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The influence of blockchain technology on decision making in peer-to-peer energy trading

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Dissertation presented as partial requirement for obtaining the master's degree in Information Management

NOVA Information Management School
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THE INFLUENCE OF BLOCKCHAIN TECHNOLOGY ON DECISION MAKING IN PEER-TO-PEER ENERGY TRADING

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Dissertation presented as a partial requirement of the degree of Master of Information Management, with a specialization in Information Systems and Technologies Management

Supervisor: Vitor Santos, PhD

DECLARATION OF ORIGINALITY

I declare that the work described in this document is my own and not from someone else. All the assistance I have received from other people is duly acknowledged and all the sources (published or not published) are referenced.

This work has not been previously evaluated or submitted to NOVA Information Management School or elsewhere.

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ABSTRACT

The increasing pressure set by climate change is bringing up new ways to take advantage of the latest emerging technology for environmental objectives. The energy sector in the cities' functioning is one of the most critical industries where more renewable and efficient solutions are needed. Peer to peer (p2p) energy trading is a mechanism that allows the participants to share the excess energy produced by their private solar panel, helping to reduce the pressure on the main grid in a sustainable way. In this context, blockchain-based p2p energy trading is the solution for which the energy sharing mechanism can become more efficient and safer thanks to the fundamental features of blockchain technology, encouraging more people to join the network and provide a significant contribution to the climate change problem. Like in all the sharing economy markets, p2p energy trading is strictly dependent on the behaviours and perceptions of participants. The first issue that arises is that blockchain technology is an incredibly new innovation and it's not clear how people perceive it, if with trust or scepticism. There is a risk that the presence of blockchain can slow down the adoption process because of lack of confidence in the technology, decreasing the potential beneficial impact of p2p energy trading. The second issue is the actual trading behaviour of the participants. The sharing mechanism is based on the willingness of the participants to share their assets but if this willingness is not constant, the whole functioning is blocked. Also, the presence of blockchain can alter the actions of participants making them more oriented towards individual benefits than those of the community. Therefore, the objective of this paper is to investigate how participants behave in blockchain based p2p energy trading, analysing their trading actions under different blockchain enabled scenarios and their willing to join such networks.

KEYWORDS

Peer-to-Peer Energy Trading; Blockchain; Sustainability; Prosumer

INDEX

LIST OF TABLES

LIST OF CHARTS

1 INTRODUCTION

1.1 Background and problem identification

Nowadays, the climate change is setting new critical challenges that put pressures to the society and the governments of the whole world. Institutions and policy makers are trying to find new solutions to keep the carbon dioxide emission as low as possible by identifying what are the main polluting activities. In general, every activity that is performed with the use of non-renewable energy, is a part of the problem. Production plants, the food industry, waste management processes and life in the cities are only few examples of sources of pollution. In this context, the European Union has developed 17 Sustainable Development Goals in order to solve the major problems that are affecting the world. Among these, three of them are related to the environment and energy, namely "Affordable and Clean Energy", "Sustainable Cities and Communities", and "Climate Action". The objectives set by the European Union are to achieve 40% cuts in greenhouse gas emissions, 32% share for renewable energy, and 32.5% improvement in energy efficiency by the year 2030 (European Commission, n.d.). A good way to achieve these ambitious objectives is to take advantage of the digital advancements that are taking place. Blockchain is surely one of the most promising technologies that can help. Despite its well-known high consumption of energy, blockchain can really play a relevant role in the picture of environmental problems. There are many beneficial usages of this technology thanks to its main aspects namely cybersecurity, accountability, transparency, and traceability (Fraga-Lamas & Fernandez-Carames, 2020). Considering this, cities around the world are the main cause of climate change and gas emissions. According to UN Habitat, cities consume 78 per cent of the world's energy and produce more than 60 per cent of greenhouse gas emissions (United Nations, n.d.). For this reason, one of the fields of application where this technology can deliver major improvements, is surely cities and the energy sector. In line with the sustainable goals already cited few lines above, blockchain can help in the development of smart grid and local energy markets (Fraga-Lamas & Fernandez-Carames, 2020). In Pieroni et al. (2018) the authors showed how Information and Communication Technologies (ICT) can be combined with blockchain in order to implement a smart grid architecture that can potentially improve quality of life and quality of services for the citizens of a smart city. Indeed, by implementing a simple mobile application, the final user can join the grid, exchange information, and buy/sell energy between the nodes of the grid, generating a large amount of data from several sources. This kind of architecture opens the door for a new actor in the energy market, the so-called prosumer. A prosumer is the one who produces, but also consumes, electric energy and sell it to the grid or neighbours in a peer-to-peer energy trading market platform. Thanks to the features of blockchain, participants can successfully trade energy autonomously produced and transfer payments in a safe environment, fostering the wide-spread shift to a decentralized renewable energy market (Thukral, 2021).

1.2 Objective

Referring to the already existing literature, the academic community already investigated how p2p energy trading and blockchain can be combined. Specifically, different market design approaches and platforms have been provided, covering the technical side quite extensively. On the other side, poor attention has been paid to the behaviour that participants would adopt under different trading scenarios, considering they are subjected to the features of blockchain. Indeed, this technology ensures a bunch of conditions that could potentially alter the normal trading actions, and that were not taken into account in already existing studies where blockchain was not included. For example, the anonymity of the network could make participants more willing to pursuit individual benefit instead of acting for the benefit of the community. Also, real time transaction could change the individual preferences to exchange energy for immediate compensation. Thinking to blockchain itself, the fact that this technology is very fresh can restrain people from joining the network because of lack of confidence, knowledge, or trust in blockchain. Understanding how people would behave in blockchain enabled p2p energy trading platform is of vital importance to guide its widespread in the society and support the transition towards a clean energy system. Indeed, p2p energy trading is not different from any other sharing economy mechanism where the willing to share individual assets with others is the core importance. This paper wants to address this lack of knowledge aiming to answer the following question:

How does blockchain technology affect participants' behaviour in p2p energy trading?

Thus, in p2p energy trading scenario, the goal of the paper would be to:

- Investigate the perceptions on blockchain technology
- Investigate trading behaviour according to price and battery level changes

1.3 Study relevance and importance

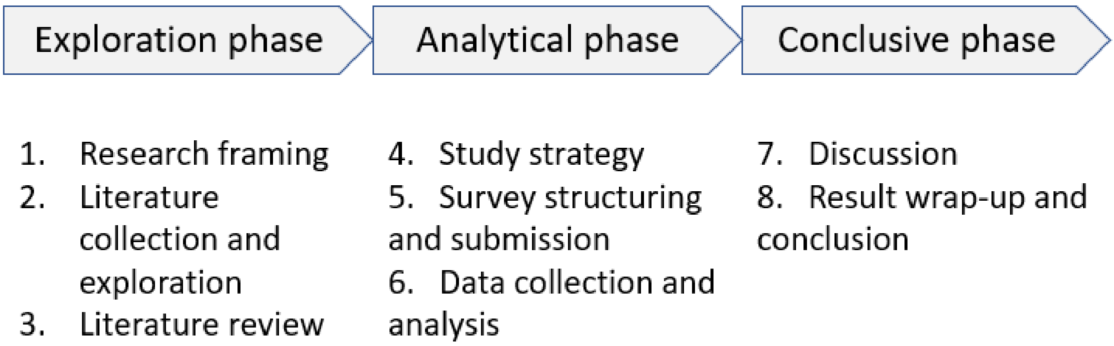
When applied to household energy consumption, blockchain based peer-to-peer (p2p) energy trading has the potential to disrupt the existing energy market by exploiting renewable energy through solar panels (Caramizaru, & Uihlein, 2020). Several academic articles have already shown the evidence of how energy efficiency can be achieved with this new way of providing electricity. In (Paudel et al., 2019) the study shows how p2p energy trading can provide significant financial and technical benefits to the participants, applying Stackelberg game theory approach where a price equilibrium is reached through the convergence of two iterative algorithms. Evidence shows that p2p energy trading can reduce the costs of the community up to 30% and, for individual consumers, bring a reduction of approximately 12.4% of electric bills, with an increase in annual income of approximately £ 57 per household (Long et al., 2018). P2p energy provision is efficient also when applied to electric vehicles. Drivers of electric vehicles can benefit a cost reduction of up to 71% of the normal market price (Hermana et al., 2016). Another study proposes a p2p trading framework that allows to export 0.99 kWh to the main grid and save 1465.90 g of daily carbon emissions but lacks attention regarding the monetary benefits of the participants (Hua et al., 2020). There is evidence that p2p energy trading can help participants to save in energy cost and control energy consumption. The technical side has been proven extensively to be extremely promising in innovating the energy sector in a clean, decentralised way while putting consumers at the centre of the system. However, research on private actors' preferences is still scarce. Individual participation is a prerequisite for the success of the concept of p2p energy trading (Sousa et al., 2019). This means that owners of private sources of energy like solar panels have to decide whether they want to consume their own produced energy, increasing their individual benefit, or sell it to the community, contributing to the benefit of the whole community. Indeed, there is evidence that the willingness of individuals to achieve individual autarky, intended as perception of being independent, autonomous, self-sufficient, energy secure, and out of control, strongly affects the acceptance of decentralized renewable energy systems (Ecker et al., 2017). In this frame, the effect of blockchain on participants' behaviour and perceptions should not be underestimated.

The contribution of this paper is both on the academic and practical side. On the academic side, research in this topic is not very extended and a step further is necessary. Specifically, the benefit that blockchain based p2p energy trading can bring incurs the risk to be undermined by the behaviour of its participants. For this reason, it is extremely important to shed light on this topic that has not been already investigated properly by the academic community. This work is aimed to bring a significant and valuable piece of knowledge. On the practical side, the results of this research would help policy makers and entrepreneurs to shed light on a new way of transitioning to renewable energy by having a better picture of how participants would act in the blockchain based p2p energy trading network. This innovative market has the potential to disrupt the existing energy sector by decentralizing it in a sustainable way and bringing benefits to its participants, but a clear understanding of people behaviour is of vital importance. If the market is properly designed considering this issue, blockchain based p2p energy trading would bring several key contributions to the power sector. Firstly, an increase in renewable deployment and flexibility thanks to consumers' and prosumers' empowerment. Secondly, the distribution of energy resources would allow a better management of congestions and balances of power provisions. Finally, the existence of ancillary services would add value to the main grid and improve energy access (IRENA, 2020).

2 METHODOLOGY

The structure of this study is composed by three main phases, as depicted if figure 1 below, where each of them cover a specific role and set of information relevant for the accomplishment of the objectives. In the first phase called exploration phase, it is outlined the frame of the research meaning the context of the topic chosen. Also, a wide understanding of the knowledge already existing is performed and the most relevant sources of information are selected, finally concluding with the definition of the methodology adopted. After this first part it follows the analytical phase where the survey is constructed and submitted following with data collection and analysis. The last conclusive phase is constituted by a discussion where the results are evaluated, finishing the work with a summary of what has been found out and general conclusions of the study.

Table 1 - Methodology



The methodology is composed of 8 detailed steps intended to sub-divide the work:

- In the **first** step the topic of the research is outlined. This step is important to clearly define the problems addressed by this study and how it relates to real life problems. This is described moving from a general picture of environmental problems into more details of peer-to-peer energy trading.
- The **second** step allows to perform a general exploration of the literatures existing about the chosen topic in order to have an overview of the direction of the research performed by the academic community.
- In the **third** step the key concepts of this study are explained by selecting the most relevant sources. This step presents three sub sections where each topic is explained into details from different points of view. Firstly, the reader is introduced in the broad world of energy trading with a precise collocation of this topic in the energy sector, finally moving into the peer-to-peer energy trading mechanism. Secondly, a section is dedicated to the explanation of

blockchain technology specifically the concept, the structure, the challenges, and opportunities, concluding with an overview of its application, with a focus on the energy sector and finally p2p energy trading. Thirdly, the last part is focused on the figure of the prosumers, exploring their behaviours and perceptions on blockchain. The literature review phase is of crucial importance since it allows to define the knowledge gap and therefore the relevance of this study.

- The **fourth** step is the first one of the second macro phase. Here the analysis strategy is defined and explained to the reader for a better understanding of how the study is constructed
- The **fifth** step is where the survey is structured and submitted. The tool selected is Google form, and the structure is as follow:
    - First part where the respondent is classified based on some biographical information.
    - Second part where it is assessed the perception on blockchain technology, the level of knowledge about this technology, and how it influences the willingness to join p2p energy trading systems.
    - Third and last part where different trading scenarios are hypothesized under the characteristics of blockchain. Here the trading behaviour of the respondent is recorded.
- The **sixth** step is composed by the analysis of the information collected. The sample of respondents is classified according to some basic statistical metrics, and the data collected are analysed. The specific information that are expected to be taken under analysis are the ones corresponding to the objective of this study, and they can be found in the first introductory section of this paper.
- The **seventh** step presents a discussion of the results obtained and their comparison with the previous studies. In this way it is possible to observe how blockchain influences individuals in the p2p energy trading scenario.
- The **eighth** and last step is intended to draw some final conclusions and key outcomes of the study. The relevance and real-life implications of this work is covered again in the light of the results obtained. Finally, the limitations of this study are explained, opening space for future research.

3 LITERATURE REVIEW

3.1 Energy trading

3.1.1 Concept

The environmental challenges of these days brought a real need for the energy system to shift to a more decentralised, decarbonized, and digital system. A successful transition can be achieved by keeping the balance among three important dimensions of energy systems as explained by the so called "Energy Trilemma". The Energy Trilemma Index is a way to evaluate the performance of the energetic system of a country among three dimensions. The first one is energy security, that refers to the capability of a nation to always meet the current and future demand for energy. The second one is energy equity, which describes the extent to which a nation can provide universal affordable energy at fair prices. The third and last one is environmental sustainability that tells how the energy system of a country is avoiding bringing potential damage to the environment (WORLD ENERGY TRILEMMA INDEX, 2020). The mechanism of energy trading emerges in this frame, and by the need to pursue the three dimensions by putting at the centre of the system the people instead of the traditional providers. The introduction of Distributed Energy Resources (DERs) allows people to play a different role in the market. A DER can be defined as a combination of three factors namely Distributed Generation (DG), Demand Response and Energy Storage, and a good example are photovoltaic panels that, for the scope of this work, is the kind of DER that is going to be taken into consideration (European Parliament, 2010). These tools allow people to shift from being consumers only to prosumers, so those people who, with DERs, both consume and produce energy. The energy produced is intended to be consumed for the household needs, but also sold and traded to external entities, such as the main grid or other privates, at a real time adjusted price. This system takes the shape of a sharing mechanism not different from the most popular and successful ones like, for example, BlaBlaCar, or Airbnb where an asset like a car or an apartment is being shared in exchange of compensation, and others takes the benefit of it without owning it directly (Zhou et al., 2020). In Zhang et al. (2018) Peer-to-Peer energy trading is defined as the direct energy trading among consumers and prosumers, which is developed based on the "p2p economy" concept, also called sharing economy, and is usually implemented within a local electricity distribution system. The same definition is adopted in Soto et al. (2020), while in Sousa et al. (2019) the p2p trading concept is explained in more general terms. Indeed, the authors explain that p2p defines a decentralized structure where all peers cooperate for common-based producing, trading, or distributing a good or service. The latter definition set the focus on the decentralized structure of the mechanism that, considering the scope of this paper, best fit with the concept of blockchain and its main characteristic that is decentralization. The P2P model creates an online marketplace where prosumers and consumers can trade electricity, without an intermediary, at their agreed price (IRENA, 2020). As DERs become more and more popular, we can expect the number of prosumers to increase, opening the doors for a more decentralized and sustainable energy market (Soto et al., 2020). The creation of this kind of energy communities reflects a growing desire of people to organise and manage energy systems in a new way (Van Der Schoor et al., 2016). It takes the shape of social movement that opens the doors for participation and democracy in the energy production. So far, there is a lack of clear legal status for energy communities, bringing up some obstacles to set up this kind of systems (Caramizaru, & Uihlein, 2020). There is multiple potential benefit that this transition would bring. Looking at the side of the energy suppliers, the pressure on the production of energy and the infrastructure itself would decrease thanks to a decentralization of the energy supply. Indeed, a less centralized operation is less vulnerable to supply chains interruption, especially in periods of high demand. Also, for those people who lives close to a prosumer, the supply of energy is potentially always available in case of cyberattacks or natural disasters that can damage the structure of the main supplier (Soto et al., 2020). The result would be a more balanced local energy generation due to a greater diversity of resources, and incentives for people to consume and produce clean energy, leading the transition to a green energy system (Zhang et al., 2018). Even if the benefits are multiple, there are some forces that goes against this transformation of energy market. One of them is the differences in net metering policies among countries and regions. Net metering is a way of billing that allows customers with a solar panel to inject back to the grid the energy produced and not immediately consumed by themselves and being billed for only their net usage of energy (SEIA, n.d.). For example, if a net metered house is generating more electricity than their current need at a specific point in time, the electricity meter will run backwards to provide a credit against what electricity is consumed at night or other periods when the home's electricity use exceeds the system's output. If local entities and regulations do not allow this mechanism, the solar energy production is limited only for private use and cannot be traded externally. There is a lot of uncertainty also on the legal side. As will be explained later in this work, blockchain technology is seen as one of the most promising tools to achieve a smooth functioning of p2p energy trading activity. The problem resides in the fact that the intrinsic characteristic of this technology is in contrast with some of the laws included in the General Data Protection and Regulation recently issued by the EU, that regulates the usage and transfer of data in the European territory (De Almeida & Van Soest, 2021).

3.1.2 Markets

In this subsection the paper will proceed firstly by reporting some key facts about the electricity market worldwide, afterwards the focus will be shifted to the p2p energy trading market explaining its potential value and functioning among the participants of the trading system.

The International Energy Association published in July 2021 the Electricity Market Report where it highlights recent developments and forecasts demand, capacity, supply, and emissions through 2022. The report also analyses electricity market prices and electricity security. Starting with the global energy demand, it is forecasted a growth of 5% in 2021 and 4 % in 2022, meaning that, even if the rate of growth has decreased, there has been an almost constant increase in the overall demand for energy. To face this increase in demand, energy production from renewable resources is expected to increase by 8% in 2021 and more than 6% in 2022. Even if these numbers sound promising, renewables are predicted to cover only half of the increase in demand, leaving the other half to polluting methods of energy production. In general CO_2 emissions from the electricity sector will increase by 3.5% in 2021 and by 2.5% in 2022, touching higher than ever values. Regarding the prices, there was a 54% increase in the first half of 2021 compared to the same period in 2020, but this was due to an unusual 25% decrease in 2020 caused by the Covid-19 unstable situation. Furthermore, extreme weather conditions set some new challenges to the supply of energy and the first half of 2021 saw shortfalls caused by extreme cold, heat or drought (IEA, 2021).

Regarding the market structure of the electricity production sector, we can state that it takes a very centralized shape, brought up during the years by a combination of factors. Surely, the pursue of economy of scale aimed to a price reduction, with the creation of power plants with bigger capacity. With the increase of plants' capacity, the efficiency of the energy provision increased and, coupled to a constantly growing innovation in the distribution system, energy can be transmitted over medium-long distances. On the customers' side, shifting the reliability on one main provider allowed to keep smaller generators in case of losses. Furthermore, having a unique production plant, and relocating it out of urban areas, could help reduce the air pollution for citizens. Finally, the legal side never really managed to adapt itself to a decentralized energy production, favouring the insurgence of only highly centralized systems (Martin, 2009). In this frame, p2p energy trading goes in a directly opposite direction compared to the legacy production modality, where few highly centralized producers with large generation capability have to fully cover the demand from the population. Taking a closer look at the distribution system, the operations have always followed a top-down approach through a star schema shape system. Once the energy is produced and transformed in the power plant, it flows to a Local Power Distributor (LPD) through the distribution grid, ultimately arriving to the final consumers. The only action allowed to the customers is to consume the energy, and the primary point of contact is the LPD which controls the flow of energy (Mazzola et al., 2020).

There are several facts that give reason to think that the energy market is struggling in front of the challenges set by climate change, increase in demand, and environmental goals. Moreover, the current structure of the sector does not leave real space for consumers. In this context, peer-to-peer energy trading represents an optimal solution for the issues mentioned above (IEA, 2021). Still, the numbers suggest that the production of renewable energy from decentralized sources including solar panels has increased within the European Union from approximately 15% in 2005 to almost 31% in 2017 (Mazzola et al., 2020). Also, 45% of total investment in the electricity sector in 2021 are for clean energy, and in 2020 the global renewable energy capacity increased by 45% compared to 2019. The largest increase in capacity was from solar panels which accounted for 48% of the increase. Even if these numbers sound promising, the forecasts for the following years are not of the best, with a constant decrease in the growth rate of renewables production from more than 10% in 2020 to a forecasted lower than 9% in 2022 (IEA, 2021).

In the following lines a general overview of a peer-to-peer energy trading market will be given. Details about the different market structures according to different models of energy trading will be explained in the following subchapter. For the sake of clarity, it is important to specify that the centralization feature of peer-to-peer market is completely different than traditional centralization of energy markets. In other words, if on one hand we have the legacy structure which is highly centralized, on the other hand we have the innovative p2p structure which, at the inside, present different substructures that can either be highly or less centralized. Even if different works use different terminology, we can identify three general market design for p2p energy trading namely centralized, fully decentralized, and distributed markets (Zhou et al., 2020). Again, a more thorough investigation on the markets and the details of each of them will be explained in the following section. Given this, there are two main different solutions for the distribution of the physical energy to the participants that set up two different concepts of energy trading. A first option would be to use a private electric power network, where private wires are built between peers to allow a peer-to-peer energy distribution. This solution sounds very well working in terms of efficiency but cost wise it is not very convenient because of high sunk costs and low marginal network operating costs. The second option is to use the public electric power network, where the grid works like a big pool where producers can inject power into the network and consumers take it in a uniformed way. In the first case, where a proper distribution network is set up for a specific market, the p2p energy exchange is physical, while in the second case it takes the shape of a more virtual market since the energy is pooled into the public grid (Zhou et al., 2020).

Even if there are multiple market structures and two different mechanisms of distribution of energy, the pricing system that stands behind is quite standard and generalized. For p2p energy trading the price is not set by a single centralized entity, but it is defined by the free-market rule where supply and demand shapes the trend. On the other side, the costs for operating are referred as “road price” and they represent the expenses for transferring the energy from the seller to the buyer following the shortest possible path (Zhou et al., 2020). Obviously, this price can vary depending on the structure of the market and distribution system, but, as already stated before, the details of the market dynamic as well as all the actors and devices involved will be explained in the following section. As explained, some structures of peer-to-peer energy trading do not limit the activity between prosumers and consumers only but extend it to retailers as well. Prosumers and consumers can expect therefore to trade energy at a price which is lower than the “outside” energy market price, creating a convenient position for everyone: consumers and retailers who buy energy at a cheaper price, and prosumers who can obtain benefits.

Looking to the legal framework that is standing now in Europe, we can state that European Commission's Clean Energy Package breaks new ground for consumers by recognising, for the first time under EU law, the rights of citizens and communities to engage directly in the energy sector. Indeed, the key roles of the actors involved in the trading mechanism are defined and energy communities can, therefore, take different types of legal structures (Caramizaru, & Uihlein, 2020). Even if policies are opening the doors for the development of a regulated energy trading market, there are numerous counter forces. The industry itself and the supply chain of electric energy is composed by many actors who have big stakes and interests in the whole chain, making it difficult to bring up radical regulatory changes. Also, the fundamental technologies that can allow peer-to-peer energy trading are developing extremely fast, and it’s not completely clear how regulations should be developed in a way that includes this strong technological progress (Zhou et al., 2020). There is clear evidence that for p2p energy trading is vital to integrate the whole mechanism, on all sides, with the current energy policy structure, spanning from the taxes until the market dynamics. Governments at this point should set incentives to let the market develop, or just define restrictions if they consider it harmful for the current system (Tushar et al., 2018).

3.1.3 Types of trading

This subsection will proceed with a more detailed explanation of the architectures, schema, and players of p2p energy trading. Also, the pros and cons of each of them will be presented, including an overview of market evaluation methods. For the sale of clarity, it is important to differentiate architectures and schema. The first one refers to the set of technologies and layers that allows the market to run efficiently. On the other side, schema refers to how the market is designed

The way the mechanism of p2p is set up is generally standardized, but it presents different possible shapes. The different architectures that composes the layered backbone behind p2p energy trading market mechanism are explained in the following lines.

A three layers architecture is proposed in Tushar et al. (2020) where each of them have some internal components. The first one is the virtual layer which ensures that all the participants are securely connected in order to decide for their energy trading parameters, and they have equal access to the virtual platform. In this way the transfer of information is possible, buy and sell orders are created and matched, and the final transaction is carried out efficiently. In this layer there are several important components. The information system is the first and most important one for the functioning of the p2p network. It performs several crucial functions such as enabling the communications among the participants and their integration on a unique platform, guarantee their equal access to the market, and monitor the market operations and set restrictions to ensure security and reliability. A technology example of such system would be blockchain, which is the focus of this paper. The second component is the market operator that defines the market allocation, payment rules, and bidding formats. The main objective is to allow participants to experience an efficient match of sell and buy orders. Thirdly, there is the pricing mechanism which, as a part of the market operator, balances energy supply and demand and shapes the price according to the trend of the community energy surplus. We can expect the price to lower in case of high surplus of energy. The last component of this layer is the energy management system (EMS). Having the access to the real time values of supply and demand, it develops the profile of the prosumer and decides the bidding strategy to participate on the trading (Tushar et al., 2020). For example, the EMS of a rational prosumer will always buy energy when the price falls below the maximum threshold and sell it when it's above that level. The second layer is the physical layer which responsibility is to facilitate the transfer of electricity from the seller to the buyer when the transaction is concluded in the virtual layer. It really refers to the material grid that allows the exchange of energy, either it is a distributed-grid network or an independent microgrid ultimately connected to the main one. There are several components in this layer as well, starting from the grid connection which refers to the whole system of connection points. Here we can find smart meters connected so that it is possible to monitor and evaluate the performance of the whole network, regarding both energy consumption and costs. Secondly, there is the metering infrastructure of each prosumer. This is a fundamental component to participate in the trading activity since it decides whether to trade in a p2p fashion based on the demand, supply, and other market parameters like price or network conditions. The third and last piece of this layer is the communication infrastructure that allows the actual exchange of information within the network (Tushar et al., 2020). The last layer is more general and is made of two more elements. The first one is the market participants, where a sufficient number is needed to efficiently produce energy and shape the price and the market. The last and second element refers to the regulation sphere which covers a fundamental role in defining the “rules of the game” but also in stimulating this kind of market to develop and give an important push to the transition to clean energy (Tushar et al., 2020).

Instead, the authors of the article (Zhang et al., 2018) proposed in their study a four layers architecture with three dimensions that present slightly different peculiarities that the previously explained case. The first dimension contains the key functions of p2p trading activity, and they are categorized in four different layers. The first layer of the first dimension is the power grid, where it resides all the physical components of the power system like feeders, transformers, smart meters, loads, and DERs. Following, the ICT layer consists of all the communication devices, protocols, applications, and flow of information. Thirdly, it is possible to find the control layer which is responsible of all the control functions of the electricity distribution system. The last one is the business layer which determines how electricity is traded. Different forms of p2p are possible here where peers, suppliers, and the DSO interacts to each other in many different ways according to the market structure. Moving now to the second dimension, different scenarios are categorized based on the size of the participants in the p2p energy trading mechanism. In a first case, individual premise refers to a system where only single houses are connected to the electricity distribution system. After this, there is the Microgrid which is intended as a collection of individual premises and DERs restricted to the same geographic area and share the same voltage transformer. Logically, the next step is the collection of microgrids, which is named as Cell and it is used to identify a wider network area where several DERs can be controlled to achieve a specific objective, both on an islanded or grid-connected mode. Lastly, a collection of Cells defines a region that can correspond to a city or metropolitan area. The third and last dimension shows the p2p trading process. It starts with the bidding where customers interact with each other to reach an agreement on the price and amount of energy to be traded. The following step is the exchange of energy in which energy is generated, transmitted, and finally consumed. It all concludes with the final settlement where bills and transactions are concluded.

To explain the functioning of p2p, a five-layer architecture is provided in (Mazzola et al., 2020) where the focus is also on the communication and data interdependencies among them. The first lower layer is the device layer, where all the physical devices are present including solar panels, batteries, or meters. The data produced here ranges from basic consumption levels to devices’ status and usage and, for this reason, there is a risk of incurring in difficulties in data aggregation. The second layer is the smart meter layer. Here all the information from the device layer is aggregated into a single entity owning a smart meter and this can be either the LPD or the DSO. It is crucial that the devices in this layer are not owned by end users to avoid any possible fraudulent behaviour. After this, there is the transmission layer that concentrates all the communications and forward them between the smart meter and the DSO or LPD. For this reason, it is of extreme importance to have security standards in place here to ensure data reliability and trust. The fourth layer is the communication layer that is responsible for integrating all the participants in the p2p marketplace. All the users' hardware is identified so that an automated match between energy demand and supply can be matched. Lastly, there is the management layer that is responsible for processing all the data coming from the lower layers and take decisions accordingly. It predicts consumption and demand levels, regulates the power flow and grid stability.

Among the three structures presented, the one proposed by (Mazzola et al., 2020) is the most suitable for the purpose of the study since it presents a strong focus on the flow of information and data with the corresponding need for security, which is the main benefit that technologies like blockchain can bring.

Given these three layers, most diffused p2p energy trading market present standardized figures and actors with defined roles and characteristics. Since this kind of trading allows the participation of different participants with different capabilities and needs, it is important tom clearly define them. In p2p energy trading it is still possible for normal customers to participate. In this case the Customers can gain benefits by making a mix of energy resources and find electric energy at cheaper prices. Also, normal customers can satisfy their constant demand of energy by diversifying the providers: instead of having a centralized main one, now they can aim at a combination of several (Mazzola et al., 2020). A different type of consumer is the already cited Prosumer who, differently by the normal customers, is capable of a certain level of self-production. In case his or her self-production is higher than the consumption, the energy is fed into the grid and the trading activity can take life. Also, according to Zhou et al. (2020) prosumers are also defined as normal customers who are equipped with DERs and are able to trade and share energy with each other. Based on supply and demand, this injection is financially compensated and energy flows to the buyer. There is a smaller category of Prosumers, Prosumer+, who have a slightly higher self-production capabilities and their level constantly stands above their consumptions (Mazzola et al., 2020). In this frame we still find the legacy Producers who do not consume energy, but they only produce and inject it. In a decentralised energy market schema, they can still benefit from it by selling energy directly to the Consumers without passing by intermediaries. Moreover, the fact that electricity is also produced by other players, this alleviates the pressure on the main providers especially in periods of high demand. Another important player in the whole p2p mechanism is the Distribution System Operator (DSO). This element ensures a congestionless energy transmission and provides the grid and all the smart meters in a uniformed way. The DSO revenues are from the road pricing, so the fee on every transaction for the energy transportation. The last important actor is the Local Power Distributor (LPD) whose service is to stabilizes the grid using large storage devices. Indeed, it is possible that sometimes the network is incurring in some unbalances both on the supply and demand side, and they have to be corrected by the LPD at an intervention fee that is paid by the party that broke the contract (Mazzola et al., 2020). For example, if a transaction is concluded and a Prosumer is expected to provide energy to a customer but there is a problem in the smart meter that provided misleading data, the LPD intervene and provides the energy to the customer, and the Prosumer is expected to pay the intervention fee to the LPD

Now that the architecture of the p2p energy trading and actors are clarified, this section will proceed on explaining more into details the already cited three market structures where p2p energy trading can take place. Different distribution options will be explained, with a final overview of the pros and cons of each of them.

The first structure is the centralized market structure. Here we can find a coordinator who communicates with each participant of the network. The role of the coordinator is to directly decide the import and export level of energy and distribute the revenues to the whole community following some predefined principles. Indeed, the main goal of this kind of structure is to maximize the welfare and benefit of the whole community. One of the advantages of this kind of structure is that, being under the control of the coordinator, the patterns of power generation and consumptions are more stable (Zhou et al., 2020). Also, it is possible to enhance social cooperation and relations inside the community, while creating potentially new services for grid operators provided by the coordinator (Parag, & Sovacool, 2016). Taking a look to the disadvantages, centralized markets put a lot of pressure on the centralized management system. It can be challenging for the coordinator to find optimal solutions to manage the network to match everyone's expectations, especially when the number of participants increases. Another disadvantage is that the privacy of the information and autonomy of each peer is not completely in their hands (Zhou et al., 2020). In Parag and Sovacool (2016), centralized markets are called community-based markets. Here, the coordinator is addressed as community manager with the responsibility of managing the trading activities inside the community and being the intermediator between the community and the rest of the system. It is important to mention that generally a community is composed by members who share the same overall objectives and live approximately in same areas (Sousa et al., 2019). Contrarily, Tushar et al. (2020) considers community-based markets to be composed by members who doesn't necessarily live in the same locations and each of them can either collaborate or compete against each other, selling energy also outside the community through the community manager.

The second possible structure is the decentralized market where, differently than the centralized, peers can directly contract and trade with each other without the central coordinator (Zhou et al., 2020). This design carries advantages as well as disadvantages. Starting with the advantages, the privacy of each participant is surely well protected since the data of their activity is not expected to be transferred to any other actor (Zhou et al., 2020). Also, participants have full freedom on their actions, and this would lead to a higher "democratization" of energy use (Parag, & Sovacool, 2016). These factors would lead to a higher degree of scalability of the network that translates in a more freedom to enter and exit the market more easily (Zhou et al., 2020). On the other hand, leaving more space to the operations of the peers would not ensure a fully efficient network, meaning that the social welfare of the community may not be maximized (Guerrero et al., 2017). The lack of a centralized control makes it difficult to predict and shape the behaviours of the operators (Parag, & Sovacool, 2016). The authors in Sousa et al. (2019) name this kind of market full p2p market structure and explain that the market dynamic can take different forms than just a direct real time trade. Indeed, peers can agree on specific amount of energy at a predefined price both on real time and forward market and choosing the type of product also. A product differentiation is included between local and green energy (Sousa et al., 2019). A similar explanation is present in Tushar et al. (2020) where, differently, this market structure is called fully decentralized market structure.

The third and last case lies in the middle between the first two structures, and it's the distributed market design (Zhou et al., 2020). Here the coordinator does not directly define the energy import and export levels or the operational status of the devices, but only indirectly sends some pricing signals (Zhou et al., 2018). The centralized feature of this structure is that the behaviours of the participants can still be coordinated to some extent, while the decentralized characteristic is in the fact that the peers' information are not fully required, and their devices are not directly controlled. Even if distributed markets exploit the advantages of both centralized and decentralized, the main issues here are that it is extremely difficult to define a proper pricing mechanism for p2p trading and a system to model the decision-making process of the participants (Zhou, 2020). It is possible to find this kind of structure called hybrid p2p market in the work of Sousa et al. (2019). In this work the market structure is explained following a two layers approach where the first layer is composed by individuals and energy collectives engaging in energy transactions between themselves and existing markets, while the second layer is composed by energy communities where community managers conduct the transactions. In this way it ends up as a combination of the two previously explained market structures (Sousa et al., 2019). The authors in Tushar et al. (2020) refer to distributed markets as composite market where the main problem resides in the fact that a prosumer need to deal with both regulated and deregulated p2p markets. How to integrate the two remains an open challenge for p2p market designers.

Once a clear explanation of the layers and market design is provided, it is possible to define some general strengths, weaknesses, opportunities, and threats of p2p energy trading. Surely what makes this system so appealing is its capability to empower consumers in the energy market, ensuring trust, transparency, and openness, which increases resilience and reliability of the system. Customers have more autonomy in deciding sources of supply and produce their own energy, and this decreases the power of the legacy centralized suppliers. Still, this system presents some weaknesses like the risk of having sub-optimal energy prices of all energy market and an overwhelming number of transactions that would make the negotiation mechanism extremely heavy. Also, such device-intensive mechanism would require a life-cycle assessment of hardware that risk lowering the benefits of this system. In terms of opportunities, surely the democratization of energy production is one of the most appealing in such centralized industry like the energy sector. More awareness about cooperation towards environmental causes would arise, through the creation of new business models. Finally, the grid operators would benefit by deferring grid investments in new lines and equipment. There are some threats and opposing forces that would slow down the development of this kind of markets. The first and most obvious one is the legal framework since in most countries' regulations have not been yet issued to allow a smooth development. Some important differences in economic power among people are present when a p2p market has to be implemented and the unpredictability of human behaviours set some real threats to the mechanism. If the network is not properly designed, the grid would incur in strong congestions leading to a not optimal power provision, a too tight dependency on the technology would occur, and potential losses of security and privacy would take place, ultimately leading to a failure of the market (Sousa et al., 2019).

At this point is clear that the members participating in p2p trading transaction would benefit from financial gains regarding energy costs, translated in a reduction of energy bills since renewable energy injected in the grid at a feed-in-tariff is cheaper than the retail price. Looking at the infrastructure itself, the cost of generation is more stable considering that solar panels are long term investments. For those structure where a coordinator is in place, we can expect long term sustainability thanks to well defined parameters of sharing gains (Caramizaru, & Uihlein, 2020). On a general scale of the society, there is a negative side of this system. Indeed, if more people engage in smaller energy communities or any other type of self-provision and consumption of energy, the demand for energy from the main grid will decrease, and this would lead to an increase of costs for those people who are not in any kind of network who take the burden for the distribution from the main suppliers (Caramizaru, & Uihlein, 2020).

3.2 Blockchain

3.2.1 Concepts

The last two decades saw an incredibly fast expansion of technological innovations that came alongside the widespread of information technologies and data gathering tools. This opened the doors for an exponential increase of new technologies that can extract the highest value possible from this wave of progress. Surely one of the most popular and discussed is blockchain. This technology was firstly created by Satoshi Nakamoto back in 2008, and it was specifically designed to support the Bitcoin rise. Briefly, Bitcoin is a decentralized crypto currency that is supposed to be a good alternative to the traditional centralized monetary system controlled by banks (Shen, & Pena-Mora, 2018). The underlying characteristics of blockchain, its fundamental technology, and data structure makes it very versatile for different industries and sectors and now the application field is expanding at a rapid pace (Wong et al., 2020). This section will proceed as follow: firstly, an explanation of how blockchain is constructed and function is provided, moving to the deriving characteristics, concluding with the types of blockchain that are available.

Defining blockchain is currently a very difficult task. Its concepts and application fields are so broad that it is complex to identify a uniquely accepted definition. Still, it is possible to find some common referring concepts on which different definitions of blockchain set the basis. These common concepts basically refer to underlying characteristics that are generally accepted about this technology. In the research of Frizzo-Barker et al. (2020) , the authors collected a set of works where a definition of blockchain was provided and grouped them together under umbrella terms to see which the most popular concepts are used to describe blockchain. The results tell that 59% of the works refer to blockchain as "distributed or decentralized ledger", 27% of them used the terms "trust, transparency, and security", while only 17% of the selected works defined blockchain in relation to "peer-to-peer" (Frizzo-Barker et al., 2020). These words will come out later on during this work when the features of blockchain will be explained, but there is clear evidence that lacks of formal definition of blockchain in relation to p2p is present. This lack of knowledge increases furtherly the importance of this research where the blockchain technology is coupled with p2p mechanism, in this case energy trading which also constitute a mechanism for resolution of social problems. For this reason, the most appropriate definition is the one provided by (Scott et al., 2017) where is stated that blockchain is based on "collaborative, open-source principles and peer-to-peer networks that suggest a commitment to principles like decentralization, social solidarity, and disintermediation" (Scott et al., 2017, p. 423). to complement this definition with a more practical one, it is possible to state that blockchain can be defined as an open and shared distributed ledger technology (DLT) with the main function of recording transaction between two parties. Data are recorded in an efficient, permanent, and verifiable way, taking the shape of a shared digital data storage (Iansiti & R. Lakhani, 2017). In this frame, a transaction is a data structure that exemplify transfer of digital assets among peers in a blockchain network (Bhushan et al., 2020). Being a distributed architecture, the objective of DLT is to establish trust, accountability, and transparency without accounting on the verification of a centralized authority (United Nations, 2020). It is possible to see blockchain as a sequence of blocks, where each block contains the information and transactions contained in the previous one through a cryptographic link (Chuen, 2015). These cryptographic links form the hash function that relate blocks among them, and every time a new block is added to the chain the hash function defines it in a unique way using as input the whole previous block. This means that to change the data of an anchored block, all the subsequent blocks have to be updated as well, all those that were connected through the corresponding hash functions. Depending on the consensus mechanism in place, that is the criteria for which data are verified and changed, the data stored in the chain are virtually immutable to a certain degree. The starting block of a new chain is called genesis block, or block 0, and it plays an important role since it can be used to validate all the transactions contained in the subsequent chain where each block is bonded permanently to the previous one (United Nations, 2020).

Now that a general introduction about blockchain is provided, the focus can shift on how this innovative technology works. The functioning of blockchain is based on five main principles. Firstly, each part involved have access to the entire database thanks to the distributed database feature, and this allows that the records of each party can be verified but it's not possible to have direct control on the data recorded in the transaction. The second funding principle is that peer-to-peer transactions refer to the fact that the intervention of a third party is not needed for communication to take place. Indeed, thanks to DLT every node of the network stores the data and forward it to the rest of the chain. Another important factor is transparency that is achieved through anonymity and pseudonymity. The information about the transactions is delivered to all the participants without revealing the identity, still validating that information that are spread. The fourth pillar is regarding the irreversibility of records that implies each transaction to be recorded in a chronological order permanently. Lastly, the transactions between nodes are triggered by a set-up of algorithms and rules, and this constitutes the digital nature of the ledger of the blockchain transaction (United Nations, 2020). Considering these funding concepts, the process of validating a transaction is composed by a sequence of procedures. Each party in the transaction has a private key and a public key, which is used as the party's identity. The two parties sign the transaction using their private keys, and the transaction is broadcasted to all the peer nodes in the network which, through a consensus mechanism, validate or reject the transaction. Once it is validated, it is placed into a new block that is connected to the previous one through a cryptographic hash. In this way there is a growing shared database, with immutable and irreversible list of records (Shen, & Pena-Mora, 2018).

The underlying characteristics of blockchain, that makes it so strong and appealing for different sectors, are the security of the system, the independency from central authorities, and the transparency and integrity of data and records. This sub section is going to explain the elements that strengthen these characteristics. The first element that plays a key role in blockchain technology is the already mentioned consensus mechanism, also called consensus protocol. It defines the strict rules to create or add a new block in a way that all the participants agree on the validity of those information that are stored in the distributed ledger. Some consensus mechanisms allow only a restricted group of nodes or participants to have the role of validating the transactions. The second crucial element is the time-stamped feature of the information. Indeed, every transaction is time-stamped, and it is possible to track and verify any payment, ownership, or contract that took place at a specific time and date. Another factor is the multiplicity of nodes or computers which makes it possible to have no central point of failure, increasing the difficulty for external attacks. Lastly, the smart contracts can execute the terms of a contract involving two parties in an automated way. Through blockchain, the contractual control of transactions can be performed, defining the terms of an agreement with an automatic release of asset (United Nations, 2020).

Based on the specific characteristics and design of the blockchain technology, we can expect to find different types of blockchain. In this last sub section, an overview of the different types of blockchain is provided, with an explanation of pros and cons of each of them. Different criteria and approaches for differentiating the possible structures will be explained.

In United Nations (2020) the authors adopt a double-differentiation criteria and identifies four possible blockchain types. The first differentiation is based on the ownership of the data structure and defines public and private blockchains. The second one refers to the extent to which participants can audit, write, or commit, and permissionless or permissioned types are addressed. Specifically, a private blockchains is one of those where the access to the network and information is controlled by a single entity. New users are allowed different level of accessibility and information can be encrypted. Considering that participants must have a permission to access, read, and verify data, it is considered less secure, and the decentralization feature is lower, since it goes against the underlying nature of blockchain where the more decentralized it is, the more secure it is expected to be. On the other hand, public blockchains are where all the nodes and transactions are public. This brings that all the information is encrypted and stored on multiple devices, increasing the overall level of security. This kind of structure implies that once the data have been verified, it cannot be altered anymore. Regarding the other dimension of differentiation, in permissioned networks only a limited set of entities are authorized to write, audit, and commit, while in the permissionless case these actions are allowed to anyone who join the network in an anonymous way. At this point four blockchains scenarios are possible: public permissioned, public permissionless, private permissioned, and private permissionless. In public permissioned blockchains, anyone can join and read but only authorized and known participants can write and commit, implying a medium level of scalability. Contrarily, public permissionless networks allows anyone to join, read, write, commit, and audit the network in anonymous identity, increasing the resiliency but decreasing the scalability lower than public permissioned case. They are generally hosted on public servers. On the other side, private permissioned blockchains restrict the possibility to join and read to only authorized participants, with the network operators who are the only one who can write, commit, and audit the information. This is considered as an extremely highly scalable structure. Lastly, private permissionless chains, that are hosted on public servers like in the previous permissionless case, expect that only authorized participants can join, read, write, commit, and audit, keeping the scalability at high levels, but lower than the private permissioned option.

In the paper of Bhushan et al. (2020) the different types of blockchain are identified in a more general and broad way, without going too much into details of each different case. Here three main types are described: public, private, and consortium. Here some concepts that in the previous article were kept apart, are mixed to give a more general description. Public blockchains, that are also called permissionless, are decentralized and open networks where each participant can freely join the network and perform actions such as writing, reading, reviewing, and auditing the chain. It is highly scalable, and everyone here collects the transaction information and create new blocks in anonymous identity incurring the risk to have contradicting blocks, decreasing the level of transparency. To avoid such issues, the consensus mechanism plays a crucial role. It is important to specify that this kind of structure present a high level of energy consumption due to the higher number of transactions and approvals, and this is a characteristic which is crucial for the purpose of this study. Moving to the second structure, the private blockchains are restricted decentralized structures where it is allowed a private share of data among a specific group of known participants. Only a restricted group of participants can perform transactions, and control the information exchanged through the chain and extra participants can only join upon invitation. For this reason, it takes a more centralized shape of blockchain, but it can still be decentralized to some extent using tools like smart contracts and some form of consensus mechanism. Here the number of transactions and the frequency of approvals is lower than the previous case, making it a low energy intensive structure. It is expected to be a highly transparent with high degree of scalability. The last structure is the consortium blockchain case, which is a combination of the two previous ones. It is a controlled network where participants are known and identified and the responsibility of consensus and block validation is assigned to a restricted group which, on the other side, can compute malicious activities in manipulating or reversing transactions, threatening the underlying nature of blockchain. Transparency in this case is high, but scalability is lower, with an even lower frequency of transactions which decreases particularly the level of energy consumption.

3.2.2 Applications

The features of the blockchain technology makes it extremely versatile and adaptable to different sectors. Indeed, there are several application fields where blockchain can play a major role in improving how things are currently done. In this section two different methods of classifying application of blockchain will be presented, where the focus of the second one is placed on the smart city perspective.

In Nofer et al. (2017) the authors provide a general explanation of blockchain including the possible real-life applications. Considering the financial background of this technology, that was firstly created for the bitcoin functioning, the differentiation is based on financial and non-financial applications. The financial applications present, first, crypto currencies that is defined as a network and medium of exchange using cryptography to secure transactions (Nofer et al., 2017). A second application is securities issuance, trading, and settlement where companies going public issue shares directly and without a bank syndicate. Private, less liquid shares can be traded in a blockchain-based secondary market. Thirdly, there is the insurance field where the whole transaction history of an insured property can be registered and tracked using blockchain. In the non-financial application, the authors identify seven more application fields. Public notary is the first one, where blockchain would substitute the central authorization. Music industry is another application field in which blockchain would facilitate the management of music rights and ownerships. In general, the decentralization feature of blockchain would allow the storing and validating of the signature and timestamp of a document, the share of these document without any third party, and the communications of widespread smart devices on the internet of things spectrum. Lastly, authenticity of products and all the market participants can be verified, including producers, merchants, and marketplaces.

A different approach is adopted in the work of Shen and Pena-Mora (2018). Here the focus is on the urban sphere and nine different sectors are taken under analysis to define application opportunities for blockchain. Indeed, the central topic is the smart city and its sustainable development that can be achieved through this innovative technology. The work starts with governance and citizen engagement. Digital governance is a new way to reduce corruption, lower administrative costs, ensure document integrity, and connect disadvantaged people like refugees and displaced people. Blockchain technology is put at the centre of four pillars namely smart city government, smart decision-making, smart administration, and smart urban collaboration in order to achieve an internal and external transformation of government organization, that can promote initiatives through a more efficient decision-making process that aligns information and institutions using Information Technologies (IT). The second sector is education, culture, science, and innovation. Regarding education, blockchain is considered a promising technology to create a continuously updated repository of the learner activities that range from academic accomplishment to external experiences like volunteering. Shifting to science and innovation, scientific researcher can solve some problems with the academic community. Blockchain would help to maintain the integrity of the research from the methodology to the intellectual property protection. The culture and entertainment industry can also benefit remarkably from blockchain especially in ensuring copyright of artists' creations who can operate more independently and transparently from third parties that sometimes retain most of the revenues. The third sector is the one related to well-being, health, and safety. Being one of the main features of blockchain, the transparency of medical data, analytical methods, reproducibility of results, and trust in medical value chain would be ensured. In this way, the costs of developing new drugs and tools would be reduced. The fourth domain is economy, which is broadly taken into consideration without addressing the cryptocurrency universe which would be a too obvious topic to analyse. Blockchain has a great potential for businesses to conduct their management in an inter-organizational way. This means that collaboration among different companies can be fostered thanks to a stronger alignment of their processes, and a more efficient share of information. E-commerce is another market that can be revolutionized by blockchain. Among many potential benefits, products and transfer of ownership can be easily tracked and recorded in a trusted and verifiable way, especially in peer-to-peer e-commerce platforms. Surely, the sharing economy is potentially the sector with the highest potential. Trust-free transaction and verified identities, without the disclosure of personal information, is what bring a potential reduction of operational costs and an increase of flexibility and scalability, being the access of more participants more facilitated. In the fifth place there is the transportation industry. Vehicle's life cycle would be improved by a better tracking of the vehicles condition data, especially in second-hand automotive markets. Transparency of data would bring major benefit to the transportation of goods as well with a digitalized exchange of shipping documentation, lading bills and compliance, all factors that account for the major costs of international trade. It is important to mention also intelligent transportation systems where traffic and mobility management requires a smooth and trusty communication of information. In this way decentralized and autonomous ecosystems can be created, including the vehicle-to-everything connection. The sixth sphere is the energy sector, which is the main inherent topic for this research. Consumers can have a clear overview of their real time consumption of energy through a more precise transfer of data from smart meters. These smart meters can send secured information and store them in the blockchain to increase the security of the grid. Another area of investigation is electric vehicles recharges. Through the solidity of the infrastructure provided by blockchain, is it possible to design systems that allow vehicles to autonomously select charging spots according to pre-defined requirements such as energy source, price, battery status, or traffic information. More information and details regarding the energy sector will be provided in section 3.2.4. The seventh domain is one of the least explored and it is the construction sector. Here trust, information sharing, and process automation play a central role in the design and construction of new buildings. In the eight place the reader can find water and waste management systems where blockchain can be put in place to reduce consumption levels. The ninth and last sphere is environment, where the main objective is to reduce and monitor carbon emission production. Air quality monitoring systems can be created to allow citizens to always be aware of the real-life air conditions. Also, it is possible to apply blockchain in tracking and auditing activities to check for the compliance production processes to carbon emission levels (Shen, & Pena-Mora, 2018).

Considering the scope of this work, the classification method that will be kept as point of reference is the second one that appears broader and as much as possible unrelated to only financial sector and cryptocurrencies. Indeed, in this work there is a first reference of blockchain enabled peer-to-peer energy trading, which is exactly the scope of this research. The scope of this research is collocated in the frame of application of blockchain for smart cities.

3.2.3 Challenges and Opportunities

Starting from the fact that the focus of the research is on blockchain application for smart city, specifically the energy sector, only the challenges of this technology in the smart city context will be considered.

The very first challenge is in the interoperability of the blockchain technology. In the frame of smart city, we can expect huge amount of online data being aggregated through different devices installed in the city. The issue here is that it is not possible to compare those new data with the already existing data (Bhushan et al., 2020). Also, being blockchain able to adopt many different forms and designs, it is a big challenge for programmers to align those different algorithms in a way that an efficient communication is established within several applications. Therefore, there is a real need for technology standards that would facilitate the interaction among the platforms (United Nations, 2020).

Another pressing issue is the storage of the data. Two potential options are possible in front of this issue. One is to follow the distributed ledger storage system which replicates the data at every node, while the second one is to use external data repository like cloud or centralized data storage. Unfortunately, each of these options carry with them additional challenges. Starting with the second one, cloud storage and centralized data repositories have a fundamental lack of reliability and security since both are subjected to risky attacks and potential loss of data. On the other side, the first issue implies problems of energy efficiency and scalability of the network. Consensus mechanisms are computationally expensive as complex computations have to be performed in order to increase the network of additional blocks (Bhushan et al., 2020). Because of this, the calculation, transmission, storage, and update of information increases the amount of energy consumed as the network increase in its size. In poor words, the more participants, the more energy consumed (United Nations, 2020). This issue has been furtherly investigated by the academic community, and in Sedlmeir (2020) the authors find out that the additional energy consumption of consensus mechanisms of an increasing blockchain network does not pose large threat to the climate, since there would be an unsignificant increase in emissions. Still, there are some blockchain architectures that are more energy intensive than others. Results tell that permissioned blockchains are the best ones to mitigate the sustainability issue (Sedlmeir, 2020).

The facts of the preceding challenge open the doors to limitations in scalability and performance. Indeed, as the network increases, the computation capabilities get weaker, increasing latency, that is the time taken to append a new block, and throughput, which refers the number of successful transactions per minute. This poses some limitation in scalability of the network and, as explained in the lines above, energy efficiency of the application (United Nations, 2020).

A lack of incentive mechanisms decreases the willingness to data verification of the network and, oppositely, punishment mechanisms should be in place to discourage malicious actions (Bhushan et al., 2020).

Finally, is the legal side and adoptability tendencies. The complexity of the interfaces makes it difficult to standardize it and, for users to learn a continuously evolving technology. This brings some scepticism of the final users to switch and perceive this as accessible and implementable technology (United Nations, 2020).

3.2.4 Use of Blockchain in energy sector

In this section a general introduction of use cases of blockchain in the energy sector will be provided, finally entering details of the peer-to-peer energy trading scenario. The spread of renewable resources of energy is nowadays the most promising solution for the decarbonization of the energy market but to make it an implemented reality some issues and challenges have to be addressed. Renewables are difficult to predict and depend on weather conditions and this poses some threats to the efficiency of electricity systems. For this reason, flexibility measures and stability of the system have to be ensured. This refers to fast-acting supply of electricity, demand response, and energy storage devices. The energy sector can achieve these characteristics thanks to an increasing amount of installed smart meters, finally entering in the digital era. A digital transformation of the sector can extract most of the benefits from the latest technologies that are available nowadays and meet the ambitious goals of emission reduction. By enhancing the communication and exchange of data among parties, it is possible to remove the centralized management of the system allowing for distributed control management techniques. The energy system currently requires three key principles such as decarbonisation, decentralisation, and digitalisation, and blockchain can potentially provide solutions for each of these three principles with an even higher penetration of IoT (Internet of Things) platforms. Decentralised energy systems can indeed be controlled efficiently through blockchain-based applications. Referring to the already cited energy trilemma, blockchain can reinforce all the three fundamental pillars namely costs reduction, trough process optimization, energy security, and promote sustainability by facilitating renewable generation and low-carbon solutions (Andoni et al., 2019). In the following lines it will be described several specific cases of application of blockchain.

The billing mechanism, through blockchain, can be automated. Indeed, the combination of smart contracts and smart billing can make the billing process of consumers and distributed generators more efficient. This would allow for micro-payments, pay-as-you-go solutions, or payment platforms for pre-paid meters (Andoni et al., 2019).

The fact that blockchain can securely and permanently capture and track data can improve the operations of sales and marketing. It would be possible to define different types of consumers based on their consumption patterns and, therefore, provide tailored value adding energy provisions (Andoni et al., 2019).

The communication of smart devices and data transmission of smart grids application is another side where blockchain can bring major benefits. Data securely transferred and standardized by the blockchain infrastructure is the main source of advantage for smart grid applications (Andoni et al., 2019).

Having in place smart contracts, the switching costs of energy suppliers can be diminished. If the mobility is enhanced and the providers' change is simplified, the competition of the energy market is expected to increase carrying a reduction of energy tariffs (Andoni et al., 2019).

Regulatory compliance and auditing processes can also be improved. Blockchain would be able to increase transparency thanks to immutable records and transparent processes (Andoni et al., 2019).

Blockchain could improve control of decentralised energy systems and microgrids thanks to automatically executed smart contracts. In this way, local energy markets can be established by localised p2p energy trading platforms that can potentially increase self-production of energy. Connected to this, identity, and security in this kind of p2p markets can be ensured and the share of resources can take place in a trusty way (Andoni et al., 2019).

The academic community explored different ways in which blockchain meets p2p energy trading. This integration is complex both on technical, programming, and implementation side and for this reason it can take several shapes and architectures, including the different p2p market types identified in the sections above.

In Hua et al. (2020) the authors propose a blockchain based peer-to-peer trading framework integrating energy and carbon markets. Here a framework including carbon allowance trading is developed to address three main knowledge gaps. First, the carbon emissions derived from generation for self-consumption, consumption from self-generation, and generation or consumption only for energy exchange of individual prosumers cannot be tracked with the existing systems proposed by the academic community. The second gap relates to the pricing schemes that are not always completely prosumer centric. Third, the design of current energy or carbon market is not efficient considering that the purchase of carbon allowance is part of energy costs, implying therefore the need for an integration of the two markets. The proposed framework addressed these three gaps respectively by including a carbon emission tracing approach that targets individual prosumers' behaviour and designing a smart contract-based trading platform that exchange carbon allowance and energy at both prosumer and microgrid level. The result obtained is a better energy balance and carbon saving performance. Still, this framework presents limitations and leaves space for further research about the prosumption patterns of individual prosumers. Indeed, it's not completely clear how the price elasticity would determine different behaviours in respect to generation and consumption but also bidding and selling prices.

In Esmat et al. (2021) the authors developed a decentralized trading platform to address several challenges that are classified in market design and practical challenges. The market design indeed must satisfy some predefined metrics such as social welfare and total cost, prevent market manipulations, ensure privacy among participants, and keep transaction costs low. On the practical and technical side, data storage and security are a pressing issue and a trusted and secured system for transactions has to be in place. In the perspective of these technical issues blockchain constitutes an excellent tool to overcome these challenges. The authors developed a blockchain-based platform capable of addressing these issues composed by a market layer and a blockchain layer. The first one makes sure that a decentralized short-term parallel market is established to achieve near-optimum social welfare solutions, while the second one ensures data security and privacy, fast settlements, and low transaction costs. Like in the previous study, the application of blockchain opens the door for important contribution of the study to the academic existing knowledge. The decentralized short-term pool-structured p2p market is aimed to maximize the social welfare of all prosumers while enabling the trading without inter-temporal dependencies. Moreover, the optimal solution is achieved by putting in place a novel decentralized clearing mechanism that, through a reasonable number of iterations, manages to decrease the margins of error while respecting the information privacy of the prosumers. The last contribution resides in the fact that for verifying the performance of the decentralized clearing method, network real-world data have been used. The limitations presented are, again, related to the behaviour of the prosumers. Uncertainties about prosumers' commitment should be taken into considerations considering deviations from the bids and differences in objectives of the participants.

3.3 Prosumer behaviour

The previous section has provided an investigation of how blockchain can be combined with p2p energy trading systems on a technical point of view. When researchers' focus is centred on the technical design of blockchain based p2p energy trading, the participants' behaviour aspect is left apart, and it constitutes the main source of limitation of their study. Well designed technical solutions embracing blockchain technology leave space for uncertainties regarding the participants in the network. How participants behave and change their trading actions is of critical relevance when analysing this kind of trading and assess its real potential value. Indeed, in the review article of Thukral (2021) blockchain application in p2p electricity trading is explained going through the different schemas it can takes and current already existing projects. Among the barriers of the penetration of this technology in the energy sector, social challenges are pointed. They represent the willingness of prosumers and consumers to participate in the blockchain enabled network. The focus here is on the fact that blockchain is a new and yet not mature technology and building confidence among stakeholders in adopting this new technology is a vital requirement for p2p energy trading to become a spread reality. Also, p2p energy trading is a type of market that could potentially bring benefit to a community of participants, or, in any case, a network of prosumers and individualistic behaviours can undermine this source of collective value that would constitute the main engine of the energy sector transformation. Indeed, like in any other form of sharing economy, it is fundamental that participants are willing to share their assets with others otherwise the value of the system is lost. This section proposes some research about how prosumers behave in p2p energy trading systems. Specifically, both the technology perception and the trading behaviour will be taken under investigation.

3.3.1 Prosumer triggers

Prosumers have specific reasons why they want to join an energy community. From a social point of view, the fact that individuals have to undertake conditions set by major providers creates a need of independency from them. In Ecker et al. (2017) the authors investigated which are the factors that influence the decisions to adopt and enter an innovative energy system. In specific, autarky aspiration, defined as independence of supply, is taken under investigation to assess its influence in different supply scenarios namely household, neighbourhood, and small town. Questions about prosumers' perception regarding the self-supply of electricity and energy were asked. The results provide empirical evidence that the autarky factor has a strong influence on the acceptance of decentralized energy systems. Moreover, the study demonstrated that individuals are willing to pay more for the realization of a supply scenario that guarantees them a higher independence, autonomy, self-sufficiency, supply security, and control. These results are reinforced by the study performed Ecker et al. (2018) where, additionally, the specific factor of autonomy is taken under examination. Results illustrates that the degree of autonomy does not considerably influence homeowners' adoption decisions, while autarky is confirmed to be the main crucial driver in this kind of decision making.

3.3.2 Trading decision and technology perception

Looking now at precise trading decisions, an investigation of how the prosumers act in a hypothetical p2p electricity trading scenario is proposed by Hahnel et al. (2020). Here the trading preferences and decision-making strategies are investigated in a surplus condition, meaning that the self-production of energy is higher than the consumption and is therefore analysed how prosumers would act in this situation. The objective of the paper is to clarify the general preferences of users towards p2p energy trading and their applied trading strategy, how trading decisions are affected by community price variations and individual autarky desires and identify different trading decisions groups. Findings suggest that most of the participants are willing to take part to p2p energy trading, and trading decisions are strongly affected by the energy storage state of charge and changes in community price (for all the three distinct groups of participants). As the level of the energy stored decreases, the willingness to sell decreases as well, incurring in periods of low clean energy, and decreasing the benefits for the community. This finding corroborates the results of Ecker et al. (2018) by confirming that autarky aspiration is the main driver in trading decision, which ultimately brings to a lower willing to share energy with the community. Indeed, as the state of charge of the battery decreases, it increases the risk to be obliged to buy electricity at a high market price, reducing the sense of autarky of the individuals. Limitations in this study are constituted by the fact that only surplus conditions are considered, and the buyer perspective is not analysed in those scenarios. Also, only not real time transactions are conducted, making the participants subjected to time preferences.

In Fell et al. (2019) an online survey experiment is conducted to assess how people perceive blockchain enabled p2p electricity trading. The research here explores the tendency to participate considering the controlling authority, the geographical location of energy production, the terms used to refer to blockchain technology, and the underlying characteristics of blockchain technology itself. The outcome of the study revealed that among the four main identified features of immutability, anonymity, transparency, and decentralisation, only anonymity turned out to make p2p trading more attractive, while the others had the opposite effect. This research is limited to willingness to join only, and it doesn't analyse trading decisions under different scenarios, like in the previous study.

Now that a clear picture of the already existing works in the academic community is provided, it is possible to identify knowledge gaps that are intended to be covered with this research. First, it is clear that in analysing p2p energy trading the behavioural aspect of the participants is poorly investigated, being the technical side more studied. In the frame of participants' behaviour, there is scarce evidence on how the presence of blockchain would affect the willingness to join and trading decisions in an integrated way. Indeed, in the existing studies blockchain perception in p2p energy trading is being investigated independently from the trading decisions under different price situations, where it has been demonstrated that autarky decisions and willingness to follow individual rather than community cover an important role. Following the research path and approach adopted in the studies presented, this paper is intended to fill the knowledge gaps by investigating how prosumers change their trading decisions, assuming the underlying characteristics of blockchain are in place. Precisely, the four characteristics identified in the study of Fell et al. (2019) namely immutability, anonymity, transparency, and decentralisation will be taken into consideration. One more additional feature of real time transactions, suggested by Hahnel et al. (2020), will also be included. This will be studied under different price and battery charge scenarios, following the framework of Hahnel et al. (2020), considering their willingness to participate and join the network in blockchain based p2p energy trading.

4 STUDY

4.1 Overview

The study aims to investigate the trading preferences and decision making in p2p energy trading under the conditions set by blockchain technology. For this reason, it consists of a scenario-based survey constructed following the structure proposed by Hahnel et al. (2020) combined with the approach adopted by Fell et al. (2019). Once a solid base of responses is obtained, the results will be observed and discussed in comparison with the findings of the cited studies to see what the influence of the technology is.

The survey scenario is set up as follows. The participants are explained that they are part of an online p2p electricity community where each of them can either sell their self-produced electricity to the community or to store it in their private energy storage system, considering they find themselves in a surplus condition, meaning their production of energy is higher than their consumption. The only additional party considered is an external energy provider who functions as insurance provision in case there is no energy supply from inside the community. The trading operation is run under the following blockchain characteristics:

- Immutability: the record of the transactions cannot be modified or deleted afterwards
- Anonymity: the identity of the participants is anonymous
- Transparency: the record of transactions is visible to all the members of the community
- Decentralisation: no central authority is in place.
- Real time transactions: the trading process can be performed in real time

Different scenarios are proposed to the participants where there are variations in both the state of charge of the energy storage system and the market price for self-produced energy. These two variables are expected to reveal respectively the autarky and financial aspirations. According to differences in sensitivity of these two groups, it will be possible to do differentiate different prosumers type among the sample of respondents.

4.2 Survey Design

The structure of the survey is expected to follow the one provided in Hahnel et al. (2020). This decision was made in order to follow the same research direction of the mentioned study and give academic relevance to this work by moving one additional step towards the topic of blockchain. Indeed, the perception of this technology and its influence will be investigated in the same fashion of Fell et al. (2019). The core value of the survey of this work resides in the combination of these two research.

The survey is composed by three main sections.

1. In the first one some demographics questions are asked to the participants regarding sex, age, civil status, employment status, highest achieved educational level. These are key information useful for achieving a sufficiently randomized sample of respondents.
2. In the second section, the p2p trading scenario is explained into details. Respondents are asked to imagine they have a solar panel installed on the roof to generate electricity as well as an energy storage unit in the basement to store the generated electricity. The electricity generated can be either be sold to the community or stored in the private battery, assuming an energy surplus condition meaning the energy produced is higher than the private consumption. The trading activity is conducted through a blockchain enabled platform where the four characteristics listed in the previous section are explained. After this first general explanation, participants are asked if they would be willing to participate in this kind of energy community. If yes, the survey is expected to continue, if not the survey will be skipped until the end. In this section, participants will come to know additional details regarding the trading scenario. Specifically, production capacity of the solar panel, storage capacity of the battery, external vendor price of electricity, and community price of electricity. The solar panel production capacity, the storage capacity of the battery, and external vendor price are expected to stay fixed through all the scenarios. What is going to change is the state of charge of the battery, and community price of electricity which varies according to the demand.
3. The third phase is the one in which different scenarios will be proposed, and data regarding the store and sell decision are collected.

The following assumptions are taken into consideration:

- transactions are blockchain enabled meaning that:
    - the record of transactions cannot be modified or deleted
    - you are completely anonymous
    - the record of transactions is visible to any member of the community
    - there is no centralized authority in place
    - only real time transactions are performed
- Storage unit (battery): fixed capacity of 10 kWh; charge status 25%, 50%, 75%
- Solar panel (PV): fixed production capacity 10 kWh; production cost 10 c€/kWh
- External vendor: energy price 30 c€/kWh
- Community: independent variable; energy prices 7 c€/kWh, 18 c€/kWh, 30 c€/kWh
- Participants: decisions sell 1 kWh, store 1 kWh

- Rule 1: in case participants' battery state of charge runs to zero, they would have to buy the energy from external provider. Oppositely, in case it is fully charge, they have to sell the energy at any price at the community.
- Rule 2: in case participants decide to store energy, the members of the community will have to buy energy from the external vendor.

The values have been simplified but are similar to the ones used in the study of Hahnel et al. (2020) to ensure the same logic behind is applied. This is decided in order to make the survey more intuitive for a broader range of respondents. The following table shows the construction of the survey with the respective range of possible responses.

Table 2 – Survey structure

Section	**Questions**	**Response**
Demographic Information	**1st section**	
	Sex	- Male - Female - Other
	Age	- <18 - 18 - 24 - 25 - 35 - +36
	Civil Status	- Single - In relationship - Married - Divorced - Widowed
	Employment status	- Student - Unemployed - Full-time - Part-time - Retired
	Education	- High school - Bachelor - Master - Phd
P2P energy trading scenario: explanatory	**2nd section**	
	Figure 1	
	Figure 2	
	Assumptions	(details are explained in the above section)

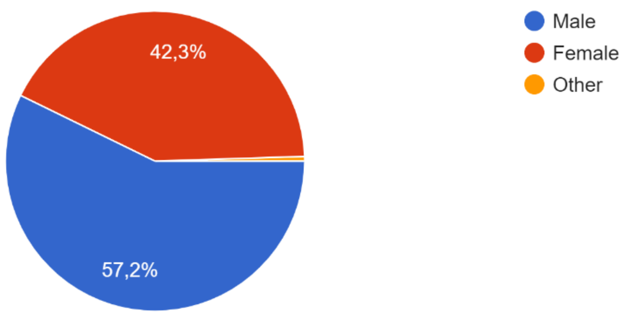
	Given these assumptions, are you generally willing to take part to this p2p energy trading ? If no, you can skip the following questions until the end of the survey.	- Yes - No
P2P energy trading scenario 1	**3rd section**	
	Selling price : 7c€/kWh Charge status: 25%	- Store energy - Sell energy
	Selling price : 7c€/kWh Charge status: 50%	- Store energy - Sell energy
	Selling price : 7c€/kWh Charge status: 75%	- Store energy - Sell energy
P2P energy trading scenario 2	Selling price : 18c€/kWh Charge status: 25%	- Store energy - Sell energy
	Selling price : 18c€/kWh Charge status: 50%	- Store energy - Sell energy
	Selling price : 18c€/kWh Charge status: 75%	- Store energy - Sell energy
P2P energy trading scenario 3	Selling price : 30c€/kWh Charge status: 25%	- Store energy - Sell energy
	Selling price : 30c€/kWh Charge status: 50%	- Store energy - Sell energy
	Selling price : 30c€/kWh Charge status: 75%	- Store energy - Sell energy

4.3 Data Collection and Analysis

The survey has been sent for a period of two months between the 15th of April 2022 until the 15th of June 2022, and a total of 203 responses are gathered through Google Forms tool. Data have been extracted and converted in Excel format, and this section will provide an overview of the database. A first subsection 4.3.1 will cover the demographic information in section 1 of the survey, the second subsection 4.3.2 will focus on the second section of the survey, and the data regarding the third and last section will be shown in subsection 4.3.3.

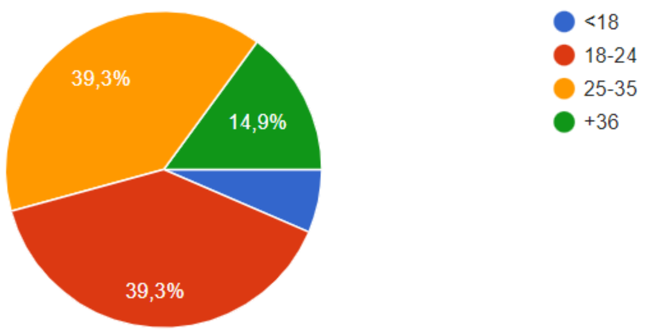
4.3.1 Demographic data – 1st Section

Chart 1- Sex



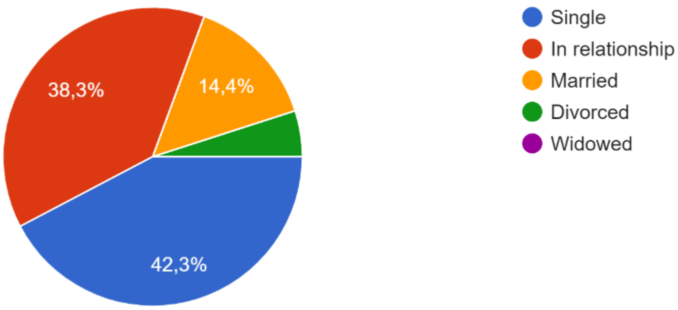
The base of respondents is slightly unbalanced, having 57.2% males and 42.3% females. A very tiny percentage of 0.5% of respondents preferred to not classify themselves as either male and female.

Chart 2 - Age



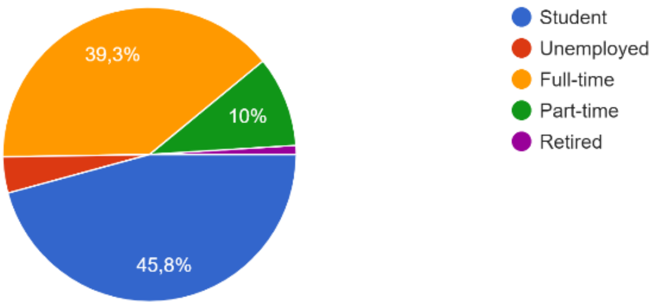
Regarding the age, the chart displays that 39.9% of respondents are between 25-35 years old, and the same percentage is for the range between 18-24 years old. The lowest percentages are the ones of the categories of +36 years old, 14.9%, and <18 years old with 6.5%. This result was to some extent expected considering the survey was distributed mainly through university channels and word-of-mouth mechanism.

Chart 3 - Civil status



Regarding the civil status, 42.3% of respondents declared to be single, followed by 38.3% of respondents currently in a relationship, and 14.4% are married. No responses were gathered regarding the widowed category.

Chart 4 - Employment status

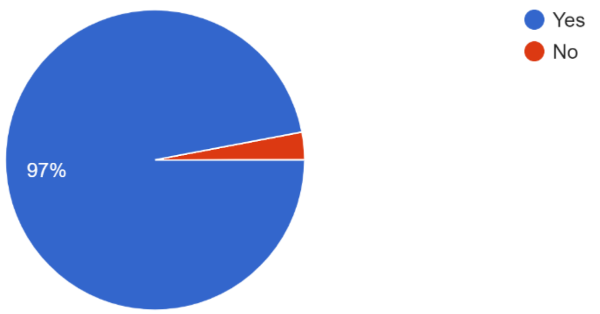


From the above chart it is possible to observe that the big majority of respondents are either working or studying. Indeed 39.3% are full time workers, 10% are part-time, and 45.8% are students. The lowest percentages are the ones of unemployed people, 4%, and retired, 1% of respondents. Again, this result was also expected to some extent considering the channel of distribution of the survey.

4.3.2 P2P energy trading scenario (explanatory) – 2nd Section

In this section of the survey, only one question was asked after the explanation of the assumptions. Below are reported the results.

Chart 5 - Willing to participate

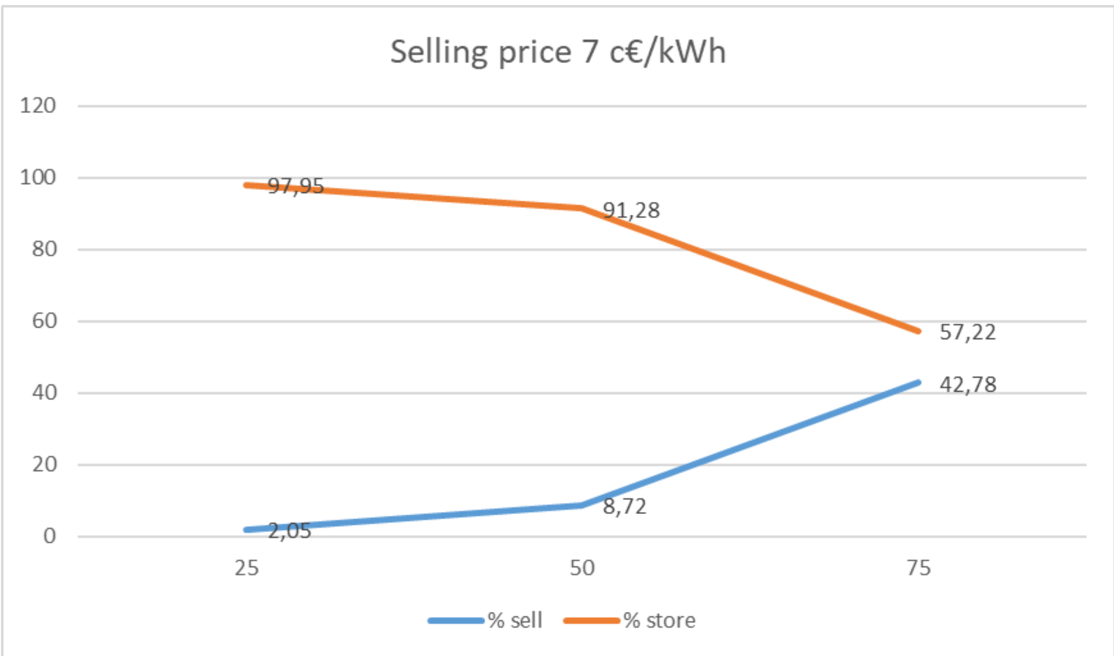


The chart clearly shows that the big majority of respondents are willing to participate in the survey. Indeed 97% of respondents declared to be willing to participate in the energy community presented in the assumptions, and only 3% decided to not participate.

4.3.3 P2P energy trading scenarios – 3rd Section

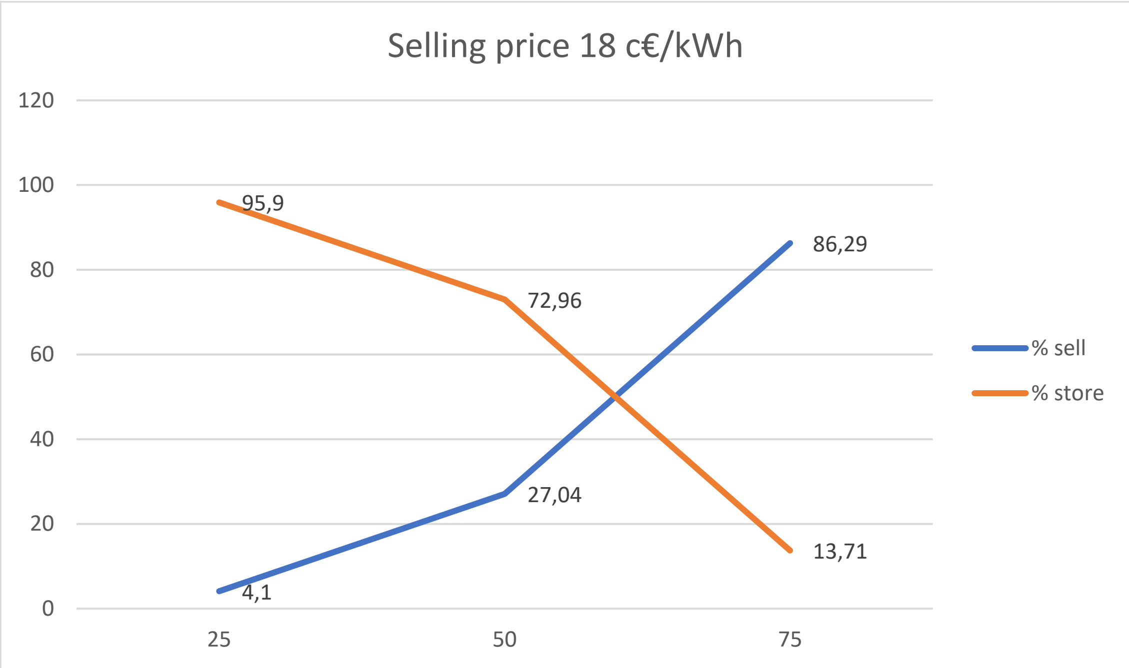
In this section the data regarding the trading decisions based on different scenarios are presented. The following graphs are reflecting the percentage of participants who, for a given state of charge and energy selling price, are choosing to either sell or store the self-produced energy. Indeed, on the horizontal axis there are the three defined values of state of charge, and the vertical axis reflects the percentage.

Chart 6 - Electricity price 7 c€/kWh and charge status 25%, 50%, 75%



In the above graph it is shown the scenario in which the selling price is set at 7 c€/kWh. At a state of charge of 25%, 97.95% of participants decided to store energy and 2.05% of them chose to sell. At 50% state of charge, 91.28% of participants decided to go for storing energy while the remaining 8.72% decided to sell. Lastly, when the state of charge is set at 75%, 57.22% decided to store energy while 42.78% chose to sell.

Chart 7 - Electricity price 18 c€/kWh and charge status 25%, 50%, 75%



The graph displayed above is now showing the scenario in which the energy price is set at a level of 18 c€/kWh. Assuming the state of charge is at 25%, 95.9% of participants decided to store the energy while 4.1% to sell it. When the state of charge is at 50%, 72.96% of the times respondents chose to store energy while the remaining 27.04% went for the sell option. At the end, when the state of charge is at 75%, the respondents chose to sell energy 86.29% of the times, while 13.71% of the times they decided to store energy.

Chart 8 - Electricity price 30 c€/kWh and charge status 25%, 50%, 75%

The last scenario is the one in which the selling price is 30 c€/kWh. With the battery 25% charged, 89.34% of the participants decided to store the energy, while 10.66% decided to sell it at the market price. When the battery is half charged, 60.41% of the responses are for the sell option and 39.59% are on the store decision. Lastly, at 75% state of charge, 97.46% of respondents decided to sell the energy while only 2.54% chose to store it.

5 DISCUSSION

In this section it is conducted the discussion and observation of the data gathered. The findings are going to be compared with what has been found out by the two articles taken into consideration so that meaningful value can be created in this study.

Starting with the demographic data presented in section 4.3.1, it is possible to observe that the genre of the participants to the survey is almost equally spread among males and females, while "others" is the lowest percentage, which allows for an almost perfect randomization of the pool of respondents. Regarding the age, the data do not present meaningful unbalances considering the channel of distribution, covering most of the participants in the range between 18 and 35 years old. Taking a closer look to chart 3, it is possible to see that the spread of the civil status of the respondents does not present any unbalances that can directly affect the result of the study. Lastly, the employment status is in line with the age range aforementioned. There is an almost equal spread between students and workers, combining part time and full time employed, which is in line with the age range of the pool of respondents. It is possible to conclude that the demographic data gathered do not harm the reliability of the study conducted since there is no reason to think they bring any bias in the set of trading decisions collected.

The second section of the survey is aimed to detect whether the assumptions explained discourage participants to start the survey and take part to the energy community presented. The result shows that 97% of the participants decided to join the energy community even if the conditions set by the presence of blockchain technology were in place. In the article of Hahnel et al. (2020) the rate of participation was even lower at a level of 77.4%, while in the study of Fell et al. (2019) it was found that the presence of blockchain technology had no relevant impact on the behaviour of respondents. In this current study the conditions set by this technology seem to not have lowered the willingness of respondents to join the energy community presented. This result can be explained by the fact that the biggest share of respondents finds themselves in a relatively young age range, which can justify the lack of hesitation in front of a new technology implemented. Still, there is no clear evidence that the higher percentage of participation than the one registered in Hahnel et al. (2020) is directly caused by the presence of blockchain. Indeed, there are many reasons that can explain this increase in participation rate. The age difference between the two studies can have an effect on the rate of participation, where in Hahnel et al. (2020) the mean age was 51. Another one can be the higher awareness towards environmental causes, which would increase the number of people willing to join sustainable projects.

In the third section of the survey the trading behaviour are recorded. The objective here is to see whether, with the presence of blockchain technology, the decisions of the participants would change. For this, a closer look to the below charts should be taken.

Chart 9 – Tendency to sell at charge status 25%, 50%, 75%

Chart 10 – Tendency to store at charge status 25%, 50%, 75%

The chart attached above shows how the tendency to sell and store, measured as percentage of participant, changes based on variations of state of charge, in all the three cases where the electricity can be sold at 7 c€/kWh, 18 c€/kWh, and 30 c€/kWh. In other words, for example, the first point of data in chart 10 on the blue line tells us that 89.34% of participants decided to store energy when the electricity price is 30 c€/kWh and the state of charge is 25%. In Hahnel et al. (2020), two hypothesis were formulated, and turned out to be confirmed, finding that the trading decisions are affected by both the state of charge of the battery and electricity price variations. This is because participants have autarky aspirations that influence their decision in trading energy, bringing them to first ensure their independency from external providers and afterwards, only when this condition is secured, start their trading activity. These results are confirmed by the current study by taking a closer look to chart 9 and 10, which present opposite trends. Specifically, in chart 9 it is possible to observe that the trend of all the three lines is upward going, saying that participants are more willing to sell their energy to the community only as the state of charge of their battery increases, which reduces the risk for them to buy energy from external provider. Also, the willingness to sell energy is higher in any case when the electricity price is higher. When prosumers decide to sell instead of store energy, they give up on their autarky condition, and this benefit given up is compensated by the price at which the energy is sold. Therefore, it is no surprise that, as the price increases, prosumers perceive the real value of their autarky is compensated and the probability that energy is being sold is also higher. This finding is of key value for policy makers and institutions who want to implement such kind of energy communities where, only when the price is set a specific price, the number of transactions will increase.

On the side of the technology implemented, data reveal that there is no real impact on the trading preferences of prosumers when blockchain technology is in place. Indeed, the findings are in line and confirms the outcome of Hahnel et al. (2020) even if the participants are aware of the conditions set by the blockchain technology. It is possible to conclude that prosumers will not change their behaviour even when transactions cannot be deleted or modified, anonymous identity is ensured, data are visible to every member of the community, no centralized authority is in place, and real time transaction only are performed.

It is important to point out an observation. The objective of the research is to analyse the prosumers' behaviour and the effect of their autarky aspirations considering the implementation of blockchain technology, changes on electricity prices, and state of charge of the battery. Indeed, the research is not intended to focus on the specific prices, but how a hypothetical change of price would impact the behaviour. For this reason, the prices chosen for this study were set as reference value considering the ones adopted in Hahnel et al. (2020), and the focus here is on how prosumers behave in front of changes in prices, regardless of the specific level of those prices. In this way, the outcomes of the study gain more value and become applicable to many different periods of time where inflation on electricity prices is changing. This study was conducted between October 2021 and June 2022 but, regardless the inflation rate in the present, we now have more clarity on how prosumers would behave in front of price changes in general, and this is where the value of the study resides.

6 LIMITATIONS

This study is built upon two research extensively mentioned in this paper, where the academic value is in the investigation of prosumers' behaviour with the implementation of blockchain technology. Specifically, the objective of the paper is to analyse the willingness to join p2p energy trading community and the trading decisions of participants. The results show clearly that prosumers have autarky aspirations that affect their trading decisions, which are influenced by the level of charge of the battery as well as the electricity price at which they can trade energy. This confirms the findings of Hahnel et al. (2020) and no influence on the trading decisions is detected due to the presence of blockchain. The willingness to join the energy community also seems to not be affected by the presence of blockchain technology, and this consolidate the results of Fell et al. (2019). These findings have real practical value for policy makers and institutions who want to set up a p2p energy trading community. Indeed, it is crucial to take into account the monetary value of autarky perceived by prosumers in order to set up balancing mechanisms to ensure the level of transactions in such markets is always kept at a sufficient level. When the electricity price is not high enough, there is not enough benefit for prosumer to give up on their autarky desire fulfilment, and most of the participants will choose to store benefit for their own household. In this case the market would not have enough supply of internal energy and no value would be created for the p2p energy community. On the other side, this research reveals that having blockchain in place would not impact the willingness to join the community of the participants and their trading behaviour. This is also a valuable contribution since the benefit of this technology would be achieved without taking the risk of having a low participation rate.

The present study still presents a set of limitations that open the doors for future work to move step forward on this research path. The very first limitation is that the assumptions assume that the trading activity is conducted in energy surplus condition only, meaning that the among of energy produced is higher than the energy consumed. This would imply that the energy traded would be "excessive" in some way and therefore not directly useful for the prosumers. Future research should investigate energy non-surplus conditions to have a better understanding of trading decisions. Also, in this paper only the supplier perspective is taken into account. In order to have a full picture of p2p energy trading communities it is important to also understand the buyer perspectives of the trading activity as well as the technology implemented. Future research should take into account also different production capacity periods. In this study it was assumed that prosumers are producing a fixed amount of energy, while it would be insightful to also take into account scenarios in which the energy production is either higher and lower, embracing, for example, situations in which different solar panel have different capacity, or different periods of the year present different sun light intensity.

7 CONCLUSIONS

The environmental crisis that is affecting nowadays is a crucially important issue that governments and policy makers need to address with practical sustainable solutions. It is clear that the systems of energy provisions are not sustainable, and they need to be redesigned to protect the environment and the people. Renewable energies are one of the most promising resources to keep carbon emissions low. The combination of new technologies with sustainable ways to distribute energy produced through renewable mechanism represents the most appealing solution to solve this critical problem. This research investigates peer to peer energy trading mechanism to exchange electricity among private households through implementation of blockchain technology. Specifically, the focus is on the trading decisions of the participants and the willingness to join such markets, having in place the underlying conditions set by blockchain technology. Indeed, for the successful implementation of sharing mechanisms it is extremely important to assess the behaviour of the participants, and which actions are needed to stimulate those.

P2p energy trading communities have a great potential for providing energy in a clean and decentralized way, disrupting the monopoly set by big energy providers. Also, thanks to the newest technologies such kind of communities can be set up in an efficient and secure way. Still, the potential benefit of these markets is as high as the additional research needed to implement them efficiently in a nearly perfect way, where suppliers, buyers, and especially the environment are all benefitting at the same extent.

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