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Distributed Demand-Response Certification using Blockchain Technology

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Preface

The PhD activity was carried out at the Engineering Department of the University of Palermo (Italy) from November 2017 to October 2020.

The theoretical development, the simulation analysis, the implementation and the first experimental tests were carried out at building 9 of the same department.

Part of the activity was developed during the visiting period at the Energy Technology Department of the University of Aalborg (Denmark), from April 2019 to July 2019 and from October 2019 to December 2019.

Abstract

The residential sector accounts for approximately 30% of the electrical energy consumed in developed countries. This demand is currently covered not only by fossil fuels but also by renewable energy sources. In addition, the "Clean Energy Package" presented by the European Commission has promoted since 2016 through specific directives the use of renewable energy and energy efficiency with the objective of a production from renewable energy sources of 32% and the increase of energy efficiency to 32.5% by 2030 as compared to the 1990 levels. These directives, in order to reduce global emissions, encourage production from renewable sources, but at the same time they require a reduction in fossil fuel production, contributing to the transformation of the electricity system from centralized to distributed. The increase in generation from renewable sources guarantees a reduction in polluting emissions, but due to its intermittent nature, such generation is difficult to manage and predict. This European framework requires the development of new energy policies at the national level able to reduce overall consumption and support the implementation of customer-centric control and management systems. It is thus necessary to study the feasibility of the different strategies available, especially for the involvement of residential users in services that can contribute to the management of the power grid.

The advent of the blockchain technology has allowed the development of new business models for the electricity market, opening this world also to end users who previously did not have the opportunity to participate in energy trading and allowing the implementation of services to ensure the correct operation of the power grid. Thanks to its characteristics and especially thanks to the feature of being distributed over the grid, the blockchain could be the solution to the balancing problems caused by the penetration of unpredictable renewable sources and could make a significant contribution to achieving the 2030 targets. Out of all the applications in the energy sector, the most popular and developed so far are Peer-to-Peer, Vehicle-to-Grid and Demand-Response applications. Peer-to-Peer energy trading concerns the direct energy exchange between end users, Vehicle-to-Grid applications concern the exchange of energy between electric vehicles and power grid for congestion resolution and ancillary services provision, while Demand Response is related to the possibility to modify the demand from end users. Demand Response does not concern energy exchanges but, such as Vehicle-To-Grid, the solution of congestion problems and the provision of ancillary services services. Demand Response allows consumers to respond to market signals by increasing or reducing their energy consumption, with the aim of responding to peaks in electricity supply or demand, contributing to greater network flexibility and stability and more efficient use of infrastructure and energy resources. This service represents an important resource to achieve the objectives to be reached by 2030, as reducing peaks in demand avoids the use of peak generators with the consequent reduction of emissions and energy prices. The use of the blockchain for Demand Response service certification allows to create a

distributed system in which even residential customers can communicate with the system operator to provide their flexibility, in a secure, transparent and traceable way.

This PhD Thesis addresses the development of a new methodology for the implementation of Demand Response programs using blockchain technology. The latter is used to define a distributed Demand Response service and a new system for its tracking and certification. A Smart Contract was designed and written to run Demand Response events, calculate the customer baseline, calculate the support provided by each customer towards the implementation of the required load curve change and remunerate each customer with utility tokens in proportion to its contribution. To test the methodology, a Hyperledger Fabric network and a Smart Contract were implemented on four nodes of the Microgrid Laboratory of the Department of Energy Technology, University of Aalborg (DK). Subsequently, a realistic scenario including two consumption nodes was developed, using electronic power converters for household profile generation and Smart Meters for consumption profile measurement. The theoretical and experimental results show the feasibility of Distributed Ledger Technologies in the management of smart grids with minimal investment in new hardware, while allowing the active participation of residential customers in Demand Response programs in a more transparent and fair way.

The Thesis provides a research path in the area of the blockchain for the energy sector according to the following structure. The first chapter introduces the mean features, the application field and the fundamental principles of the blockchain technology. In chapter 2 there is an overview of the Italian electricity market, the involved actors, and all the necessary background for better understanding the following chapters. Also, it is explained how blockchain technology can contribute to the electricity market, the new business models, the energy regulations as well as the newly enabled energy scenarios. Chapter 3 describes in details the three most successful blockchain applications in the energy sector. Then, in chapter 4, it is presented a blockchain architecture and its network for the execution of Demand Response events, without the need for intermediaries acting between the system operator and the end users. Finally, chapter 5 describes the experimental set up used for testing, the implementation of the blockchain network and the obtained results.

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List of Acronyms

ARERA	**A**utorità di **R**egolazione per **E**nergia **R**eti e **A**mbiente
BRP	**B**alance **R**esponsible **P**arty
BSP	**B**alance **S**ervice **P**rovider
B2B	**B**usiness to **B**usiness
B2C	**B**usiness to **C**onsumer
BTF	**B**izantine **F**ault **T**olerance
CBL	**C**ustomer **B**aseline **L**oad
CRE	**C**ommission de **R**égulation de l'**E**nergie
DLT	**D**istributed **L**edger **T**echnology
DR	**D**emand **R**esponse
DRAS	**D**emand **R**esponse **A**utomation **S**erver
DSO	**D**istribution **S**ystem **O**perator
DSR	**D**emand **S**ide **R**esponse
ECC	**E**uropean **C**ommodity **C**learing
EMS	**E**nergy **M**anagement **S**ystem
ENEL	**E**nte **N**azionale per l'**E**nergia **El**ettrica
ENTSO-E	**E**uropean **N**etwork **T**ransmission **S**ystem **O**perators
ERGO	**E**lectric **R**echarge **G**rid **O**perator
ESS	**E**nergy **S**torage **S**ystem
EVM	**E**thereum **V**irtual **M**achine
GDPR	**G**eneral **D**ata **P**rotection **R**erulation
GME	**G**estore dei **M**ercati **E**nergetici
GSE	**G**estore dei **S**ervizi **E**nergetici
G2V	**G**rid to **V**ehicle
IoT	**I**nternet **o**f **T**hings
ISO	**I**dipendent **S**ystem **O**perator
MB	**M**ercato di **B**ilanciamento
MBL	**M**aximum **B**ase **L**oad
MBMA	**M**eter **A**fter **M**eter **B**efore
MGO	**M**etering **G**enerator **O**utput
MGP	**M**ercato del **G**iorno **P**rima
MI	**M**ercato **I**nfragiornaliero
MPE	**M**ercato a **P**ronti
MPEG	**M**ercato dei **P**rodotti **G**iornalieri
MSD	**M**ercato dei **S**ervizi di **D**ispacciamento
MTE	**M**ercato a **TE**rmine
NAESB	**N**orth **A**merican **E**nergy **S**tandards **B**oard
NILM	**N**on-**I**ntrusive **L**oad **M**onitoring
PAB	**P**ay **A**s **B**id
pBTF	**p**ratical **B**izantine **F**ault **T**olerance
PoA	**P**roof of **A**uthority

PoS	**P**roof of **S**take
P2P	**P**eer to **P**eer
PUN	**P**rezzo **U**nico **N**azionale
PoW	**P**roof of **W**ork
REC	**R**enowable **E**energy **C**ommunity
RES	**E**nowable **E**nergy **S**ources
RTE	**R**éseau de **T**ransport d'**E**lectricité
RTOs	**R**egional **T**ransmission **O**rganisations
SMP	**S**ystem **M**arginal **P**rice
TSO	**T**ransmission **S**ystem **O**perator
UPI	**U**nità di **P**roduzione **I**ntegrate
UPR	**U**nità di **P**roduzione **R**ilevanti
UVA	**U**nità **V**irtuali **A**bilitate
UVAC	**U**nità **V**irtuali **A**bilitate di **C**onsumo
UVAM	**U**nità **V**irtuali **A**bilitate **M**iste
UVAP	**U**nità **V**irtuali **A**bilitate di **P**roduzione
UVAR	**U**nità **V**irtuali **A**bilitate di **R**icarica
VN	**V**irtual **N**ode
V2G	**V**ehicle to **G**rid
V2H	**V**ehicle to **H**ome
V2V	**V**ehicle to **V**ehicle
V2X	**V**ehicle to everything

Chapter 1

Introduction

1.1 The Blockchain Technology

Since 2008, when the first and most famous blockchain application for transactions in Bitcoin was created, many companies have tried to use this technology for applications in various sectors, such as: finance, electronic voting (e-voting), copyright and patent management, smart contracts, tracking of goods (supply chain) and energy market. Blockchain is, indeed, not the synonymous of Bitcoin, but a technology based on Distributed Ledger Technology (DLT), hence characterized by a distributed register. Bitcoin is the first and most famous crypto-currency in the world, founded in 2008 with the aim of creating an electronic payment system that allows two parties to negotiate directly with each other without the need for a third party of trust. The traditional e-commerce system relies on financial institutions, which serve as a means of processing electronic payments. This system suffers from the inherent weaknesses of a model based on the trust of unknown users towards a third party that acts as the guarantor for both. This results in a brokerage cost that increases the transaction cost, limiting the minimum size of transactions that can be carried out and excluding the possibility of small transactions. Bitcoin was created to cope with these problems, proposing a new technology based on cryptographic evidence instead of trust, which allows the exchange of currency between two unknown users without the need for a third party. The new cutting-edge technology used by the Bitcoin application is precisely the blockchain. The latter allows to record events ordered in time and ensures that the recorded events are difficult to delete or modify even if malicious users try to do it, since every change requires many resources and/or the approval of most of the network nodes and not of a single authority as in the case of the classic centralised systems. Therefore, users have not to rely on third parties, which often make decisions for their own interests. For this reason, it is particularly useful in cases where two people want to make a deal, but do not trust each other [1].

Before the advent of blockchain, the transactions of any good were recorded in a centralised database managed by an institution, which theoretically can do any operation on the data, and therefore has to be trusted to avoid misbehavior on data. In the financial field, this central role is run by the bank, whereas in the electrical energy world the central role is played by different entities depending on the type of transaction. A third-party operator manages all financial and energy transactions in the wholesale energy market (GME in Italy, CRE in France, etc.), while the Transmission System Operator (TSO) manages all the financial and energy transactions in the balancing market (Terna in Italy, RTE in France, etc.) checking the technical feasibility of each one. Moreover, recent indications from the European Network of Transmission System Operators (ENTSO-E), are stressing the more and more important role of Distribution System Operators (DSO) for managing the flexibility of local resources connected to their grids in a more extended flexibility market [2]. These transactions (financial or electric energy transactions) are in every case recorded in a database. The novelty introduced by the blockchain is the distribution of data and trust in the network while overcoming the problems afflicting decentralised systems. In distributed systems, each node has the same capabilities and the same level of access to complete information. This provides a solid foundation for trust, as it democratizes the entire system. Furthermore, since the data is stored on all the nodes of the system, in the event of a cyber-attack there is no single point of failure, so the system can continue working. On the other hand, in a traditional centralised system (database), one relies on a single central authority that controls "who can do what" in the system. This latter type of system is more vulnerable in the event of a cyber-attack, but it is good when the party that controls the system is reliable and behaves honestly.

Another unquestionable benefit of the blockchain technology is the inherent integration of communication protocol in Business to Business (B2B) and Business to Consumer (B2C) applications. In a multi-party environment with N actors, such as electrical energy applications (trading is one example), there is a high number of connections. What if such connections are designed with the same communication technology? That would considerably reduce the integration costs in B2B and B2C environments. In B2B applications for electricity trading in power systems, such as the day-ahead energy market, the communication technologies currently used are many. Such as many are the platforms for trading. As an example, the EPEX SPOT is a platform that matches orders in a transparent manner to all parties, however, it is only one of the involved communication technologies, since many others are used to transfer this information to the European Commodity Clearing (ECC) and for the latter to take obligations from buyer and seller. Communication to the TSO from ECC will have to be made too, and this may take place through further communication technology [3]. By adopting blockchain technology, the three main dimensions of B2B integration (data format, business process and communication protocol) would thus keep balanced, giving the dimension of the communication protocol the right importance making it homogeneous for all parties.

The blockchain is a DLT, where the ledger is structured in blocks, shared and managed by network nodes. The blockchain can be public or private depending on the access to the ledger, whereas it is named *permissioned* or *permissionless* depending on who is authorized to maintain the ledger. In a nutshell, a blockchain is a chain of blocks, each block contains several transactions, and the whole information is shared among all the nodes participating in the blockchain. Each node can see all transactions, thus creating a network that allows the traceability of all transactions. In this way, whatever is their role (consumers, companies, certification authorities, operators, ...) network participants are fully accountable for their actions and contracts with each other. Each block is connected to the previous one and to the next one through the use of cryptographic functions called "Hash functions". The Hash functions allow converting a message of any length, in this case the data related to a block, to a message of fixed length (a digest named *hash*) that identifies it uniquely. Furthermore, it is not easy to find two messages that have the same hash, this property is named collision resistance. In other words, they create a string associated with the data of the reference block for which, once the function is applied, it is no longer possible to return to the original data. The peculiarity of these functions is that they are easy to calculate and always give the same result using the same input data (deterministic functions). Blockchain technology exploits these functions to create the chain of blocks: on each block, there is a *hash* calculated using the transaction data contained in the block itself plus the *hash* of the previous block. In this way, each block stores information (the *hash* of the previous block) from all the transactions that are on all the nodes of the network and, thanks to the chaining system, it is unmodifiable (if not by modifying all blocks), see figure 1.1.

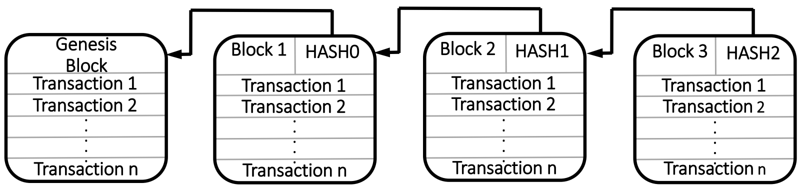


FIGURE 1.1: Implementation of BC blocks.

The blockchain goes beyond the functions of a distributed database, i.e. a database that is not physically located on a single server (computer), but instead it is located on multiple computers at the same time, all perfectly synchronized on the same documents. In fact, unlike a database, blockchain transactions are validated before becoming part of new blocks, requiring approval from most of the nodes participating in the network, and, once confirmed, it becomes difficult to alter as it in turn requires an incredibly high computational power or the approval of most network nodes.

Figure 1.2 shows an example of the process to insert a new transaction in the blockchain. The process can be divided in six steps:

1. Request of transaction.
2. The new request of the transaction is sent to the network.
3. The transaction is sent to the nodes responsible for transactions' validation.
4. If the transaction is valid, the validator node inserts the new transaction in a new block containing other valid transactions and compete to validate the block (consensus process).
5. After the validation of the new block, the successful validator can insert the new block on the chain.
6. Once the new block is part of the chain, all participants will be able to see its content.

Furthermore, thanks to decentralization, it is possible to prevent market abuse through monopolies and to reduce costs and regulatory oversight. The nodes that provide the validation of transactions and blocks are called "miners". The validation of the transaction can be carried out using specific algorithms called "Consensus Algorithms" or by running some codes shared on the blockchain called "Smart Contract". Details on smart contract, the different consensus algorithms and the process for achieving consensus over a block of transactions are reported, with specific reference, in later sections.

This feature provides the authoritative validation that in a centralised system is guaranteed by the trusted authority or more in general by the system manager. The use of the blockchain technology thus allows to obtain:

1. *Transparency* (in public blockchain), because each block added to the blockchain is accessible to all participants and is in the archive of all participants.

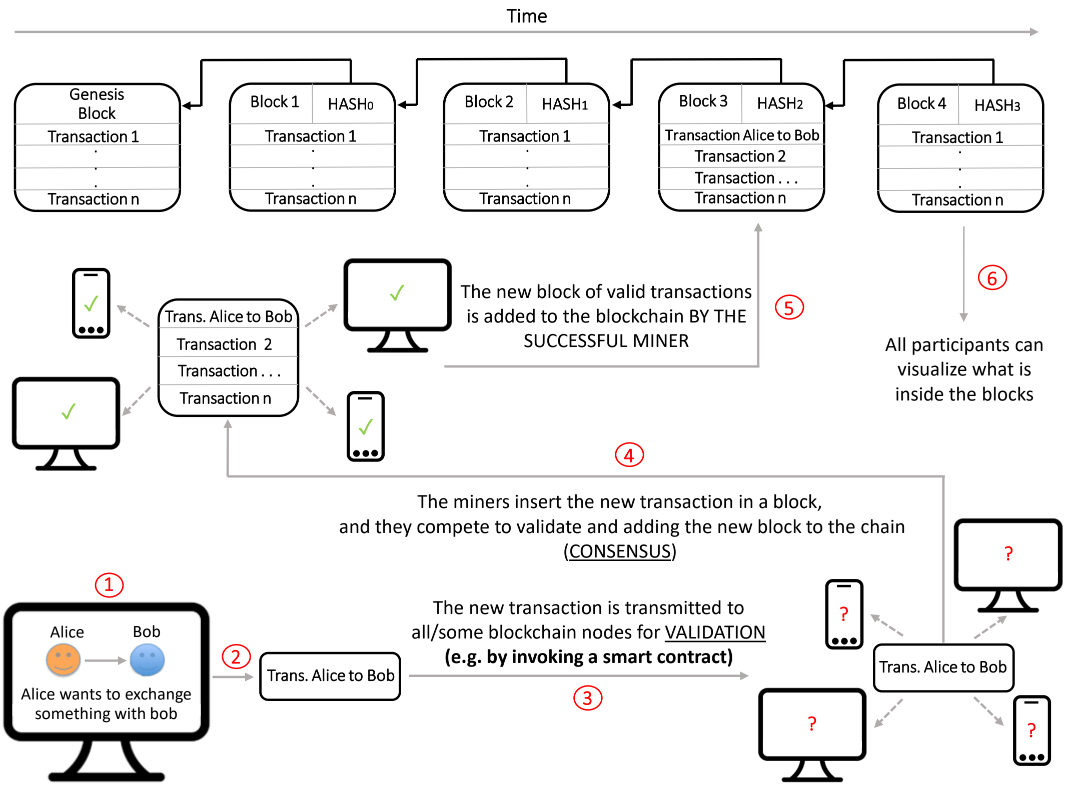


FIGURE 1.2: How a blockchain with validation and consensus works.

2. *Trust*, based on cryptographic functions, which allows the blockchain to work in distributed and unreliable environments.

3. *Immutability*, since a block, thanks to the use of hash functions, once added, can be changed only having an extremely high computing power in case of permissionless blockchain (more than the one used for mining the single block) or with the approval of most of the participants in the network in the case of permissioned blockchain.

4. *Confidence*, since there is a shared reading among all the participants.

5. *Efficiency* (to be evaluated case by case), since it can not require intermediaries than the classic transaction management system, thus simplifying processes, infrastructures and increasing operational efficiency.

6. *Control* and *security*, since it allows the use of cryptography allowing greater data protection and lower risk of fraud.

As already mentioned, the blockchain is not the only alternative for storing a small amount of data of transactions and using them. The works in [4] and [5] offer a flow diagram that allows assessing whether the considered application really needs a blockchain-based approach or not. In the flow diagram, a few features are considered "basic requirements" for applying blockchain. These are:

- multiparty;

- decentralised operation;

- need for transactions history;

- no need for high speed for the process.

The blockchain is the digital paradigm that allows to guarantee the security and immutability of shared data, as it is an immutable and time-stamped series record of data that is distributed and managed by cluster of computers. Thanks to the advantages it provides compared to classic centralised databases, today many companies are investing on the use of this new technology to develop and test many applications in different sectors.

1.2 Application fields

The word "blockchain" is synonymous of technological innovation, especially when used in those sectors where security of exchanged data, transparency and trust take priority. Blockchain is considered a next generation information technology with many potential benefits in several fields beyond digital currencies. As mentioned before, the first application of blockchain technology was the cryptocurrency Bitcoin, but blockchain represents a much bigger opportunity than Bitcoin. The most important feature of this new technology is the possibility to perform transactional activities of any kind without a trusted third party. So Bitcoin, and the technology introduced with it, is much more than a digital currency; the blockchain is an information technology. This technology is one of the first major identifiable implementations of decentralisation models that have the potential to reorganise all sorts of human activities thanks to their ability to provide frictionless and trust free interaction between people and technology [6], [7]. Below are the different sectors in which the use of blockchain technology is having the most success.

1.2.1 Cryptocurrency and Finance

The most widely accepted application for blockchain technology is in the field of finance, especially in the field of cryptocurrency, as it ensures the much appreciated transparency between the parties. Unlike classical currencies, cryptocurrencies do not involve coins or cash, as all payment units are exclusively digital. These cryptocurrencies are generally generated collectively across the whole system and, in most cases, when a cryptocurrency is launched, a defined number of units is established. The concept of "mining" (extraction) for the process of generating units has become widespread, and this explains why we often hear talk of "cryptocurrency extraction". Both the generation system and the individual operations are performed collectively using the blockchain of that cryptocurrency. The similarity with real currencies that include banknotes and coins is the fact that several cryptocurrencies, in addition to Bitcoin, such as Ethereum, have a countervalue (demand and users). If the units of a cryptocurrency possess a certain countervalue, convertible into central bank currencies such as Euro, the prerequisite for its use as a means of payment is basically fulfilled. But in order to actually pay with digital money, the seller must also accept the respective cryptocurrency as a means of payment. A key pair, consisting of a public and a private key, is required to execute the payment. The public key is visible to everyone and has the same function as a bank account number: it serves as the starting address from which a user initiates a payment with the respective cryptocurrency. The private key is used to verify the transaction. Only the owner of the respective account can see the key used to sign the transaction. When making the payment, users only have to enter the amount and the destination address, i.e. the beneficiary's public key. To date, there are almost 3000 different cryptocurrencies, but not all of them are reliable or well established in the market. Among the most famous and used are Ethereum, Ripple, IOTA, Litecoin, Bitcoin Cash and Monero. The use of cryptocurrency allows you to take advantage of all the features provided by the blockchain, but there are also disadvantages such as large fluctuations in value, possible hacker attacks, exclusively virtual money, no access to the account after the loss of the private key and no loss insurance.

In addition to its use in the field of cryptocurrency, the blockchain is increasingly being used in other financial services, such as stock exchanges, payments, repurchase agreements and digital identities. Many banks and financial institutions have also started to invest in blockchain in recent years [7]–[9].

1.2.2 Healthcare

The healthcare sector is also investing in blockchain projects. All the features of blockchain technology make it possible to create collaborative processes between multiple parties without the need for a third party and without necessarily trusting the players in the network, while at the same time ensuring transaction validity, tamper resistance, certainty of immutability, authenticity and origin of data and their integrity, transparency and ease of control. These characteristics are of great interest to healthcare organizations. Thanks to the blockchain, the management of patients, medical records and health data promises to be more secure, as part of a sharable and unchangeable database that can be consulted by medical staff, while respecting patient privacy. In addition, medical records that are scattered due to transfer between different healthcare institutions can be combined to provide an opportunity to monitor the personal health of patients. It could facilitate the adoption of the Electronic Health File because, to date, each clinic/doctor's office generates a different file for the same patient. Thanks to the blockchain, it should be easier to archive the complete clinical history of patients, both those coming from health care facilities and from the Apps used by individuals to monitor pressure, heart rate, medication intake, etc... In this way the patient is also safer. His clinical history is shared and not modifiable, the doctors who treat him can verify, for example, which drugs have been prescribed, avoiding the use of incompatible drugs that are dangerous for his health. In addition, the blockchain could also offer benefits for health service payment processes, traceability of drug deliveries, validation of patient identity and consent to the processing of health data. Rather than having individual facilities manage the data, it would be possible to electronically attach consent to the data, thus giving the patient the opportunity to express consent for specific data analysis and processing purposes and specific privacy preferences. In Europe, there are many initiatives in this area [10], [11].

1.2.3 Agribusiness

It has always been very complex in the agri-food sector to maintain the authenticity and ownership of products, with the consequent introduction into the market of falsified products, uncertain prevention, imitations or unauthorized resale and processes that have not always guaranteed the complete transparency of the supply chain. Food traceability is the ability to keep track of every food or feed or substance that is used for consumption, and all the processes they have undergone, through all stages of the chain. Tracking food is for the benefit of both the consumer and the producer. The consumer, today more and more careful about the information about a certain product, wants to know in a clear and certified way information about the product he is consuming, while the producer would like to better manage stocks, reduce waste and open new market opportunities.

The blockchain system can be used as an innovative solution for the transparent certification of agricultural products, able to enhance the relationship of trust between the consumer and the agri-food chain, promoting high quality agricultural work as a guarantee of the food safety of the citizen and contributing to improve transparency and protection of the mark of origin for the benefit of consumers and businesses. In the agri-food sector, the blockchain makes it possible to trace a food product right from the cultivation and then from the geo-location of the cultivated land, retracing the supply chain to the retailer of this product in a meticulous and immutable way. In this way, an increase in security, speed and confidentiality of information throughout the supply can be achieved.

Since 2017, there has been a significant increase in blockchain applications in the agri-food sector [12], [13], mostly to support the traceability process. One of the most recent is SeedsBit [14], an innovative blockchain platform developed by the SNAPPLab of the University of Palermo for tracking and tracing of food products and related production processes.

The stakeholders have strong confidence in the guarantee of the immutability of the information promised by the blockchain platforms, in the improvement of the transparency along the supply chain and in increasing the effectiveness and efficiency of data recovery processes in case of food safety critical situations.

1.2.4 Insurance

Traditional insurance policies are often processed on paper contracts, which means that claims and payments are subject to errors and often require human supervision. Moreover, most of the time, claims management is long and therefore expensive. The digitization of data and the use of blockchain in the insurance universe has the potential to automate many processes, such as claims management, thereby reducing the associated costs compared to traditional management. Blockchain and smart contracts would ensure the confidentiality of information and the automatic execution of contracts in the event of a claim, allowing the process of issuing and managing policies to be optimized, with immediate and certain settlement of damage to policyholders. smart contracts play a key role in this area, as they could for example encode the conditions to allow the transfer of the refund from the insurance company to the insured or activate an automatic refund transfer only if the customer, following a car crash, repairs the car at a car repair shop whose identity has been certified. The use cases are many and range from the processing of claims to the simplification of routine interactions and from risk prevention to property and accident insurance [15]. The use of the blockchain in the insurance industry would eliminate fraud and simplify many processes that are usually long and difficult to manage.

From a system architecture point of view, the most appropriate choice could be to adopt a combination of public and private blockchain, where the private blockchain, managed by the nodes of a trusted third party company, could be used to record claims policies and data, while the public blockchain could be used for reimbursement in terms of cryptocurrency tradable on the markets (e.g., Ether, Bitcoin). Alternatively, the insurance company may decide to use only a public blockchain, agreeing to incur higher transaction costs in order to improve its reputation and gain customer confidence with the guarantee of full decentralisation.

Today, several companies, such as IBM, Allianz and KPMG are developing several projects in this area.

1.2.5 Copyright protection

Property monitoring has always been a difficult topic, especially with the development of the internet and social media. From peer-to-peer file sharing services such as Napster to web-based photographs, copyright has not always been respected. From the point of view of a file holder, copyright is often ignored. Therefore, unauthorized (even illegal) file sharing and the use of copyrighted content remains a significant problem. Blockchain technology is a solution that can be applied to solve these problems. Considering that a file is duplicated thousands of times over the network, this network is designed to regularly update and reconcile all copies so that all records are consistent. No single computer or organization is responsible for the blockchain. The property of not having a central storage location makes manipulation or corruption almost impossible. Starting with the basic record, all changes added to the ledger can never be altered. Therefore, whenever a copyrighted file is used illegally, a digital ledger containing the owner's information and detailed transaction history is truly public and easily verifiable.

For example, Binded [16] presents itself as "the world's first copyright platform" for blockchain, creating "a unique fingerprint (cryptographic hash) for each copyright record. By tracking copyright records, Binded facilitates copyright protection by allowing access to the circulation path of copyright knowledge through the blockchain. With a fingerprint at their fingertips, photo owners can monitor the online sites that use them. A demonstration of the attractiveness of this technology by large companies in the industry was given by Spotify. The multinational company, leader in music streaming, bought a start-up called "Mediachain Labs" [17] which developed a decentralised database of multimedia content and an automatic attribution engine. When the system recognizes the use of content registered on the platform, it automatically remunerates the right owner with a dedicated cryptocurrency. Another very interesting platform is Monegraph [18] which, in addition to allowing anyone to register their creative work on Bitcoin's blockchain, offers a number of additional services that allow users to avoid having to rely on intermediaries to manage the sale of licences. Through this system, in fact, the rights holder can freely set prices and conditions and, at the same time, receive payments.

However, there are also limitations to copyright protection such as initial authentication when uploading a file, such as proving ownership when a user uploads something. Other limitations, such as monitoring issues, the use of anonymous and untraceable buyer licenses are still to be resolved.

1.2.6 Voting

Voting is a fundamental element of any collaboration between people, with methods ranging from a show of hands to the ballot box, to new online voting systems. Traditional voting systems present various problems both in terms of security and cost. Just think of the system of balloting that can be manipulated to make the vote take the desired turn and the cumbersome system of counting the votes that requires a lot of labor and can not always be considered transparent as voters must trust electoral commissions, regardless of the high cost of elections. Internet voting (e-voting or online voting) allows voters to transmit their votes remotely from any computer connected to the Internet, potentially from anywhere in the world. Managing voting through online platforms is not an easy task, as on the one hand it is necessary to guarantee the privacy of the voter, both in terms of identity and preference expressed by the vote; on the other hand it is necessary to be able to have a certain degree of verifiability, i.e. to make the vote expressed by the voters represent their exact preference and above all is not manipulated.

Online voting systems save a lot of money for elections because voting and counting activities are digitalized, but security issues can arise. The security of an online voting system is necessary to ensure the reliability of the result and the confidence of the voter in the voting system itself. Trust requires sufficient transparency to allow the voter to accept the results of the vote without reservation. An e-voting method must therefore be developed with great consideration for certain key aspects of computer security and data protection. First of all, it is necessary to guarantee the authenticity of the preferences expressed by voters in order to ensure an exact final count. To achieve this goal, it is necessary to ensure that each vote is recorded without any possibility of change and to eliminate the possibility that voters may exploit imperfections in the system to vote more than once, while remaining anonymous. Therefore, e-voting systems should be robust and reliable enough to ensure the exact correspondence between the votes expressed and the votes recorded, despite the occurrence of possible network communication losses, server failures or cyber-attacks.

The use of blockchain technology could solve most of the problems related to both traditional voting systems and e-voting systems. First it is possible to solve the problem of transparency of the counting process, as with the blockchain you can track votes, thus ensuring transparency and protecting privacy as transactions remain anonymous. Regarding the e-voting systems, using the blockchain would be impossible for a user to vote twice, as on a chain. Also thanks to the immutability of the blockchain, once the vote is inserted in a block and becomes part of the chain is impossible to remove or modify it. The whole voting process would be transparent, secure, fast and much cheaper than a traditional voting system.
Today there are several projects that offer online voting systems based on blockchain. Among the most famous are Polys and Crypto-Voting. Polys [19] is an online voting project developed by Kaspersky innovation hub based on blockchain that can be used by companies, universities and political parties. The system is based on the use of devices connected to each other through a blockchain network that allows you to transmit and process together, securely, all the votes: both those at a voting station using the Polys Voting Machine and those released on their own devices. Voters are authenticated with documents that prove their identity and receive a unique Qr code of which only the voter is aware. This code is necessary to access the voting system and to check, through a special web application, that the vote has been registered in the blockchain. For reasons of privacy and secrecy of votes, the name and choice, are not stored in the blockchain. The voting access code can be associated with an election in a specific area. This means that at the time of voting, the user is shown only the representatives for that vote specified even if the user is in a voting station located in another country. In addition, the automatic counting of votes significantly reduces personnel and resource costs for the organizers, allowing the results to be available as soon as the election is over, making the whole process much faster and more efficient. While, Crypto-Voting [20] is an innovative integrated electronic voting system based on Blockchain technology, funded by Sardegna Ricerche under the POR FESR Sardegna 2014-2020 and developed by the cooperation between Net Service S.p.A. and the Department of Mathematics and Informatics of the University of

Cagliari. The project aims to implement an online voting platform through the use of two concatenated permissioned blockchain: one to register the voters entitled and record the voting operation of the voters and another to count the votes assigned to the various candidates. The main purpose of the platform is to allow voters who are away from home or living abroad to vote remotely through mobile devices or personal computers. The voting operation consists of marking a symbol in a virtual ballot paper shown on the screen of your device. The voting process is divided into three phases, the first two, preparation of electoral lists and voting management, are performed on the first blockchain, while the third and final phase, the counting of votes, is performed on the second blockchain. This provides a transparent and public double ledger containing all voting results, which can be verified at all stages of the voting process.

1.2.7 Energy

The continuous growth of energy production from Renewable Energy Sources (RES) distributed throughout the territory has led to a change in the structure of the traditional electricity system and consequently of the energy transaction model. The electrical system was born as a centralised system, with power flows from production plants transferred through High Voltage transmission lines to Medium and Low Voltage grids to the end-users. The advent of distributed generation and small domestic production plants has led to a change in both the electricity system and the energy transaction model, from centralised to distributed, with power flows that are inverted on the distribution networks and with energy input to the grid at all voltage levels. Both distributed generation plants and small plants are decentralised and widespread in the territory, these, thanks to technological innovation, have undergone a fast evolution. Especially for domestic plants, production was initially intended for self-consumption while the surplus was fed into the grid. With the advent of storage systems, surplus energy started to be stored, but a share of the energy remained destined to the grid. This share started to reach important levels, both for the increasing number of producers and for the higher efficiency of the plants. In addition, the intermittent production from renewable sources, if not optimally managed, can compromise the stability of the electrical system. One solution could be the storage of this energy and the balanced Peer-to-Peer (P2P) exchange between end-users. The traditional energy transaction model, where each transaction is mediated by a third party, does not involve direct energy exchanges between end-users. The reason is mainly due to the lack of information technology that would allow this.

Thanks to its characteristics of decentralization, immutability, trust, transparency, traceability and total distribution over the network, the blockchain could be the solution to many problems if massively applied to the energy field.

This distributed technology is well suited to the energy applications because with the advent of RES, the grid is also becoming a distributed system, and the blockchain could, therefore, help to support the grid change and enable new business models for the energy market. For this reason, today many projects in the energy field are using blockchain technology.

In general, the applications of the blockchain in the energy field can be divided into two main categories:

- *Electricity trading*: includes all applications for which two parties exchange electricity with a unit of value, such as P2P energy trading. These can be managed centrally by a network operator (DSO or TSO) who will verify the correspondence of the exchanges in order to obtain the maximum benefit in technical terms for the network or they can be managed in a distributed way, as in some cases the constraints of the network are not so rigid.

- *Renewable energy certification* and *demand traceability*: includes applications related to the certification of energy from renewable sources and the traceability of demand/response aggregation. In this case, the blockchain records the injection of green energy into a site in the grid or recognizes the participation of a certain prosumer in an aggregation program or a demand response program, improving transparency on the certification of renewable energy or the mechanisms of remuneration of demand response services.

The possible applications are many, but the most popular and promising are: P2P energy trading, Vehicle-to-Grid (V2G) and Demand-Response (DR).

Before the advent of blockchain, it was difficult, if not impossible, to perform energy transactions between end-users in a safe and transparent way, as the market and the electricity system were structured so that energy transactions were centralised and managed by trusted entities. The blockchain, thanks to its features and advantages, has become very famous for enabling the trade of P2P electricity between small producers and consumers, especially within the microgrid.

Blockchain technology also offers many advantages when applied to automotive systems. With this in mind, the so-called V2G applications have been developed in recent years. V2G represents a system for management, storage and distribution of energy by batteries of electric cars, allowing also to guarantee their diffusion at more convenient prices. Thanks to this technology and the integration between electric vehicles and the grid, owners have the possibility to use their car as a mobile power station integrated into the grid, so that the energy stored in the batteries can be transferred to the grid in case of demand or to other vehicles. In parallel to facilitating transactions between vehicles or vehicles and grid, the implementation of blockchain-based solutions could solve some problems related to the after-sales of the vehicles, such as the traceability of original spare parts, identification of counterfeit parts or the recovery of the vehicle at the end of its life in a circular-economy perspective. To date, it is virtually impossible to find this information because it is either inaccurate/incomplete at the time of transmission or has been modified by hackers. In this sense, the blockchain offers a more secure and transparent way to communicate thanks to the continuous sharing of information between nodes of the same and the increased difficulty of tampering with individual blocks.

In addition to P2P energy exchange and V2G applications the blockchain offers the possibility of allowing the exchange of energy services rather than the direct exchange of energy between two users or user and network. To respond to power fluctuations due to RES penetration into the electrical system, DR management is a very effective solution. In general, DR is a structured program that aims to change the load profile of users in response to problems on the grid, such as congestion or temporary unavailability of electricity caused by failures or intermittent production from non-dispatchable RES.

Using the blockchain, DR programs can be run directly between the network operator and users, unlike the current scenario in which the aggregator mediates between the user and the network operator. In this case: the TSO/DSO requires a reduction/increase of the load and users respond accordingly by reducing or increasing the load. The transaction is not a direct energy exchange between two parties, but a request to provide a service, where users will then be remunerated if they respond adequately. One of the main problems in the provision of traditional DR service is the lack of transparency between the different parties involved, but through the blockchain it is possible to manage this problem. In addition, the blockchain allows small prosumers to participate in capacity and balancing markets by aggregating them into virtual load units that can be managed as needed.

These three applications, as well as the Energy Communities introduced by the European Directive on the use of renewable energy sources, are new ways of organising energy resources, necessary to achieve the objectives of energy savings and RES penetration set for 2030.

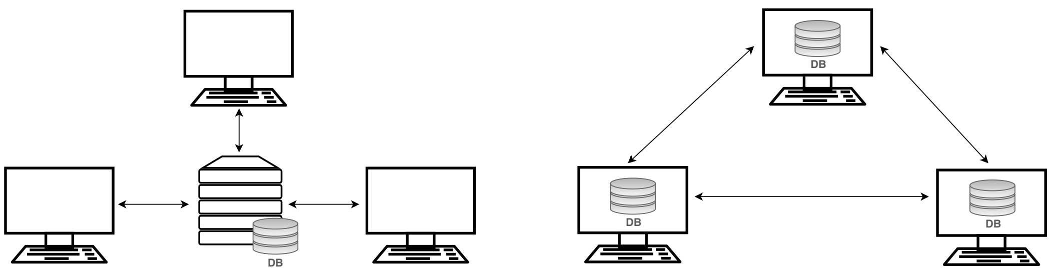
More details on Energy Communities are given in 2, while the P2P, V2G and DR applications and their experiences are outlined in chapter 3.

1.3 Blockchain technology fundamental principles

1.3.1 Distributed and centralised systems

The data management computer systems, based on the place where the database (DB) is located, are divided into centralised and distributed.

A computer system is called centralised when the DB containing the data and applications is located on a single processing node. The DB can be local if it is located on the same computer of the user, or remote if it is located on another computer or server where one or more users can access remotely (see figure 1.3 (a)). Depending on the mode of operation, centralised systems are divided into single-user systems, in which services are aimed at one person at a time, or multi-user systems, when both data and management application programs are placed on a server accessible from client computers through a network of computers (client-server architecture). While, a system is called distributed when the applications, between them cooperating, or the DB are located in two or more computers connected in a local or geographical network. In general terms, a distributed system consists of a set of logically independent applications that work together to pursue common goals through a hardware and software communication infrastructure. The DB can be located in several computers located in the same place, or distributed in a network of computers connected to each other in the form of a distributed system (see figure 1.3 (b)). The data on a distributed network are data with information constituting a single logical structure but physically stored on several autonomous computers and connected through a network. The location of the data is transparent to the users' applications and the information is available for use by different applications and users in the network of computers, regardless of the geographical location where the data is stored.



(a) (b)

FIGURE 1.3: Centralised (a) and distributed (b) networks.

The two main advantages of centralised systems are:

- *High security*, since the database is managed by a single central authority that controls "who can do what" in the system.

- *Data protection*, since the data and programs all reside on the same DB, one update applies to all, one backup applies to all.

On the other hand, although efficient from a data protection point of view, centralised systems are characterized by several disadvantages:

- *No transparency*, since the DB is governed by a central authority that can theoretically modify the data.

- Applications are run on a single process that represents the only component of the system, so there is *one single point of failure*.

- *Slow execution* and *poor interactivity* depending on the number of users connected to the central computer at a given time.

In general, the centralised systems are more vulnerable in the event of a cyber-attack, but they are good when the party that controls the system is reliable and behaves honestly.

In distributed systems, each processing node has the same capabilities and the same level of access to complete information. This provides a solid foundation for trust, as it democratizes the entire system. Furthermore, since the data is stored on all the nodes of the system, in the event of a cyber-attack there is no single point of failure, so the system can continue working. In general, distributed system, and so the blockchain, is more suitable in cases where there is more than one administrative authority and there is a lack of trust between these parties [21]. So the main advantages are:

- *Transparency*, since there is no authority managing the system and all data is accessible and owned by all users.

- *Reliability* and *fault tolerance*, because thanks to the redundancy of the process nodes in case of failure of one of them the system will continue to operate.

- *Scalability*, since as the requests increase, the system can be expanded with simplicity because high computing power is not required for individual nodes, and the more nodes there are in the network the more resources are made available.

- *Economicity*, since the computing power is distributed among the different processing nodes, rather than concentrated on a single node as for centralised systems.

- *Integration*, since it allows to connect different machines, even different ones, as long as they are able to interface to the same communication subsystem.

Distributed systems therefore allow to solve problems that afflict centralised systems, but they also have disadvantages, such as:

- *Complexity*, since it is needed to manage several nodes at the same time rather than a single node.

- *Security*, since it is difficult to control access, the distribution of data is intrinsically insecure and each user may theoretically modify some data.
- *Communication*, because in order for a distributed system to be efficient, high standards of communication are required.

The blockchain technology is a DLT, so a technology that is based on the distribution of the database over multiple nodes but that allows to overcome the security problems that afflict distributed systems through the use of encryption. Security is achieved through the use of consensus algorithms that are more or less complex, depending on whether the blockchain is permissionless or permissioned. In permissioned blockchain, a new user needs the prior approval of an entity before joining, while permissionless blockchain allows anyone to participate in the network. In permissioned blockchain, the identity of participants is known, while in permissionless blockchain participants are anonymous. Data security and trust between participants is achieved by using the consensus algorithms. A consensus algorithm can be defined as the mechanism by which a blockchain achieves consensus on the validity of transaction blocks and thus the data recorded on the blockchain. In a permissioned blockchain they are lighter as users need a permission to participate in it and therefore they are known and theoretically trusted. While, the consensus algorithms are more complex in a permissionless network because users are anonymous and the consensus algorithm has the task of ensuring trust between users. In addition to consensus algorithms, blockchains also make extensive use of cryptography to maintain the security and immutability of the registry, or the use of smart contracts to execute or validate transactions. Below, the consensus process with the most widely used algorithms and smart contracts are better explained by referring to blockchain both permissionless and permissioned.

1.3.2 Consensus algorithms

As the name "consensus" suggests, it consists of finding an agreement on the validity of something, in this case transactions and, then, the blocks can be inserted in the blockchain. This mechanism makes it possible to eliminate the trusted third party of traditional centralised systems, so it can be said that it is the most important part of the blockchain execution. In blockchain applications, consensus on the validity of transactions, and therefore blocks, is achieved by running consensus algorithms, which are more or less complicated and can be based on different principles such as solving a puzzle or a simple voting mechanism. Consensus algorithms must ensure the so-called Byzantine Fault Tolerance (BTF), so they must allow the distributed system to work even if some nodes fail or act dishonestly. The complexity of the algorithm depends on whether the blockchain is permissioned or permissionless. Usually, these algorithms are more computationally-intensive in the permissionless blockchain, as users are unknown and therefore the consensus algorithms is necessary to ensure that the users are not malicious and the consistency of the data stored in the blockchain. On the other hand, permissioned blockchain use lighter consensus algorithms only necessary to ensure the integrity of the data exchanged, as users are known and usually there is no need to verify that a user is malicious. The most famous consensus mechanism that ensures the BTF is the Proof of Work (PoW), used in Bitcoin [1], where the user who adds a new block on the chain is the one who solves a computationally-intensive problem before the others. In Bitcoin, users competing for the insertion of new blocks are called "miners", because the system, as a result of the effort made to solve the algorithm, pays the user a fixed number of new bitcoins. Being a permissionless blockchain, in Bitcoin anyone can be a network node and can theoretically run the consensus algorithm and compete for new blocks insertion, earning both the bitcoins issued by the system and the fee that users pay to miners to have their transaction inserted into a new block. The higher the computational power, the higher the probability of validating a block, but once the algorithm is resolved and a new valid block is found, it must be approved by 51% of the nodes of the entire network, otherwise the block will be rejected and the miner will not be remunerated. In addition, as the network grows in size, to maintain high security, the power consumption needed to perform the consensus operations also increases. Theoretically a malicious user could insert a false transaction within a block and validate it, but the block would not be approved by the other nodes and therefore discarded. Due to the high energy consumption for the execution of the algorithm, to date about 600 kWh per transaction [22], and the impossibility to own 51% of the network nodes, a malicious user can't insert a transaction that is not true. Therefore, thanks to this mechanism, not only are malicious users eliminated from the system but also miners are forced to validate the blocks correctly, otherwise they would not be remunerated and the mechanism would become economically unsustainable due to the high costs in terms of energy consumption.

An alternative way to PoW to reach consensus, requiring much less computational effort and this energy consumption, is the Proof of Stake (PoS) consensus. Unlike PoW, where the algorithm rewards miners who solve the algorithm with the aim of validating transactions and creating new blocks, with PoS, the creator of a new block is chosen depending on its wealth, also called "stake". The larger the stake, i.e. the amount of digital currency owned by a user, the greater the probability that the system is not being hacked. Furthermore, the more an individual is exposed to a cryptocurrency, the more likely it is that he or she is behaving optimally. In the blockchains that use PoS there is no reward for generating the new block, all digital currencies were created at the beginning and their number never changes. In fact, in these systems, the miners are called "forgers". They do not earn on the reward for generating a new block, but on transaction fees. Finally, in blockchains that use PoS, participants with significant cryptocurrency are selected on a pseudo-random basis not to extract but to coin the blocks and add them to the blockchain. The pseudo-random selection process starts after the system has analyzed several factors to ensure that only individuals with a higher stake are selected, but also others with a lower stake. To date, Ethereum's blockchain uses PoW to validate blocks, but for several years its creators have been planning to switch to PoS with a protocol called "Casper" [23] because of the high power consumption needed to feed the PoW process. Today, a Bitcoin transaction requires the same amount of electricity to power an American family for 19 days [22]. And these energy costs are paid in fiat coins, leading to constant downward pressure on the value of the digital currency. For this reason, Ethereum developers would like to leverage PoS for a "greener" and therefore less expensive distributed consensus. One of the weaknesses of PoS is security. In a PoW system, due to the high cost of executing an attack, a hacker would risk spending more than he would earn, so malicious users are excluded. A system that uses PoS without particular penalties might be cheaper to attack. For this reason, the Casper protocol provides in some circumstances for the loss of the deposit that the (malicious) user has deposited to participate in the creation of new blocks and of his privilege to be part of the consensus mechanism. Another solution could be to increase the price of the cryptocurrency, thereby increasing the cost of attacks.

The kind, and related complexity, of a consensus algorithm strongly characterizes each blockchain technology since it is on the nature and strength of the distributed consensus that the security of the blockchain is based. It is the consensus management model that determines the difference between permissionless and permissioned blockchain. In a permissionless blockchain, trust between users, which are anonymous, is ensured by the consensus algorithm. While, in a permissioned blockchain, where the users are known and allowed by an administrator of the network, it is possible to use lighter consensus algorithms. Usually, in a permissioned Blockchain, a central authority determines who can access it, defines who is authorized to be part of the network and the roles a user can have. Within these networks, the validators are known, so there is no risk of a 51% attack resulting from miners collusion. As a result, transactions are cheaper, as they are verified only by a few nodes, called validators, which are considered trusted. When the consensus is performed by a group of known and reputable nodes the mechanism is called Proof of Authority (PoA) [24]. Validators are member nodes authorized to participate in validating transactions and adding blocks to the blockchain. Knowing the identity of the miners means that their work does not have to be controlled and verified by the other nodes, further reducing the time and cost of execution. Since trust is not derived from the consensus algorithm used, simpler and faster algorithms can be used in permissioned networks. The most used are the practical-Byzantine-Fault-Tolerance (pBFT) algorithms, characterized by low complexity and high practicality in distributed systems. For the pBFT system to work, the number of malicious nodes must be less than or equal to 1/3 of all system nodes in a given vulnerability window. The more nodes in a pBFT network, the more secure it becomes. When a user sends a transaction request, it is received by a validator, then one of the validators is randomly elected "leader". When a new block is generated, the leader orders the transactions that should be included in the block and sends this list of ordered transactions to all other validators on the network. When each validator receives the list of the ordered transactions, it starts executing the transactions one by one. As soon as all transactions are executed, it calculates the hash code for the block. Then it transmits its response (the resulting hash) to the other validators on the network and starts counting their responses. If he sees that 2/3 of all validators have the same hash code, he will commit the new block on the blockchain.

The consensus mechanisms used for permissioned blockchain as well as PoS-based mechanisms offer the advantage of being more environment-friendly than PoW-based algorithms, as validators are not competing to find the solution to the mathematical quiz and therefore do not need to use the computational power typical of other types of consensus. In general, each consensus algorithm has disadvantages and advantages, each one is valid for some applications, others are not but, certainly, for the execution of an energy blockchain, algorithms very expensive in terms of computational resources are to be avoided.

1.3.3 Smart Contracts

Contracts are useful tools that have always been used when two or more parties want to establish, regulate or terminate a relationship of any kind. In the digital era, the blockchain technology offers many advantages in terms of transparency, information symmetry and disintermediation, but it also offers the possibility to implement the so-called "Smart Contract" (SC). A SC is defined as the "translation" into a code of a contract between the parties that can verify automatically specified and predefined conditions and execute actions when conditions between the parties are fulfilled and verified. So, it is a tool that guarantees the same trust as a traditional contract, but with the advantage of automatically verifying the terms of the contract, performing actions such as money transfer and assessing the situation, if one of the parties does not comply with the terms. SCs deployed by a blockchain are shared on network nodes and are usually executed to implement transaction logic and verify their validity, or to execute transactions automatically if certain conditions are met. SCs are stored on the blockchain, thus distributed, and no one has complete power over the contract. Moreover, being implemented on the blockchain, they inherit some interesting properties:

- *Immutability*, because after the creation, a SC can never be modified. No one can change the contract code, not even the creator of the contract itself.
- *Transparency*, because each blockchain user can view the SC's code and verify its validity.
- *Trust*, because the contract is distributed on the network and validated by the blockchain. A single node cannot force the contract against the specified features because the other nodes in the blockchain would not approve it.

In the blockchain world, the SCs were introduced with Ethereum [25], a global and open-source permissionless blockchain for decentralised applications that implements SCs for cryptocurrency transaction execution. The programming language used for Ethereum SCs is "Solidity", a Turing complete language, but not suitable for the implementation of complex codings such as the evaluation of optimal power flows or other optimization codes. Ethereum SCs are compiled in "bytecode" and are read and executed by a virtual machine called "Ethereum Virtual Machine" (EVM). Each node of the Ethereum network has its EVM, which represents the environment where SCs are executed. To write a transaction within the Ethereum blockchain, a SC is executed, and a fee is paid for this execution, whose currency is expressed in "gas". The amount of gas to be paid is directly proportional to the length and computational complexity of the SC to be performed, it is also possible to establish the value "gas price", i.e. the amount of Ether (the Ethereum cryptocurrency) per unit of gas you are willing to pay; The modification of this variable, affects the priority of recording of the transactions on the blockchain, in fact, with a higher gas price, the transaction will be recorded in a lower amount of time than a transaction made with gas price of lower value. There is therefore an increase in the speed of registration of the transaction, but with a higher price. Figure 1.4 shows the way in which Ethereum smart contracts are implemented referring to the energy exchange between two users.

As already said, Ethereum is a permissionless blockchain. The use of permissionless blockchains provides greater security in case data can be released publicly but, due to privacy and the computation time of the heavier consensus algorithms, may not be adequate for all applications.

A permissioned blockchain that implementes SC is Hyperledger Fabric [26], a platform designed for the use in business contexts, with a highly modular and configurable architecture that enables innovation and versatility for a wide range of use cases in the industry. Fabric, unlike Ethereum, supports SCs written in generic programming languages like Java, Go and Node.js. The SCs are called “chaincodes” and they work as a reliable distributed application that acquires its security/trust from the blockchain and the underlying consensus among the peers. In an Hyperledger Fabric network, the SC represents the main element of the network, because

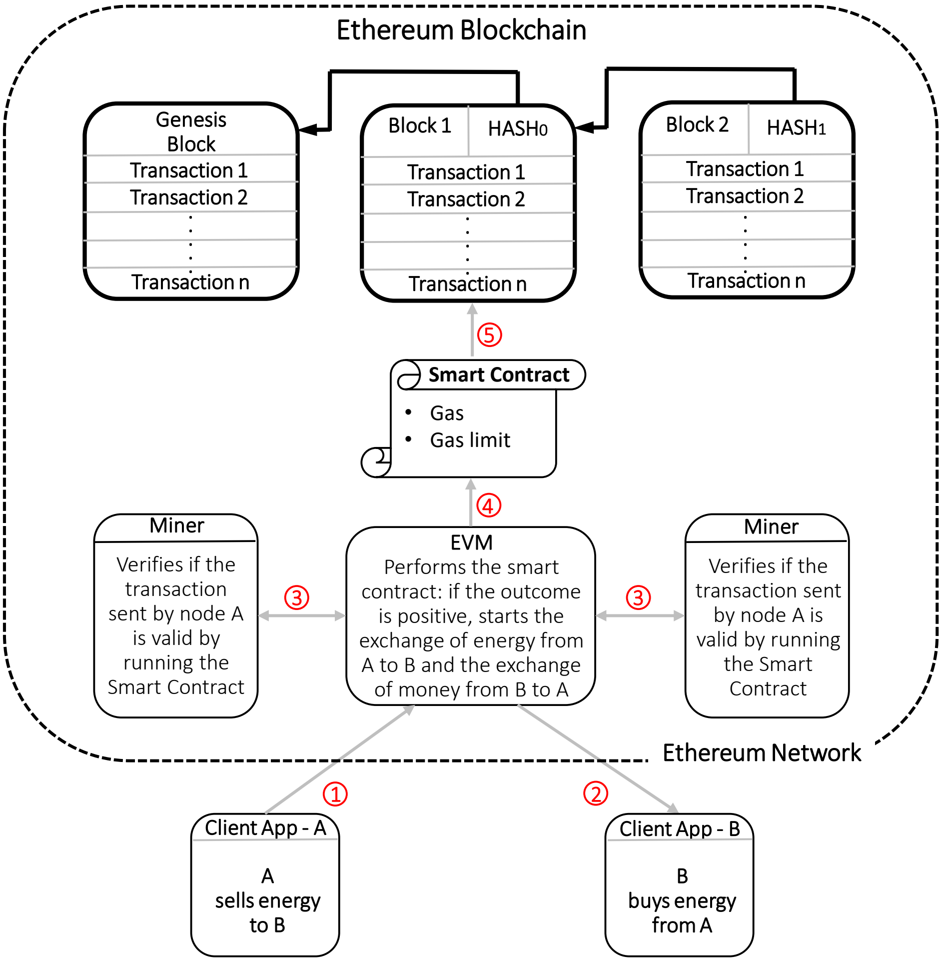


FIGURE 1.4: Ethereum Smart Contract implementation.

it is the component that implements the logic of each kind of transaction and verifies the integrity of each transaction sent by network users. The chaincodes are tools that allow the users to interact with the blockchain ledger, in fact any operation, even a simple query, is performed in Fabric through the SC. The SCs are installed on each peer, and every time a user sends a transaction proposal on the network, this transaction proposal is processed by the SCs of all peers. Then, if the transaction sent by the user is consistent with the logic implemented by the SC and verified by all peers, the new transaction after the consensus process is recorded in a new blockchain block. The whole process to record an energy transaction and all the components of the network are shown in figure 1.5.

In conclusion, we can say that the SCs are software programs that allow the transfer of ownership of any digitally identifiable good from one person to another or the implementation of the transaction logic for a given application. In P2P electricity transactions, as an example, the SC can be used to execute energy transactions directly when the trading conditions set by the prosumers are met, or to assign to the prosumers digital tokens corresponding to the energy injected into the grid and destroy them as the user consumes electricity [27]. Tokens are issued by the blockchain platform. They can either represent, as in this case, the representation of a digital asset, or they can be used as a payment (payment token), or they can prove the ownership of a right (service or utility token). Such right can be related to the property of a financial asset (service token) or to the possibility to obtain a service/benefit

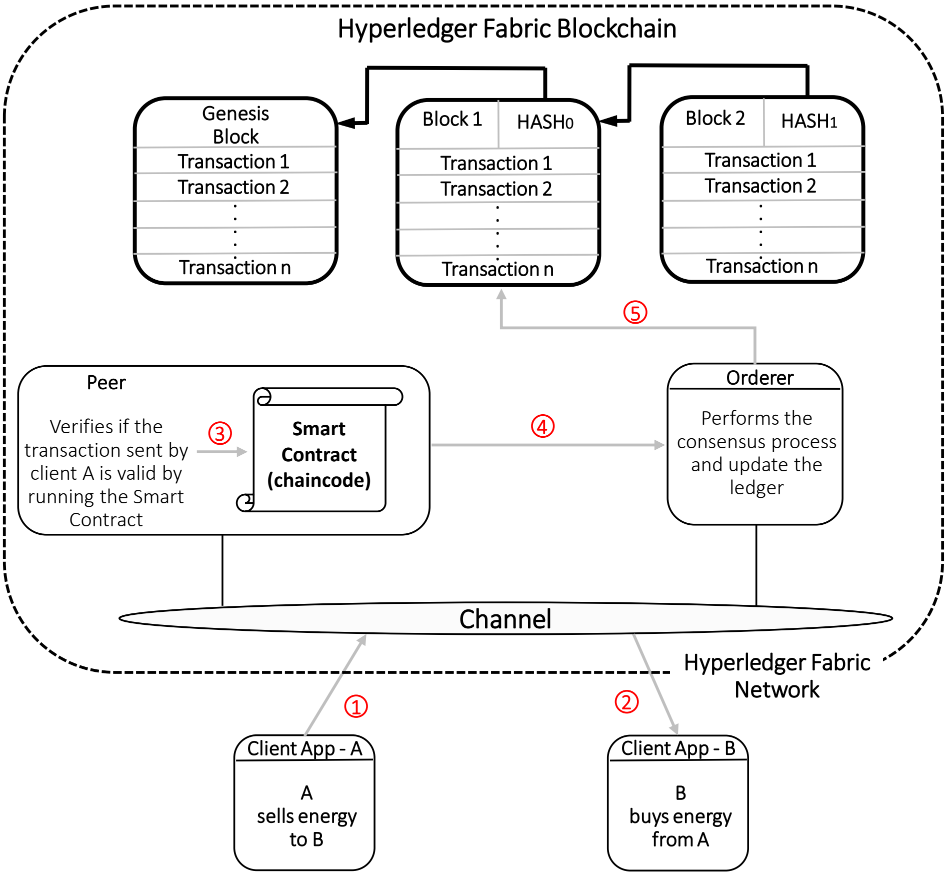


FIGURE 1.5: Hyperledger Fabric Smart Contract implementation.

(utility token) through the platform. In the DR applications, tokens can be used to implement the logic of the DR programs, to certify the energy service provided by users through remuneration [28]. For V2G applications the SCs can be used to certify the car charging or to implement the logic for the network support services provided by the electric vehicles [29].

1.3.4 Blockchain and General Data Protection Regulation

In the previous paragraphs, it has been explained how a blockchain works, its characteristics, types and different consensus processes, but the protection of personal data of users participating in it has still not been mentioned. The General Data Protection Regulation (GDPR) became effective on 24 May 2016 and applied in EU countries from 25 May 2018, with the aim of providing guidelines for the protection of personal data in computer systems, including the blockchain [30]. The GDPR introduces a system of governance of personal data based on a responsible figure called "Data Controller", who is also the data controller. The latter must prevent and correct any errors and must also be able to demonstrate compliance with GDPR to the authority, for example through internal documentation or policies. The innovation but also the problems of the blockchain arise from the fact that it proposes to transmit and store information on an immutable decentralised register, validated not by a traditional central authority (such as a bank or government) but by the "public" itself. The core of this technology is the decentralization, transparency and immutability of data, concepts that seem contrary to the directives of the GDPR.

The GDPR provides the six essential principles for data protection:

1. treatment must be lawful, fair and transparent;
2. the processing of data must be limited to the specific purpose for which they were originally collected (purpose limitation);
3. it is possible to collect only the data absolutely necessary for the specific purpose (data minimization);
4. data must be accurate and up-to-date (accuracy);
5. data must not be kept longer than necessary (retention limitation);
6. data must be processed securely (integrity and confidentiality).

Most issues in the compatibility between GDPR and blockchain relate to permissionless blockchain, such as Bitcoin, which are open, without ownership and designed not to be controlled. In this case, indeed, all participants can act as validators. Conversely, permissioned blockchains, although decentralised, allow access to a limited number of users, who obey to strict rules and own given features. The GDPR was created to be applied to a centralised context, so one of the first problems to find compliance is the difficulty of identifying a Data Controller in the blockchain. A direct consequence is that in case of dispute, there is no competent jurisdiction, since there is no one responsible for the data. Then, according to the fifth principle of GDPR, the data must be kept for a period of time no longer than is necessary to achieve the purposes for which they are processed. The blockchain does not allow to delete data once written in the chain. Finally, according to the GDPR, personal data may be transferred to a third country if the Commission has decided that the third country ensures an adequate level of protection. In the permissionless blockchain, it is complicated to verify these guarantees as users from all over the world can participate. On the other hand, in the permissioned blockchain, it is possible to overcome this problem through the use of specific clauses.

Contrary to how it may seem at a first analysis, thanks to the characteristics of immutability and replication, the blockchain can play a key role in GDPR. If designed correctly it is able to ensure transparency and control of personal data. In fact encryption and decentralised structure make the blockchain network very resistant to tampering and its transparent nature offers clear access to data in line with the objective of returning control and visibility of the data. The blockchain offers a radically different approach to computer security, which can go so far as to certify the identity of a user, ensure the security of transactions and communications and protect the infrastructure that supports operations between organizations. A paradigm shift that can allow you to take full advantage of shared online services. Regarding the ownership of personal data there is the possibility to choose different options. The use of permissioned blockchain implies the presence of a network administrator, which is also responsible for of user identity management. For example, in the energy sector the role of administrator of the network is different depending on the application:

- in P2P it could be the DSO because responsible for the correct operation of the low and medium voltage grid;
- in V2G the recharging column aggregator which "sells" capacity to the system operator;

- in the DR, it could be the TSO as responsible for the processes of regulation of the electricity grid;
- in the energy communities the administrator of condominium or the head of the community.

More complex solutions provide the possibility to store personal data outside the blockchain, registering only a link of these within the ledger. So, the blockchain would only be used to store evidence that some data exist rather than to store the data themselves, thus allowing the removal of personal data without breaking the chain. Some projects are analysing the use of particular hash functions that add an electronic lock between the different blocks, giving an administrator the digital key to unlock and modify them.

Table 1.1 summarize the main requirements of the GDPR and how the use of blockchain technology (permissioned) allows to fulfill them.

TABLE 1.1: Compliance between GDPR requirements and blockchain.

GDPR requirements	***Permissioned Blockchain***	***Permissionless Blockchain***
Data Controller identification	The Data Controller can be the network administrator or a user chosen for the purpose.	Difficult to identify, each user can be a validator.
Competent jurisdiction identification	The administrator can represent a competent jurisdiction in case of dispute.	Difficult to identify.
Data retention limitation	It does not allow to delete data once written in the chain, but there is the possibility to store on the blockchain the link of data stored externally.	It does not allow to delete data once written in the chain, but there is the possibility to store on the blockchain the link of data stored externally.
Identification of a commission for the transfer of personal data to a third country	The problem can be overcome through the use of contractual clauses or certification mechanisms	Difficult to track the location of the participants.
Data transparency and security	Encryption, decentralised structure and immutability ensure security and transparency of personal data.	Encryption, decentralised structure and immutability ensure security and transparency of personal data.

Having assessed the compatibility between blockchain and GDPR, other regulatory aspects remain open. In fact, in Italy, several projects define new business models and propose improvements to existing ones, but in order to move from the definition phase to the market one, a legislative step is required to extend the recent legislation on energy communities and V2G recognizing the role of new technologies in the technical management and economic of electricity distribution networks. These topics will be discussed in more detail in the next chapter.

Chapter 2

Regulations, Business Model and Actors in the Energy Market

2.1 Introduction

The electricity market is a particular market with an inherent complexity. The mechanisms that regulate the movement of energy volumes are managed in a precise and systematic order to ensure transparency and competition on the one hand, and reliability and continuity of service on the other. The electricity market is made up of several well-defined phases, and in each phase one or more players can operate according to the purpose of the market phase itself. There are many players involved in the energy business, each with its own role and identity. In general they can be distinguished: *Prosumers*, *Aggregators*, *Energy Market Manager*, *Balance Responsible Party*, *Balance Service Provider*, *TSO*, *DSO* and *Energy Retailer*. As the electricity system evolves, the electricity market and the role of the different actors is also changing, enabling new business models that need to be properly regulated.

This chapter aims to describe the various phases of the Italian electricity market and the actors involved in each phase, defining their functions and tasks, the new business models and the main regulations. Special attention is paid to the players involved in regulatory services and, consequently, to transactions connected to the balancing of the electricity grid.

2.2 The Italian electricity market

The electricity from the generation plants is transported to consumers through the power grid, an articulated system of cables and infrastructures. The power grid uses high voltages for transport over long distances to reach the consumer with lower voltage lines passing through substations. In the transmission phase, electrical power from large thermal-electric power plants or from renewable sources (injection points) is injected in a High-Voltage grid, called the transmission grid. The interconnections of this grid are the electrical stations (SST) from which the distribution networks start, at lower voltage (medium and low voltage) that supply the consumption points connected to them. The distribution takes place through a first transformation of the medium voltage current (15-20 kV) starting from primary cabins (i.e. transformer stations) connected to the transmission grid and from medium low voltage (below 1kV, generally 400 V) starting from secondary cabins, and then reaching the user at the applicable voltage value (230 V for residential and 400 V for industrial). This complex system is regulated by a central brain (Terna's National Control Centre). The TSO in Italy is Terna S.p.a., which is responsible for dispatching, i.e. the management of energy flows on the grid. This activity requires the monitoring of electricity flows and the application of the provisions necessary for the coordinated operation of the system elements, i.e. the production plants, the transmission grid and auxiliary services. The DSO, on the other hand, is in charge of the transport and delivery of electricity to the final customer, through the medium and low voltage distribution networks through the city networks. The DSO manages the distribution network and the meters of which he is the owner; he also takes care of the consumption reading, which he communicates later for the calculation of the energy bills. At the end of the supply chain there is the energy retailer (or sales company) that is responsible for the retail sale of energy to the end customer, buying energy from the electricity market or directly from producers and managing the commercial and administrative aspects related to the supply of energy.

The electricity market as it is constituted today is relatively young and constantly evolving. The electricity supply chain includes all the stages necessary for energy to be used correctly, from production to consumption. The figure 2.1 shows the *5 main stages* and the voltage level for each stage:

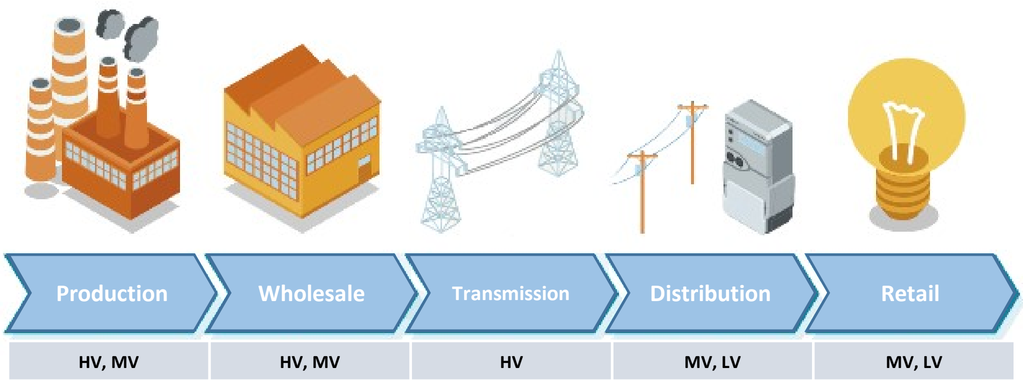


FIGURE 2.1: Main phases of the electricity supply chain.

In general, the production companies take care of the generation phase by transforming the sources in nature (renewable or fossil) into electricity. In wholesale, the production companies sell big quantities of energy to the companies responsible for retail sales. The energy produced and sold wholesale, is transported on the transmission grid, from the production companies to local distributors, on the national high-voltage grid. Subsequently, the distribution companies deal with the transformation of electricity from high to medium/low voltage and the distribution to end customers (houses, companies, public administration, ...). Finally, the retail companies manage the relationship with the final customer. In fact, they purchase electricity from the power exchange or directly from producers and manage all commercial and administrative aspects related to the supply of electricity.

In past times, as a state monopoly, the price of energy was imposed at national level and therefore there was no market for electricity. The turning point in the electricity business and the consequent birth of a real electricity market took place following the Legislative Decree 79/99, known as *Bersani Decree*: the objective of the decree, in line with the indications of the European Union, was to promote, according to the criteria of neutrality, transparency and objectivity, competition in the activities of production and sale of electricity, while ensuring adequate availability of dispatching services according to criteria of economic efficiency. A state-owned company (Ente Nazionale per l'Energia Elettrica, ENEL) whose objective was to manage the entire electricity supply chain was divided into several companies, each with a specific task related to the production, transmission, distribution and sale of energy. In 2004, the *electricity exchange* became operational and since July 1, 2007, the electricity market has been completely liberalized.

While pursuing economic logic, the electricity market is conditioned by certain technical constraints which must be taken into account to ensure safe and reliable operation of the power grid. The main constraint is the electricity infrastructure which, by its nature, is shared by all market players and has structural limits linked to the amount of transportable energy. Secondly, it is necessary to keep voltage and frequency within predefined limits by constantly balancing energy demand and production. Precisely for this reason the electricity market is divided into several sessions in which the volumes of energy are sold and purchased to meet both economic and technical requirements.

In an ideal condition, the market should be *nodal* and *instantaneous*: the term *nodal* refers to a market whose reference is the single node of the network while the term *instantaneous* refers to the possibility of balancing instant by instant the energy exchanged in each node. It is easy to understand how this condition is absolutely unreachable in the exercise of a very extended real network, which is why it was necessary to introduce new standards that would simplify the management of the network both from a temporal and spatial point of view. Regarding time, the standard market unit of measurement is generally *one hour*: a longer time span could lead to problems in maintaining the electricity balance, a shorter one would make it too complicated to conduct market operations. Instead, the space is managed with a division of the national territory into *market areas*.

Figure 2.2 shows said division and allows to distinguish 6 zones:

- **North** (Aosta Valley, Piedmont, Liguria, Lombardy, Trentino Alto Adige, Veneto, Friuli-Venezia Giulia, Emilia-Romagna).
- **Central North** (Tuscany, Umbria, Marches).
- **Central South** (Lazio, Abruzzo, Campania).
- **South** (Molise, Apulia, Basilicata, Calabria).
- **Sicily**.
- **Sardinia**.

If there are relevant nodes within a zone, it is possible for them to conduct an ad hoc *nodal market*; in the absence of particular differences between nodes, the market is configured as *zonal market*. The greater the extension of a zone, the greater will be the network constraints present and therefore more complex will be the operations of adjustment of power flows to ensure electricity balance. The price of electricity is defined zone by zone in the power exchange: on the basis of zone prices the *Prezzo Unico Nazionale* (PUN) is calculated, defined as the weighted average of the zonal prices of the *Day Ahead Market* (Mercato del Giorno Prima, MGP) in relation to total purchases. The value of the PUN is therefore not fixed but varies in relation to supply and demand and tends to change from hour to hour. In general, the PUN is high at times when it is more complex and expensive to produce energy while it tends to fall at times when energy production exceeds demand. Trading operations are conducted in two types of markets: *bilateral markets* and *exchange markets*. In bilateral markets supply and demand meet independently without the help of predefined platforms, unlike exchange markets where transactions are settled by organized platforms. Exchange markets are the most common in Europe also due to their

FIGURE 2.2: Italian electricity market zones.

higher efficiency and lower transaction costs. In general, the remuneration of energy volumes takes place in two different ways: *System Marginal Price* (SMP) or *Pay As Bid* (PAB). The SMP is a uniform price, the accepted bids are valued at the equilibrium price of the system, equal to the value of the last accepted bid (called *marginal offer*). The operators for sale obtain a revenue equal to the price of the marginal offer [€/MWh] multiplied by the total volume of energy sold on the market [MWh]. The PAB is a discriminatory price, the accepted bids are valued at the price offered for each of them. In general, the most used mode of remuneration is the SMP (i.e. MGP), which guarantees greater transparency, lower costs for the system and greater access to the market for new operators. For some specific markets (i.e. *dispatching services market*), the remuneration of the accepted bids is done by PAB mechanism.

2.2.1 Phases of the electricity market

The electricity market in Italy is divided into *Spot Electricity Market* (Mercato a Pronti, MPE) and *Forward Electricity Market* (Mercato a Termine, MTE). In turn, the spot electricity market is divided into the *Day Ahead Market* (MGP), the *intraday market* (Mercato Infragiornaliero, MI), the *Daily Products Market* (Mercato dei Prodotti Giornalieri, MPEG) and the *Dispatching Services Market* (Mercato dei Servizi di Dispacciamento, MSD), see figure 2.3.

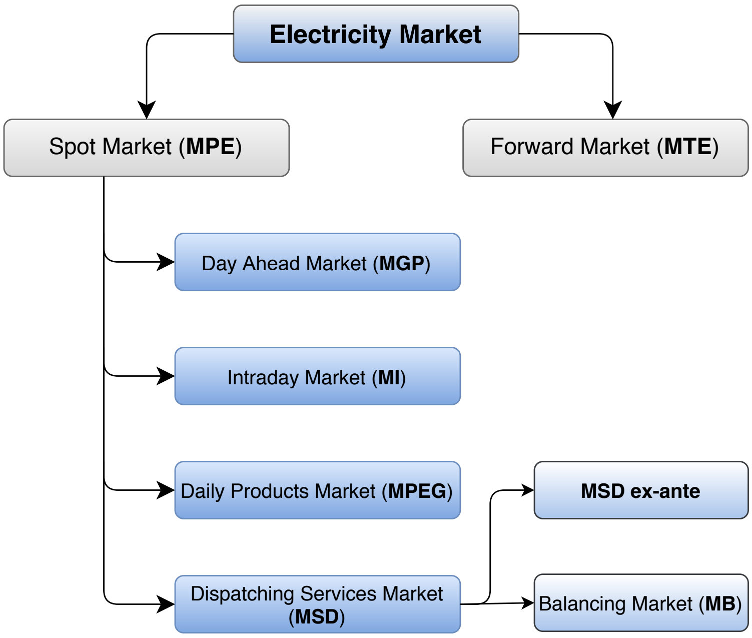


FIGURE 2.3: Phases of the Italian electricity market.

On the **MGP** are negotiated the hourly schedules for supplied and consumed electricity. Producers submit offers in which they indicate the amount of energy that they will feed in and the minimum price at which they are willing to sell, buyers submit offers in which they indicate the amount of energy that they will consume and the maximum price at which they are willing to buy. With reference to the day of delivery, the MGP session opens at 8.00 a.m. on the ninth day before delivery and closes at 12.00 noon the day before (hence the name of the market). The market outcome is defined according to an SMP auction mechanism and is communicated after the closing of the market session. Accepted bids are valued at the hourly zonal price, while accepted bids are valued at the PUN.

The **MI** allows operators to make changes to the injection and consumption programs defined in the MGP through additional offers to buy or sell. The MGP is divided into 7 sessions and opens at 12.55 p.m. the day before delivery. The last session, which determines the closing of this market phase, opens at 5.30 p.m. of the day before delivery and closes at 3.45 p.m. of the day of delivery. Also in this case, as for the MGP, the mechanism of remuneration is of type SMP but, to difference of the MGP, both purchase and sale are valued to the hourly zonal price.

In the **MPEG** the trading of daily products with energy delivery obligation takes place. On the MPEG daily products are negotiable with:

- *Unit price differences*, for which the price indicated in the formulation of the offers is the expression of the differential, compared to the PUN, at which the operators are willing to negotiate such products.
- *Full unit price*, for which the price indicated in the formulation of the offers is the expression of the unit value of exchange of the energy object of the contracts.

The delivery profiles negotiable on MPEG are *Baseload*, quoted for all calendar days and where the underlying is the energy to be delivered in all relevant periods of the trading day, and *Peakload*, quoted from Monday to Friday and where the underlying is the energy to be delivered in the relevant periods from the ninth to the twentieth of the trading day. MPEG sessions take place on weekdays from the second day before delivery until 5.00 p.m. on the first working day before delivery. It follows that on Fridays, for example, both products with Saturday delivery and products with Sunday, Monday and Tuesday delivery will be negotiate

In order to guarantee the correct and safe functionality of the electrical system, the balance of injection and consumption must be maintained moment by moment in order to guarantee the continuity and safety of the supply of the service. For this purpose, the dispatching service has been created, defined as "*the activity aimed at providing arrangements for the coordinated use and operation of production facilities, transmission grid and ancillary services*." (Legislative Decree 79/99). The dispatching service is provided in Italy by Terna S.P.A. (TSO) according to conditions defined by the Authority. Through the Dispatching Services Market, Terna purchases the resources necessary for the management and control of the system. In this particular market, accepted offers are remunerated at the price presented according to the PAB methodology. The **MSD** is divided into two distinct phases: the programming phase, or ex-ante MSD, and the Balancing Market (MB). The ex-ante MSD is divided into six programming sub-phases. The bidding session on the ex-ante MSD is unique and opens at 12.55 p.m. on the day before the day of delivery and closes at 5.30 p.m. on the day before the day of delivery. On the ex-ante MSD, Terna accepts offers to buy and sell energy for the resolution of residual congestion and the constitution of reserve margins. The MB is divided into 6 sessions. For the first session of the MB, the valid offers presented by the operators in the previous session of the ex-ante MSD are considered. For the other MB sessions, the relevant bidding sessions all open at 10.30 p.m. on the day before the day of delivery and close 1.5 hours before the first hour which can be negotiated in each session. On the MB, Terna accepts offers to buy and sell energy in order to carry out the secondary regulation service and maintain the balance, in real time, between energy input and withdrawal on the grid. The balancing resources negotiated on the MSD are found by relevant production units enabled (users of the dispatching of enabled units are obliged to submit bids). Through pilot projects, at the moment they can also submit bids other than the classic relevant units identified by the grid code as long as they are enabled according to the regulations of these projects. Table 2.1 shows a summary diagram of the Italian electricity market in which it is possible to distinguish phases, aims of the exchanges, operators and remuneration mechanisms.

TABLE 2.1: Italian electricity market organisation scheme.

	MGP	**MI**	**MSD**	
Exchanged resource	Energy	Energy	Energy for grid congestion resolution	Energy for real-time balancing
Unit allowed to participate	All input and output bidding points		All input and output points enabled for dispatching services	
Operators allowed to participate	Market operators	Market operators	Dispatching users	Dispatching users
Remuneration	SMP	SMP	PAB	PAB

2.3 Actors of the electricity market

2.3.1 Prosumers

The term *prosumer* is the combination of the terms *producer* and *consumer* and indicates an end-user connected to the distribution network (medium and low voltage) that consumes and produces energy. An example are energy consumers, private individuals or companies, who locally install generator systems to cover part of the energy consumed and feed any surplus of energy produced into the grid. The installations mainly concern photovoltaic systems (small and medium size) and micro-wind systems (medium size). These are increasingly associated with storage systems, usually electrochemical, for better production management. The technological experience reached and the reduction of the production cost of the batteries guarantees an optimal solution to the problems related to the intermittence of the source and to the peaks of production. This does not mean, however, that the prosumer must or wants to be *offgrid*, i.e. detached from the grid: in fact, all users are normally connected to the grid, either active or passive. Sometimes storage systems can be installed even in the absence of a production plant in order to accumulate the energy coming from the grid in periods of low load, and at lower prices, and use it in peak periods thus obtaining a saving. The current Italian technical norms (CEI 0-16 and CEI 0-21) identify a storage system as a generator, so a consumer who installs a storage unit at home automatically becomes an active user and therefore a prosumer. It is therefore interesting to evaluate the network/prosumer interactions and those between prosumers themselves: these interactions can be well mapped to blockchain applications in the electricity market, which guarantee data tracking in a safe and reliable way. end-users, whether active or passive, no longer represent the last stage of energy delivery but can become part of the grid regulation processes through, for example, participation in DR programs. Participation in such programs is subject to the signing of a supply contract and the regulatory contributions are not paid out individually but as an aggregate. From this point of view, a prosumer can be a residential user or a large company, it can have an adjustable energy structure; in any case, the interface to the service is managed by a third party responsible for the process defined *aggregator*.

2.3.2 Aggregator

The participation of the prosumers in the DR service takes place through their aggregation in virtual units, which are constituted and managed by a subject known as "aggregator". According to the European energy efficiency directive (2012/27/EU), the aggregator is defined as: “a DR service provider that combines multiple short-duration consumer loads for sale or auction in organized energy markets”. The aggregator has the responsibility to respond to the modulation orders given by the TSO or DSO, in order to avoid any imbalance of load on the grid that can occur at certain times of the day when the energy supply does not meet the demand [31], see figure 3.5. The aggregator responds to these orders by requesting, in compliance with the constraints and requirements necessary for the aggregate resources, the modulation of the load from consumers that make up the virtual load unit. The term aggregator usually refers only to the consumer manager, but at the same time, this entity can also aggregate generation units thus giving rise to a “Virtual Power Plant”, i.e. an entity responsible for managing multiple generators or a producer aggregator [32]. Aggregators are therefore third party companies that start contracts with individual end-users (residential, civil, industrial, consumer and prosumers) in order to create an aggregate operating individually and act as Demand Side Response Provider (DSR Provider). Through an appropriate combination of actions on the load profile of individual users, the DSR Provider provides the network with an active power regulation service [33]. The actions generally relate to changes in the power consumption and/or supply of the users participating in the programs and are carried out in response to the needs of the network. The effect of these changes is to support the grid in the presence of contingencies such as peaks in demand, grid congestion, overloads or other failures, avoiding or otherwise reducing the risk of system failure and ensuring more economical and efficient operation. The task of the aggregator is therefore to supply "flexibility" to the system receiving an economic remuneration tied to the entity of the offered service. The responsibility for the entire process lies with the aggregator, who must eliminate the uncertainty linked to the individual user and guarantee the provision of the service. An example of aggregator operating on the Italian territory is Enel X: since 2017, the year in which the Regulatory Authority for Energy, Network and Environment (hereinafter referred to as ARERA or the *Authority*) allows the participation of the demand in the Dispatching Service Markets (ARERA 300/17), Enel X has played the role of BSP distributing the order of flexibility among the customers in its portfolio who have given willingness to reduce or increase consumption and modulate load and/or generation. As an aggregator, therefore, it generates value for customers, identifying, enabling and rewarding the flexibility of the load, and at the same time generates a value for the network quickly providing a certain dispatching capacity. In the UVAC experimental project (ARERA 372/17), Enel X was the main aggregator with the award of over 110 MW of installed capacity on over 30 sites [34]. As regards the UVAM project (ARERA 422/18), 25 different aggregators have already been allocated capacity: Enel X holds the highest share among all the entities involved with 41% of the market share (694 MW)[35]. In January 2020 it also started the first project in Italy to aggregate residential storage units to offer balancing services to the grid. The project was started in the provinces of Brescia, Bergamo and Mantova and allows the inclusion of residential storage units in UVAM aggregates. The provision of balancing services was in the past reserved to large production plants or industrial loads, so that residential users will also be able to participate in demand management programs in the form of aggregates.

2.3.3 Energy Markets Manager

The Manager of Energy Markets (Gestore dei Mercati Energetici, GME) is the company responsible for the organization and management of the Italian electricity market. Established by the Manager of Energy Services (Gestore dei Servizi Energetici, GSE), it is fully owned by the Ministry of Economy and Finance and carries out its activities according to the indications of the Ministry of Economic Development and the Regulatory Authority for Energy networks and Environment (Autorità di Regolazione per l'energia Reti e Ambiente, ARERA). The aim of the GME is to promote competition among producers by ensuring the availability of an adequate level of power reserve. On the Day Ahead Market and on the Infraday Market, producers sell energy and buyers buy it wholesale: on both markets, the GME acts as a counterparty in trading. It also manages the Dispatching Services Market where the counterparty is TERNA. The capacities related to DR programs by aggregates are currently allocated according to the regulations of the pilot projects (see paragraph TSO): in the future, given the purpose of the programs, the offers will be presented in the MSD. The GME plays a specific role in the market monitoring for the Italian Regulatory Authority, originally resulting from deliberation n.115/2008 of the ARERA, containing specific provisions for the monitoring of the electricity market in Italy, and later reinforced by the provisions of Regulation (EU) n. 1227/2011 on the integrity and transparency of the wholesale energy market [36].

2.3.4 Balance Responsible Party and Balance Service Provider

The *Balance Responsible Party* (**BRP**) is a market operator or its representative, responsible for its own imbalances in the electricity market, as defined in [37]. A BRP (or dispatching user) can be an end-customer or producer or its intermediary (wholesaler) who signs the dispatching contract with the System Operator and who is responsible for the execution of the feed-in and withdrawal programs negotiated on the wholesale markets. The term *Balance Service Provider* (**BSP)** refers to the final customer or producer or its intermediary (wholesaler) who is responsible for providing the dispatching services to the System Operator, which are necessary to maintain a real-time balance between supply and demand for electricity. The figure of the BSP coincides with the role of the aggregator and may or may not coincide with the dispatching user [38]. The BSPs provide the TSO with the resources for the *ancillary services*, i.e. services necessary to guarantee the security of the entire electrical system. Providing ancillary services essentially means modifying one's feed-in or withdrawal programs in order to respond to TSO requests, offering a regulatory contribution to the network. In general, BRP injection and withdrawal programs can be formed on MGP and/or MI and can subsequently be modified by the TSO by accepting offers submitted by BSPs on the MSD to take network constraints into account. It is also possible that a BRP has programs that are independent of MGP and MI, in this case dispatching takes place entirely on the MSD. The objective of balancing is to ensure a continuous balance between inputs and withdrawals in order to maintain the performance requirements related to system frequency (EU Regulation 2017/1485). A general review of the dispatching discipline is underway in relation to the new market environment and the increased flexibility requirements of the system. The concept of "aggregation" was born in response to these needs and allows, through figures such as BRP and BSP, to supply the system with reserves of flexibility previously inhibited by previous regulations.

2.3.5 Transmission System Operator

The *Transmission System Operator* (TSO) is a company responsible for the control and management of the transmission network. The main task of the TSO is to transport electricity over long distances through the high-voltage grid (from 150 kV to 380 kV in Europe) that connects large production centers (thermal power plants, nuclear power plants, large renewable energy sources) to industrial users' cabins or distribution networks. Due to the high costs for the installation and maintenance of infrastructure, the TSO generally operates as a natural monopoly and is subject to state regulations. In Italy, Terna plays the role of TSO. The management of the grid includes the monitoring of power flows and voltage control in all nodes of the system: the TSO guarantees the stability and reliability of the electricity system by balancing the demand and production of electricity in real time.
The dispatching service is totally managed by Terna: through dispatching, the units that will provide the supply and the consequent supply of services necessary to guarantee the security of the national electricity system are identified; moreover, the

regulation of the economic items deriving from the execution of the contracts and from the actual imbalances is carried out [38]. The dispatching service is supplied on the base of contracts signed with BRP, (single units), or with BSP (eventually aggregated units). Through the MSD, the TSO procures the necessary resources for the supply of ancillary services by selecting the most economical offers formulated by the BSPs. In case of particularly serious and unexpected contingencies, the supply of the resources can happen also through impositions (obligations, also not remunerated).
Participation in MSDs implies that the service delivery units are enabled for the purpose. The network code provides for the modalities of enabling units considered traditional: in response to the evolution of the energy context and its needs, in recent years, several pilot projects have been issued with the aim of assessing the impact on the system of units that previously were not considered suitable to provide ancillary services, such as power plants from renewable sources or small consumption and/or production units (P < 10 MW). For these projects, the Authority (ARERA) indicated Terna as the body for the definition of the new technical performance requirements of the relevant production units and the new Enabled Virtual Units. Terna's task was to identify, initiate and manage the projects, drawing the necessary conclusions regarding their impact on the system. Further detail are given in the paragraph 2.6.1.

The TSO plays a fundamental role in the management of the electricity system: it not only represents the main actor in all the crucial phases of the system's operation, but also operates, under the Authority's instructions, a constant action of research and innovation of the grid, the results of which will be the basis of future regulations.

2.3.6 Distribution System Operator

The *Distribution System Operator* (DSO) is a company responsible for the management of low and medium voltage distribution networks that it sometimes owns. High voltage transmission grids have the task of transmitting large amounts of energy over long distances (national extension): in the vicinity of end-users, electricity undergoes a voltage transformation and is distributed through the distribution network (regional extension). The distributor's tasks include making new connections, solving grid faults and reading energy consumption via meters (of which it is the owner). Despite distributing it, the distributor does not physically supply the energy: there is an important difference between the company that distributes the energy and the one that sells it. The Authority requires two different entities to distribute and sell electricity and, in case a company takes care of both operations, the latter is obliged to create two different companies (one for sale and one for distribution). The assignment of the distributor is made by geographical area through assignment by the ARERA: this implies that the consumer cannot choose the distributor but only the energy supplier. The most important distributor in Italy is E-Distribuzione, which distributes energy to more than 90% of consumers on the national territory.

In the context of large penetration from unpredictable sources at the distribution level, the main task of DSOs remains to provide a secure supply of electricity while ensuring an acceptable quality of service, but in order to pursue these objectives they must manage an active network increasingly complex and articulated. As far as network balancing is concerned, the supply of ancillary services by load aggregates (connected to medium and low voltage networks) implies an evolution of the distributor's role: the distribution companies will have to facilitate the supply of global ancillary services provided by BSPs and, in the near future, will also acquire the role of buyer of resources for local ancillary services, i.e. services necessary for the safe operation of distribution networks or portions of them only. The actual effectiveness of local ancillary services will have to be tested and validated by special pilot projects before the practice becomes standard and is included in the network codes [38].

2.3.7 Energy Retailer

Since the issuance of the Bersani Decree, several figures in the energy business were born, figures that were previously unnecessary because the market was a state-monopoly. A new player, appeared from the liberalization of the market, is the *Energy Retailer* (also called *supplier*). Since January 1st, 2007, all customers have the possibility to choose their supplier on the free market. In the transitional period that has as its objective the total liberalization of the electricity market, scheduled for 2022 [39], the Authority has established a service defined of *Maggior Tutela*, a service in which the contractual and economic conditions of the supply are defined by the ARERA itself. The customers are therefore divided into customers of highly protected customers (Maggior Tutela) and customers of the free market. Only for the latter, the suppliers manage all commercial and administrative aspects of the electricity supply. In Italy there are currently over 40 Energy Retailers. Among them, the majority share of sales to the end market belongs to *Enel Energia*, with about 35% of the market share [40].

2.4 The blockchain for the electricity market in Italy and Europe

Time and thus scalability seems to be quite relevant when blockchain technology must be coupled to different electrical energy markets. The aim of this subsection is to understand how, in the current organization of the market, the blockchain techology could be used for the energy market. The electricity market in Italy and in most European countries has changed a lot recently due to the transition to a low-carbon economy. Electricity is currently traded at wholesale level or at retail level. Trading takes place between generators, suppliers and traders (wholesale) or between suppliers and end-users (retail). Recently, however, apart from these, new forms of energy trading are appearing. These are defined as P2P markets. Considering the type of transactions, the electricity market can further be divided into regulated and non-regulated markets. The first type comprises spot and forward markets, while the second mostly comprises Over The Counter(OTC) markets, which typically are forward markets based on bilateral contracts. A large part of the exchanges into non regulated markets are devoted to purely financial transactions. The main problem with bilateral transactions that could be solved through the blockchain technology is the limited access from operators. The latter as an example, in the regulated markets in Italy, must be recognized by the GME. In this case, the scalability issue can be considered not as a primary need, since the exchanges are future deliveries. The wholesale electricity markets include both spot and forward market schemes. The main difference between the two is the way in which the deal is carried out. In the first case (spot market), deal is organized into market sessions with defined reference period of delivery, where each counterpart offers its capacity and price. The most relevant figure is the Day-Ahead Market (DAM) where the deal is limited by the defined market sessions but price setting is hourly; in the forward market instead, the deal is continuous and in addition to price and volume is also negotiated the delivery period (futures). In both cases, deal is carried out on virtual platforms (IPEX, EEX...) collecting offers and implementing the algorithm for clearing. In forward markets, supported by bilateral trading, a supplier and a consumer agree on a trade contract by directly interacting with each other. In this case, trading can take the market price published by the power exchange as reference price. In organized bilateral trading, market participants submit generation and demand bids to a market platform, which is cleared continuously; one market player can bilaterally accept the bid of another market player, resulting in different prices for each trade. While the so-called exchange markets (spot and forward) have as counterpart in Italy the GME, bilateral deal is carried out between two parties and thus there is no central counterpart, but the physical delivery must always be accepted by the market manager (GME in Italy). This is why the outcomes of non regulated platforms for OTC must be notified to GME and finally to the TSO. A generic transaction on the futures market implies as main information: the parts in the contract, the amount of energy that is object of the exchange offered or to be purchased, the profile with which such capacity is offered (baseload, peak, offpeak), and duration (month, three-months, year). The introduction of the blockchain technology to support wholesale markets, and in particular regulated and non regulated bilateral (OTC) markets can reduce the counterparty risk and improve transparency while keeping the privacy-preserving feature. The Enerchain project [41] is developing a blockchain-based P2P trading platform to complement, or replace, the wholesale electricity market improving transparency. The retail market implies the presence of a wholesale buyer that then sells to individual customers. This is, for example, the case of aggregators. In this case, blockchain technology could improve transparency among consumers and between the TSO and the aggregator.

As the European Directive on common rules for the electricity markets claims, "integrated short-term markets are missing", while these short-term electricity markets would allow “trading RES-E across borders” and are the “key for the successful integration of RES-E into the market”. The same directive recognizes that “the advent of digitalization, internet-based metering and trading solutions enable industry, businesses and even households to generate and store electricity, as well as participate in electricity markets via Demand Response solutions. Besides, the electricity market of the next decade will be characterized by more variable and decentralized electricity production, an increased interdependence between Member States and new technological opportunities for consumers to reduce their bills and actively participate in electricity markets through Demand Response, selfconsumption or storage [37]. The directive also encourages local energy communities as a means for fostering renewable energy penetration.

Still, it seems, that the so-called P2P markets are still in an experimental phase. The work in ref. [42] makes a wide overview of P2P markets. The paper outlines three different types: (i) full P2P market; (ii) community-based market; and (iii) hybrid P2P market. In the full P2P market, agents (i.e. producers, consumers and prosumers) interact without third parties (i.e. retailer or market operator). A couple of agents can agree on a certain amount of energy exchanged for a given price without centralized supervision. In this case, the agents should be able to understand whether the transaction is technically feasible and to what extent it influences other nodes in the grid. The community-based market is more structured, it implies the presence of a third entity, namely a community manager, to rule transactions among agents inside the community. This entity also manages the interaction of the community with the main grid. The hybrid type is a combination of the two previous market structures, ending up with different layers for trading energy. In each layer, communities and single agents may interact directly. This third type is more organized than a P2P market but not as structured as a community-based market.

P2P markets are the natural environment for blockchain technology and distributed ledgers. What appears evident is that while some wholesale markets (forward) do not account for technical feasibility of transactions that are successively fixed in other shorter-term markets or even after the time of delivery, P2P markets may require a strong technical control over transactions while they are carried out, since there no possibility to fix possible technical issues. Therefore the claim from the directive about strengthening the short-term markets becomes more realistic, although technical feasibility of blockchain solutions considering time for validation, consensus and conflicts resolution must be always assessed. Theoretically, addressing a full P2P market would imply the non-existence of the grid intended as a means to compensate for possible imbalances, leaving the full control of operations to decentralized agents. In this sense, load and generation forecasting, as well as local availability of storage units, would enable the implementation of full P2P electricity exchanges and make full use of the blockchain technology. Finally, the new electricity market in Europe should be as much as possible "integrated" and efficient. As far as integration is concerned, the same rules for price formation should be shared and agreed upon and this could be easily done using a transparent business integration tool supported by the same protocol (i.e. blockchain technology). As far as efficiency is concerned, the values of all assets at any instant should reflect all available information. In an efficient market place indeed, the suppliers and buyers together adjust product price immediately in real-time to the new information available. Both features can be attained using the blockchain technology as enabler of B2B and B2C integration and transparency in data exchange. Table 2.2 summarizes the principal features involved in energy market issues.

2.5 Business models and new energy services

If we think about the traditional energy transaction model we can say that it is a centralized model, where all energy transactions are performed through trusted entities (GSE, TERNA, Distributors and Suppliers) that manage the whole process from production to delivery to the end-user. As it happens for the financial transactions, in which the bank acts as an intermediary to process the electronic payments. This system suffers from the inherent weaknesses of a model based on the trust of unknown users towards a third party that acts as trusted third-party for both. This results in an intermediation cost that increases the transaction cost, limiting the minimum size of viable transactions and excluding the possibility of small transactions. In fact, in the electricity market the domestic user does not have the possibility to buy directly from the producer and bargain on the purchase price, but buys from a supplier at the PUN, which has purchased energy wholesale. The same concept applies to small producers from renewable sources. The energy produced is injected into the grid and remunerated at a price set by the authority. This energy then reaches the end-user through the TSO, DSO and energy retailers. Also in this case the end-user does not have the possibility to interface with the small producer. The use of blockchain in the financial world, to date, has made it possible to overcome these problems, just think of Bitcoin or Ethereum, which allow the exchange of currency between two unknown users without the need for a third party to act as guarantor for both.

TABLE 2.2: Features involved in the energy markets issues.

	Spot markets	**Bilateral (regulated and OTC)**	**Blockchain and P2P**
Control over energy transaction	Centralised	Decentralized	Decentralized
Number of participants	Many	2	Those taking part in the BC community
Conditions for entering t he market	Yes	Yes	No
Participants transparency	None	Between the two participants	Verified by the authentication mechanism
Timing	Mostly day or weekly	Mostly Hourly	15' to hourly
Trading	Through the market platform	Directly or through a trader	Directly
Price setting	Merit order or Demand/Offer agreement or "pay as bid" when needed	Influenced by exchange markets	Influenced by exchange markets
Price transparency	To all	To those who take part in the transaction	To those taking part in the BC community
Counterparty risks	Minimum	High	Minimum
Need for balancing	Strong	Strong	Limited
Contract and products	Standardized and subjected to precise rules	Not standardized	Not standardized

The direct consequence is the reduction of the transaction cost, since the exchange takes place between the users involved in the transaction without the need for an intermediary, thus also allowing the possibility to perform small transactions. This powerful new technology therefore allows transactions of a valuable asset directly between end-users without the need for an intermediary to act as guarantor. And if the asset of value was energy? Every user of the network would have the possibility to interface directly with the producers and vice versa, with a consequent reduction in transaction costs and therefore energy. From a centralized transaction model, we move on to a distributed model, in which all network users can buy or sell energy from whoever they want or from whoever best meets their needs, generating new business models of the electricity market and new management logics of network services such as ancillary services.

2.5.1 Energy business models enabled by the blockchain

The increasing use of small power generators, mainly solar photovoltaic (PV), connected to the distribution network and the increasing electrification of transport and buildings are more and more leading to the digitalisation of the electrical system. All new assets on the offer and demand side are adding complexity to the energy sector, making monitoring, management and control crucial to the success of energy transformation. The energy market has for years been open to prosumer, the small renewable energy producer that does not consume everything it produces. But the market model, as described above, is still centralized, with inefficiencies and high costs. Digital technologies such as blockchain can support renewable energy penetration by improving monitoring, operation, maintenance and control and generating new market mechanisms. Thanks to the blockchain in fact, new prospects have been opened for the creation and diffusion of new markets for energy where people and companies with an "individual production" can directly sell their excess production to the market or buy it in case of need, creating new scenarios that can also bring important benefits in terms of balancing networks. The use of this new technology in the energy sector has contributed to the evolution of new business models, with the focus on local P2P and wholesale electricity trading, as well as innovative means of financing projects in developing countries. A key tool provided by the blockchain that enables further development of initiatives in the energy sector are SCs. Thanks to SCs, it is possible to automate the rules and sanctions relating to an agreement and automatically enforce obligations, removing the need for an intermediary. The implementation of SCs performed on blockchain networks can help modernize electricity grids, improving the use of renewable energy, operation and management of the grid, allowing especially the development of new market logic. SCs could also be used to automatically buy and sell energy for end-users or companies based on real-time price signals. End-users become active participants in the market, able to buy and sell their electricity without the need for trusted authority or intermediary. The use of blockchain technology in conjunction with SCs allows the development of efficient, effective and affordable services to help transform the energy sector. In addition, blockchain, as a tool for data management, facilitates coordination between different actors because everything is shared, transparent and immutable.

According with ref. [43], the new business models enabled by blockchain in the energy sector may be many, but those more feasible and that promise value creation throughout the energy sector are related to:

- **Certification of origin systems for renewable energy markets**: applications that document the origin of renewable energy production, release of certificates for each unit of renewable energy produced and tracking transfers of ownership between market players for their statements on green energy and compliance requirements.

- **Demand Response programs**: applications that perform real-time aggregation, measurement, tracing and verification, settlement and trading associated with participation in a given demand response event without the need for an aggregator to interface customers and DSOs, with the potential to involve domestic users in the programs.

- **Electric vehicle charging networks**: applications for the management of customers, vehicles and charging infrastructure using cryptographic identities to provide services to the electricity grid.

- **Transactive energy systems**: market projects where electricity grids are balanced and controlled through the execution of P2P energy exchanges between end-users. Thus allowing the purchase and sale of energy between neighbour and encouraging the installation of domestic production systems.
- **Wholesale energy trading**: market projects where the blochckain is used to reduce the counterparty risk, improve transparency and to preserve privacy in the wholesale market.
- **Grid management**: applications for the management and tracking of the supply chain and maintenance of power grid.
- **Metering and billing**: applications for tracking and certification of user consumption.

For all the considered applications, there are some specific and general challenges concerning the use of the blockchain technology [44], [45] that are worth mentioning and that are listed in Table 2.3.

2.5.2 The blockchain technology for ancillary services provision

In addition to P2P electricity transactions, V2G or DR programs, another application of blockchain technology in the energy sector could be the full management of network operations related to voltage and frequency regulation, the so-called ancillary services. With decentralization, the number of transactions to guarantee ancillary services will increase significantly as a consequence of deep penetration of RES. While for P2P trading the aim of enabling technologies like blockchain is to incentivize and simplify electricity trading between users by limiting third parties intervention, for ancillary services provision, the so-called third parties (system operators and balancing responsible parties) themselves could trade it with prosumers. The prosumers have to be notified about the need for real or reactive power injection into the network. As a result, this service would lead to trade between end-users and system operators, in order to improve the energy supply service. For this application, again a transparent and secure blockchain, in which all users can join, is needed but with a verification and consensus protocol controlled by a pre-established set of nodes (verification nodes). In this case indeed, such as in other cases already seen, the algorithm for deciding which node should provide what power at what time is an optimal power flow. The main potential of blockchain technology, in this scenario, is that it can provide a secure foundation for different markets that focus on ancillary services provision and, at the same time, reduce barriers to market entry for smaller devices connected to the network. Because electricity grids are critical infrastructures, there are many different rules and regulations to ensure that entities participating in ancillary services provision respect the contractual relationships they have with network operators [46]. Because of these complex regulations, small prosumers do not provide ancillary services, although they theoretically could. With blockchain technology, SCs could be used to apply the current ruling system for ancillary services into the digital world. Once SCs have been defined correctly, they can be used to facilitate market processes for the collection of ancillary services in a safe and efficient manner. Furthermore, these SCs could facilitate market processes for ancillary services provision from all users of the network (from large industrial consumers to home users). An example of this approach is the D3A framework developed by the Energy Web Foundation, which aims at the integration of decentralized assets up to different domestic devices in local and national markets for energy and ancillary services. WePower with the Estonian TSO Elering or Tennet with the battery storage company Sonnen are currently examining how smart contracts could be applied to perform tasks that help to balance the network. Thinking of a future scenario, network operations could become an increasingly digitized business with elements that traditional network operators could not provide. Thus, the government may choose to allocate network operations to a different entity that has the ability to manage digitized power grids more efficiently. This is a model that we already know from transmission grids in the United States, where the ownership of resources is of utilities, while the Independent System Operators (ISO) deal with network operations. Although the technological barriers are still many, such as the management and accounting of assets and the veracity of the measurement of the same assets, with the use of the blockchain it is possible to make a positive contribution to overcome them [47].

2.6 New energy regulations

The decarbonisation of the national energy system and the consequent shift to a mix more based on the contribution of RES, wind and photovoltaic, is certainly an important objective from an environmental and economic point of view, as well as being substantially imposed by European directives. But a transformation like this has significant consequences for the electricity system and the electricity market, which in some way must be governed, to avoid problems on the availability of electricity for families and companies. The point is that the increase in the production of energy from RES inevitably reduces the contribution of production from conventional power plants, which in recent years have decreased in number or, in any case, tend to produce less energy. The problem is that the new generation from RES are not programmable, they are unable to generate electricity 24 hours a day. The growing share of energy produced by non-programmable RES power plants, especially photovoltaic, is concentrated in specific hours of the day. This leads to the need for more power margin to ensure the safety of the system.

To address these issues, the European Council has adopted two directives of the "Clean Energy Package", presented by the EU Commission in 2016, on the promotion of the use of energy from RES (2018/2001/EU, RED-II) and on increasing energy efficiency (2018/2002/EU), in addition to the Regulation on the governance of the Energy Union (2018/1999/EU) and the Directive on energy efficiency in buildings (2018/844/EU). These directives set a target of production from RES of 32% and an increase in energy efficiency of 32.5% by 2030, while the governance regulation provided for the submission of national energy-climate plans by the end of 2018. The new governance regulation facilitates mutual assistance between Member States in the event of an electricity crisis, so that they can benefit from better preparation and less interruptions during peak periods. To this purpose four measures of the Clean Energy Package have been adopted. Directive No. 2019/944/EU of 5 June 2019 and Regulation No. 2019/943/EU of 5 June 2019 are related to the internal electricity market and aim to make it more flexible and competitive, taking into account the increasing penetration of production from RES. To avoid financing fossil fuels, the regulation provides for an emission limit of 550 grams of fossil CO2 per kWh of electricity: new power plants with higher emissions will not be able to participate in the capacity markets by providing energy in case of need to ensure the security of the electricity system. Old power plants will be allowed to continue, but only under certain conditions and until July 1, 2025. The other two measures, Regulation 2019/941/EU and 2019/942/EU are related respectively to the prevention of blackout risks and cooperation between national energy regulators and complete the Clean Energy Package.

These directives have then been adopted by the various European countries to achieve the objectives set by the EU Commission. Below are described the main directives and applications developed in Italy with the aim of promoting production from RES, increasing energy efficiency, the competitiveness of the electricity market and ensuring the reserve of energy necessary for the correct operation of the power system.

2.6.1 Aggregation of local energy resources

The electrical system must be able to guarantee at all times that the energy required by all consumers is balanced by the energy produced by the power plants. During the last decade, this power margin has always been guaranteed by conventional power plants, but in the last three years the legislator and the ARERA (or the Authority) also in response to the directives of the EU Commission have decided to experiment with an expansion of the entities entitled to contribute to the balancing of power flows on the electricity system. Already in 2015, the Authority started a process of reform of the dispatching service in a manner consistent and coordinated with European norms. The objective is to enable all relevant [1] production units to participate in the MSD, including those supplied by non-programmable sources, relevant consumption units and non-relevant production and consumption units in aggregate form, also through DR programs. In order to achieve this goal, the authority has indicated Terna as the institution for defining the new technical performance requirements of the relevant production units and the new Virtual Enabled Units (Unità Virtuali Abilitate, UVA) and for identifying, starting up and managing projects, obtaining the necessary conclusions regarding their impact on the system. The regulatory starting point is represented by Legislative Decree 102/2014 (today replaced by Legislative Decree 73/2020) which represents the transposition of the European Directive 2012/27/EU on energy efficiency (today replaced by 2018/2002/EU), with the aim of establishing a framework of measures for the promotion and improvement of energy efficiency that contribute to the achievement of the national energy saving target. Following this decree, with Deliberation 300/17/R/eel [48], ARERA has promoted the opening of the MSD to electricity demand, non-programmable renewable sources and storage systems, with experimentation through pilot projects. In particular, the Deliberation distinguishes between:

1. **Consumption enabled virtual units** (Unità Virtuali Abilitate di Consumo, UVAC), characterized by the presence of only consumption units.
2. **Production enabled virtual units** (Unità Virtuali Abilitate di Produzione, UVAP), characterized by the presence of only non-relevant production units, whether programmable or non-programmable, including storage systems.
3. **Relevant production units** (Unità di Produzione Rilevanti, UPR), characterized by the presence of relevant generating units powered by non-programmable

[1] the term "relevant" refers to production/consumption units with a total power of the associated groups of not less than 10 MVA

renewable sources and relevant generating units that meet the minimum technical licensing requirements for at least one of the dispatching services between: congestion resolution at the planning stage, tertiary reserve resources and balancing resources.

4. **Relevant production units integrated** with storage systems (Unità di Produzione Integrate, UPI), characterized by aggregates consisting of relevant production units (UPR) and storage systems able to guarantee the provision of the primary control service in any operating condition provided by the Network Code.

5. **Mixed enabled virtual units** (Unità Virtuali Abilitate Miste, UVAM), characterized by the presence of both non-relevant production units and consumption units and storage systems.

As the ARERA definition establishes, UVAMs are characterized by the presence of production units (relevant and not relevant), storage systems and consumption units, connected to the grid at any voltage level. More in detail, UVAMs are characterized alternately:

1. by the presence of non-relevant production units (including storage systems, which may also include the batteries of vehicles that connect to the electricity grid through charging infrastructures equipped with V2G technology), with charging units of relevant production not already obligatorily enabled that share the point of connection to the grid with one or more consumption units, provided that the power input to the connection point is not more than 10 MVA, and consumption units;

2. by the presence of relevant production units that are not already obligatorily enabled and that share the connection point to the grid with consumption units and have a power input at the connection point greater than 10 MVA.

For qualification requirements, UVAMs must be able to make available a capacity of at least 1 MW, to increase and/or decrease. There is no limit in relation to each individual production or consumption unit of which the UVAM is composed. The UVAM systems have been designed with the aim of expanding as much as possible the audience of possible participants. The project, approved with the Deliberation of ARERA 422/2018/R/eel (operative since November 1, 2018) is part of the pilot projects, provided for by the aforementioned Deliberation 300/2017/R/eel, aimed at collecting useful elements for the reform of dispatching and the expansion of dispatching resources. However, there are some pre-requirements for the qualification as UVAM [49], i.e. it must not be qualified to the Capacity Market and must have a modulation threshold of 1MW, the lowest threshold at European level.

As indicated in the regulation, UVAM are enabled to provide services such as congestion resolution, balancing, tertiary reserve, but the plan of Terna and ARERA is to test the participation of UVAM on other types of services, such as secondary frequency/power regulation and to progressively involve also consumers in the tertiary and/or domestic sector.

Already in June 2019, more than 120 UVAM for a total power of 830 MW with more than 25 entities classified as BSP [50] have been enabled to MSD services. For the whole 2020, 991.4 MW have been assigned on the entire national territory, divided into 800 MW for North and Centre-North and 191.4 MW for Centre and South.

Being part of a UVAM can be advantageous because in addition to the ordinary remuneration related to the energy activated (€/MWh) there is also the remuneration of availability of the resource with a fixed fee, calculated in €/MW, unlike for large power plants. It should be considered that industrial operators, who contribute to the development of UVAM, have to bear fixed investment costs to install and set up the equipment necessary to develop the service and annual operating costs. The remuneration of the activated energy alone, which is affected by the volatility of the market price, is therefore generally not sufficient to cover these costs, thus requiring the adoption of a fixed fee to balance the accounts.

One of the most important features of the project is the inclusion of storage systems functional to electric mobility, opening the way to the experimentation of V2G technology. In Italy, V2G technology has been regulated by a Decree of the Ministry of Economic Development of January 30, 2020 (Mise Decree) [51], which establishes the methods of diffusion, the rules for participation in the energy market and the rewards for those who use their electric vehicle to help the national power grid by providing services of tertiary reserve, balancing or frequency and voltage regulation.

The V2G decree establishes that electric vehicles and charging stations can participate in the MSD in aggregate form via UVAM. This is possible because there is no limit in relation to each individual production or consumption unit of which the UVAM is composed. The decree states that in the case of UVAM consisting exclusively of charging infrastructure, the minimum power to be made available can be reduced up to 0.2 MW, increasing and/or decreasing, given the low power of electric vehicle batteries. It also provides an incentive to cover the additional costs associated with the installation at the charging points of technologies designed to ensure the interaction between the vehicle and the network. Finally, the decree provides simplified modalities for the participation in UVAM for some categories of charging stations (such as domestic ones) and above all it opens the possibility to provide new types of services, such as frequency and voltage control. The decree speaks of "Virtual Units Enabled for charging" (Unità Virtuali Abilitate di Ricarica, UVAR), consisting exclusively of charging points for zero emission cars.

Also in this case the ARERA has the task to implement ad hoc dispositions to integrate this novelty to the dispatching services. With the document for consultation 201/2020/R/eel the ARERA defines the first guidelines for the revision of its electrical dispatching regulation to promote the participation of electric vehicles in the MSD, through charging infrastructures equipped with V2G technology. In the document, rules are indicated to define how to include new generations of V2G technology charging columns in advanced dispatching projects, in order to contribute to the balancing of the electrical system. The proposal to reduce the minimum power to be made available upstream and/or downstream from 1MW to 0.2 MW has been accepted and applied to all UVAM in order to preserve the principle of technological neutrality. With regard to the coverage of additional costs of the charging infrastructure for the provision of ancillary services provided by the Decree, a decision has not yet been taken, but in the document for consultation ARERA anticipates that these rules will be defined as soon as the Italian Electrotechnical Committee (CEI) has identified the minimum technical requirements that must have the devices and meters installed at the connection point (even when integrated into the charging infrastructure) for the provision of ancillary services.

Considering that in Italy there are about 40,000 electric cars (estimate end 2020), assuming that 10% of these cars are connected to the grid for charging in the evening and night and assuming an average size of 10 kW for each column, the electrical system could count on 40 MW of additional capacity to be managed with increasing

/decreasing services. Of particular interest are the public/private companies that own hundreds of vehicles; think, for example, of the large electric company fleets that, connected with V2G systems to the grid, could provide some MW of capacity for each one. Much will also depend on how the cars are used; it is clear that the most suitable type of charging for V2G modes is the slow charging performed in the evening or at night, using private domestic or corporate columns. Fast recharging, on the contrary, requires that priority is always given to vehicle refueling so it lends itself in a very limited way to V2G applications.

In general, the UVAM project as well as the V2G applications are proceeding quite well, constituting interesting mechanisms for achieving the objectives of the Clean Energy Package to 2030. The opening of the MDS to new users, allows the reduction of the use of conventional power plants for the regulation of power flows on the grid and the provision of ancillary services with the consequent reduction of CO2 emissions and the incentive of users to install RES plants. In addition, the possibility of being able to use own electric vehicle to help the grid in the ancillary services in return for remuneration is a way to encourage people to purchase electric vehicles, which will not only contribute to the reduction of emissions, but will also have an economic return.

2.6.2 Renewable energy communities

The EU Renewable Energy Sources Directive 2018/2001 (RED-II) defines the role of prosumers and Renewable Energy Communities (REC) with the aim of increasing the decentralisation of electricity generation in the context of the liberalisation of the energy market. The RECs, which exist since several years in some northern European countries such as Denmark and Germany, are made up of aggregates of producers, consumers and possibly also prosumers, where renewable energy is produced by units owned by a community of citizens, with the aim of providing environmental, economic and social benefits to the community's members rather than financial profits. Within a REC it is allowed to produce, store, consume and sell renewable electricity produced within the community and to access all electricity markets, either directly or through aggregation. Members of a REC are users belonging to the same building or condominium. There is in fact a "location" requirement in the definition of Renewable Energy Community. Members of a REC can be the holders of connection points in low voltage electricity networks downstream the same MV/LV transformer substation, such that their participation in the REC does not involve any modification and/or upgrading of the existing electricity network. They can be final customers, producers and/or final customers and producers provided that they all belong to the same perimeter. In a REC there is usually an agent who applies to the authority to obtain the expected benefits from the self-consumption of renewable energy produced within the community itself. The authority, on the basis of the measurement data collected at the collection and injection points of the consumption and production plants, assesses the collectively consumed electricity and grants incentives to the representative of the community, who is generally the owner of one or more production plants within the community. In Italy, for example, the decree-law 162/19 (Milleproroghe Decree), which transposes the European RED-II directive, states that the REC representative must submit a request to the authority (GSE) with all the information necessary to identify the energy community [52]. The decree encourages the self-consumption of energy that comes from renewable energy production plants, which can also be deferred through storage systems. The infrastructures that receive the economic benefit are the production plants from renewable sources. They must individually have a nominal power less than or equal to 200 kW and must have entered into operation after 01/03/2020 and within the following sixty days from the date of entry into force of the transposition of Directive 2018/2001/EU (30 June 2021 as final date). The community downstream of a cabin will include both the production plants and the utilization plants. The GSE then recognizes an incentive equal, on an hourly basis, to the sum of two terms:

1. The product between the unit amount refunded (totalling 0,822 c€/kWh for the year 2020) and a quantity of energy equal to the minimum between the electrical energy supplied by the RES installations covered by decree-law 162/19 and the total electrical energy taken from the connection points that are part of the same REC.

2. The product between the coefficient of avoided losses (1.2% in the case of production plants connected to medium voltage networks or 2.6% in the case of production plants connected to low voltage networks), the hourly zonal price and a quantity of energy equal to the minimum between the electrical energy injected by the plants allowed by decree-law 162/19 and the total electrical energy taken from the connection points forming part of the same REC.

This incentive is granted to the agent of the community, who then distributes it to users who consumed at the time in which the incentive was granted. The first term of the two above indeed is as larger as the minimum between injected and consumed electricity is higher, namely as the effect of levelling (in terms of energy) is increased. Therefore, the more users consume at the time the renewable energy plant produces, the better it is. Besides, the self-consumption of energy allows to obtain several advantages both for the user of the energy community and for the network operator. The user will have an economic return due to the energy not purchased and the incentives, while the network operator will have as main benefit the reduction of power flows on the power lines with the consequent reduction of losses. In addition, the electricity produced and consumed on site could, in perspective, reduce the need to upgrade existing networks or build new networks, as it would contribute to the reduction of the maximum power required at the connection points. A further advantage is the optimisation of the use of delivery cabins and connection points, reducing connection costs. However, currently, in Italy the latter two benefits are not fully implemented due to the energy (and not power) related incentives. As a result these latter benefits can only be considered in a future perspective.

The blockchain technology applied to the implementation of the REC concept would first of all allow full transparency of the incentive process for self consumption. Users would be identified on the blockchain as part of the REC and the hourly incentive process described above could be carried out through suitable SCs, in charge of distributing the benefits to all those that have taken part to the hourly energy balancing. In this way, not only the production/consumption network would be decentralised, but also the user management system, while ensuring privacy. The blockchain would facilitate the spontaneous aggregation of loads and generators without the need for a representative of the community, but all users would be in direct contact with the authority, which, hour by hour, through the smart contract could recognise the incentives directly to the users while attaining the required technical objectives.

TABLE 2.3: Specific and general challenges.

Application	Specific challenges	General challenges
Peer to Peer and decentralized energy trading	Implementation of efficient market algorithms as smart contracts; Balancing demand to supply and need for machine learning algorithms; Interoperability of current smartmeters with blockchain platform;	-Compatibility with low power nodes. -Regulatory challenges. -Costs of integration. -Latency. -Privacy and GDPR compliance. -Scalability (management. of large amount of data). -Bandwidth. -Power consumption.
Wholesale energy trading	Involvement of all market actors.	
Energy trading support for small generators and end-consumers	Interoperability of current smart meters with blockchain platform; Compatibility with existing market structure	
Metering and Billing	Interoperability of current smart meterswith blockchain platform; Metering data verificationfrom multiple actors for consensus;	
Vehicle to Grid	Interoperability with current existing V2G control technology	
Demand Response for Primary/Secondary/ Tertiary regulation	Communication of current smart meters with blockchain platform; Metering data verification from multiple actors for consensus; Latency; Bandwidth compatibility	
Green certificates and carbon trading	Communication of current smart meters with blockchain platform; Metering data verification from multiple actors for consensus	
Grid management	Higher throughput and transaction speeds that would allow real-time verification;Interoperability with current existing metering technology; Generation of massive datasets	
Power Purchase Agreements	Interoperability of current smart meters with blockchain platform; Metering data verification from multiple actors for consensus	

Chapter 3

Blockchain experiences in power systems

3.1 Introduction

The blockchain technology is currently gaining a huge popularity because of the wide variety of use cases where it can be used and the benefits it provides. A confirmation of this popularity is provided by the 2019 hype cycle curve developed by Gartner related to the blockchain technology, where a wide range of applications can be found [53]. Moreover, if we observe the position of blockchain technology for the utility industry in 2019, it is still on the rise, witnessing the big expectations as a critical technology for delivering reliable, affordable and ubiquitous commodity services in the power systems field. As already said, the widespread of renewable and distributed generation leads rethinking the management of energy flows on the power system. The blockchain technology in the energy field has today become a realistic perspective, particularly for microgrids, where energy production is intrinsically distributed. The decentralized structure of a blockchain is perfectly adapted to the control of production processes within a microgrid. It is understood that this technology can guarantee the traceability and security of energy transactions. As introduced in the first chapter, today in this sector the blockchain applications are mainly oriented at P2P energy trading, electric vehicles or DR.

In this chapter, the features of blockchain technology useful for energy system applications are analyzed, the main energy applications are addressed in more detail, and the suitability of blockchain for these applications is evaluated.

3.1.1 Features of the blockchain for power systems applications

There is a basic difference between blockchain applications that only manage digital assets and applications that interface with physical objects. This is also the case of the electrical energy world, where physical electricity transactions must be managed through smart meters and actuators. In this case, other than a cryptographic signature or a digital recognition of a virtual item, there must be a similar "certification" for a physical measurement or control system, as well as for the software controlling the actuators or other operations in the virtual dimension. Indeed, in the physical world, complex applications (e.g. SCs) are also needed that may provide a set of execution commands permitting to adhere to predefined workflows.

In the case of P2P trading applications, the triggering event is connected both to availability of money, from one side, and to the availability of energy in the considered time frame, from the other. Actually, in the electrical energy field, these conditions are necessary but not sufficient for any transaction to take place. There are some technical requirements connected to the capacity of connections and regulatory issues that must be considered. Such conditions cannot be verified in a distributed fashion in most cases and this calls for the action of DSOs, whose role becomes fundamental to ensure efficient integration of this technology in the grid. For this reason, the permissioned blockchains may be more adequate to physical world applications, especially in the power systems area where physical objects belonging to a third party are involved in the transaction. In these blockchains, only a few "permissioned" nodes can create and write blocks. These nodes are not anonymous and they may implement different functions. With respect to this issue, it is advisable that, as an example, one of the blockchain nodes is owned by DSO that supervises transactions and provides a certification about their technical feasibility [54]. This happens through a "validation" procedure that can take place between steps 2 and 3 in figure 1.2. As an example, if validation of electricity transactions goes through the running of an Optimal Power Flow or similar procedure for which electrical data must be known, only the DSO can currently run it. In addition, in the energy sector, the timing and the cost of transactions is a significant challenge. The use of permissionless blockchains provides greater security in case data can be released publicly but, due to privacy and the computational time of the heavier consensus algorithms they are not suitable for handling energy transactions. For this reason, energy-related applications are more efficiently handled using permissioned blockchains, despite that in the literature there are many solutions that use permissionless ones.

Another challenge is about using the blockchain for aggregation purposes and for balancing. As an example, the NEMoGrid European project [55] involving various companies and research institutes from Germany, Switzerland and Sweden examines the economic and technical impact of electricity trade between households within an area, i.e. when selling solar power generated locally to other households. In this way, an insight into the mechanism of price variation in the presence of a P2P business model is gained as well as the suitability of blockchain technology to support flexibility and grid stability issues through aggregation in small pilot regions.

In the electricity sector, most applications deal with the emission of utility tokens. These are digital tokens of cryptocurrency that are issued in order to fund the development of the cryptocurrency and that can be later used to purchase a good or service offered by the issuer of the cryptocurrency. As a consequence they prove the ownership of an asset/privilege. In the applications here dealt with, these tokens can be exchanged (for example) as a counterparty of (green) electricity generation. So, in this case, if one party generates green electricity is remunerated by SC is shared on the blockchain with a utility token. The latter can then be exchanged with security tokens also called securities, like bitcoin, storing a value.

Another important feature is the flexibility in supporting SCs or other forms of logic. Indeed the possibility to implement SCs and not only "local" client applications that do not change the state of the blockchain is a very relevant feature for blockchain platforms. SCs are able to process digital transactions and can be used to guarantee that a specific workflow is met. In all the applications concerning power systems, there is a need for SCs. In all cases, where a technical verification over the infrastructure is needed, the SC needs to run power analysis or power optimization codes. As an alternative, the SC can check some metadata sent as inputs of the SC. The difference is that in the first case all nodes run the SC to verify the transaction validity, while in the second case there is a trusted authority that must issue a "permission", used under the form of metadata. The mechanism of SC execution, delivering e-tokens if given flexibility at node A is provided, is depicted in figure 3.1. The output of the SC is the feasibility of the transaction and thus the consensus about starting the actuation of devices and the transfer of digital assets.

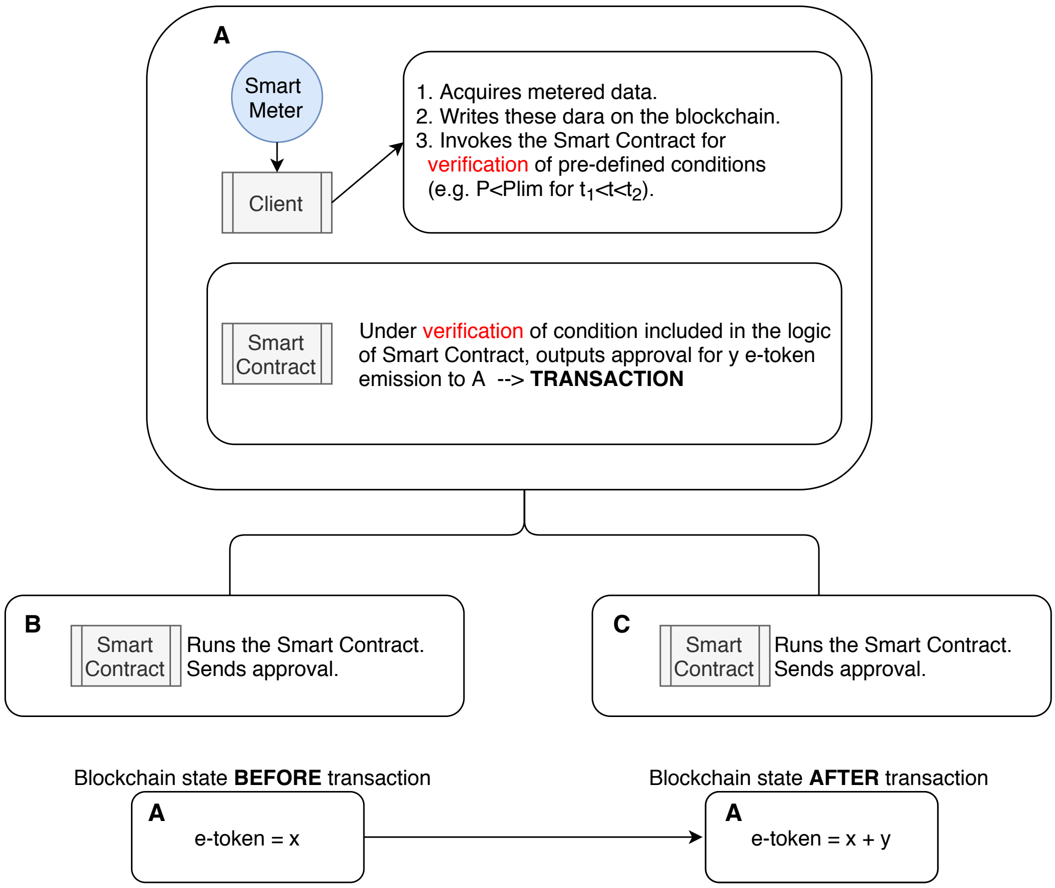


FIGURE 3.1: Example of a Smart Contract execution.

In addition, the decentralization of the network, the transparency of exchanged data and the possibility to carry out transactions without the intervention of third parties allows to avoid market abuse, reduce transaction costs and create new business models for the electricity market directly involving end-users.

3.2 Peer-to-Peer energy exchanges

3.2.1 Peer-to-Peer principles

A Peer-to-Peer system, in general, is a system consisting of a computer network in which the computers of connected users act at the same time as clients and servers. The most popular application of P2P networks is file sharing. With this architecture, users are able to directly access each other's computers, viewing and retrieving files in mass storage and making available the files they wish to share. Other applications may be decentralized machine learning or decentralized social networks. Each of the computers of the users who are part of the P2P network downloads, keeps the exchanged files stored and, above all, shares them with other users. In these systems the simultaneous use of all the physical locations in the computers where the same file is located is managed, optimizing the use of bandwidth in proportion to the number of people connected at a given time, so as to reduce the time of downloading files. Thus, a user is able to download portions of the same file from multiple users in proportion to the bandwidth available to each user who owns the file. In relation to the file to download, is named *seed* the user who owns a full copy of the file object of transaction and *leach* the user who has not yet finished downloading a full copy of the same. Figure 3.2 shows the comparison between the architecture of a classic client-server network and a P2P network.

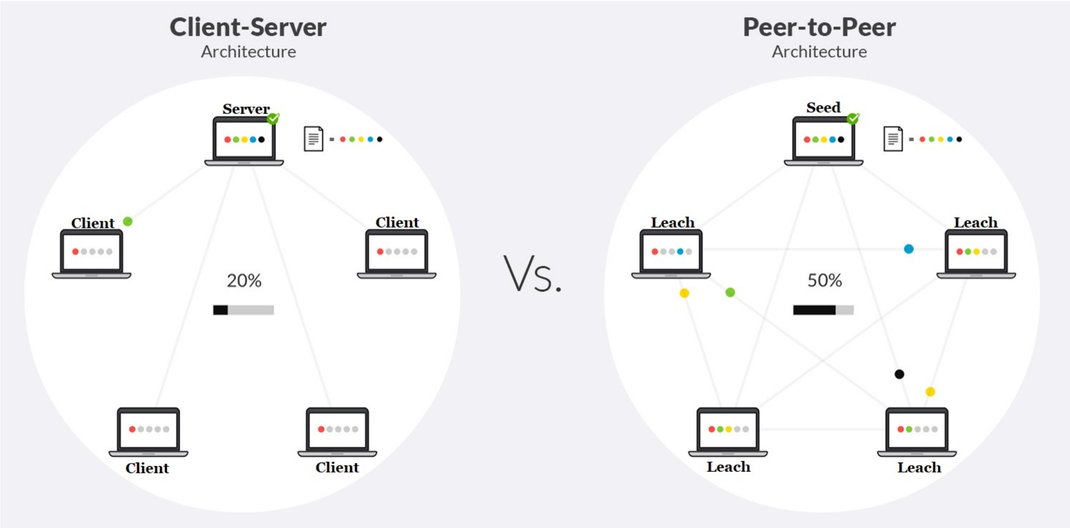


FIGURE 3.2: Client-Server architecture Vs. P2P architecture.

There is no standard communication speed, since each user receives and sends what the bandwidth of his ADSL or fiber line allows him. Among the advantages it can be immediately noticed the absence of hardware costs, such as dedicated servers. This also means that file download speeds can be much faster, in relation to the number of files searched by users connected to the network. A problem to take into account is the security of the network user, as there are serious risks of external attacks, if the router is not adequately protected (for example through a firewall).

The blockchain, which is a distributed network and can also be P2P networks, allows to overcome this problem through the use of encryption and consensus algorithms. In addition, as already mentioned in the introduction chapter, each node of the blockchain contains all the info exchanged on the network and as with P2P networks it works as both a client and a server. To date P2P networks have been used to exchange video and audio files, such as Torrent, Gnutella and Napster. But thanks to blockchain the principle of P2P networks can be applied to different realities, including energy exchanges, ensuring trust among network users.

To date, in Italy, a prosumer can only inject excess energy produced into the grid and access a service called "net-metering". The net metering service is a particular form of on-site self-consumption that allows the electricity produced and fed into the grid at a certain time to be compensated for the electricity absorbed and consumed at a second time. In the net metering the electrical system is used as a tool for the virtual storage of electricity produced but not simultaneously self-consumed. Periodically, the GSE, through the meter readings that are communicated by the DSO, verifies how much energy has been consumed and how much injected. The GSE does this verification annually, but every quarter it makes an estimate of the advances and pays them to the prosumer. At the end of the year the estimates are corrected and the report for the past year is paid. If at the end of the year it turns out that more kWh have been injected into the network than those that have been consumed, the prosumer receives a compensation which is the sum of two items:

1. the first is a refund, for each of the kWh consumed;

2. the second is a sale consideration for the kWh injected and not consumed.

The value of the refund, is calculated considering a price that is not exactly the one paid by the user in the bill, but it corresponds to a 30% lower price. In fact, the taxes paid on the invoice are not refunded. It is, however, a considerable amount that is equivalent to 70% of the bills paid. The value of the second element, that is the consideration for the kWh injected in the grid, is valued by multiplying the injected energy by the price per kWh valid for the territorial area in which the plant is active and detected in the market, in particular in the MGP.

As it is possible to understand from the net metering service, the prosumer cannot choose to whom and how much to sell the excess energy produced, but it is all managed by the GSE and the DSO that communicates the consumption and injection data; it is a centralised system. The possibility of developing different business models also depends on the technology that allows them to be implemented. In this perspective, blockchain technology thanks to its features enables the possibility of implementing an energy transaction directly between "peers", in the form of an exchange or sale of the energy surplus to other user of the power network, thus P2P energy exchanges (see figure 3.3).

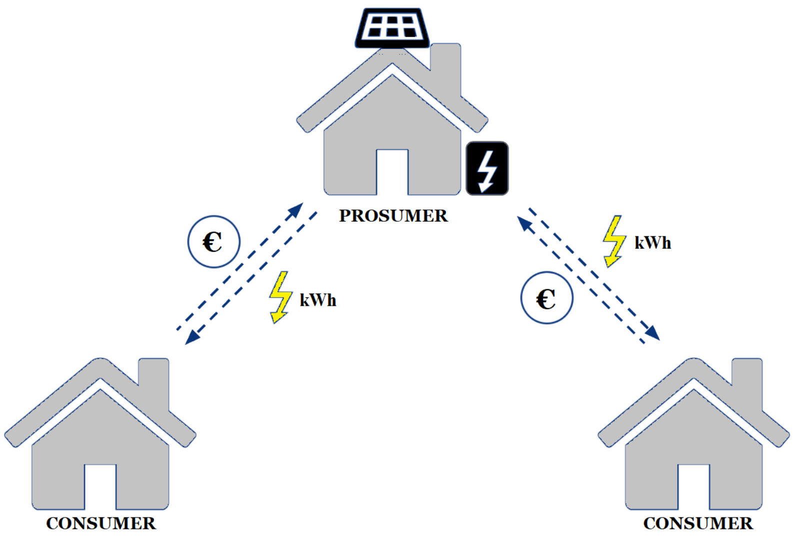


FIGURE 3.3: P2P energy exchange.

The blockchain can be used as an immutable distributed register of energy transactions capable of certifying the energy exchanged between two users without the need for a trusted third party, such as the GSE or DSO, thus providing the conditions to create a P2P energy market. With this system, the prosumers are in a position to sell their surplus energy on the market and to be able to stipulate and manage contracts with customers who today are not, as can be a neighbor.

3.2.2 Actors of the P2P

A P2P energy transaction directly involves two users, a producer/prosumer selling and a consumer/prosumer buying. Depending on the scenario, the buyer can be a company that buys energy on the wholesale market and that resells to retail market or simply an end-user that consumes the energy purchased from the neighbor. But, an energy transaction indirectly involves the system operator. On the low voltage grid, the system operator has no decision-making possibility over the execution of the transaction, as LV networks are generally designed considering a unitary contemporaneity coefficient, but must ensure that the transaction is physically possible, so that the grid is efficient. This can be guaranteed by paying a fee to the system operator for each transaction executed, exactly as it happens for the system charges of the energy bill. On the other hand, for the transactions on the high or medium voltage, the system operator has decision power because it can carry out the load flows analysis before allowing the execution of the transaction. This analysis can be performed on-chain through for example a SC execution or off-chain through dedicated software. Finally, there is the blockchain network manager, who is also responsible for users' identities. The latter may be a specific company or the same energy that already has dealings with the user.

3.2.3 P2P benefits

P2P energy exchanges give rise to an energy ecosystem that has the potential not only to provide economic and environmental benefits, but also to improve grid reliability and production plant efficiency. The fragmentation of the energy market into local markets through the introduction of many decentralised energy sources also increases competition to the benefit of consumers. Increased competition has already started the energy transition by shifting the energy production market from fossil fuels to renewable energies. The benefit of this market transition is not only ecological, but also has a real financial advantage because renewable energy production products have a lower energy cost. The creation of a P2P energy market can also contribute to the balancing of the power grid by reducing, for example, load peaks. By aggregating different users, prosumers and consumers, it is possible to create energy communities that acting in a coordinated way can contribute to the balancing of the network. So, in general the benefits are economic for customers who can choose to whom to sell the energy they produce in surplus or from whom to buy the energy at certain times of the day. The flexibility to sell and buy could also encourage end-users to install small renewable energy plants. Regarding the system operator, the benefits are especially in terms of grid operation because, thanks to local markets, during peak hours small communities will be able to supply themselves by unloading the grid with the consequence of reducing the need to expand power lines and the installation of new production plants to meet the energy demand.

In addition, using blockchain for P2P energy exchanges it is possible to achieve benefits in terms of:

- *Optimization*: better monitoring of consumption, quantity and price control.
- *Transaction costs*: potential cost reduction for the presence of third parties (e.g. brokers).
- *Exchange between individuals*: the user will be able to sell his energy.
- *Automatic execution*: use of SCs to reduce time, costs and control activities.
- *Security*: information distributed over several nodes, difficulty of computer attack.
- *Wider choice*: the user can choose to consume clean energy by choosing the system from which he wants to buy.

3.2.4 State of art

In the literature there are many works focusing on this application proposing a blockchain-based framework to enhance the P2P electricity exchanges between the prosumers of a microgrid [56]–[60]. For example, the work in [59] proposes an authorized blockchain that uses hyperledger fabric to provide a network of P2P energy transactions in order to cope with the growing volume of renewable energy, using Energy Storage System (ESS). The work in [60] proposes a platform for exchanging energy through ESS and exchanging tokens automatically through SCs, solving the security problem through the blockchain private network and improving transparency and immutability through the P2P system. The proposed architecture consists of a private blockchain network in which energy is exchanged through ESS and energy tokens through the blockchain. Users register sales and purchase offers on the blockchain, after which the Distribution System Operator (DSO) compares the total amount of the purchase and sale. Trade is realized if the amount of energy to buy and sell is equal. So the SC moves the token and the energy according to the accomplished trade, and then the result is recorded on the blockchain.

Several companies have instead developed applications in this sector. The first P2P blockchain application is the so-called "Brooklyn Microgrid" developed in New York supported by Siemens Digital Grid and LO3 Energy [61], [62]. The first plants have been connected among them in 2016 and the network developed allows the the prosumers to sell the excess electricity directly using SCs based on Ethereum and pBFT consensus, implemented on Tendermint. The first process included 5 prosumers and 5 nearby consumers and brought to the first energy transaction ever registered on a blockchain worldwide. The energy surplus is registered by smart meters suitably designed for managing energy data and measurements. These are then translated into energy tokens that can be exchanged on the local market. The token indicates that a given amount of energy has been produced by the photovoltaic panels and can be transferred from the portfolio of a consumer to the end-users by the blockchain technology. The microgrid users interact with the platform specifying their individual price preferences under the form of availability to pay or sell electricity. The platform can visualize energy prices in real-time. In the initial phase of the project, the users manually acted on the platform, they could for example make an offer at a given price and a given hour. The public register keeps the terms of the contract, the parties that carry out the contracts, the volumes of energy injected and the consumption measured by the measuring devices as well as the chronological order of the transactions. Any member of the community can have access to all historical transactions in the log and verify the connections. More than 300 homes and small businesses, including about 50 photovoltaic prosumers and a small wind generator, have signed up for the second phase of development, with fully automated devices. The Brooklyn MicroGrid project aims to serve as a testbed for the development of new business models that promote consumer involvement in energy community projects. Local energy exchanges open up the possibility of saving on energy costs.

After Brooklyn MicroGrid, other companies around the world have started developing P2P energy trading projects. In 2017, Enyway was founded in Hamburg [63], with the mission of facilitating a democratic use of energy through the connection between producers and consumers. It allows consumers to buy electricity from individual owners of a wind turbine or a solar roof. Users choose the projects from which to buy energy on the map of Germany, with the help of images and data, as in the case of apartments/rooms offered on AirBnb. In France, the Sunchain [64] experience is expanding. It allows energy exchanges between prosumers and consumers using the blockchain not associated with a crypto-currency. Power Ledger [65] is an Australian company that has developed a renewable energy trading platform enabled by blockchain technology. Since November 2018, the Power Ledger blockchain has been used to track solar energy transactions between 18 families in Fremantle, Western Australia, allowing residents to set their own prices and exchange solar energy generated from their roofs with neighbors who do not have solar energy. In Japan, the Power Ledger blockchain platform will be used to create, track, trade and provide for the regulation of renewable energy credits generated by solar systems on the roof of buildings. The so-called Non-Fossil Value credits allow electricity retailers to obtain certificates of renewable energy for electricity that has been fed back into the grid by photovoltaic systems. In the next phase of their collaboration, Power Ledger's decentralized accounting technology will ensure that every transaction is immutably recorded in real-time, in order to prevent renewable energy certificates from being used more than once.

3.3 Vehicle-to-Grid

3.3.1 Vehicle-to-Grid principles

Electric vehicles are a natural field of application for blockchain technology. The new mobility concept, aiming increasingly towards a "digital" model, inevitably requires improved safety and reliability standards. According to [66], financial services, supply chain and mobile are three of blockchain's main areas of application. In addition to facilitating transactions between vehicles, SCs and real-time data exchange, the implementation of blockchain-based solutions could solve today's difficult problems such as the traceability of original spare parts to identify counterfeit parts or traceability of vehicle consumption to facilitate recovery at the end of its life. In this sense, the blockchain offers a more secure and transparent way to communicate thanks to the continuous sharing of information between nodes of the same and the increased difficulty of tampering with individual blocks. The expected arrival of millions of battery-powered electric vehicles in the coming years represents a major challenge for the power grid. At the same time, however, the electric car also provides very interesting opportunities to improve the management of electrical systems without having to invest unsustainable amounts of money to adapt the distribution infrastructure [67]. In this vision the Vehicle-to-X (V2X) concept was born, which refers to an exchange between a vehicle and another element of a power grid. Electric vehicles can be considered as mobile accumulators capable of exchanging energy with the grid, other electric vehicles or the owner's home. This leads to four scenarios: Vehicle-to-Grid (V2G), Grid-to-Vehicle (G2V), Vehicle-to-Vehicle (V2V) and Vehicle-to-Home (V2H). Figure 3.4 shows a general representation of these four scenarios.

V2G requires cars to act as accumulators so that they can be converted into reserves at critical times to stabilize the grid and avoid overloading. Underlying this mechanism is an energy exchange process managed by a power inverter operating in both directions (low voltage for the grid and high voltage for the battery), whose operation is optimized according to the needs of each component of the reference grid. The bi-directional inverter is able to take energy from the grid to charge the battery (G2V), or supply energy to the grid by taking it from the battery (V2G), see figure 3.4. All this is managed by a control unit that must meet the requirements of the network operator, respecting the minimum charge level and full charge time

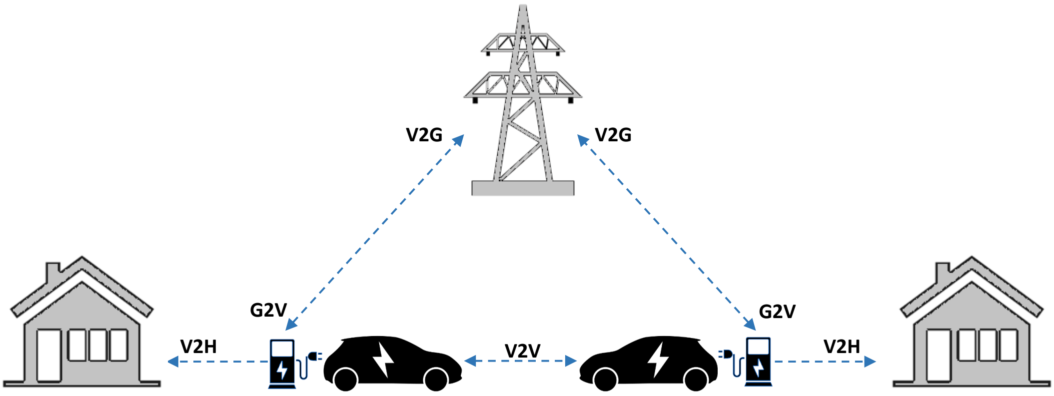


FIGURE 3.4: V2X scenarios.

will be provided by the owner of the vehicle. Depending on the commands it receives from a network operator, the bi-directional inverter either takes energy from the grid to charge the battery or takes energy from the battery to send it to the grid like any generator. The management software is designed to provide the intended service (according to the command of the network operator for V2G, according to the maximum utility for the user for V2H).

Considering that an electric car spends several hours a day parked in a public parking or in a private garage, in many cases connected to a charging column, it is evident how this power can be used, for part of the time, as a resource for the electrical system to balance the need for energy at all times with the production from non-dispatchable RES. The V2G provides for the exchange with the network of energy with the aim of increasing or reducing the overall power absorbed by the electrical system. The V2H provides the same thing, but instead of the electricity network there is the home and the goal is to have maximum savings in the bill for the end customer. In this case it is the owner of the house or the energy management system that intends to increase self-consumption, to make the most of self-production or reduce the peaks of imported power, saving on costs related to the power involved.

V2V applications, on the other hand, concern the possibility of transferring energy from one vehicle to another through the use of a cable or even wireless. Due to the distribution network not yet fully equipped with charging columns scattered all over the territory, in case of battery discharge far from the charging points, until today, the only solution was to contact a tow truck and be transported to the nearest charging column. The V2V system allows electric cars to communicate with each other and enable the exchange of energy between two vehicles. However, it is necessary to upgrade the on-board power electronics so as to allow two-way flow of energy, which currently only goes from the energy source to the engine.

Distributed technologies and Blockchain therefore become ideal for managing systems like those described that, having to rely on the exchange of resources and information in an environment without hierarchies, is by its nature P2P. The use of blockchain in V2X can be a guarantee of efficiency and reliability of communication combined with transparency and security of information. In addition, the use of SCs would allow to implement the logic for network support services provided by electric vehicles. In this case, charging the car represents a service that the user offers to the network and for which he will be remunerated with energy tokens. In this scenario, electric vehicles can contribute to DR, improve grid resilience and reduce peak loads through charging and discharging. The Blockchain allows to verify and record all transactions that take place in a V2X network, ensuring its correct operation and allowing, at the same time, to acquire data useful for its continuous improvement. Applications based on the Blockchain allow people to make their charging stations available to the public in moments of inactivity, receiving tokens in exchange, so drivers of electric vehicles can search for the nearest charging stations by refueling their batteries before they discharge.

3.3.2 Actors of the V2G

As already said, the V2G is a technology that enables the exchange of energy between the electric vehicle and the network, own home or another electric vehicle. The potential of this technology is really high because with an adequate implementation of the infrastructure, it will be possible to have millions of electric vehicles that will act as mobile energy assets and that will not only support local networks, but also contribute to the national transmission system. On average, electric cars on the market have battery packs between 30 kWh and 50 kWh, with real autonomy ranging from 200 to 400 km. That said, it is clear that the contribution that a single car can provide to the power grid is not very high, since it is necessary that each vehicle does not fall below a certain charge limit, necessary both for the health of the battery and for the owners' needs. It is necessary a population of electric vehicle batteries that provides, in a coordinated way, both the power and the energy necessary to provide a significant contribution in an area of the electricity market. For this reason, in order for electric vehicles to contribute to the needs of the power grid it is necessary that they are aggregated and properly managed. This role is fulfilled, as for the DR, by the aggregator, which aims to aggregate vehicles that do not belong to them by managing their loading/unloading cycles to sell services on the energy market, representing the point of contact between the owners of electric cars and the system operator. The authors in [68] identify 12 possible actors for V2G applications, but in general the main actors are the system operator, the aggregator and the electric vehicle. The electric vehicle is identified with the owner of the vehicle itself, the system operator can be the TSO or DSO, while the aggregator can be different depending on the business model. For more details about business models for V2G please refer to [68]. According to [69] the main players, even the most sensible, who can take on the role of aggregator for V2G applications can be:

- Delivery company, car sharing or any company that deals with transport and offers mobility services to customers. This type of actors are called "fleet managers" and have the role of managing the availability of the fleet and then sell its services to the market or to an operator. In this case the fleet is connected to a single network point, just think of the car sharing parking lots or the garage of a delivery company. As fleet owner can decide to charge electric vehicles during off-peak hours and sell the energy stored by the vehicles during peak hours contributing to the reduction of network overload.

- The energy retailer. In this case the aggregator is the owner of a fleet distributed in the territory who can choose to manage the vehicles in order to provide services to the system operator. In this case the aggregator must have as many electric vehicles in its program as possible in order to generate revenue from the sale of ancillary services.

- Battery manufacturer. In this case the owner of the electric vehicle chooses to transfer, in exchange for a reduced rental fee, the ownership of the battery to the battery manufacturer, who manages the battery and has full responsibility for possible damage caused to the battery as a result of providing V2G services.

- An operator specifically created to manage the charging points and communicate with the owners of electric vehicles to control the charges and discharges. This figure is called Electric Recharge Grid Operator (ERGO).
- Communication company. The aggregator is a platform provider that aggregates electric vehicles to enable them to participate in energy markets and services such as frequency response. It acts as a bridge between needs and available resources (electric vehicles, batteries, charging stations).

In blockchain applications, the aggregator, regardless of its identity, could be the platform manager. In this case, the blockchain would contribute to the exchange of data in real-time between the vehicles and the system operator and to the remuneration of users following the service provided in a transparent and automatic way, for example by using SCs.

3.3.3 V2G benefits

V2X applications allow to have a "widespread battery" available that can balance supply and demand of energy in cases of high consumption or that can help to reduce the costs in the bill. The benefits of V2G and G2V applications are in support of the electrical system. In both cases, the electric vehicle is considered as a mobile battery that can interact with the electricity grid allowing the stabilisation of power flows. For this purpose, the vehicle, by storing energy at the lowest peak consumption times and returning any excess amounts, could provide ancillary services of frequency regulation (primary, secondary, tertiary) and real-time balancing to the electrical system, when these are required [70], [71]. These services are different for the different scales of time in which they operate (the primary intervenes within 30 seconds from the time it is necessary, the secondary and tertiary over time gradually longer) and for the way in which they are activated (the primary changes the power input based on the frequency measured locally, the other services are controlled by signals sent centrally by the TSO). The availability of this resource, today inevitably limited, but in the perspective of great capacity, creates a new offer of services that, in the market mechanism that regulates ancillary services, tends to reduce prices, and therefore reduces electricity costs for customers. Moreover, these applications will certainly decrease the use of fossil fuels in thermal electric power plants, which, otherwise, would end up in many cases to stay in service for the only purpose of ensuring the reserve margins necessary for a stable operation of the power network.

V2H applications, on the other hand, could favour end-users who own a photovoltaic system and who have an interest in making maximum use of the energy they produce themselves, reducing to minimum the cost of buying from the grid [71]. Electric vehicles could replace expensive static storage systems to accumulate the excess energy produced by moving it to hours when consumption is high but there is no sun or it provides low energy. The installation of a dedicated storage system for the photovoltaic system involves an initial expense that can be an unprofitable investment that would discourage the customer. The user who has chosen to purchase an electric vehicle, instead, will find, at no additional cost, a storage of available energy, at least for a certain number of hours per day. The benefits thus obtained result in a lower net cost of managing the vehicle. V2H technology can be useful even in the absence of renewable generation: the battery of the electric vehicle can be recharged at home during the night, when energy costs less and in the morning, when it costs more, some of this stored energy can be used for domestic use. Again, at night the electric car will recharge to start the cycle again the following morning.

Regarding V2V applications, the benefits are mostly of a management nature, as users would not need to reach a charging station but can recharge from other vehicles. These scenarios can be used in support of the power grid by charging unloaded vehicles from other vehicles that are in maximum charge conditions and recharging them during off-load hours. Obviously, everything must be coordinated with the needs of vehicle owners in order to have a residual charge to meet their needs.

However, V2X applications raise serious doubts about the effects these could have on battery life. Currently, in fact, their duration is estimated on the basis of a certain number of charge and discharge cycles to which corresponds a certain distance. A more frequent exchange of energy when the car is stationary could in theory accelerate its wear and tear and therefore its life, bringing it ahead of time beyond the efficiency limit of 80%, which is considered the limit below which it should be replaced.

3.3.4 State of art

In the literature, there are many works with the aim of integrating electric vehicles into the grid and optimally coordinate charging and discharging using blockchain technology. In [72], the authors propose a private blockchain to implement a secure pricing scheme for charging and discharging electric vehicles, but in this case, all is executed through optimal SCs to meet the needs of electric vehicles, individual energy consumption preferences and maximize the utility of the network operator. Through the execution of dedicated SCs between an aggregator and owners of electric vehicles, the energy exchange and cryptocurrency exchange process are performed automatically and securely. While, one of the most recent works in this field [29], shows a model of electricity exchange based on a blockchain with the aim of performing P2P transactions between electric vehicles in V2G networks. Moreover, the authors, in order to verify the feasibility of the proposed work, designed and released the SC implementing the mechanism developed on Ethereum, finally verifying the effectiveness of the proposed scheme.

While in the world projects on V2G have already started a few years ago, in Italy on May 24, 2019 started the testing of the V2G system developed by Enel X, Nissan and RSE. Through a special control platform, the charging infrastructure installed in the experimental micro-network of RSE allow to use Nissan LEAF cars to stabilize the network, increasing or reducing energy flows [73]. From the collaboration between FCA, Terna and Engie EPS, bidirectional charging systems have been experimented at the historic Fiat plant in Mirafiori, where work has begun to build the largest charging system in the world, where 64 charging points at 50 kW have already been built with 32 columns that will be tested using the new 500e. By the end of 2021 there will be 700 total charging points available, with 25 MW of total capacity, five of which will be obtained through photovoltaic panels [74].

In Europe, the largest V2G experimentation project is in development in London, in the Northumberland Park bus terminal. It is called Bus2Grid and involves about 100 battery-powered public transport [75]. This initiative will initially test the potential of 28 buses connected to the grid at the same time when they are not in use, and will be carried out by SSE Utilities Solutions Ltd, a company working in the field of alternative energy solutions, the City of London and the city's public transport company. It is estimated that already in this way they will be able to cope with the peaks of consumption by feeding 1MW of energy into the network. It has even been estimated that if all 9,000 surface area public transport in London were electric and used V2G technology, 150,000 private homes could be supplied with electricity. Other projects are in development in Denmark and Germany. In 2016, Nissan, Enel and Nuvve launched the world's first fully commercial V2G Hub in Denmark. In Copenhagen, the energy company Frederiksberg Forsyning installed 10 Enel V2G units and added 10 Nissan e-NV200, 100% electric vans to its fleet [76]. When not in use, commercial vehicles can be connected to the V2G units to receive or transfer energy to the national grid, and through the Nuvve aggregation platform, they are transformed into effective mobile energy solutions, helping to stabilise the Danish electricity grid. In Germany, in 2018, the Nissan LEAF became the first 100% electric car to have passed the pre-qualification phase as a power storage system according to German TSO guidelines. By overcoming all the regulatory parameters of the German TSO for primary power regulation, the Nissan LEAF was accredited for the first time ever as a power reserve for the power grid. Nissan, together with TenneT and The Mobility House, carried out the SINTEG pilot project related to V2G technology to increase the share of renewable energy in Germany and to reduce CO2 with electric vehicles [77]. As part of this project, batteries in Nissan LEAF electric cars are used to store locally produced renewable electricity in order to stabilize the grid during peak demand. More specifically, wind energy produced in northern Germany is used to charge electric vehicles in the region. At the same time, the electricity from the batteries of these vehicles is injected into the grid to prevent an increase in fossil fuel generation.

3.4 Demand Response

3.4.1 Demand Response principles

As unpredictable renewable energy generation increases in power systems, mismatches between production and consumption are more likely to occur. This implies various technical and market consequences, such as congestion of the distribution networks, peaks in energy prices and ultimately the curtailment of renewable energy plants. For example, figure 3.5 shows a load unbalance on the grid that can occur at certain times of the day when the energy supply does not meet the demand.

One of the cheapest solutions for operating the system in order to deal with these problems is implementing DR programs. In a nutshell, the term "DR" refers to any program that encourages end-users to take actions in order to shift or modify their energy consumption profile.

The actions can be performed directly by specialized operators, BSP, or by end-users who decide to act either independently or on the basis of information (almost) in real-time [78].

DR programs are thus designed to encourage the end-users' participation, and their response to prices is essential to get efficient and competitive market and technical outcomes. It was proved that for wholesale electricity markets, as for any other kind of market, the more the demand actively participates, the more competitive and robust the market becomes [79]. DR programs remunerate end-users of electricity for agreeing to modify their consumption for a specified amount of time. Aggregating many electricity users together can amount to substantial control over demand, giving system operators new ways to balance the grid [80].

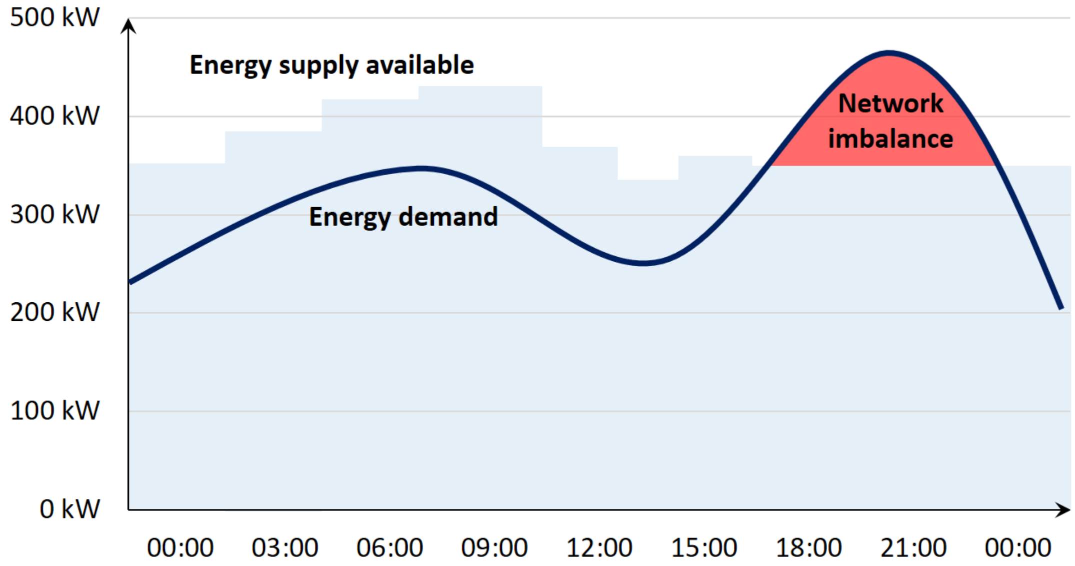


FIGURE 3.5: Mismatch between supply and demand.

The benefits of DR are known in the literature, because by shifting and appropriately lowering the peaks of power demand, the use of generation systems with higher marginal costs would be less needed. As a result, the costs associated with congestion would decrease, less investments would be needed for the transmission and distribution networks, and sector competition in liberalized markets would be stimulated. In the same way, if a renewable generation plant injects electricity when loads are low, an increase of electrical load in some other periods can avoid the curtailment of such sources, thus, reducing the associated economic losses.

Sometimes, DR is considered synonymous of energy efficiency as it modifies the energy demand/production in a given period of the day to better match the generation. Even if this practice often has an effect on energy efficiency, DR and energy efficiency need to be distinguished. Some uses of electricity can be shifted to a different time of the day; others, if avoided at a particular time, will not be transferred to a different time. For example, if a customer chooses not to use a shiftable load [81] (like a washing machine) at a given time, he/she can use it at another time of the day, but if the same customer uses air conditioning (non-shiftable load) at less power, he/she will not maybe turn it on again, since it may not be needed in other times of the day. In this latter case the use of energy is reduced not delayed. DR is a very important tool to avoid technical problems on the network and keeps the costs of the electricity system operation low, while allowing the penetration of higher shares of renewable electricity on the grid and to avoid the need for peak power plants to cope with imbalances in the network.

DR can be generally implemented acting on two tunable knobs: *capacity* and *balancing* [80]. The purpose of working on capacity is to moderate peak electricity demands, so customers participate in the program by making their own load capacity available. The peak demand happens only a few times per year and can be mitigated, without DR, building new generation capacity. At residential level it is possible to shift some loads or reduce them [82], although it can have an impact on user comfort. In addition, since it is based on low energy consumption appliances, an aggregator is needed to participate in the energy market. In this way, there is no need to build new expensive power plants for facing the peaks and customers can receive economic benefits by meeting the DR requests [83],[84]. With the DR as capacity the customer (industrial or commercial/residential aggregates) can choose to shut down or shift some loads during a few hours per year in order to reduce the total load on the network during the period where a peak load is expected. The customer load reduction can be done at three levels:

1. industrial level;
2. commercial level;
3. residential level.

Regarding the first level, some industrial customers can easily vary the time for many of their processes, so they can shut down parts of the industrial process (shiftable-load), reducing their power consumption during the DR event, and to resume the process after the DR event. The commercial customers can reduce the load for example by just dimming the lights of a lobby of a big hotel for a few minutes, providing stability to power system when demand increase. From the point of view of load management, the residential level is the simplest because at home there are both shiftable and non-shiftable loads, therefore it is possible to shift some loads or reduce them. In this way, there is no need to build new expensive power plants for facing the peaks and customers can receive economic benefits by meeting the DR requests [84].

The second category, DR as balancing, has the purpose to balance in an automatic way predictable variation in renewable energy output. This automated DR works by connecting with a building's heating, ventilation, air conditioning, and lighting systems to adjust them in real-time as grid conditions change. Using this kind of DR, grid operators can directly regulate the use of customers' electricity so as to cope with the rapid change in production from renewable sources. Thanks to the use of smart appliances (devices that can receive data from network operators about when to switch on or off), it is for example possible to balance production and load. Another example may be the aggregation of electric vehicles to provide services for adjusting the frequency in real-time when they are connected to the network. Therefore, with DR as balancing, it is possible to match the production from renewable sources by adjusting the demand in real-time, to reduce energy price as it rewards the consumption from renewable sources and avoids renewable sources curtailment. Moreover, it provides grid operators a tool for regulation services and, finally, creates a revenue stream for consumers. The final objectives of these two kinds of DR can be reached using different programs as depicted in figure 3.6 [81], [82], [85].

As shown in figure 3.6, the DR programs can be divided into two main categories: *Load Response Programs* and *Price Response Programs*. In the Load Response Programs, participants receive incentives or reduction in bills by reducing load when the utility asks them to do so. The load reduction can be carried out through three different strategies:

1. *Direct Load Control*: the utility directly controls the customer's load by using some remote control device in order to remotely control the consumer's appliances. This program is often used for residential customers and they can curtail their loads according to a contract (Contractual) or on a voluntary basis (Voluntary).
2. *Interruptible Programs*: the customer shuts down some loads for a short time interval. The participants can be commercial or industrial customers and receive

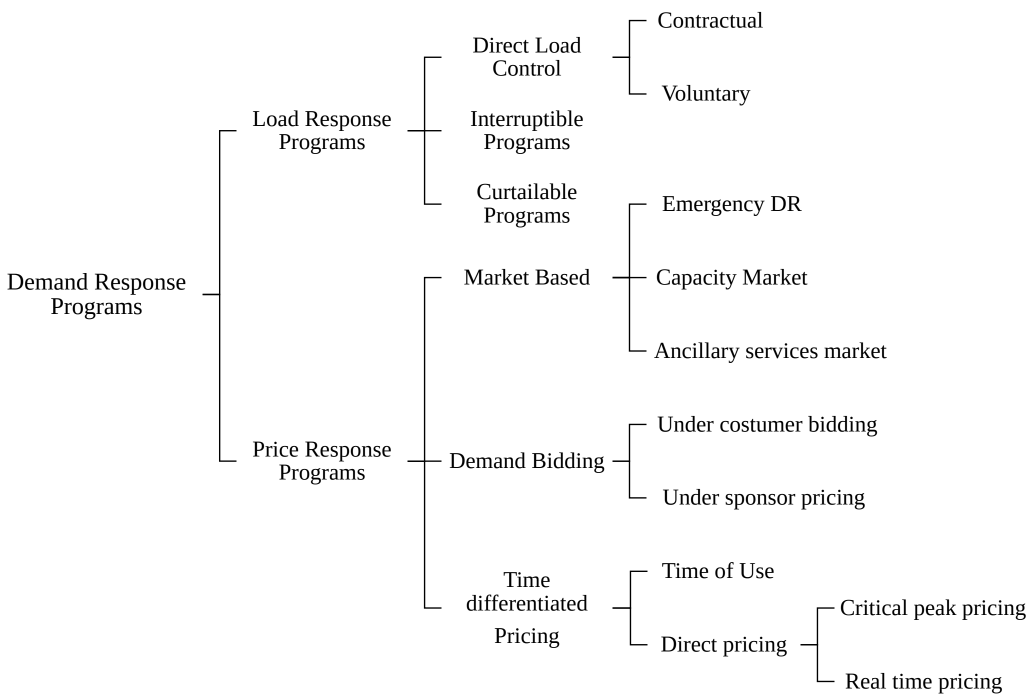


FIGURE 3.6: Classification of DR programs.

upfront incentives or rate discounts, but they can face penalties if they don't respond to the program.

3. *Curtailable Programs*: the customers that cannot turn off their supply can participate to the DR event reducing their load.

The *Price Response Programs* is mostly used for industrial or commercial customers, who are offered an economic incentive for taking part in the program. This type of programs can be divided in three categories: *Market Based*, *Demand Bidding* and *Time differentiated price*.

The*Market Based* programs focus on reducing the wholesale market price and can be of three kinds:

1. *Emergency DR*: participating customers are paid incentives for load reduction during emergency conditions.

2. *Capacity Market*: the participants can provide pre-specified load reductions when system contingencies arise.

3. *Ancillary services market*: allows customers to bid on load curtailment in the spot markets operating reserve.

In the second category, *Demand bidding*, the consumers make offers on specific load reductions in electricity wholesale market and can be divided in two branches:

1. *Under customer bidding*: customers bids the price that is lower than market price for reducing specific load at specific time at most a day ahead or in some cases an hour ahead.

2. *Under sponsor pricing*: market administrators communicate the reduction price per kWh to the customers, who receive a reduced electricity price based on the amount of load reduction.

Finally, in the *Time differentiated pricing programs*, suppliers expose customers to variable electricity prices so that they can move loads from high-price periods to low-price periods with the consequent flattening of the load diagram. These programs are divided in:

1. *Time of use*: is the simplest time differentiated pricing program. The energy price is divided into three fixed blocks of time (peak, off-peak, intermediate) and usually you have higher prices during peak hours and lower prices during off-peak hours. This program offers consumers the opportunity to reduce their electricity bills by shifting their load from peak hours to peak or valley hours.
2. *Direct pricing*: in this program the energy price follows the hourly variation of the wholesale market prices with two different mechanism:
   (a) *Critical peak pricing*: used during contingencies or high wholesale energy prices. It is similar to the time of use program but it adds the third block called "critical peak period" and the blocks may not have a fixed price and a fixed time frame.
   (b) *real-time pricing*: it follows the real-time variation of energy price informing the customer of price variation as little as of 5 minutes interval.

Another classification can be carried out according to how load changes are brought about. From this point of view, two categories are distinguished: *Price-based DR* and *Incentive-based DR*. The first refers to changes in use by customers in response to changes in the prices paid. The second offers incentives to customers for a modulation of the demand; these incentives can either be separate or additional to retail electricity. Some DR programs penalize customers who sign up but do not respond or do not fulfil their contractual commitments when events are declared [86].

3.4.2 Actors of the DR

As already said in paragraph 2.3.1 the aggregator is an actor of the electric market that has the task to supply capacity to the system operator grouping in virtual units the users of the electric system, with which it establishes agreements on the modulation of the power both in reduction and in increase. During a DR event the system operator communicates the request for load modulation to the aggregator in a given area of the electrical system. The aggregator, knowing the total capacity of the customers of that area who have decided to participate in the DR service, responds to these orders by requesting, in compliance with the constraints and requirements necessary for the aggregated resources, the modulation of the load to the customers that make up the virtual load unit. Through an auction between the system operator and the aggregator, the power reduction/increase and the price that the grid operator will pay to the aggregator for the service is determined. At the end of the DR event, the aggregator remunerates the customers according to the designed DR program. The actors who are part of the DR service can be different depending on the type of market in which it participates and the customers who participate, there may be different types of aggregator. The following table 3.1 shows and describes the role of the main actors in the DR service, according to the responsibilities they take.

The role of the Aggregator can be played in different ways. In fact, the Aggregator can be an energy supplier that offers aggregation services, a service provider

TABLE 3.1: Main actors of the Demand Response service.

Grid Operator	Aggregator	Customers
TSO or DSO	***Parallel Aggregator:*** participates in different market at the same time (electricity, water,heat).	- Industrial, commercial and domestic consumers. - Big and small producers.
	Large-scale Aggregator: aggregates large production or consumption units connected in HV or VHV.	- Industrial and commercial consumers. - Big producers.
	Micro Aggregator: aggregates small production units.	- Small producers.
	Global Aggregator: aggregates both small production and consumption units.	- Small producers and consumers (i.e. domestic).
Role		
Notify the aggregator of the need for balancing on the network following the forecast of a stability problem.	Identify the load and/or generation of itscustomers necessary to increase or decrease the use of energy. Remunerate customers whohave responded positively to the request.	Implement the plans of modulation, according to the DR programs discussed in the previous paragraph

specialized in aggregation services that collaborates with a supplier or a joint venture between a traditional supplier and a service provider or an independent market player. In the literature, there are different business models underlying aggregation, but not all of them are actually applicable. Table 3.2 shows a summary of the different business models that are currently appearing throughout Europe, distinguishing between aggregators that combine different roles and independent aggregators.

Table 3.1 shows that the type of aggregator depends on the market phase in which it participates, the size of the production and consumption units it aggregates and the type of users it involves in DR programs. While table 3.2 shows that the aggregator can perform only one or more activities depending on whether it is a combined or independent aggregator. In blockchain applications depending on the users involved and the tasks it performs, the aggregator can be both combined and independent. The type and business model may change from application to application.

3.4.3 The baseline

The last step of a DR event consists in the remuneration of the customers who have responded positively to the request to modify the load as communicated by the Aggregator or, as in this case, by the DSO. In order to measure the load modification of the customer, it is necessary to identify a "Customer Baseline Load" (CBL). The CBL is the reference consumption of each customer that participates to the DR program and is used to assess the effects of the DR on a given customer or a set of customers

TABLE 3.2: Business models for aggregation.

Business Model	Description
Combined aggregator - Supplier	Supply and aggregation are offered as a package and there will be one BSP per connection point because aggregator and BRP are the same entity. The main benefits are reduced complexity and the absence of financial settlements between suppliers and aggregators.
Combined aggregator - BSP	There are 2 BSPs on the same connection point, the BSP (independent aggregator) and the BSP (supplier). The aggregator has an agreement with the consumers of the supplier and the supplier will have to be compensated for the electricity that was sourced on day-ahead or other markets.
Combined aggregator - DSO	DSO and aggregator coincide. Customers buy electricity from retailers, but now the DSO provides DR services to them. DR results can be sold on the market as negative consumption. This can be done by the DSO or by a subsidiary to the DSO company due to regulatory issues.
Independent aggregator as a service provider	The aggregator is a service provider for one ofthe other market actors but does not sell at own risk to potential buyers. The aggregator and the other market actor should have a long-term and exclusive relationship because,since the independent aggregator has no balancing responsibility, he will gainthe full benefits of his actions. The other market actor, nevertheless, is exposed to price risk
Independent delegated aggregator	The aggregator sells at own risk to potential buyers such as the TSO, the BSP and the wholesale electricity markets.
Prosumer as aggregator	Large-scale prosumers, such as commercial and industrial prosumers,choose to adopt the role of aggregator for their own portfolios.

load profile. In fact, the DR effect can be quantified as the difference between the consumption during the DR event and the CBL (see figure 3.7). In the implementation of a DR program, the estimation of the CBL is fundamental, because the difference between the CBL and the actual consumption represents the customers' performance under the DR program and is the reference to design the economic compensation mechanism. The accurate estimation of the CBL is critical to the success of DR programs because it involves the interests of multiple stakeholders including utilities and customers. In the literature, there are many methods to evaluate it [87]–[92], but not all of them can be used efficiently in a DR program because they are too complicated.

The work in [91] also classifies CBL evaluation methods into three general categories:

1. *Averaging methods*: based on the hypothesis that the load profiles of an individual customer in several adjacent days are similar, thus, the CBL can be simply

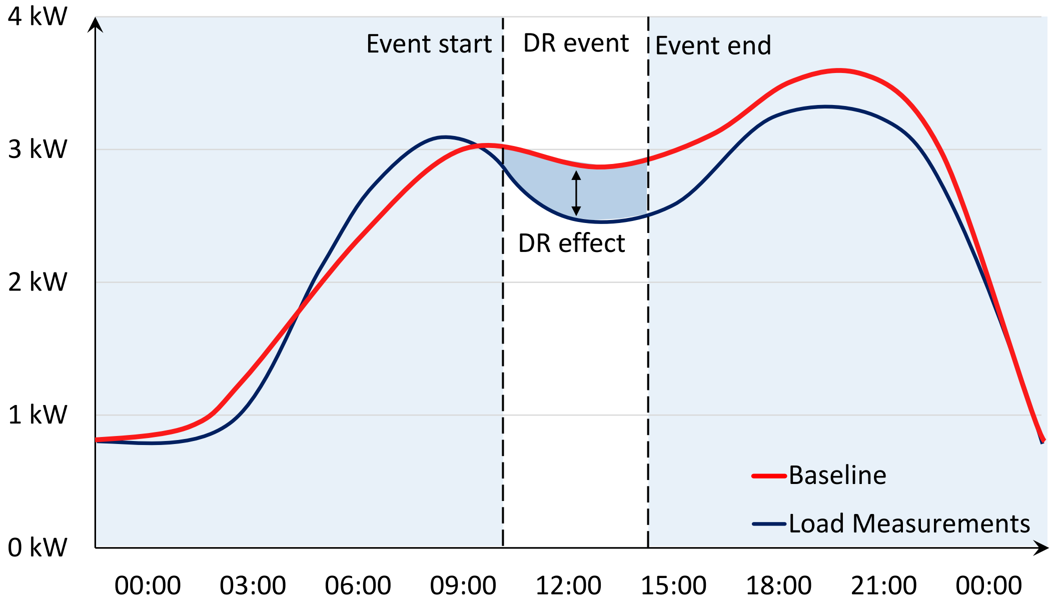


FIGURE 3.7: Comparison of baseline with the performed load profile during the DR event.

estimated based on the average load of days prior to the event day.

2. *Regression methods*: try to fit a linear function to describe the relationship between the load and explanatory variables such as historical load and weather data (e.g. temperature, humidity and wind speed) and then use this function to estimate the CBL of the event days.

3. *Machine Learning methods*: try to find the potential relation between the load and its impact factors. Unlike regression models, Machine Learning methods can find the hidden non-linear relation and exhibit high levels of estimation accuracy.

The methods of calculating CBL, especially when these are parts of a shared mechanism, are required to be simple, transparent, and easy to understand for both utilities and customers. Hence, although machine learning methods may deliver higher estimation accuracy, they are difficult to be applied in practice due to their inherent limited transparency. The proliferation of methodologies increases the complexity of operating in the field of DR, making the comparison of the solutions adopted by the various utilities more difficult for both customers, aggregators and BSP.

The North American Energy Standards Board (NAESB), an industry forum for the development and promotion of standards in wholesale and retail gas and electricity markets, developed a set of common definitions and practices defining five types of baseline evaluation methodologies and the suitability of each method for each type of service provided by the DR service [93], see table 3.3.

Each of these methodologies has numerous possible variations, but in general:

- *MBL* are adopted for verifying the contribution of demand resources to capacity commitments.

- *MBMA* are adopted for ancillary services (in particular frequency regulation).

TABLE 3.3: NAESB baseline evaluation methodologies.

Evaluation Method	Description	Service Type	
		Capacity	*Balancing*
Maximum Base Load (MBL)	"method based solely on a demand resource's ability to reduce to a specified level of electricity demand, regardless of its electricity consumption or demand at deployment"	✓	
Meter Before /Meter after (MBMA)	"method where electricity demand over a prescribed period of time prior to deployment is compared to similar readings during the sustained response period"	✓	✓
Baseline Type-I (BT-I)	"method based on a demand resource's historical interval meter data which may also include other variables such as weather and calendar data"	✓	
Baseline Type-II (BT-II)	"method that uses statistical sampling to estimate the electricityconsumption of an aggregated demand resource where interval metering is not available on the entire population"	✓	✓
Metering Generator Output(MGO) or Behind the-Meter Generation	"method used when a generation asset is located behind the demandresource's revenue meter, in which the demand reduction value is based on the output of the generation asset"	✓	

- *BT-I* are the most commonly adopted, especially for measuring demand reductions offered in the energy markets.
- *MGO* are used when there are on-site generation units.

Depending on the type of DR program it is possible to choose the CBL evaluation method, but in general the BT-I, like the averaging methods, are the most suitable for the blockchain applications because they are simple to apply, quite reliable and can be used for both capacity and balancing services.

3.4.4 DR benefits

Electrical systems have three important characteristics. Firstly, because electricity cannot be stored economically, the supply and demand must be kept in balance in real-time. Secondly, grid conditions can change significantly from one day to the next or from one hour to the next, mainly due to the increasing penetration of energy produced by RES. Demand levels can also change quite quickly and unexpectedly, and as a result imbalances between supply and demand can jeopardise the integrity of the large scale grid in a matter of seconds. Thirdly, the electrical system is capital-intensive, as both large power plants and transmission systems have long delivery times and a multi-decade economy. These characteristics of electrical installations require that electrical networks are planned and operated years in advance to ensure that installations can operate reliably in real-time despite the many uncertainties surrounding future demand. In the competitive electricity market, the entities serving the load (integrated services or retail electricity suppliers) buy or build 60 to 95% of their electricity in advance, with the expectation that they will be able to generate or buy enough electricity on the spot market in real-time to meet system changes. With DR is possible to address these uncertainties by increasing the flexibility of the electricity system while keeping costs relatively low and facilitating the integration of renewable energy. Network operators, Independent System Operators (ISO), Regional Transmission Organisations (RTOs) or utilities and other entities can use the DR to reduce or shift loads instead of traditionally building more generation [94]. DR offers a number of financial and operational advantages to all actors of the electrical system. These benefits can be grouped into three main categories:

1. *Operating*: the electrical system requires large amounts of reserve generation to protect against generation fluctuations from RES. The energy produced by RES replaces the energy from conventional generators, but the capacity of these generators needed to maintain the security of the system is lacking. DR can provide these security services through load reduction and displacement. In addition, the use of DR to ensure system safety reduces the need to operate the power plants at partial load, which is inefficient and generally results in higher fuel costs. It also reduces dependence on the import and export of electricity through interconnections with neighbouring regions. This is particularly interesting from an economic point of view, as it allows these interregional links to be used only when it is profitable, rather than out of the need to balance the system.

2. *Planning*: a significant component of the total costs of the electrical system is represented by the costs of acquisition and maintenance of generation plants. The use of DR to reduce the generation capacity of the system could result in a substantial reduction in total costs. With DR it is possible to balance the fluctuations due to generation from RES thus avoiding the use of peak power plants, usually expensive. It also increases the usefulness of existing installations as more consistent production can be maintained. A further consequence of this is the potential to reduce emissions from fossil fuel power generation. The DR service is also useful to avoid grid congestion, thus maximizing the usefulness of the network and delaying or eliminating the need for upgrades and reinforcements of power lines.

3. *Economic*: the participation of responsive demand in the electricity market has a number of key advantages. First, market power can be reduced for both suppliers and geographic location, allowing demand to respond to prices differentiated by geographic location and duration, as this limits the ability of large generators to manipulate the wholesale price of electricity. In addition to the short-term efficiency gains related to prices, the DR demonstrates significant long-term efficiency gains in the form of efficient capacity planning. So, at market level the economic benefits are the lower wholesale market prices because the DR avoids the need to use the most expensive power plants to be operated in periods of otherwise high demand, lowering generation costs and prices for all purchasers of wholesale electricity. For customers, the economic benefits translate into savings on bills and incentives gained by adjusting their electricity demand in response to time changes. Over the long term, a sustained DR reduces the need for aggregated system capacity, allowing the utilities and other retail suppliers to buy or build less new capacity.

The most important advantage of DR is undoubtedly the improvement of the efficiency of production resources due to a better balance between energy produced and consumed avoiding the use of inefficient and expensive peak power plants. The greatest potential for reducing peak demand and shifting over the day is held by residential users [95], rather than commercial or industrial users. But to date, in countries where DR service is used to address issues that can affect the electricity system, it is mostly large consumers who take part in the service. This work aims to provide a new DR model that can also be easily and efficiently applied to residential users.

3.4.5 State of art

The issue of decentralized management of DR is discussed in many recent works that aim to propose new control and management models without the need for a central controller that exchanges data with all distributed resources. The work in [96] shows a blockchain platform for the storage of information on the use and energy generation of the prosumers of a microgrid, thanks to SCs performed on the Ethereum blockchain that assess the expected flexibility of each prosumer, the associated remuneration or penalty and the rules for the entire energy balance in the microgrid considered. The literature also shows some other studies that approach the DR problem with the use of DLTs. Other interesting works [97]–[99], propose new systems to provide energy flexibility services to system operators (TSO or DSO) through DR actions based on blockchain technology, but considering only the interaction between system operators and BSP without taking into account how prosumers operate the load variations. These works propose to integrate blockchain solutions in the currently existing DR programs with the aim of reducing information asymmetry for the customers.

DR programs for peak load and congestion management on power lines have been in use in several countries for many years, but its application has long been limited to large consumers. According to a recent report by the IEA [100], the global potential for technically available DR is about 4,000 TWh and could reach 7,000 TWh by 2040, with more than 85% of the volume growth attributable to the construction and transportation sector. Most of the potential is in the residential and commercial sector, involving air conditioning and household appliances. Also according to IEA, the full implementation of the technical potential would lead to about 200 GW of additional flexibility for the global electrical system in 2040. This level of DR would avoid investments in new electrical infrastructure (new power generation, transmission and distribution capacity) totalling 270 billion dollars. Despite growing interest, however, the DR market is still rather limited today (about 45 GW globally), partly due to existing regulatory constraints.

According to the European Commission, 20 GW of DR are currently used, but the potential in the EU could reach 160 GW in 2030. The rapid spread of renewables and the electrification of mobility and the civil sector will in fact increase the value of flexibility, thus increasing the economic value of DR interventions. DR in the residential sector is considered an emerging market in Europe, with an estimated 1.3 GW of activities already involved today [101]. The residential sector, in particular, has a great untapped potential of 200 GW, 97% of which is connected to air conditioning systems and water heaters. However, access to these resources for DR is challenging; less than 1% of all existing residential air conditioning and hot water systems currently have integrated connectivity.

To date, there are no real experiences but only projects in development such as DELTA [102], eDREAM [103] and BLORIN [104]. The H2020 DELTA project, proposes a platform consisting of virtual nodes to manage problems on the grid due to load peaks and imbalances through cooperation and interactivity of end-users. In this case there is no SC to manage the flexibility of the prosumers, but a multi-agent system running on VNs that updates the energy profiles for each prosumer in the aggregator portfolio, with load forecasting and optimization tools that provide the necessary information for self-balancing and prevent internal energy loss or stability. The European eDREAM project aims to develop innovative solutions for the implementation of real-time DR strategies supported by the use of blockchain technology. These technological solutions will allow an optimal and rapid detection of flexibility within the power grid, secure data management, microgrid control and new business opportunities. The eDREAM technologies will be accurately validated both in laboratory scale (Greece) and in two pilot sites (UK and Italy). The BLORIN project aims to create a technology platform based on the blockchain for the dissemination of renewable energy and the management of energy exchanges. This platform will help the creation and dissemination of solar Smart Communities and will be able to facilitate interactions between prosumers, manage charging infrastructure for electric vehicles and coordinate exchanges with the DSO. Blockchain technology will be used to manage energy exchanges between prosumers, to aggregate them and to provide DR services. The BloRin platform will be developed and tested at the Engineering Department of the University of Palermo, together with the industrial partners Exalto Energy & Innovation and Regalgrid, and will then be field tested in two Sicilian islands, through the contribution of distributors, S.EL.I.S. Lampedusa S.p.A. and SEA Società Elettrica di Favignana S.p.A., active partners of the project. In Lampedusa will be tested a micro-grid that will involve a mix of photovoltaic systems and storage systems with the possibility to manage the demand profile of various users thanks to DR programs. In Favignana the model will be used for the management of electric vehicle charging systems in order to enhance their contribution as distributed storage for the improvement of the quality of grid operation.

These projects aim to respond to the challenges arising from the growing uncertainty in balancing energy due to the increasing contribution of renewable sources, proposing at the same time a useful tool for the evolution of the electricity market in a direction that involves end-users on regional, national and international scenarios.

3.5 Suitability of the blockchain for power system applications

The blockchain is an emerging technology for sharing decentralized data and transactions through a large network of untrusted participants. This new technology, thanks to the advantages it provides, has several use cases, but as a database and computing platform also has disadvantages compared to conventional databases. The blockchain may be an appropriate choice for some use cases, while conventional technologies are more appropriate for other use cases. So, considering the topic of this thesis, one of the main problems to be addressed is to determine whether the application of blockchain technology for power systems is suitable or not. A recent paper has discussed in general the suitability of the application of the blockchain technology to a specific issue, providing a simple flowchart to be used for this purpose [5]. The flow chart is reported in figure 3.8, with some modifications introduced for blockchain applications to power systems.

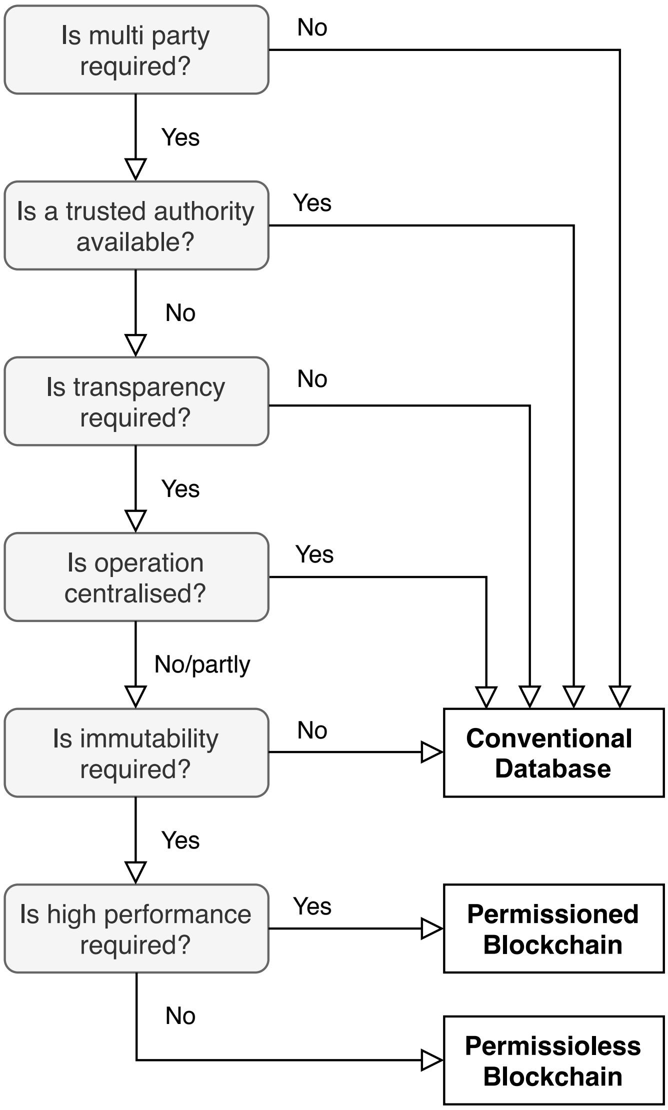


FIGURE 3.8: Blockchain suitability evaluation graph for power system applications.

Trying to understand the real need of blockchain technology for the electricity sector, both in P2P electricity trading, such as in V2G applications and in DR related applications, the issue is certainly multi-party. Smart meters and actuators at the prosumers' premises are decentralized sources of data, for which it is required to have the whole transactions history especially for assessing offers and demands along time and for quantifying remunerations (e.g. in DR applications). Finally, time constraints for blockchain can either be strict or not in these applications because meters currently register energy in given time intervals and it is always possible to extract synthetic indicators for any profile. Additionally, in these cases, there is a need for transparency from all the involved parties, generally to overcome the traditional knowledge asymmetry between the system operator/energy retailer and customers. Transparency is a key feature especially for public and regulatory institutions, and it is generally desirable also for private companies. Indeed, it is worth to notice that, very often, DSOs and TSOs are involved into legal disputes with aggregators, prosumers, consumers and energy retailers due to various reasons (theft of electricity, excessive voltage drops, loss of service continuity, damages to the grid due to faults at the user's installation, etc.). In many cases, thanks to its characteristics of immutability, confidence and transparency, the blockchain could provide a quick solution to many disputes. This could modify the process described in [5] reinforcing the main role of transparency and immutability in the choice of the blockchain solution. Indeed, figure 3.8 shows that, without a trusted authority, if transparency or immutability are required, the use of blockchain is always suggested. Full transparency, however, is needed towards pricing mechanisms and especially in the communication channel connecting system operator/aggregator/energy retailers and each end-user. Such a communication channel can even be invisible or partly visible to other consumers. In this case, the requirements for performance can lead to different types of blockchain. The classification depends on the access rules to the ledger and the permission to write it. As already said, the blockchain can be public or private depending on the access to the ledger, whereas it is named permissioned or permissionless depending on who is authorized to maintain the ledger. Moreover, with respect to the proposal in [5], the flow chart is slightly modified including also the answer is not "partly", due to the many different features of cyber-physical problems, such as power systems applications. The power system sector involves several authorities such as system operators (TSOs and DSOs), aggregators, certification entities for physical apparatus providing data (IoT), Data Protection Officers (under GDPR 2018). Despite these authorities do not trust each other, the technical authorization for an energy transaction is always given by the system operator, while financial assets of the parties as well as their identities are guaranteed by the blockchain itself under national regulation. Data Protection Officers instead call for the need for a centralized administration of the data system, thus indicating permissioned blockchain infrastructures. Operation control can only partly be decentralized since some technical issues are managed at central level (i.e. balancing). When high performance, in term of scalability, is required either security or decentralization must be limited, according to the blockchain trilemma assumption [105], thus again pointing at permissioned blockchain technologies. The blockchain trilemma states that a blockchain system can provide at most two of the following three properties:

1. Maximal decentralization of block production.

2. Network security (its resistance to attacks).

3. Scalability of the network (its ability to support load growth, related to the number of transactions that the network can process in a given time interval).

Decentralization refers to a low computational burden for any node of the blockchain, meaning the possibility even for a low computational power unit to fully take part in the blockchain community. Security is the property for which even in the presence of malicious attacks, none of the contents of the blocks could be altered or other malicious actions are prevented (e.g. the double spending of utility tokens). Finally, Scalability is related to the possibility to increase the speed of transactions, namely the number of transactions that can be validated and agreed upon per second. This dimension concerns the efficiency of the technology in validating and "finding a consensus" on transactions contained in a block. Therefore, with respect to this item, both the technical validation if needed and the consensus algorithm have particular relevance.

Focusing on the three applications of energy blockchain detailed in this chapter and considering the flowchart proposed together with the points of the blockchain trilemma can be said that the blockchain technology, especially the permissioned, is suitable for applications in the energy sector. In fact, both in P2P, V2G and DR the blockchain is able to guarantee the three points of the blockchain trilemma, allowing to perform the applications in a safe, fast, decentralized without neglecting transparency and trust between network users. Moreover, thinking of the increasing development of microgrids, the decentralized structure of a blockchain is perfectly suited to the control of production processes and energy management within a microgrid. Users of microgrids may be able to supply themselves so that they do not require power from the grid and thus avoid overloads. In addition, producers could pay for active voltage control that maximizes their production or, vice-versa, the distributor could be willing to pay for the supply of reactive power in order to maintain voltage quality. The participation of microgrid nodes in ancillary services, such as voltage regulation, in addition to improving grid management, can therefore lead to higher revenues for the nodes themselves. Also the continuity of the service, as well as the willingness to accept interruptions of the supply, will constitute an asset to which correspond respectively a price of sale or purchase.

Chapter 4

Development of a blockchain network for DR service traceability and certification

4.1 Introduction

DR programs are a set of activities with the aim of optimizing energy consumption in specific time intervals, namely DR events. DR programs are currently implemented by means of centralised communication architectures, in which data and operation logic over data are managed by a single entity. In current DR programs implementations, an aggregator takes care of sharing the load modification burden among the end-users according to a logic and based on data that are not transparent to end-users and neither to the system operator who requested the modulation service. On the other hand, highly stochastic behavior of generation units on the grid will ask for more flexibility of energy resources in the system and thus for further involvement of end-users. Such variability, has increased the need for balancing services and close to real-time markets. This can be managed by means of a suitable technology that handles transparently and with limited delay the communications between end-users and aggregators, when the request of modulated power from the latter suitably accounts for high variability supply and demand.

However, as emerges from the reports [106], [107] about real world practices in this area, end-users are rarely involved in DR programs for ancillary markets for primary regulation and if so, they only provide some capacity to be activated by directly turning on/off the loads, such as it happens in Finland and UK with heating electric loads. More frequently, end-users can take part to secondary and tertiary regulation. As already seen by the literature review above, DR programs can be implemented using Distributed Ledger Technologies and in particular blockchain platforms. The use of blockchain platforms for DR services provision, while providing transparency, information symmetry and security to those who take part to the platform, entails some challenges that are detailed below.

The new General Data Protection Regulation (GDPR) requires the existence of one liable party and one entity, the Data Controller, natural or legal person, public authority, agency or another body, which, alone or jointly with others, determines the purposes and means of the processing of personal data. The compliance with GDPR with respect to this issue calls for the use of *permissioned* blockchain platforms. Blockchain platforms are indeed currently deployed as *permissioned* and *permissionless*. As explained in chapter 1, *permissioned* blockchain needs prior approval from one entity before taking part to it, whereas *permissionless* blockchain lets anyone participate in the system. In *permissioned* blockchain, the identity of participants is known, while in *permissionless* blockchain participants are anonymous.

Another challenge in using the blockchain for DR certification concerns the timing of transactions implementation. Using *permissionless* blockchain ensures greater security, but, due to the computation time of the underlying mining algorithms, is not adequate for managing close to real time operations. For this reason, a more adequate choice concerns the use of a *permissioned* blockchain for energy related applications and, in particular, DR programs implementation.

The Third Energy Package of the European Union [108], already in 2009, required all Member States to ensure the implementation of intelligent metering systems for the long-term benefit of consumers. Such intelligent metering systems are usually referred to as Smart Meters (SMs). By SMs, consumers should also be able to access dynamic electricity price contracts. The report from the Commission *Benchmarking Smart Metering Deployment in the EU-27 with a focus on electricity* sets targets for the massive roll-out of SMs: 72% of end-users in EU-27 are expected to have SMs by 2020. Such as in most member states, in Italy, the implementation is carried out by the Distribution System Operator (DSO). The Directive from the EU parliament on common rules for the internal market in electricity identifies two drivers. The first driver is allowing DSOs to manage local flexibility resources. In this way, network costs could be significantly reduced. Another key driver to competition and consumer engagement is information. Previous Commission consultations and studies have shown that consumers complain about a lack of transparency in electricity markets, thus, reducing their ability to benefit from competition and actively participate in markets. Consumers do not feel informed enough about alternative suppliers or the availability of new energy services. They also complain about the complexity of offers and procedures for switching suppliers. The reform will also ensure data protection as increasing use of new technologies (notably smart metering systems) will generate a range of energy data, carrying high commercial value [109].

However, current SMs are not sufficiently "smart" from a distributed architecture perspective. The "smartness" of the metering infrastructure basically refers to the possibility for a DSO to read the metering data remotely and eliminating the need for customer consumption estimations. Moreover, they can provide the metered data directly to the customers through a dedicated local channel.

The SMs for the Italian electric energy market are an exemplary case. In their 2.0 release (SM2G), they present two separate channels of communication. The first channel is directed towards the central distribution system (*chain 1*) for exchanging information with the DSO and validated data with the retailers. The second channel (*chain 2*) is directed towards any local home automation system for more intelligent management of consumption at home, but it provides non-validated data. The *chain 1* allows for real-time communication using the A-band PLC technology, while the *chain 2* uses the C-band PLC that provides the same or better performance than the A-band PLC as it is subject to minor disturbance [110]. The lack of connectivity between SMs and the Internet and the impossibility to install customers' code on them for security reasons, hinders the possibility to use them as nodes of the blockchain. This is currently not possible and creates some problems when it comes to open the market to third parties who could manage the blockchain platform.

The same situation can be found in other member states such as Denmark, whose SMs deployment status has reached almost 100%. Danish smart metering infrastructure follows a philosophy similar to the Italian one with a local communication channel where the customer can incorporate in-home displays or monitoring systems, and an external channel sending data to the DSO's concentrator. In the Danish case, RF proprietary standards or Wireless M-bus are commonly used between the

SMs and the data concentrators, while the local interface is usually provided with a serial port where Internet-based communication modules can be attached. This increases the flexibility of the system compared with the Italian case but is still not enough to directly support blockchain applications [111].

This chapter aims to describe the integration of a blockchain platform for DR events execution into the existing power network without the need for additional devices and using the already installed SM. For this purpose will be described the current protocol used by many states for the execution of DR events, the blockchain platform used, the architecture developed and the logic implemented for the development of a new system for the execution and certification of DR events.

4.2 Blockchain Techology and OpenADR

Most part of the DR programs are today implemented as centralized systems: decisions on loads control are taken by the system operator or aggregator based on dynamic programming optimization [112], fuzzy logic-based decisions [113], or other profit maximization schemes [114], [115], and proposed to the customers. This stems from information asymmetry and centralized control over available information deduced by smart metering devices. Even when a decentralized dispatch based on price signals affecting the user decisions [116] is implemented, prices are decided in a centralized way.

In this work, the decision logic is distributed and cooperative, but the validation of measurements and the DR logic itself are still centralized. However, it will be shown that the design choices that appear as limiting the blockchain potential, on the other hand, reproduce a realistic scenario, where all market actors are represented and take part. Essentially, DR systems are mostly based on a classical client–server service architecture, where a server keeps the links with industrial, commercial or residential customers for collecting measurements and issues control signals. Figure 4.1 shows a general architecture, where the System Operator through a client-server messaging infrastructure is able to exchange information and DR signals with the customers.

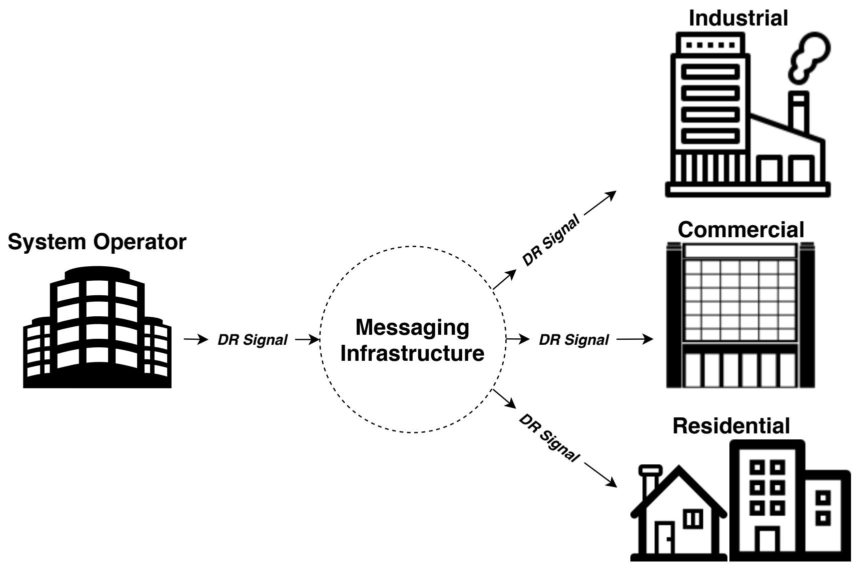


FIGURE 4.1: General DR messaging architecture.

The most applied protocol to exchange information and signals in DR contexts is the Open Automatic DR, OpenADR [117]. The latter is an open access protocol that is implemented on a client server architecture and uses HTTP for transport implementation, while Public key cryptography ensures security. OpenADR is a method developed with the aim to allow continuous transmission of DR signal to a customer. This gives the customer constant visibility of wholesale prices and helps to better balance supply and demand. The advantages are to facilitate a timely and predictable response for the system operator, while allowing the end customer's choices. OpenADR creates a common language, the ADR 2.0 protocol, to communicate a DR event over an IP-based network, such as the Internet. OpenADR 2.0, the basis of today's global standard, is managed by the OpenADR Alliance. Many providers, in several U.S. states, parts of Europe, China, Japan, Australia and Korea, now support this protocol, which ensures operation when a system operator calls an event. OpenADR works by having pre-programmed systems to take action based on receiving a signal. System operators initiate a DR event through a Demand Response Automation Server (DRAS). The DRAS is responsible for communicating specific details about the event, such as duration, start time and price signals to the end-user devices. The DR signal communication is always carried out by using two actors, VTN (Virtual Top Node) and VEN (Virtual End Node). A VTN always controls many end nodes and is responsible for transmitting event specifications, such as price, and programming signals. DR aggregators, or those who sign up end customers and sell their reduced loads on the wholesale market, can be either the top node or a final node, depending on who is calling the event, see figure 4.2

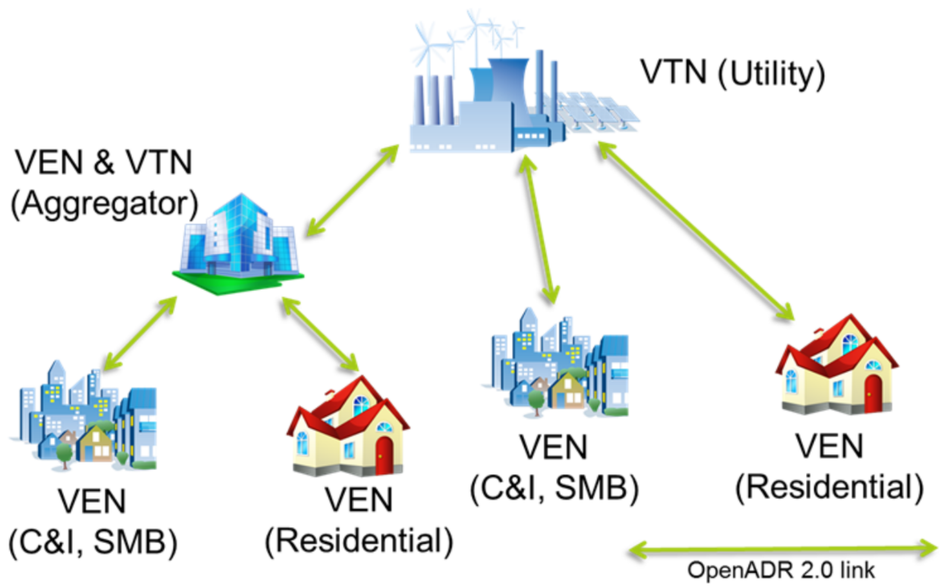


FIGURE 4.2: OpenADR actuators architecture.

The customers are the VENs that provide the demand reduction to the aggregators. Examples of messages conveyed via OpenADR from VTN to VEN include:

- PRICE_ABSOLUTE: the price per kilowatt-hour.
- PRICE_RELATIVE: a change in the price per kilowatt-hour.
- PRICE_MULTIPLE: a multiple of a basic rate per kilowatt-hour.
- LOAD_AMOUNT: a fixed amount of load to shed or shift.

- LOAD_PERCENTAGE: the percentage of load to shed or shift.

A VEN can be integrated into the hardware of the on-site energy management system, or as a separate hardware device to pass signals directly to the end devices or building control system, see figure 4.3.

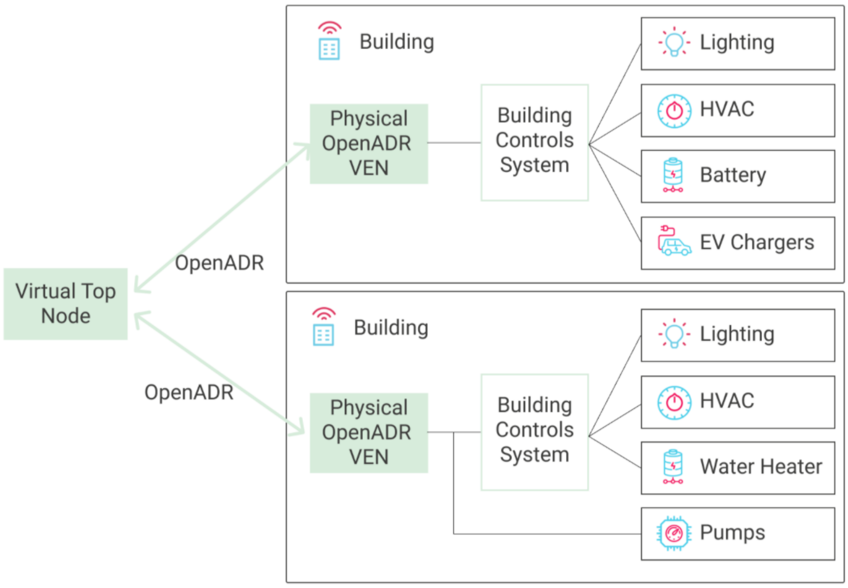


FIGURE 4.3: VEN integration in buildings.

The OpenADR protocol allows to obtain high speed in response from customers, gives a constant visibility of prices and allows to choose the devices on which to act according to the signals received. The high speed in response allows to support ancillary services such as frequency regulation. This service can only be accomplished via real-time signaling because it requires fast response, often two-to-four seconds. But, the architecture used, although efficient, suffers from the weaknesses of classic client-server systems, such as low scalability or the presence of centralized elements. In fact, the failure of a VTN leads to the failure of the connected VENs and consequently the non-participation of users in the DR event.

The use of blockchain for DR as compared to OpenADR standard allows to obtain three main benefits:

1. Transparency over measurements and pricing mechanisms.

2. High scalability.

3. No single point of failure.

Figure 4.4 shows a possible abstraction of the two communication models.

The OpenADR standard uses Hypertext Transfer Protocol (HTTP) as a transport layer. HTTP is ideal for pull clients and possible for push if security issues are handled. Also, the OpenADR standard uses Extensible Messaging and Presence Protocol (XMPP) as a transport protocol. This protocol is ideal for push applications and fast DR while pull is also possible. Virtual End Nodes can utilize HTTP or XMPP but both of the protocols are mandatory for a VTN. Thus, the OpenADR standard event communication process is a push pull action between the VTN and the VEN.

As it can be seen, blockchain technology, as transport layer of the distributed applications (aApp), relies on several layers: the P2P network layer is responsible for

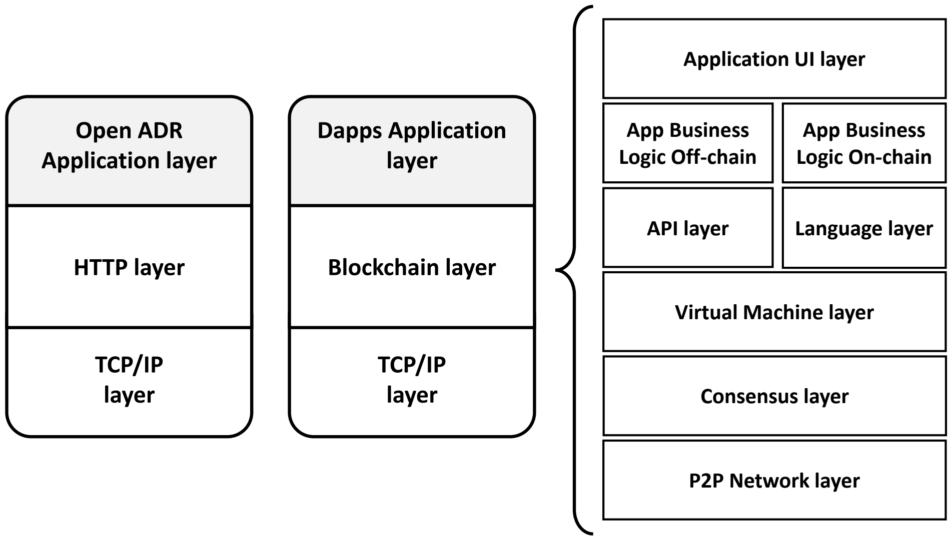


FIGURE 4.4: Abstraction model for OpenADR and blockchain.

inter-node communication, discovery and data transfer (usually transactions and block propagation). The consensus Layer includes code required to generate the order of blocks creation and validate blocks created by other nodes in the network. The virtual machine layer is a "transactional engine", responsible for changes in a blockchain's world state. The fourth blockchain abstraction layer consists of two "branches": Application Programming Interface, API, used by on-chain applications in runtime, and programming languages, used in development time and compiled for runtime into a binary code that can be put into blockchain and understood by the VMs. The language level refers to the SC development language. Starting from the Application business (on chain and off chain) layer, the code is usually written by third-party developers and not by core blockchain teams. In fact, these are application-specific projects that utilize the underlying blockchain in order to deliver some vertical solutions. The final layer is the actual User Interface, UI, of the dApp presented to the user [118].

The blockchain, compared with OpenADR is more complex, but at the same time allows you to obtain several advantages and overcome the weaknesses of OpenADR model, such as the integration of the platform with existing systems without the need to install third-party software. In this case the VTN and VEN logic is implemented by the blockchain (for example through a SC) rather than an external application.

4.3 Hyperledger Fabric blockchain

Hyperledger Fabric is a *permissioned* blockchain with highly modular and configurable architecture, which allows for innovation, versatility and optimization in a wide range of use cases. As a *permissioned* blockchain the participants are known to each other rather than anonymous [32]. Instead of being an open and *permissionless* system that allows unknown identities to participate in the network (requiring computationally expensive consensus protocols such as PoW to validate transactions and secure the network [119]), Hyperledger Fabric members are registered through a Membership Service Provider (MSP) of trust. The direct consequence of the non-use of consensus protocols like the PoW, and therefore the lack of mining operations, is the reduction of costs and the times for transactions execution.

Hyperledger Fabric is also the first blockchain platform to support SC, called "chaincodes", written in generic programming languages like Java, Go and Node.js [26]. As introduced in the chapter 1, a SC is a code that implements a shared logic supporting the transactions and managing access and modifications to a set of key-value pairs in the "current ledger state". This important feature makes this blockchain an easy-to-use tool for a wide variety of distributed applications. The Hyperledger Fabric blockchain is based on a particular modular architecture that logically arranges the components of the node, and then of the network, into different containers. Figure 4.5 shows the main modular components of the Hyperledger Fabric network.

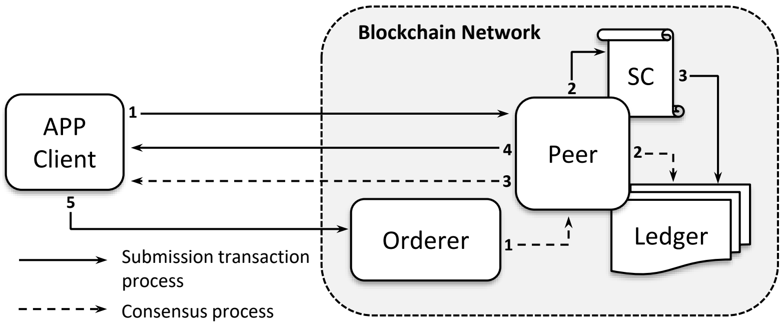


FIGURE 4.5: Main components of an Hyperledger Fabric node.

As it is shown in figure 4.5, the elementary network consists of five components: a Peer, a SC, a copy of the ledger, an App client and an Orderer. The status of the ledger is implemented as a local database, Hyperledger Fabrik uses either LevelDB or CouchDB. LevelDB is the default and is particularly appropriate when ledger states are simple key-value pairs. CouchDB is a particularly appropriate choice when ledger states are structured as JSON documents because CouchDB supports the rich queries and update of richer data types. The peer is the fundamental element of the network because is the entity that maintains the copy of the ledger and hosts and runs the SC in order to perform read/write operations to the ledger. Peers are owned and maintained by members of the blockchain network. The App client, external to the blockchain network, is the necessary element to communicate with the peer and show to the members (end-user or administrator network) the results following a query or a "transaction proposal". The solid line arrows of figure 4.5 show the process of execution and diffusion of a transaction. The network member, through the App client, signs the "transaction proposal" and sends it (1) to all peers participating in the blockchain. Each peer receives the signed transaction proposal and invokes the SC (2) calling up a function that interrogates the ledger (3) and generates a "proposal response". The proposal response signed by all peers is sent to the App Client of the user who submitted the transaction proposal (4), that checks the signatures of all peers and compares the replies of the proposal to determine whether they are the same. If they are the same, you can proceed to the next step. If the transaction proposal is a simple query, it is not sent to the Orderer but directly displayed by the App Client of the user who submitted the transaction proposal. If the transaction proposal implies instead a change of the ledger status, after comparing the correspondence of all the answers obtained by the peers, the App Client sends the response within a "transaction message" to the Orderer (5) that is the component responsible for the consensus process. The transaction message will contain the transaction data and peers' signatures. The Orderer does not need to inspect the entire content of a transaction to perform its operation, it simply receives the transactions, orders them chronologically and creates transaction blocks.

Transactions must be written to the ledger in the order in which they occur, even though they occur involving different groups of participants in the network. In order for this to happen, it is necessary to establish the order of the transactions and create a method to reject the erroneous transactions that were entered in the ledger by mistake (or maliciously). This task in Hyperledger Fabric is entrusted to the Orderer. The dashed line arrows of figure 4.5 show the update process of the ledger after the consensus process performed by the Orderer. Once the transactions order has been established, the new transactions are sent to the peers in blocks (1), the peers update the ledger with the new transactions block (2) and, to conclude, the peers send to the App Client a message (3) to communicate the updating of the ledger.

Another important feature of Hyperledger Fabric compared to other blockchain is the possibility to choose the consensus protocol that best represents the existing relationships between the participants. Until version 1.0, there are two consensus mechanisms available, namely, SOLO and Kafka. SOLO is the simplest mechanism, which only broadcasts the transaction without establishing any real consensus. Clearly, it is not recommended for production. On the other hand, Kafka uses a fault-tolerant distributed streaming platform called Apache Kafka [120]. It also enables distributed ordering service, so that we can have multiple Orderer nodes to avoid a single point of failure [121]. In addition, the consensus protocols of Fabric do not require a native cryptocurrency to incentivize expensive mining activities or to fuel the execution of SCs. The absence of cryptographic mining operations allows the platform to be distributed at the same operating cost as any other distributed system. The combination of these features makes Fabric a very performing platform in terms of transaction processing and transaction confirmation latency, and provides privacy, transaction confidentiality and the implementation of SCs.

Regarding privacy within the blockchain network, Hyperledger Fabric allows choosing three different solutions. The first consists of the use of communication mechanisms, called "channels", which allow for data isolation and confidentiality and by which the peers can communicate with each other. On a specific channel, the ledger is shared across the peers taking part to that channel, and transacting parties must be properly authenticated to a channel in order to interact with it. Hyperledger Fabric offers the possibility of creating different channels on the same network, allowing a group of participants to create a separate transaction ledger. If two participants form a channel, these two participants, and no one else, have copies of the ledger for that channel preserving the privacy and confidentiality of both. Figure 4.6 shows a double channel network on which Peer 1 and Peer 3 have the access to only one ledger, while Peer 2 has the access to both the ledgers. All members of Hyperledger Fabric blockchain are usually grouped into organizations and multiple organizations can be grouped into consortia. An organization can host more than one peer and client.

Starting from version 1.2, in order to preserve the confidentiality of data on the network without creating different channels, Fabric offers a second solution creating "private data collections", which allow a defined subset of organizations on a channel to support, commit or query private data without having to create a separate channel [122].

The last solution consists of the use of attributes included inside the digital identity of the network's members to determine permissions to use different functions

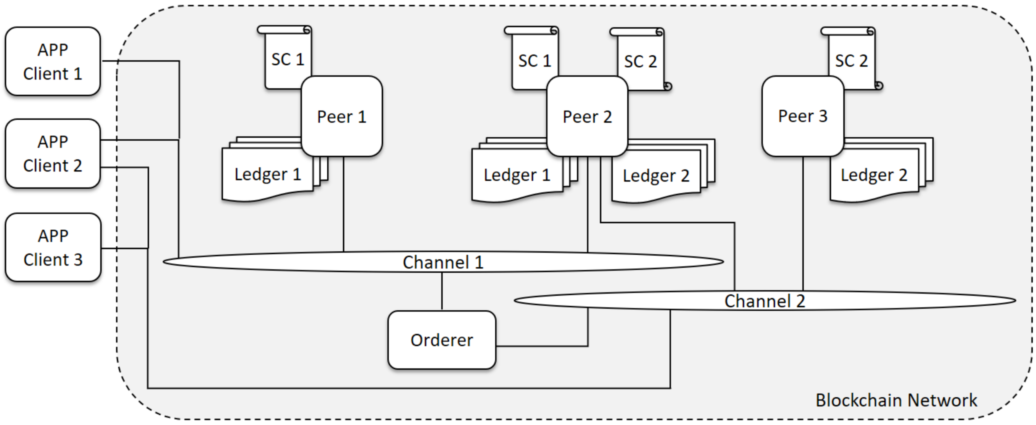


FIGURE 4.6: Double channel Hyperledger Fabric nrtwork.

implemented by the SC. The identities of all the members of the network are encapsulated in an X.509 digital certificate and they are certificated and verified by a MSP. So the MSP of an organization is needed to verify the identity of the users belonging to that organization. Even if the SC is the same for all peers and can be viewed by all users participating in the blockchain, using the attributes is possible to determine the permissions to access the different functions implemented by the SC and to manage the privacy among the various network users [123]. Using this solution each customer can read from the blockchain only those data that concern him, such as his own baseline, his own consumption or earned tokens, but he cannot read any data related to another customer.

4.4 Integration of the blockchain into the power network architecture

The proposed blockchain-based platform has been set up for DR programs implementation. The system has been developed considering the possibility of integration with existing technologies generally used for the low voltage grid. Considering a microgrid consisting of consumers and prosumers and considering the use of second generation SMs, figure 4.7 shows the proposed architecture.

The permissioned blockchain-based solution for handling DR operations is developed using an Hyperledger Fabric network. In this architecture, measurements are collected from the external channel of the SMs and sent to the data concentrator and then the same measurements are sent by the retailer to the blockchain. The data concentrator may appear as a single point of failure of the network, however, in general, it is not so because several concentrators could be deployed to serve districts or local areas, in addition in case of failure on the data concentrator the consumption data of the users will be recorded by the SM and sent to the blockchain by the retailer at a later time. The network continues to work even in case of a data concentrator failure. Concentrators require the computational power to act as blockchain clients and off-the-shelf embedded devices are sufficient for this goal. Furthermore, the customers, can verify that the data taken from the data concentrator has not been tampered by checking the matching between measurements provided by the retailer and those provided by the local channel. The aggregating device solves the problem of direct connection of the current SM to the blockchain and provides a data-flow

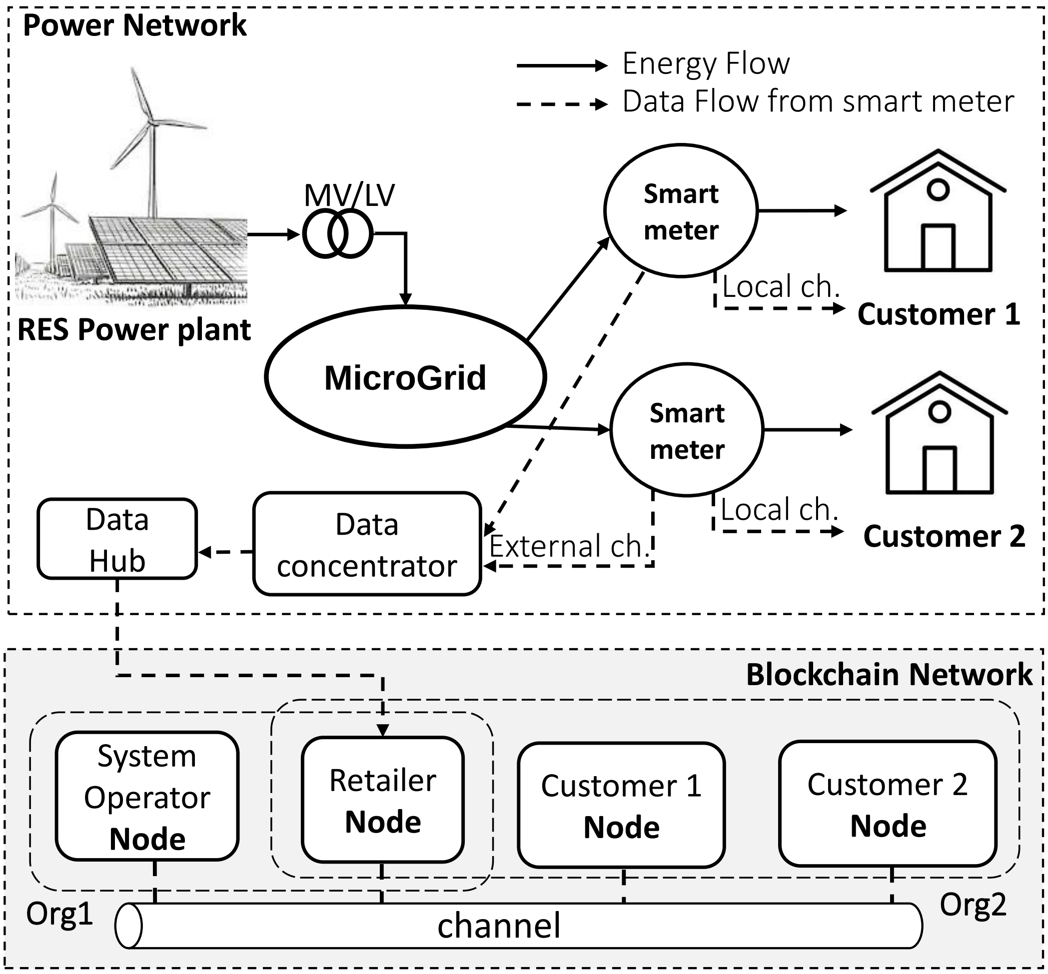


FIGURE 4.7: Proposed blockchain-based architecture for DR.

that is trusted for the customer permitting further validation by checking the matching with data coming from the retailer and the distributor. Additionally, customers have the potential to deploy their own client applications, reading data from the SM and checking whether they match those registered by the retailer on the blockchain. The blockchain users, through a client application, invoke a purpose-developed SC for elaborating, in a distributed manner, the transactions logic.

Moreover, the SC invoked by the system operator asking for the DR service computes the baseline for each user by reading the measurements registered on the blockchain. In a nutshell, the SC is the element that allows to implement the DR service in all its parts, from recording customer load profiles on the blockchain, to event execution and customer remuneration.

According with section 4.3, in order to manage the roles, the privacy and the permissions in the blockchain network, two organizations were considered. The first one (Org1) is composed of the system operator and the retailer, while the second (Org2) is composed of the retailer and the customers (see at the bottom in figure 4.7). In addition were considered two Membership Service Providers, MSP, one for Org1 and one for Org2. So the MSP of Org1 is managed by the system operator and is needed to verify the identity of the retailers, while the MSP of Org2 is managed by the retailer and is needed to verify the identities of the customers. Privacy within the network is handled with the third method explained in section 4.3. Regarding the consensus, to test the network, was used only one Orderer and SOLO consensus mechanism because the aim of the work is to show the possibility of integration of the blockchain system with the existing technologies and the development of a new certification system for the DR.

This architecture can be perfectly integrated with the existing market model for DR, giving a role to the existing actors. What is here called system operator is the entity requesting the DR event, while the 'retailer' is the entity receiving the measurements from the data concentrator collected through the SMs and is responsible for the energy billing.

4.4.1 Smart metering system

For the proposed architecture, it was assumed that the SMs are owned and operated by the DSO (system operator), while the billing is managed by the retailer. This is the most frequent scenario among the EU Member States. The DSO uses the acquired information for both managing the network (e.g., controlling network losses) and providing retailers with validated data to be used for billing. Then, the DSO collects the measurements and makes them available to the retailer through the so-called "data management hub". This dataflow has the main goal to provide suppliers with validated consumption data for billing. The validation process ensures that collected data are sufficient and consistent for the billing phase using advanced data reconstruction algorithms [110]. The community shown in figure 4.7 is operating as a microgrid that is able to exchange energy with the grid, but each customer has a different consumption pattern, so an individual SM is needed for each customer. For the testing 3-phase Kamstrup OMNIA meters were used, employed in Denmark. The load profiles of the customers are sent by the SMs to the data concentrator through the external channel of the SM itself. The communication between the SMs and the data concentrator is based on the standard EN 13757-5 that implements a radio mesh topology. Moreover, they are IEC 62056 compliant, the latter being the international standard of the DLMS/COSEM specification (Device Language Message Specification/Companion Specification for Energy Metering). The models of SM used for this application, belonging to the Kamstrup OMNIA suite, are compliant with international standards. They measure active positive energy (EN 50470-1 and EN 50470-3), reactive energy, and active negative energy (IEC 62052-11, IEC 62053-21 and IEC 62053-23), as well as Power Quality features according to EN 50160 [124].

Once the consumption data are available on the Data hub, the retailer takes them and records them on the blockchain. In this way, all parties are sure that the recorded consumption data have not been modified by untrusted users before being sent to the blockchain. In any case, customers can verify the authenticity of the data using the local channel of the SM.

4.5 DR event formulation

The DR formulation takes into account a scenario where the system operator asks the customers to modify their loads to meet the technical requirements of the grid. All actions are performed through different functions of a purpose-developed SC. The system operator sends DR signals to change the loads, in the range of the available flexibility obtained as the sum of the flexible powers declared by the customers. Each customer has a different inclination (availability) to follow the communicated indications. Indeed, loads adapt according to an *availability function* that analytically implements the customer's willingness to participate in DR events: some customers are flexible enough to change their typical load profile, others do not want or cannot adapt. Customers' typical consumption profiles are the baselines, they are references to compute the actual customers' adaptation to DR events. All customers of the cluster are assumed taking part in DR events, which are considered composed by the following steps, which are run periodically:

1. During a generic day, SMs record the customers' load profile and sends it to the data concentrator.
2. At the end of every day, the retailer records on the blockchain the load profile for each customer.
3. Before the communication of a new DR event, the system operator triggers the baselines and availability profiles calculation functions of the SC.
4. The day before a DR event, the system operator notifies the DR event on the blockchain: day, time window and total load reduction/increase.
5. The SC, considering the baselines and the availability profiles evaluated, distributes the overall request to the customers.
6. The day of the DR event, each customer reads from the blockchain the desired load reduction evaluated by the SC in order to satisfy the system operator's request.
7. The DR event takes place.
8. The customers' load consumption during the DR event is recorded on the blockchain as explained in steps 1) and 2).
9. The day after the DR event, the market operator triggers the SC to check if customers' consumption has been compliant with the system operator's request.
10. If the customers' consumption has been compliant with the request, the SC remunerates them with energy-tokens.

The baseline of a customer c consists of a vector of typical power consumption in 24 hours, whose general expression is given below in 4.1.

$$\mathbf{B}^{(c)} = \left[\bar{P}^{(c)}_{B,1}, \bar{P}^{(c)}_{B,2}, ..., \bar{P}^{(c)}_{B,h}, ..., \bar{P}^{(c)}_{B,24}\right] \tag{4.1}$$

The horizontal bar above the symbols of power consumption $\bar{P}^{(c)}_{B,h}$ indicates that load values related to a specific hour h of the day d are dynamically averaged over multiple days according to:

$$\bar{P}^{(c)}_{B,h} = \frac{1}{X} \sum_{j \in \mathrm{High}(X,Y,d)} P^{(c)}_{B,h,j} \quad \forall\, h \in \{1, 2..., 24\} \tag{4.2}$$

for the weekdays baseline, and

$$\bar{P}^{(c)}_{B,h} = \frac{1}{X} \sum_{j \in \mathrm{Low}(X,Y,d)} P^{(c)}_{B,h,j} \quad \forall\, h \in \{1, 2..., 24\} \tag{4.3}$$

for the weekend baseline.

The left term in 4.2 and 4.3 is the value of the baseline at hour h by averaging the power of the X days with the highest consumption 4.2, or the lowest consumption 4.3, within the Y non-DR days preceding the day d, that is day on which the DR event is notified to customers. In the rest of the section, the day d is not explicitly indicated as it is the day on which the DR event is notified to customers, which is assumed is the day before the DR event.

Both for weekdays and for weekends, this averaging methodologies work on the same set of the Y days that do not include DR or curtailment programs. The baselines are evaluated over the Y preceding days, on which the *HighXofY* method was applied for the weekdays baseline, and the *LowXofY* method for the weekend baseline. Finally, the sliding window over the last Y days permits to take into account seasonality.

The vector sum of all the baselines for the customers belonging to a cluster CL is the typical power profile of the aggregated load, as indicated in 4.4.

$$\mathbf{B}^{(CL)} = \sum_{c \in CL} \mathbf{B}^{(c)} \tag{4.4}$$

When the system operator communicates a load reduction for a given hour h, the customer's client application runs the SC to check what is the assigned load reduction during hour h leading to the maximum remuneration.

This assigned load reduction for each customer is calculated by the SC taking into account the *"Availability Profile"* (A) of the customer, which represents the customer's inclination to respond to the request by the system operator. This quality figure shows customers' performance as the sum of two terms: the first provides information on how difficult is the reduction requested by the operator, named *difficulty*; the second provides how good is the customer's compliance while following DR indications, named *compliance*. Additionally, $\boldsymbol{A}$ evolves at any new DR event. For ease of notation, the superscript (c) has been omitted in all subsequent formulas. The $\boldsymbol{A}$ of a generic customer is a vector of 24 elements, as many as the hours in a day. The 24 elements of the vector $\boldsymbol{A}$ represent the availability to modify the load at hour h, during the *i-th* DR event. This value is composed of two terms weighted by β and $1 - \beta$, both ranging between 0 and 1, as in 4.5.

$$A^{*}_{h,i} = \beta \, \frac{\Delta P_{B,h,i}}{\bar{P}_{B,h}} + (1-\beta) \, \frac{\sigma}{\sigma + \Delta P_{DR,h,i}} \tag{4.5}$$

In this expression, $\Delta P_{B,h,i}$ is the difference between the baseline $\bar{P}_{B,h}$ at hour h and the target consumption $P_{t,h,i}$ at the same hour; σ is the sensitivity of the SM (typical value is taken as 30W, considering an accuracy of 1). $\Delta P_{DR,h,i}$ is the absolute difference between the customer's load profile measured during the DR event and the target load profile. The two terms of the *Availability Profile* are both normalized as $\Delta P_{B,h,i} \ / \ \bar{P}_{B,h} \in (0,1]$ and $\sigma/(\sigma + \Delta P_{DR,h,i}) \in (0,1]$. Both terms are calculated at the *i-th* DR event occurring at hour h. The first term accounts for what fraction of the baseline has been requested to be changed, $\Delta P_{B,h,i}$=$|\bar{P}_{B,h}$-$P_{t,h,i}|$ (See figure 4.8). The bigger is the first term and the higher is the effort requested to the customer.

The second term accounts for the actual "capacity" of the customer, $\Delta P_{DR,h,i}$ = $|P_{h,i}$-$P_{t,h,i}|$, defined as the difference between the measured load profile $P_{h,i}$ and the requested target load $P_{t,h,i}$ for the customer c at the hour h. This term measures the customer's capability to 'follow' the directions given by the system operator. The smaller is $\Delta P_{DR,h,i}$ and the more compliant to the system operator's request is the

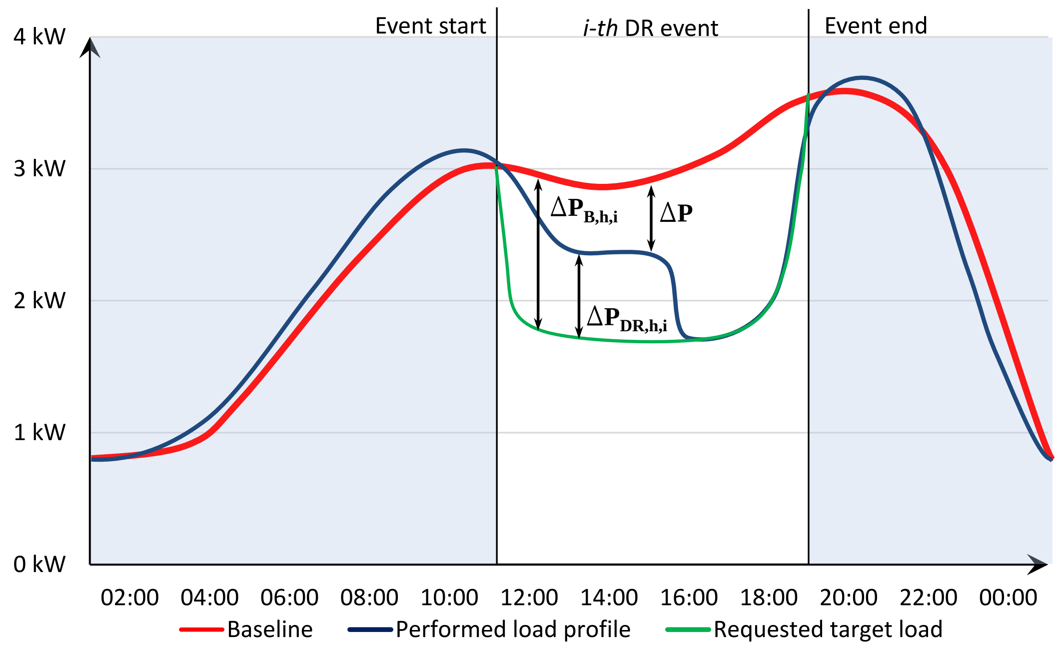


FIGURE 4.8: Quantities involved in an exemplary DR event.

customer's load profile. In 4.5 $\Delta P_{DR,h,i}$ is compared to σ, which is the sensitivity of the SM, so when $\Delta P_{DR,h,i}$ is close to zero, the second term is close to 1.

In 4.5, the value of $\beta \in [0, 1]$ defines which of the two terms is the most important to evaluate customer behaviour. On one hand, β higher than 0.5 will award those customers who had been requested more effort in the adaptation (first term), even if they have low compliance (second term). On the other hand, β lower than 0.5 will award customers that follow precisely the target profile (second term), even if it does not require such an effort (first term). We propose to set β = 0.2 as the second compliance term has more stability effects on the system than the first on difficulty. In fact, in the long run, the system will require greater effort to those that performed better, therefore their difficulty is expected to increase in subsequent DR events. However, when the required effort increases too much, the customer will presumably not be able to respond adequately. As a consequence, the availability profile will reduce in a closed-loop control. Instead, if the weight of the difficulty term is dominant ($\beta > 0.5$), more reduction will be assigned to those that were requested more, without caring if they are able to follow the indications. Figure 4.9 reports how the availability profile depends on $\Delta P_{B,h,i}$, and $\Delta P_{DR,h,i}$, which are hypothesized belonging to domestic users whose residential committed power is 3 kW. The figure shows how the $A_{h,i}$ values, hosted in the z-axis, are between zero and one in the three cases discussed above for $\beta \in \{0.2, 0.5, 0.8\}$.

According to figure 4.8, from 11:00 to 16:00, the customer did not fully satisfy the reduction requested by the system operator ($\Delta P_{DR,h,i} \neq 0$), instead, he fully satisfied the request from 16:00 to 19:00 ($\Delta P_{DR,h,i} = 0$). Therefore, if the difficulty to accomplish the request for the customer is high, even if he was not compliant, the availability will tend to be high anyway. If the difficulty to accomplish the request is low, the not compliance is more severely considered and the availability is low. Of course the two terms are then weighted using β.

The *Availability* is thus recalculated at each DR event but to account for past events and filter out steep behavioural variations, a memory term is considered. The

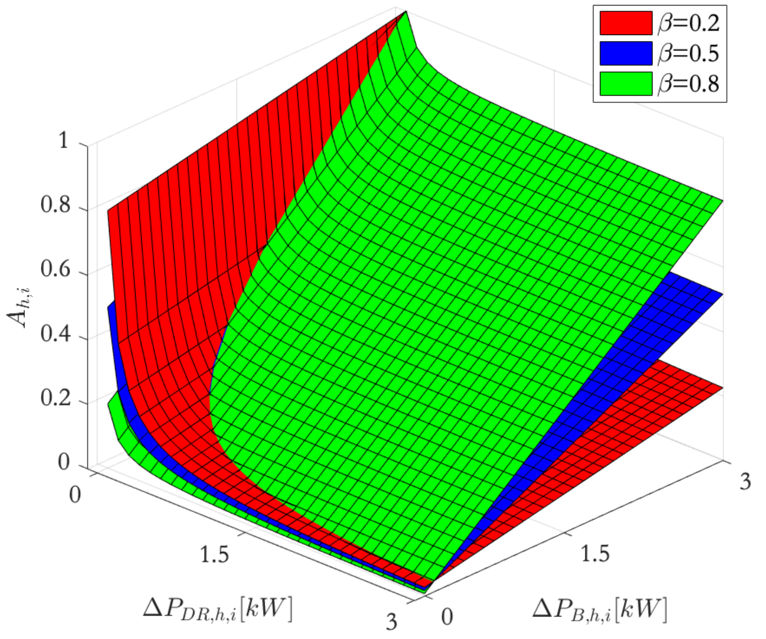


FIGURE 4.9: Availability of a customer at hour h for the DR event i, when $\beta \in \{0.2, 0.5, 0.8\}$.

value of *Availability* becomes more and more defined as the number of DR events to which the user takes part increases, using the learning rate α. Such a real parameter takes a value lower than 1. As a result, the *Availability* of a generic customer calculated after the *i-th* DR event is expressed as follows:

$$A_{h,i} = \alpha \cdot A^*_{h,i} + (1-\alpha) \cdot A_{h,i-1} \tag{4.6}$$

where:

- i indicates the last DR event;
- $\alpha \in$ [0,1] is the learning rate for the time-based adaptation of the *Availability Profile* of the customer.

In this case, α has been set to 0.2 to filter out steep behavioural variations of users. As explained in the following paragraphs, the Availability is used to calculate the fraction of load reduction required to each customer belonging to a cluster *CL* (will be considered only a load reduction and not an increase to simplify the explanation). The easiest way to attribute a load reduction to a single customer belonging to a cluster is to share it proportionally to the ratio (baseline)/(baseline of the cluster) at a given hour. However, this method does not account for the availability of a customer to respond to a given input from the system operator. On the other hand, altering the strict proportional partition of the load reduction leads to a request that can be higher or lower than the overall request. For this reason, on the one hand it is proposed to include availability in the evaluation of the load reduction fraction to be given to each customer, on the other hand it is proposed to iteratively correct the assignment in order to achieve a good correspondence between assignment and request. In this way, the whole DR technique will gain reliability and precision. If ϕ is the overall desired load reduction communicated by the system operator for a given hour h for the *i+1* DR event, the SC will distribute this overall request to the customers belonging to the cluster *CL* considering the $A_{h,i}$ of the customers, and using the following iterative algorithm that at any step j assigns a fraction of the residual load reduction, $\Psi_{h,j}^{(c)}$, as follows:

$$\Psi_{h,j}^{(c)} = \phi_j \cdot \frac{(1 + A_{h,i})}{2} \cdot \frac{\bar{P}_{B,h}^{(c)}}{P_{B,h}^{(CL_j)}} \tag{4.7}$$

where $c \in CL_j$ and $CL_j \subseteq CL_{j-i} \subseteq \cdots \subseteq CL_0 = CL$:

$$\phi_j = \begin{cases} \phi & \text{if } j = 0, \\ \phi - \sum_{c \in CL_j} \sum_{k=1}^{j-1} \Psi_{h,k}^{(c)} & \text{otherwise.} \end{cases} \tag{4.8}$$

The total load reduction requested to a customer at step j is, therefore, expressed by:

$$\Delta P_{B,h,j}^{(c)} = \sum_{k=1}^{j} \Psi_{h,k}^{(c)} \tag{4.9}$$

In 4.7, the iterative algorithm, at any step, assigns to the cluster a fraction of the residual reduction load between 0.5 and 1, as $A_{h,i} \in [0,1]$. The cluster CL_j changes at any step j of the algorithm; in fact, those customers that have already been requested to reduce their loads to zero do not participate in the next assignment steps, therefore $CL_j = \{c \mid \Delta P_{B,h,j}^{(c)} < \bar{P}_{B,h}^{(c)}\}$. The exit condition of the iterative algorithm is that the residual reduction is lower than a threshold. As reported in 4.5, if the customer is reliable and/or has a very high potential to respond to the request, then, he/she will be called to a higher effort during the next DR event. The *Availability* is initialized to 0.5 when the user has not yet participated in any DR event at the specific hour h, assuming a neutral behavior. Then, at any DR event, the *Availability* will be updated according to 4.6 and the SC will assign a load variation according to 4.7. In 4.7 the alteration of both the individual and cluster baselines are functional to the update of the assignment of the load reduction to the customers, according to their availability.

4.5.1 Reward mechanism

In all DR programs described in section 3.4.1, customers are expected to reduce or increase their load, but what changes between programs is how customers respond to demand and especially how they are remunerated for the service provided.

Currently, in the management of DR events, the system operator communicates to the Aggregator or BSP the request for load modulation in a given area of the electrical system. The participation of customers in the DR programs is regulated by a contract with the Aggregator which establishes an incentive for the customer if he/she is able to meet the request and the payment of penalties when the request is ignored. The Aggregator, knowing the total capacity of the customers of that area who have decided to participate in the DR service, responds to these orders by requesting, in compliance with the constraints and requirements necessary for the aggregated resources, the modulation of the load to the customers that make up the virtual load unit [31]. Usually, through an auction between the system operator and the Aggregator, the power reduction/increase and the price that the system operator will pay to the Aggregator for the service is determined. At the end of the DR event, the Aggregator remunerates the customers of that virtual unit according to the designed DR program [82]. It is clear that this system, suffers from a lack of transparency towards the end-users.

With the proposed blockchain-based architecture the aggregation in virtual units of consumers/producers is done through the blockchain. So, the system operator can communicate the DR request directly to customers and at the end of the DR event the SC will remunerate them based on the load variation provided in response to the request. The day in which the DR service takes place, the customer's consumption is recorded by the SM and is written by the retailer on the blockchain. At the end of the day, the SC assigns each customer a remuneration based on the load adaptation with respect the baseline following DR's request.

Customers' remuneration is an important aspect of DR programs. Some of the remuneration methods present in the literature provide a constant reward for each unit of energy consumption that has been modified by the customer, others consider the remuneration as a function of the change in the customer's profile [31], with the time of the day (as in Time-of-use schemes) or with the type of customer. As an example, in [125] the authors consider different remunerations for five categories of customers, while in [126] the authors propose a remuneration scheme that considers an incentive price dependent on the customer's power changes following a DR program, and the differences between the amount of power purchased by the Utility on the Spot market and the retail price for customers, so as to limit the loss for the Utility.

In this work, a remuneration mechanism based on the variation of power over baseline using a quadratic remuneration function is used. The latter is usually adopted for economical evaluations in the electric energy field [127], and for the DR event is expressed as follows:

$$r = \sum_{h=1}^{24} \mathcal{H}(\bar{P}_{B,h} - P_h) \cdot (\bar{P}_{B,h} - P_h)^2 \tag{4.10}$$

Where $\mathcal{H}$ is the Heaviside function; it is 1 when the argument is positive, and 0 otherwise, permitting to remunerate only load reductions and neglecting load increments. In 4.10, $\bar{P}_{B,h}$ is the baseline value at hour h, P_h is the measured load profile at hour h and their difference is representative of customer response during the DR event. In the assumed scenario, the system operator requests load reductions and only those consumers that reduce their load will receive a reward, according to a parabolic law. Additionally, the proposed approach may be modified using different remuneration functions (e.g. depending on the season, the day of the week of the DR event, etc.)

4.6 Implementation of the DR program through a purpose-developed Smart Contract

In the proposed architecture, the blockchain network interfaces with the grid through the SMs. It was assumed that the power network is a microgrid supplying consumers, while the blockchain network consists of a node owned by the system operator, one by the retailer and two by the customers (see figure 4.7).

As already explained, the aggregation of the customers in virtual units is done through the blockchain, so the system operator can communicate directly to the customers the request of load adaptation in order to avoid a congestion on the network in certain hours of the day, for example. The proposed application runs through the SC a capacity/incentive-based DR program applied at residential level implemented using a Load Response program. Therefore, it was assumed that customers participate in the program by making their load capacity available. The test scenarios have been developed considering that customers may choose to shift some loads in response to the DR event in order to reduce the total load on the grid during the period when the peak load is expected. When the system operator communicates a DR event, the SC running on the peers distributes the total load reduction to the customers proportionally to their own baseline and their availability profile according with 4.9. The customers respond to the request by shifting some loads during the DR period in order to better satisfy the request and to receive the maximum remuneration.

The SC represents the main element of this blockchain-based system, because it is the network component that allows to implement the logic of each kind of transaction, to execute the above-mentioned DR program and verify the integrity of each transaction sent by the network users. The SC is installed on each peer, and each time a user submits a transaction proposal over the network, this transaction proposal is processed by the SC of all peers, then the App Client of the customer who submitted the transaction receives the responses to the transaction proposals from the SC of all the peers and compares the correspondence of the responses obtained. If the responses received are consistent it means that the submitted transaction is compliant with the logic implemented by the SC and that all peers have verified this consistency, so the App Client can send the response within a transaction message to the Orderer who inserts it into a new block and sends it to all peers who update the ledger. Using the SC a distributed consensus on transactions consistency is achieved. The SC was developed by using the general programming language "Golang" (Go). All transactions are processed by invoking properly structured SC functions. Listing 4.1 shows the SC entry point for the main functions invocation. The next section describes how these functions are used and invoked by the Apps Client of the various network users in order to perform a DR event.

LISTING 4.1: Main DR SC functions.

```
func (t*SmartContract) Invoke(stub
    shim.ChaincodeStubInterface)pb.Response{
    function, args:=stub.GetFunctionAndParameters()
    fmt.Println("invoke␣is␣running"
    +function)

    if function=="recordEnergy"{
        return t.recordEnergy(stub, args)

    }else if function == "queryEnergyValue"{
        return t.queryEnergyValue(stub, args)

    }else if function == "queryDailyEnergy"{
        return t.queryDailyEnergy(stub, args)

    }else if function=="evaluateBaseline"{
        return t.evaluateBaseline(stub, args)

    }else if function=="evaluateAvailability"{
        return t.evaluateAvailability(stub, args)

    }else if function=="notifyDRevent"{
```

```
        return t.notifyDRevent(stub, args)

    }else if function=="queryLoadReduction"{
        return t.queryLoadReduction(stub, args)

    }else if function=="getDRToken"{
        return t.getDRToken(stub, args)

    }else if function=="queryEarnedToken"{
        return t.queryEarnedToken(stub, args)
    }

    fmt.Println("invoke␣did␣not␣find␣func:" + function)
    return shim.Error("Received␣unknown␣function␣invocation")
}
```

Chapter 5

Experimental tests

This chapter describes the results obtained by implementing the architecture proposed in chapter 4 using a hardware testbed for the emulation of the domestic power profiles. It also describes how this emulated scenario integrates with the metering architecture, as well as with the blockchain network. Finally, the integration with an Energy Management System is described with the aim of ensuring intervention and automating the user's response to a DR event.

5.1 Experimental setup

To validate the proposed solution a hardware testbed was assembled for emulating the power installation and the behaviour of domestic consumers. The setup allows to implement two Households equipped with both shiftable and non-shiftable loads. Moreover, they are interfaced with the grid via SMs that record the aggregated power. These tests were carried out at the Microgrid laboratory of the Department of Energy Technology at Aalborg University.

The experimental setup is shown in figure 5.1. It consists of four bi-directional DC/AC converters, which operate in grid-connected mode and whose power references are fully controllable. The unit responsible for the real-time control and pulses generation for the inverters is the real-time control platform dSPACE shown on the top of the setup. This system implements the primary control, PLL and power control loops for each inverter independently. Moreover, it also enables wireless control of the power references via an MQTT interface and provides local monitoring capabilities of voltage and current waveforms. The dSPACE platform was programmed using MATLAB/Simulink, where the corresponding primary control loops, PLLs and power control loops were developed and compiled, before being deployed into the system. The monitoring platform is associated with the ControlDesk dSPACE software which is just used to supervise the proper operation of the system. The testbed includes two SMs, one for each simulated Household, and an isolation transformer for the grid connection. A detailed diagram of the complete architecture is provided in figure 5.2.

On the top part, the power electronic system in the setup for one Household is shown. The inverters are supplied by a DC power source. In the AC output, an LCL filter is used to reduce the harmonic content of the generated waveforms. From each pair of inverters, one is used for emulating the non-shiftable component of the load profile, while the other is used for the shiftable loads. Both of them are finally connected to the same point downstream the LCL filter and subsequently, to a common SM that measures the total consumption of the house. It should be noted here, that the SM has been installed with its terminals inverted, so a power injection into the grid is considered as consumed energy by the emulated Households.

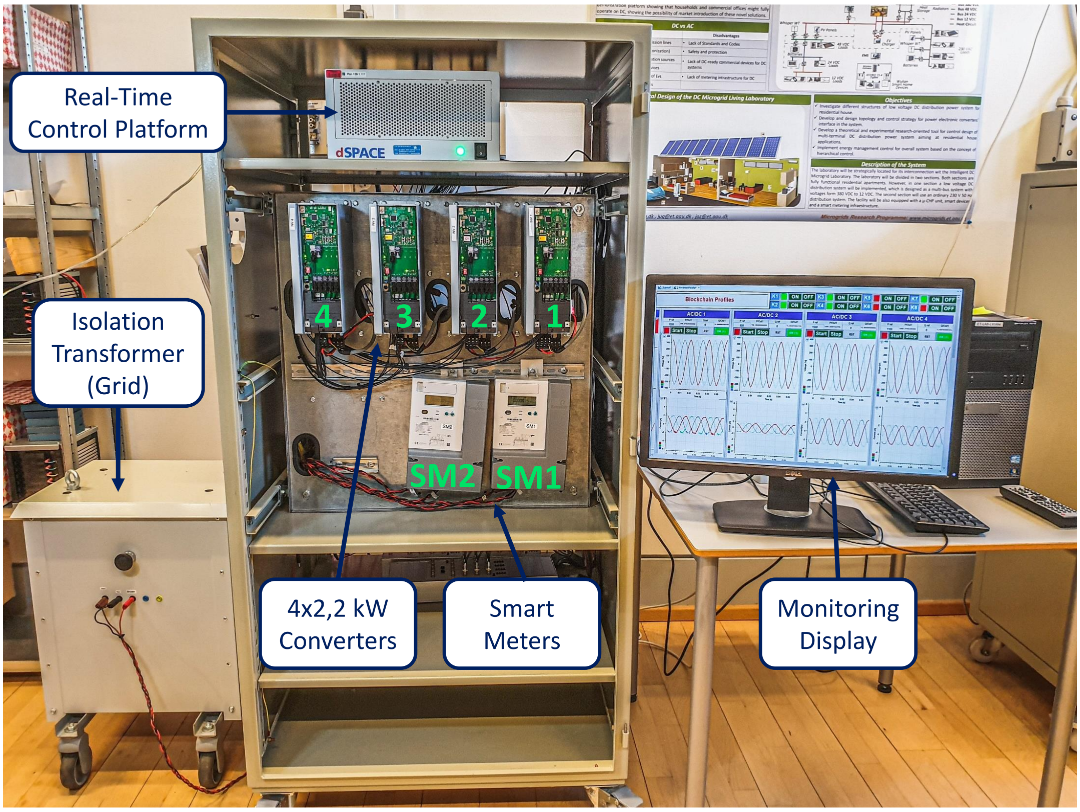


FIGURE 5.1: Experimental testbed emulating two residential consumers.

Following the architecture showed in figure 4.7, four peer nodes were deployed together with the hardware setup and the SM infrastructure to form a blockchain network as illustrated in the box at the bottom right of figure 5.2: a system operator node and a retailer node on one PC and two customer nodes on the setup PC. A copy of the DR SC and a set of specifically developed client Apps were also installed on each node with the aim of allowing every user on the network to interact with the blockchain. To keep the system as generic as possible, and ease the integration with third-party solutions, the client Apps were conceived as RESTful web services with communicate on the back-end with the blockchain network. These Apps were implemented using the general programming language Node.js. The client Apps and the main functions used to interact with the blockchain network are shown also in figure 5.2.

The role of the system or grid operator is to manage the identities of the retailers, trigger the baseline calculations (*evaluateBaseline*) and execute DR events (*notifyDREvent*). Therefore, the system operator App provides a RESTful interface for registering retailers into the blockchain network. It also implements a module for periodically triggering the calculation of the baseline, which is performed at the end of each day. Finally, another RESTful service is used for posting DR events, where the system operator specifies the start time, the end time and the requested load reduction.

The retailer manages the customers' identities and is responsible for uploading customer consumption data on the blockchain (*recordEnergy*), taking them from the data concentrator. It also triggers the SC function to generate the tokens for the participation in DR programs (*getDRToken*). The retailer App provides three functionalities: (i) a RESTful service for the registration of customers, (ii) a periodic module

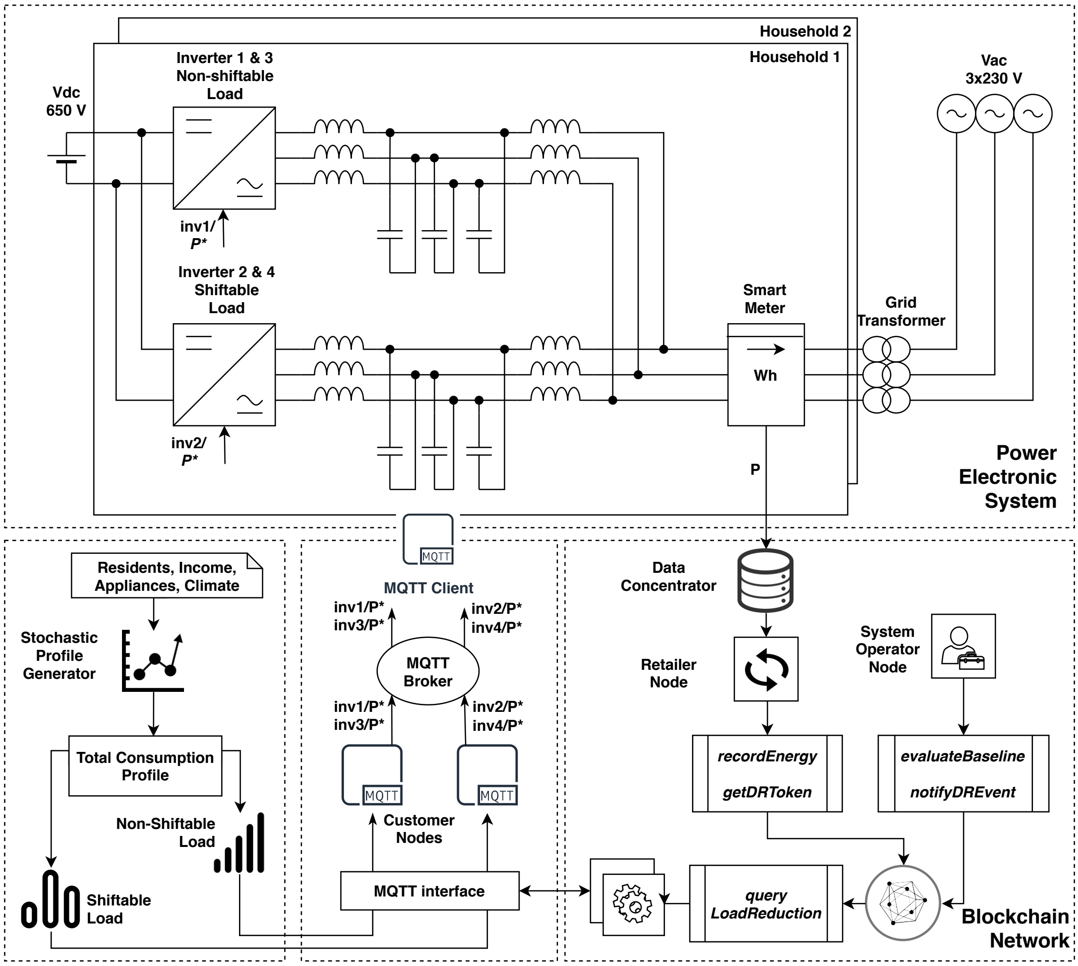


FIGURE 5.2: Conceptual diagram of the inverters connection for one customer, blockchain network and SM architecture.

for reading the SM measurements and recording them into the blockchain every day, and (iii) a periodic module to trigger the evaluation of DR tokens for the customers when DR events are implemented.

Finally, the customer nodes are just responsible for reading the load reduction established by the system operator after triggering a DR event (*queryLoadReduction*) and its implementation using the available shiftable loads. Therefore, the customer App periodically checks if a DR event has been triggered for a given day and arranges the shiftable part of the load profile accordingly. This modification is performed by means of interacting with the MQTT interface which sends the consumption profiles to the inverters for the emulation.

Every time a network user through the App invokes a SC function to execute a transaction, the transaction information is diffused between the blockchain network peers through the so-called "gossip data dissemination protocol" [128]. Peers use this protocol to transmit information on the communication channel in a scalable way. Gossip messaging is continuous and each peer on a channel constantly receives current and consistent data from multiple peers. Each gossip message is signed, allowing participants sending false messages to be easily identified. Peers affected by delays, network partitions or other causes causing missed blocks will eventually be synchronised with the current ledger status by contacting the peers having these missing blocks. This communication protocol based on the division of the workload for the execution of transactions makes it possible to optimise the performance of the blockchain network in terms of security and scalability:

- it allows to manage the identification of peers and their membership in the channel, continuously detecting available and offline peers;
- diffuses the data of the ledger through all the peers of a channel allowing the synchronisation of data to those peers that have missing blocks;
- updates the newly connected peers very quickly on the changes that occurred to the ledger during their disconnection.

To generate the aforementioned Household power profiles a previously developed stochastic model for the generation of residential loads was used [129]. This model provides appliance disaggregated 1-minute resolution data for a given Household with a set of appliances, residents, income level, and surrounding climate characteristics, which determines the behaviour of the users. The appliances are allocated based on the ownership probability. Among them, in the non-shiftable part, we can find refrigerators, televisions, laptops, pc, stoves, microwaves, oven, iron, coffee maker, toaster, water heater, etc. On the other hand, only washing machines, dryers and dishwashers are considered as shiftable loads.

5.2 Setting up of the blockchain network

Before performing the DR event, it is needed to set the blockchain network.

For this applications the network is formed by the following components:

1. PC0, that hosts:
    - A Certification Authority (CA);
    - An Orderer Service Node;
    - A DSO peer (Peer0);
    - A CouchDB instance (couchDB0);
    - An App Client for Peer0;
2. PC1, that hosts:
    - A Utility peer (Peer1);
    - A CouchDB instance (couchDB1);
    - An App Client for Peer1.
3. PC2 (the setup PC), that hosts:
    - A Customer1 peer (Peer2);
    - A CouchDB instance (couchDB2);
    - An App Client for Peer2.
    - A Customer2 peer (Peer3);
    - A CouchDB instance (couchDB3);
    - An App Client for Peer3;

The first step is to install Hyperledger Fabric on all the PC. This very simple procedure is described in the official Hyperledger Fabric documentation and must be repeated on every PC [130]. Once Hyperledger Fabric is installed on all the peer nodes and the network components described above are running, the next step is to generate the communication channel between the peer nodes, where they all can authenticate with their respective identities.

Subsequently the digital identities of the users that will participate in the network are generated. The developed network consists of two organizations, which are part of the so-called "DRconsortium". The MSP of the system operator manages the identity of the retailer (Org1), while the MSP of the retailer manages the identities of the customers (Org2). The identities are comprised of X.509 digital certificates, which are distributed to each user. Listing 5.1 shows a snippet of the NodeJS code used register, create and import the identity of the Customer1 into a folder called *wallet*.

LISTING 5.1: Snippet of the code used for user's registration.

```
const secret = await ca.register(
    {
        affiliation: 'org2',
        enrollmentID: 'customer_1',
        role: 'client',
        attrs: [
        {name: "ID", value: "smartmeter:20360162", ecert: true},
        {name: "IDprovider", value: "utility:1234", ecert: true}
              ]
    }, adminIdentity);

const userIdentity = X509WalletMixin.createIdentity('Org2MSP',
    enrollment.certificate, enrollment.key.toBytes());
wallet.import('customer_1', userIdentity);
```

In the first part, in addition to the affiliation, the user's name and role, two attributes are specified: the first identifies the user with the SM ID, while the second identifies the authority that provides the identity to the user. The second part generates the X.509 certificate with the identification data of the user and places it inside the *wallet*. These two attributes are essential to implement the privacy of data shared on the network as explained in the paragraph 4.3. The smart meter ID is used to allow the customer to access only his/her own consumption data or earned tokens, while the utility ID is used to prevent the customer from accessing the data of a customer with the same ID but provided by another retailer. For example, listing 5.2 shows a snippet of the purpose-developed SC that gives permission only to the retailer to use the function.

LISTING 5.2: Privacy implementation in the SC through the attribute based access control.

```
// ==== Get the Attribute value for the Retailer ====
ID, ID_found, err := cid.GetAttributeValue(stub, "ID")
    if err != nil {
            return shim.Error(err.Error())
        }
        fmt.Println("ID found : ", ID_found)
        fmt.Println("ID is : ", ID)
```

```
// ==== Check if the Attribute matches the value ====
var allowedREs allowedUsers
var jsonResp string
k:=0
allowedREsFromState, err := stub.GetState("allowed␣REs")
if err != nil {
        jsonResp = "{\"Error\":\"Failed␣to␣get␣state␣for␣"+
        ID + "\"}"
        return shim.Error(jsonResp)
        } else {
                err = json.Unmarshal([]byte(allowedREsFromState),
                & allowedMOs)
    for _,value := range allowedREs.IDs {
        if ID == value {
                continue
        } else {
                k+=1
            }
    }
    if k == len(allowedREs.IDs) {
                return shim.Error("You␣are␣not␣allowed␣to
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣record␣Energy␣values:␣only␣the␣Retailer␣can
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣call␣this␣method")
    }
}

// ==== Check if the Smart Meter is enabled to work on this BC ====
var allowedMeters allowedUsers
h:=0
allowedMetersFromState, err := stub.GetState("allowed␣Meters␣"+ID)
if err != nil {
        jsonResp = "{\"Error\":\"Failed␣to␣get␣state␣for␣"+args[0]+
        "\"}"
                return shim.Error(jsonResp)
        } else {
                err = json.Unmarshal([]byte(allowedMetersFromState),
                & allowedMeters)
    for _,value := range allowedMeters.IDs {
        if args[0] == value {
                continue
        } else {
                h+=1
        }
        }
        if h == len(allowedMeters.IDs) {
                return shim.Error("This␣Smart␣Meter␣is␣not␣enabled
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣to␣work␣on␣this␣BC␣or␣the␣owner␣is␣another␣Market
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣Operator")
    }
}
```

The first part gets the retailer ID attribute, the second checks if the attribute contained in the X.509 certificate of the retailer matches to the one stored on the blockchain by the network manager, in this case the DSO. Finally, the last part verifies whether the SM, so the customer, for whom the retailer intends to store the energy value is enabled to work on the blockchain.

Once all the digital identities of users have been generated and they are enabled by the network manager to work on the blockchain, the SC is installed on each peer and the blockchain network is ready to work. In a Hyperledger Fabric network there are two different types of peers depending on whether the SC is installed or not. In the application developed, each peer hosts a copy of the SC, but in larger networks there will be many other peer nodes that do not host a copy of the SC. A peer can run a SC only if it is installed on it, but can know the interface of a SC by connecting to a channel. All peers can validate and subsequently accept or reject transactions on their copy of the ledger. However, only peers with a SC installed can take part in the transaction approval process, as explained in paragraph 4.3, which is crucial for the generation of valid transactions. In Hyperledger Fabric, peers can take on multiple roles depending on how the network is configured. There are two basic types of peers:

1. *Committing peer*: every peer node of a channel is a committing peer. It receives blocks of generated transactions, which are then validated before being inserted into the own ledger copy;

2. *Endorsing peer*: each peer of the network can be an endorsing peer if it has an SC installed. However, to actually be an endorsing peer, the SC on the peer must be used by an App Client to generate a digitally signed transaction response.

In this context a realistic scenario could be one in which the customers are committing peers, so they own only the App Client and a copy of the ledger, but to interact with the ledger they trigger the SC of the endorsing peer owned by the DSO, the retailer or the aggregator. In this way clients do not need computing power to run the SC.

A SC approval policy identifies organizations whose peer must digitally sign a generated transaction before it can be accepted on a copy of the committing peer ledger. Endorsing peers are divided into two categories:

1. *Leader Peer*: when an organization has multiple peers in a channel, a leader peer is a node that takes responsibility for distributing transactions from the orderer to the committing peers;

2. *Anchor Peer*: if a peer needs to communicate with a peer in another organization, he can use one of the anchors peer defined in the channel configuration for that organization. An organization can have zero or more anchors peer.

A peer can be committing peer, endorsing peer, leader peer and anchor peer at the same time. Only the anchor peer is optional, but for all practical purposes there will always be a leader peer and at least one endorsing peer and a committing peer.

In the considered scenario all the peers are committing, endorsing and leader, but only the DSO peer is an anchor peer because it need to communicates with both organizations..

5.3 Operational workflow of applying the blockchain technology for a DR program test in a laboratory environment

In the developed application, two main roles are considered, the system operator, which requests the DR event for balancing the network, and the energy retailer that provides services to the customers. In other context, however, both entities can be unified in the DSO. The DR event is executed through the following steps:

1. *Every day*, the **retailer** sends the customers' load profiles to the blockchain through the SC, taking them from the DSO data hub. In addition, the system operator triggers the SC to evaluate the baselines and the availability profile of the customers;

2. *The day before DR event*, the **system operator** notifies the blockchain network about the day, time window and total load reduction, which is distributed automatically by the SC to the customers according to their estimated baselines and their availability profile, according with 4.9;

3. *The day of the DR event*, the **customers** read from the blockchain the desired load reduction evaluated by the SC in order to satisfy the system operator's request. Their actual consumption for that day is also recorded as stated in point 1;

4. *The day after the DR event*, the **retailer** triggers the SC for customer' remuneration with the aforementioned utility tokens. Was assumed that the SC assigns them only if customers' consumption during the DR event is compliant with the desired load reduction, ignoring the possible penalties if the consumption is not compliant.

In order to consider the variability of the load profile due to the seasons or the customer's behaviour variation over time, a total time horizon of 36 days was considered for implementing the experiment. Since generating 36 days of load profiles using directly the hardware setup implies an unnecessary time-consuming process the experiment was divided into three phases:

1. *Pre-allocation*: First, 33 days of load profiles were directly recorded into the blockchain with the same resolution of the SM (15 minutes).

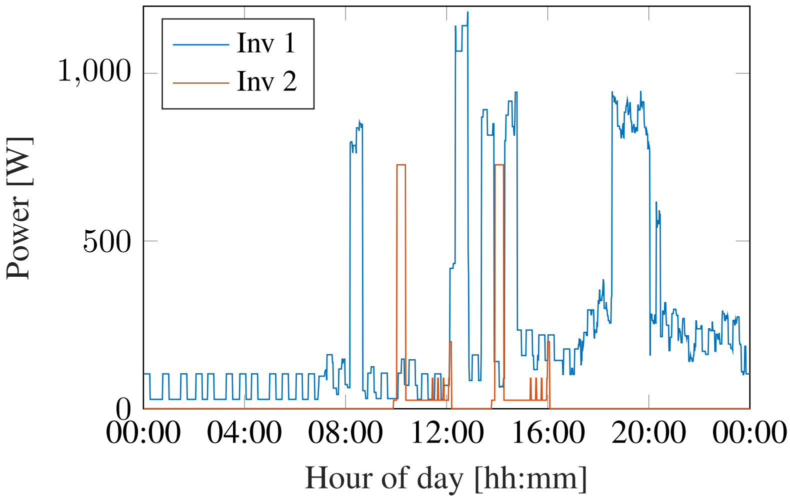
2. *Normal behaviour emulation*: Subsequently, 2 days of normal consumption profiles for the two Households were emulated using the previously described testbed. In order to downscale the time of the experiment by a factor of 3 (8 hours needed to simulate 24 hours), the SMs were configured to record the average power every 5 minutes, while the power references for the inverters generated by the model with 1-minute resolution were updated with a frequency of 20 seconds. In addition, a time adjustment routine was included in the retailer App Client so the 5-minute resolution data read from the SMs were transformed into 15-min resolution data due to the downsizing.

3. *DR event emulation*: In the last day, the system emulated a DR event created by the system operator. The customers respond accordingly by moving the shiftable loads to the requested reduced period. This is done by the customer App Client interacting with the MQTT interface which sends the power profiles, so the shiftable appliances profiles are reallocated.

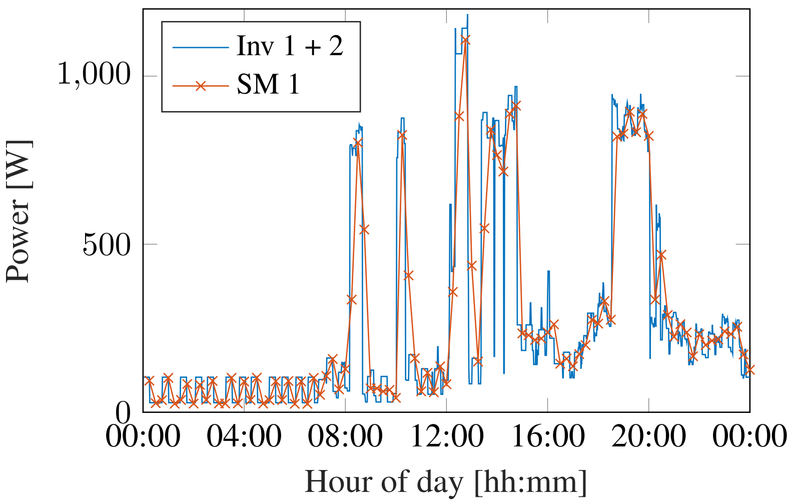
To automate all of this process, a MATLAB script was created. This script communicates with the four Apps Client of each node using the MATLAB RESTful web services functions webread and webwrite. In addition, the MQTT library was employed to periodically update the references of the power profiles during fases 2 and 3.

5.4 Test of the physical setup for DR event execution

As a first step, the system must record the consumption profiles making use of the SM infrastructure, which is accessed by the retailer node. In the considered scenario, after the 33 days of preallocation, this method is used for the two days of normal behaviour (days 34th and 35th) and the day of the DR event (day 36th). Since the behaviour of the power system is the same for both normal and DR days, a 24-hour profile of Household 1 for a normal day is presented in figure 5.3.



(a)



(b)

FIGURE 5.3: Profiles sent to inverters and recorded by SM into the blockchain, for non-shiftable & shiftable loads (a) and total profile (b) for Household 1.

As can be seen in figure 5.3(a) the consumption profile is divided into two components which are sent as power references to a pair of inverters (1 and 2 for Household 1, and 3 and 4 for Household 2). The first inverter (Inv 1) generates the non-shiftable component of the Household consumption profile, while the second inverter (Inv 2) is responsible for emulating the shiftable component of the load. The same for Household 2 and inverter 3 and 4.

Following the power electronic system architecture presented in figure 5.2, the output of each pair of inverters is connected to a common SM meter and subsequently to a common point of coupling with the grid. Therefore, the SM is only able to measure aggregated consumption (shiftable and non-shiftable components). Moreover, while the resolution of the power profiles sent to the inverters is 1 minute, the SM takes 15-minute resolution average power samples at the output of the system.

Figure 5.3(b) shows a comparison between the expected aggregated consumption inverters 1 and 2 and the actual power profile recorded by SM 1 for day 34th, which was obtained by the retailer App Client by accessing the DSO data hub and subsequently inserted in the blockchain network. It can be observed how the power recorded by the SM totally matches expected set points, although with a lower resolution.

Regarding the quality of the emulation, the average absolute error between the expected and the recorded profiles for the 24 hours test was approximately 10 W. Moreover, the total daily energy consumption was around 1% lower than expected. These errors are probably a result of power losses in the system. Each inverter controls its output power after the LCL filter to compensate for passive losses, yet the use of a common AC/DC source and the parallel connection of the inverters can lead to small circulating currents. These could be avoided by using, for instance, individual isolation transformers, nevertheless, their impact is so small in our scenario that no measure was taken.

5.4.1 Baseline and optimal power reduction calculations

After the 35th day, the system operator decides to trigger a DR event. Therefore, a DR event corresponding to a power reduction of 300 W per 15-minute average from 07:00 h to 19:00 h is requested by calling the dedicated function of the SC. At this point, 35 daily power profiles for each Household have been recorded on the blockchain and the baseline is calculated with these information. These baselines were evaluated by the SC using equations 4.2 and 4.3 considering Y=35, X=21 for the weekdays and X=14 for the weekend baseline. The day in particular for the considered DR event is a weekday. Figure 5.4 shows the calculated baseline (BL), as well as the optimal power reduction (OPR) obtained for each Household. For this test it was considered that Households provide all the shiftable power, so their availability profile is equal to 1 and the OPR evaluated by the SC, according with equation 4.7, is proportional to the baseline of each Household.

It can be observed, that both baselines differ between them since each Household has its particular behavioural patterns. For instance, it can be seen that although the demand peaks occur around the same time for both consumers, the Household 2 has a higher demand peak during the evening than Household 1, while Household 1 has a higher power consumption during the central hours.

Therefore, the OPR algorithm in the SC takes into account this, to proportionally distribute the requested reduction between the two customers. This is illustrated in figure 5.5 where the 300 W reduction is allocated every 15 minutes for Household 1 (blue bars) and Household 2 (orange bars).

5.4.2 DR event certification and reward system

The previous subsection has described how the OPR is generated for each Household. Finally, in this section, the behaviour of the user during the DR event day

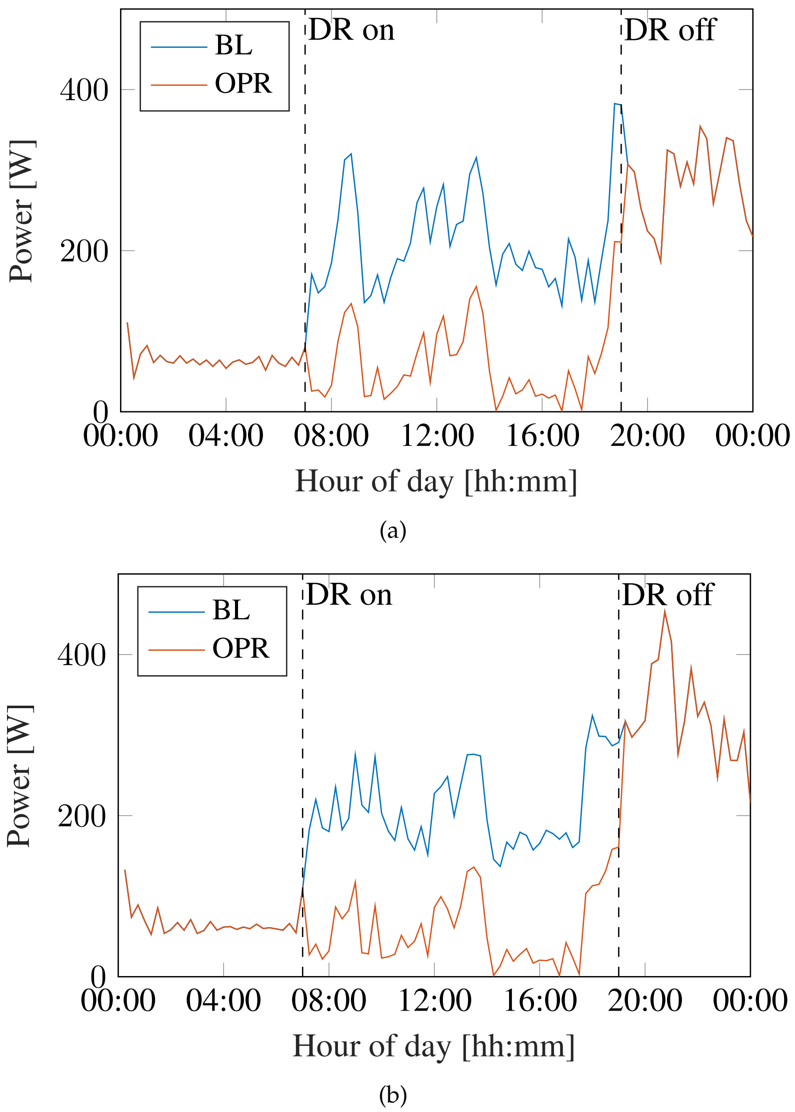


FIGURE 5.4: Baseline calculations for day 35th and OPR for the following day with DR event for Household 1 (a) and Household 2 (b).

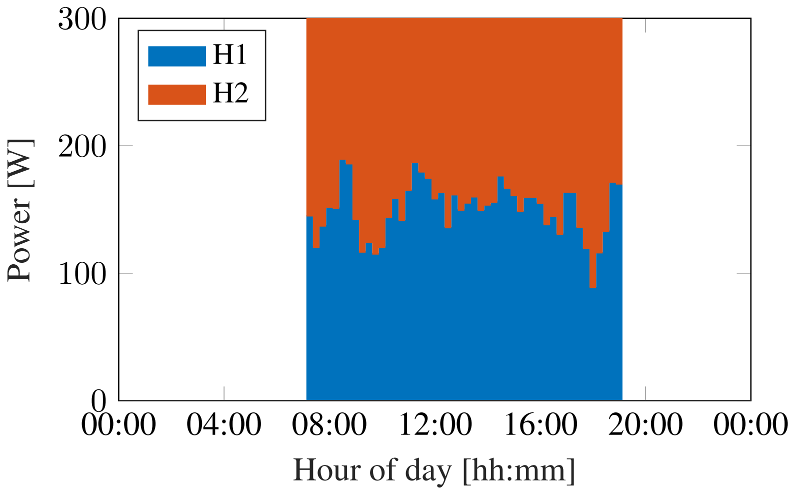
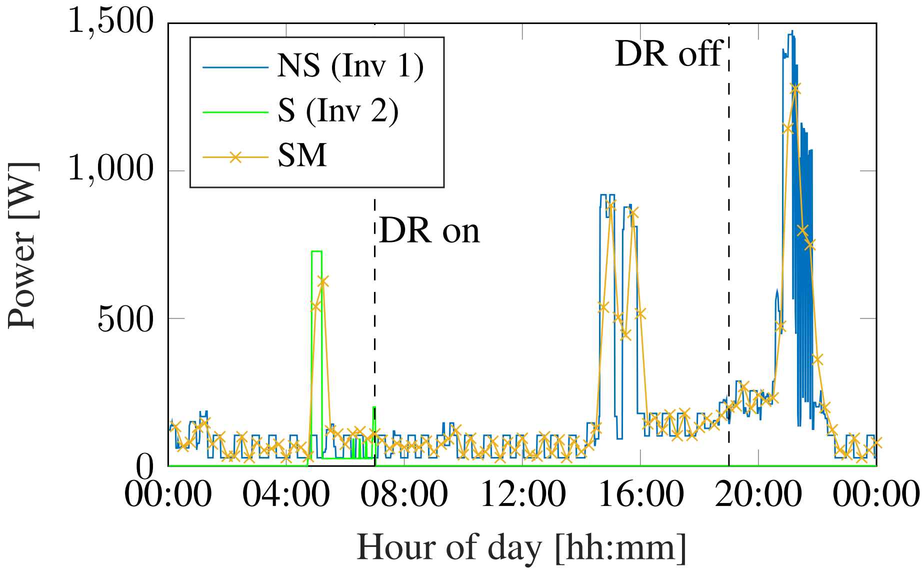


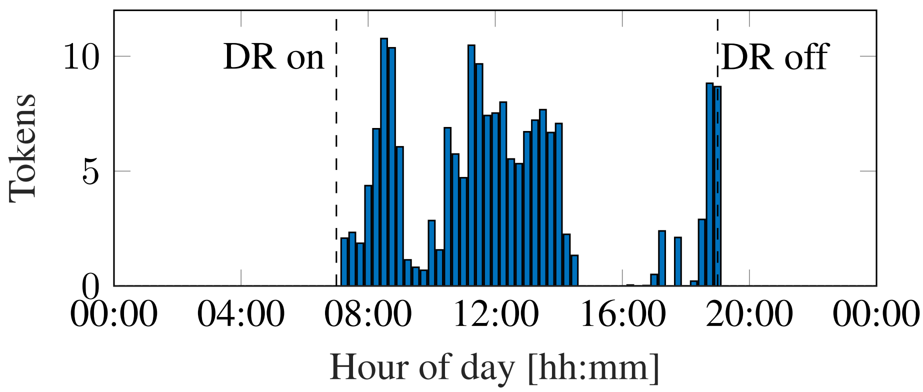
FIGURE 5.5: Proportional reduction requested to each Household.

and its consequences are evaluated. Figure 5.6 and 5.7 (a) show the consumption profiles of both Households during the DR event day, distinguishing non-shiftable and shiftable loads, as well as the aggregated samples taken by the SMs. For a more interesting test case, only Household 1 is considered to fulfil the DR event.

In figure 5.6 and 5.7 (a), the green line represents the shiftable consumption. Household 1 has reallocated the shiftable loads to the periods before the DR event trigger to comply with the required power reduction. On the other hand, the shiftable loads in Household 2 are used during the DR event.



(a) Household 1. Non-shiftable (NS) and shiftable (S) profiles sent to the inverters for the DR day and the records of the SM.

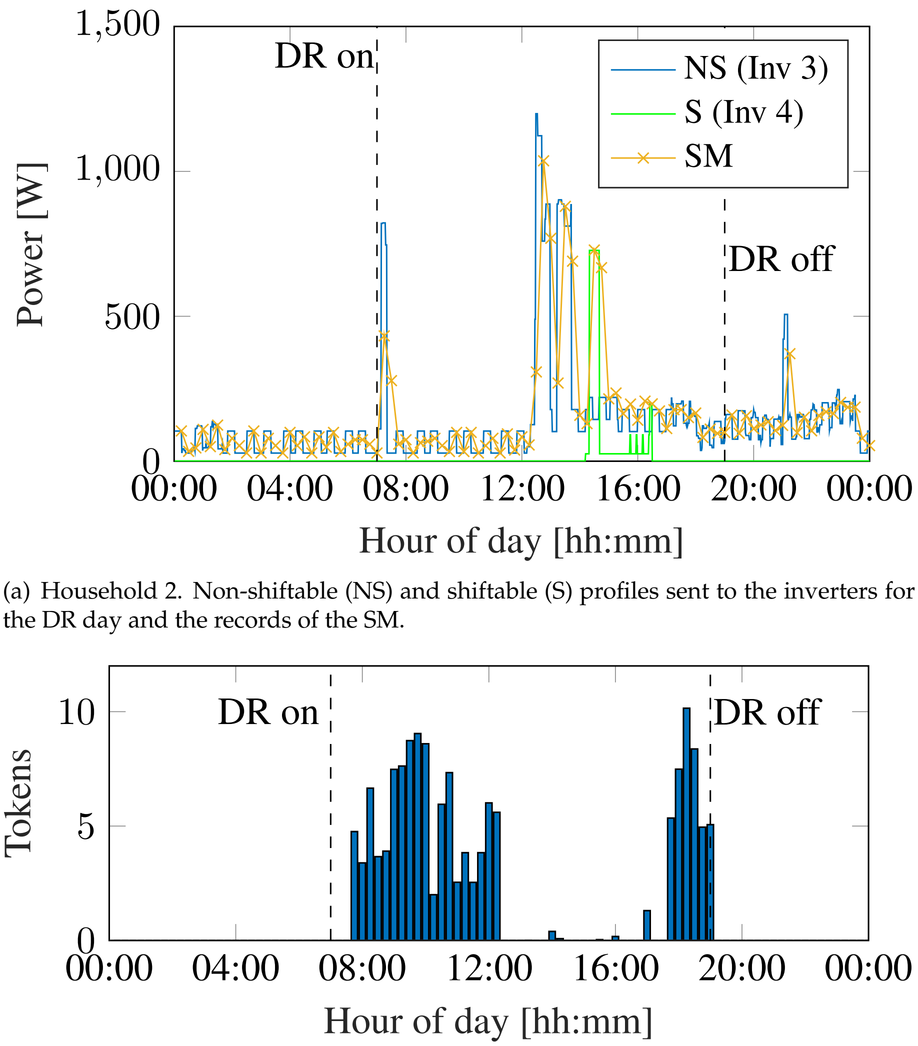


(b) Household 1. Number of tokens awarded for the DR response in 15-minutes intervals.

FIGURE 5.6: Response of the Household 1 to the DR event and rewards given after the day.

This leads to different rewards for each user as depicted in figure 5.6 and 5.7 (b), which represents the 15-minute tokens awarded to each users following equation 4.10. Household 1 was able to keep its consumption low for almost all the DR period so in total 188 DRtokens were awarded. Household 2, however, incurred a high consumption for more hours as compared to Household 1, so the reward was only 147 DRtokens.

It should be observed at this point, that even though a power reduction was



(a) Household 2. Non-shiftable (NS) and shiftable (S) profiles sent to the inverters for the DR day and the records of the SM.

(b) Household 2. Number of tokens awarded for the DR response in 15-minutes intervals

FIGURE 5.7: Response of the Household 2 to the DR event and rewards given after the day.

asked by the system operators, both users have high consumption during the DR event. However, this was expected as the flexibility in this scenario is limited to shiftable loads. This means that the system operator should also consider this issue, and what are the possibilities for the users for setting realistic power reduction periods and figures.

Through this experiment a real blockchain network was tested, but customers were simulated through inverters controlled by a real-time control platform. The DR signal sent by the DSO on the blockchain is used by the control system to modify the power reference given to the inverters to generate a load profile compliant with the DR event. In a real application this task can be performed by an Energy Management System (EMS) owned by the user and external to the blockchain that implements the load management logic based on the DR signal sent by the DSO.

For this experiment no EMS was considered, but an EMS able to handle local loads at low cost and to be interfaced with the blockchain to meet the requirements of load modulation following a DR event was developed later and is described in the last paragraph.

5.5 Experimental network performance

In public or permissionless blockchain, like Bitcoin, anyone can join the network and execute a transaction. In Bitcoin, due to Proof of Work (PoW) based consensus, a creation time of 1 block each 10 minutes and a fixed block size of 1 MB is considered. The peak throughput of transaction processing is between 3.3 and 7 transactions per second. The confirmation of six blocks takes about one hour. Ethereum uses a PoW-based consensus that can process about 25 transactions per second.

In private or permissioned blockchain, such as Hyperledger Fabric, the generation time of one block is shorter, thanks to simpler consensus processes based on faster and less computationally intensive algorithms. In Hyperledger Fabric, transaction messages are sent to the Order service. The Orderer then receives the transactions on that channel and queues the messages. The Orderer creates a new transaction block and delivers it to all peers via the aforementioned gossip protocol. The gossip protocol connects the peers in the channel and transmits the channel logs and data in a scalable way. In the public Bitcoin blockchain, all transactions are handled through a series of sequential operations in blocks and are added to the ledger. This sequential process will not gain performance benefit when using more powerful hardware. In Hyperledger Fabric, the consensus is carried out by the Ordering service, which is designed in a modular and fully connectable way. There is the possibility to select scalable consensus mechanisms (Solo, Kafka) for application use cases. The Ordering service, which can be set up as a cluster of Orderer nodes, process messages, ensuring that each Ordering process receives transactions and generates blocks in the same order. This event-driven synchronization design ensures better performance than that of the public blockchain.

The parameter to modify and improve the performance of an Hyperledger Fabrik network are configurable in the file "configtx.yaml" and are:

- *BatchTimeout*, defines the time to wait before creating a new block;
- *MaxMessageCount*, defines the maximum number of transactions to be inserted in a block during the batch time;
- *AbsoluteMaxBytes*, defines the absolute maximum number of bytes allowed for transactions serialized during a batch time;
- *PreferredMaxBytes*, defines the maximum number of bytes allowed in a batch. A transaction larger than the preferred maximum bytes will result in a batch larger than the preferred max bytes.

To achieve higher throughput, it is possible to increase *MaxMessageCount*, but as more computational power is required, the block size gets larger and more bandwidth is needed. In general, by changing the parameters in configtx.yaml it is possible to optimize the transaction throughput, but this differs from case to case depending on the application. In this application, the authors used the default parameters indicated in Table indicated in Table 5.1. In this way, the maximum number of transactions per second is 25, that is 50 transactions per batch time. Considering the scenario discussed above, and that the network was implemented using the internal telecommunication network of the Microgrid Laboratory (with very low latency), the following Table indicated in Table 5.1 shows the time required for each type of transaction or query executed by invoking the different functions of the DR smart contract.

TABLE 5.1: Used parameters and execution time of SC function for the experimental tests.

blockchain Parameter	**Value**
BatchTimeout	2 s
MaxMessageCount	10
AbsoluteMaxBytes	99 MB
PreferredMaxBytes	512 kB
SC function	**Average execution time [s]**
recordEnergy	10.2 per load profile (96 energy values)
queryLoadProfile	0.065
evaluateBaseline	12 per customer considering 35 days
queryBaseline	0.065
notifyDRevent	2.3
queryLoadReduction	0.065
getDRToken	2.3
queryEarnedToken	0.065

With regard to memory consumption, it has been estimated that the size in bytes of a transaction for the recording of a power value or DRtoken of a customer is 5 kB, so one block consisting of 10 transactions has a size slightly greater than 50 kB (51.2), while the size of a transaction for recording the baseline, or a DR event, is 10 kB. In general, for the tests executed in this work, the memory consumption can be considered negligible, but considering a real scenario, with hundred of thousands of end-users, the size of the chain could become not negligible. In this case, clients with not enough storage capacity could participate to the blockchain as 'light clients', i.e. installing only the App Client, invoking the SC and accessing the ledger on the nearest peer.

5.6 Energy Management System integration

The development of the EMS and tests were carried out at the laboratory of the University of Palermo reproducing through the use of virtual machines the same blockchain architecture described above. The load profiles of customers were recreated and recorded on the blockchain through the use of a Matlab code in order to bypass the experimental setup used in the previous application.

An Energy Management System is in general a system capable of automatically managing the loads of a user based on weather conditions, energy price signals or user routines in order to optimize energy consumption. To ensure effective intervention and to automate user response to a DR event, the DR signal sent by the system operator on the blockchain network can be included as EMS input data. For this purpose was developed an EMS based on a Non-Intrusive Load Monitoring (NILM) [131] measurement system able to disaggregate the total user load, recognize the installed appliances and store information on the rated real and reactive power of the appliances and on their typical use profile. The energy measurements are processed by the EMS, that in ordinary service shifts the flexible appliances (predefined by the user) to off-peak hours according to an economic optimization, minimizing the user's costs related to the electricity supply. Furthermore, the integration of the EMS with the blockchain allows to manage DR events. In detail, when the system operator needs a load reduction, the SC sends to the EMS the customer baseline and the amount of load to be reduced by that specific customer, together with the starting time and the duration of the event. As described above the SC distributes the overall request considering the availability profile of the customers, that represents the customers' ability to respond to the request from the system operator, and evaluates the customers' remuneration for the service provided.

According to the availability profile of the customers, the SC builds a ranking of the availability of the customers, updating for each DR event the distribution function of the overall request according to the availability profiles. Also in this case it is assumed that the participation to the DR service is regulated by a contract establishing an incentive to the customer if he is able to meet the request and the payment of penalties when the request from the system operator is ignored by the customer. The higher the incentive, the more compliant the load modulation with the request. Under these conditions, the customer's participation to the DR service always generates economic benefits, quantified in terms of DRtokens.

The objective function of the EMS algorithm for each generic customer, shown in equation 5.1, is composed by the cost related to the electricity supply, while the incentive for the participation to the DR event, for what explained above, can be neglected.

$$min\, C_{el,supply,h} \cdot P_{optim,h} \quad \forall\ h\ \in\ T \tag{5.1}$$

In this equation, $C_{el,supply,h}$ is the electricity supply price according to on-peak, mid-peak and off-peak hours and $P_{optim,h}$ is the optimized performed load consumption of the customer during a generic hour h of the day and during the i-th DR event. Although all quantities of the following formulas are related to the single customer, to the generic hour h of the day and to the i-th DR event, the subscripts were omitted for ease of notation in all subsequent formulas.

Supposing the customer being a consumer (without load injection ability), when a DR event happens, the EMS algorithm gets from the blockchain the OPR evaluated by the SC, composed by a vector of zeros besides during the DR event, together with the baseline P_{BL}, in order to evaluate the target load, as in equation 5.2.

$$P_{target} = P_{BL} - OPR \tag{5.2}$$

The baseline is also acquired because, in general terms, although the EMS also evaluates the historical trends of the user, this may slightly differ from the baseline recorded on the BC.

$$P_{BL} \cong P_{fix} + \sum_{m=1}^{M} P_{flex,m} \tag{5.3}$$

In equation 5.3, P_{fix} is the load due to fixed appliances and P_{flex} is the load due to each of the M flexible appliances according to the user's usual behaviour. The fixed and flexible loads are recognized by the NILM algorithm analyzing the customer usual consumption, and it then specifies which of the load can be deferred. The optimization algorithm schedules the flexible appliances according to the cost minimization criterion, obtaining a so-called "optimized load profile". If the rated power of each flexible appliances is indicated with $P^*_{flex,m}$, the optimized profile can be expressed as:

$$P_{optim} = P_{fix} + \sum_{m=1}^{M} \delta_m \cdot P^*_{flex,m} \tag{5.4}$$

where δ_m is a vector of Boolean variables (one value per each hour and each appliance) equal to 0 if the appliance is off and equal to 1 when it is on. As already stated, the participation of the customer to the DR event has been schematised within the optimization algorithm through an inequality constraint rather than as part of the objective function, as shown in equation 5.5, allowing to respect the flexibility request within a predefined tolerance:

$$\Delta P_{DR,h} \leq \varepsilon \tag{5.5}$$

where $\Delta P_{DR,h}$ is the difference between the optimized load profile and the target profile.

$$\Delta P_{DR} = \left| P_{optim} - P_{target} \right| \tag{5.6}$$

Combining equations 5.2, 5.4, 5.5 and equation 5.6, and highlighting the term with the Boolean variables, this constraint can be expressed as:

$$\sum_{m=1}^{M} \delta_m \cdot P^*_{flex,m} \leq \varepsilon - P_{fix} + (P_{BL} - \Delta P_{BL}) \tag{5.7}$$

Other two constraints were included to the optimization algorithm, in order to allow to shift the flexible loads with respect to a standard schedule avoiding load reduction or peak shaving (equation 5.8) and to guarantee that the hourly load is lower than the contractual power (equation 5.9).

$$\sum_{h=1}^{T} P^*_{flex,m} \cdot \delta_{m,h} = \sum_{h=1}^{T} P_{flex,m,h} \ \ \forall \ m \in M \tag{5.8}$$

$$P_{perf,h} \leq P_{contract} \ \ \forall \ h \in \ T \tag{5.9}$$

The output of the EMS algorithm is the rescheduled optimal combination of flexible loads during the day when a DR event happens, respecting the reduction request and minimizing the cost beared by the customer. This is expressed mathematically by the vector of δ_m. In this way, the customer can avoid to pay a penalty for not complying with the request and the entire process is executed in an automated way.

In order to demonstrate the possibility of interaction between the BC and the EMS, a case study with a limited number of appliances was developed. A randomly generated domestic load profile was employed for the P_{fix}, while, for the flexible load, a dishwasher and a kettle were employed. Rated power of flexible appliances were derived from [132]. Load profiles for the user historical behaviour (data recorded on the EMS through the NILM algorithm) are shown in figure 5.8, with a detail of 15 minutes. Further parameters employed in the case study are shown in Table 1. The electricity supply prices are equal to the economic conditions set by the Italian energy authority for the first trimester of 2020 [133].

After the optimization, the flexible appliances were rescheduled as shown in figure 5.9. It is possible to see that the kettle was shifted of a limited amount of hours, in order to reach the mid-peak period and to save money, while the dishwasher, being usually turned on during the DR event, was shifted during the off-peak period to comply with the system operator request, and to save money as well.

This application describes the interaction between a SC working on an energy blockchain and a domestic EMS algorithm aimed at minimizing the cost for the customer related to the energy supply. The cooperation of these systems allows the customer to comply automatically with the DR request from the system operator.

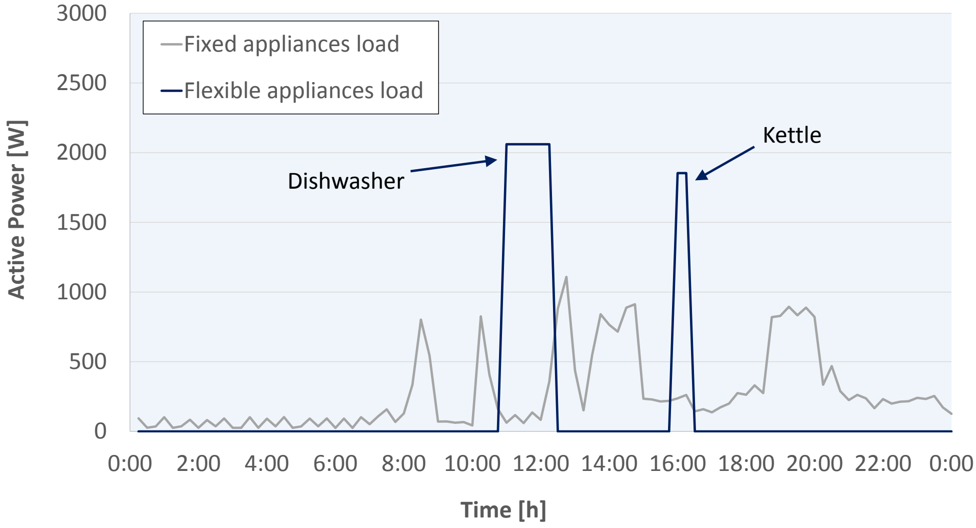


FIGURE 5.8: Historical customer trends of fixed and flexible loads.

TABLE 5.2: Parameters employed for the case study.

Parameter	Symbol	Value
Number of flexible appliances	M	2
Dishwasher rated power	$P^*_{flex,1}$	2060 W
Kettle rated power	$P^*_{flex,2}$	1853 W
User contractual power	$P_{contract}$	3300 W
Reduction order	OPR	1000 W
Start time of DR event	t_{start}	10:30 A.M.
Duration of DR event	t_{DR}	2.25 h
On-peak electricity price	$C_{el,supply,on-peak}$	7.666 c€/kWh
Mid-peak electricity price	$C_{el,supply,mid-peak}$	6.799 c€/kWh
Off-peak electricity price	$C_{el,supply,off-peak}$	6.799 c€/kWh

This aspect is very important to take into account since the domestic applications of DR often highlight the risk of not meeting the request due to many uncertainties. Nevertheless, although the EMS system described is based on a NILM algorithm to identify the appliances, the automated shifting of the loads would require the installation of smart plugs on each flexible appliance.

It is worth to underline that, in the case study shown above, meeting the DR request would imply the shifting of the dishwasher to off peak hours, while the shifting of the kettle in mid-peak hour was performed only for the economic convenience of the customer. Through this action, the maximum daily peak of the user increased from 2.4 kW to 2.7 kW, although it occurs in a different moment. Furthermore, the effective customer load reduction was much lower than the system DR request, since the flexible load rated power was about the double of the requested reduction, causing a load valley instead of a peak. These two phenomena suggest that the DR management is the result of a trade-off between user's and system operator's needs, thus including a further subjectivity aspect in the electricity supply. To take this into account, BC's role could become even more important if, after each

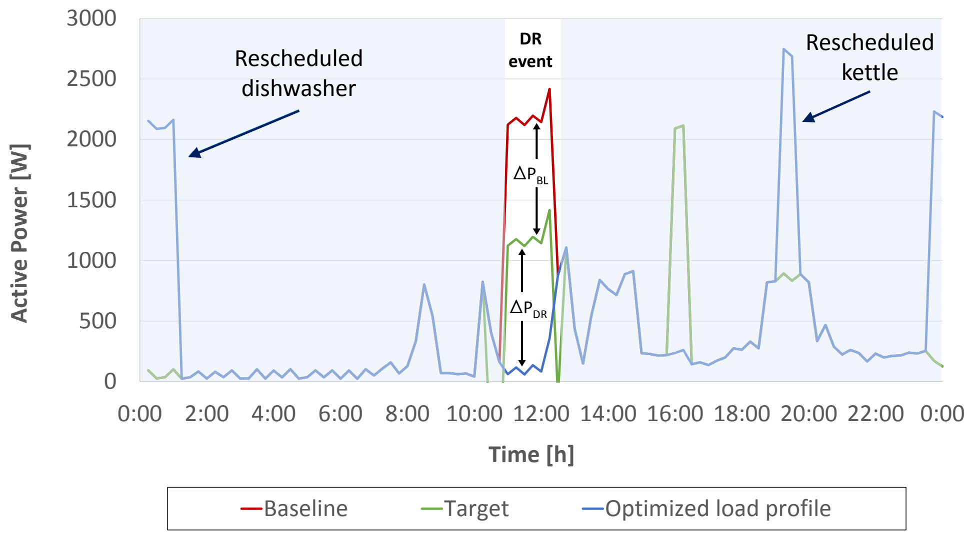


FIGURE 5.9: rescheduling of flexible appliances after optimization.

customer's EMS algorithm has optimized the local load, all customer programs have been sent back to the SC to verify whether the cumulative load reduction is in line with the system operator's needs. This would give BC the role of a peers manager, in addition to being a virtual aggregator.

5.7 Integration in the MSD

DR is an important tool that helps to maintain the correct operation of the electrical system due to RES penetration, as it allows to adapt the energy demand to the supply in a short time. During peak periods and in response to market signals, users can make self-produced energy available or reduce their consumption in exchange for remuneration or other forms of financial incentives.

Today in Italy, DR services allow commercial and industrial users to help with electricity regulation by participating in the MSD. As already introduced in Chapter 2, with Resolution 300/2017/R/EEL of the ARERA, Terna opened the MSD for the first time to small power plants with non-programmable production, loads and storage systems (UVAM). Currently, UVAMs represent the benchmark form of aggregation in Italy. UVAMs permit users to provide flexibility by modulating consumption or production through DR programs. Managed by BSPs, UVAMs offer capacity to the MSD and are remunerated on the basis of the variation of the exchanged energy derived on the MSD (€/MWh) plus a fixed amount (in €/MW/year) proportional to the offered capacity, and awarded by auction.

According to Terna's UVAM MSD Regulation [134], UVAMs can provide the following dispatching services:

a resolution of congestion, increasing and/or decreasing;

b rotating tertiary reserve, increasing and/or decreasing;

c tertiary replacement reserve, increasing and/or decreasing;

d balancing, increasing and/or decreasing;

UVAMs provide the services indicated above if they are able to modulate loads with the following features:

- within **15 minutes** of receipt of Terna's dispatching order for the services referred to in points a), b), d);

- within **120 minutes** from the receipt of Terna's dispatching order for the services referred to in point c);

and support such modulation for a period at least equal to:

- 120 minutes for the services referred to in letters a), b), d);

- 480 minutes for the services referred to in letter c);

In addition, the BSP interface device with Terna systems must be able to send every 4 seconds the total power input/output at the input/output points included in the UVAM and receive the balancing orders through the file transfer mode provided by the IEC 60870-5-104 protocol, thus using a mainly Ethernet transport network [135].

The blockchain network developed and described above allows the aggregation of users in a transparent way and without the need for a BSP, generating UVAM able to provide flexibility to the power network. The experimental test was conducted to demonstrate the possibility of certification and direct execution of DR events between system operator and end-users, with the aim of generating a new system that involves more domestic users to the MSD. In fact, unlike UVAM, it was considered that the DR signal is notified on the network the day before the event, but the results obtained are encouraging for applications on current UVAM. The execution times of main SC functions shown in table 5.1 (2.3 seconds for a write operation on the blockchain and 0.065 seconds in reading) are compliant with the timescale envisaged by Terna. With such timing, UVAMs can provide balancing services on the MSD. Even better if the DR signal is used by an EMS capable of automating user response.

Regarding the IEC 60870-5-10 protocol imposed by Terna for data exchange, the blockchain may become compliant by integrating the support of such a protocol into the blockchain clients. In such a case, Remote Terminal Units used in current UVAMs interface Terna's control systems [136] could also integrate such blockchain clients. This last aspect needs further studies and insights that will be developed in future work.

Conclusions

The DR service represents an important resource to achieve the objectives set by the European Directive RED-II by 2030. The reduction of peak demand and the shifting of some loads in other hours of the day allows to avoid the use of peak generators with the consequent reduction of atmospheric emissions and energy prices. The use of blockchain technology for tracking and certification of DR service makes it possible to create a distributed system where even residential customers, representing on average one third of a country's consumption, can communicate with the system operator to provide their flexibility, in a secure, transparent and traceable way. In this way, residential users can also contribute to the achievement of the goals set for 2030.

In this thesis, it is defined and presented a blockchain-based platform which can be integrated with the current technologies on the power system without the addition of other devices, and demonstrates how the use of SCs is suitable for defining and implementing DR programs. The blockchain is a flexible and powerful tool that may suffer of timing and scalability issues. The experimental part of this thesis aims to demonstrate the technical feasibility of implementing DLTs and in particular a permissioned blockchain technology in smart grids, to further enable customers participation in the DR mechanisms, improve transparency in users' remuneration for their contribution to DR programs and that the timing for handling data with the blockchain is compatible with the timing of DR events. The proposed solution uses the blockchain as a multipurpose tool for handling messages and data among the actors providing transparency and security, for computing customers' load baselines, for enforcing the load reductions and finally, for remunerating customers according to their contribution. The experiments demonstrate that all the above indicated goals can be achieved while preserving customers' privacy, by using the Hyperledger Fabric communication channels both for data and for the SC computation. In particular, a new method for the certification, remuneration and optimization of the DR programs is outlined and implemented. The experimental approach proposed in this thesis solves the above raised challenges of current DR platforms :

- improves information asymmetry;
- guarantees data security;
- can put the basis for future disintermediation.

At the same time, the proposed approach overcomes the listed challenges of blockchain platforms for DR:

- is compliant with GDPR by means of the use of a permissioned blockchain platform and the provision of organisations for restricting the access to personal data;
- is scalable and allows participation of end users to real time markets, due to the lighter consensus algorithms of permissioned blockchain;

- compensates the insufficient "smartness" of available SMs.

The main contributions of the thesis consist in:

- Experimental development of a laboratory scale hardware-software test bed for blockchain based DR programs platforms testing.
- Development of a Blockchain based platform for DR service certification and CBL evaluation. In details, the implemented functions are: measurements acquisition; CBL calculation; reward functions evaluation.
- Design and implementation of a dedicated SC for the above functions execution.

With the proposed blockchain-based framework, it would be possible to remove intermediaries like the aggregator or BSP, since the aggregation in virtual units of consumers/producers can be done directly through the blockchain. In this way, the system operator can communicate the DR request directly to customers and the blockchain will remunerate them based on the service provided following the request, generating a new business model for aggregation and allowing even small users to participate in the balancing services market. In addition, the interaction with a domestic EMS aimed at minimising the cost of the energy bills allows the customer to automatically meet the DR request from the system operator. This is very important to take into account as domestic DR applications often highlight the risk of not meeting the demand due to many uncertainty.

Since the main challenges of using blockchain technology reside in latency and thus limited scalability as well as power consumption, future tests will consider more customers to check the scalability of the proposed solution, as well as different technologies for peripheral devices to check power consumptions and timing in all scenarios. The current application seems to be compatible with the time frame for participation in the MSD, but further tests with a larger number of users need to be conducted in order to be certain. Besides, further work will be aimed at identifying the way utility tokens can be negotiated against services offered and what services are more suitable to be offered in this scheme (discounts on bills, discounts for buying behind the meter storage, etc..). The data concentrator, which has been used for getting measurements from multiple meters is compliant with an IoT scheme operated by the energy distributor. In the future, the removal of the negative side of having a data concentrator will be considered, by the implementation of suitable compensation measures at the customers' premises.

Publication List

The following list concerns the publications related with the PhD thesis.

Authored publication in proceedings

C1- M. L. Di Silvestre, P. Gallo, M. G. Ippolito, E. R. Sanseverino, **G. Sciumè** and G. Zizzo, "An Energy Blockchain, a Use Case on Tendermint," 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Palermo, 2018, pp. 1-5, doi: 10.1109/EEEIC.2018.8493919.

C2- M. L. Di Silvestre, P. Gallo, E. R. Sanseverino, **G. Sciumè** and G. Zizzo, "A new architecture for Smart Contracts definition in Demand Response Programs," 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Genova, Italy, 2019, pp. 1-5, doi: 10.1109/EEEIC.2019.8783960.

C3- P. Gallo, S. Longo, F. Montana, E. Riva Sanseverino and **G. Sciume**, "Blockchain-based DR logic: a trade-off between system operator's and customer's needs," 2020 IEEE 20th Mediterranean Electrotechnical Conference (MELECON), Palermo, Italy, 2020, pp. 576-581, doi: 10.1109/MELECON48756.2020.9140494.

C4- F. Benanti, E. R. Sanseverino, **G. Sciumè** and G. Zizzo, "A Peer-to-Peer Market Algorithm for a Blockchain Platform," 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Madrid, Spain, 2020, pp. 1-6, doi: 10.1109/EEEIC/ICPSEurope49358.2020.9160609.

Authored journal papers

J1- M. L. Di Silvestre, P. Gallo, J. M. Guerrero, R. Musca, E. Riva Sanseverino, **G. Sciumè**, J. C. Vásquez, G. Zizzo, "Blockchain for power systems: Current trends and future applications", Renewable and Sustainable Energy Reviews, Volume 119, 2020, 109585, ISSN 1364-0321, doi: 10.1016/j.rser.2019.10958

J2- M. L. Di Silvestre, P. Gallo, E. R. Sanseverino, **G. Sciumè** and G. Zizzo, "Aggregation and Remuneration in Demand Response With a Blockchain-Based Framework," in IEEE Transactions on Industry Applications, vol. 56, no. 4, pp. 4248-4257, July-Aug. 2020, doi: 10.1109/TIA.2020.2992958.

J3- **G. Sciumè**, E. J. Palacios-García, P. Gallo, E. R. Sanseverino, J. C. Vasquez and J. M. Guerrero, "Demand Response Service Certification and Customer Baseline Evaluation Using Blockchain Technology," in IEEE Access, vol. 8, pp. 139313-139331, 2020, doi: 10.1109/ACCESS.2020.3012781.

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