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Blockchain and Internet of Things for Electrical Energy Decentralization: A Review and System Architecture

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October, 2022

TECNOLOGIAS
E ARQUITETURA

Department of Information Science and Technology

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Resumo

A descentralização nas redes elétricas ganhou importância crescente, especialmente nas últimas duas décadas, uma vez que os operadores da rede de transporte (ORT), operadores da rede de distribuição (ORD) e consumidores estão mais conscientes das questões de eficiência energética e sustentabilidade energética. Globalmente, devido à introdução de tecnologias de produção de energia junto dos consumidores, nos setores residencial e industrial, estão a surgir novos cenários de produção de energia descentralizada. Para garantir uma adequada gestão de energia nas redes elétricas, integrando produtores, consumidores e produtores-consumidores, vulgarmente designados por prosumers, é importante adotar sistemas e plataformas inteligentes que permitam fornecer informações sobre consumo e produção de energia em tempo real, bem como para obter o preço de compra e venda de energia. Nesta pesquisa, a literatura é analisada para identificar as soluções adequadas para implementar uma rede elétrica descentralizada baseada em sensores, blockchain e contratos inteligentes, avaliando o estado da arte atual e projetos piloto já em curso. É apresentado um modelo conceptual para um modelo de rede elétrica, com produção de energia renovável, combinando Internet das Coisas (IoT), blockchain e contratos inteligentes.

Palavras-Chave: Indústria 4.0; Internet das Coisas, Internet da Energia, Blockchain, Contratos Inteligentes, Descentralização de Energia, Consumidor-Produtor.

Abstract

Decentralization in electrical power grids has gained increasing importance, especially in the last two decades, since transmission system operators (TSO), distribution system operators (DSO) and consumers are more aware of energy efficiency and energy sustainability issues. Therefore, globally, due to the introduction of energy production technologies near the consumers, in residential and industrial sectors, new scenarios of decentralized energy production (DEP) are emerging. To guarantee an adequate power management in the electrical power grids, incorporating producers, consumers, and producers-consumers, commonly designated as prosumers together, it is important to adopt intelligent systems and platforms that allow the provision of information on energy consumption and production in real time, as well as for obtaining the price for the sale and purchase of energy. In this research the literature is analysed to identify the appropriate solutions to implement a decentralized electrical power grid based on sensors, blockchain and smart contracts, evaluating the current state of the art and pilot projects already in place. A conceptual model for a power grid model is presented, with renewable energy production, combining Internet of Things (IoT), blockchain and smart contracts.

Keywords: Industry 4.0; Internet of Things; Internet of Energy; Blockchain; Smart Contract; Energy Decentralization; Prosumer.

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1 Introduction

1.1 Motivation

It is estimated an increase of electricity consumption 2.1% each year until 2040, increasing the share of electricity in the total energy demand from 19% in 2019 to 24% by 2040 which will lead to need of new energy generation models [1]. These alternative models bring the need to evaluate how current traditional models work and how can be improved.

In traditional markets, energy transactions are carried out through a centralized model with several intermediaries, which corresponds to the old-century architecture of the electrical power grid and is still presented nowadays. However, with the growth of energy consumption and population, there is a need to adopt new models that better respond to the needs of new cities, since the centralized model has higher financing costs and security of supply issues [2]. Decentralized models can achieve an improvement in performance and scalability of approximately 40% when compared to traditional centralized systems [3], and brings less transmission losses and lower load peaks when using solar energy[4]. Distributed and decentralized concepts emerge, as the first one consists in maintaining a central authority but distributing the power generation in a bidirectional way and the second with focus on the promotion and management of the power generation and consumption at a local and private level [5]. Therefore, it is important to analyze how electricity markets work, regulations, actors and to evaluate if there are conditions to promote decentralized renewable energy solutions at a smaller scale.

Electricity markets are complex, with a variety of actors ranging from the production, transportation, distribution, and commercialization of energy. In most countries, it is necessary for a company or organization to establish itself as a trader to be able to sell energy, which in the case of decentralization constitutes a barrier for small prosumers [6] (the term prosumer represents entities or people that both produce and consume energy) [7]. At the European level, the European Commission published the European directives 2018/2201 [8] and 2019/944 [9] in order to foster the implementation of energy communities and promote the adoption of decentralized energy production systems. These directives provide orientations to governments to reduce the bureaucracy and legislation for local energy production. In a recent publication [10] by the Joint Research Center (JRC) Science for Policy Report, related to "Energy Communities: an overview of energy and social innovation", it states in its conclusions that "economic factors such as income levels and the ability to acquire ownership in renewable installations can play a role too. Community renewable energy initiatives are more prevalent in higher-income Northern European countries and less developed in Southern, Central and Eastern Europe", there is a substantial difference in several countries in the implementation of this type of technologies. Another important finding is the need to create conditions for these types of initiatives to compete in equal terms with other market participants, referring that actions and tenders can be simplified and include local community benefits.

One of the advantages of energy decentralization is the fact that increasing the amount of renewable energy sources in the electrical power grid, near the point of energy consumption, makes possible to decrease the environmental problems and reduce energy losses because production and consumption are closer and it is not necessary to use the transmission or distribution electrical power grid for power exchanging [11]. In recent years the number of consumers installing photovoltaic panels for energy production is increasing, mainly due to financial incentives from central governments in the form of feed-in-tariff system with 10 year or more duration. As the contracts established by these systems are ending, the energy selling prices are decreasing, not bringing must advantage to their owners, opting by storage batteries, that are also an expensive option. The solution is to sell the surplus of energy directly to other consumers based on innovative technology information systems that can leverage the gains of those involved [12].

With the need of consumers that produce their own energy and eventually sell the surplus production, it is necessary to ensure that there are technologies at their disposal so that they can do it as quickly and safely as possible. Blockchain technologies have been following this evolution, and several frameworks allow to respond to different types of use in the energy area [13], allowing for system transparency and ensuring secure data transfer, creating records of transactions carried out that can be consulted by the various actors of the process. All this information is based on a constant monitoring system that allows information to be obtained in real time and is thus recorded immutably [14].

Another important aspect to note with the decentralization of energy is the fact that synergies can be created between different types of consumers, who can share infrastructures. An example of this situation is industrial parks, large consumers of energy, which with rising prices seek new strategies and alternatives to the current market. It is possible in this way to create and share networks with the objective of obtaining financial gains [15].

The use of monitoring and power devices connected to the electrical power grid can play an important role in the design of smart grids, as it may enable to adjust supply and demand in real time, thus also adjusting tariffs in the same period. Virtual power plants are one of the possibilities for the interaction with consumers [16]. They allow prosumers to associate virtually, thus ensuring a dynamic and flexible management of available power and resources. This way, by ensuring the grouping of prosumers, it is possible to reduce the load problem in the public electrical power grid with the introduction of these intermittent energy sources in the system. The advantage of virtual power plants is that they interconnect these production units, but at the same time ensure that their ownership and operation remain decentralized. The management of this entire system is carried out through a control mechanism that allows the information to be monitored and visible to each of the actors using data encryption protocols, ensuring the security of the process. In this way, it is possible to use more accurate mechanisms for forecasting energy supply and demand [17].

The possibility of having an entity to support consumers in the management, monitoring and maintenance of their equipment, makes it possible to reduce operation and maintenance costs, derived from the aggregation of services, being part of a larger network. [18]. It is expected by the end of 2022 the value of smart homes market size to be value approximately 50 billion dollars and an annual growth rate of homes switching to smart homes is expected to be 14% [19]. The existence of a growing market for houses with this type of infrastructure, generates a huge amount of data, which must be processed and properly analyzed. Blockchain networks, through its processing capacity, can analyze large amounts of data generated by Internet of Things (IoT) systems and, together with other open-source technologies, can guarantee interoperability between systems. Often referred as Industry 4.0, the merge of cyber-physical systems and IoT with the ability to share information, learn, treat data and make decisions is one of the pillars of the digitization revolution[15]. By integrating these types of systems on a management platform, with more buildings and facilities, it is then possible to formulate an energy market, thus creating properly aligned tariffs. It should be noted that there are questions related to the speed at which the equipment is able to answer, as well as ensuring that consumers do not have privacy concerns, thus enhancing the exchange of information necessary for the entire system to process the information [7].

Decentralization of energy is nothing new, however, the ability to join multiple facilities and have a dynamic network management capability is something that is more difficult to achieve when bringing together such diverse actors and introducing the residential segment. In this research we propose a conceptual model for a decentralized energy production system, bringing together prosumers and consumers, through an energy transaction platform that aggregates blockchain and IoT. The introduction of sensors in a broad way and allowing equipment and systems to be managed dynamically is something innovative.

An article was published in MDPI in 1st of December 2021, with the title “Blockchain and Internet of Things for Electrical Energy Decentralization: A Review and System Architecture” with the reference *Energies* 2021, *14*(23), 8043.

1.2 Energy Production. Current Problem and Status

Decentralization of energy is already a reality. In Portugal, the first renewable energy community came into force in august 2021 in Miranda do Douro, through a project called “100 Aldeias”, and is intended to expand to other villages.

Despite the importance of these first projects, current installations mostly focus on self-consumption of energy and not on trading. An example of this situation is the legislation published in the different member states, based on European directives that have been repeatedly updated, as the markets are centralized and are not prepared to accommodate the intermittence generated by a massive decentralization of energy, nor do they have the flexibility necessary to manage the supply and demand of small prosumers. It is therefore important to look for solutions that can manage in real time an electricity distribution network that brings together producers and consumers, integrating various solutions that can thus absorb any excess energy, as well as contain systems that can, at a given moment, supply possible peaks. of consumption. New information technologies are an important asset, and the digitalization of the electricity grid makes this path the future, so an energy management system that integrates the various aspects is of the utmost importance.

1.3 Objectives

The aim of this research is to identify the current constraints and point out a solution so that the production of energy on a smaller scale can happen in a mass way. For most electricity consumers to participate in the energy transition there is a need to simplify procedures and use innovative technologies to achieve the desired outcomes, reducing human interaction and promoting automated systems. In this research the integration of sensors, internet of things and blockchain is analyzed and a conceptual model is presented using action and design research supported by the revision of literature for the promotion of renewable energy sources, bringing together several small energy producers and consumers, using energy management systems (EMS) and a sensor network, which, together with blockchain technologies, allow the creation of a reliable, safe, fast, flexible and robust decentralized system.

To achieve this objective, the main systems, and processes for the implementation of each of the phases of the model proposed here were analyzed. How can an electricity distribution network be constituted, how the various consumption points can be connected, both from the point of view of electricity connections, as the network, data, and information sharing, how the network should be built? In the end, it is necessary to carry out the transaction between the parties, so an assessment of current technologies is carried out for the execution of transactions of goods in the energy area using smart contracts.

1.4 Document structure

After this introduction, this research is structured into five more chapters.

The second chapter provides theoretical background with the main goal to give to the reader preliminary information about the main concepts of the research.

The third chapter presents the methodology used to perform the PRISMA review and the respective results and analysis, followed by the discussion where a decentralized electrical power grid constituted of prosumers and consumers is analyzed.

The fourth chapter explains the used methodology, followed by the presentation of a proposal for a trading platform with the goal of managing energy transactions in the electrical power grid. In the fifth chapter is proposed a blockchain consensus mechanism that allows the safe exchange of information, as well as the signing of smart contracts that permit formalizing the relationship between the various market players, thus ensuring the transparency of the entire process.

The sixth chapter presents the conclusions regarding the proposed solutions and limitations to the review.

2 State of the Art about Energy Decentralization and Blockchain

To promote energy decentralization, it is necessary to adopt several concepts that, working together, allow the implementation of a system that works as an aggregator of producers and consumers, with well-defined rules and a clear market operation. Local energy production aims to create more flexible and resilient systems with new ways to produce energy from different sources (e.g., solar, wind and biomass), which allow better results for everyone involved, whether through cost reduction or greater environmental sustainability. Despite this recent commitment to decentralization, it remains important that the current participants in the system are an integral part of the new solution, due to the existing complexity, namely the need for electrical power grid connections, so the DSO is an integral part of the process, as well as the energy traders [20].

Blockchain networks allow to support the integrity and transparency of an entire process, ensuring transactions, since to make changes an attacker needs to have the support of a high percentage of the network, which depends on the type of mechanism chosen [21]. Data protection from users is also a concern, because for the system to work it is necessary that users agree on the transfer of data, as well as agree to execute transactions in an automated way [22]. Besides security concerns, blockchain adoption can have many other uses to help in the implementation of a local energy production system. In the following topics we present information about the main concepts that support this review.

2.1 Local Energy Production

Nowadays, industries, small and medium enterprises and citizens rely on the current centralized markets and infrastructures for the provision of energy. All these key actors in the system face challenges related to increased energy costs, protection of energy provision to ensure power supply access and CO_2 emissions. In this sense, it is necessary to assure that the electrical system has the necessary characteristics and conditions to guarantee its robustness and give the necessary confidence to all involved agents. As companies develop, new services emerge, as well as new installations, creating challenges in terms of energy consumption and production. Many consumers, with the development and maturation of new energy production technologies, with considerable increases in system efficiency, became producers to have greater autonomy. These challenges force the system to have greater flexibility to accommodate new consumption and production points. With new energy and IoT technologies, it is possible to tackle these problems and promote the adoption of decentralized systems that can contribute to enhance energy efficiency, since they have the capacity to allow the safe exchange of data and information, ensure the transparency of the process, enabling a broader participation by consumers, thus leading to new possibilities for business models. Due to the distributed nature, with several production points with less installed power, it manages to improve the computational power, as well as reduce the infrastructure costs [23]. Energy decentralization can bring solutions to increased energy demand, resource usage and energy poverty because it allows to create renewable energy communities, introducing social neighborhoods with low-income people, so that any production peaks can be used to bring energy to these homes, thus reducing their energy needs from the electrical power grid [24].

Peer-to-peer (P2P) transactions and decentralized energy production allow everyone who produces energy, for example, through solar photovoltaic systems, to sell their energy to other facilities for use in the proximity, safely, and also promote and adequate relation between supply and demand [25]. This transaction system can be a turning point in the market. However, there are regulatory issues that must be obeyed and that vary according to the country where they are inserted. If there is not a dedicated energy distribution electrical power grid between producer and consumer, it will be necessary to inject into the main distribution electrical power grid, requiring the authorization of the distributor, and a set of legislation procedures. The alternative is also for traders to buy this energy directly and then sell it at "normal" prices in the market; however, the involvement of a third party causes prices to increase [26].

With the increased number of decentralized installations introduced in the systems, intermittency issues arise. The distribution networks currently implemented were designed to supply energy to consumption points, not to receive an eventual excess of production. This paradigm shift causes disruptions in the network that impose additional management costs on the part of the competent entities [22]. It is important to mention that these entities must maintain the balance of the network and for this they may have to overprovision their grid capacity, thus increasing costs. This is why it is so important to have demand/response mitigation strategies and incentives for consumers to adhere to these mechanisms [27]. There is also the need to control power systems because weather conditions affect solar and wind energy production. Based on these conditions the energy produced by photovoltaic units can have a variation, causing in certain conditions an energy production surplus for local grids, specially households [28].

By adding a larger number of installations at the community and neighborhood level, the complexity is increased; however, it also allows the management to be carried out with a greater number of equipment, thus allowing a more complex electrical power grid management. More installations in the electrical power grid have the advantage of reducing losses in the electrical power grid, since production is local and does not need to use the transmission electrical power grid. One of the proposals made to solve some of these problems is to convert the generated energy into a virtual currency, thus allowing the settlement between the various actors [18]. The Ethereum framework, for example, uses the concept of "gas" payments for smart contracts and transactions, where "gas" corresponds to a metric of the computational effort for the operations. The virtual coin used in this case is the Ethereum token ether, and all smart contracts work based on this [24]. One ether corresponded to 2908,88 € according to Coinbase as of 14th of January 2021.

Blockchain can be a powerful tool to help to implement microgrid solutions to provide robust and secure transactions and data exchange between all actors of the process, in order to promote energy decentralization [29]. Table 1 presents the main differences between the centralized trading approach used with energy companies and the proposed peer-to-peer trading approach [26].

Table 1 – Differences between centralized and decentralized trading.

Description	Centralized trading	Decentralized trading
Regulator [30]	Centralized regulator (one entity) with common rules.	Possible to implement specific regulations for an energy renewable community, defined by the members.
Energy Distribution [31]	Centralized, managed by one entity.	Possible to decentralize, building an internal distribution electrical power grid, maintained by the entity that manages de community.
Primary Energy Supplier [26]	Large scale generators.	Prosumers with renewable energy systems.
Trading [26]	Central markets, fixed price tariffs.	Bidding prices or prices according to usage factor. Pay as clear markets.
Contract type [32]	General contract for low voltage clients based on legislation. National	Standardized smart contract with rules defined

Description	Centralized trading	Decentralized trading
	regulators provide standard contractual clauses that must be complied with by all suppliers.	by the entity that manages the community.
Management [33]	Third party, smart meter. Operations are carried out by network, transmission, and distribution operators.	Smart meter & smart contract, energy management system. All this information is stored on the network for all actors to analyze.
Policy and network changes [26]	Policy maker, national action plans, legislation.	Consensus of network participants.

2.2 Blockchain Technology

The concept of blockchain was introduced back in 2009 with Bitcoin [34]. It is a chain of transactions stored in a distributed ledger in a chronological order and each block as a link to the previous block having registered certain type of information. Each block has a header and a body. The header contains the version number, the hash value of the previous block, Merkle root and time stamp. The body contains the information of the transaction, important data [2]. This structure allows blockchain to retain some of its most important characteristics and suitable for energy trading.

Blockchain technologies bring several advantages regarding the energy sector, allowing trading and energy exchange between energy producers and consumers without the control of a central entity [35]. Blockchain can be used for: management; trading; security; transparency; awareness; communication; and certification.

For management purposes, the invoice and billing system using smart meters and smart contracts makes possible to settle accounts and invoices automatically for consumers and distributed generators. For trading, market management is an important point, since distributors and traders need to carry out their energy consumption forecasts. With blockchain, together with other technologies, it is possible to make an intelligent management of it. Improved data transfer using smart devices makes possible, through data transmission, to cross information. Note that these technologies are also being used to improve automatic connections, allowing control systems and networks to correct tariffs in real time, promoting P2P transactions, helping consumers to generate and sell their energy without the need to have energy storage [25].

For trading using smart contracts there are contractual transaction protocols based on programming languages suited for each usage domain that are automatically executed when all parties provide the required data. Using protocols and user interfaces, these contracts must comply with legal procedures, all data must be securely stored and available for consultation during the execution period, and all contracts must be fully recorded for future verification. The smart contract itself must also be able to prevent security breaches and external interactions if possible, as well as control data accessibility for all parties involved on a contract [36]. To promote the trading between peers and allow the tracing and tracking of transactions the concept of token was introduced. There are several types of tokens depending on its use and can be categorized in three main types: payment tokens; security or asset tokens and finally utility tokens. Payment tokens are used for payments and corresponds to an asset in the form of digital currency. Security tokens are equities, bonds and represent real assets. Utility tokens are used to give users voting permissions, rewards and governance for their stakes. There is a fourth category the yield token that can be used as a reward token in the Proof of Stake consensus mechanism. Tokens can also be fungible and non-fungible, according to the capacity to hold data. NFT are used for blockchain trading, for example the amount of energy that is traded and they have information about the data from smart meters. Fungible tokens correspond to cryptocurrency such as Bitcoin. The advantages of using these different types of tokens is to guarantee traceability [37].

For security and transparency purposes, ensuring safety transactions using programming verification techniques, guaranteeing the confidentiality of data, user and transparency with standardized processes that cannot be changed during time [18]. Other important aspect is related with commercial data and sensitive information from prosumers, such as coefficients of local generation and related information that can lead to a price reduction [38]. Blockchain networks can be permissionless or need a permission for the participation, and that can influence the type of usage and the type of participation from the different actors. In a sector such as energy, networks with permission are the most suitable to ensure the adequate level of security [39]. Several cryptography and privacy models and techniques have been developed.

To add value for consumers, advertising and communication with customers is made in a direct way, almost individually, according with their preferences, using for that purpose the information collected through energy management systems. Improved sharing of resources supported by the electrical power grid management, makes possible to offer other services, such as energy storage, as well as charging stations for electric vehicles, because currently most projects located for power generation must ensure consumption at the same time as production, due to the lack of storage. The blockchain network can thus contribute to the management of the electrical power grid , helping to minimize the intermittency generated by the introduction of renewable energy into the electrical power grid [40]. Increased competition with smart contracts that can streamline the process of changing energy suppliers, which allows for a reduction in energy tariffs [41].

One of the advantages of blockchain is the fact that it is able to certify the origin of the energy produced, thus being important for green certificates and to assure consumers that the energy they are purchasing is actually from renewable energies, something very important in social terms, so it has this most advantageous benefit as well [42].

For the process of blockchain there is a need to select a consensus mechanism. Several mechanisms are available and have positive and negative aspects as stated in Table 2.

Table 2 - Comparison between consensus mechanisms

Consensus Mechanism	Brief Description	Positive	Negative	Type of blockchain
Byzantine Fault Tolerance(BFT/PBFT/RBFT)[43]–[50]	Introduced to reduce the existence of malicious nodes. All participants are accepted by the network owner.	• Used for high computational power • Reduced energy consumption • Larger scalability • Low transactions fees	• Need permission of the owner of the network to participate • Adapted for more small networks	Private/Permissioned
Proof-of-Authority (POA)[51]–[53]	Select several users to have enough authority to validate transactions. It relies on	• Lower need for computational power • Reduced resources and less energy needed	• Reduced number of actors with higher power to approve transactions. • Lack of trust between peers	Private and consortium/Permissioned

Consensus Mechanism	Brief Description	Positive	Negative	Type of blockchain
	reputation consensus	• Suitable for constrained hardware • Low processing fees	can lead to conflicts and therefore can stop transactions.	
Proof-of-Credit (PoC)[23]	Like proof of stake but uses a master node and the credit is a special type of stake.	• Low energy consumption • No competition between miners •	• High initial investment for new miners	Consortium, Private
Proof-of-Stake (PoS)[5], [20], [43]–[45], [54]–[59]	New blocks of transactions are added to the ledger by users based on their stake using specific algorithms. Users receive a compensation with each block.	• Low energy consumption • No competition between miners • No central authority • A node need more than 2/3 of the network to be able to make changes on previous transactions	• High initial investment for new miners	Public, Consortium
Proof-of-Work (PoW)[11], [43], [60]	New blocks of transactions are added to the ledger by miners with high computational power. Users win rewards with each new block.	• High adoption rate	• High energy consumption • Depend on users computational power • Miners with more computational power more often are rewarded thus reducing the control on a small group. • Competition between miners • Lack of trust between users	Public

In complement with the consensus mechanisms described in the previous table, there are other mechanisms available, but with less expression such as Proof of Capacity, similar to the Proof of Stake, but with implications related to the database storage as the validator nodes must commit space in order to make a new block [28] and Proof of Benefit also related to the Ethereum platform [59]. There are other consensus mechanism like Federated Byzantine Agreement (FBA), Proof of Activity (PoAc), Proof of Burn (PoB) and Proof of Elapsed Time (PoET). The main used consensus mechanisms are Proof of Stake through Ethereum network and Practical Byzantine Fault Tolerance through Hyperledger Fabric.

2.3 Internet of Things

To implement a decentralized energy system, it is important to ensure that an adequate data exchange process is in place, because of the need to have real time information about energy consumption and production. This need requires the deployment of the "smart home" concept, supported by IoT technologies, with the introduction of sensors, smart devices and communication protocols that builds the foundation of P2P transactions, allowing consumers to trade energy with safety. According to the world economic forum, digitalization in the energy sector could value more than 1.5 trillion of dollars by the year of 2025 [57]. Currently consumers have at their disposal innovative technology that allow to know with detail energy consumption, appliances consumption in a certain time [61]. Therefore, in the context of the model proposed in this research, IoT provides local sensing to account for energy transactions without central supervision.

The growing interest on IoT technologies extends into several application areas [62]. For example, industrial IoT is considered to be the core of ubiquitous digitization, integrating different type of sensors such as smart meters and other hardware, in order to enable information systems to present information in real time with energy profiles to support management in decision making process related to intensive consumption equipment [15].

Although there are multiple IoT architecture proposals [63], a basic IoT architecture can be divided in three layers: Objects, Network, and Application. The Objects layer collects data from the physical world using sensors that are integrated in electronic devices called sensor nodes. These devices include other components [64] that are essential for the node operation, such as a processing unit, a communication transceiver, and a power source. Some devices may also act on the physical world using actuators. The Network layer connects the Objects layer to the Application layer, being normally composed of several types of communication networks, which form the data communication infrastructure used by the different entities of the IoT. This layer also handles other IoT tasks, such as data storage and cloud computing. The Application layer provides specific services for the users based on the data collected by the Objects layer, such as automation of processes, using of data mining and control algorithms, and user interface through IoT clients.

It is important to mention that the integration of equipment with sensors requires that consumers have to deal with additional technology, applications that require the collection of data and the additional interpretation of information [65]. The IoT is constantly growing, allowing to exchange huge amounts of information daily, which also raises issues related to information privacy. Blockchain can be a complementary technology to guarantee these situations, and improve the behavior in terms of storage and security [53].

Smart meters are important devices in this system, as stated in Figure 1,where it is possible to see consumers and prosumers with these devices.

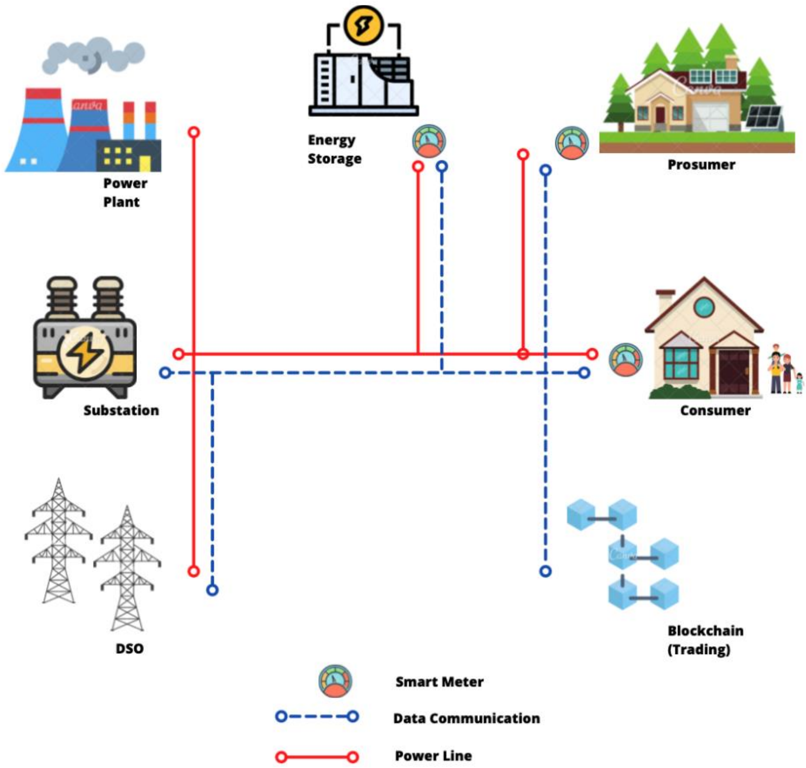

Figure 1 – Energy trading system concept.

With smart meters, it is possible to have information about energy consumption and production within short time intervals (e.g., 15 minutes). This is important data for trading platforms. All data is encrypted and placed in the blockchain for smart contract purposes [20].

Another rising concept is the Internet of Energy (IoE) with the objective to integrate all products and equipment related to energy and need to have a safe and reliable method to exchange data and information such as smart grids, energy production systems, electric vehicles charging stations, smart storage and other relevant parts of the system, allowing the possibility to make real time decisions in a controlled environment [19]. With the amount of data to be processed and analyzed, it is important to have fast networks that allow sending information and obtaining large datasets. Currently many countries have already adopted or are adopting 5G networks, which allow bringing flexibility and speed of these networks to make it possible to adopt the concepts of fog and edge computing, bringing the important capabilities of net computing closer to the places where information is consumed [1].

This new concept also brings the need to store data and introduce cloud infrastructures to have a backup of information. The use of cloud computing allows the distribution of effort between different resources with the increase of performance to other tasks, such as smart contracts and therefore enhanced transactions. In case of failure, the existence of cloud services keeps data available to other members of the platform [61].

2.4 Related Work

The various areas of blockchain usage have already been explored in some way in previous studies, with application cases. In the revised literature it was possible to identify some projects that intend to implement models to promote energy decentralization. Some platforms that have already been developed, such as PONTON Gridchain and Enerchain, are used for electrical power grid management and energy P2P direct trading. Electron is an Ethereum based platform that allows real-time switching of energy suppliers and provides P2P trading. SolarCoin rewards prosumers per each MWh generated. Energo focuses on machine-machine connections and the possibility of making transactions between them, as is the case with electric vehicles and charging stations that can interact with each other, thus making transactions through a digital wallet.

B.S. Lee et al, proposes a platform based on Ethereum for the creation of a relationship between consumers and prosumers through smart contracts [66]. A scheme with energy routers is also being implemented, where in each microgrid there is an energy router that is a node of blockchain which is operated by the blockchain-based multi-factor electricity transaction match mechanism. In this scheme, a set of transactions, records, and fund settlement are recorded. It includes a node application module, an electricity transaction acquisition module, a blockchain nodes module and a smart contract module [30]. A double chained model of blockchain can be implemented to facilitate and expedite transactions between prosumer and consumers and establish smart contracts and then form coalitions for negotiation and energy exchange [7].

A cooperative approach for P2P transactions and improved privacy concerns in a secure environment is also possible. Cooperatives may have energy to sell but selling energy to energy companies is currently not profitable due to the low prices they practice for local producers. A P2P approach between cooperatives is proposed in [6]. An example of possible parties involved in a cooperative P2P approach are solar PV panels, smart appliances, smart HVAC systems, electric vehicles, energy storage systems and smart meters that can measure the energy and share data in a bidirectional way, where DSO can obtain information from the equipment and send information, e.g., to change the type of electricity tariff. Once each of the elements has an identification, it is possible through blockchain technology to identify the energy consumed and produced by each of the systems and distribute energy between them, that is, when equipment are able to consume, energy is distributed to them and when surplus exists it is stored [18].

Ali et al. present a system to group prosumers using blockchain to manage the possibility of scaling the infrastructure and the respective decentralization in a P2P trading scheme [16]. It proposes a scheme called SynergyChain to promote the scalability of the solution, as well as the decentralization of the prosumer grouping mechanism in the P2P context. It includes a learning module that improves the system's adaptability [3]. A financial platform to facilitate investments in renewable energy sources based on the Ethereum blockchain is also a solution. It implements a P2P Marketplace, based on price, thus bringing together investors and prosumers. The traded energy and its value are represented by “tokens”, which are exchanged between participants automatically through pre-established conditions in smart contracts [67].

Another proposed system, called ETSE and developed under the PETRAS BlockIT project, facilitates the energy transaction between prosumers. Management is carried out through smart contracts in a blockchain network associated with smart meters. The system analyzes the various types of attacks that can then be promoted, bearing in mind the prevention of attacks [21].

Pradhan et al, present a system based on an on-chain and off-chain permissioned ascription (FPA) system over Hyperledger Besu that includes Istanbul byzantine fault tolerant (IBFT) 2.0 consensus algorithm for smart contracts. It includes a development of a working prototype for a P2P energy trading system [39].

Yahaya et al, propose a system to trade energy based on blockchain for 5G smart communities, and the system is divided in two main areas, residential consumers, and electric vehicles. A reputation-based algorithm and a reward-based system were developed. Using MLR, a forecasting system is used to better manage electric vehicles intermittent charging behavior and is justified to have 99.25% of accuracy in its pattern. Security and privacy are also analyzed to protect data of users and avoid vulnerability attacks [19].

A proposal for energy transactions between different companies and installations in ECO-Industrial Parks is also presented, using a peer-to-peer scheme to promote automated negotiations. Based on different needs from the various agents, a process that uses internet of things and blockchain is the foundation of an energy trading system. A prototype of a platform was developed, dApp, and enables smart contracts to be performed based on several conditions [15].

The economic value of these innovative energy trading systems is one the main reasons for the recent developments of studies in the energy sector. A proposal to evaluate the merit of P2P transactions for households is developed and presented based on two different optimization models and also consider the merit of these transactions to utility companies based on the rationale of reducing installed capacity and power fluctuation [12].

In some proposals the contribution of TSO and DSO are relevant to deal with the intermittences of renewable energies and developed a flexible system to manage the energy flow in the networks. Using an on-line platform joining prosumers and the previous identified actors, based on blockchain and smart contracts, is possible to improve the efficiency of transactions and deal with an increased amount of renewable energies in the network [68].

A market clearing mechanism is fundamental for the correct balance of the grid. Mehdinejad et al, propose a market clearing scheme to assure the transactions between agents without their private information. It is based on an energy token market and a primal-dual-subgradient method developed for decentralized markets with demand response mechanisms and also demurrage [38].

Cao et al., developed a blockchain assisted software defined energy internet to create a decentralized ledger based on Practical Byzantine Fault Tolerance (PBFT) consensus mechanism. Is targeted for industrial energy market that are dealing with the rise of energy prices and to overcome the credit crisis. Decentralized energy is enhanced by blockchain and distributed energy market smart contracts [4].

FederatedGrids is a tool to predict future energy production and demand to allow a dynamic market to trade and share energy, allowing prosumers to have more information for their decision making process [69].

A constrained hardware device uses software to promote energy trading, to execute smart contracts and store information in a cloud infrastructure in case of failure. A distributed system receive data from TSO and energy markets, in this case from Spain. This allow to have the prices of energy sold in the markets before performing smart contracts to guarantee that the prices in the blockchain are not higher. The trade of energy happens only after a set of pre-validated steps are executed [61].

Xu et al, propose two different algorithms to charge electric vehicles and to publish dispatch tasks. These two models are based on consumers behavior and electric vehicles charging standards [51].

Developed a PoS public blockchain to manage a microgrid and promote a decentralized P2P energy trading market. Miners of the blockchain to reduce the effort for mining new blocks accept to lose part of their stake to compensate power losses. The scheme tries to bridge the price gap between producers and consumers. Using a test case scenario with 27 prosumers prove the adequation of the model[43]. Yang et al. proposes a similar approach with an energy trading model with a proof of stake consortium network where pre-selected miners must compensate power losses. A new cryptocurrency is created “elecoin” and is used to reward miners [54].

An implementation of a P2P energy trading scheme based on Ethereum blockchain is introduced. Based on dynamic pricing and on demand-offer adjustment, prosumers and consumers can trade energy within a microgrid [55].

Using prospect theory and adaptive learning Yao et al. propose a distributed trading strategy to allow trading between market actors. Smart contracts are used to fast deploy matching according to previous set conditions and prosumers conditions such as comfort requirements, price responsiveness and transmission distance. Uses Remix Ethereum platform to deploy the network [31].

Based on the proof of credit consensus mechanism a consortium blockchain is the used framework for energy trading to adapt user behavior. Two level hierarchical incentive mechanism is deployed. The fist level a pricing scheme built on Shapley value and PoC consensus for market actors motivation and the second level is used and energy analysis algorithm to evaluate fluctuation of net load [23].

Use of blockchain and auction mechanisms to promote P2P energy trading in microgrids. Two different frameworks are proposed based on Ethereum with double auction and uniform price double sided auction mechanism. Several test are conducted to evaluate the added value of the proposals and illustrates that the current proposal are and added value to the actual model [5].

Gamification is one of the main topics used to enhance energy trading between peers. Tsao et al. propose a microgrid based on two players: a DSO and a prosumer. The DSO is the key element that indicates the electricity price and blockchain investment. The prosumer determines the amount of electricity to be generated. The objective is maximized gains for each market actor using also bank credit and smart contracts to operate. Using blockchain the prosumer have information to decide if should generate energy to the grid or not comparing advantages and disadvantages of each model [70].

Lucas et al. developed a framework for demand response to leverage the implementation of renewable energies in the grid. Using Blockchain and Hyperledger Fabric framework, developed a proof of concept using a laboratory environment to test the viability of the proposal. To promote the flexibility of the system a storage system is used to inbound and outbound of energy [46].

Pop et al. presents a flexible system of demand response using blockchain and smart contracts. Prosumers are the main actors as they validate information on the blockchain in order to keep their information private but knowing the information on the private grid at the same time because data is shared without private information [59].

3 Literature Review and identification of main key concepts for energy production decentralization

Using a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology, it was possible to select the articles to answer the problem raised by this research. The methodology used is based on Moher et al [71]. To guide the research, the key question was identified: "Can innovative blockchain technologies help prosumers on energy decentralization?". Five databases were used to search for available articles written in English, as presented in Table 4.

The selection of articles was conducted based on full text and abstract of the study. To search the articles we developed a query using our key question and was based on three keywords (Table 3): "Blockchain", to identify main technologies in this field; "Smart Contracts", to analyze main developments for trading on energy decentralization; and, finally, "Prosumers", to identify the articles related to this concept, that is, consumers that area also producers of energy. These keywords were selected because the aim of this research is to analyze the different processes proposed in the literature that allow energy consumers/producers to make their energy available to other owners, using blockchain technology. Journal articles and conference papers were considered to obtain the main recent contributions related to our search. Duplicates were removed from the inquiry.

Additional studies were identified though backward and forward search identifying best practices and examples based on the reference of references and on relevant legislation at European level to better understand the path proposed by policy makers. Five additional articles were identified, one study developed by the European Commission and two relevant European directives are included in this research, for a total of fifty-nine references. Three researchers performed the screening process independently—every research was screened by two of the researchers, and in case of disagreement a third one would decide. Figure 2 provides a summary of the different steps of the review.

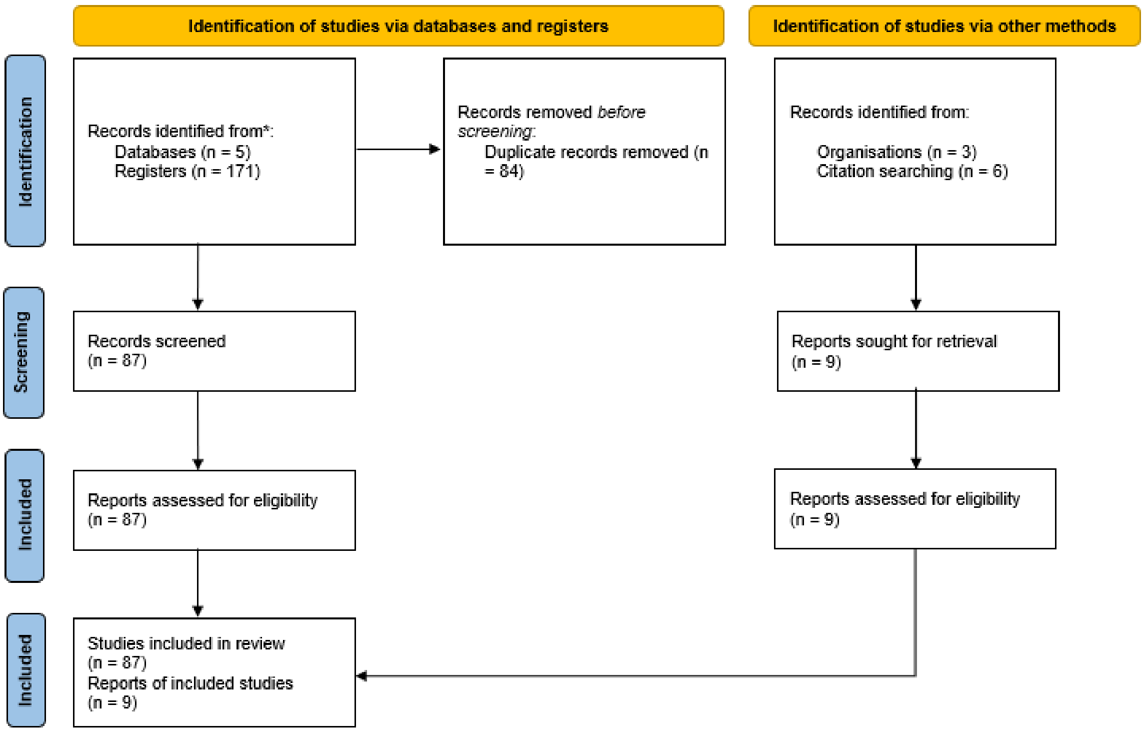

Figure 2 - Preferred reporting items for systematic reviews and meta-analysis (PRISMA) stages.

3.1 Identification of the Needs for a Review

In most energy markets, they start with a central entity, then follow a flow of actors that ends at the final energy consumer. With the introduction of information and technology mechanisms properly adapted to the electrical power grid, it was possible to introduce renewable energy sources into the energy mix, thus creating paradigm shifts in the markets. As the power production from these forms of energy are intermittent, it is necessary to design the electrical power grid to accommodate these changes and maintain security of supply that allow a correct dimensioning of the electrical power grid by guaranteeing the supply of energy through natural gas plants in operation or safeguarding the storage of energy produced at times of lower peak consumption. These changes thus open the door to prosumers that produce and consume energy; however, there is a needed for reliable systems that allow supply and demand to be adjusted in these cases, where trading platforms based on smart contracts can play a major role [72].

In this research we analyze the literature aiming the proposal of an integrated system of prosumers and trading platforms, properly adjusted with the electrical power grid operator, since it is necessary to ensure the supply of energy through the public electrical power grid, to guarantee the supply.

3.2 Objective of the Review and Review Protocol

The objective of this PRISMA literature review is to define the best model for a P2P energy trading system using an innovative blockchain approach based on IoT sensor devices that will enable smart contracts. The main steps of the review protocol are identifying the keywords, identifying the main databases, and applying filters to obtain the final articles for the review. In Table 3 a list of used keywords to identify the articles for review is presented.

Table 3 - List of keywords.

ID	Keywords
1	"Blockchain" AND "Smart Contracts" AND "Prosumers"

Five databases were used and are presented in Table 4.

Table 4 - List of used databases.

ID	Database
1	Scopus
2	IEEExplore
3	Ebscohost
4	Science Direct
5	MDPI

A set of quantitative filters were applied based on the previous keywords and databases and are displayed in Table 5.

Table 5 - Quantitative filters.

Inclusion	Exclusion
Full Text	Not in Full Text
Abstract	Not in Abstract
Articles in English	Not in English
Journals and Conference Proceedings	Not in Journals and Conference Proceedings
Not Duplicates	Duplicates

3.3 Results and Data Extraction

After the application of the filter of the review protocol and removal of duplicates, a total of 87 articles were obtained, as shown in Table 6.

Table 6 - Resulting articles after filter application.

<table>
<tr><th rowspan="2">Database</th><th colspan="5">Filters</th></tr>
<tr><th>Full Text</th><th>Abstract</th><th>English</th><th>Journals/ Conferences</th><th>Duplicates</th></tr>
<tr><td>Scopus</td><td>358</td><td>78</td><td>73</td><td>70</td><td rowspan="5">84</td></tr>
<tr><td>IEEExplore</td><td>540</td><td>54</td><td>54</td><td>49</td></tr>
<tr><td>Ebscohost</td><td>244</td><td>47</td><td>26</td><td>26</td></tr>
<tr><td>Science Direct</td><td>273</td><td>17</td><td>17</td><td>12</td></tr>
<tr><td>MDPI</td><td>80</td><td>15</td><td>15</td><td>14</td></tr>
<tr><td>Total</td><td colspan="4">171</td><td>87</td></tr>
</table>

With the data that was extracted from the different databases, it was possible to evaluate the years, citations, and journal and conference rankings of each article. There was an almost equal distribution of papers from conference proceedings and articles from journals (57% journals). The h-index for the journals has a mean value of 130 points, based on Scimago. Most articles are very recent (from 2020), as shown in Figure 3, followed by 2019 and 2022, which shows the recent nature of the topic.

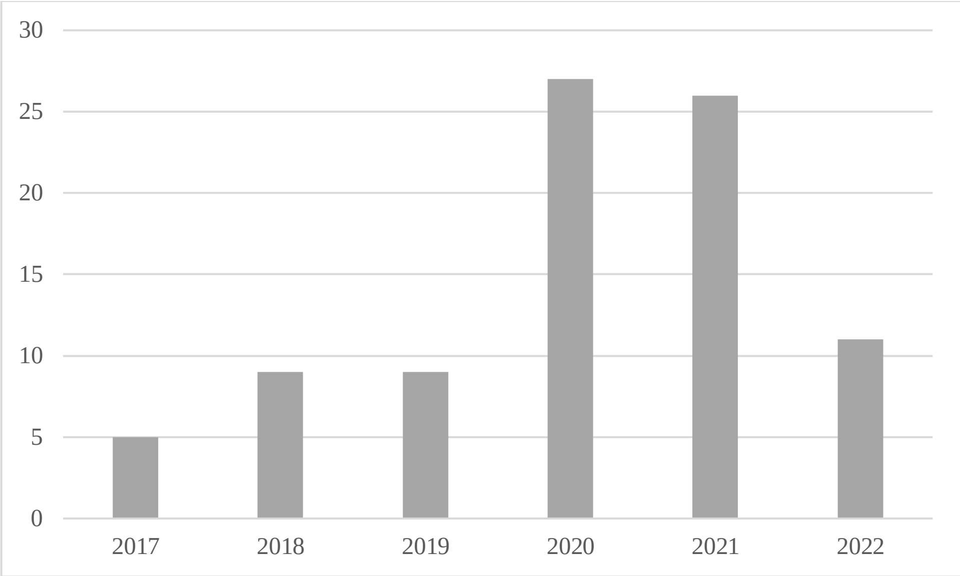

Figure 3 – Distribution of resulting articles by year.

An evaluation of the relations between main keywords was made to evaluate the connection between articles and is presented in Figure 4. It illustrates that blockchain, prosumer and smart contract are the more referred keywords and have interconnections with other relevant areas.

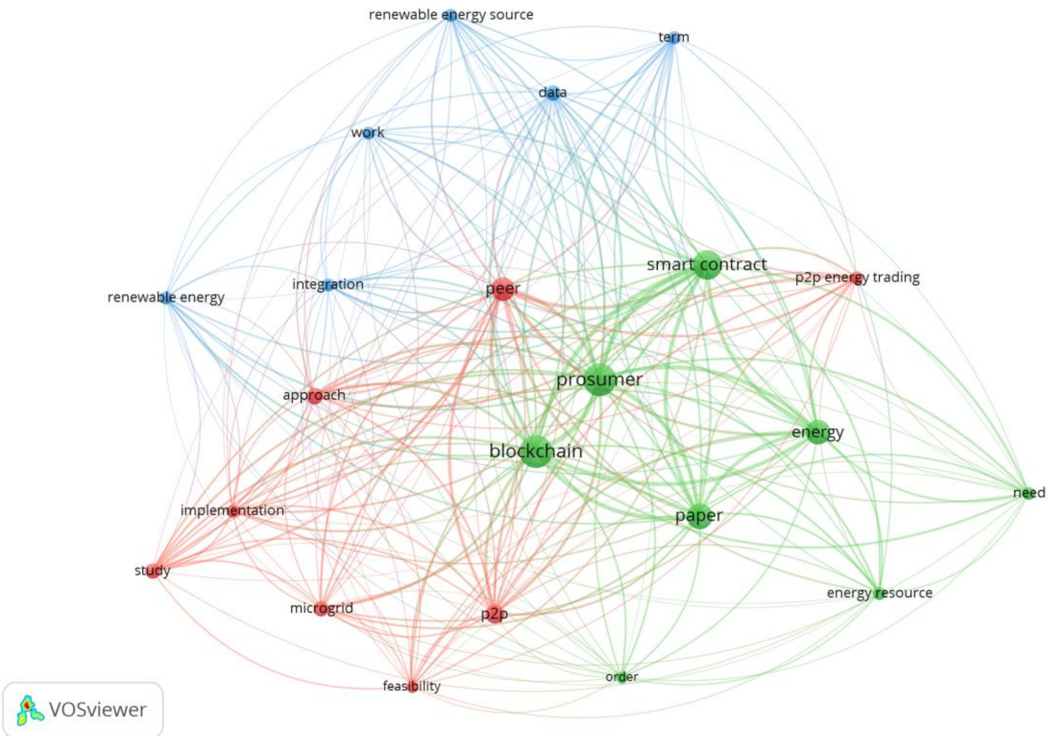

Figure 4 - Network visualization

3.4 Literature Review Analysis

The revision of the different articles was made reviewing abstract and conclusion first, and the full text after. With the analysis of these articles, it was possible to identify five different concepts that must be a part of a decentralized system, including energy production and consumption, data exchange, trading and formalization of contracts. Table 7 classifies the articles according to the adoption of each concept for microgrid and decentralization implementation and it is possible to verify that the majority or articles focus on trading and smart contracts design.

Table 7 - Classification of the reviewed articles according to energy decentralization concepts.

Articles	**Energy Decentralization Concepts**				
	Grid Architecture	Smart Devices and IoT	Trading Platform	Blockchain Technology	Smart Contract Design
[1]	•	•	•	•	•
[2]			•	•	•
[3]		•	•	•	•
[4]			•	•	•
[5]	•	•	•	•	•
[6]			•	•	•
[7]	•	•	•	•	•
[11]		•	•	•	•
[12]			•	•	
[13]		•	•	•	•
[14]			•	•	•
[15]	•	•	•	•	•
[16]		•	•	•	•
[17]	•	•	•	•	•
[18]	•	•	•	•	•
[19]		•	•	•	•
[20]	•	•	•	•	•
[21]			•	•	•
[22]			•	•	
[23]	•	•	•	•	•
[24]	•	•	•	•	•
[25]	•		•	•	•
[26]	•	•	•	•	•
[27]			•	•	•
[28]	•	•	•	•	•
[29]	•	•	•	•	•
[30]			•	•	•
[31]			•	•	•
[32]	•	•	•	•	•
[33]			•	•	•
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[35]			•	•	•
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[61]		•	•	•	•
[67]			•	•	•
[68]	•		•		
[69]			•	•	•
[70]			•	•	•
[72]	•	•	•	•	•
[73]	•	•	•	•	•
[74]	•	•	•	•	•
[75]	•	•	•	•	•
[76]	•		•	•	•
[77]	•	•	•	•	
[78]			•	•	•
[79]			•	•	•
[80]			•	•	•
[81]			•	•	
[82]	•		•	•	•
[83]		•		•	
[84]			•	•	•
[85]			•		•

Articles	Energy Decentralization Concepts				
	Grid Architecture	Smart Devices and IoT	Trading Platform	Blockchain Technology	Smart Contract Design
[86]			•	•	•
[87]			•		
[88]	•		•	•	•
[89]				•	•
[90]			•	•	•
[91]			•	•	•
[92]			•	•	•
[93]			•	•	•
[94]			•	•	•
[95]			•	•	•
[96]			•	•	•

On Table 8 we describe these five concepts in terms of type of energy decentralization adoption. All the concepts must be a part of the energy decentralization network to ensure the correct functioning of the system and to unsure transparency and security of all the process. Grid Architecture, refers to the design and constitution of the distribution power gird between the various market actors; Smart Devices and IoT, describe the implementation scheme and description of used solutions and details of equipment, sensors, systems, smart meters; Trading Platform – Description of the solution, architecture and scheme, implementation proposal; Blockchain Technology have the details of technologies, solutions, consensus mechanisms, proposal of implementation; Smart Contract Design presents the solution proposal, details of used code, relationship between actors and entities.

Table 8 – Energy decentralization adoption.

Concepts	Type of Adoption
Grid Architecture	To provide the connections between producers, consumers, DSO and suppliers. Renewable energy systems, energy storage, electric vehicle can be part of a decentralized system that may help to manage energy grids. A properly dimensioned and designed electrical power grid allows for adequate management and for the best adjustment of demand and supply, bringing together various elements of the infrastructure, charging points, storage, and energy production system. To accommodate energy surplus from prosumers in case of need.
Smart Devices and IoT	Solutions such as smart metering, real-time monitoring, asset tracking and management. Demand-response management is extremely important for the success of the implemented solution. Predictive models are used to help match offer and demand. Smart meters need to be tamper-proof devices.
Trading Platform	Allows to make a match between offer and demand at the bet pricing offer. Users can use the system to have personalized advice and control energy tariffs. Implementation of a forward market by allowing a flexible management of the grid.
Blockchain Technology	Used to improve transparency of the process and provide a consensus mechanism. Added privacy and protection mechanisms to ensure users ID and immutability of transactions. Information can be stored in a chronologically order and all blocks are duly protected with cryptography. Implementation of a distributed ledger.

Concepts	**Type of Adoption**
	Blockchain networks can be Public, Consortium or Private. Can use on-chain and off-chain conditions to validate transactions.
Smart Contract Design	Smart contract design solves an economic dispatch problem of distributed energy resource to reach a consensus between producers and consumers and provide the best offer for each part.

4 Methodology to develop a new conceptual model for energy production

It is intended to evaluate how to implement a new energy production model, which allows leveraging the decentralization of energy, with greater confidence on the part of energy consumers and lead them to produce energy. For that purpose, we used action and design research methodology, which allows us to analyze literature, evaluate current applications and thus propose new solutions and opportunities in this area.

Table 9 – Action and design research framework

Action	Research	Design
Problem Centralized model ▼ **New Solution** Decentralized model	**Question** How to decentralize energy production? ▼ **Answer** Using Blockchain and IoT	**Old Model** Centralized architecture (Regulated) ▼ **New Model** Decentralized architecture proposal (Self-Regulated)

Starting from what is the centralized model of energy production, currently implemented in most national electrical systems in European countries, it is intended to analyze how the growing need for energy by the various types of consumers, residential and others, can influence energy prices. Thus, and analyzing the current way of functioning current systems, it is important to verify how it is possible to bring citizens and companies to the market, producing their energy with the aim of reducing their energy bill and promoting greater energy independence. To this end, a comparative analysis is carried out between the two types of systems, centralized and decentralized, to identify current gaps and understand how local energy production can contribute positively to the sector.

Through a literature review, the main current constraints for the integration of decentralized production in the network are then identified, as well as the problems that prevent consumers and producers from participating more actively in the system. Starting from this base, several hypotheses for the functioning of a micro-production grid of electricity are then identified, with an integration of the various agents and forms of consumption, which include, for example, electric vehicles. By adding to this energy network, the current functionalities of online networks, with the capacity to send and process large amounts of data, it is possible to create an integrated system in which it is possible to easily know how much energy was produced by a given installation.

The challenge is therefore to combine the various micro production networks with the public service network and provide the self-consumption management entities with tools that allow them to manage this process in an agile way. Currently there are numerous tools that can be used to work together and, in this way, allow prosumers to sell their energy, ensuring a correct link between demand and supply. Most of the literature addresses the developments related to blockchain and the way in which it allows to keep records of all transactions that are carried out, thus creating an immutability that allows traceability. These records are added to blocks using different consensus mechanisms, with different ways of working, which can then be consulted. In this research we analyze these various consensus mechanisms and perform a comparison to validate the most suitable for a given network design. In addition to registering transactions, we must define the rules for this to happen. These rules are defined through smart contracts that are triggered when certain conditions are met. Also, for the execution of these contracts there are numerous solutions that can be adopted. It is therefore important to select a suitable design and contract creation considering the chosen system. We also analyze the contracts considering the technology and consensus mechanism chosen.

We then analyze a centralized network and a decentralized network, we have a way of measuring consumption and production, and we also have a mechanism that allows us to carry out and record transactions. But what we want is to have a mechanism with some flexibility in the network, a mechanism that allows us to manage this flexibility. It is here that we bring an innovation compared to the existing systems and those proposed in the literature, in which the proposed regime is practically fixed, without forecasts and without flexible management. In this sense, we introduced the internet of things, which together with new generation networks allow the sharing of energy production and consumption in real time, making forecasts for a certain period and, if necessary, activating equipment to guarantee an adequate connection between supply and demand.

In Figure 5 a hyporesearch is presented based on literature. What we are going to analyze in the research is how these different constituent elements of the network can be built, what is the ideal process to answer the main question, if it is possible to promote energy decentralization, through energy production in small networks, using innovative technologies that promote consumer confidence.

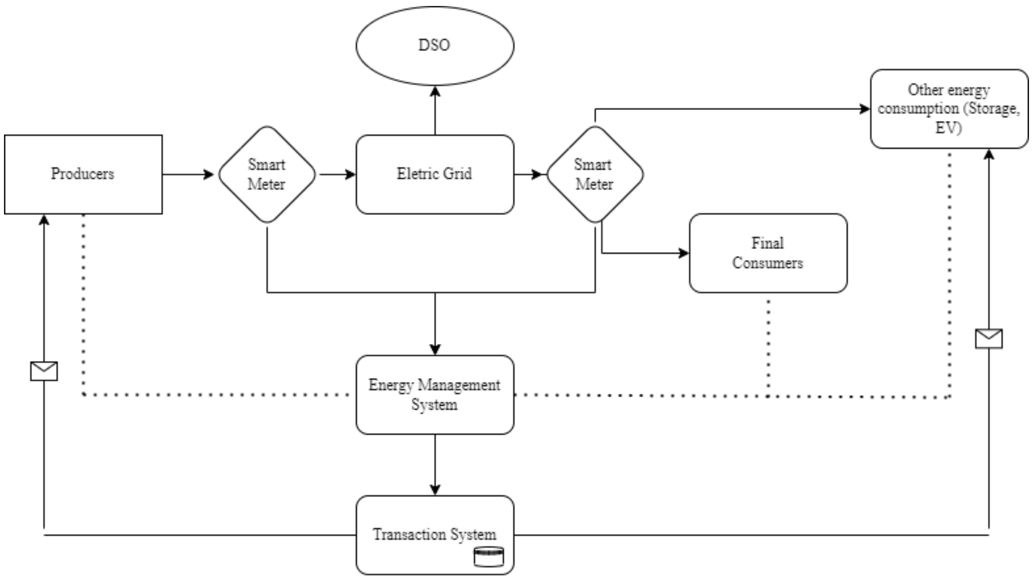


Figure 5 – Main hyporesearch to test and to analyse

4.1 Planning and Action

For the development of this research a PRISMA review was used based on the research question already identified and several models were revised that can lead to the implementation of a reliable solution. In *Figure 6* is presented a brief diagram of the planning of the research and the developed actions.

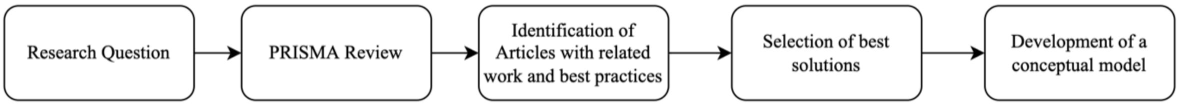


Figure 6 – Research Planning

This review was also used for data collection from relevant cases to evaluate production and consumption profiles and to evaluate current legislation, mainly European legislation, that is used to leverage the implementation and adoption of renewable energies. Several documents were analysed to identify the current path for energy distribution and decentralization. Key actors are also a relevant part of the process. To prepare this research an identification and analysis of different market players was carried out because of the current characteristics of the electricity sector, with central authorities, DSO, suppliers, aggregators, prosumers, consumers, entities that manages self-consumption installations, municipalities, and national governments. All these players are key elements for the development of appropriate legislation that can allow the adoption of decentralized solutions. In this research barriers and opportunities were also identified that can foster the adoption of these innovative solutions, since all proposed solutions must take to account legal barriers and physical constrains that might exist, so for that purpose.

In the planning phase 4 main barriers and areas were identified the situations identified that must be taken into consideration and are referred in Figure 7.

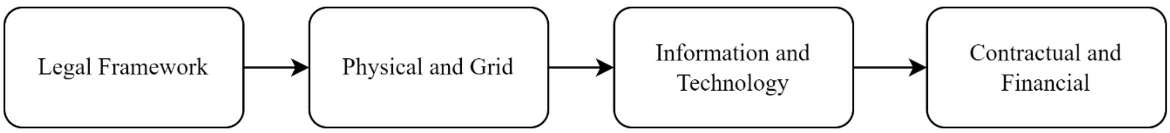


Figure 7 – Main general barriers for the implementation of decentralized systems for energy production

Legal frameworks despite being different in each country must allow the adoption of distributed and decentralized solutions with the main problem being the connection to the grid. In most of the proposed solutions and in the case of this research, DSO is a relevant part of the process and must be taken into consideration. Therefore, the proposed solution is not a closed and internal grid but a grid that takes into consideration the majority, the existence of a public grid. Second, the physical and grid barriers, as the installations and buildings must have conditions to accommodate these systems. As an example, there is the urban and old centers in cities where these solutions cannot be installed because of the characteristics of the buildings and architectural issues, therefore the solutions to use renewable energies must be the installation of energy production systems in the outskirts of the cities and use the public grid to bring energy to these homes. Regarding information and technology there is a need to deploy a model with fast and reliable connections as well as a platform to help to connect all sensors and equipment, to have a flexible system and real time data and information. This only can be achieved with modern networks, fog, and edge computing, that can take computation power near consumers. Finally, there is the need to deploy viable business models and ensure the contracts and transactions between producers and consumers using a permissionless blockchain platform to control the process and ensure safety and reliability of energy trading.

4.2 Analysis and Conclusion

To develop a conceptual model, several data was analyzed to evaluate different models and hypotheses to adopt a main concept to implement energy decentralization at a broader scale. In the revised literature the main challenge is to ensure that the energy prices practiced in this closed market is fair and transparent and in most of the cases the flexibility of the system is not detailed, so the focus of this research is the promotion and adoption of flexibility rules and enforce smart contracts for consumers and prosumers to have the needed confidence to implement a real energy community and reduce the energy bill by trading energy between neighbours. For that purpose, the analysis methodology followed the path illustrated in Figure 8.

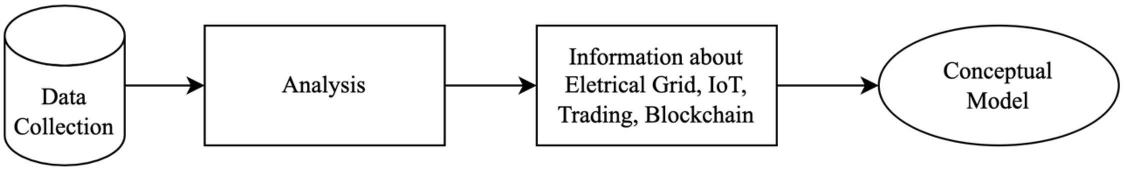


Figure 8 – Data analysis and development of a conceptual model

Data was segmented in four different main areas: Electrical grid to identify how the connections are made between different energy consumption point and also to the public grid to accommodate energy excess; Internet of Things to accelerate energy transition, incorporate intelligent systems such as smart meters and sensors that can enhance data exchange between peers; Trading to allow different actors to establish an energy market and access to more affordable energy prices; Blockchain and innovative solutions such as smart contracts to allow safety and transparency of the process. Each one of these areas allow the formulation of a concept to answer the challenges. In Figure 9 the key elements of each area that constitutes the basis for the hyporesearch are presented.

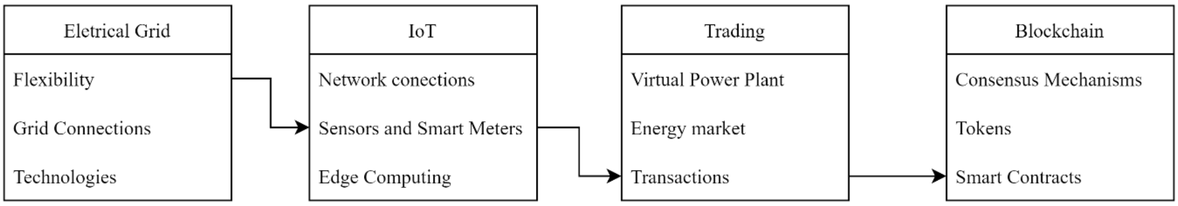


Figure 9 – Key elements of each of the main areas

The research focuses on the evaluation of these different elements to evaluate if it is possible with these features to have a robust electrical energy system at a local scale. Regarding the electrical grid it is necessary to identify the components to implement a flexible system that allow the balance between supply and demand. It is also important to see if the production technologies and equipment can adapt to this flexibility. Regarding IoT the basis is to allow fast data exchange and if possible, in real time. This will help to build the energy market and give important information to all key players. Trading is one of the added values of the process, because it will allow to producers to sell energy excess and consumers to buy energy at lower prices. Finally, there is a need to process the transactions in a fast, safe, and robust manner. Blockchain, with its main features gives the needed framework to implement such scheme.

To the development of the conceptual model and to design a robust network, an analysis of the previous elements was made and in chapter 5 is detailed how an energy decentralization system can be built with added value to energy consumers.

5 Conceptual Model for Energy Decentralization

Based on the findings, we propose a community concept of renewable energy sources, grounded on IoT technologies to help to facilitate energy trading and transactions between prosumers and consumers. Current proposals and projects on most cases only focus on one of these concepts. Pop et al [40], implement a similar concept but used a non-tested consensus mechanism, that, in our opinion, is not the preferred solution to implement. The renewable energy community concept, despite the social benefits and advantages to be open to all participants, must have a closed and controlled environment to work properly. Ideally, in this concept it will be helpful to have a mix of consumers, residential and non-residential buildings, public lighting, and electric vehicle charging stations, to better adjust offer and demand.

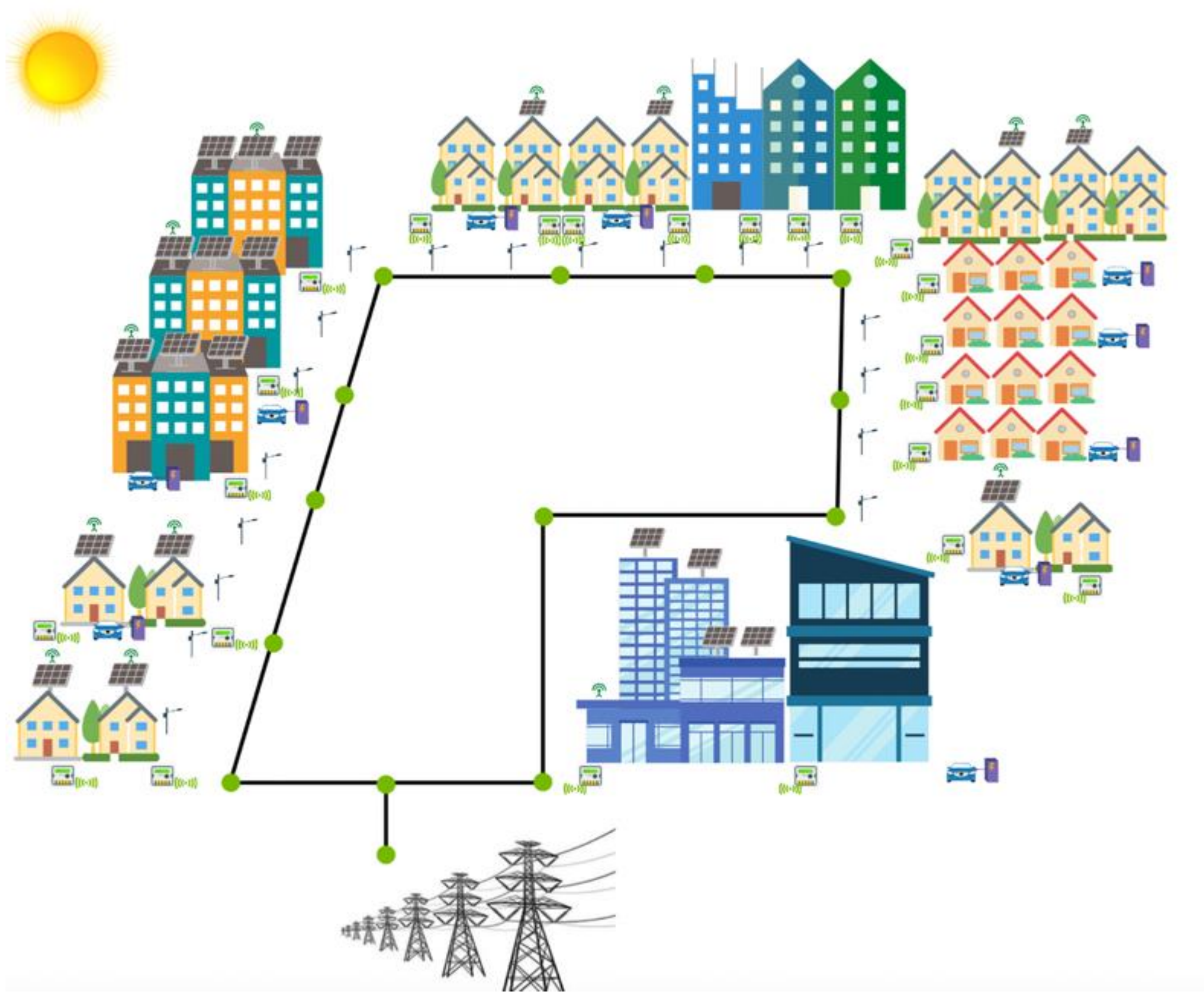
5.1 Electrical Power Grid Architecture

In this system architecture, each local of production and consumption is a node in the electrical power grid. Each node has a smart meter, and all nodes are connected to an electrical power grid and share data with the central trading platform. The interaction between actors occurs when conditions pre-determined by a smart contract are triggered [21]. For smart contracts to be initiated, each user of the electrical power grid, whether producer or consumer, must be duly registered in the network and have a unique identification. It is necessary to have an account that has the balance of energy sold and purchased and for a transaction to take place, each user must have the necessary funds for this to occur. As soon as there is a match between demand and supply, then there is an exchange of assets [29].

Theoretically, the electrical power grid concept proposed in this paper can be internal, that is, an electrical power grid owned by these prosumers, or it can be a central system electrical power grid managed by a distributor that has to approve all electrical connections that are made, as well as new connections to manage production and consumption.

This management of production and consumption is the central point of the whole process, since the production and consumption units may not match, so it is necessary to develop mechanisms that allow to adjust the production, store, connect equipment remotely in the consumer units, or alternatively make the injection in the electrical power grid so that the surplus can be drained [85].

Figure 10 shows a proposed architecture, comprised by an electrical power grid and a data network. Each building, as well as public lighting and public charging stations, is a node on the network. They are all connected to the trading platform, sending information collected through smart meters, such as energy consumption and production, in kWh, for each period of the day, and the identification of the production system and consumption point.



Node in the electrical power grid (flow of information)

Public lighting (consumption point)

Electric vehicle charging point

Producers of renewable energy

Smart meters

Public electrical power grid

Figure 10 - Renewable energy community concept.

Figure 11 presents a proposal that illustrates how the different areas of a smart home can be connected in a distributed way, managed by a wireless sensor network (WSN) composed by smart sensor/actuator nodes, and integrating a management system.

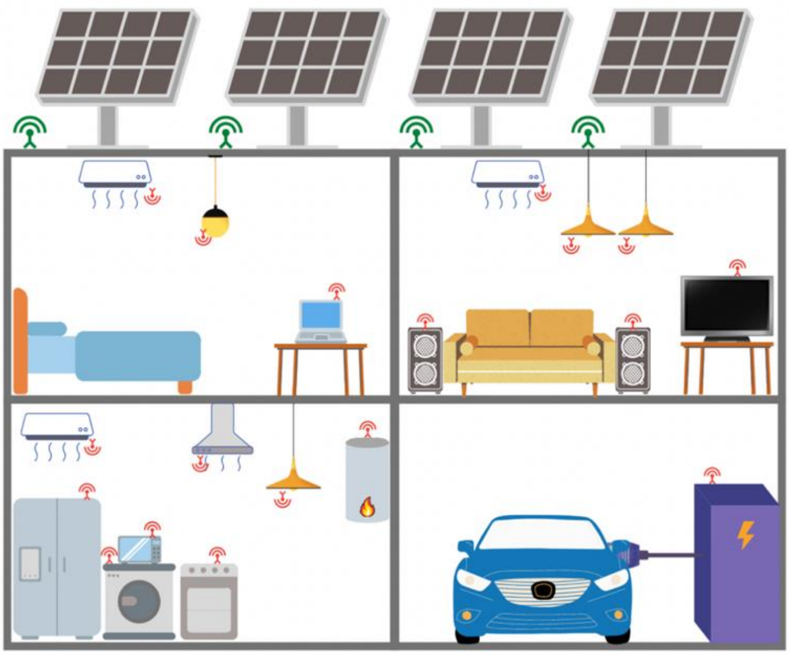


Figure 11 - Smart home based on WSN nodes for prosumer applications.

Each equipment can be triggered by the central management system for load balancing to bring supply and demand closer together. For the purpose of this paper, we do not consider energy storage system because of the cost that still represents, with high investment and maintenance [54].

5.2 Smart Devices and IoT Framework

To have a successful system in place, there is a need to develop smart homes, that is, houses that provide innovative IoT systems, integrating sensor devices and other smart appliances that promote comfort, user convenience, improved security and above all, energy efficiency. Nevertheless, smart homes may also have negative aspects and challenges, such as the complexity of facilities and connections, initial learning curve by homeowners, connection to other systems and products, as well as issues related to privacy and security due to the traffic and data that are generated [74]. It should be noted that, in the scope of the IoT, the fact that there are more connected devices increases the security problem, as these devices (e.g., motion sensors, light switches, window sensors, weather sensors/stations, and smart plugs) tend to use more lightweight and less secure protocols, which can lead to compromising situations. This problem happens because, with the massification of the IoT, it is intended that this equipment is above all inexpensive, but also small and with low complexity. Another problem is the high number of parties involved in the process, that is, as there are many accesses, security concerns arise, information passes through the equipment and an attack can go through the sensor devices with the goal of attacking another party [21].

In the proposed scheme, it is important that all connected sensor devices have security protocols to address data and privacy concerns and ensure that regular audits prevent and correct vulnerabilities. An energy management system must be available for every house and installation for the process to be successful. This system will be connected to the dynamic pricing mechanism for trading purposes [11]. One of the key elements of our proposal is the incorporation of and energy management system that can help consumers to better understand their behavior, thus adjusting the consumption profile based on machine learning.

To be possible to use the appliances for load balancing, there is a need to evaluate the hours and functioning type of each equipment. Table 10 presents an example with a start time and end time for each appliance, the ability to participate in the flexibility of the network, the power rating, and the number of working hours. These values can be set in the beginning of the process but based on the energy management system of the different houses and installation, may be adapted for better management of the grid. This system must be installed in every house.

Table 10 - Example of appliances operational time specification.

Appliance	Flexible Load	Start Time (hour)	End Time (hour)	Working Time (hour)	Power Rating (kW)
Refrigerator	No	0:00	24:00	24	0.125
Electric Vehicle	Yes	19.00	06:00	6	3.65
Air Conditioner	Yes	19:00	24:00	7	1.00
Cloth Dryer	No	06:00	22:00	4	0.74
Dish Washer	No	22:00	23:00	1.5	0.47
Hair Dryer	No	06:00	08:00	0.5	1.00
Pool Pump	Yes	12:00	21:00	8	2.00
Television	No	07:00	24:00	4	0.25
Water Heater	Yes	06:00	23:00	3	1.50
Electric Stove	No	06:00	21:00	5	1.50
Light	No	16:00	24:00	7	0.5
Personal Computer	No	08:00	18:00	5	0.25
Vacuum Cleaner	No	10:00	12:00	0.5	1.5
Iron	No	21:00	23:00	2	1.5

The control of the appliances must be done with the help of energy management systems, which can control devices using automatic scheduling techniques , production and consumption of energy, and help on energy prediction, management of smart contracts and energy trading, as represented in Figure 12 [73].

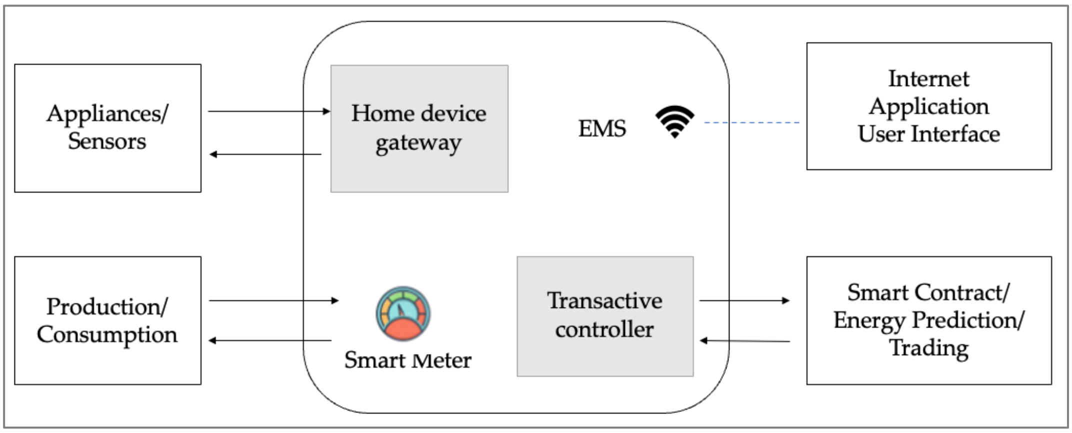


Figure 12 – Energy management system architecture.

Using a current clamp system, which is a non-intrusive way of measuring an existing electric circuit, embracing the live wire with the current clamp, it is possible to monitor power usage of high-power demanding appliances, such as air conditioners or battery chargers of electric vehicles. In Figure 13 it is possible to observe the power usage of a battery charger of electric vehicle, and calculate the amount of consumed energy, together with the charging schedule of the vehicle.

For regular appliances, smart plugs that measure energy consumption can be used to schedule the appliance or calculate daily power usage.

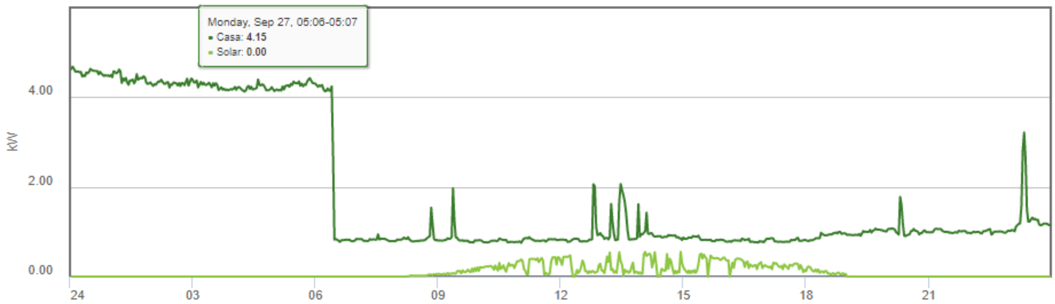


Figure 13 - Power signature of a charging electric vehicle

The goal of the centralized management system is to help on the management of energy demand and reduce peaks of consumption, as illustrated on Figure 14. In this way it is possible to reduce peaks and adapt consumption, thus making a better management of the grid [76]. Using smart relays to toggle appliances on and off when there is a need to adjust the electrical power grid load, allows the system to intervene and, for instance, to start the charging of electric vehicles at night or change the charging schedule. It is important to evaluate possible peak hours using data from Table 9 and adjust the schedule accordingly.

When the energy load within a neighborhood is not balanced, the system evaluates each household individually to determine where the smart balancing measures should be applied.

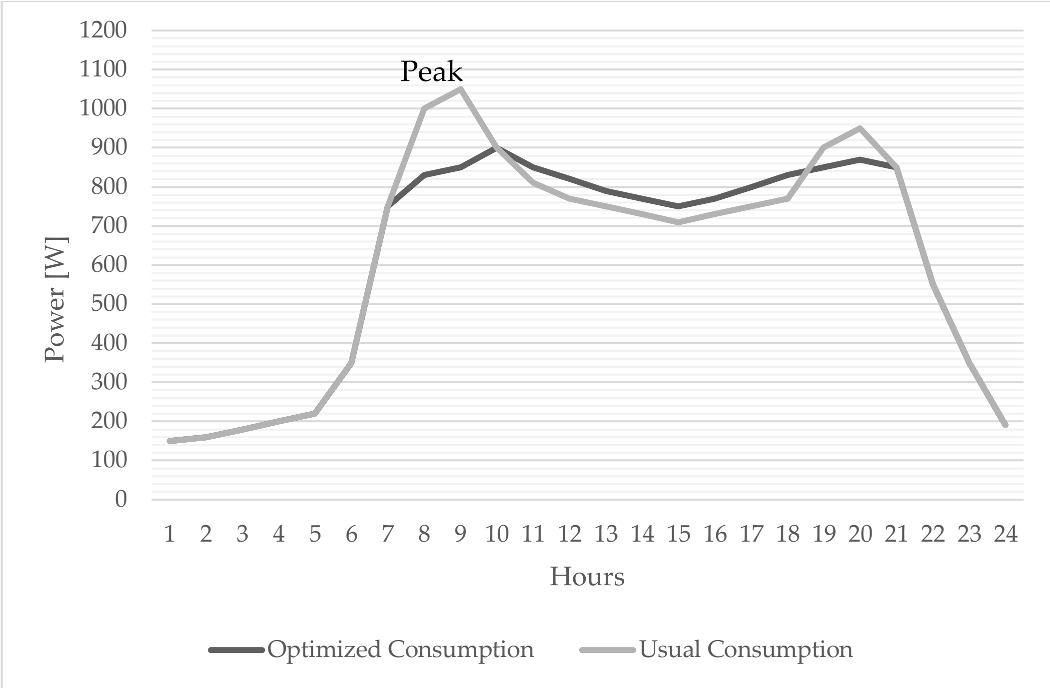


Figure 14 – Example of power consumption in a residential house with management of demand and response in smart grids.

To develop the forecast of energy consumption can be used multiple linear regression (MLR) to evaluate the previous consumption profile based on independent and dependent variables. The objective is to understand the variables that most influence future consumptions and, in that sense, adapt profiles for settlement market using the flexibility of the system[19]. The equation that represents is given by:

$$y = \propto_0 + \propto_1 x_1 + \propto_2 x_2 + \cdots + \propto_r x_r + \varepsilon \quad (1)$$

Y is the load consumption of a certain installation, x_1, x_2, …, x_r, are independent variables, α_1, α_2, …, α_r are regression coefficients and ε is the error rate or residual random variable, refers to measurement errors, and can be considered the absolute difference between the current and forecasted value. In our proposed model, MLR is applied each hour to predict future consumptions of each consumption point and the information is sent to the trading platform. An important point for the implementation of this analysis is the existence of a significant consumption history that allows its use. A rule of thumb that is used is $N > 50 + 8m$, where N is the minimum number of historical readings we need to have and m the number of predictors or variables. If we consider the list of equipment displayed in Table 10 we have 14 predictors that can influence consumption loads in a residential home, so the minimum number of past historical consumptions must be 162, which represents a minimum of 162 days of past consumption, because each hour must be compared to the previous day. To obtain this information each consumer must present the last 6 monthly invoices with the information to be stored in the EMS.

For the implementation of the MLR the following conditions must be fulfilled:

- if the residuals have a normal distribution, linearity and homoscedasticity (homogeneity of variances);
- If there are no outliers (the diagram of extremes and quartiles can be seen);
- If the number of cases is sufficient;
- If there is no evidence of multicollinearity.

5.3 Trading Platform

To promote P2P transactions, it is necessary a platform that acts similarly to what currently happens in traditional markets, a multi-settlement pool market. Based on that, we propose the following: First, use a futures market to forecast future transactions, as well as ensure a balanced supply and demand in real time; Second, use tools that allow prosumers to understand the state of the market and thus maximize their profits; Third, all information transactions are carried out based on smart contracts on a blockchain network and authentication using consensus mechanisms [72]. Figure 15 presents a concept for a trading platform using P2P and blockchain. It considers that, despite the importance of the decentralized model, it is still relevant the participation of the DSO in order to maintain the balance of the network and manage the electrical power grid connections [32].

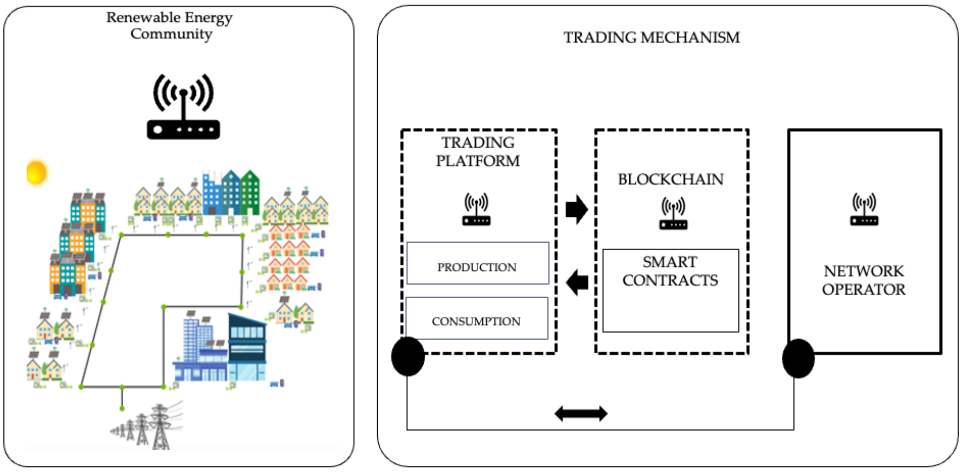


Figure 15 – Peer-to-peer (P2P) trading platform concept.

Each node of the electrical power grid must publish information about its demand or generation of energy needs in the future market. This situation must be carried out based on the EMS mentioned before, which will at a given moment make the forecast of future consumption, as well as transmit this information to the electrical power grid; in this case, the period works with time intervals of one hour. With this information energy producers can adapt the systems for the needs of the electrical power grid. This information flows through smart contracts, threading the information to each of the parties and being duly registered for later consultation if necessary. It should be noted that immutability is one of the advantages of using blockchain mechanisms and respective consensus algorithms. Therefore, for this purpose, each consumption node must submit its demand profile for each corresponding time interval, and each production node must submit its generation capacity with selling price for the same period. This information is used by the trading platform for market clearing and energy trading [72]. IoT devices can be used to define the profile of consumers and producers, and to adjust in real time. It is important to state that, in some situations, offer and demand could not match, and in these cases, utilities must also be part of the process, to ensure that energy is always available. Feed-in tariffs are also an important part of the process. In Figure 16 it is possible to see the flow of the operation and the interaction between all actors.

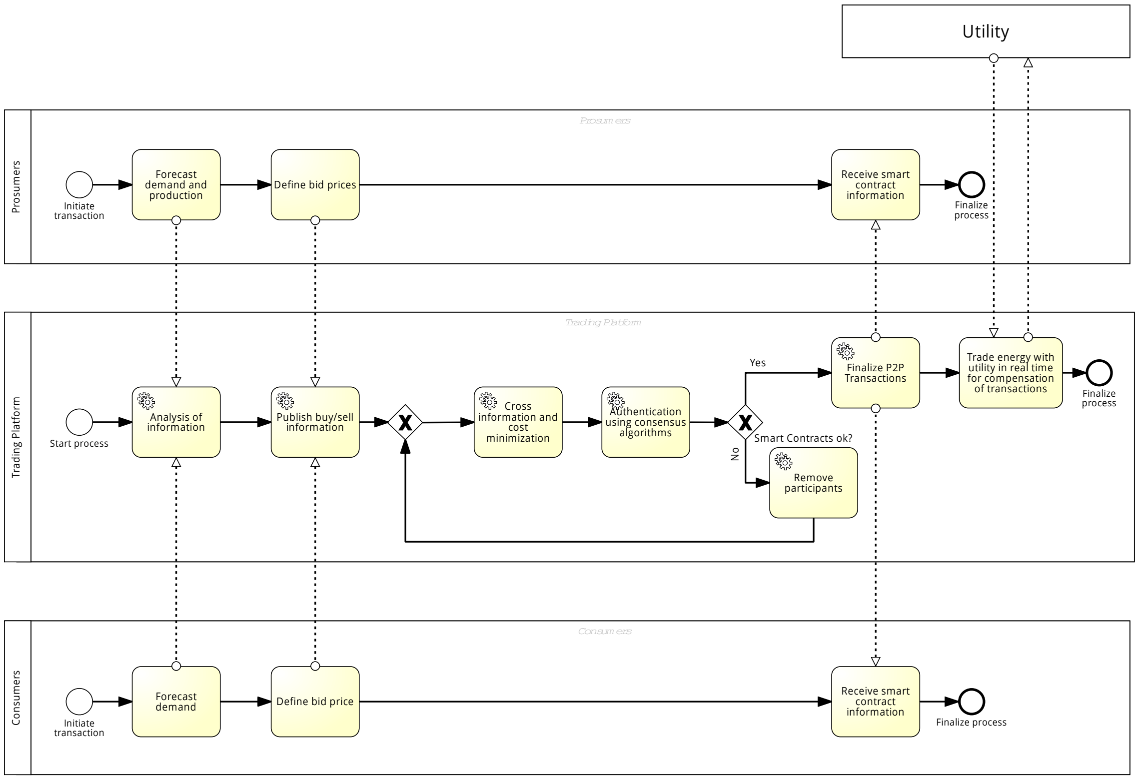


Figure 16 – Proposed market operation diagram.

For trading it can be used a trading system based on tokens and cryptocurrencies, such as Bitcoin, Ethereum and Ripple [34]. For each prosumer, availability would be displayed through energy tokens that illustrates the energy account of each of them. This represents the tradable energy unit. Prosumers can buy or sell tokens using blockchain to ensure that a token is used only once. This information is stored in a trading platform to control the account of all users. Data is then shared through control messages on the network to smart meters and based on smart contracts. A trading platform using artificial intelligence (AI) and machine learning (ML) would provide personalized advice based on consumer profiles, consumption, energy prices and other relevant information such as detailed energy consumption from different types of appliances [34].

In Figure 17, it is possible to view in orange, the electrical power grid, where each smart meter is a node that exchanges data with the blockchain network. When a prosumer produces a unit of energy, the smart meter shares this information to the blockchain. Through smart contracts, this information is stored on the account of the prosumer to balance available energy tokens. These energy tokens can be bought by consumers and, by exchange through blockchain transactions, the amount of each token is passed from the buyer to the producer. In order to manage this process, the trading platform must have an AI algorithm to help consumers and producers to maximize gains or minimize costs and guarantee that produced energy is all consumed inside the community [34].

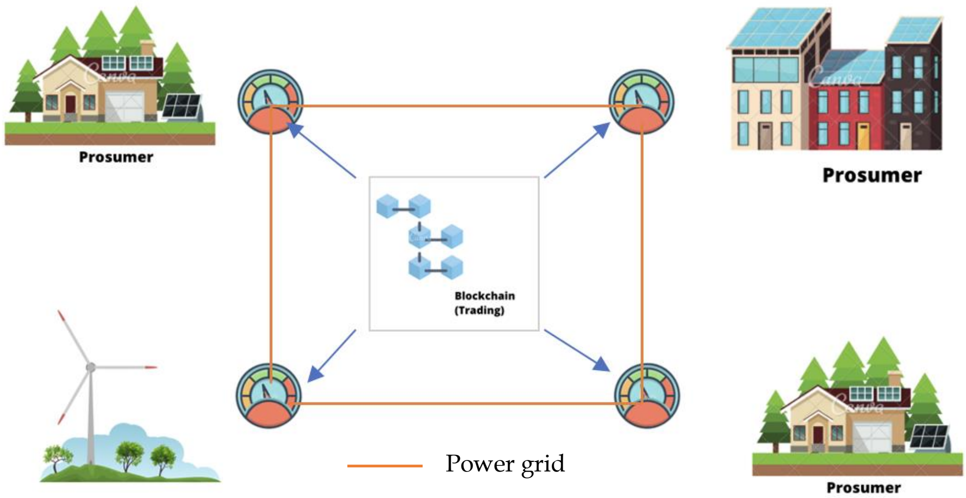


Figure 17 – Trading system representation.

To stablish the structure and information contained in the smart contracts, it is possible to define a transaction structure using information about participants, assets and transactions. In Table 11, a list of information to complete a transaction is proposed. Information about consumer and producer is also presented containing personal information, an identifier that can be an email address or an IDgrid. The introduction of this ID is one of the advantages of our proposal, making possible to build an identifier of each participant. The "Balance" represents the digital currency, the token used for the transaction. When the transaction happens, the number of tokens is updated on the digital wallets of the participants. Regarding the assets, two are proposed, 'RES' and 'kWhlisting'. 'RES' represents all registered renewable energy systems, which have the identifiers 'RESid' and 'ownerid' ID, the e-mail address of the producer. 'kWhoffer' is automatically presented by the system and updated every hour with the following information: 'listingid', with date and time of RES electricity exchange; and 'state', which can have two options, 'AUTHORIZE_OFFERS', that represents that offer are accepted from producers and buyers, or 'BIDS_CLOSED', representing that offers and bids are no longer accepted. 'RESOffer' and 'BuyOffer' are other fields with the values that producers and buyers are offering [35].

In Table 11 all resources to be included in a smart contract are presented.

Table 11 – Members, resources and trades of the trading platform.

Members	Resources	Trades
Consumer/Producer • Name • E-mail • IDgrid • Balance	RES • RESid • ownerid kWhoffer • listingid • state • RESOffer • BuyOffer	AuthorizeOfferCom • listingid RESOffer • reservePrice • kWhavailable • listingid • producer BUYOffer • BidPrice • kWhQuantity • listingid • consumer Bid_Closed • Listingid RetailPrice • RetailPrice

Transactions have four main attributes. 'AuthorizeOfferCom' represents the beginning of the bidding phase. Each hour, a message is automatically sent to all participants inviting to participate in the bid. 'RESoffer' represents the amount of energy in kWh and token price per kWh. 'BUYOffer' allow consumers to send bids, identifying the amount of energy needed and the price they are willing to pay. With 'Bid_Closed', the process is closed, the smart contract processes the information and the trading is processed [35].

Within the smart contract processing, we have the clearing price of the market, as represented in Figure 18. After this process, the 'CloseBidding' is initiated to close the process. Using RESOffers and BUYOffers, the global amount of kWh available for sale, (kWhavailable), and kWh to be purchased, (kWhwanted), are calculated. The market clearing price, (MCP), as token/kWh, can be determined in each hour by the average bid price offered by all buyers, as proposed by Pipattanasomporn et al. [35]. The principle to match buying and selling offers is based on the FIFO (First-In First-Out) algorithm, and the highest offer to buy energy is the one that wins the auction. To assure the low price of the system a 'RetailPrice' is considered to evaluate the lowest price of the open market in order to ensure that the prices practiced inside the network are lower than in the retail market.

To guarantee the proper functioning of this entire process, it is necessary that the network where the system is based has a performance capacity duly established, otherwise it will not be possible to carry out transactions every hour. Thus, the selected mechanism must address, in addition to security-related issues, also the performance and possible scalability of the solution. The solution now proposed may only consider residential buildings, but in order to better adapt to demand and supply, the ideal would be to insert into the network other types of buildings that can absorb any peak of energy consumption during the day [56].

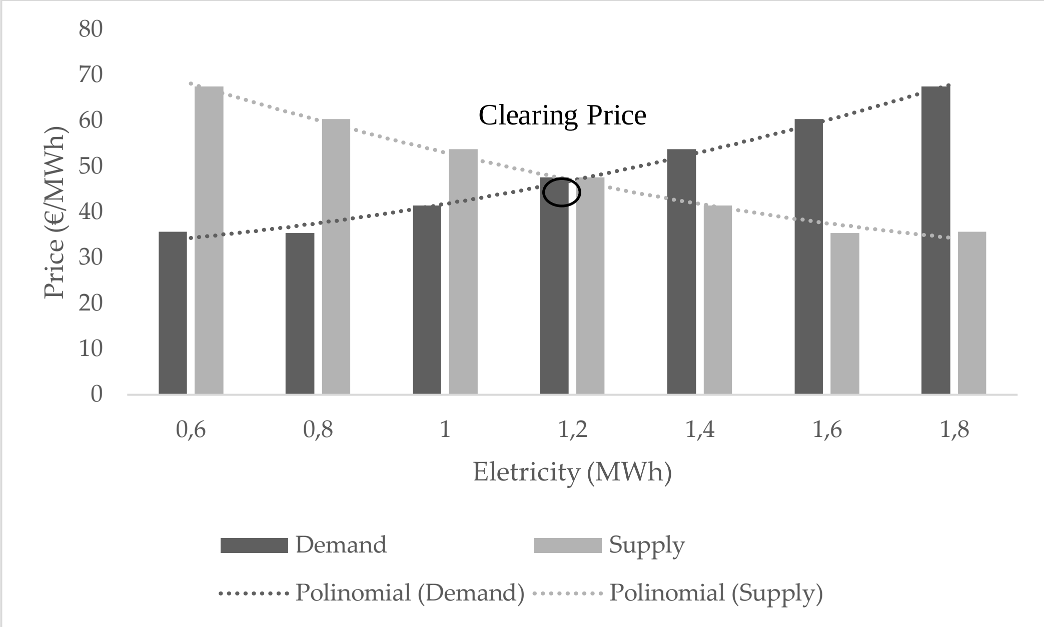


Figure 18 - Clearing price of the market.

Based on offer and demand, it is possible to set the clearing price of each auction [53], which represents the balance between producers and consumers and which results from the auction that is held every hour, as stated in Figure 18. This price is determined automatically through the trading mechanism and consider an average price for selling energy of 0.039 €/kWh and a buying price of 0.095 €/kWh on the peak period between 13 to 23 hours [80].

5.4 Blockchain Implementation

For blockchain implements is predicted a P2P private network with blockchain nodes and distributed ledgers containing information about smart contracts that deal with transactions and share data between all actors. A distributed ledger contains de records of added transactions and does not allow them to be deleted and this information is stored registered and distributed in several machines [89]. It is important to ensure data security and privacy of all process. Each customer must have an exclusive identity with a identifier that distribute and replicates the copy of the transaction to all the peers in the network for validation [11]. For this purpose, a consensus mechanism must be in place. Several mechanisms and platforms can be adopted. Currently the main adopted platforms are Hyperledger Fabric, Ethereum, IOTA, Multichain and R3 Corda [89]. NEO is also referred as one of the main protocols to implement smart contracts. Hyperledger Fabric more targeted for an enterprise environment and a more closed atmosphere with few open access tools. Neo is also a framework with less adoption and fewer information available for users. Ethereum is a more open source tool with higher adoption [5], but asking to implement such framework in new microgrids with the need to have an higher investment because of the stakes, can be challenging.

Proof of Work (PoW) can be used in order to ensure the immutability of the information [11], however, PoW is a consensus mechanism that is energy intensive as it consumes 47.1 TWh per year [49]; therefore, it is not the most adequate option for energy efficiency purposes [40]. The Ethereum platform is one of the most used algorithms in the energy area and it is based on the Proof of Stake (PoS) concept, which does not need large amount of computational power to solve the problem to make a new block and in terms of rewards is better for investment in the network. In terms of security, an attack can be very difficult, as it needs the majority of support [28]. In the PoS consensus mechanism, a node that has the right to create a new block is elected, and for that it must have an interest in the transaction, called "stake", such as the virtual currency itself. This process, however, may have some limitations, as the node that demonstrates that it has more in stake may be the one that most often will have the right to create new blocks. To democratize this process, there are platforms that require authentication and permissions, as well as making it difficult to change their stake values. The proposal we present in chapter 4 considers these last two points [73]. Another consensus mechanism, Hyperledger Fabric, uses practical byzantine fault tolerance (PBFT) consensus, which is suitable for enterprises and private networks and guarantees added control over transactions, better performance and scalability [66]. Can also provide on-chain and off-chain approvals that are important to enhance the performance of the solution. Off-chain computing allows the trusted entity that manages de blockchain to change conditions of transactions, that performed offline. These states are then transferred to the network to perform smart contracts to continue the process [19].

To implement the process referred in Table 11, it is proposed the use of the Hyperledger Fabric framework, an open-source platform that can be used for P2P trading. It has a modular architecture and is considered to have good performance with high capacity to incorporate different modules that increase privacy and encryption [78]. Hyperledger Fabric is more flexible and more suitable to develop private networks and adapted for specific needs than Ethereum based systems, as presented on Table 12, namely, the number of transactions per second (TPS) allowed on Hyperledger Fabric is much higher, up to 3500 TPS. Using several performance metrics to compare different consensus mechanisms such as block time, latency, throughput, memory and CPU utilization, it is possible to confirm that consensus mechanisms available on Hyperledger Fabric have better performance that Ethereum, for example, latency on byzantine fault tolerance mechanism can be up to five times lesser than on Ethereum when 1000 transactions were processed and throughput was 3 times higher [39]. Another important aspect is the framework used to implement smart contracts. On Hyperledger fabric, several languages can be used and on Ethereum Solidity, which is a specific object-oriented language for implementing smart contracts.

Table 12 – Comparison of consensus mechanisms for smart contracts.

Properties	**Hyperledger Fabric**	**Ethereum**
Blockchain category	Private	Public
Consensus mechanism	Raft/BFT-based	Proof of Stake
Mining Fee	Yes	Yes
Energy consumption	Medium	High
Security	Medium	Low
Scalability	No	No
Transaction per second (TPS)	160-3500	12-15
Smart Contract	Chain code smart contract (Go, Java, Python, Node.js)	Solidity
Open Source	Yes	Yes

In Figure 19**,** it is possible to see a simplified example of a blockchain framework for decentralized purposes. The blockchain would be used as ledger, a database of energy transactions, and as a management system using information from smart meters [34]. Based on blockchain solutions, it is possible to have an adequate demand-response system in place that offer a fair platform for prosumers to trade energy. It is important to mention that blockchain networks can be placed in three categories: Public, Consortium and Private. In public networks all participants can read or write on the blockchain and participate in consensus procedure, in consortium networks the consensus procedure is controlled by pre-selected nodes, and in private networks authorizations are made by one entity. These different approaches have different security degrees maintained by cryptographic tokens to guarantee data quality and validation on the blockchain network [42].

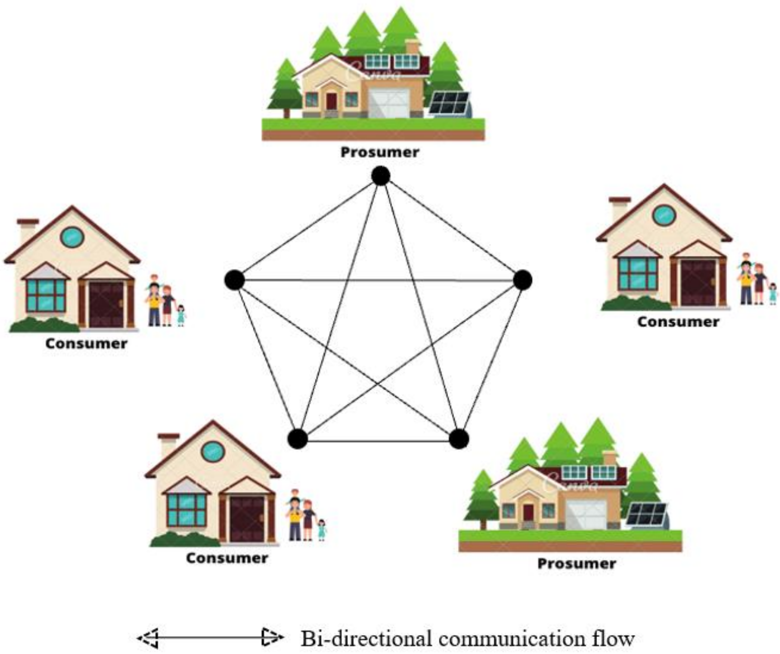


Figure 19 – Blockchain flow of information between the blockchain nodes.

The information that flows on the blockchain will trigger the conditions set on the smart contracts and each node will have a copy of the ledger. This will help to improve trust and transparency on the process with information available on different locations and guarantee that energy is not sold in duplicate [34]. There are also some constraints that must be observed, namely data storage and scalability. The size of the chain is always increasing, as due to the immutability, transactions related to smart contracts cannot be eliminated. In this sense, it is necessary to be aware of storage dimension [65]. IoT needs communications and produces a big amount of real time data. With the increase of the network in different areas, more resources are needed, and the system must have the characteristics to incorporate more data and yet be able to perform. Another important aspect is anonymity and data privacy. It is important that authentication and authorization mechanisms are in place. Hyperledger Fabric guarantees this aspect where information is managed according to different levels of permission. Reliability is also important; transactions rely on data from sensors and the EMS system and traceability of the information must be made possible. If users do not trust the information, then it is impossible to implement such system. Sensors of each appliance and equipment communicate to EMS, and smart meters also communicate with the management system. Every hour, based on forecast algorithms, such as Prophet, it is possible to send previsions for the bids at production and consumption levels. This information is then stored on smart contracts.

Smart contracts are self-executable code and contain a set of rules that must be followed for a transaction to take place. They contain automatic setup conditions for demand and response and information about energy profiles and operation of each house and production system. They contain also information about bids, price components, traded and available quantities, market information and prosumers systems [31]. They also contain other relevant information, such as contract duration, capacity limits, number of allowed transactions, incentives, suspension mechanisms [32]. Smart contracts are a part of a blockchain code, contribute for the transparency of all the process and do not need a central entity to operate [86]. Each entity has an identifier, and each installation is a node on the network. Smart contracts are performed on each node automatically, based on previous set conditions, and operate through a virtual machine with blockchain as the distributed virtual machine [41]. The main operations of a smart contract are: performing parts of the blockchain algorithm; exchanging information within the blockchain with other nodes; and allowing other nodes to perform the next operation [75].

Smart contracts allow to buy or sell energy and monitor and control of all transactions. All payment processes between producers, consumers and the main grid happen through these contracts. It is important to promote the interaction and participation of prosumers and consumers [17], in order to have the maximum number of offers and therefore maximize gains for producers and consumers.

6 Conclusion

6.1 Key findings

Electricity supply requires compliance with rules that depend on each country, so it is difficult to find a model that can be implemented without observing certain specificities, even knowing that the intention is to move from a centralized model of electrical energy production and consumption to a decentralized model. In electrical power grid with industrial or non-residential consumers with larger installations, there is a need to ensure a backup in the energy supply that must be ensured by the public electrical power grid. Additionally, in most electricity markets the installed production of the electrical power grid must also be duly authorized by the licensing entity, and in close collaboration with the distribution system operator (DSO), to ensure that the public electrical power grid is able to absorb any excess of energy production, but also guaranteeing the energy supply for the consumers, always.

With the publication of new legislation across Europe based on the recent energy European directives, it is possible across most member states to implement pilot projects for renewable energy communities, and several are already underway to test and evaluate different methodologies. Based on the reviewed articles, it was also possible to verify that across the world many projects are being implemented with successful results, with increased gains in reducing energy costs. With this information, it is possible to verify that the technologies are ready, but there are still legal barriers in some countries that must be addressed to be able to implement these types of electrical power systems. Consumer awareness must also be a part of this process, if homeowners are not willing to participate, it will not be possible to implement these models.

This paper proposes a model of an electrical power grid and blockchain network, which responds to most self-consumption installations with relevant dimensions and requires the existence of a trading mechanism that allows the integration of producers, consumers, and prosumers, thus making the matching between electrical energy supply and demand. The blockchain solution also provides for the existence of smart meters in all installations, sensors in the equipment, and even energy management systems, which can transmit to the trading system information on consumption and production in real time. The formalization of the relationship between the various actors must be carried out through smart contracts that must be duly authorized by the owners of each energy production system, as well as by the consumers. Blockchain operating conditions, such as the mandatory “IDgrid”, which allows users to be identified, provides the system with credibility and security. The match between energy supply and demand should be done at all hours during the day, thus ensuring a proper optimization of the electrical power grid operation. Thus, it is possible to guarantee a balance between electrical systems, promote transparency and ensure the proper functioning of the entire process. Management and operational costs are also reduced due to the absence of the central entity, allowing producers, consumers, and prosumers to obtain a fairer tariff offer.

Some limitation such as the scalability of blockchain can be overtaken by applying this approach to local communities in a size that current blockchain consensus mechanisms can be handled efficiently in an appropriate time.

Important also to highlight the need for national legislations and current models to be adapted to allow the implementation of these solutions, to allow consumers to install PV solutions in a fast and reliable way, adjusting flexibility in grids to better accommodate the integration of electricity generated from the decentralized systems

The development of decentralized energy networks requires a case-by-case analysis of situations. Currently, the implementation of these cases tends to happen in a specific cluster, without great variations in the type of installations implemented. In these situations, the consumption profile tends to be more stable, so it is easier to adapt the production power to be installed, as well as manage any peaks. It is therefore important, in mixed systems, to ensure that the installed management system responds to the needs of the network and considers the load profiles in the various consumption facilities and that, in the case of surpluses, their correct disposal and application is foreseen.

The main limitations with current research relate to data and the need to obtain real data from more facilities to test the proposed methodology. Considering that the flexibility of the system depends heavily on the number of installations on the network, it was important to test in various environments to verify the scalability of the solution.

6.2 Further research

From the carried-out analysis, most of the literature focuses on issues related to the constitution of the blockchain and the respective smart contracts. The formalization of aspects related to transactions are very relevant, however, to maximize the gains of both parties, producers and consumers, it is very important that the network is intelligent and able to adapt and balance production and consumption. Therefore, several areas need additional research:

- The flexibility of the network has not been properly studied and in this sense the work developed in this research contributes in a positive way, however, it highlights the existing limitations that are related to the active participation of the various nodes in the intelligent management of the network and in the approximation of the offer and energy demand;
- The study of various types of networks and an active analysis of the integration of the various actors, forms of energy production, as well as the equipment incorporated and installed in each of the installations of consumption;
- Integration of intelligent energy management systems with electricity grid systems and demand and supply adjustment and deploy of real time information for an energy market.

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