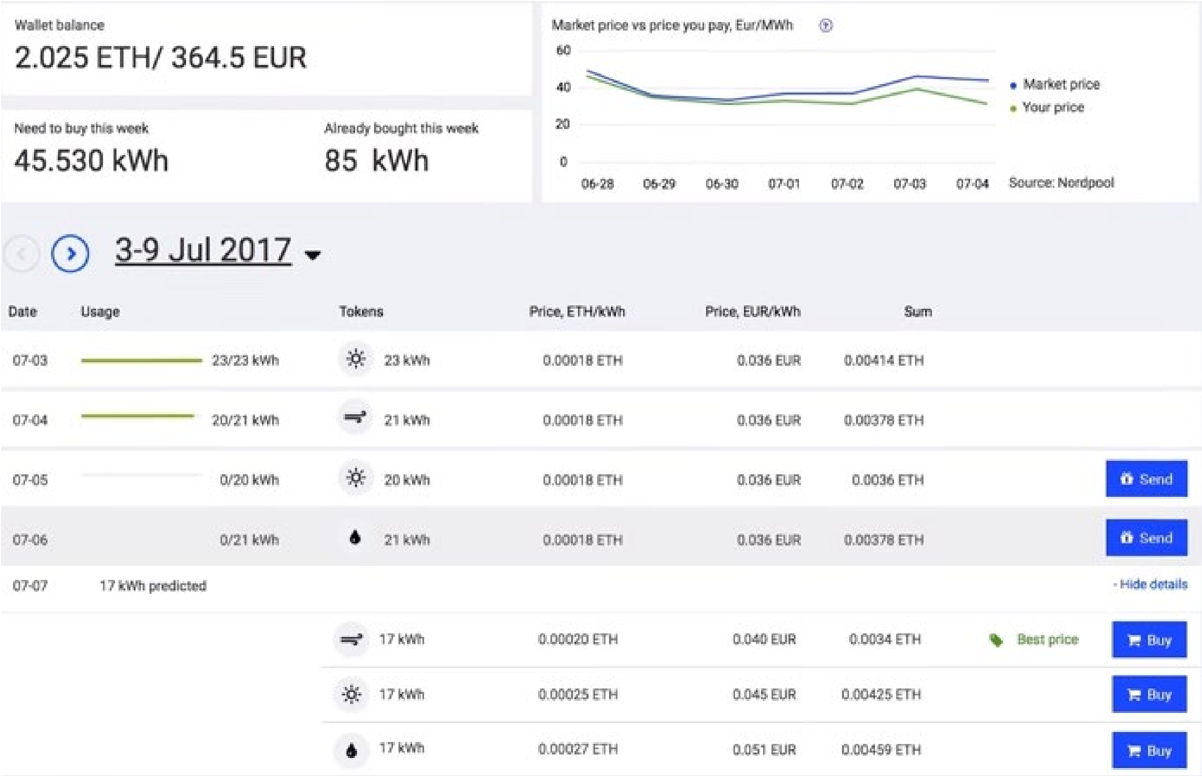


Figure 18: The WePower blockchain energy-trading platform. Corporate customers are able to view energy offers from renewable producers and participate in the auction system by placing their bids (WePower, 2019).

Lastly, Powerclub in cooperation with Power Ledger has created a virtual power plant where its customers can get access to premium electricity prices. All customers need to have an installed PV panel, battery and smart meter in their properties. Their excess produced power is sold to the company which aggregates it to form a virtual power plant, from which the consumers in need can purchase power in premium rates (Powerclub, 2019).

4.1.4 RES integration and operational complexity reduction

Except for providing better electricity purchase and sale prices for consumers and producers respectively, decentralized energy trading also helps with the integration of renewables. As stated in 3.2.1, variable renewable energy is characterized by volatile production, which accordingly makes short-term and long-term operation and planning a challenging task for TSOs (Dagoumas & Koltsaklis, 2019).

In this phase of development, blockchain can contribute to load balancing within micrograds, which are more likely to have higher penetrations of VREs. When connected to the central grid, these may cause a power surplus, leading to instabilities or even overheating that can damage infrastructure (Mollah, et al., 2019). Balancing in microgrids can be partially achieved through peer-to-peer energy trading, without requiring system operators to provide balancing services, as prosumers can sell their excess energy at any time to other participants in the network, matching supply and demand. For instance, a prosumer may store their unused solar power in a battery during noon time when production is at its peak while demand in the microgrid is low and sell it to other households through a P2P platform in the evening when demand is high. Prosumers would have an incentive to sell during peak hours as prices would rise together with demand. Accordingly, system operators would be able to utilize smart contracts to automate energy storage and grid balancing (e.g. trigger the contract to store energy when there is excess supply or, conversely, deploy the stored energy in case of lower production) and thus manage to increase the integration of renewables (IRENA, 2019a).

As participants in microgrids ought to have an active role and be responsive to conditions such as energy prices and supply and demand, they need to be supplied with the right tools that will support them in the management of their production and consumption. Most companies with peer-to-peer energy exchange services provide access to such tools. The startup Greeneum utilizes blockchain and smart contracts technology to provide its customers with hourly prediction over their solar power production and overall market demand, so they can organize better their buying and selling habits and contribute to grid balancing (Greeneum, 2019). Other companies like Grid+ offer applications based on blockchain that automatically inform users about demand response signals from system operators. This way, consumers are able to turn off certain home appliances in order to reduce their demand and be compensated for their contribution to grid balancing (Consensys, 2018).

Of course, blockchain cannot be the unique solution for grid transition, especially in this early stage of development. It shall be combined with transmission system upgrades and other new technologies such as AI, storage and EVs as well as IoT, which will form a smart grid ecosystem capable of automatically balancing supply and demand and integrate greater quantities of renewables.

Finally, by employing blockchain and smart contracts system operators can simplify operational procedures, not only by automating balancing services but also by deploying a blockchain platform where they would be able to track decentralized transactions in real-time and define the amounts of electricity traded[53] (IRENA, 2019a).

4.1.5 Cybersecurity solutions

As outlined in 3.2.1, the growth of the attack surface in power systems caused by the increasing number of interconnected smart devices combined with the rise in sophisticated cyber threats can be proven disturbing or even catastrophic for the integrity and the infrastructure of the grid in case of large-scale cyberattacks (Rob, et al., 2016). Thanks to its main characteristics, namely, immutability, traceability and interoperability, blockchain may be included in a security architecture together with other technologies and standards. This can assist utilities and energy companies to securitize their ICT systems further and protect sensitive information while at the same time facilitate the safe transition to smart grids[54].

The three main categories that blockchain can contribute to, regarding cybersecurity and cyber threat risk mitigation are:

- ***Access management:*** By combining cryptography with authentication protocols, blockchain can prevent unauthorized access to sensitive systems or classified data. Moreover, it may safely store identification data such as fingerprints, which can be used for user authenticating purposes in different devices of the grid such as SCADA systems (Sengupta, et al., 2020).

[53] This information could be used for power flow tracking to simplify grid management (e.g. define the tariffs to be charged to each customer according to their usage of the public grid to transmit their stored energy to other consumers) (Andoni, et al., 2018).

[54] Smart grids are more prone to cyber threats due to their high interconnection and number of digital devices (Onyeji, et al., 2014).

- ***Data Privacy:*** It is one of the most critical aspects of the IoT devices that constitute the communication and control systems of a power grid. Utilities can guarantee the data privacy of their customers by using advanced encryption techniques to securitize their smart meters and recording smart meter data in private blockchains. To enhance data integrity, utilities can also implement an encrypted communication system within the corporate level where data will be accessed by users with unique private and public keys (Mengidis, et al., 2019).
- ***Interconnectivity:*** Thanks to its decentralized nature, blockchain can enable smart meters and other devices to safely communicate with the nodes of electricity providers without depending on a central authority or server. This can be achieved by creating a consortium blockchain with multiple utilities as participants, which will act as nodes of the system. Smart devices owned by customers can communicate with them by sending encrypted messages that can only be decrypted from non-failed nodes[55]. Ultimately, this solves the problem of single point of failure (Zhang, et al., 2019).

Finally, smart contracts can also be utilized to store a wide range of information concerning devices within a microgrid. These may include data about a device's model, operating system version or a vulnerability detection and can be used to automatically trigger the smart contract to perform a system update or inform other microgrids using the same device about the issue (Li, et al., 2019).

4.2 Blockchain-enabled solutions for the oil & gas industry

In contrast to the electric power industry, the application of blockchain in the petroleum industry is still in its infancy. In the O&G sector, new technologies have to pass through several phases before mass adoption occurs, due to high costs and increased probability of component failures or other complications. We can divide them into two categories based on their maturity:

- Unproven new technologies that have not been widely tested within commercial conditions.
- Proven new technologies which have been approved for commercial use, but have not yet reached mass adoption.

In the case of blockchain, it can be still considered an unproven new technology, as it has been tested in a small extent within O&G commercial operations (see Appendix B), while almost half of the companies in the sector with ongoing blockchain projects claim that they are still in an experimental phase.

[55] In case that a node of the network is breached, it can no longer provide consensus which is required to decrypt the received messages. However, the number of breached nodes should always be lower than the non-breached ones to be able to control the network (Zhang, et al., 2019).

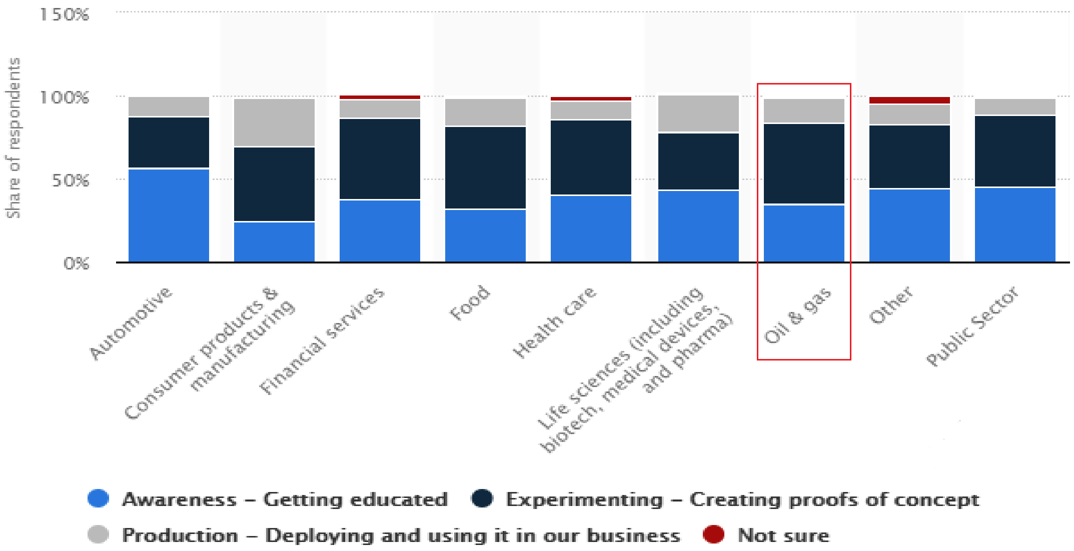
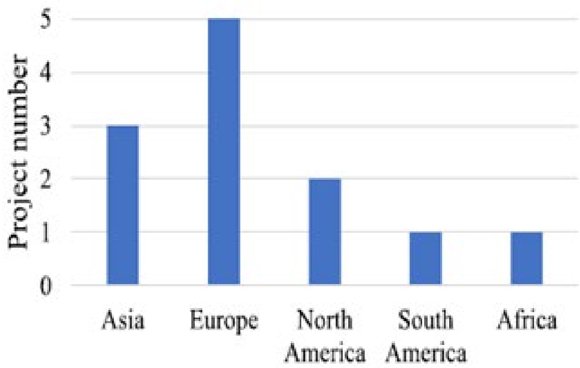


Figure 19: Blockchain adoption phases by O&G organizations (Statista, 2018).

Usually, only major O&G companies or large NOCs have the capacity to test emerging technologies on a large scale, by forming partnerships[56], and adopt them first in commercial operations (European Commission, 2016b).

In 2018 only five out of twelve major blockchain projects were in operation within the petroleum industry, while most of them were located in Europe (Hongfang, et al., 2019).



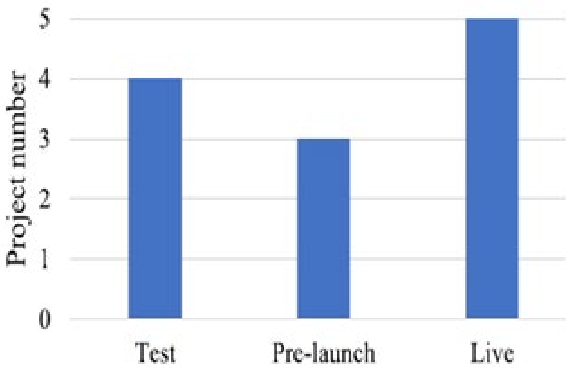


Figure 20: Number of major blockchain projects in the O&G industry by continent and by status (Hongfang, et al., 2019).

The most prominent of these projects across the value chain of oil and gas are:

- The OOC Oil & Gas Blockchain Consortium, formed by ten IOCs and the Offshore Operators Committee. It focuses on promoting research and developing blockchain solutions for the exploration of hydrocarbons, finance of oil and gas activities, supply chain and land management.

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56 Companies in the petroleum industry have three strategies related to new technologies: 1) to test and implement the latest cutting-edge technologies (mostly by forming partnerships), 2) postpone adoption of new technologies until they have been broadly tested by others and are more mature, and 3) decide if they will implement a new and untested technology based on the specific project (selective decision-making), which is most useful in relatively new industries such as unconventional O&G (Jacoby, 2012).

- A post-trading management platform based on blockchain, specifically for energy commodities, developed by the start-up Vakt in cooperation with a number of major O&G companies and banks (see 4.2.2).
- A blockchain-based digital platform implemented by ADNOC and IBM. The main applications of the platform concern optimization of supply chain, tracking of oil and gas shipments and better management of its subsidiaries. In addition, ADNOC intends to utilize the technology to automate a range of processes and reduce drilling time by up to 30% (Hongfang, et al., 2019).

The DLT technology is believed to have the most potential in operations such as hydrocarbons trading and tracking, supply chain management, cybersecurity and regulatory compliance. However, several other use cases will be discussed in the following chapters.

4.2.1 Upstream

Although the main activities of the upstream segment are exploration and production of hydrocarbons, blockchain has so far been tested and applied to a limited extent, only in auxiliary upstream processes. These include activities related to royalty transactions, better coordination among different stakeholders and reduction of the reconciliation times, as well as tracking of land records and equipment.

Lease agreements and royalties

The exploration of hydrocarbons, and hence the primary activity of the upstream sector commences with a lease agreement. That is a legal agreement between the owner of the land (lessor) where the reserves are found and the interested party that will conduct the exploration (lessee). Through this agreement, the party can get access to the land and its mineral resources.

Typically, these contracts include several terms such as primary terms (concerning the period of the lease), granted use terms (contains the rights of the lessee, exploration techniques, penalties etc.), and royalty terms. Royalties are connected to the results of the exploration phase and determine the percentage of production profits to be paid from the lessee to the lessor. These terms are entered into separate systems and have then to be transferred or sent from one party to the other. This process is not only time consuming, but can also be unsafe due to data leakage to third parties (Inkpen & Moffett, 2011).

The blockchain technology can provide a fast and secure method to fulfil royalty transactions through the use of smart contracts. A relevant application has been tested and applied in 2018 from GuildOne. The smart contract is accessible only by qualified third parties (e.g. regulators and banks), while contracting parties can register the contract terms in the same system for increased safety. After the parties have reached consensus on the contract terms, the operator has to enter into the software the oil or gas production volume. The smart contract then calculates the royalty amount based on the specified terms (e.g. 5% on production) and issues the payment order. When the operator approves the payment, the funds are automatically deducted from their bank account and are sent to the lessor's account. Regulators are able to track the transaction proceedings throughout the process (GuildOne, 2018b) (GuildOne, 2018a).

While the application of smart contracts in royalty transactions is relatively new and has not been applied to a large extent in operations, it has significant prospects to reduce royalty calculation workload by 30% to 80%, safeguard the content of the contracts, reduce transaction times and simplify back-office processes.

Reduction in reconciliation times

To maximize the extraction of hydrocarbons, operating companies in the upstream sector usually cooperate with various contractors that have specialized technical capacities. These companies are compensated by the operators for the resources they have spent, a process that is called “reconciliation”. But, as a result of the large number of contractors, their identification and certification (i.e. that they truly completed the agreed contract) is a slow process that puts a burden on reconciliation times, which can take up to 100 days. Moreover, contractors issue payment billings from their own ledgers and send them via mail, which adds to the overall complexity and safety concerns.

A platform for the reduction in reconciliation times based on the blockchain technology is being explored by IBM in cooperation with SAP. When a contractor has completed the activities agreed with the operating company, they access the platform with a personal key that helps in the identification process and issue a payment billing. The operator receives the information in real-time and can cross-check the accuracy of the information provided in cooperation with the department responsible for the project.

After the operator fulfils the payment, the transaction “block” is validated and linked to previous blocks, creating an immutable record in a decentralized database that can be accessed at any time in case of disputes between the parties. This way, reconciliation times can be reduced from up to three months to a couple of days (SAP, 2018). Another solution in a similar context is provided by the startup Ondiflo.

Optimal asset and resources management

Blockchain can also be utilized in upstream O&G for optimal management of land records as well as tracking and maintenance of equipment. These use cases provide solutions to the challenges discussed in 3.2.2.1.

Land records management

Petroleum companies are required to obtain and register land rights before any exploration and production activities can commence. On certain occasions, the aforementioned process can be complicated since these companies operate globally in countries with different regulations concerning land registration and use. Additionally, land ownership disputes are frequent and can result in land seizure in certain countries. That necessitates the use of a transparent and immutable database for land transaction recordings.

The DLT technology can provide such a solution through the use of a platform on which petroleum companies will register the acquisition or sale of land. Involved third parties will also be able to view these transactions after given the necessary access rights to the platform. For example, government authorities such as tax offices or land registries will be able to view and record in real-time the land acquisition of a petroleum company. By developing relevant solutions, O&G companies can also simplify the government licensing processes for hydrocarbons exploration and substantially reduce ownership conflicts and fraud (Consensys, 2018a).

Equipment records management

During the last decades and as O&G companies increased the upstream operations under challenging such as deepwater, the complexity of tracking equipment performance grew exponentially. Furthermore, as the number of contractors and manufacturers providing the necessary equipment rose as well, their maintenance became even more complicated. Today O&G exploration companies are required to acquire thousands of parts from their suppliers to build oil rig platforms or perform drilling and other upstream activities.

By utilizing the safe and transparent attributes that blockchain has to offer, petroleum companies can build equipment lifecycle tracking applications. For example, a company after receiving a component (e.g. blowout preventer) from its supplier enlists all the relevant information[57] on the blockchain platform. In combination with sensors and data analytics, the performance of the equipment is tracked on the platform and can be available for any future reference. In case of failure, the supplier responsible for its maintenance is automatically informed via the platform[58] (Mawet, et al., 2017). Moreover, by registering the costs of equipment of the platform, companies can perform audit tasks and easily track expenses.

Recently, Data Gumbo developed a similar blockchain-based platform for O&G equipment maintenance, certification and regulatory reporting. The company also developed a similar solution for O&G firms to track and optimally manage resources used in upstream operations (e.g. water).

Resources management

The rapid expansion of unconventional resources in regions such as North America created an unprecedented demand for water and sand. Large quantities of these resources are necessary, especially during the initial stages of the fracturing process, to stimulate the unconventional reservoir and produce hydrocarbons economically. In the case of water, the majority of costs come from transportation[59], as freshwater sources are often distant from the well location. The acquisition and management of these resources need to be done under transparent processes and in close cooperation with water managers and policymakers (Oikonomou, et al., 2016).

The US-based company Data Gumbo utilized the blockchain technology in 2018 to develop a solution for total water management. The platform enables O&G producers and water management companies to optimally manage their orders and contracts. Producers are able to execute orders and payments on the platform through smart contracts with multiple vendors that provide water solutions (e.g. water suppliers, wastewater treatment services, disposal services). Compared to the traditional time-consuming way these contracts were executed (e.g. e-mail and fax exchanges) the process can be digitalized and simplified by utilizing this transparent and secure blockchain platform (Data Gumbo, 2019).

Another company with a similar solution is Ondiflo. The platform combines blockchain with IIoT and analytics to automate the water management process of O&G companies. By measuring the wastewater tank levels every five minutes, the specially designed sensors can transmit messages to water disposal services in real-time through the platform. The accuracy of the metrics is over 90%, and by utilizing historical records from the blockchain platform,

[57] This data may be the cost of the equipment, the date that it was bought and began operating, the proposed date of maintenance and the information of supplier and manufacturer. The supplier will be automatically informed on the specified day that maintenance has to take place.

[58] The given petroleum company may choose to add its suppliers and other stakeholders on the platform so the data can be exchanged in real-time and accelerate the maintenance procedures.

[59] In the US, the water transportation costs alone can reach $1 per barrel for a relatively short route (about an hour round trip between the freshwater source and the drilling site) (Luft, 2015).

companies can forecast water levels for the next 48 hours. Finally, water service companies can issue invoices on the platform and receive payments with no delays (Ondiflo, 2019).

4.2.2 Midstream

The most blockchain-based solutions for the O&G sector have been applied in the midstream segment until today, and in particular for the trading of liquid fuels, petrochemicals and refined products. These constitute solutions to the problems discussed in 3.2.2.2.

Decentralized trading

The trading of petroleum products is one of the most complex operations in today's O&G industry. This is mainly caused by the diverse locations shipments have to be sent to, especially after the shift of demand towards Asia. Other reasons include the wide range of participants and transactions, along with the continuous exchange of information that needs to be appropriately recorded and stored in secure databases.

In this immense system, it is expected that the typical petroleum company which fulfils international oil and gas transactions has to face several management challenges. These are related to the amount of paperwork[60], risks of fraud and error, sluggish exchange of critical data among parties and inefficiency in transactions. By considering the traditional process (see Appendix D) a shipment of oil or gas has to pass through in order to reach the buyer and the amount of paperwork involved, it is easy to comprehend why trading of energy commodities needs an innovative solution that will automate most of these manual proceedings.

A number of these solutions is provided today by blockchain and smart contracts. These technologies can offer multiple advantages, namely:

- Considerably reduce transacting times and paperwork
- Provide a transparent record of transactions
- Decrease labour costs and back-office proceedings
- Contribute to regulatory compliance and dispute resolution
- Safeguard data exchanged among the involved stakeholders

It is estimated that companies can save between 30% and 60% thanks to the automation of several procedures. For instance, by utilizing a smart contract to carry out an LNG trade, the overall process becomes significantly more straightforward. A major benefit that smart contracts provide is that they allow permissioned stakeholders to view trade information in real-time and participate in the transactions. This way the involved banks can fulfil payments automatically when the shipping personnel sends on the smart contract the necessary documents after the LNG carrier has arrived, insurance companies can access the details of the trade (e.g. quantities sold, trade route) and complete the insurance of the cargo, and regulators are able to track the overall trading proceedings to ensure that it is in accordance with the country's laws (EY, 2017). Most importantly, all transactions are permanently recorded on the blockchain, providing a history of transactions to be used for audit purposes, while the immutability of data establishes additional trust among the transacting parties.

Energy commodities trading was one of the first blockchain use cases implemented in the petroleum industry. Already since 2017, Natixis, in cooperation with IBM and Trafigura developed the first solution for crude oil trading based on blockchain. Most of the processes

[60] The documents required during an oil and gas export are: 1) Bill of lading, 2) Certificate of origin, 3) Certificate of quantity and quality, 4) Certificate of insurance and 5) Letter of credit (Consensys, 2019b).

the digital platform managed to automate have been traditionally manual. The key stakeholders, including buyer, seller and their banks, can view all the phases of the trading simultaneously, from the initial confirmation of the shipping to the final quality inspection and delivery. The decentralized platform offers all the benefits of blockchain, such as transparency of transactions, reduction in mediators and increased measures against fraud (Natixis, 2017).

In a similar context, Mercuria, a commodity trading company, developed in 2017 together with ING and Societe Generale a digital blockchain platform for liquid fuels trading. The initial test of the platform was carried out in a shipment of crude oil which was tracked all the way from its starting point in Africa to delivery in China. The trade included stakeholders like traders, inspectors and banks all of which were supervising the process in real-time and conducting the necessary actions. The involved banks alone managed to reduce processing times for document approvals and payments from three hours to 25 minutes (Energy Futures Initiative, 2018).

Mercuria was also involved in the founding of Vakt in 2018. Other well-known oil companies that initially invested in the implementation of the platform include BP, Shell, Equinor, Total and Chevron. In contrast to previous cases, the platform is used for post-trade management alone, which includes all the processes required for the settlement of the trade (i.e. transfer of crude oil's ownership from the seller to the buyer) (Infosys, 2018). More specifically, after the arrival of a crude oil shipment, each party enters the transaction details in the ETRM software. The information is then transferred to the Vakt platform, which confirms their validity, and the banks (permitted to participate) of the transacting parties fulfil the transfer of funds. The seller then shares on the platform the final invoice with the buyer and the trade is completed (Ledger Insights, 2019b).

The platform currently manages substantial quantities of crude oil, as it operates primarily in the North Sea, where Very Large Crude Carriers (VLCC) are utilized for shipments, with carrying capacity between 1.9 and 2.2 million barrels of crude oil[61] (EIA, 2014).

Finally, Vakt is connected to the Komgo blockchain-based platform, which allows companies to automate commodity trade finance processes. For example, the bank of a crude oil buyer might issue a digital Letter of Credit[62] on the platform that will be received instantly by the seller. This can accelerate the transfer of funds and enhance trust among the transacting parties (Consensys, 2019b).

4.2.3 Downstream

The downstream segment is of particular importance to the brand name of O&G companies as it involves the sales and marketing of products to the final consumer. As discussed in 3.2.2.3, petroleum companies today have to face vast supply chains where counterfeiting and other problems related to product quality are a common phenomenon. The blockchain technology has been tested and applied to a small extent in quality control cases until now, but it is believed to play an increasingly important role in petroleum products certification. Other use-cases currently being explored include downstream reconciliation, automation of payments and regulatory compliance (see 4.2.5).

[61] The total value of the cargo of a fully-loaded VLCC could reach around $60 million, according to the current crude oil prices.

[62] A Letter of Credit is a document issued by a bank that guarantees that a payment from a commodity buyer will be received by the seller on the pre-agreed time and amount.

Quality control

The downstream supply chain consists of a large number of participants, such as distributors of oil and gas, packaging companies and retailers, all of which use separate IT systems, creating communication gaps with the producing company. These parties have to store, manage and transfer various products intended for different uses, such as liquid fuels, petrochemicals and lubricants.

Quality issues associated with these products include unintentional defective production, but in some instances, companies alter the quality records to market products that do not meet the minimum legal requirements. Counterfeiting (e.g. illicit use of a company name for the sale of inferior quality products), which costs petroleum companies and their retail subsidiaries billions in annual revenue losses is mostly associated with packaged products like lubricants (Consensys, 2018b).

The DLT can be utilized for product certification purposes and to track shipments on shared, blockchain-enabled platforms (e.g. with partners or authorized parties such as government entities). This way, companies active in the downstream sector can transform their operations and make them more efficient and transparent (Hongfang, et al., 2019).

For example, a lubricant company, after it completes the necessary quality inspections, can record batches of its products on the blockchain platform. Each batch will be registered as a block and will then receive a unique hash function, which will be printed on the physical package, along with a QR code. This way retailers and final consumers will be able to scan these hashes which will be connected with the online product database to confirm the authenticity and good quality of the products. Government entities that are responsible for the quality inspection of relevant products can also get permission to participate on the platform to view the registration of products in real-time. In addition, the platform can be utilized to track raw material quality based on certain factors such as country of origin or supplier[63].

A project for quality tracking of petrochemicals was developed in 2018 by the startup Finboot which was partially acquired by Repsol in 2019. The blockchain platform is primarily used to certify products based on their quality. This is done through the digital equivalents of the product samples: after a sample has successfully passed quality inspection, it is certified and connected to a unique code. Then a digital equivalent of the particular sample is created as a block on the platform and it is connected to the code of its physical equivalent in addition to its characteristics (e.g. origin, quality category, etc.). This way, the products can be tracked along the supply chain, while consumers and other interested parties will be able to easily access and review them on the online platform. Repsol processes 60,000 such samples annually, so such a transparent database will greatly assist in the quality inspection of its products (Kotecha, 2019).

4.2.5 Support services

This chapter describes additional blockchain solutions that do not fall within a specific segment of the O&G value chain. These include cybersecurity solutions to the problems described in 3.2.2.4 as well as solutions for regulatory reporting.

[63] Each time a supplier provides a product of good quality they will automatically receive a positive rating on the platform. This way, the company will be aware of its good and bad suppliers. The suppliers may also be allowed to participate in the platform to view their ratings and improve their services.

Cybersecurity solutions

As cyber threats in the O&G sector increase in intensity and sophistication, the securitization of IT systems, sensors and digital devices becomes more and more critical. Petroleum companies are also increasingly aware of those risks and they evolve their cybersecurity strategies accordingly. Of course, they should set priorities to protect the most vulnerable and critical infrastructure firstly. Many governments and regions including the US, EU and Saudi Arabia, have provided cybersecurity policies and standards to local petroleum companies to assist them in developing and improving their strategies. Furthermore, many companies in the field have taken collective actions to address the current cyber threats they face and cooperate in developing solutions.

Apart from the above, companies should provide relevant training to their staff, ensure that their partners adhere to specific security standards and continuously upgrade their systems and security measures (e.g. firewalls, network monitoring equipment, etc.). While, to date, these security solutions have worked rather well, they have several security gaps that need improvement (BCG, 2016) (Williams & Ciepiela, 2019). If companies utilize the DLT in specific processes, they would be able to achieve a much higher level of system integrity. It should be clarified that blockchain cannot provide an all-encompassing cybersecurity solution, but it enables securitization of databases through encryption technologies, guarantees immutability of records, uses key cryptography to ensure information is received only by the intended recipient and combines transparency with safety for intra-company or government visibility of sensitive procedures.

Those characteristics of the DLT can offer valuable cybersecurity solutions for the following systems used in O&G operations:

- **IIoT**: Whereas these devices come with multiple benefits like increased efficiency, they are required to be always online and keep constant communication between them through a centralized system. Blockchain can offer solutions to the single point of failure problem that centralized IIoT systems face, by a decentralized data management system. One such solution is offered by Filament, which has invented a system that connects IIoT devices with smart sensors. The sensors then allow for device identification and communication through a blockchain platform that ensures the integrity of the overall system. For example, a sensor connected to an offshore drilling rig can detect a malfunction of a component and send a request for a spare part through the blockchain platform (Kshetri, 2017).
- **ICS**: As pointed out previously, Industrial Control Systems such as SCADA are particularly vulnerable as most of them are at least decade-old and not designed to withstand cyberattacks. Besides that, an increasing number of devices is connected to them, and therefore, their exposure can result in potential widespread failure of a variety of IT systems.

  Blockchain can be used to protect data in ICS environments by encryption methods which will provide greater visibility to authorized participants but will not be accessible or viewable by unauthorized parties (Hongfang, et al., 2019). Another way to protect the data of control systems is by using smart contracts. Each ICS node will execute a smart contract which will record all the data it transmits to other nodes in real-time. The data is then replicated randomly in an encrypted format across a number of devices within the network. This way, if a device is tampered with, its data can be recovered from other devices of the network. The attacker should know beforehand the exact locations of the replicas to erase the data and also hold the encryption keys in order to unlock access to them (ISA, 2019).

Segment	Operation	Potential Cyber threats & outcomes	Blockchain countermeasures
Upstream	Geophysical & seismic surveys	Data theft	Storage on blockchain (cryptographic format)
	Exploratory & appraisal drilling	Corrupted devices; ICS vulnerabilities; Equipment failure	Replication of data with smart contracts / sensors for the identification of devices
	Development drilling	Data theft / corruption; IP theft	Storage on blockchain / Replication of data with smart contracts
	Well completion	Data theft / corruption	Storage on blockchain (cryptographic format)
	Production	Data theft/ corruption; Corrupted devices; ICS vulnerabilities; Equipment failure; IP theft	Communication protocols / sensors for the identification of devices / Storage on blockchain
Midstream	Trading	Data theft / corruption; Software malfunction; Issues in financial transactions	Trading on blockchain-based platform / smart contracts
	Transportation	GPS spoofing / data corruption; Corrupted devices	Sensors for the identification of devices / data storage on blockchain
	Storage	Data theft / corruption	Storage on blockchain (cryptographic format)
Downstream	Refinery / petrochemical operational controls	Data theft; Corrupted devices; ICS vulnerabilities; Equipment failure	Replication of data with smart contracts / Storage on blockchain (cryptographic format)
	Logistics software	Unauthorized access; Software malfunction	Use of cryptography and encryption keys
	Retail distribution	GPS spoofing; Retail and consumer data leakage; Issues in financial transactions	Data storage on blockchain / transactions on blockchain platform

Figure 21: Figure 21: Overview of cyber threats in different segments and operations of the O&G value chain and respective blockchain countermeasures. With green colour the operations with low vulnerability/minimal impacts from a possible cyber-attack, with yellow those with average vulnerability/modest impacts and red with high vulnerability/severe impacts (edited by the author).

Overall, blockchain can offer multiple benefits that traditional centralized databases usually lack, with the most important being data immutability and traceability. For example, in a blockchain platform for oil and gas trading, each transaction is cryptographically recorded as a block and receives a unique hash and a timestamp. Apart from the auditability and transparency this system offers, it also provides the involved organizations with the assurance that the transactions recorded on the blockchain are authentic. Finally, blockchain solves the single point of failure problem that most of the centralized databases used by O&G companies suffer from.

Regulatory affairs

The highly regulated nature of the petroleum industry necessitates for constant reporting processes that cost companies valuable time due to the complicated paperwork and the extensive number of authorities involved, such as environmental and tax. By using a blockchain platform to fulfil transactions, O&G companies can automate these processes. The transactions will be recorded on the platform in real-time and the companies will be able to authorize government entities to view them and ensure that they comply with the respective laws. Most importantly, companies can track their payments to involved parties during development of fields to ensure compliance with tax laws, as well as their entire supply chain to ensure accordance with environmental laws (especially in the occasion of hazardous materials) (Hongfang, et al., 2019) (Consensys, 2018b).

For instance, blockchain could be used in the case of Production Sharing Agreements, where the government is usually required to allocate a percentage of the proceedings to certain public affairs such as social benefits or the creation of reserves for future generations (Inkpen & Moffett, 2011). In the case of developing countries that lack the transparency to fulfil such processes, the fair distribution of revenues from oil and gas resources can be challenging.

Blockchain can be used on this occasion to provide transparency in the way that those funds are managed.

After a government has received revenue from an agreement, the data is shared on a blockchain platform with other involved parties. If the government proposes to attribute a percentage of the revenues to a public company, a smart contract that contains the terms for both parties is created and after the transaction has been completed it is automatically recorded on the platform. Similarly, the funds will continue to be tracked on the platform after the public company has received them to ensure appropriate spending and accordance with regulations.

5. Business plan: Greek islands microgrid

5.1 Background

A major problem for the Greek energy sector today, which has remained unresolved for many decades, concerns the islands that are not interconnected to the mainland country. The total number of the “non-interconnected” islands amount to 29, with 19 of them being small autonomous systems (with electricity demand up to 10 MW), 11 medium autonomous systems (demand between 10 MW and 100 MW) and 2 large autonomous systems (more than 100 MW of demand). The high capital requirements for the specific interconnections have been the main reason for the absence of viable energy supply in these islands today. Most of them cover their energy needs by using polluting thermal power stations. This not only has negative impacts from an economic and environmental point of view but also creates multiple additional issues for the local population (e.g. health issues from the pollution of the environment), the energy security of those areas (e.g. power outages are an occasional phenomenon for these islands) and for the whole country in some extend (e.g. being dependent on larger quantities of imported fossil fuels) (Ministry of Environment and Energy, 2019).

The first phase of interconnections for 7 islands in the Cyclades islands group was completed in 2018, while in 2021 the interconnection of Crete with the mainland grid is expected to be finalized. Later interconnections between 2028 and 2029 are scheduled for 8 islands of high voltage and 16 islands of medium voltage. These developments will not only contribute to the settlement of the aforementioned issues, but also to the complete abolition of the extra charges[64] that consumers have to pay along with their utility bills.

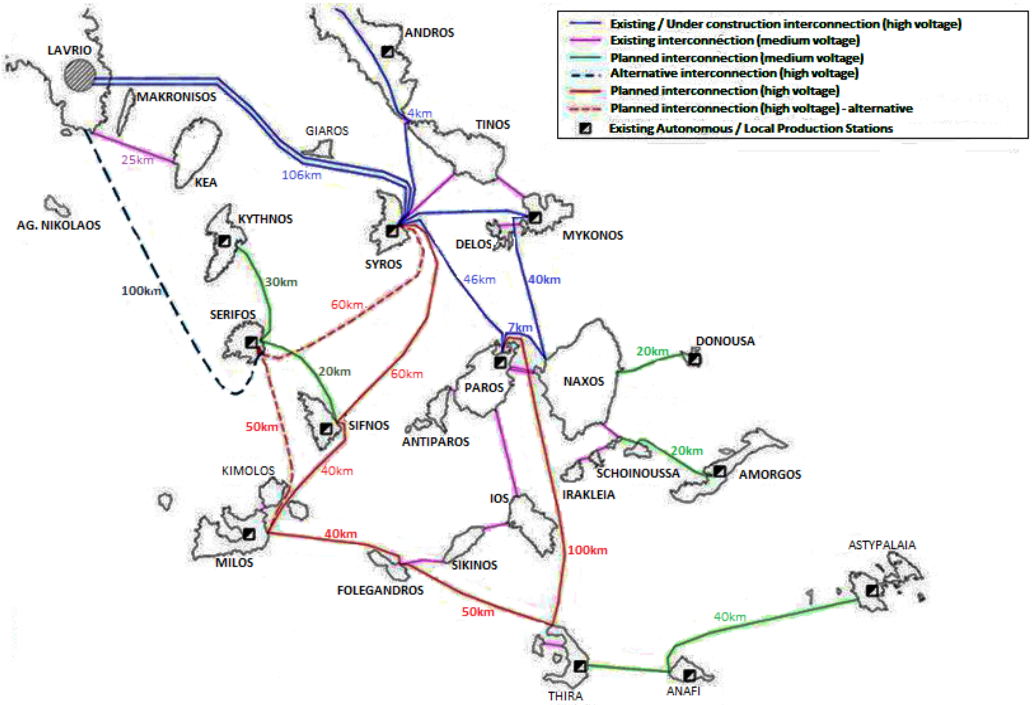


Figure 22: Existing and future interconnections of the Cyclades islands and their length (HEDNO, 2019a).

[64] These charges are equally distributed among all consumers in the country and cover the additional costs required for power generation in non-interconnected islands. The savings from the abolition of these costs are estimated between €400 and €450 million. The dependence on fossil fuels will be reduced by an average of 3% or 900 thousand tonnes less petroleum will be required for energy generation purposes (Ministry of Environment and Energy, 2019).

Despite the high numbers of interconnections in the following years, a significant number of islands, mostly of low demand, will remain autonomous, and therefore other methods should be considered for their electrification to become viable. For instance, the installation of a large number of RES (mostly photovoltaics) and storage solutions is promoted for a number of these islands from the Ministry of Environment and Energy, supported by EU initiatives such as the Horizon 2020. Islands included in the "smart islands" development program are Meyisti, Astypalaia and Symi, while in the cases of Ikaria and Tilos hybrid renewable energy stations were installed. In this context, we will analyze the opportunities that arise from these initiatives and present a business plan of a blockchain-enabled P2P energy trading platform, which will be offered to local consumers and prosumers.

5.2 Description of the business

Similarly to the cases of peer-to-peer electricity exchange discussed in 4.1.2, the proposed business model will be based on the notion of collaborative consumption and will utilize the blockchain technology as the main tool for the development of the platform. The energy within the island microgrids under consideration will be produced by RES installed by the company[65]. In case of expansion of the business model to other islands, existing renewables may also be included, if available. In the first stage of development, the company will provide to a given number of locals the necessary tools to produce and exchange their energy. These tools are:

- ***PV panels:*** In this stage, the prosumers will produce energy only with photovoltaics, which will be installed in their premises. In a later stage, other options may be available such as small wind turbines, which can also be installed in private properties. The company will also install its own PVs on its premises.
- ***Smart meter:*** It will be installed on the premises of both prosumers and consumers and it will assist them in the exchange of energy. It will also help the company record generation and consumption data. The company will commit funds to research and produce a customized smart meter compatible with its systems and platform.
- ***Application:*** The application will be available for smartphones. It will allow the users to access the platform where they can exchange energy, pay their subscription, purchase tokens, view their electricity usage information, and other options.

5.2.1 Location

In the initial phase of the project that will be presented in this chapter, the microgrid will be applied in two islands, but it could be expanded to other islands accordingly, based on their characteristics. Solar irradiation is one of the main aspects that were considered for the selection of the islands, as photovoltaics will be the primary source of power for the microgrid in this phase. The solar potential of the country and particularly of its islands is significant, as depicted in the map below.

Other important factors for the selection were the island not being part of the future interconnection plans with the mainland country, a relatively high population, as well as a high

[65] The conventional methods of production (mostly diesel generators) in the island under consideration will continue operations in a small degree along with RES (hybrid system), as the production of RES will not cover the overall demand. However, according to the Council directives of the EU, all oil-fired power plants should halt operations until 2022. In this case, if a greater number and variety of renewables are installed in the islands along with storage solutions so as a reliable supply of electric power is guaranteed (e.g. apart from VREs, other renewables such as biomass plants should be deployed as well), a 100% renewable-powered island could be achieved.

average cost of electricity generation of conventional units, which will be gradually phased out, so as to achieve a comparative advantage with the addition of RES.

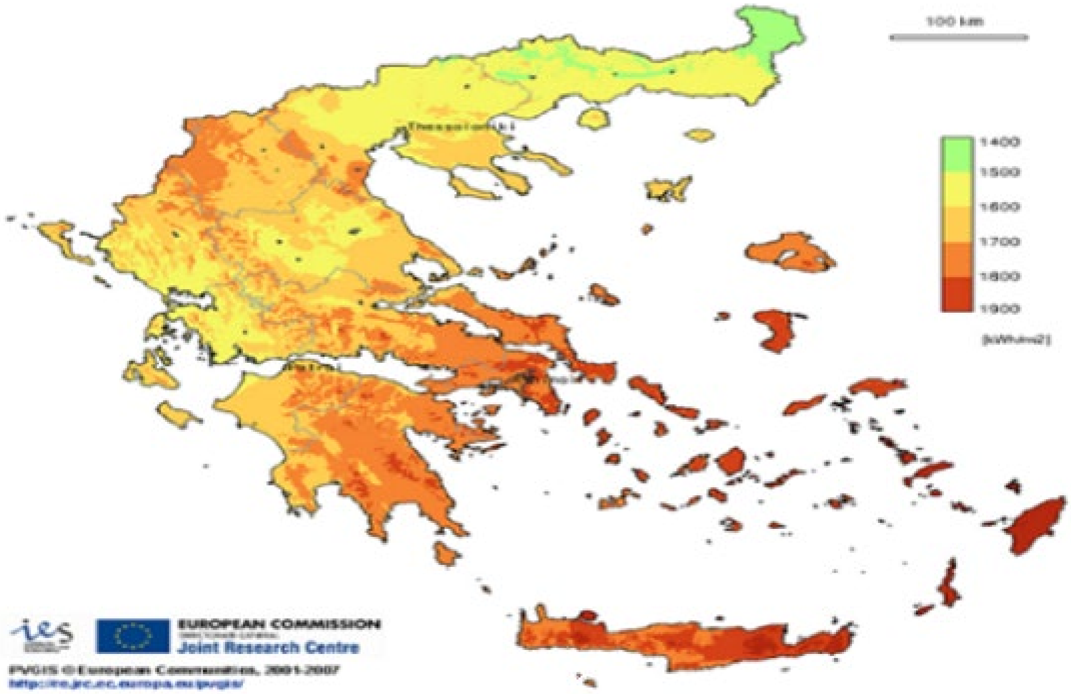


Figure 23: Yearly solar irradiation (kWh/m²) in Greece (JRC, 2019).

For the reasons highlighted above, the islands of Othonoi and Ereikoussa near Corfu were chosen, as they have high solar radiation levels (between 1700 and 1900 kWh/m²), they are not included in the future interconnection plans, and have characteristics that support the inclusion of other renewables as well (e.g. wind potential with average wind speed between 6.5 and 9.1 m/s) (JRC, 2019). The islands Othonoi and Ereikoussa have permanent populations of 392 and 496 people, around 190 and 210 households, as well as 4 and 5 hotels, respectively.

Figure 24: The location of Othonoi (left) and Ereikoussa (right) Islands.

5.2.2 Legislative status

The primary laws that need to be taken into consideration for the present business plan concern the licencing process of RES, the installation of PV panels for net metering purposes, peer-to-peer electricity trading, and energy communities.

The licencing process for the installation of RES was simplified under the law 3851/2010, which exempted natural and legal persons from the obligation to obtain an electricity generation licence for renewable installations under certain conditions. These related to the capacities of the installations and, more specifically, photovoltaic installations and biomass or biofuel power plants under 1 MW, wind farms under 100 kW and geothermal power plants under 500 kW.

Net metering was introduced by the law 3593/2014. Before the adoption of the law, the only option of producers was to sell their electricity directly to the grid, at a predefined rate. The introduction of the particular legislation allowed natural persons with PVs installed in their properties to consume the energy they were producing and thereby to reduce their energy bills. In non-interconnected islands apart from Crete, the capacity of photovoltaics installed in a private property for net metering purposes could not exceed 100 kWp (HELAPCO, 2018).

As for peer-to-peer energy exchange, currently, there is no law expressly referring to it. Nevertheless, in 2018 an important step toward this direction was taken by the introduction of law 4513/2018 which was the first to address and formalize in Greece the concept of energy communities. According to the law, energy communities are cooperative organizations, members of which can be individuals or local government bodies[66] and their ultimate purpose is the promotion of social and economic solidarity along with sustainability and innovation in the energy sector. Furthermore, energy communities can support local businesses, authorities and individuals to become producers of energy and, in that way, store and use their energy, reduce their electricity bills, tackle energy poverty, and increase energy security in small islands (Lawspot, 2018).

Although the company presented in this chapter has a similar concept to that of the law concerning energy communities, as it promotes prosuming along with collaborative consumption, it is not entirely compatible, as it is a privately held company, with its customers being local electricity consumers and prosumers. The products that the company offers are the equipment to be used to produce and trade energy while the services are the platform that facilitates the trade and typical maintenance of the relevant equipment. Therefore the company is described as a “hybrid corporation” that cannot currently be established according to the legislation but could be introduced in the future if legislative provisions allow it.

5.3 Market research

Solar PV power generation worldwide has experienced unprecedented growth between 2010 and 2019, rising from 32 TWh to 720 TWh, while it is also expected to lead the developments in renewable generation in the next five years by accounting for more than half new RES additions (IEA, 2019f). In Greece, 7% of the electricity demand is covered by solar PVs while their total capacity grew from 0.19 GWh to 2.65 GWh in the period from 2010 to 2018, projected to further rise to 3.65 GWh by 2021. Currently, in the country, more than 80

[66] Each individual is allowed to participate up to 20% in the organization’s capital, while local government bodies either up to 50% in islands with less than 3100 inhabitants or up to 40% in any other area.

companies are active in the sector of photovoltaic systems installation and management (HELAPCO, 2019).

5.3.1 Customers

The islands of Othonoi and Ereikoussa, like most autonomous energy systems dependent on conventional energy sources for their power generation, frequently experience power outages, which can also last for prolonged periods. By installing a combination of different unconventional energy resources in addition to energy storage, the resilience of these power systems can be increased considerably. Inhabitants of such areas will also benefit from the reduced power bills in the short term and from the cleaner environment in the long term.

The platform will commence its operations with a total number of 90 households as consumers (50 in Ereikoussa and 40 in Othonoi) and 20 prosumers (10 in each of the two islands). Up to the sixth year of the project, new additions of consumers and prosumers will be made. The company's goal is to reach 90 prosumers in the sixth year of operations and serve the majority of consumers in both islands (a combined number of around 290 households).

The PV network of Ereikoussa Island will consist of:

- 51 photovoltaic systems (crystalline silicon). 40 systems of 5 KW and 10 systems of 10 KW will be installed in the properties of prosumers and 1 system of 50 KW will be installed at the premises of the company. The total capacity of the PV system will be 350 KW.
- One 250 kWh li-ion battery storage system.

The PV network of Othonoi Island will consist of:

- 41 photovoltaic systems. 30 systems of 5 KW and 10 systems of 10 KW will be installed in the properties of prosumers and 1 system of 30 kW will be installed at the premises of the company. The total capacity of the PV system will be 280 KW.
- One 140 kWh li-ion battery storage system.

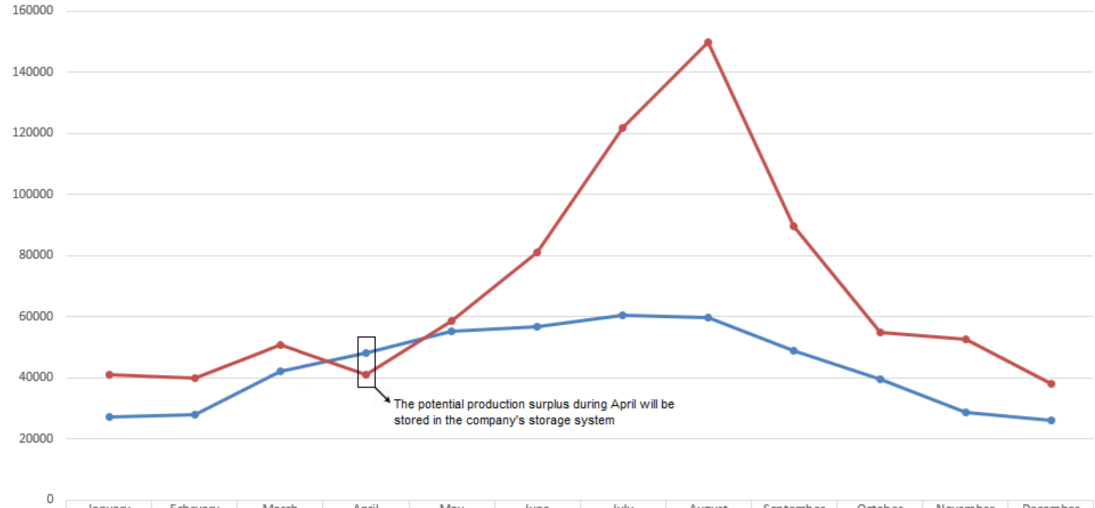
Island	Company PV capacity	No. of prosumers	Prosumers' total PV capacity	Storage capacity	No. of potential consumers
Ereikoussa	50 KW	50	300 KW	250 kWh	170
Othonoi	30 KW	40	250 KW	140 kWh	120

Apart from the above systems, a number of diesel generators will continue to operate in the two islands, as the capacity of PVs will not cover the entire electricity demand, and therefore the system can be considered as "hybrid". Based on the energy demand during 2019 in the two islands, we estimate that conventional diesel engines of a combined capacity of 720 KW for Ereikoussa and 520 KW for Othonoi were required. The Public Power Corporation will be able to decommission more than 50% of those generators after the commissioning of the photovoltaics in the islands' energy systems.

Electricity consumption and generation (PVs)

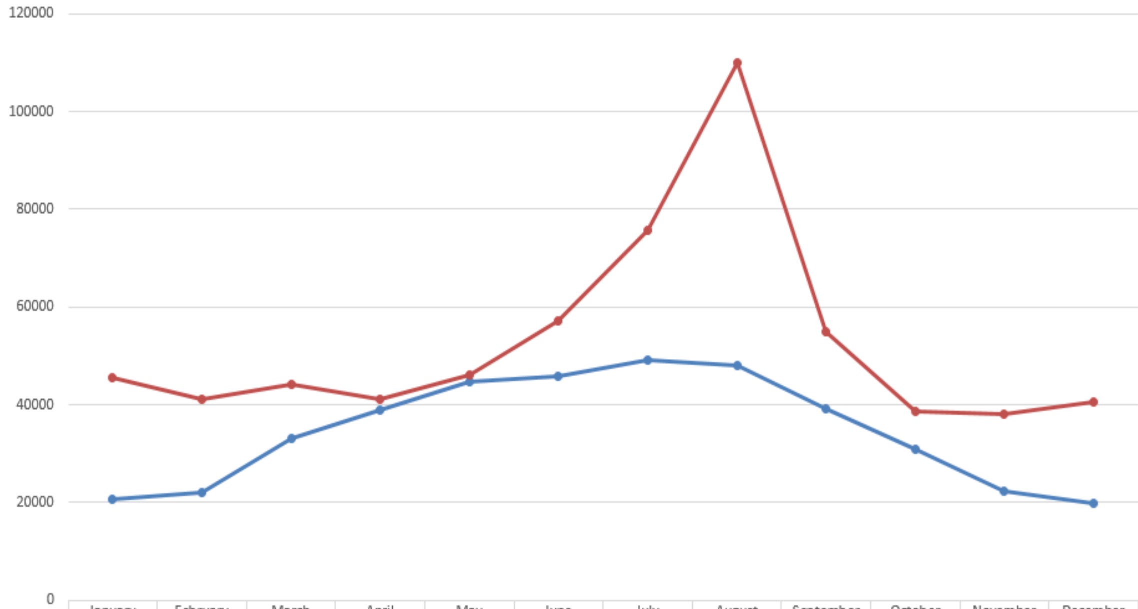
The yearly electricity consumption in Ereikoussa for 2019 was 819 MWh and for Othonoi 635 MWh, or an average of 68.2 MWh and 52.9 MWh per month in each instance. If we divide the consumption between the low-season and high-season period we can see that in the months from June to September, due to the large numbers of tourists that arrive in the islands we have an average consumption of 110 MWh (Ereikoussa) and 74 MWh (Othonoi) per month while the rest of the year the average consumption falls to 47 MWh and 42 MWh respectively.

If we take into account the proposed hybrid system with a photovoltaic capacity of 350 KW for Ereikoussa and 280 KW for Othonoi, then we can cover in both cases between 40% and 80% of consumption in the high-season months (between June and September) with the PV generation alone. The average annual PV generation is projected to be 521 MWh (Ereikoussa) and 414 MWh (Othonoi) or an average of 43 MWh and 34 MWh per month, which of course rises during the summer months as irradiation is higher.



	January	February	March	April	May	June	July	August	September	October	November	December
Ereikoussa Production	27141.8	28084.7	42002.1	48251	55295.8	56912.8	60605.65	59558.45	48869.45	39530.75	28796.95	26135.2
Ereikoussa consumption	41110	39990	50810	41010	58490	80910	121610	149900	89660	54780	52650	38020

Figure 25: Energy consumption in kWh (red) in the island of Ereikoussa. PV generation in kWh (blue) per month under the proposed scheme.



	January	February	March	April	May	June	July	August	September	October	November	December
Othonoi Production	20596.52	22175.44	33242.72	39012.4	44714.88	45771.04	49066.64	47978.28	39082.96	30985.64	22287.44	19710.88
Othonoi Consumption	45460	41260	44280	41160	46110	57260	75680	109890	54850	38570	38190	40720

Figure 26: Energy consumption in kWh (red) in the island of Othonoi. PV generation in kWh (blue) per month under the proposed scheme.

In the hypothetical but unlikely scenario where the PV-produced energy (produced only by the prosumers) is shared equally among all participants[67], we can see that the average conventional energy consumption per household is reduced by up to 79% in Ereikoussa and up to 60% in Othonoi, and replaced by clean photovoltaic energy.

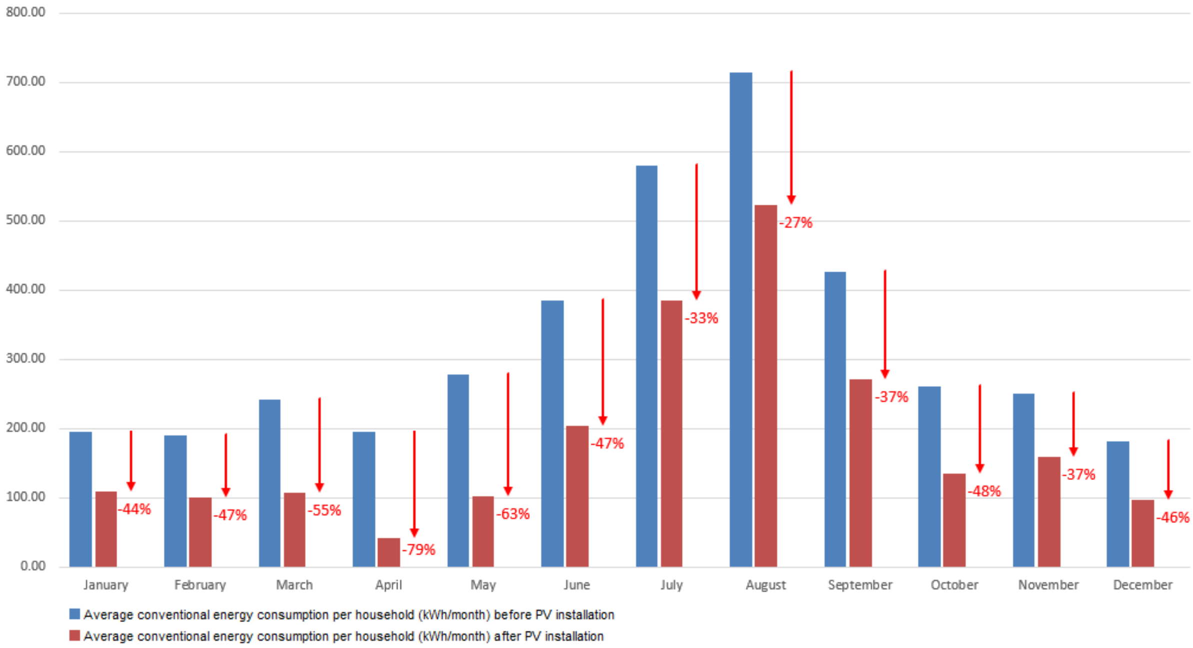


Figure 27: Consumption of grid energy per household (generated by diesel engines) before and after the installation of PVs in the island of Ereikoussa.

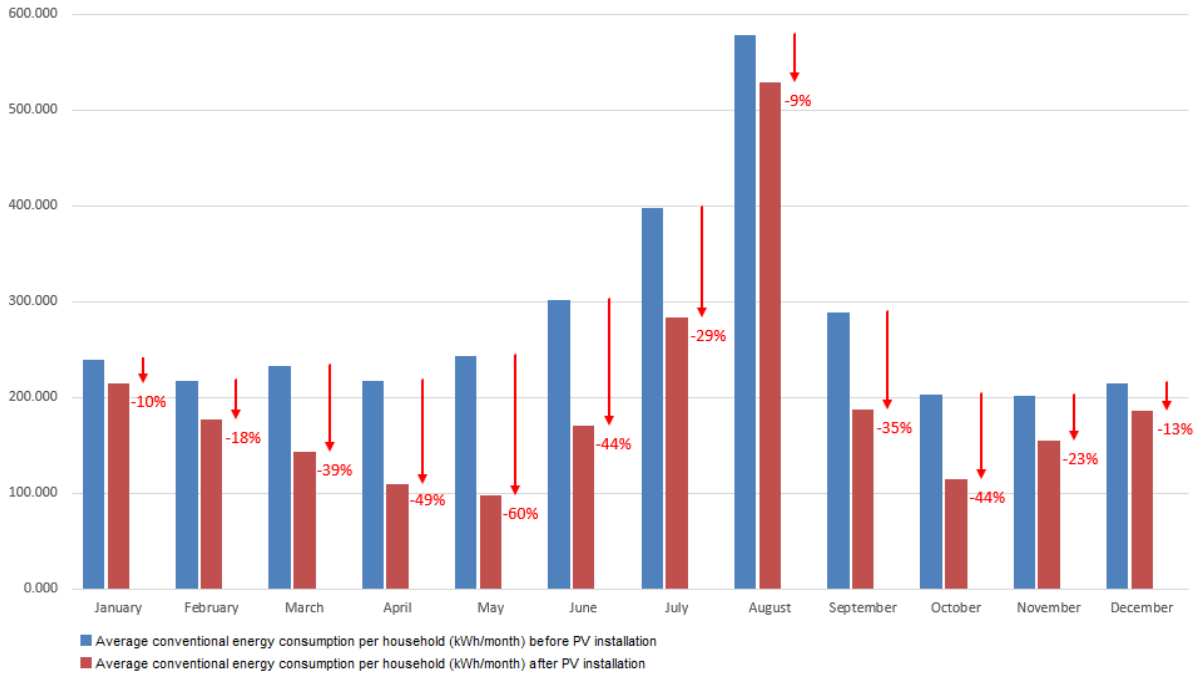


Figure 28: Consumption of grid energy per household (generated by diesel engines) before and after the installation of PVs in the island of Othonoi.

[67] Consumers will be able to buy the amounts of renewable energy that they believe they need on the platform and therefore the PV power will not necessarily be shared equally among them. The amount of energy available on the platform is estimated based on the total production of the company plus that of the prosumers' minus the energy used by the prosumers.

It should be noted that the above metrics are calculated based on the PV generation of the prosumers alone (generation by the company is excluded) and therefore, the reduction in the usage of conventional energy will be much less and it may reach up to 100% during certain months.

In this stage of the project, the energy demand that is not covered by the photovoltaic generation will be covered by the conventional energy produced by diesel generators. In a potential future development, the installation of greater capacities of photovoltaics or other RES such as wind turbines combined with larger storage solutions could offer complete energy autonomy to the island.

5.3.2 Competition

At the time, the only provider of power on the island is Public Power Corporation (PPC). While two other energy providers have more recently initiated operations in a number of islands, including non-interconnected ones, they have not yet expanded to Gavdos, Agios Efstratios, Agathonisi, Antikythera, Ereikoussa, Megisti, and Othonoi. This may present an opportunity for the company to not only pursue the current project but also to expand it to the above islands.

As the company's goals are to offer affordable and clean energy to consumers and address energy poverty, it will offer lower electricity rates on its platform than those of Public Power Corporation. As the platform will operate with bids, prosumers will be able to sell the energy they produce not at a fixed price, but at a range of prices that will depend on demand. Of course, the rates that will be offered to prosumers (see 5.4.4) will be higher than those offered for net metering by the Distribution Network Operator.

5.3.3 SWOT Analysis

Strengths	Weaknesses
- No competition in Greece in the peer-to-peer energy trading sector - Consumers are enabled to decrease both their carbon footprint and their electricity bills - Consumers can receive an extra source of income by selling their excess energy - Addressing energy poverty on a local level - Promoting clean energy usage and sustainable development - Supporting local economies	- Possible shortage in workforce with expertise in blockchain - The project utilizes unproven technologies (mostly refers to blockchain) - No other similar projects in the country in order to compare results - Possible lack of funding due to the increased risk of the project
Opportunities	**Threats**
- Commitment from Greece as an EU member-state to increase the share of RES in its energy mix - Non-interconnected islands are a high priority for installation of RES, as they cover their energy needs mostly by using polluting fossil fuels - Necessity to increase RES penetration in the country amid EU-imposed penalties for $CO2$ emissions - The project can receive community support as it enables engagement and participation of the local society	- Many consumers lack the necessary technological familiarization - At first and until the project gains popularity, some consumers may be hesitant to engage in peer-to-peer energy trading - Poor grid infrastructure in a number of islands - Legislative uncertainty and legal barriers - Limited land availability in small islands

5.4 Operations and business strategy

The short-term goals of the company presented therein are to contribute to clean energy generation in the islands of Ereikoussa and Othonoi, to ensure a reliable supply of electricity, and to offer cost savings for the residents, which can also help to tackle energy poverty on a local level. Ultimately, the company aims over the long-term to promote environmental protection and energy transition in local communities and to convert Ereikoussa and Othonoi, in addition to other Greek islands in a later stage, to "smart islands" (as characterized by the relevant EU schemes) with more than 60% of RES generation.

5.4.1 Characteristics of the platform

The platform of the company will run on a private and permissioned blockchain and each of the specially designed smart meters of the participants will constitute a computing node of the network. This type of blockchain was chosen over public and permissionless blockchains, as the energy sector is considered a regulated industry and certain criteria should be met.

The permissioned nature of the blockchain will help the company to easily control the platform and its members. Interested parties that wish to join the platform will have to apply in order to gain access and after their application and details have been reviewed (e.g. if applying for a prosumer account they should state their energy production resource and its capacity) and are approved, they will get the respective permission. This way, the company can guarantee to its customers and community that access is only given to trusted third parties which fulfil important criteria.

As for the private characteristic of the blockchain, it will not only help the company with the above procedures but will also make available to it the personal details of the participants[68] which will be used only for billing and customer listings purposes. Another relevant spec of the private blockchain networks is that they have faster processing rates and transaction speed, which is crucial in the particular case of energy trading.

While there is a range of services that can be offered through a blockchain platform in the energy industry (e.g. P2P energy trading for utility companies, P2P energy trading for consumers and prosumers that extends to a global level, and platforms for both utilities and private users), the model that the company utilizes in this occasion is addressed mainly to prosumers and consumers (in a later stage producers can be included) and its operations are limited to a local level.

Finally, smart contracts will also be utilized on the platform to fulfil ancillary processes. These include the processing and record-keeping of transactions as well as the creation of the "SLR" tokens, the native token of the platform.

5.4.2 Microgrid equipment

The PVs, inverters, and other devices will be purchased and installed by the company on its own rented property as well as in the properties of the participants. The smart meter will be

[68] In the case of public blockchains, the personal details of participants are not known to the governing body (pseudonymity is used), which would constitute a problem in the particular case, as they would be necessary for specific business procedures.

developed by the company, which will dedicate the necessary funds for R&D purposes and will be produced by a contractor that specialises in relevant devices.

The battery will be used to store any excess energy, which will be sold to other participants via the blockchain platform when required. It is one of the essential components in the microgrid, as it guarantees the short-term stability of the system in case of disruptions. It will also play an important role for any future RES additions in the island. The same site where the battery will be installed, will also be used to install the photovoltaics and to store other required equipment as well, such as devices for the monitoring of PV power generation and consumption.

The company will follow two repayment plans for the PVs and other equipment that will be used by the participants. In the first, participants with an installed capacity of 10 KW will repay in full the cost of installation, while in the second, those with 5 KW capacities will repay it in instalments. This is due to the 10 KW photovoltaics being in the "corporate plan" as they will be installed either in hotels or other companies.

5.4.3 Transactions

Each transaction is initiated when a prosumer submits an offer on the platform[69] for a given amount of energy, and a consumer responds by making an offer in SLR tokens. The transaction is then automatically completed with the electricity transferred to the consumer and the prosumer receiving the agreed amount of tokens in their virtual wallet. The nodes of the transacting parties (smart meters) record the transfer of tokens and electricity on the immutable blockchain record, which can be accessed by any member of the platform thanks to the transparent nature of blockchain. The relevant data (together with PV production data received by the PV monitoring system[70]) are also sent to the control centre of the company and are used for forecasting, balancing and billing purposes.

A smart meter installed in the property of the company will record the amounts of electricity produced and sold to the participants. This information, combined with data from the energy storage monitoring system, will help the company to be constantly updated on its availability of stored energy and optimize storage management.

5.4.4 Pricing

Currently, the price offered by the Public Power Corporation, the only provider that operates on the islands of Ereikoussa and Othonoi, is €0.1105 per kWh for consumption up to 2000 kWh and €0.11938 for consumption greater than 2000 kWh (for private customers). On the P2P platform, the price of energy will be adjusted depending on the supply and demand and therefore the rate offered by the company will not be fixed.

The range of prices will vary between €0.088 and €0.098, with low-end rates being increasingly possible in periods of high generation but low demand (e.g. in the months of April, as shown in Figure 28 and Figure 29) while high-end rates in periods of increased demand and relatively low PV generation (e.g. in the month of August). The energy from the platform

[69] For higher amounts of energy to be available on the platform and serve more customers, prosumers will be able to consume for their own needs a certain percentage of the energy they produce. For instance, prosumers with 10 KW PVs will be able to use without extra charges up to 50% and those with 5 KW up to 30% of their generated electricity. The company may adjust this term based on the prevailing conditions (e.g. increase the limit in case of excess production and low demand).

[70] The PV monitoring system can display PV production data (hourly, daily) and information about the inverter (AC voltage, DC voltage), in addition to real-time monitoring of all the photovoltaic modules within the microgrid which can be used for ensuring proper functioning of all the devices.

in comparison to that from the grid is up to 9.51% cheaper per month in the island of Ereikoussa and 34.27% in Othonoi. This difference is due to the greater number of consumers in Ereikoussa (and therefore less energy from the platform available per user).

Figure 29: Average monthly electricity costs (in EUR) for consumers in Ereikoussa that buy energy from the grid (red) and from the P2P platform (green).

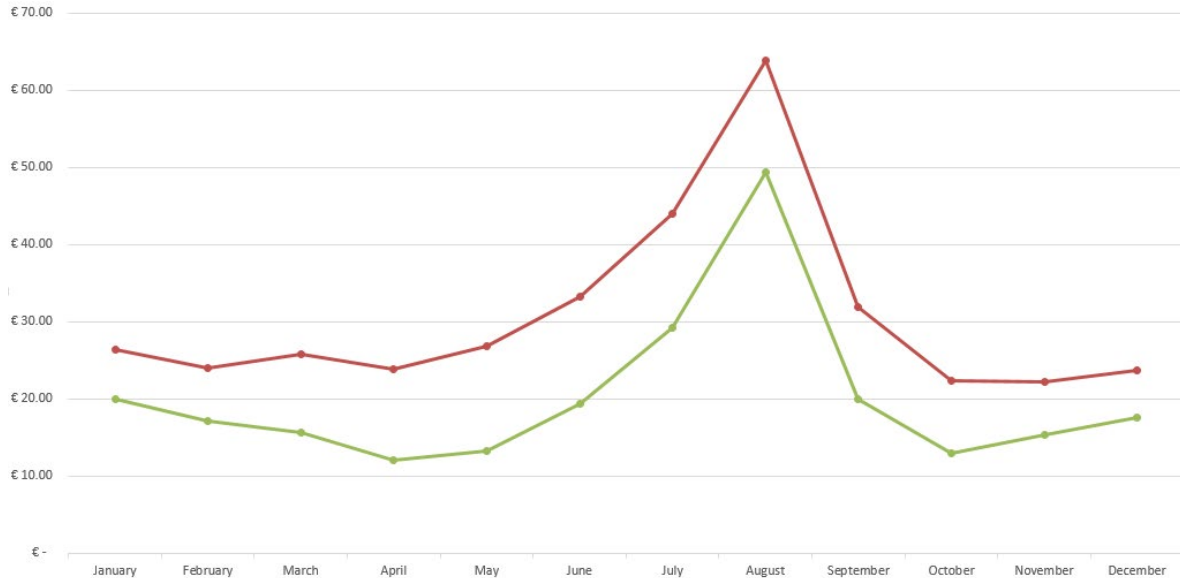
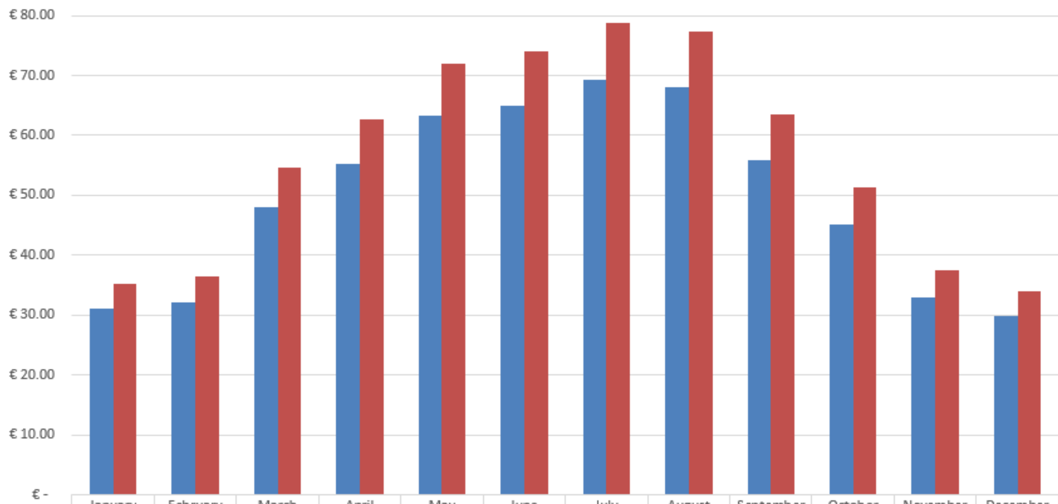


Figure 30: Average monthly electricity costs (in EUR) for consumers in Othonoi that buy energy from the grid (red) and from the P2P platform (green).

It needs to be mentioned that the prices offered to the prosumers to sell their energy on the platform are higher than those offered for net metering by the Distribution Network Operator. A prosumer selling their energy on the P2P platform can gain between €0.088 and €0.094 while the prices offered for net metering currently stand at €0,080 per kWh sold to the grid for those who initiated net metering with PVs after the 1st of August 2019. Below we can see the revenues of a prosumer with 10 KW PVs that sells energy to the grid and the respective revenues by selling the same amount of energy on the P2P platform.



	January	February	March	April	May	June	July	August	September	October	November	December
Grid selling revenues 10 KW	€ 31.02	€ 32.10	€ 48.00	€ 55.14	€ 63.20	€ 65.04	€ 69.26	€ 68.07	€ 55.85	€ 45.18	€ 32.91	€ 29.87
Platform selling revenues 10 KW	€ 35.28	€ 36.51	€ 54.60	€ 62.73	€ 71.88	€ 73.99	€ 78.79	€ 77.43	€ 63.53	€ 51.39	€ 37.44	€ 33.98

Figure 31: Average revenues of a prosumer with 10 KW PVs, by selling their total produced energy to the Distribution System Operator on the grid (blue) and by selling on the P2P platform (red) in Ereikoussa Island.

We can see from the above graph that prosumers have a strong incentive to sell their energy on the platform since they can earn an average of €81.90 of additional revenues annually by selling their electricity peer-to-peer.

5.4.5 Marketing and promotion

The company will invest primarily in marketing campaigns during the year of preparations and the first two years of operations. The early campaigns will have as a main point to inform the public about the benefits of P2P energy trading and attract the necessary amount of prosumers, while the later campaigns will mainly target new customers so as to form the initial customer base and increase the users of the platform. Advertisements and other informational campaigns will be placed locally and will be based on three pillars:

- Promotion of the competitive electricity prices offered by the company through the P2P platform and comparison with the prices of other energy providers. Reference to the benefits for the local economy and mainly for the environment.
- Highlight the ease of use and the user-friendly environment of the platform, the secure online payments system as well as the user-support services offered.
- For those who wish to become prosumers, emphasize the options for the repayment of the photovoltaics. Moreover, point out the average savings from using their produced electricity in combination with the average annual earnings from selling through the platform.

Through the above actions, the company can manage to inform the local population about the multiple advantages the P2P energy trading can provide to the communities of the islands. Other promotional activities, such as discounts and free trials, may also take place as needed.

5.5 Financial data and forecasts

Ereikoussa and Othonoi are two of the islands with the highest average total cost for power production in Greece. This is mainly due to their electrification being dependent on conventional diesel engines alone. More specifically, in 2018, the average total cost for conventional power production was €790.51 per MWh or €0.79 per kWh on the island of

Ereikoussa and 1035.85 per MWh in Othonoi, the third-highest among other islands in the country. These figures further rose in 2019 to €904/MWh for Ereikoussa and €1,151/MWh for Othonoi.

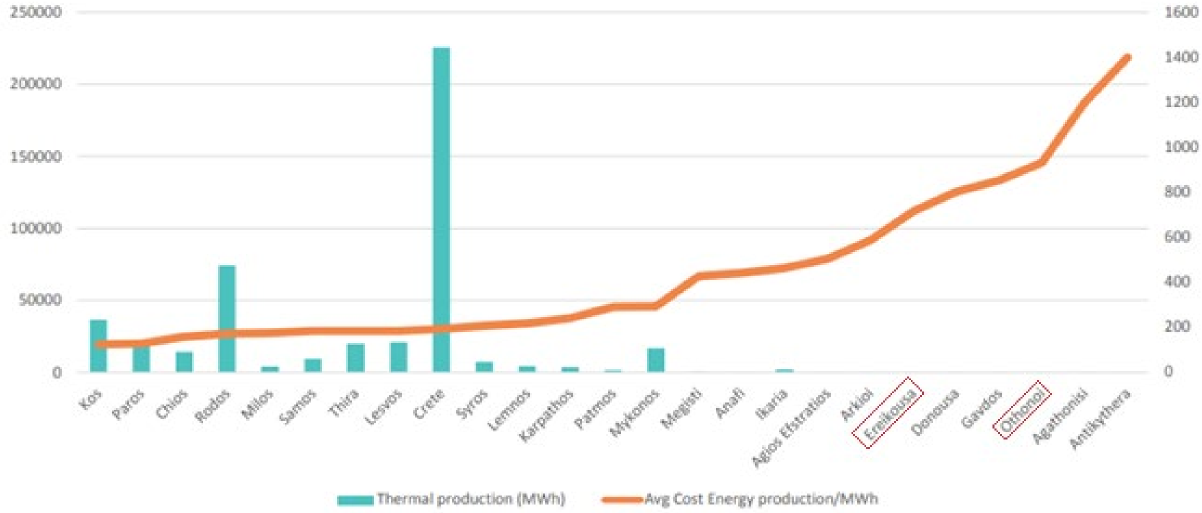


Figure 32: Average cost of energy production in Greek islands (European Commission, 2019)

Other islands with high electricity production costs that are not in the interconnection plans include Antikythera (€1,417.28/MWh average total cost), Donousa (€850.33/MWh average total cost) and Gavdos (€780.32/MWh average total cost). These are also good cases for a possible future expansion of the proposed company.

In islands with high penetration of renewables, the cost was significantly lower. Such cases are those of Crete (average cost of €191.91/MWh with 39 wind farms, 582 photovoltaic farms and 1945 roof photovoltaics), Samos (average cost of €177.73/MWh with 6 wind farms, 57 photovoltaic farms and 6 roof photovoltaics) and Chios (average cost of €142.72/MWh with 14 wind farms, 50 photovoltaic farms and 334 roof photovoltaics) (HEDNO, 2019b). In these islands, the company could also conduct operations, but through a different business model (B2C and not peer-to-peer) by cooperating with the operators of RES and enabling them to sell power directly to customers through the blockchain platform.

5.5.1 Sales forecasts

The company will have different streams of revenue that will derive from the P2P platform subscriptions, the token purchases, electricity sales, and installation of equipment. More precisely, revenues will include:

- A monthly subscription paid by the prosumers and consumers to use the platform and buy and sell electricity. This is due to the benefits deriving for both parties from the use of the platform that includes sales revenues and savings in terms of using cheaper energy compared to the conventional[71]. Prosumers will also benefit from maintenance service for their equipment and therefore will pay a “premium” subscription fee.
- A monthly interest fee (6.1%) until repayment will apply for those prosumers that will repay their equipment in instalments. The prices offered for the PVs and other needed

[71] It is estimated that if prosumers with PVs of 10 KW (hotels and other businesses with high energy consumption) consume the maximum allowed percentage of their energy (50% of the energy generated per month) and sell the rest through the platform, they will have average revenues of €677.54 in Ereikoussa and €673.77 in Othonoi per year. In addition to that, the avoided energy costs from using their PV-generated electricity will be an average of €822.73 for those located in Ereikoussa and €818.14 in Othonoi per annum.

devices and equipment is €15,840 for 10 KW PVs and €9,200 for 5 KW PVs. Other equipment revenues will originate from the sales of smart meters to both prosumers and consumers.

- A percentage fee on transactions will be paid by consumers of the platform. The 290 consumers of the platform will need to pay a fixed fee on each transaction that amounts to 6% of the transaction's value (increased to 7% after the 15th year of operations). The fee is minimal and it is estimated that the amount paid by the average consumer will be €0.90 per month in Ereikoussa and €1.05 in Othonoi.
- Electricity sales. As mentioned before, the company will produce energy using photovoltaics of 50 KW in Ereikoussa and 30 KW in Othonoi. The company will either store some of its produced power in the storage system for later use or resell it directly to other participating consumers via the platform. The electricity will be traded by using tokens[72]. The tokens will be available in packages of 100, 200 and 300 SLR. One SLR will be equal to 1 kWh and their cost will depend on the spot price of electricity on the platform at a given time.

Based on the above, the company can expect to produce the following amounts of electricity and have the respective revenues from electricity sales:

Island		January	February	March	April	May	June	July	August	September	October	November	December
Ereikoussa	Electricity produced (kWh)	3877.4	4012.1	6000.3	6893	7899.4	8130.4	8657.9	8508.3	6981.3	5647.2	4113.8	3733.6
	Electricity sales revenues	€ 368.35	€ 381.15	€ 570.03	€ 654.84	€ 750.44	€ 772.39	€ 822.51	€ 808.29	€ 663.23	€ 536.49	€ 390.82	€ 354.69
Othonoi	Electricity produced (kWh)	4166.8	4203.8	6067.2	6903.7	7907.7	8138.1	8665.2	8516	7022.9	5779.7	4375.5	3953.6
	Electricity sales revenues	€ 237.51	€ 239.62	€ 345.83	€ 393.51	€ 450.74	€ 463.87	€ 493.92	€ 485.41	€ 400.31	€ 329.44	€ 249.41	€ 225.36

The total expected revenues amount to a total of €7,023 per annum for Ereikoussa and €4,314 for Othonoi, after the 5th year of operations when the average selling price of the company will be €0.095 per kWh.

As for the revenues generated by the fees paid by the consumers, it is calculated based on the total energy transacted within a month on the platform (after the deductions of the amounts used by the prosumers) and the average price per kWh:

[72] After a consumer has made an offer to buy electricity on the platform, the agreed amount of tokens will be transferred from their virtual wallet to that of the prosumer who sold them the electricity. The prosumers then can either redeem their tokens for fiat money or keep them in their virtual wallets until the spot price of electricity on the platform rises, in order to maximize their revenues (e.g. during summertime). The fiat money will be credited to the prosumers that wish to redeem their tokens one month after their request.

Island		January	February	March	April	May	June	July	August	September	October	November	December
Ereikoussa	Electricity sold on the platform (kWh)	18611.5	19258	28801.4	33086.4	37917.1	39025.9	41558.1	40840	33510.4	27106.8	19746.4	17921.2
	Total fees paid by consumers (170)	€ 103.85	€ 107.46	€ 160.71	€ 184.62	€ 211.58	€ 217.76	€ 231.89	€ 227.89	€ 186.99	€ 151.26	€ 110.19	€ 100
Othonoi	Electricity sold on the platform (kWh)	16671.8	17667.5	26250.2	30589.8	35056	35927.7	38455.7	37645.6	30751.8	24592.4	17907.2	15920.9
	Total fees paid by consumers (120)	€ 93.03	€ 98.58	€ 146.48	€ 170.69	€ 195.61	€ 200.48	€ 214.58	€ 210.06	€ 171.6	€ 137.23	€ 99.92	€ 88.84

These revenues will not be stable, as new additions of prosumers will be made up to the 10th year of operations, and therefore the amounts of electricity sold on the platform will increase as well. Additionally, the combined revenues from the smart meter sales to consumers are expected to be €160,000 in the first 6 years of operations, when new additions of consumers will take place each year. The total manufacturing and R&D costs for the smart meters are projected to reach €41,800.

Finally, the revenues from the monthly subscriptions paid by prosumers and consumers are estimated as follows:

	1st year	2nd year	3rd year	4th year	5th year	6th year	7th year	8th year	9th year	10th year	15th year
Total subscription fees paid by consumers	€ 6,480	€ 10,800	€ 14,400	€ 18,000	€ 19,440	€ 20,880	€ 20,880	€ 20,880	€ 20,880	€ 24,360	€ 27,840
Total subscription fees paid by prosumers	€ 12,000	€ 20,700	€ 25,200	€ 28,200	€ 35,700	€42,000	€ 45,600	€ 45,600	€ 45,600	€ 54,000	€ 59,400

Subscription fees are considered a major source of revenue for the company and thus contribute significantly to its profitability.

5.5.2 Cash flows

By utilizing the revenue data presented in the previous chapter, together with the expected expenses of the company per year, we have forecasted the cash flows for the first 20 years of operations. As shown in the table below, in year 0 (preparatory phase, PV and network installation) the net cash flow is €-429,960 which is the initial capital used mainly to cover equipment costs (e.g. PVs, inverters, battery, monitoring systems) in addition to development costs of the platform and other expenses to a lesser extent (e.g. salaries, project development, marketing expenses, etc.).

	Nominal values (€)			Present values (€)		
Year	Net Cash Flow	Free Net Cash Flow	Cummulative Net Cash Flow	Net Cash Flow	Cummulative Net Cash Flow	IRR (%)
0	-429,960	-429,960	-429,960	-429,960	-429,960	
1	70,276	80,626	-349,334	77,626	-352,334	-81%
2	5,090	15,440	-333,894	14,312	-338,022	-69%
3	20,096	30,446	-303,447	27,172	-310,849	-48%
4	32,812	43,162	-260,285	37,088	-273,762	-31%
5	39,571	49,921	-210,364	41,299	-232,463	-19%
6	50,039	60,390	-149,974	48,100	-184,362	-11%
7	27,474	37,825	-112,149	29,006	-155,356	-7%
8	18,372	28,722	-83,427	21,206	-134,150	-5%
9	8,310	18,660	-64,767	13,264	-120,885	-3%
10	24,734	35,085	-29,682	24,012	-96,874	-1%
11	20,831	31,181	1,499	20,546	-76,328	0%
12	20,739	31,089	32,588	19,723	-56,604	1%
13	20,642	30,992	63,580	18,930	-37,674	2%
14	20,540	30,891	94,471	18,166	-19,508	3%
15	16,716	27,067	121,537	15,325	-4,183	4%
16	16,604	26,955	148,492	14,693	10,510	4%
17	16,487	26,837	175,329	14,085	24,595	5%
18	16,363	26,713	202,042	13,498	38,094	5%
19	16,234	26,584	228,626	12,933	51,027	5%
20	16,097	26,448	255,074	12,388	63,415	6%
TOTAL	48,067	255,074	255,074	63,415	63,415	5.7%

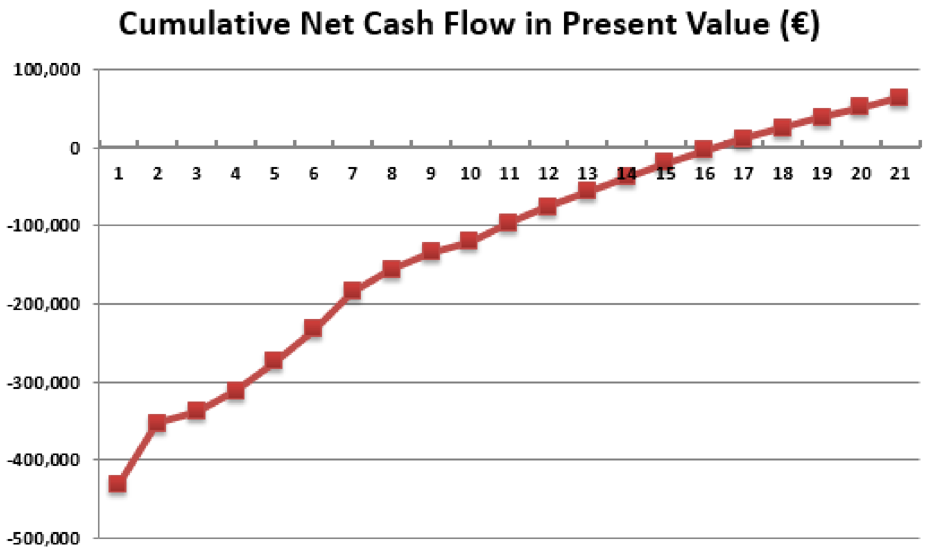
In the first year, the total profits from the operations in both islands are estimated at €199,605 while the expenses[73] at €93,846 (excluding loan instalments, loan interest, and taxes) which form a net cash flow of €70,276. In the second year of operations, both revenues[74] and expenses are lower, at €100,622 and €83,252 respectively, forming a nominal net cash flow of €5,090. From the third year up to the sixth, revenues steadily increase, reaching €157,274, as demonstrated in the table.

In the seventh, eighth and ninth year, we have significant reductions in the profits as most prosumers have repaid their equipment, while in the 10th year, profits rise back to €118,972, thanks to more prosumers entering the program and an increase in the fees paid by consumers. In the eleventh year, profits are reduced to €108,299 and stay at the same levels up to the fifteenth year when they further fall to €103,063. Total expenses remain at €73,109 after year 11, as there are no new installations of PVs, and the required personnel is reduced.

	Revenues (€)	Expenses (€)	
Year	Gross revenues	Operating costs	Total
0			
1	199,605	93,846	95,776
2	100,622	83,252	85,182
3	118,222	82,976	84,906
4	132,821	79,577	81,507
5	142,433	79,577	81,507
6	157,274	79,577	81,507
7	125,594	79,577	81,507
8	112,880	79,577	81,507
9	100,167	79,577	81,507
10	118,972	76,478	78,408
11	108,299	70,979	73,109
12	108,299	70,979	73,109
13	108,299	70,979	73,109
14	108,299	70,979	73,109
15	103,063	70,979	73,109
16	103,063	70,979	73,109
17	103,063	70,979	73,109
18	103,063	70,979	73,109
19	103,063	70,979	73,109
20	103,063	70,979	73,109
TOTAL	2,360,164	1,523,804	1,564,403

[73] Expenses in the first year of operations, apart from operating costs also include the costs for the installation of additional equipment such as 20 KW PVs (operated by the company) in Ereikoussa and Othonoi, along with other required equipment.

[74] This is mainly due to prosumers of 10 KW PVs repaying in full the costs of their equipment in the first year, while in the following years repayment is made through instalments by prosumers of 5 KW PVs.



Finally, we can observe that the cumulative net cash flow (present value) only becomes positive after the 16th year of operations, and the IRR of the project is 5.7%.

5.5.2 Financing requirements

The company will require initial funding of €523,806, which will cover the CAPEX (e.g. photovoltaics, storage system, monitoring system, etc.) and OPEX (e.g. R&D, platform development, salaries, rent, etc.), mainly during the "preparatory" phase. To a lesser extent, it will also cover the CAPEX and OPEX for the expansion of the company's PV network, which will take place during the first year of operations.

	Preparatory phase		Year 1	
Cost type	CAPEX	OPEX	CAPEX	OPEX
PVs	€ 34,200	-	€ 11,400	-
Storage system	€ 140,400	-	N/A	-
Inverters	€ 7,200	-	€ 2,400	-
Monitoring equipment	€ 37,744	-	€ 1,104	-
Other equipment	€ 33,326	-	€ 5,684	-
Project development	€ 23,590	-	€ 276	-
R&D costs	-	€ 41,800	-	N/A
Platform-related costs	-	€ 57,400	-	€ 2,870
Maintenance	-	N/A	-	€ 9,712
Salaries	-	€ 40,300	-	€ 56,400
Accounting & Law services	-	€ 9,000	-	€ 3,000
Marketing expenses	-	€ 5,000	-	€ 1,000
Funding per cost type	**€ 276,460**	**€ 153,500**	**€ 20,864**	**€ 72,982**
Net funding required	**€ 429,960**		**€ 93,846**	

As we can discern in the table, the lion's share of capital expenditures during the preparatory phase goes towards the storage system, which will be larger in capacity compared to the company's PV system as it will be used to also store the excess energy of prosumers. Concerning the operational expenditures during the same period, a great number of funds are spent for R&D purposes (includes the development of the smart meter) and for platform-related issues, which concerns the development of the P2P platform (includes expenses for the salaries of engineers in addition to needed software and hardware). In the first year of operations, the majority of funds are used in operational expenditures, and more precisely for salaries and employee benefits, which make up 60% of the year's budget.

The above costs will be covered by funding from different financing sources.

- **Bank loan**: It will cover 30% of the costs in the preparatory phase, which translates to an amount of €128,988. The loan will be repaid over 20 years, with an average expected interest of 5%. The annual instalment plus interest is estimated to be

€10,350, with the interest fees over the 20-year period coming to a total of €78,019 (cumulative amount repaid €207,007).

- **Government subsidies**: The Ministry of Energy has announced a funding of up to 40% aimed explicitly toward energy communities for amounts up to €1,000,000. The company can expect to fund around €207,000 of the project through this government subsidy.
- **Private investment funds**: The company will seek financial assistance from investment funds and other institutional investors specializing in the energy sector. Funds from such sources will reach up to 20% of the investment in the preparatory phase and 40% in the first year of operations.
- **Alternative financing**: As the project is directly linked to the local community and aims to tackle problems such as pollution and energy poverty, the company will seek funding through alternative concepts like crowdfunding. The amount that is targeted to be raised is equivalent to around 5% of the initial investing or €23,000.
- **Other sources of funding**: Several financing options are available through grants from EU organizations. European Commission offers a grant of €20,000 through the "Horizon 2020" directive, targeted for initiatives that promote clean energy in islands within the European Union (European Commission, 2018). Other organizations such as the "Clean Energy for EU Islands Secretariat" can also provide funding and technical support for relevant initiatives. Finally, the ELENA fund managed by the European Investment Bank supports similar projects by providing up to 90% financing exclusively for technical assistant and project development costs. Therefore, the company can cover more than €20,000 from the particular fund (Clean Energy for EU Islands Secretariat, 2019).

5.5.3 Sensitivity analysis

In order to determine the sensitivity of the company's profitability and economic viability based on different factors, the following scenarios will be analysed:

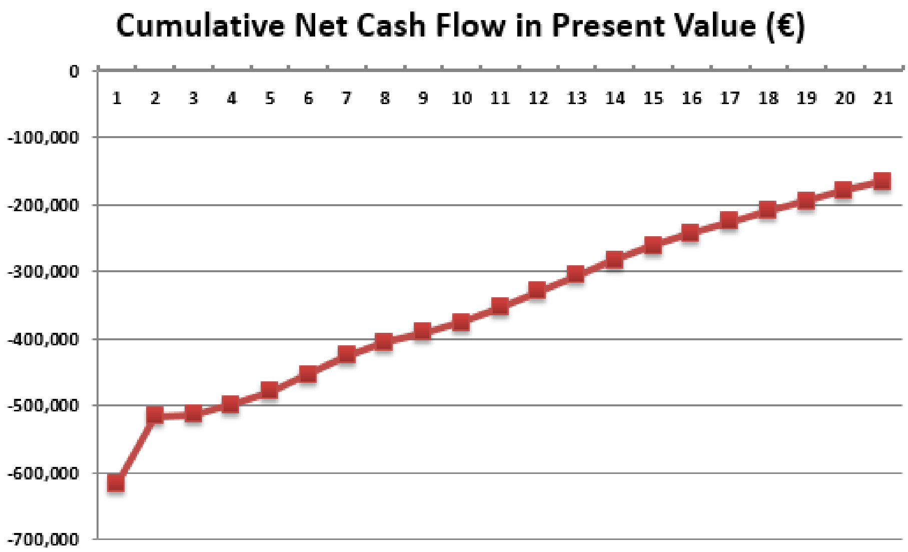
"Fewer prosumers" scenario

This scenario will help us to estimate how sensitive the company's profitability is to a possible reduction in the number of prosumers in both islands. The scenario will include 50% fewer prosumers than the basic scenario. The company will own more PVs than in the basic scenario. More specifically, the data of the scenario is the following:

Island	Number of prosumers	Prosumers' total PV capacity	Company's PV capacity
Ereikoussa	25	175 KW	175 KW
Othonoi	20	150 KW	130 KW

The company manages to produce a greater amount of energy thanks to the more considerable capacity of PVs and have an increase in electricity sales revenues compared to the basic scenario. Nevertheless, the two main problems with the "fewer prosumers" scenario are the loss of revenues caused by the small number of prosumers, as well as the higher capital costs for the project (as the PVs are owned and should be paid by the company in this scenario). The main points that should be noted are:

- The capital requirements for the initial investment increase to €616,260 in the "fewer prosumers" scenario, a 43.3% increase compared to the basic scenario.
- The gross revenues stay around the same levels, with a slight decrease of 0.18% in the course of the 20-year period of the project.
- Revenues from electricity sales rise from €226,648 in the basic scenario to €858,624 during the same period, but subscription fees revenues fall by 39.4% (€329,700 loss) in comparison to the basic scenario.
- The IRR of the project is 0.5%, while the cumulative net cash flow (present value) is estimated at €-164,663.



From the above details, we can conclude that the revenues of the company are highly dependent on the number of prosumers that participate on the platform due to the subscription fees and the equipment sales. Another reason that the profitability of the company is affected in this scenario is the high costs for the installation of PV equipment in large scales.

"Fewer consumers" scenario

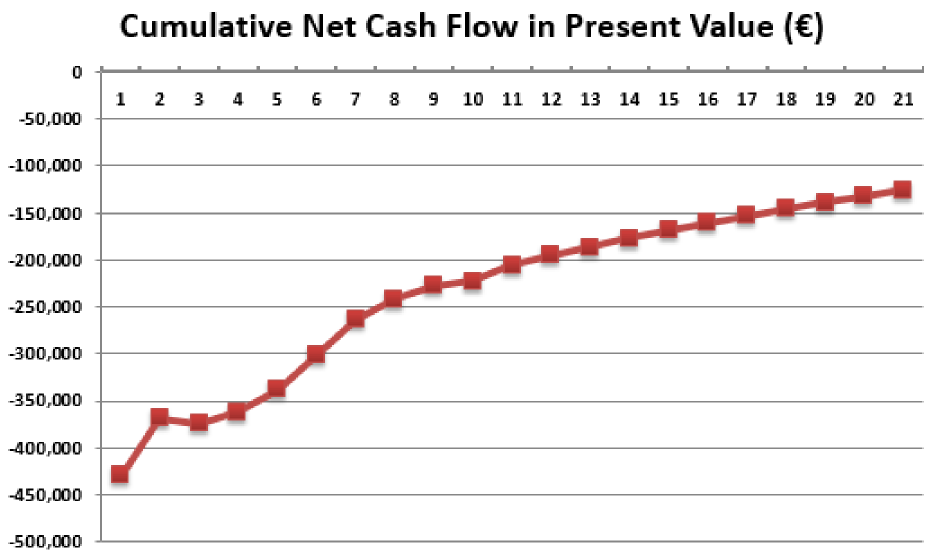
Similarly to the previous scenario, we will assess what impact a 50% reduction in consumers will have on the company's revenues through the "fewer consumers" scenario. The details are:

Island	Company PV capacity	Number of prosumers	Prosumers' total PV capacity	Number of consumers
Ereikoussa	50 KW	50	300 KW	85
Othonoi	30 KW	40	250 KW	60

As three income streams of the company come through consumers (electricity sales fee, the subscription fee for the platform usage, and smart meters sales), the company marks consequential revenue losses in the particular scenario. The impacts on the profitability of the company are as listed below:

- The gross revenues of the company fall by 13.5% during the 20 years of the project.

- Revenues from smart meter sales decrease by 54.9%, while those of monthly subscription fees by 50.9%.
- The IRR is estimated at -0.4% and the cumulative net cash flow at €-125,276.



The number of consumers is, therefore, closely related to the profitability of the company, and the right strategy to create a strong customer base should be followed.

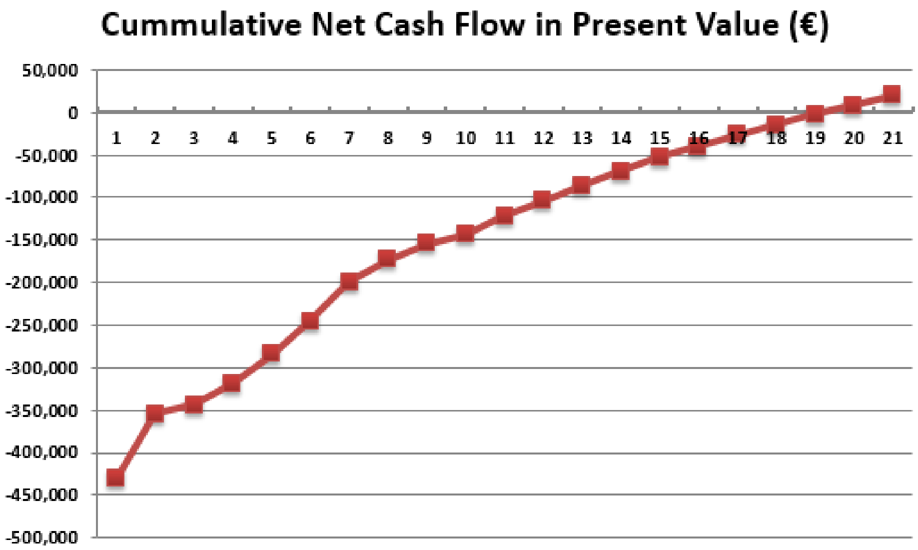
<u>"Decrease in electricity prices" scenario</u>

This scenario takes into account a possible decrease in the electricity selling prices of the P2P platform by 30%. Special emphasis should be paid to the particular scenario, as it gives insight into the flexibility of the company's pricing policy in case of increased competition (e.g. if other energy providers with competitive pricing commence operations in either of the islands).

Island	Company PV capacity	Estimated generation / year (kWh)	Average price per kWh (company)
Ereikoussa	50 KW	74,455	€0.0665
Othonoi	30 KW	45,420	€0.0665

The company has two revenue streams connected to the price of electricity on the platform (electricity sales revenues and the fixed transaction fee). As we will see the impact on revenues is attributed mainly to the electricity sales and, to a lesser degree, to the fixed transaction fee, which constitutes less than 2.9% of the annual revenues. The results of the scenario are the following:

- A 3.74% decrease in total gross revenues during the project period.
- The revenues from electricity sales fall from €226,648 (basic scenario) to €157,436.
- The project's IRR drops to 4.5% and the cumulative net cash flow to €19,411.



We can conclude that while a reduction in electricity prices would disrupt the revenues of the company, it would not severely impact the sustainability of the company, and therefore it can be used accordingly. For instance, the company can review its pricing policy annually to determine whether a reduction in prices is necessary to attract new customers or maintain the existing customer base.

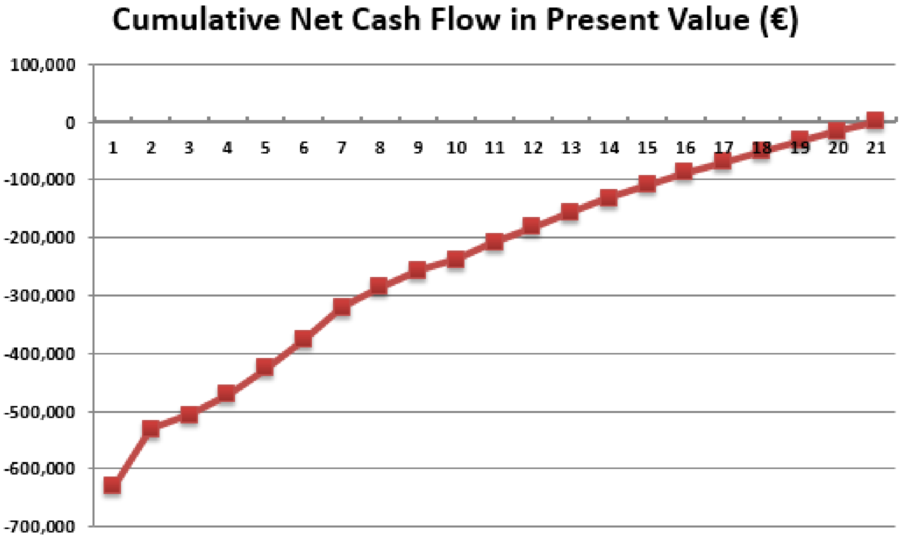
"Other RES" scenario

The last scenario will test if a combination of wind power (owned by the company) and PVs (owned by the prosumers) will yield more revenues and whether it is a preferable solution rather than the basic scenario, which includes only photovoltaics. The capacity of PVs owned by prosumers is reduced slightly, to maintain the same electricity generation levels as in the basic scenario. The details are specified in the table below:

Island	Company wind capacity	Number of prosumers	Prosumers' total PV capacity
Ereikoussa	50 KW	50	230 KW
Othonoi	30 KW	40	220 KW

While the initial amount of the investment increases significantly in the specific scenario, the power generation rises as well (since the wind turbines have a higher output than the PVs) and so do the revenues from electricity sales:

- The company's electricity sales revenues grow by 123% to €506,490 over the 20-year period while the total revenues rise by 11.6%.
- The initial investment amount increases by 46.6% due to the increased costs of wind turbines and higher related expenses (e.g. transportation, installation, etc.).
- The IRR of the scenario is estimated at 3.9% and the cumulative net cash flow €1,198.



The above details lead us to the conclusion that while wind power can offer higher electricity generation levels, it also comes with a considerably higher capital cost, which results in an investment that is less attractive than in the case of the basic scenario.

Moreover, to better assess the viability of each of the scenarios, we can use the levelized cost of energy measurement. LCOE is used to define the average total cost of generating a unit of power over the lifetime of a given energy project and is given from the following formula:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where:

I_t = Investment expenditures in year t (€)

M_t = O&M expenditures in year t (€)

F_t = Fuel expenditures in year t (€) (if applicable)

Et = Electricity generation in year t

r = Discount rate

n = Project lifespan (years)

For both scenarios, a lifespan of 20 years and a discount rate of 4% is considered. Based on the above formula and the data of each scenario, the levelized cost of energy in the basic scenario is €0.34 per kWh while in the "other RES" scenario that also includes wind power €0.25 per kWh. It needs to be mentioned that for the calculation of LCOE only the power systems owned by the company were taken into account.

In general, the median levelized cost of energy for solar PV production projects is €0.27 while the maximum is €0.56 and thus the basic scenario has an acceptable LCOE and more precisely it falls within the second quarter (between €0.28 and €0.349) of projects that utilize the solar PV technology, which means that it has a better LCOE than at least 26% of them (Open EI, 2020).

While the "other RES" scenario has a better levelized cost of energy than the basic scenario, it is not competitive compared to other projects that utilize wind power (onshore), since the maximum LCOE for such projects is €0.12. As a result, the most viable investment, according to the LCOE calculations, is that of the basic scenario.

Conclusions

The purpose of this dissertation is to review the main characteristics of blockchain technology, and based on its technical advantages, analyse the role it has played up to this day in the transformation of the energy industry and, more specifically, in the electric power and oil & gas sectors. In addition, a case study is also presented that aims at showing how blockchain can provide solutions for the Greek energy ecosystem.

Based on the characteristics of the technology presented in Chapter 2, we named its main advantages and disadvantages, as well as specific prominent use-cases for the energy sector. These included the securitization of smart energy systems, transparency in operations, decentralization of energy systems, and applications of smart contracts.

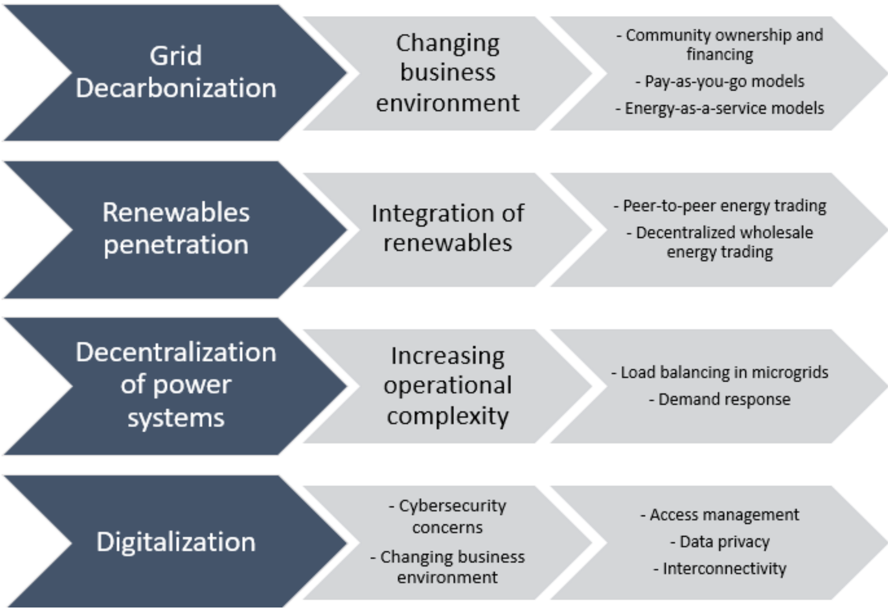
A number of ongoing trends in the energy sector were described in Chapter 3. Concerning the electric power industry, these included grid decarbonization and decentralization as well as renewables penetration. In contrast, for the oil & gas industry, the growing demand for refined products, the development of unconventional resources, and environmental concerns related to the industry's procedures were the most crucial cases. A common trend for both industries is digitalization, which constitutes the cornerstone for the development and promotion of blockchain and other new technologies, as well as the driving force behind the reshaping of the energy industry or, alternatively, Energy 4.0.

This analysis contributes to understanding better the usefulness of blockchain applications that have taken place as of today in the two aforementioned industries and the problems they are trying to resolve, outlined in Chapter 4. In essence, most of those applications constitute a solution or at least an effort to partially tackle the challenges facing the energy sector today.

In the electric power industry, the trends mentioned above introduce several challenges, as depicted below. More specifically, the trend of grid decarbonization, led mainly by climate policies and increasing consumer needs, tends to reshape the traditional business environment of the industry.

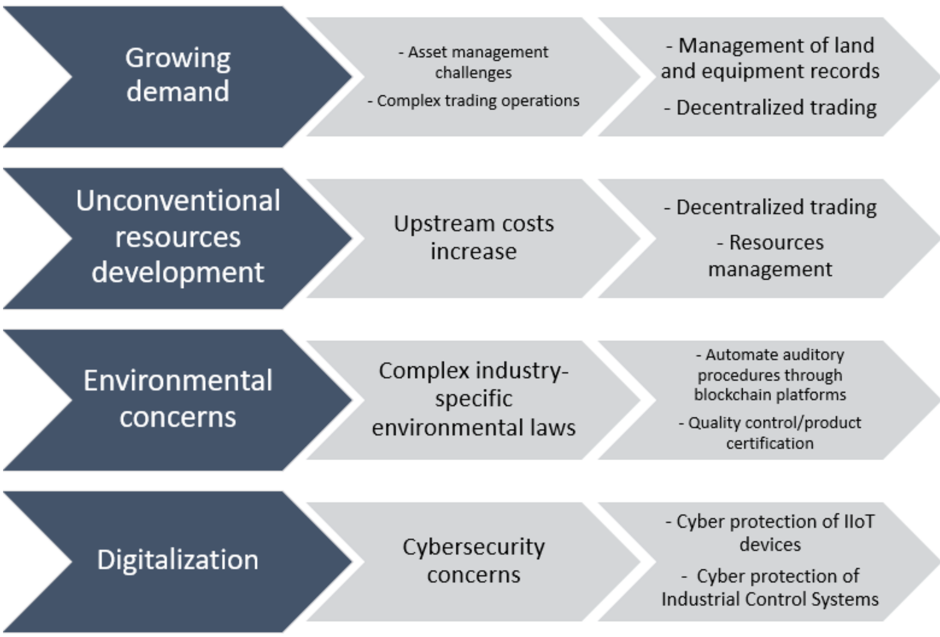
Another major trend is the continuous penetration of renewables, which creates the need to properly manage and integrate these sources into the pre-existing systems, while the decentralization of power systems increases their operational complexity significantly.

Lastly, the constant digitalization of power systems expands their attack surface and creates various cybersecurity threats that can harm transmission and distribution systems. All these challenges are being addressed today to different extents by blockchain-based solutions. For instance, in the case of changing business environment, blockchain can assist companies in modernizing their services (e.g. by offering pay-as-you-go services) and the way they raise investment capital (e.g. utilizing community ownership schemes).



With regards to the oil & gas industry, the growth in demand for liquid fuels, particularly in developing nations, has forced exploration & production firms to develop an increasing amount of reserves, many of them in remote locations, consequently making their management more complicated. An alternative way that these companies seek to cover demand is by developing unconventional resources such as shale oil, which comes with numerous drawbacks, including higher costs. By utilizing blockchain to automate their trading procedures or for equipment management purposes, companies in the sector will be able to lower their operating costs substantially.

On the other hand, many of the environmental concerns surrounding the oil & gas sector are connected to past accidents or the industry's polluting nature and have prompted regulators to impose strict and complex industry-specific laws which make it harder for companies to comply with in many occasions. Finally, along with the digitalization of core industrial systems, cyber threats that may pose a severe disrupting factor across the value chain of the O&G sector have been developed. A number of blockchain solutions that can safeguard IIoT and Industrial Control Systems are currently under consideration.



In the 5th and final Chapter, the use-case scenarios described previously are adapted to show how blockchain is able to address a major challenge of the Greek energy sector. Through the business plan presented in the particular chapter we manage to show how the technology can electrify with clean and affordable energy the non-interconnected Greek islands and, in parallel, cope with problems such as energy poverty and promote energy communities. Although regulatory factors stand in the way of the realization of such a venture at present, this example shows that the blockchain technology can indeed be utilized to resolve industry- and country-specific issues. At the same time, its underlying capabilities enable companies in the energy sector to develop new products and services, reduce their costs, access new markets and adapt their business models. Consumers on the other hand will be enabled to get access to environmentally and economically sustainable energy, produce and transact their energy with their community and have a more active role in their energy management.

Giving the structure of the thesis, it needs to be addressed that whereas there is a constant emerge of blockchain startups and blockchain-based platforms that utilize different tools and are aimed toward different industries, we do not yet have a standardized design that also constitutes the point of reference for the particular technology. A notable factor for the lack of a “dominant design” is the technical challenges that blockchain faces at present, namely those of scalability, speed, and flexibility.

As previously mentioned in 4.1, it is expected that the technology will reach maturity, and therefore escape the exploratory phase not earlier than in 5 years. Despite the high number of companies that have recently begun to develop blockchain solutions, it is more likely that large firms with substantial capacity for R&D investments and patent acquisitions are going to lead the way and establish a blockchain dominant design. For this to happen, the dominant design should overcome its current limitations and evolve to be advantageous for large-scale industry applications.

The choices of major industry participants are among the most critical factors for determining a dominant design, as at least a 50% market share is required for a particular design (compared with other rival designs) to be established as the industry’s standard. By all means, this is only possible if it can prove its superiority compared to the currently employed technologies and processes. Once such a design prevails, it will develop accordingly to serve different industry needs, including the energy one.

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Appendices

A. Evaluation of suitability for blockchain in energy applications

Blockchain is not suitable for applications that contain an isolated user and it is recommended that traditional databases are used instead in such occasions. In the case of the petroleum industry, the different users within a blockchain environment may be different collaborating companies, contractors, service firms, regulators, tax authorities and banks. If high performance is required within the network, a private blockchain is recommended due to the smaller number of participating nodes (see 2.1.2).

Moreover, if policies or smart contracts are not involved but data sharing still needs to be controlled, DLT technology is proposed (e.g. it may lack some characteristics, like time-stamped blocks, compared to the blockchain).

Finally, if transactions need to be kept private, a permissioned blockchain network is recommended; otherwise, a hybrid blockchain can be utilized that includes features from both permissioned and permissionless blockchains (Xu, et al., 2019).

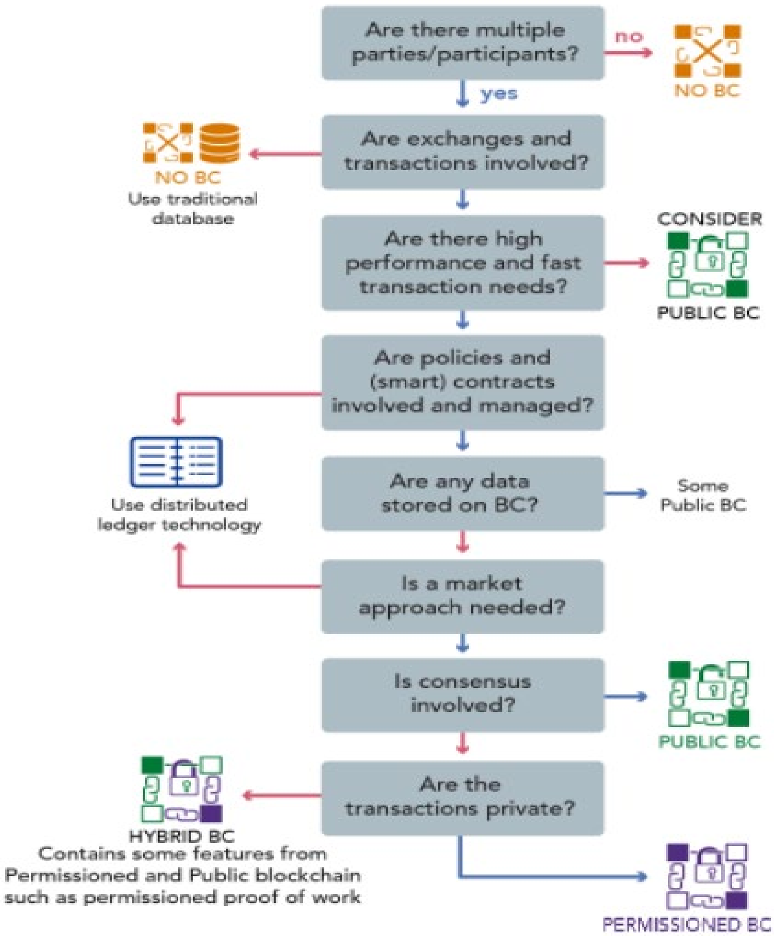

Figure 33: Roadmap to blockchain project evaluation (Mylrea & Gourisetti, 2018).

B. Hype cycle for the blockchain technology in energy

According to Gartner's hype cycle (Ledger Insights, 2019a), blockchain is still in the section of "Innovation Trigger" (i.e. still explored by early adopters) in the O&G sector, while for application in utilities it is ranking slightly higher, near the starting phase of the "Peak of Inflated Expectations" section. This translates into the technology gaining popularity for applications in the particular sector, with the most prominent one currently being peer-to-peer electricity exchange (Singhi, 2019).

In both industries, the technology is expected to reach maturity in 5 to 10 years, while it has increased expectations compared to many other industries, as can be seen in the graph below.

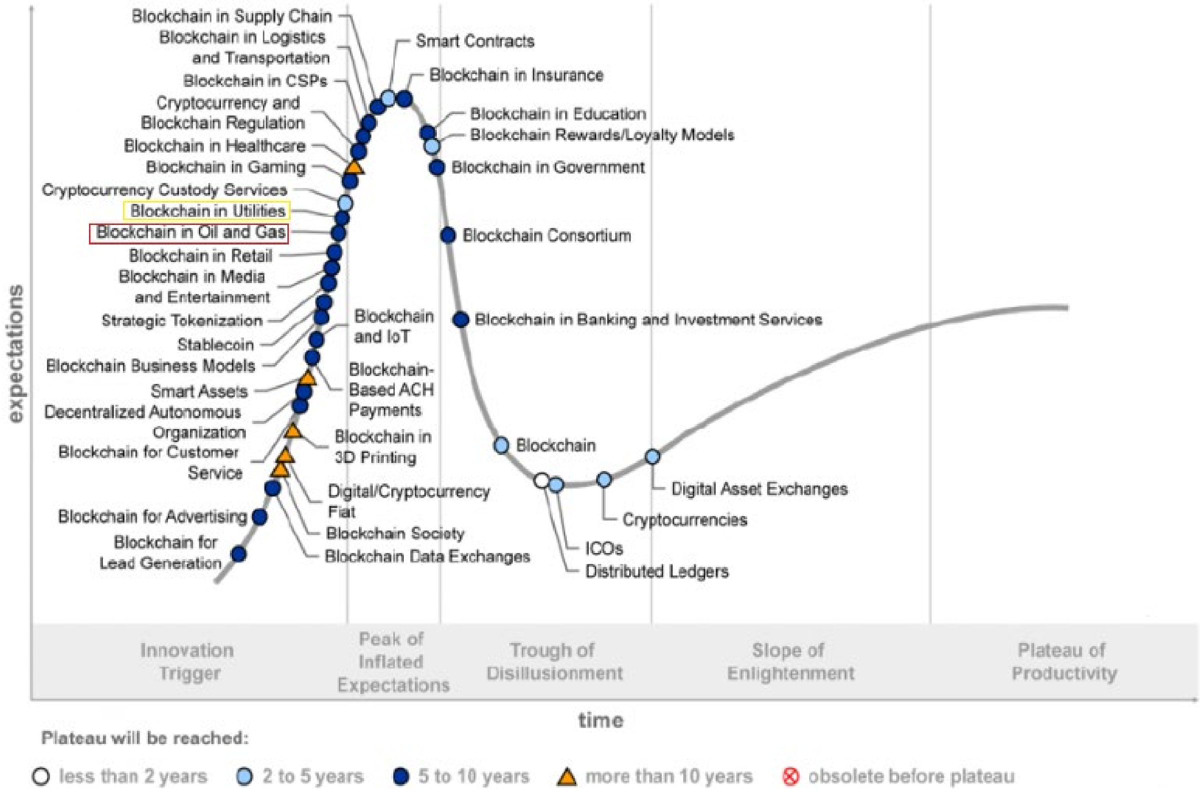

Figure 34: Hype cycle for blockchain technology in Oil & Gas and Utilities (Gartner, 2019).

C. Example of a peer-to-peer energy transaction

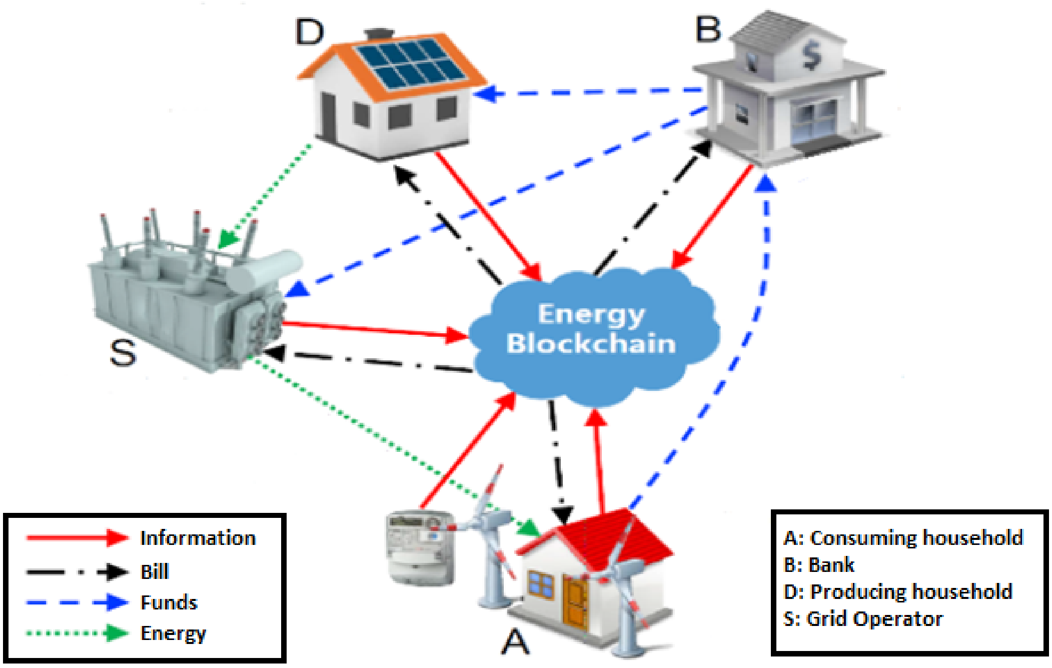

Figure 35: A typical peer-to-peer energy transaction with an intermediary entity (Xia, et al., 2019).

1. User A (consuming household) wants to buy an amount of electricity and sends through their smart meter the relevant request to the blockchain-enabled P2P energy trading platform. They also set a maximum price they are willing to pay for.
2. User D (producing household) has produced through their PV panels an excessive amount of energy and wants to sell it on the platform. Depending on the platform, they might either input a minimum asking price per kWh for their energy or allow the system to suggest a price based on the P2P market's clearing prices and historical data.
3. Both users input the relevant details (e.g. amount to be sold/bought, asking price). The matching of offers can either be done through an automatic price negotiation or an auction process. The auction process includes bidding from the interested consumers, which is done in 15- or 30-minute intervals. If User A is the highest bidder, they win the auction, and their offering price is set as the clearing price of the particular time interval.
4. Once the offers are matched and approved, the seller (User D) transmits the agreed amount of energy to the grid (S), and the buyer (User A) sends the funds[75] to the Bank (B) which are to be transferred to seller's account.
5. The grid transmits the energy to the buyer and the bank sends the funds to the seller. The grid operator also receives a fee for the transmission costs.
6. Once all transactions have been completed, they are recorded on the blockchain and the platform automatically issues and sends to the relevant recipients the bill with the transaction details.

[75] These funds can either be cryptocurrencies, native tokens of a given platform, or fiat currency. Depending on the case, a third-party intermediary such as a bank might be needed to transact tokens or cryptocurrencies (used to fulfil transactions within the network) with fiat currency.

D. The traditional commodities trading ecosystem

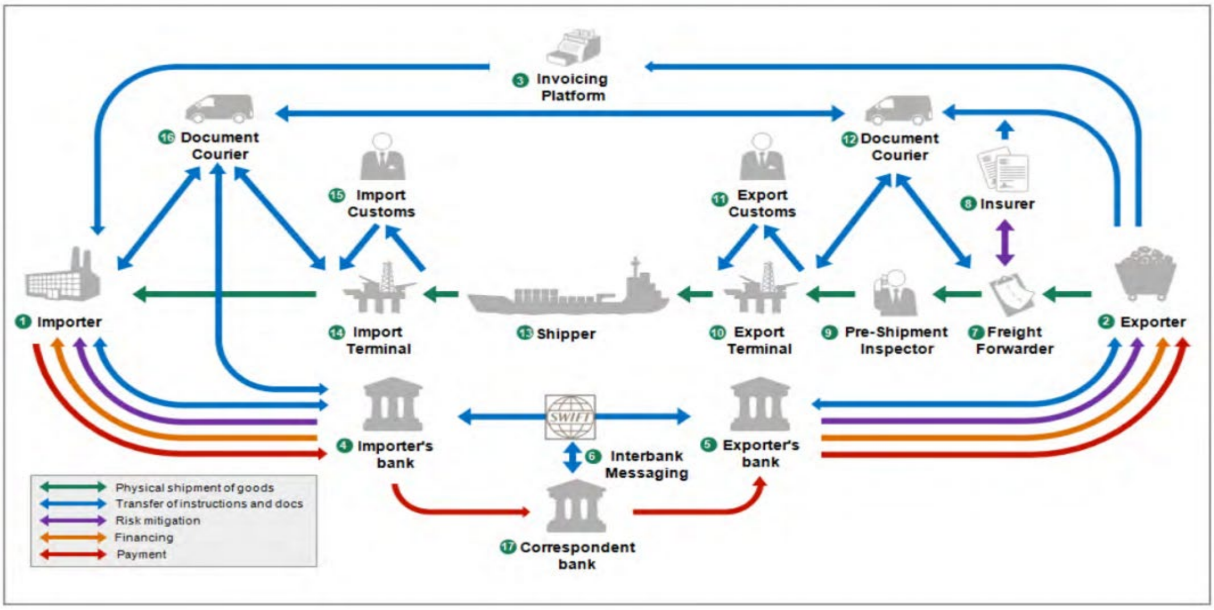

Figure 36: The commodities trading ecosystem (Consensys, 2019b).

1. After the importer has sent the Purchase Order and the two parties have agreed on the contract terms, the exporter issues and send the invoicing documents.
2. The importer then transfers via its bank the funds to the exporter's bank. In the case of international payments, a correspondent bank is required for the transaction between the two banks.
3. After the freight forwarder receives the command for the dispatching of the shipment, the goods are insured by law and quality control takes place.
4. The products are then transported from the exporter's oil and gas terminals to the facilities of the shipper and go through customs before their departure. Booking the shipping of oil and gas products can take between 90 and 120 days.
5. When the products arrive at their destination they again go through customs and then transported to the importer's facilities.