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Consortium Blockchain-based Peer-to-Peer Matched Energy Auction Framework

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A Thesis presented for the degree of
Doctor of Philosophy

Department of Engineering
Durham University
United Kingdom
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Dedicated to

My Family and Friends

Consortium Blockchain-based Peer-to-Peer Matched Energy Auction Framework

Diana Olivia Martinez-Trejo

Abstract

Integrating distributed energy resources into smart grids has created opportunities for small energy producers. While big suppliers dominate the energy market, all energy consumers and producers, known as prosumers, should have the same opportunity to trade with each other. Using local energy will encourage local communities to join forces and invest in their clean energy, putting them at the centre of key decisions within their community. With this in mind, the model proposed in this thesis aims to enable prosumers to trade energy within their local area based on a double auction mechanism that matches buyers and sellers using some indication of their electrical proximity. The peer-to-peer energy trading mechanism presented here considers the distance on the distribution network as an extra charge for the use of premises.

The primary motivation of the presented research work is to enable prosumers to be part of a local energy market and encourage large-scale updates instead of relying on central producers to provide the energy they need. The first contribution of this research is the development of a Demand-Prioritized Double Auction Mechanism. This mechanism ensures that all buyers participating in the trade will receive the requested energy. Additionally, prosumers are incentivised to cooperate while defining their reserved price and distance preference. Finally, the second contribution is the Consortium Blockchain Network. This network allows DSOs to access specific transaction data while prosumers have a second channel to submit their bids/offers. Combining these two proposed initiatives will enable prosumers to be part of a local market where the energy they trade is locally produced and consumed. Moreover, the DSOs will benefit from each trade without imposing the same tariff for every trade but based on the use of the distribution network when the trade is completed.

The research has been tested on a radial low-voltage distribution network under a decentralised scheme in smart grids. Results demonstrate that it is possible to promote local consumption and production while considering the costs produced by energy distribution. Losses to prosumers were minimised, and the scalable capacity of the Consortium Blockchain Network was displayed. Future research needs to focus on an alternative method to match the traders so that the system is entirely decentralised. Also, the security implications of the Consortium Blockchain Network need to be considered.

Supervisors: Dr Sun Hongjian and Dr Gagangeet Singh Aujla

Declaration

The work in this thesis is based on research carried out at the Department of Engineering, University of Durham, England. No part of this thesis has been submitted elsewhere for any other degree or qualification, and it is the sole work of the author unless referenced to the contrary in the text.

Some of the work presented in this thesis has been published in journals and conference proceedings - the relevant publications are listed below.

Publications

Diana Martinez-Trejo, "*Blockchain based Peer-to-Peer Energy Trading*", 2020 IEEE PES Transactive Energy Systems Conference (TESC). doi: 10.1109/TESC50295.2020.9656943

Diana Martinez-Trejo, Huw Thomas, Hongjian Sun, "*Peer-to-Peer Energy Trading Mechanism based on Welfare and Physical Distance Charges*", 2022 IEEE PES Transactive Energy Systems Conference (TESC). doi: 10.1109/TESC53336.2022.9917258

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Although the authorship of this thesis may suggest that it was a solo effort, it was, in fact, a collaborative endeavour that would not have been possible without the help, support, and patience of many people in all aspects of my life. While my memory is fallible, I have tried to acknowledge as many contributors as possible.

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Thirdly, I am deeply grateful to all my friends and adopted families who have been a source of encouragement and support throughout my journey. I want to thank Lourdes, Mike Watts, Liz, and Jonathan Brown, who have been like family to me. I am also particularly thankful to Ariam and Maura, who have been there for me through all the ups and downs. Daphne has been the most supportive and understanding person, and Karen's words of solace and support have been invaluable. Special thanks to Brian Pavlakovic who gave support while working on this thesis. I thank Bryony for always lending me an ear and a shoulder to lean on. Terri Edwards' guidance and advice have made this thesis readable, and I am grateful to all the Mexicans I have met with whom I have shared so many memories.

Finally, I would like to acknowledge the efforts of the prior researchers whose work laid the foundations for my own.

"*The Earth speaks to all of us, and if we listen, we can understand.*" Uncle Pomme, 'Castle In The Sky' (1986).

Contents

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Nomenclature

List of symbols and abbreviations.

B

BFS	Breadth-first search.

C

CA	Certificate Authority.

D

$DERs$	Distributed Energy Resources.
DLT	Distributed Ledger Technology.
DSO	Distribution System Operator.
DPDA	Demand-Prioritised Double Auction Mechanism.

E

$EMSs$	Energy Management Systems.
EVs	Electric Vehicles.

F

FCA	Financial Conduct Authority.

G

GUI	Graphic Interface User.

I

ICT	Information and Communications Technology.
IEDs	Intelligent Electronic Devices.
IEEE	Institute of Electrical and Electronics Engineers.
IIoT	Indutrial Internet of Things.
IoT	Internet of Things.
ISO	Independent System Operator.

L

LV	low-voltage (distribution network).

M

M2M	Machine-to-Machine.
MSP	Membership Services Provider.

N

NIST	National Institute of Standards and Technology.

O

OTC	Over-The-Counter.

P

P2P	Peer-to-Peer.

P2P	Peer-to-peer.
PBFT	Practical Byzantine Fault Tolerance.
PMUs	Phasor Measurement Units.
PoA	Proof of Authority.
PoET	Proof of Elapsed Time.
PoS	Proof of Stake.
PoW	Proof of Work.
PVs	From photovoltaic, mostly use as reference to solar panels.

S

SBFT	Simplified Byzantine Fault Tolerance.
SCADA	Supervisory Control And Data Acquisition.

V

VPP	Virtual Power Plant.

W

WAMS	Wide Area Management System.

List of Algorithms

Chapter 1

Introduction

Integrating Distributed Energy Resources (DERs), such as small and medium, into the primary grid has changed the role of consumers to prosumers, who can now generate and consume energy. This change has led to a new challenge for researchers' need for Peer-to-Peer (P2P) energy trading to manage these rapid changes in the existing Energy Management Systems (EMSs) [2–6].

The rise of smart grids has increased interest in blockchain technology as a possible solution for P2P energy trading. Blockchain technology was first introduced in 2008 to serve as a public transaction ledger for the cryptocurrency bitcoin [7]. The objective was to create a P2P currency by removing the need for a trusted third party.

Energy Management Systems must maintain an energy balance by purchasing supply to cover residual demand at retail prices and selling surplus to the wholesale market at wholesale prices [4]. However, communication between the Market and Distribution Management System needs improvement. Researchers suggest that using Blockchain in the Energy Management System would help take control of energy trading transactions between prosumers, reducing the computational burden involved in communication and decision making [8, 9].

In the Energy Management System, a general P2P scheme is a method by which households, not businesses, interact directly. This scheme differs from centralised direct load control structures, where some entities may have control of some appliances. The proposed P2P energy trading auction framework considers a smart grid system for P2P energy trading in a radial low-voltage (LV) distribution network under a decentralised scheme consisting of nodes and a set of distribution lines connecting these nodes. The information flows between peers in a decentralised manner, which means that every peer can interact with others through financial flows using an online platform with a Graphic Interface User (GUI) on a Raspberry.

Researchers are working on using blockchain technology to build a platform for P2P energy trading, with some projects even making it possible within the same building [10–17]. However, it is still an ongoing endeavour. This research proposes a blockchain architecture to enable prosumers to match their electrical energy offers in a way that uses their electrical proximity. In addition, this proposed framework creates a structure for a free trading market to optimise welfare (profit) instead of any fixed feed-in tariffs.

The interaction channels (e.g. Blockchain and GUI) are separate from the physical network. Users can sell and buy energy to/from their neighbours or the grid. This research considers this a realistic assumption since pilot projects are based on this concept, and it does not interfere with existing corporate arrangements. Each transaction is recorded on the Blockchain, and final charges are based on the actual consumption/injection of the energy for each prosumer; this information is obtained by the smart meter on the GUI.

1.1 Current Challenges on P2P Energy Trading

The development of smart grids is a significant step towards enhancing the electrical grid infrastructure by incorporating a vast number of sensors, information, communication technology, and acting electronic devices [18, 19]. The Smart Grids consist of super grids that connect various energy systems and offer potential solutions for long-term storage challenges. On the other hand, microgrids are considered a suitable option for integrating decentralized energy resources, which provide advantages such as reliability and cost-efficiency. However, implementing control and business processes in microgrids poses several challenges that need to be thoroughly researched and addressed [20].

For P2P Energy Trading, the availability of grid information is crucial. The system requires intelligent sensors to gather data, which is then relayed to control centres for effective decision-making. Moreover, communication is essential to translate data into an accessible format, enabling the development of predictive algorithms that manage grid elements more efficiently through analysis. Smart technology helps manage a bidirectional energy grid where energy flows from and into the centre or from one part of the periphery to another without touching the central generating facility.

The security of Smart Grids is essential to ensure the reliable and secure delivery of information in real-time without infringing on customers' privacy [21]. The security measures must ensure privacy, message integrity, message authentication, and non-repudiation. Blockchain technology can be used to share certain information throughout the network, as it provides a P2P distributed ledger forged by consensus. Blockchain technology tracks various assets, physical or digital, such as vehicles, diamonds, patient records, or insurance records, by grouping transactions into blocks. The system of smart contracts agreed upon by members governs the business rules governing transactions.

Blockchain technology syncs up with a consensus mechanism, which ensures that peers agree on a specific state of the system as the true state. This mechanism improves transaction processing speed, transparency, and accountability across the network [22]. Blockchain technology creates distributed consensus between mutually distrustful parties, creating a single instantaneous source of truth, even though all the messages discussed to do the consensus mechanism go through a central hub. For additional confidentiality, members can join one or more channels that allow data isolation, and authenticated peers share a channel-specific ledger in that channel [23–

26]. Blockchain technology is prevalent in different applications, from the finance sector with cryptocurrencies to the medical industry with patient data records [8, 9, 23–26].

Recent research on the usage of blockchain within the smart grids [8, 9] has shed light on some interesting differences between Mixed and Public types of blockchain. One critical insight is that any network participant can access data. Another significant discovery is the potential for cryptocurrencies to facilitate secure transactions between peers through smart wallets. However, the most significant finding is the continued prevalence of Proof of Work as a consensus algorithm despite its high energy consumption. These findings further support the idea of using blockchain as a platform for P2P Energy Trading, though more investigation is necessary to determine its practicality at the distribution level.

1.2 Research Motivations and Objectives

The challenges mentioned earlier have led to the following motivations for this thesis:

- Energy costs can significantly affect society. In developed economies, the cost of energy affects the operating costs of other industries, impacting their competitiveness. High energy costs also affect people's quality of life by increasing the cost of goods and services, reducing disposable income, and making it difficult to meet their basic needs. Therefore, local production and energy consumption are important to the community.
- DERs (Distributed Energy Resources) are helpful for electricity generation, but their intermittent nature makes their integration into the grid challenging. Planning trading in DERs to meet environmental, economic, and social requirements is also complicated.
- Energy prices influence energy consumption. For instance, consumers may take advantage of energy reduction initiatives and use more efficient equipment. For

example, a consumer can decide when to charge their car and when to use the car to power the house as a backup battery. However, the Distribution System Operator (DSO) may need to introduce service tariffs to reduce peak demands. Additionally, with the introduction of P2P (peer-to-peer) energy trading, the DSO will need to implement a way to charge such trading within the grid.

1.2.1 Research Objectives

Based on the challenges cited before, the proposed research uses Blockchain network characteristics to define a free market where prosumers can choose what to do with their energy while helping their local community. Throughout this thesis, the following research objectives will be addressed, and Chapter 5.1 summarises how they have been addressed. These objectives include:

1. ***Create a Double Auction Framework to facilitate local trading of renewable energy by prosumers***

   Justification: This objective aims to promote social contributions and support the national grid by charging distribution fees based on participants' relative location. Participants may benefit from this system by appealing to the social benefits of local energy trading, such as profiting from trading their energy.

2. ***Deploy a Consortium Blockchain Network for energy trading***

   Justification: A Consortium Blockchain Network refers to the union of a public and private blockchain that is partly decentralised. This objective aims to execute a blockchain architecture suitable for implementing the proposed Localised Energy Auction Framework. Chapter 2.3.1 will further explore the benefits of blockchain in P2P Energy Trading.

1.3 Research Contributions

The main contributions of this thesis are summarised as follows:

- Small energy producers can trade energy locally when integrating distributed energy resources into smart grids. The proposed framework model allows prosumers to participate in a double auction mechanism that pairs buyers and sellers, with electrical proximity being a critical factor in the trade. This peer-to-peer energy trading mechanism includes an additional fee for using the distribution network premises based on their position on the distribution network.
- This research proposes two initiatives to enable prosumers to be part of a local energy market: a Demand-Prioritized Double Auction Mechanism that ensures all buyers receive requested energy and incentivises prosumers to cooperate and a Consortium Blockchain Network that allows DSOs to access transaction data and prosumers to submit bids/offers. By combining these initiatives, prosumers can trade locally produced and consumed energy while DSOs benefit from each trade based on the use of the distribution network. However, DSOs will not decide or influence how the trades between prosumers are settled; DSOs will only get the payment for their network usage.

1.4 Thesis Outline

The following is an overview of the remaining chapters in this thesis:

In **Chapter 2**, the reader will find a detailed review of the existing literature on peer-to-peer energy trading based on blockchain technology. The chapter surveys various projects and blockchain characteristics and outlines the research approach taken in response to identified limitations of the blockchain peer-to-peer energy trading frameworks.

Chapter 3 introduces the Demand-Prioritised Double Auction Mechanism, which utilises oversupply to ensure buyers receive the energy they need. Additionally, excess energy from the seller's side is distributed among all participants to promote fairness. The chapter compares the behaviour of users during trading and highlights the benefits of the proposed mechanism over a standard double auction mechanism. The proposed approach maximises user satisfaction by considering user preferences when matching trades.

In **Chapter 4**, a Consortium Blockchain Network is defined. Capable of implementing the Demand-Prioritised Double Auction Mechanism. The chapter outlines the critical contribution of the network, which is the definition of different channels (state channels) to separate the communication of prosumers and third parties, such as DSOs.

Finally, **Chapter 5** concludes the findings from the previous chapters and identifies potential directions for future research.

Chapter 2

Background

One of the European Union's energy policy goals is expanding the share of coming from renewable energy. However, centralized schemes may need help to fulfil it under the enlarged number related to distributed generation units. Integrating distributed energy resources in smart grids has opened new avenues for the energy management system. Moreover, data calculation from smart meters is a significant time constraint due to the available data. This Chapter presents the state-of-the-art contributions from research projects to develop peer-to-peer energy trading into smart grids. Several studies suggest that using blockchain in the energy management system would help control the energy trading transactions between prosumers to reduce the computational burden involved in communication and decision-making. After that, this Chapter will present some key terms used in the proposed research.

2.1 Energy Management Systems on Smart Grids

The Smart Grid System applies metering, communication and control and strategies to improve the efficiency, reliability, economics, and sustainability of the production and distribution of electricity[27]. The Smart Grid term started to be used in 2008 and is commonly defined as a Medium/Low Voltage distribution network assembled and operated by the Distribution System Operator (DSO) with the help of Information and Communications Technology (ICT)[28].

The Institute of Electrical and Electronics Engineers (IEEE) has taken this definition further. Partitioning the smart grid as a large scale “system of systems” where each National Institute of Standards and Technology (NIST) smart grid domain can be expanded into three smart grid foundational layers:

- Power & energy layer;
- Communication layer;
- Informational Technologies / computer layer.

the last two represent enabling technologies and implementations, and their combined operation makes the grid “smarter”.

The ICT & data management side of the equation has been grouped into three domains:

- Transmission & distribution;
- Customer / end user;
- Operations / markets /service providers.

Appropriate and reliable data gathering from smart grid equipment is critical for the online diagnosis of these assets to take preventive measures or provide real-time balancing. However, current implementations are limited because of the ICT structure.

Smart grids are not simply utilities and technologies; they are a means of giving enough information and tools to the prosumer so they can make choices about their energy usage. This information includes how much electricity they use when they use it and its tariff. Furthermore, they incorporate real-time pricing, enabling prosumers to save money by using less power when electricity is most expensive [21].

One of the benefits associated with smart grids is when a power outage occurs. The grid will detect and isolate the outages, containing them before they become large-scale blackouts, so energy suppliers will be better prepared to address any issues such as severe storms, earthquakes, large solar flares, and terrorist attacks. Because of its two-way communication, smart grids will support automatic rerouting when equipment fails or outages occur.

The primary focus of introducing smart technologies at the transmission and distribution level is to enhance fault detection and self-healing of the network without the need for intervention by technical support. In some ways, this occurs already, as the basic hierarchy model used to illustrate the traditional electric grid has been superseded in recent years by radial networks and networks where some degree of rerouting is possible. Thus, in a conventional network, where the flow of current across the network as a whole or some part of it reached critical levels, it was possible to reroute flows through less stressed parts of the grid. The danger of rerouting was that it merely shifted the problem to another part of the network, stressing that element. With unplanned power outages, a domino effect may follow, damaging all network customers. Alternative techniques for dealing with these situations include a controlled “rolling blackout” whereby specific regions covered by a network are subject to power cuts for a predetermined period or voltage reduction across the entire network. Smart technology does not change the essential nature of the problem. It makes information on the network’s current state significantly more available to those maintaining it.

Relaying information to the control centres where critical decisions on how to respond to the increase of available information about the state of the grid, such as data gathering with intelligent sensors, has to be taken in a timely and effective manner. Moreover, communication translating data into an accessible and easy-to-use format enables the development of predictive algorithms to manage grid elements more effectively through analysis. While the precise technologies may vary, the same new and intelligent approach is being applied to every level within the system.

This is reflected in the amount of information available and the timeliness, with more frequent readouts on the state of critical network components and more up-to-date provision of that information (often in real-time, as opposed to historic). In addition, smart technology will assist in managing a bi-directional energy grid. Historically, grids were designed with energy flowing out from the centre to the point of use. This flow changes as the smart grid is essentially a “distributed network” with energy flowing from and into the centre or, increasingly, from one part of the periphery to another without touching the central generating facility. However, the local generation raises the prospect of a subnetwork generating more power than it uses, whereas, in a conventional network, this is both destabilising and dangerous.

The principal functions of the smart technologies at the transmission and distribution level of the grid are:

- **Automation** substation and power systems.
- **Diagnostics** load measurement, voltage stability monitoring, outage detection.
- **Automated crisis management** dealing with outages, system instabilities, and critical overload.

These principal functions are, in turn, supported by a number of key components within the architecture. The goals for these components are supported by:

- Widespread adoption of system standards (i.e. IEC61850).
- Wide Area Management System (WAMS) provides real-time monitoring via Phasor Measurement Units (PMUs).
- Fast and robust communications (i.e. IP routers and Ethernet communications).
- Advanced Machine-to-Machine (M2M) control and communication supported by Intelligent Electronic Devices (IEDs).

The DSO is defined as the entity responsible for operating the grid and the market of its distribution system. The DSOs rely on these components to operate properly, having grid and market operators. The functions of the grid operator would include the following [29]:

1. Processing DER interconnection request.
2. Conducting operational security studies.
3. Addressing system performance issues, such as potential overloads or low/high voltage violations, via switching or other operational actions.
4. Coordinating outage management.
5. Acting as the local balancing entity for load and generation.
6. Ensuring non-discriminatory access to the grid.
7. Maintaining the condition of the grid and managing grid assets.
8. Load forecasting.

The functions of the market operator would include the following:

1. Coordinating the purchase and sale of power and energy products.
2. Coordinating the interchange of power to other markets.
3. Dispatching generation in a security-constrained manner.
4. Controlling resource output consistent with predefined requirements.
5. Providing billing services to market participants.
6. Loading forecasting.
7. Supporting the maintenance outage scheduling.

IEDs enable local and/or remote sensing and control substation equipment at what is typically an M2M level, meaning they fit very closely with the Internet of Things (IoT) concept. A typical mid-sized US utility will have between 2,000 to 5,000 devices online at any time (2012), providing Supervisory Control And Data Acquisition (SCADA) communications, condition-based monitoring, and regular checking for event-related data in their substations. The increasing proliferation of IEDs is significant as it embeds communications and intelligence within the distribution network, providing utilities with new opportunities to monitor and manage their networks. The result, in theory, should be greatly improved overall reliability, represented by fewer outages and lower operational costs due to a reduction in the need for expensive repairs.

The economic transaction with customers in the DSO territory will be based on regulated tariffs, including the hourly cost of capacity, energy and ancillary services in the DSO market and at the wholesale delivery points, where the DSO has interconnected the bulk power system. One of the critical components to enable such transactions will be the IEDs.

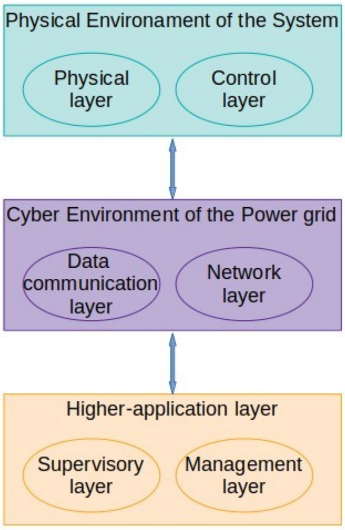


Figure 2.1: Hierarchical organisation of a smart grid.

With the inclusion of new smart technologies, the smart grid has continued to evolve and become more complex. For this, a smart grid can be organised hierarchically into six layers: the physical layer, control layer, data communication layer, network layer, supervisory layer, and management layer. The first two layers, the physical and control layers, can be seen jointly as the system's physical environment. The data communication and network layers comprise the power grid's cyber environment. The supervisory layer, together with the management layer, constitutes the higher-level application layer where services and human-machine interactions take place [30]. This organisation is depicted in Figure 2.1.

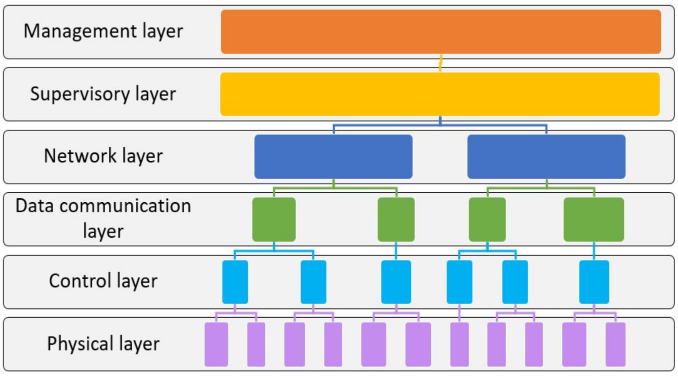


Figure 2.2: A conceptual control system with layering.

Figure 2.2 describes a smart grid system conceptually with a layering architecture, with the physical layer as the lowest level and the management layer as the highest. Each layer is described as follows [30]:

1. The physical layer is where the physical/chemical processes must be controlled or monitored.
2. The control layer includes control devices encoded with control algorithms with robust, reliable, secure, fault-tolerant features.
3. The data communication layer passes data between devices and different layers.
4. The network layer includes the data packet routing and topological features of control systems.
5. The supervisory layer offers human-machine interactions and centralises the decision-making capability.

6. The management layer makes economic and high-level operational decisions.

2.1.1 Hierarchical security architecture

The smart grid aims to create a reliable, efficient, secure, and high-quality energy generation, distribution, and consumption system by utilising advanced information, communications, and electronics technologies. By integrating modern ICT into the power grid, we can move away from outdated, proprietary systems and towards more universal ones such as personal computers, TCP/IP/Ethernet, and others.

The Smart Grid requires reliable and secure delivery of information in real time. It needs throughput and latency, the main criterion adopted to describe the performance required for everyday internet traffic. Obtaining information about customers' loads could interest unauthorised persons and could infringe on their privacy. Security measures should ensure the following [21]:

1. *Privacy* that only the sender and intended receiver(s) can understand the content of a message.
2. *Integrity* that the message arrives in time at the receiver in the same way it was sent.
3. *Message authentication* that the receiver can be sure of the sender's identity and that the message does not come from an impostor.
4. *Non-repudiation* that a receiver can prove that a message came from a specific sender, and the sender cannot deny sending the message.

The control system design is divided into four parallel areas to achieve resilience: human systems, complex networks, cyber awareness, and data fusion. The hierarchical perspective shares a similar divide-and-conquer philosophy but views the system differently in a hierarchically structured way [30].

2.1.2 Energy Management System

The UK Financial Conduct Authority (FCA) has recently emphasised the importance of promoting market-based forms of financial intermediation to alleviate the burden traditionally borne by commercial banks. Conventionally, EMSs are a combination of hardware and software that help users to:

- **Monitor:** Regulate information collection on energy consumption to establish a basis for energy management and explain deviations from targets.
- **Analyse:** An information system that stores and analyses energy consumption data. It helps users identify trends in how they use energy at various production levels of a manufacturing process or ambient temperature for a building.
- **Target:** Setting targets to reduce or control energy consumption based on an appropriate standard or benchmark.
- **Control:** Implementing management and technological measures to correct any variances from the target. This operation is a conservative definition of an EMS system and is primarily centred on technology.

According to the improved approach, an EMS is people participation. It is incomplete without “Engagement”.

- **Engagement:** The main objective of engagement is to connect users’ actions with energy consumption. By displaying real-time consumption information, users see the immediate impact of their actions. Letting users know their real-time consumption alone can be responsible for substantially reducing energy consumption.
- **System Architecture:** An EMS consists of smart energy meters, sensors and devices that monitor energy consumption and factors affecting consumption. These devices transmit data over a wired or wireless network to a central

private server. An interactive application helps users in analysing and reporting information while engaging users.

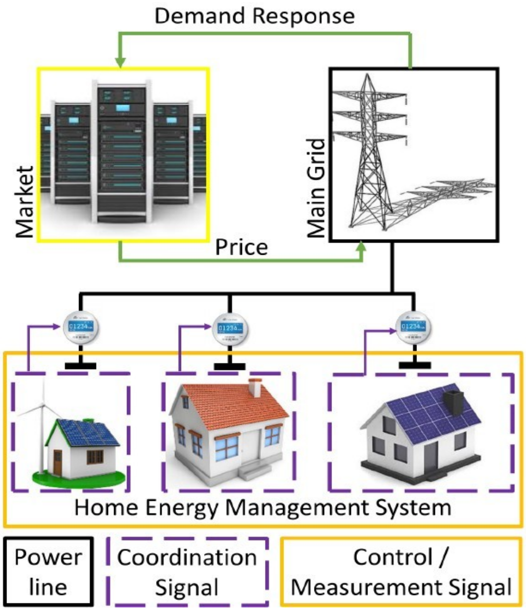


Figure 2.3: Energy and Data Management.

Figure 2.3 shows the need for a two-way communication layer that helps the EMSs control the energy distribution while keeping the data record for each transaction. With this in mind, EMS adopted peer-to-peer (P2P) energy trading systems in smart grids.

2.2 P2P energy trading in smart grids

With the increasing number of users becoming consumers and producers (also known as prosumers), the centralised architecture of the smart grid would not manage the flow of energy and information from an economic perspective to utilise the power in a prompt and local manner. This situation requires dealing with local excess production at short notice using, for example, an electronic trading platform while keeping the energy local. The demonstration described on [31] discusses the growing trend of private households generating renewable energy and the need to utilise this energy locally and promptly. It proposes the development of a cloud-based electronic trading platform called "PeerEnergyCloud" to deal with local excess production at short notice. The work focuses on learning profiles and forecasting energy consumption and production, allowing visitors to switch on and off appliances and see the effects on the forecast and agent system's behaviour.

Work presented on [32] proposed a hierarchical system architecture model to identify and categorise the key elements and technologies involved in P2P energy trading. The first dimension consists of the essential functions involved in P2P energy trading (power grid layer, ICT layer, control layer, business layer). The second dimension is the size of the peers participating in the process (premises, microgrids, cells, regions). The third dimension is the time sequence of the P2P energy trading (bidding, exchanging, settlement). There are different technologies and terms among P2P energy trading used in implementing the process; however, identifying, defining, and categorising these terms would help any reader understand the current work.

The literature from Morstyn et al.[33] defines a federated power plant based on a Virtual Power Plant (VPP). This federated power plant is formed through P2P transactions between self-organising prosumers and describes coordination strategies (Direct: bidirectional communication and Indirect: incentive signals). The P2P platform provides a market mechanism facilitating mutually beneficial energy transactions between subscribed prosumers. Therefore, the platform could identify opportunities for grid services and advertise these as contracts that groups of prosumers could fulfil. A key objective of using the P2P market is to provide a transparent mechanism that prosumers can trust to balance their preferences and requirements fairly. This work is an obvious example of a P2P platform that is a good tool for enabling energy trading amongst prosumers, however, VPP have a very limited presence in the energy markets[34].

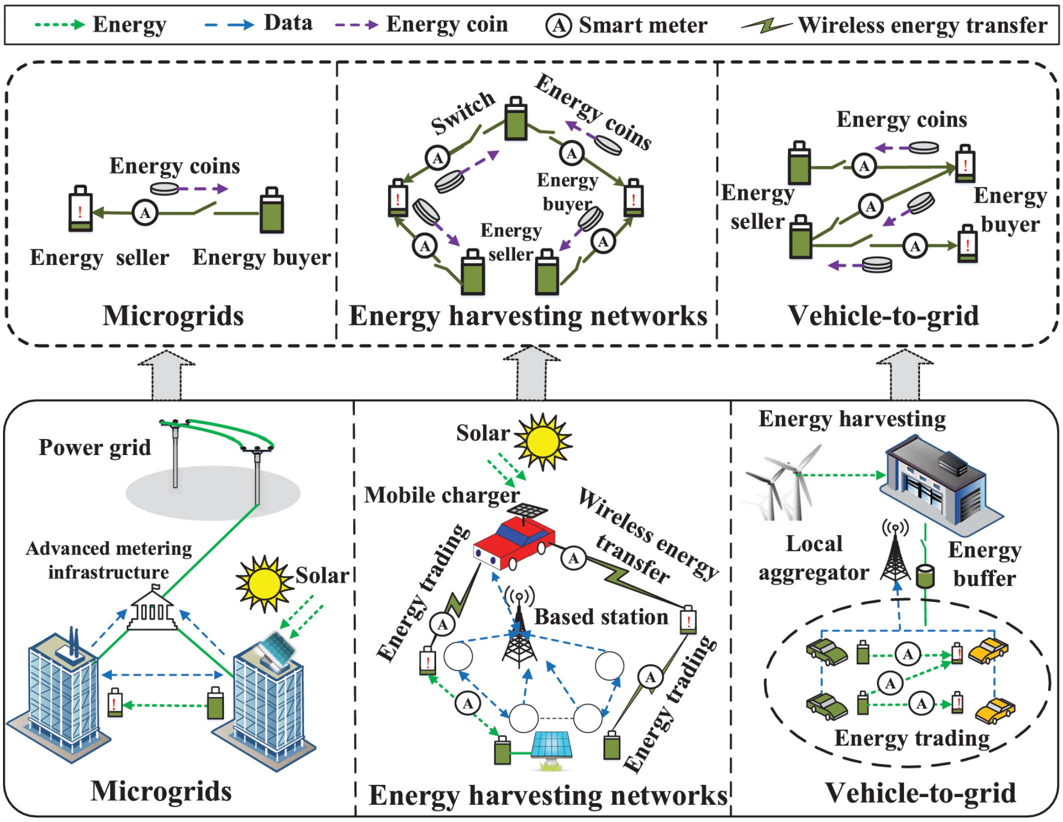


Figure 2.4: Three typical P2P energy trading scenarios in Industrial IoT (IIoT). Source [23]

2.2.1 Energy Trading scenarios

The main difference between the Internet of Things (IoT) and the Industrial Internet of Things (IIoT) is the main focus for each. IoT is more concerned about the users' experience, while IIoT focuses on industrial applications. With the increase of emerging technologies that have been introduced into industrial systems, i.e. DERs, Electric Vehicles (EVs), smart meters, and with the combination of these technologies, there are typically three P2P energy trading scenarios on IIoT[23]:

1. **Microgrids**: smart buildings with solar panels (PVs) and/or wind turbines, each building can harvest its energy and trade it with another in a P2P manner.
2. **Energy harvesting networks**: industrial nodes that can charge themselves through a mobile charger using wireless power transfer.

3. **Vehicle-to-Grid networks**: acting as energy storage devices by feeding energy back into the power grid.

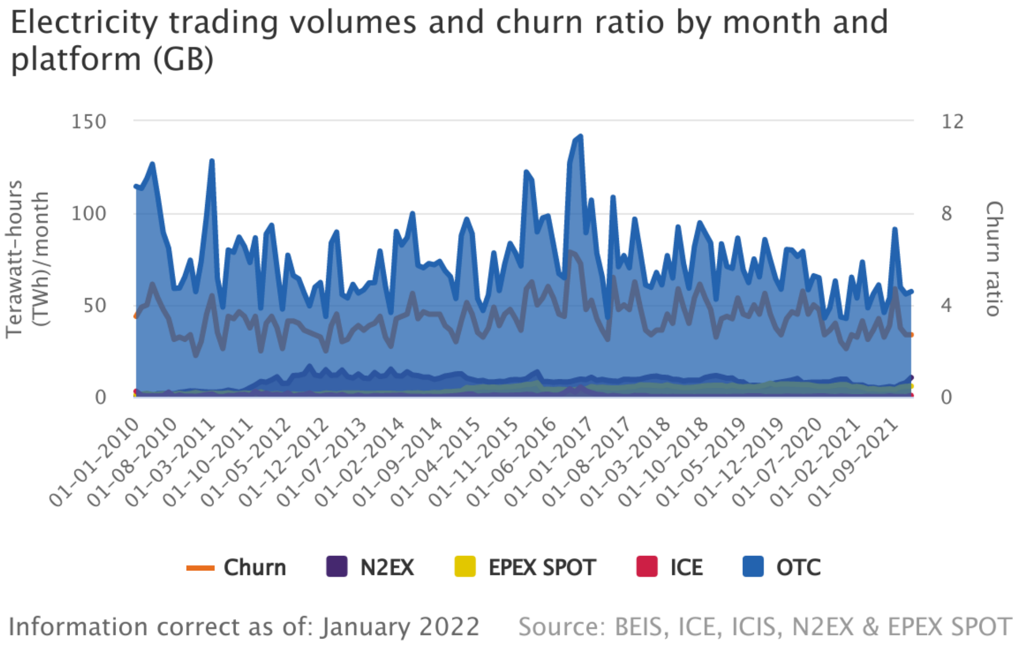
Figure 2.4 presents these trading scenarios.

The objective of the EMS at the distribution level mainly involves achieving overall economic dispatch by allowing the best utilization of DERs. The primary functions include the general economic operation and power quality of the entire system without restricting the type of energy trading scenario. To accomplish this, the EMS needs to have an efficient performance [35]. However, many research articles [36–38] have been published on various issues related to the planning and operation of the EMS, giving the alternative of P2P energy trading.

Energy-trading companies face a changing environment of regulations and an immense complexity of systems, operations, locations, products, committees, etc. Companies seek to improve their cost management while addressing the underlying complexity of their operations.

In a study by Smith and Jones et al.[39] five specific areas of complexity were presented that energy-trading companies should consider; among these, three areas relevant to this research were: “IT cost and complexity, Organizational cost and complexity and, Location cost and complexity”. The first complexity is the awareness of consumers’ real needs, whether they need a “special” service or not, i.e. use of applications. The second complexity was focused on unnecessary layers of overlapping activities. Having essential organizational structures is essential for a quick response to decision-making processes. The third complexity aimed to combine or shut down overlapping offices, getting the view of a more distributed service instead of being centralized.

Figure 2.5 shows the total monthly volumes of electricity traded in GB across different trading platforms. The churn ratio is also shown. ‘Churn’ is the number of times one unit of electricity is sold. A diverse range of products and platforms is available for those looking to trade power in GB. However, most electricity trades are still



Electricity trading volumes and churn ratio by month and platform (GB)

Information correct as of: January 2022 Source: BEIS, ICE, ICIS, N2EX & EPEX SPOT

Figure 2.5: UK electricity trading volumes and churn ratio by month and platform. Source [40]

made over-the-counter (OTC). Baseload products persistently dominate, accounting for most OTC traded volumes. The average churn rate in Q4 2021 was 2.76, which is 0.68 points lower than the previous quarter. However, it is still 0.24 points higher than in Q4 2020: indicating that liquidity has decreased quarter-on-quarter but increased year-on-year[40].

Liquidity is an essential feature of mature markets, often reflecting many buyers and sellers. Churn is one metric used to assess market liquidity. It shows how often a unit of electricity is traded before it is delivered to end consumers. Churn ratios are calculated by dividing total traded electricity volumes by the total amount of electricity demanded[41].

Liquid markets[40] also facilitate new entry by making it easier to buy and sell electricity at a reasonable price. For example, in a liquid market, a new supplier can more easily enter the market and buy the electricity they need to cover their consumers' demand whilst also having confidence in the price they are paying for that electricity. Volumes on the respective platforms tend to reflect the time horizon of the contracts traded, not the total market liquidity contribution.

2.2.2 Market Layer

Smart grids are not just regarding utilities and technologies; it is about giving enough information and tools to the consumer so they can make choices about their energy usage. This information includes how much electricity they use when they use it and its tariff. Furthermore, it incorporates real-time pricing, enabling consumers to save money using less electricity when it is most expensive[42–44].

Currently, the electricity market consists of the following elements[30]:

- **A central wholesale market**: wholesale electricity markets are multi-unit uniform-price auctions operated mostly by an Independent System Operator (ISO). These auctions feature dual settlement systems: there is a day-ahead auction, running daily for each hour of the following day, and real-time auctions, running every few minutes during the day of the contract.
- **Several retail markets**: in which the retailers that purchased energy from the wholesale market sell it to end-user customers.
- **A transmission service market** that determines the allocation and prices for transmission rights on power grid lines.

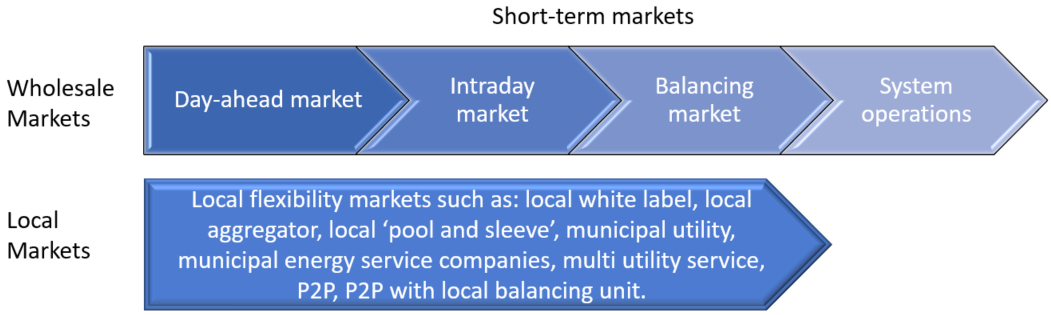


Figure 2.6: Wholesale and local market relationships in the short term. Adapted from [45]

Depending on the implemented services, the local flexible market[45] could interact with wholesale markets. Balance responsible party services could provide flexibility to reduce electricity costs while the Day-ahead and Intraday markets are open. Additionally, aggregators could provide additional benefits trading in balancing markets. Figure 2.6 shows the parallelism between local and wholesale markets. Flexibility markets are limited to short-term wholesale markets for simplicity.

Hall et al. [43] analyses these local flexible markets. The P2P market uses a software platform to allow commercial customers to select a mix of distributed generations to meet most of their demands. This model requires the software platform operator to partner with a third-party license supplier for the billing and balancing functions and to ensure secure supply where a consumer's selected generation package is insufficient to cover demand. Like 'sleeving', the consumer's load is preferably met by distributed generation. However, the software platform can pool the distributed generation instead of being met by one generator. This type of market can result in a better power purchase agreement deal for generators and a tariff that meets the consumer's needs, which may be price-based but can also incorporate socio-economic or environmental values.

The P2P model operates an exchange outside incumbent wholesale trading agreements, distinct from other exchanges that provide an alternative route to market for independent generators. This market is best suited to operating within a single distribution network to secure full embedded benefits. Re-localisation of energy value needs to be stronger. Demand side management and participation are outside the scope of this model, as are energy efficiency improvements that need more optimal flow power analysis.

Figure 2.7 presents the time framework for a general P2P energy trading system. t_x gives the time to settle the transactions; this period generally is defined as 15 minutes. The system will receive both bids for sell and buy, followed by specific criteria to match each user that will be trading. Once they are matched, the results are sent back during the completion period. In the end, a period to update the

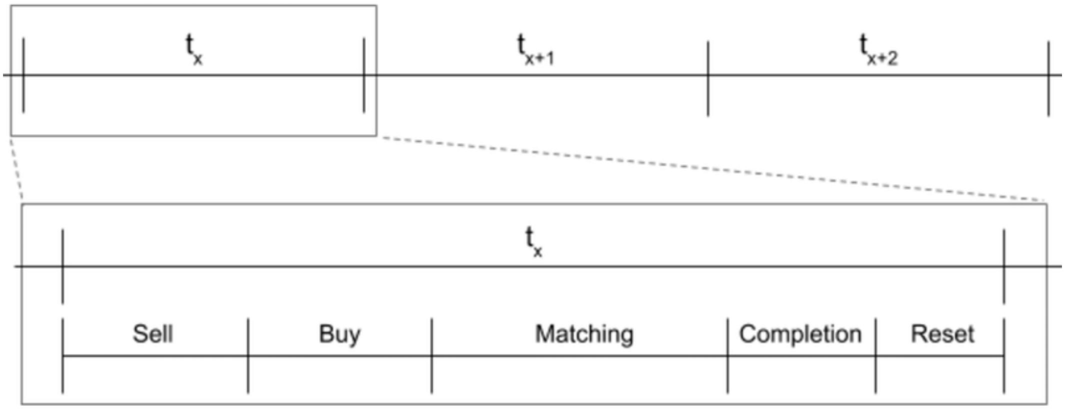


Figure 2.7: Time framework for a P2P energy trading system. Source [26]

system is given as a reset[26].

With the trading process defined, it is possible to structure the trading periods by splitting them into defined sections. The purpose of the segments defined in Figure2.7 are described below[26]:

- **Selling:** In this period, participants will place their sell orders.
- **Buying:** In this period, buyers would list interest against the sales created in the Selling period.
- **Matching:** This period will deal with the matching aspect of the system, wherein buyers would be matched to specific sales.
- **Completion:** This section has been added due to the DLT nature of this platform. Time is given to ensure that transactions are completed successfully.
- **Reset:** This section again has been added due to the DLT nature of the platform. This section will reset all necessary fields and arrays ready for the next period.

Work from Esmat et al. [46] divides the P2P market structure into three challenges; data storage, security and financial settlements. The market design should satisfy the target market performance metrics such as social welfare or total cost. Also, it should prevent malicious agents from trying to manipulate the market while protecting the privacy of the prosumers without revealing their identities. Additionally, it must be able to consider all possible types of DERs. With this in mind, decentralised market designs could offer all the above characteristics while maximising prosumers' profits.

Work from Long et al. [47] offers a clear view of the structure and design of P2P markets, as they are classified using general criteria by auction, multi-agent, and analytical models. All the models analysed have one thing in common: P2P sharing mechanisms do not need a central control system, but a local market operator is required to collect the bidding/offering information and provide the pricing signal to individuals in the Microgrid.

Most P2P trading platforms developed in recent literature rely on a so-called Continuous Double Auction (CDA) design for their market mechanism[48–53]. A CDA design is an efficient market mechanism that allows prosumers to trade with each other through bilateral agreements; thus, the specific traded quantities amongst them can be determined. In CDA, buyers and sellers place their buy and sell orders respectively; hence the term double, and the market is in a continuous state of clearing, hence the term continuous. The market clearing mechanism of the CDA only depends on the time it is being traded. Thus, the CDA's orders matching process limits the prosumers' options to a single time slot for buying and selling energy. These limitations affect the types of flexible local devices that can participate in the market.

Discrete-time auction contrasts CDA, where all traders move from initial allocation to final allocation in a single step. The Clearinghouse is a prime example of a discrete-time two-sided auction. Its key feature is that bid and ask messages are collected during the trading period and cleared at the end. Given the supply and demand revealed in the messages, a maximal trade vector is selected subject to a unified price constraint[54].

There are different varieties of CDA, and most are all referred to as just "double auction". All of them would aim to satisfy the following properties of an ideal mechanism[55]:

1. Individual Rationality (IR): no prosumer should lose from joining the auction. In particular, for every trading buyer: $p_0 \leq P(B)$, and for every trading seller: $p_0 \geq P(S)$.
2. Balanced Budget (BB) comes in two alternatives:
    - Strong Balanced Budget (SBB): all monetary transfers must be done between prosumers; the auctioneer should not lose or gain money.
    - Weak Balanced Budget (WBB): the auctioneer should not lose money but may gain money.
3. Truthfulness (TF), also called Incentive compatibility (IC) or strategy-proofness: also comes in two options (when unqualified TF generally means the stronger version):
    - The stronger notion is dominant-strategy-incentive-compatibility (DSIC), which means that reporting the true value should be a dominant strategy for all parties.
    - The weaker notion is Nash-equilibrium-incentive-compatibility (NEIC), which means that there exists a Nash equilibrium in which all parties report their true valuations.
4. Economic Efficiency (EE): the total social welfare (the sum of the values of all prosumers) should be the best possible. In particular, this means that, after all trading has been completed, the items should be in the hands of those that value them the most.

Unfortunately, achieving all these requirements in the same mechanism is impossible. However, some mechanisms satisfy some of them[56].

Table 2.1: Variants of Double Auction Mechanism and their properties

	Average Mechanism	Vickrey-Clarke-Groves Mechanism	Trade Reduction Mechanism	McAfee's Mechanism	Probabilistic Reduction Mechanism
IR	✓	✓	✓	✓	✓
BB	✓	✗	✗	✗	✗
TF / IC	✗	✓	✓	✓	✓
EE	✓	✓	✗	✗	✗

Table 2.1 summarises different variants of the continuous double auction mechanism and the properties that include based on their previous description.

When trading, the price setting can depend on the strategies or behaviours of the providers, in this case, the sellers. Work from Niyato et al. [57] defined such strategies as:

- **Market Equilibrium Pricing Model**, there is no awareness of the existence between sellers. Therefore, there is no competition or cooperation, and the spectrum price is chosen only to satisfy the buyers' demand.
- **Competitive Pricing Model**, where there is awareness of the existence of other sellers, each seller is interested in maximising their personal profit.
- **Cooperative Pricing Model**, similar to the competitive pricing model, there is an awareness of the existence of each seller. However, the sellers cooperate with each other.

Moreover, in literature [58, 59], cooperation between two or more economic agents is a problem that appears in several contexts in economics, cooperative game theory, where exchangeable utility and complete public information are assumed, different subsets of participants could agree to cooperate to achieve a monetary payoff (seller/buyer surplus). The core of the cooperative game is the set of solutions that simultaneously satisfy a set of constraints for all players[60]. Work by Lo Prete et al. [61] uses this cooperation to quantify how microgrid development affects prices, costs and benefits for parties in the network under alternative sets of assumptions. Their results present how the cooperative game framework can be helpful to regulators and policymakers in identifying the beneficiaries of microgrid promotion policies and correcting the market failures in utility pricing that can distort incentives for microgrid investment.

The following subsections will introduce key concepts used in the present research. McAfee's Double Auction Mechanism defines the pool of users who can trade during a specific period, welfare calculations for each type of user, and the use of the connections based on the grid to determine the distance between two users.

2.2.3 McAfee's Double Auction Mechanism

This CDA introduces the option for buyers and sellers to have a dominant strategy. McAfee's mechanism always produces complete information on the first best prices; however, the mechanism may prohibit the least valuable profitable trade. This mechanism satisfies the $\frac{1}{n}$ convergence to the buyer's bid double auction efficiency. On a double auction market with B number of buyers and S number of sellers, it aims to trade goods between participants while being truthful. Each participant has a private reserved price to sell $P(S_i)$ or to buy $P(B_j)$ in $£/kWh$, and a certain amount of the energy to sell $E(S_i)$ or to buy $E(B_j)$ in kWh.

To solve the winner determination problem for McAfee's double auction [62], the next steps are followed:

1. Sort the private reserved price for sellers in increasing order.

$$P(S_1) \leq P(S_2) \leq \cdots \leq P(S_S) \tag{2.1}$$

   This sorted list will produce the seller curve.

2. The private reserved price for buyers is sorted in decreasing order.

$$P(B_1) \geq P(B_2) \geq \cdots \geq P(B_B) \tag{2.2}$$

This will produce the buyer curve.

3. The number of Buyers x and Sellers y that will be considered in the trading are inside the area where the intersection of both curves is:

$$(x,y) \in \left\{ \begin{array}{lll} [P(B_x) & \geq & P(S_y)] \quad \& \\ [\sum^y E(S_i) & \geq & \sum^x E(B_j)] \end{array} \right\} \tag{2.3}$$

   where x number of buyers are short-listed to participate in the trading to get the amount of energy from the y number of sellers.

4. If the condition given by (2.3) is achieved then the price p_0 to trade is defined as

$$p_0 = \frac{P(S_{y+1}) + P(B_{x+1})}{2} \tag{2.4}$$

   where S_{y+1} and B_{x+1} are the next seller and buyer on the intersection, respectively. The price taken into consideration is the following participant of the intersection to preserve the mechanism's truth; this wistfulness. However, if this is not the case and the condition is not met, then the price used for the trade is given by

$$p_0 = \frac{P(S_y) + P(B_x)}{2} \tag{2.5}$$

   and the seller S_y and the buyer B_x are exempt from participating in the trade despite being already in the pool of participating traders.

   Truthfulness is achieved when a participant obtains maximum benefit from the auction by bidding their true value. As the price is set by participants that do not partake in the auction, there is no benefit for a participant to under or overbid, as they risk losing the auction without increasing their benefit; hence truthful bidding is the dominant strategy[62].

5. The quantity of the energy that each seller is allowed to send will depend on the previous condition $p_0 \in [P(S_y), P(B_x)]$, if this is met, then the amount of energy is determined by

$$E'(S_y) = \begin{cases} E(S_y) & if \quad \sum^y E(S_i) \leq \sum^x E(B_j) \\ Max(0, E(S_y) - \theta) & if \quad \sum^y E(S_i) > \sum^x E(B_j) \end{cases} \tag{2.6}$$

where $\theta = \sum^{y} E(S_i) - \sum^{x} E(B_j)$. But if the condition $p_0 \in [P(S_y), P(B_x)]$ is not met, then the amount of energy is determined by

$$E'(S_{y-1}) = \begin{cases} E(S_{y-1}) & if \quad \sum^{y-1} E(S_i) \leq \sum^{x-1} E(B_j) \\ Max(0, E(S_{y-1}) - \theta) & if \quad \sum^{y-1} E(S_i) > \sum^{x-1} E(B_j) \end{cases} \tag{2.7}$$

where $\theta = \sum^{y-1} E(S_i) - \sum^{x-1} E(B_j)$.

Algorithm 1 McAfee's Double Auction Algorithm

```
Require: Seller curve $\mathcal{P}(\mathcal{S}_1) \leq \mathcal{P}(\mathcal{S}_2) \leq \cdots \leq \mathcal{P}(\mathcal{S}_\mathcal{S})$
Require: Buyer curve $\mathcal{P}(\mathcal{B}_1) \geq \mathcal{P}(\mathcal{B}_2) \geq \cdots \geq \mathcal{P}(\mathcal{B}_\mathcal{B})$
Ensure: $(x, y) \in \left\{ \begin{array}{ll} [\mathcal{P}(\mathcal{B}_x) \geq \mathcal{P}(\mathcal{S}_y)] & \& \\ [\sum^{y} \mathcal{E}(\mathcal{S}_i) \geq \sum^{x} \mathcal{E}(\mathcal{B}_j)] & \end{array} \right\}$
  if $\left[\frac{\mathcal{P}(\mathcal{S}_{y+1})+\mathcal{P}(\mathcal{B}_{x+1})}{2}\right] \in [\mathcal{P}(\mathcal{S}_y), \mathcal{P}(\mathcal{B}_x)]$ then
      $Sellers = [\mathcal{S}_1, \mathcal{S}_2, ..., \mathcal{S}_y]$
      $Buyers = [\mathcal{B}_1, \mathcal{B}_2, ..., \mathcal{B}_x]$
      if $\sum^{y} E(S_i) < \sum^{x} E(B_j)$ then
          $\theta = \sum^{y} E(S_i) - \sum^{x} E(B_j)$
          $E'(S_y) = Max(0, E(S_y) - \theta)$
      else
          $E'(S_y) = E(S_y)$
      end if
      $p_0 = \frac{\mathcal{P}(\mathcal{S}_{y+1})+\mathcal{P}(\mathcal{B}_{x+1})}{2}$                ▷ Case 1
  else
      $Sellers = [\mathcal{S}_1, \mathcal{S}_2, ..., \mathcal{S}_{y-1}]$
      $Buyers = [\mathcal{B}_1, \mathcal{B}_2, ..., \mathcal{B}_{x-1}]$
      if $\sum^{y-1} E(S_i) < \sum^{x-1} E(B_j)$ then
          $\theta = \sum^{y-1} E(S_i) - \sum^{x-1} E(B_j)$
          $E'(S_{y-1}) = Max(0, E(S_{y-1}) - \theta)$
      else
          $E'(S_{y-1}) = E(S_{y-1})$
      end if
      $p_0 = \frac{\mathcal{P}(\mathcal{S}_y)+\mathcal{P}(\mathcal{B}_x)}{2}$                ▷ Case 2
  end if
```

Algorithm 1 summarises the previous steps that are taken to get the winners on McAfee's Double Auction Mechanism. Case 1 and 2 represent the two cases based on the condition $p_0 \in [P(S_y), P(B_x)]$ given in step 4.

An example scenario is used to demonstrate the process of the Double Auction Mechanism; see Figure 2.8. All the values used for the energy demand (in kWh),

Table 2.2: Parameters used in McAfee's mechanism example.

Parameter	Value
Set of sellers (ID)	[3,24,11,20,13,6,45,4]
Set of buyers (ID)	[16,39,10,9,5,8,12]
Set of amount of energy to sell (kWh)	[30,25,18,40,50,21,14,70]
Set of amount of energy to buy (kWh)	[20,16,50,70,24,19,60]
Set of reserved prices from sellers (£)	[20,10,16,5,16,25,7,2]
Set of reserved prices from buyers (£)	[17,28,6,30,8,15,23]

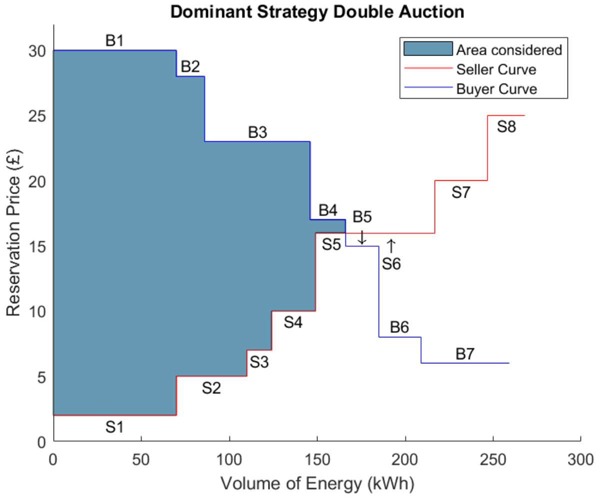


Figure 2.8: McAfee's mechanism to determine the winners of a double auction

energy production (in kWh), reservation price for both sellers and buyers in (£) and distance preference for buyers and sellers (in km) are randomized. For this scenario, there are eight sellers and seven buyers, some sellers have similar prices, and the total amount of energy to sell is greater than the total amount of energy to buy. Table 2.2 presents the parameters submitted for this scenario and are displayed in order of submission. Following Algorithm 2:

1. Once the values are reported, the new set of reservation prices for sellers is arranged in ascending order:

   $\mathcal{P}'(\mathcal{S}) = \{2, 5, 7, 10, 16, 16, 20, 25\}$

   And the new set of reservation prices for buyers is arranged in descending order:

   $\mathcal{P}'(\mathcal{B}) = \{30, 28, 23, 17, 15, 8, 6\}$

2. Then, the intersection is found between the prices of 17 and 16 for buying and selling, respectively. On this point $x = 4$ and $y = 5$, see Figure 2.8. Ensuring that the conditions mentioned above stated in Algorithm 2 are met by using the values of $x = 5$ and $y = 6$:

   $$\frac{16+15}{2} = 15.5 \notin [16, 17]$$

   Therefore the seller and buyer in the intersection are considered as the based price, and they will not be part of the trading. The subset of seller's IDs considered to trade is $[24, 20, 45, 4]$, and for the subset of buyers is $[39, 9, 12]$.

   The price proposed for the trading is calculated as follows:

   $$p_0 = \frac{16+17}{2} = 16.5 \in [10, 23]$$

3. Since the buyer and seller from the intersection is not considered, the accumulative energy is

   $$\sum_{i=1}^{y-1} \mathcal{E}(\mathcal{S}_i) = 149, \; \sum_{j=1}^{x-1} \mathcal{E}(\mathcal{B}_j) = 146$$

   Since $\sum^{x-1} \mathcal{E}(\mathcal{B}_j) < \sum^{y-1} \mathcal{E}(\mathcal{S}_i)$ then $\theta = \sum^{y-1} E(S_i) - \sum^{x-1} E(B_j) = 149 - 146 = 3$ the energy that seller S_4 will trade is

   $$E'(S_4) = Max(0, E(S_4) - \theta) = Max(0, 25 - 3) = Max(0, 22) = 22kWh$$

This scenario presents Case 2 of Algorithm 1, where the price calculated from the next buyer and seller from the point of intersection is not in the range of the buyer and seller of the intersection. Moreover, it illustrates the repercussion on the last seller trading when the accumulative amount of energy to buy is less than the amount of energy to sell.

2.2.4 Matching mechanism

Two main approaches can be taken with the market establishing contracts between participants. The first and more traditional approach is automating each participant's trades individually. The second is to have a single entity that performs the matching of all buyers and sellers together, negotiating all contracts simultaneously. The first benefits individuals to the maximum potential but may not find the optimal solution for the network. The second allows for matching to be decided on a market level, reducing overheads. However, this method is generally more open to abuse by having a single entity controlling all contracts being created.

The choice of option to use would also depend on which algorithm would match buyers and sellers. There are many types of matching algorithms. In these (in general), sellers would announce what they have to sell, and buyers would report what they want to purchase. A system would then match buyers and sellers based on price and/or preferences, using regret matching, sharing electricity schedules, auctions or rank order lists.

Electronic exchange is an integral part of trading and affects the efficiency of the securities market. Different algorithms are available for matching orders; however, choosing an appropriate algorithm is crucial for the trading system. First-In-First-Out (FIFO) and Pro-Rata are the two most common algorithms for matching orders[63].

FIFO is also known as the price-time algorithm. On the FIFO algorithm, buy demands take priority in the order of price and time. Then, buy demands with the same maximum price are prioritised based on the bid time, and priority is given to the first buy demand. This process is automatically prioritised over the buy demands at lower prices.

The Pro-Rata algorithm also prioritises the highest-priced to buy, but demands may be partially filled. However, demands with the same highest price are matched each order size proportionately.

Tubteang et al. [64] proposes a matching approach based on cost path and a congestion solution, based on the bus transfer factor and partitioning zone approach, for P2P electrical energy trading. The trading processes consist of the market operator and DSO mechanism. The operator is required to consider the overall market for effective energy trading. The market operator mechanism matches traders based on the least-cost path. In the DSO mechanism, the DSO checks the congestion problem in the distribution line before permitting the trading. The proposed line congestion management process occurs after the market clears so traders can trade liberally initially.

Thomas et al. [65] propose a novel Closest Energy Matching (CEM) double auction mechanism and compare it with four other mechanisms. This proposed mechanism matches each buyer with the seller whose available surplus energy is closest to the amount requested by the buyer. CEM allows the auction to take into account current energy requests as well as the potential future demand without requiring additional information.

Work from Murkin et al. [66] proposes an algorithm for automating the sale and purchases of electricity, aiming to optimise the market while providing increased control to households. Murkin's work defines three preferences to get a total score for each transaction: price, energy type and distance preference. The first and last preferences were used as a base for the proposed score-matching mechanism, where price, distance and welfare preferences are considered.

In conclusion, the matching process typically sees two groups; each group member has a list defining their preference over the parties in the other group. These two lists are then used to determine how the participants from each group are matched. The matching process used in this research will be detailed further in Chapter 4.

2.2.5 Consideration of Distance between Nodes/Peers

The trading pair from any matching mechanism is considered from the price alone, regardless of the technical factors. In the actual dispatch of energy, another parameter, such as distance, could be considered in the matching process. The distance can be used as a parameter to calculate the cost of usage of the distribution network while trading, which leads to a conditional match. A conditional matching approach based on the cost path that includes line congestion management, using the bus transfer factor and partitioning zones for power adjustment to avoid unnecessarily curtailing traders' power, is presented in [64].

Jogunola et al. [67] propose a slime-mould-inspired optimisation method for addressing the path cost problem for energy routing and the capacity constraint of the distribution lines for congestion control. Then, they extend the optimised path algorithm to match the energy prosumers, ensuring all consumers are matched with producers to reduce the network costs collectively. In works such as [68, 69], the distance between participants addresses the network's power losses.

Work from Paudel et al. [70] proposed an electrical distance approach to calculate the network fees for P2P energy trading. Here they use an electrical structure of the network with the same number of node connections as the physical layer. However, this approach can not be used by the DSO to charge for the use of the grid.

In contrast, Mengelkamp et al.[71], address the difference between a physical microgrid, which consists of an actual power distribution microgrid, and a virtual microgrid, which links the microgrid participants over an information system. Virtual microgrids cannot physically decouple from the superordinate grid, unlike a physical microgrid. Physical microgrids typically have a limited number of connection points to ensure an efficient grid connection and swiftly decouple from the grid in case of power outages. Most of the literature is based on a virtual microgrid which have not been well accepted in the energy market[34].

Several techniques have been proposed for path optimisation problems in cyber-physical networks, including the Dijkstra algorithm[72] and the Bellman-Ford algorithm [73], among others; the computation time for these algorithms is excessive when the network scale becomes large. Nature-based algorithms have emerged to address the computational complexity of path optimisation problems, including bioinspired techniques such as genetic algorithm, particle swarm optimisation, and ant colony optimisation [74].

2.2.6 Welfare of participants

Another parameter that should be considered in a matching mechanism is the users' welfare, representing the electricity value for each user by defining a utility function for the buyer and a cost function for the seller. For each user, the utility/cost function defines the level of satisfaction obtained by the user as a function of its total power consumption/production throughout the operation period.

Sellers in the market submit their available energy for trading with buyers. The cost of supplying $E(S_i)$ energy offered by seller i to the market can be approximated by a quadratic convex function[75]:

$$C(E(S_i)) \;=\; aE^2(S_i) \;+\; bE(S_i) \;+c$$

where a, b and c are all predetermined positive constants which reflect the amount of energy that a seller is willing to sell at different prices at a given time. The important issue is that the cost function is non-decreasing. The cost function needs to be non-decreasing since it is assumed that shedding each extra kW brings an additional cost to the seller[76]. Therefore, the welfare of the seller i is modelled by the following:

$$W_{S_i} \;=\; p_0 E(S_i) \;-\; C(E(S_i)) \tag{2.8}$$

where p_0 is the corresponding price in the trade for the amount of energy $E(S_i)$ of the seller i. The sold energy by seller i in each time slot is the summation of any sold energy to all connected users, and this energy is constrained by the limitations of the type of generation.

$$E(S_i)^{\min} \leq E(S_i) \leq E(S_i)^{\max}, \;\; \forall i \,\epsilon\, \mathcal{S}_S$$

If the generation of the seller is from renewable sources with zero marginal cost, and sellers are not interested on selfconsume, it can be modelled as a "must-take" generation. The "must-take" generation, such as from solar or wind generation, can be modelled by setting upper and lower limits equal to each other, resulting in the corresponding $E(S_i)$ variables becoming constant instead of an optimisation variable.

Buyers with flexible loads participate in the market assuming that their flexible loads are continuous and they can adjust their demand regarding market price. The satisfaction level of the buyers is based on their demand from the market and can be modelled by a utility function. The standard form of the utility function is a non-decreasing function with a nonincreasing marginal benefit. Also, no energy consumption means that there is no benefit for buyers. Thus, the utility function for each buyer j with demand $E(B_j)$ should satisfy three properties[77]:

1. Utility functions are non-decreasing. This implies that the marginal benefit is nonnegative
$$\frac{dU(E(B_j))}{dE(B_j)} \geq 0$$
2. The marginal benefit of users is a nonincreasing function. That is, the utility functions are concave
$$\frac{d^2U(E(B_j))}{dE(B_j)^2} \leq 0$$
3. When the consumption level is zero, the utility functions are equal to zero.
$$U(0) = 0$$

To satisfy these properties, the quadratic utility function for buyer j proposed in [77] is considered :

$$U(E(B_j)) = \begin{cases} \omega E(B_j) - \alpha E^2(B_j) & if \quad E_{B_j} < \frac{\omega}{2\alpha} \\ \frac{\omega^2}{2\alpha} & if \quad E_{B_j} \geq \frac{\omega}{2\alpha} \end{cases}$$

where ω and α are the free parameters differentiating consumers ω can be interpreted as the maximum price the consumer is willing to pay for the energy, and $\frac{\omega}{2\alpha}$ is the minimum level of consumption that satisfies the consumer the most. Since each buyer behaves independently, these parameters vary among buyers at different times of the day or in various climate conditions. The welfare of buyer j is defined as the utility of the demanded energy minus paid money for this energy as formulated in

$$W_{B_j} \;=\; U(E(B_j)) \;-\; p_0 E(B_j) \tag{2.9}$$

Any buyer can demand energy from different sellers, and the total demanded energy is framed by

$$E(B_j)^{\min} \leq E(B_j) \leq E(B_j)^{\max} \quad \forall j \,\epsilon\, \mathcal{B}_B$$

where $E(B_j)^{\min}$ denotes the baseline demand of buyer j, which is from “must-run” appliances, and $E(B_j)^{\max}$ is the maximum energy the buyer is willing to demand from the market. Buyers with inflexible loads can be modelled by setting upper and lower limits equal to each other, resulting in the corresponding $E(B_j)$ variable becoming constant instead of an optimization variable.

Rahbari et al. [78] introduce the incremental welfare consensus algorithm for solving the energy management problem in a smart grid environment with distributed generators and responsive demands. The authors use the above definitions for utility and cost functions with the difference that the utility function when $E_{B_j} \geq \frac{\omega}{2\alpha}$ is calculated as $\frac{\omega^2}{4\alpha}$, while Samadi et al. [77] uses $\omega E(B_j) - \frac{\alpha}{2}E^2(B_j)$ when $E_{B_j} < \frac{\omega}{2\alpha}$ instead of $\omega E(B_j) - \alpha E^2(B_j)$.

Khorasany et al. [79] propose a decentralized P2P energy trading scheme for electricity markets with high penetration of DERs. Their overall objective function for social welfare maximization can be written as follows:

$$\max_{\boldsymbol{x},\boldsymbol{y}} \left(\sum_{i=1}^{S_S} WS_i + \sum_{j=1}^{B_B} WB_j \right)$$

where WS_i and WB_j are the welfare of seller i and buyer j, respectively. The optimization objective is to find the generation of all sellers (x) and the demand of all buyers (y) to maximize social welfare. The authors use the previous definitions for the welfare of buyers and sellers described above.

On the other hand, Sorin et al. [80] model the production cost and consumer utility functions as quadratic functions of the power set-point, using three positive parameters a_n, b_n and d_n defined as follows:

$$C_n(P_n) = \frac{1}{2}a_n P_n^2 + b_n P_n + d_n, \quad a_n, b_n, d_n \geq 0$$

These functions are used for their relaxed consensus and innovation approach to solve the multi-bilateral economic dispatch in a decentralized manner.

The quadratic cost and utility functions presented before are realistic for a large class of conventional generators. They are some of the best assumptions to make when having limited insight into the actual utility functions of small users[80]. Therefore, Chapter 4 will use the definitions of welfare for the buyer as in (2.9) and for the seller as in (2.8).

2.2.7 Data Processing

Peer-to-peer energy trading is under development after integrating renewable energies and decentralised systems. One example is presented by Thakur et al.[81], who proposed a distributed double auction trading using blockchain, allowing any participant to participate in the trading. Blockchain has attracted more attention for producing decentralised systems in the past four years. Some literature[82–87] has concluded that blockchain will improve this area, such as the security of processing participants' information, enabling participants to partake in trading while not trusting each other, among other characteristics. With this in mind, researchers are investigating a better way to integrate the surplus energy produced by the DERs into the main grid while maintaining a balance and getting a more innovative electricity market.

The EMS uses different protocols to interact with the various elements on the microgrid. Two main protocols are used to control intelligent appliances: ZigBee and Z-Wave. Zigbee uses the IEEE's 802.15.4 personal-area network standard to communicate between 10 to 20 metres with other Zigbee devices. It works at 2.4 GHz like most Wi-Fi-enabled devices, but so far there is no report of interference, although this is a possibility. On the other hand, Z-Wave has a maximum theoretical distance of about 100 metres, running on a different spectrum, so there is no possibility of being interfered with by Wi-Fi. Version 3.0 has 128-bit symmetric encryption (making it relatively secure).

Smart relays are more reliable than meter interfaces because they feature power meter functionality and permit tool groups of appliances or individual elements to switch ON or OFF.

2.3 Distributed Ledger Technologies

With the integration of DERs into the power grid, the role of some consumers has been changed to prosumers[2, 3], i.e. who can generate and consume energy, leading to a change based on the existing EMSs. However, these rapid changes are introducing a new way to buy enoverergy and changing the effects on energy trading amongst prosumers resulting in a new challenge that researchers have to face: the P2P Energy Trading[4–6].

Since it was reported in 2008, blockchain has been attracting interest from different sectors; the applications covered are categorized based on the various industrial domains they serve, including financial[87], healthcare[88], logistics[89], manufacturing[90], energy[85], agriculture and food[91], robotics[92], entertainment[93], as well as other industrial fields[84]. Invented by Satoshi Nakamoto to serve as the public transaction ledger like the cryptocurrency bitcoin[7], blockchain has created a P2P currency by removing the need for a trusted third party.

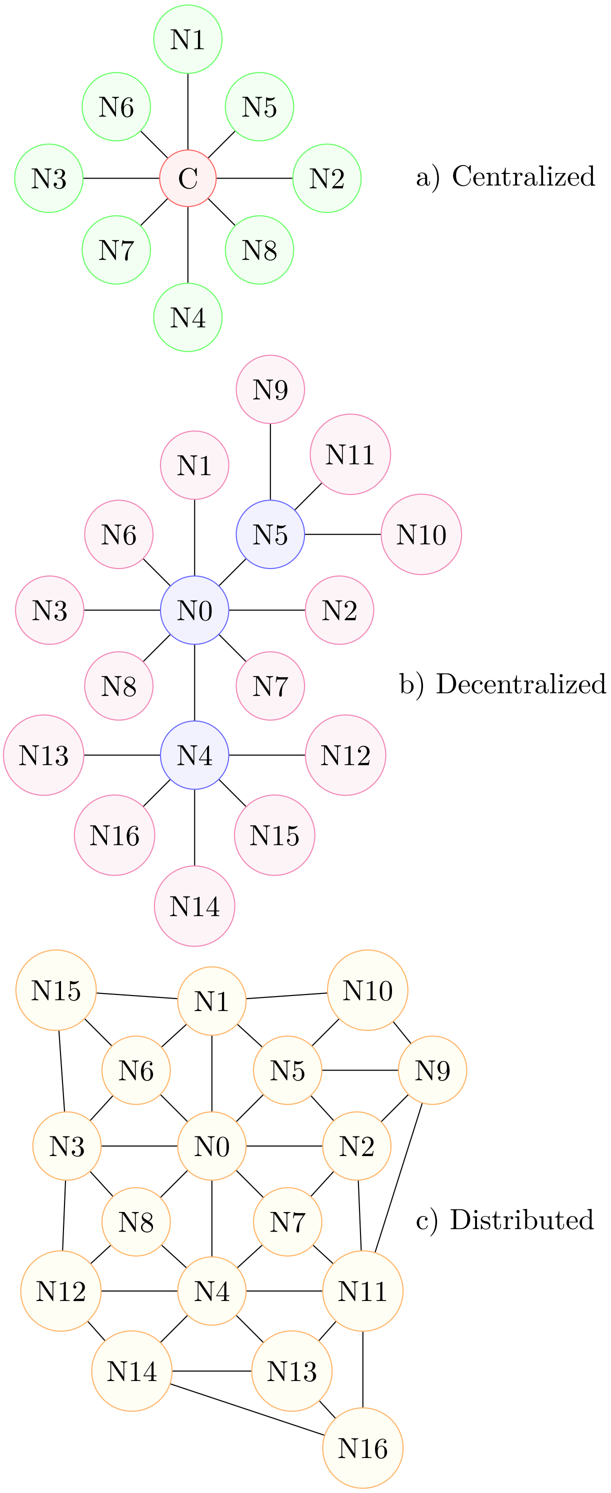
Blockchain technologies have been prevalent in many applications, not only in cryptocurrency but also in the energy sector, as a new feature on smart grids. Smart grids provide a new interface for integrating DERs while balancing energy supply and demand, working towards a distributed energy market[86]. This type of market promises higher energy efficiency and lower carbon emissions by implementing P2P energy trading; therefore, blockchain has been proposed as a tool for P2P energy trading. Several research projects address the challenge of making a profit while integrating more DERs into the main grid[85].

Before introducing blockchain, it is essential to understand the term “distributed ledger”. Traditional ledgers used to record money or property had been replaced by digital ledgers, comprising time-stamped digital records. With the increase of machine-to-machine communications, Distributed Ledger Technologies (DLTs) provide a means to facilitate trusted exchanges among IoT devices. Now a combination of cryptographic puzzles, incentive mechanisms, and security protocols enables the combined creation of DLTs [82].

DLTs rely on peering nodes to record, share, and synchronize transactions and data in their individually maintained local ledgers, unlike centralized files and databases. This data structure lives across multiple nodes, i.e., computer devices generally spread among locations or regions[82]. The diagrams in Figure 2.9 represent the different types of DLTs. In the case of blockchain, information is organized into blocks that are securely and transparently chained together. These blocks become immutable global knowledge among all peers using consensus algorithms to achieve data synchronization [83]. DLTs include blockchain technologies and smart contracts. Smart contracts are programs stored in the blockchain and triggered when predetermined conditions are met: these programs can be used to automate a workflow. Note that all blockchains are DLTs, but not all DLTs are blockchains.

2.3.1 Blockchain

Blockchain is now a P2P DLT forged by consensus, combined with a system for smart contracts and other assistive technologies, the addition of smart contracts made the application of blockchain wider [22]. Initially, the objective was financial transactions, but later the track of various assets was added[94, 95]. Those transactions are grouped into blocks, and there can be any number of transactions per block. The blockchain syncing has to do with a concept of consensus, ensuring that



a) Centralized

b) Decentralized

c) Distributed

Figure 2.9: Types of Distributed Ledger Technologies

peers agree to a particular state of the system as the true state. Thus, eventually, each node has an exact copy of the blockchain throughout the network.

Different node computers in the network validate each block by solving cryptographic mathematical puzzles or hashes. At this time, the blockchain adds a new block with a unique cryptographic hash, time stamp, and data to the chain. Data on the block is immutable and effectively cannot be altered unless an agreement of the blockchain network majority changes all prior blocks in the chain.

Blockchain breaks down to creating distributed consensus between mutually distrustful parties, in many ways, allowing to create of a single instant source of truth. Although all the discussing messages that do the consensus mechanism go through a central hub, distributed ledgers are distributed because the blockchain is replicated amongst all nodes.

There are two types of transactions within the blockchain network; one uses digital currencies or cryptocurrencies, and the second is profile promotion. With the use of cryptocurrencies, the users make their transactions based on a designed cryptocurrency. In contrast, in profile promotion, the users are incentivised by getting discounts or promoting their status within the network.

Figure 2.10 presents an example of how blockchain enables such transactions. In this case, Martha has a solar panel, and she has an excess of energy she wants to sell; one of her neighbours needs energy and has decided to buy energy that is produced locally. Both are connected to the Local Transactive Microgrid [96] and submit their wishes to transact energy. Based on the specifications defined in the smart contract, the transaction between them is approved or denied. This case exemplifies how two people who do not trust each other can trade energy without the help of any third parties.

Sometimes blockchains are likened to being just databases; however, the differences between blockchain and Databases are threefold:

1. **Structure**: while blockchain is a write-only data structure, the data on data-

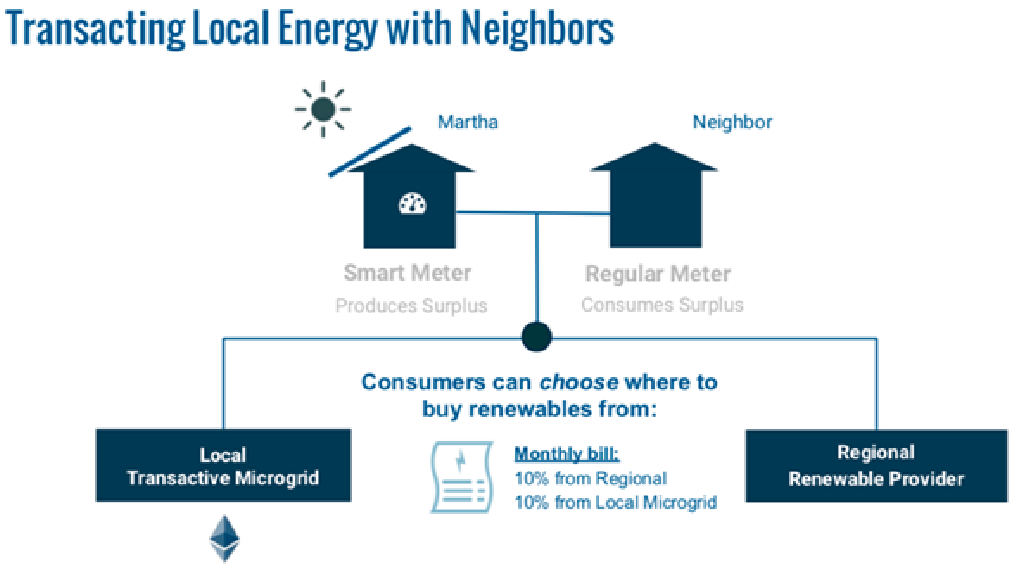


Figure 2.10: Use of blockchain for energy transaction based on Transactive Microgrid. Source from [96]

bases can be easily modified. Databases utilise a client-server architecture, while blockchain uses a distributed ledger network architecture.

2. **Administrator permissions**: in databases, the users can make any changes to any part of the data and/or its structure, but in the blockchain, users cannot have such permissions, unless it is defined in a permissioned blockchain.
3. **Design**: as was explained above, the essence of blockchain is to be used on decentralised applications, whilst data is on centralised applications.
4. **Transparency**: Malicious users can alter database data, but data submitted in the blockchain has to be agreed upon by consensus with the majority of its users.

2.3.1.1 Blockchain Aspects

There are different characteristics of blockchain, such as cryptographically sealed, consensus-based, immutable records, chronological and time-stamped, irreversible and auditable, among others[97]. However, this research will focus only on the characteristics that present advantages or disadvantages for Smart Grids applications, i.e., types of blockchain and consensus, since these two characteristics present the most impact.

1. ***Blockchain types***

   There are four different types of blockchain[94]:

   Public: also known as a "Permissionless blockchain" in which anyone can join the network; it is mainly used when a network can "commoditise" trust. Parties can transact without necessarily verifying each other's identity; therefore, they do not require a set number of peers to be online.

   Private: one organisation controls this network by defining who can participate, execute a consensus protocol and maintain the ledger. A private blockchain can be run behind a corporate firewall and even hosted on-premises.

   Permissioned: this type requires the pre-verification of the participating parties within the network. Transactions allow other parties to understand where in the supply chain a particular item is. Each participant involved in the supply chain needs permission to execute trades; therefore, they have to guarantee up-time and require a high level of quality of service on the communication links. Public blockchain networks can also be permissioned.

   Federated: also known as "Mixed" or "Consortium", running under the leadership of a defined group. It is mainly used by organisations that operate a node each and validate the transactions on the blockchain. Unauthorised individuals are not allowed to participate in the transactions and verification processes. However, this type has a scalability advantage.

2. ***Types of consensus***

   All algorithms do two things: ensuring that the data on the ledger is the same for all nodes in the network and preventing malicious parties from manipulating the data. Among these algorithms, there are[95]:

Proof of Work (PoW) involves solving a computationally challenging puzzle to create a new block. The computationally heavy algorithm requires a tremendous amount of energy to be consumed. Nevertheless, it has a high latency of transaction validation.

Proof of Stake (PoS) generalises PoW and saves expensive computational resources that are spent under a PoW consensus regime. PoS is also a system for validating transactions, so the purpose is the same as the PoW, but the result is obtained differently. Nodes are selected by the probability of the number of stakeholders. The nodes are validators because they validate the transactions to earn a transaction fee.

Proof of Elapsed Time (PoET) instead of competing to solve the cryptographic challenge, this consensus algorithm is a hybrid of a random lottery and a first-come-first-serve basis. Each validator is given a random wait time, and the one with the shortest time is elected as the leader. This leader gets to create the next block on the chain.

Simplified Byzantine Fault Tolerance (SBFT) implements an adapted version of the *Practical Byzantine Fault Tolerance (PBFT)* algorithm and seeks to provide significant improvements over PoW. A single validator who bundles proposed transactions and forms a new block the validator is a known party, given the permissioned nature of the ledger. Consensus is achieved due to a minimum number of other nodes in the network ratifying the new block.

Proof of Authority (PoA) can be used for permissioned ledgers. It uses a set of authorities and designated nodes that are allowed to create new blocks and secure the ledger. Ledgers using PoA require sign-off by a majority of authorities for a block to be created.

The literature reviewed thus far in this chapter provides essential insights into the use of blockchain for P2P Energy Trading. One interesting finding is the sharp difference between Mixed and Public types of blockchain. Another important finding was that cryptocurrencies might be an excellent solution to ensure transactions between peers. The most exciting finding was the high use of Proof of Work as a consensus algorithm, even though the energy consumed to solve the algorithms is too high. Very little was found in the literature on the type of transaction used by the projects, most of the time because of the lack of technical reports or copyright. This finding was unexpected and suggested more research in this area. These results may be limited to public information available for each project. These results further support the hypothesis that blockchain can be used as a platform for P2P Energy Trading. However, further work is required to establish its viability regarding the energy balance in the transmission line.

2.3.2 Blockchain-based Energy Trading Systems

Based on the analysis carried out by Zhang et al. [8], all the research projects discussed focus only on developing business models and ignore the possibility of introducing those models to smaller-scale local energy markets. The design of ICT and control systems was not considered. It focuses on the ICT technologies suitable for local P2P energy markets but forgets to deal with P2P energy trading. Some use blockchain technology to simplify metering and billing systems in the energy markets.

Another analysis was performed among some real-world projects, and the findings are shown in Table 2.3. Moreover, Table 2.4 summarise a description based on some of the research projects in the same field, later each project is presented.

2.3.3 Summary of Challenges

Based on the analysis done in [8] and [9], amongst all the projects discussed, there is a big focus on developing business models while ignoring the possibility of introducing those models to smaller-scale local energy markets. The design of ICT and control systems is sometimes not considered or focuses on the ICT technologies suitable for

Table 2.3: Real-world projects discussed to present the utility of the proposed architecture for P2P energy trading.

Project	**By**	**Where? When?**	**Based on**	**Description**
ME SOLshare	SOLshare supported by Grameen	Shakti Dhaka, Bangladesh 2018 (up to 1,500 homes) 2015 - 2017 (150 homes)	Rooftop solar panels, batteries and SOLbox	ICT back-end (SOLweb and SOLapp) for P2P energy trading between users, plus mobile money payment, data analytics and grid management services. SOLbox works as a DC bi-directional power meter, solar charge controller, and M2M communication-enabled end-user device that functions as an individual node, allowing the trading network to grow from the bottom-up.
Green Running	UCL Energy Institute's, LoLo CDT in Energy Demand	Hackney, London, UK 2017	Solar panels and communal battery storage	blockchain-based P2P energy trading solution. Provides real-time cost updates per appliance and safety alerts if appliances are left ON. Use Non-Intrusive Load Monitoring (NILM) and advanced machine learning algorithms to disaggregate and analyse electricity data down to an individual appliance level. Focus on enabling the sharing of clean energy at affordable prices.
Sonnen Community	Natural Solar Sonnen	Arizona, US, 2017. Italy, 2017. Norway, 2016. Australia, 2016. Germany, 2015	Photovoltaic system and Sonnen batteries. Batteries community	Use a VPP, an online network based on the blockchain idea for sharing self-generated power. The surplus is not fed into the main grid but into a virtual energy pod that serves other members when they cannot produce enough energy due to bad weather.
TransActive Grid, Brooklyn Microgrid (BMG)	Lo3 Energy, TransActive Grid, Siemens Digital Grid	South Australia, 2017. Brooklyn, US, 2015	Microgrid PV and battery storage. Hybrid smart meters	P2P transaction system that creates a P2P market using blockchain technology and can still function if the main grid fails during storms or other catastrophes.
Piclo	OpenUtility	UK, 2014	Platform	Service for DSOs who want to tender for customer flexibility as an alternative to reinforcing networks in congested areas. Smart meter data is used to match customers with local renewable generators. Cloud-hosted software platform.
Vandebron	Vandebron Energy B.V.	Netherlands, 2014	Platform	P2P marketplace. P2P energy trading platform from suppliers' perspective.

Table 2.4: Research projects based on P2P energy trading. The notation used is "NI" for no information found.

Project	Based on	Network Size	Key points
Secure iNtra-regional-Inter-regional P2P Electricity Trading System (SNIPPETS) for EVs[98]	blockchain-based payment system and Platform for EVs	Intra-Regional-Inter-Regional	Use of Ethereum as a payment platform
Blockchain-Enabled Robust-Game Electricity Transaction Model of Multi-Microgrid System (MMS) Considering Wind Power Uncertainty[99]	Ethereum client Ganache, Metamask wallet and Remix online compiler	Multi-Microgrid	Use of a Private Ethereum client to perform trading transactions while using tokens for payment
V2X blockchain power trading and energy management platform[100]	vehicle-to-everything (V2X) blockchain platform	Regional Microgrids	blockchain power trading and EMS platform combining AI and IoT technologies for EVs
Trading Management Platform based on permissioned blockchain with Paillier algorithm[101]	Hyperledger Fabric	Microgrids	Design of a trading platform based on Hyperledger Fabric while focusing on security
P2P energy trading model with fast-PBFT and Stackelberg game theory[102]	Game-theoretic approach for trading	Microgrid	Fast-PBFT as underlying consensus algorithm
Energy trading scheme based on consortium blockchain and game theory[103]	Consortium blockchain	NI	Only Energy Aggregator nodes participate in the consensus process since they are node certified by the regulatory centre
A localised P2P Electricity Trading system with COnsortium blockchaiN (PETCON) method[104]	Consortium blockchain	Localised (tested on a real urban area of Texas)	Consortium blockchain based on local aggregators to audit and verify transaction records among plug-in hybrid electric vehicles.
BEST: a blockchain-based secure energy trading scheme for electric vehicles[105]	Consortium blockchain	Software-Defined Networking (SDN)	blockchain is used to validate EVs' requests
A Multi-Agent System based electricity trading architecture[106]	Own Consensus	Local (simulated with Australian residential area data)	blockchain-based transaction settlement mechanism is proposed to settle the energy trading transactions
SURVIVOR: blockchain-based Edge-as-a-Service Framework for Secure Energy Trading[107]	PoW for each EV	SDN-enabled V2G environment	Consensus-based mechanism is used to authenticate the energy trading transactions in the system.

Figure 2.11: Location of the projects described in this survey by country. (Note: colour red represents one project, blue two projects, olive three projects and dark green four projects)

local P2P energy markets. Some use blockchain technology to simplify metering and billing systems in the energy markets. However, there is some lack of dealing with P2P energy trading by the energy markets.

Another analysis was performed among some real-world projects, and the general findings are shown in Table 2.5. Figure 2.11 represents each country's contribution to the survey. A brief resumé of each is presented before continuing with further analysis:

SolarCoin [10]

SolarCoin Foundation, a Delaware (U.S.A) registered Public Benefit Corporation, created 2014 an open community project run by volunteers called SolarCoin. The project rewards solar energy producers with blockchain-based digital tokens at one SolarCoin (SLR) rate per Megawatt-Hour (MWh) of solar energy produced. Global, decentralized, and independent of any government. It is a digital asset that uses blockchain technology to encourage global solar energy production, driving the transition from a fossil-fuel economy to a solar-backed economy. It also is spendable and

Table 2.5: General overview of some real-world projects. The notation used is "Y" for applicable, "N" for not applicable and "NI" for no information found.

Project	**Country**	**Year of start**	**Network Size**	**Hardware design?**	**Based on**
SolarCoin	US	2014	Global	N	Platform with blockchain-based digital tokens
Vandebron	Netherland	2014	National	N	Platform
Bankymoon	South Africa	2015	National	Y	Bankymoon smart meters with their own unique bitcoin addresses
Brooklyn Microgrid	US	2016	Multi-apartment	NI	Hybrid smart meters
GrünStrom-Jeton	Germany	2016	NI	N	Token based Platform
Grid-Singularity	Austria	2016	Community	N	Decentralized data exchange platform
Power Ledger Platform	Australia	2016	Community	N	Applications based on blockchain Platform
Dajie	UK	2016	Microgrid	Y	IoT devices and blockchain Platform
Trans-ActiveGrid	Germany	2017	Regional	N	blockchain platform to sell/buy energy
NRGcoin	Belgium	2017	Regional	N	blockchain-based Smart Contract Platform
Green Running	UK	2017	Community	NI	AI algorithms and blockchain platform
PONTON Gridchain and Enerchain	Germany	2017	National	NI	blockchain trading Platform
The Sun-Exchange	South Africa	2018	Community	N	blockchain-based payment system
Share & Charge	Germany	2018	National	N	Electric Vehicle charging stations and Platform
Electron	UK	2018	NI	NI	Platform

tradeable like a cryptocurrency but focuses on incentivizing real-world economic and environmental activity: forsooth-produced solar energy. The distribution part of the program is designed to last 40 years.

Vandebron [11]

This is an online platform where consumers can buy electricity from independent producers, primarily renewable generation. It acts as a platform that links consumers and generators while balancing the market.

Bankymoon [108]

This platform allows people to top up smart meters using the digital currency bitcoin in real-time. This currency allows consumers to pay for their utilities without using traditional banking solutions subject to high transaction fees. The Bankymoon smart meters come with their unique bitcoin addresses. When a smart meter receives payment in bitcoin, Bankymoon computes the tariff and then tops up the meter for the user. The integration of digital currency payments into smart meters enables individuals to “send” electricity, gas, and water to anyone, anywhere in the world, by topping their utility meters using bitcoin [109].

Brooklyn Microgrid [110]

Through blockchain technology, Brooklyn Microgrid developed Exergy, a permissioned data platform that creates localized energy marketplaces for transacting energy across existing grid infrastructure. On the Exergy platform, prosumers, generating energy through their renewable resource, can transact energy autonomously in near-real-time with consumers on the platform in their local marketplace. The Distributed Systems Operator uses price as a proxy to manage energy use, load balancing, and demand response at negotiated rates. The distributed system operator is granted access to consumer data like - building management systems.

GrünStromJetons [12]

GrünStromJetons are proof of the purchase of locally generated electricity from hydropower, wind power or solar energy, which is available to every electricity customer, regardless of their place of residence or electricity provider. The GrünStromIndex blockchain-based system observes the energy consumption by using smart meters and rewards those consumers with more consumption from alternative sources by giving them GrünStromJetons. These GrünStromJetons can be traded and exchanged.

GridSingularity [111]

Grid Singularity is a green blockchain technology company leading the development of an open, decentralised energy data exchange platform under the auspices of the Energy Web Foundation (EWF). To coordinate increasing numbers of small energy producers and flexible loads in a trustless, open, decentralised network. Grid Singularity is building a grid management agent: D3A. The D3A creates a novel market model for the transactive grid, enabling a broad spectrum of energy market-related transactions on a single platform layer.

PowerLedger [13]

PowerLedger produces five applications:

1. **xGrid:** P2P electricity trading across the regulated electricity network. By utilizing blockchain technology, xGrid allows neighbours to trade low-carbon energy, make an income from their excess generation and receive a better return on renewable energy investments.

2. μ **Grid:** P2P electricity trading behind the regulated electricity master meter that enables electricity metering, big data acquisition, rapid micro-transactions and microgrid management at an unprecedentedly granular scale. It also breaks the nexus between energy generation and consumption in these environments by generating revenue from renewable energy assets, including PVs and batteries.

3. **Power Port:** Electric vehicle metering and settlement. Designed for anyone interacting with EV charging stations. Providing transparent, secure and real-time metering, Power Port also enables a simple, convenient and instant payment method.

4. **C6 and C6+:** Carbon Credits and Certificates. C6 provides significantly improved efficiency and cost savings by using automated reporting to generate carbon credits and certificates. Underpinned by Power Ledger's blockchain technology, C6+ offers complete ledger visibility, ensuring all transactions are entirely immutable and reliably audited. Further trust and security are built into trading carbon credits with C6+ through smart contracts.

5. **Asset Germination Events (AGE):** These are the ways in which communities can fund and generate revenue from shared renewable energy infrastructure. AGEs empower communities to monetize their co-owned renewable energy assets such as PVs, wind turbines, EV charging stations, batteries and more. This application promotes faster uptake of renewable energy assets and communities having a more resilient and cleaner energy system.

Dajie [112]

Based on the combination of IoT devices and blockchain technology. IoT devices create a network of nodes in a local Microgrid to allow people to exchange energy peer to peer. At the same time, the blockchain platform simplifies the management of their transactions. When the consumer installs one of their IoT devices and registers to the platform, then, for every kWh of energy produced, one energy coin will be generated in real-time by the Dajie platform and stored in a safe wallet.

TransActiveGrid [96]

The TransActiveGrid project is based in Brooklyn and is the fruit of the cooperation between LO3 Energy and ConsenSys. The concept allows residents with solar panels on their roofs to sell energy directly to their neighbours without a middleman's administrative or financial burden. The power goes directly from one house to another, and payment happens with blockchain.

NRGcoin [14]

This is an industry-academia project initially developed at Vrije Universiteit Brussel and is currently up-scaled in an industrial context by Enervalis. The NRGcoin mechanism replaces traditional high-risk renewable support policies with a novel blockchain-based Smart Contract, which better rewards green energy. For every 1kWh of green energy, consumers pay 1 NRGcoin directly to the Smart Contract. This ratio ($1kWh = 1NRGcoin$) always holds, regardless of the retail value of electricity. The Smart Contract then pays all grid fees and taxes to the DSO from the coins paid by the consumer. The Smart Contract then validates the reported injection of green energy by prosumers using a variety of methods [113].

The Smart Contract mints new NRGcoins and rewards prosumers for their injected green energy if all reports check out. Prosumers can then sell those coins on a currency market or use them later to pay for green energy. Consumers buy their NRGcoins to pay for their consumption in the currency market. The associated coins are not destroyed when energy is paid but remain in circulation. The minting rate decreases with time to prevent excessive inflation.

Green Running [114]

Based on a blockchain system: Verv hub, which can identify the power usage of individual appliances in the home using artificial intelligence. This knowledge, mapped against behavioural trends such as when appliances are usually used, is how Green Running uses machine learning to predict what energy will be needed for a home in advance to get the best possible price from the grid. This advanced monitoring can anticipate the demand and calculate the supply to enable peer-to-peer trading. It also pulls in environmental factors such as the weather, using satellite data from cloud cover and opacity to predict how much solar power will be generated for a home with that energy source.

PONTON Gridchain and Enerchain [15]

Enerchain consists of a first project that aims to support off-market P2P energy trading, basically an OpenBazaar, but optimised for energy traders. For this, traders install a blockchain node and the required trading screen over which orders can be transmitted and completed trades. Both are exchanged directly between the participants via the blockchain[115]. Enerchain proceeds as a "blockchain think tank" so that PONTON analyses developments on the business or technological level. Potential processes are then be specified in detail and validated through prototypes.

TheSunExchange [16]

This is a blockchain-based payment system where anyone can buy solar cells and lease them to schools and businesses in Africa. The Sun Exchange arranges the monthly lease rental collection and distribution. The user gets paid in bitcoin or local currency, wherever in the world the user is. Solar projects are insured for fire, damage and theft.

Share&Charge [116]

Share&Charge is a decentralised protocol for EV charging, transactions and data sharing. Charge Point Operators (CPO), Mobility Service Providers (MSP) and Grid Operators can easily integrate the Share&Charge core client and offer their customers a seamless, intelligent and secure charging experience. At the same time, end customers will benefit from seamless access, smart charging and safe integration of all devices.

Electron [17]

Electron has three different areas of operation:

- **Meter Registration Platform:** a shared registration platform for all UK gas and electricity supply points to facilitate faster switching, trying to extend to different types of assets.

- **Flexibility Trading Platform:** a typical trading venue for all demand-side response actions to enable collaborative trading in the current hierarchical system as well as P2P and micro-grid trading.
- **Community Energy Projects:** these take place in a decentralising and democratising energy system. Coordination of millions of distributed energy resources and trading interests is key to maximising system value.

Several tools were built, which are available as open-source.

A brief summary is presented below concerning the research projects mentioned in Table 2.4.

Secure iNtra-regional-Inter-regional P2P Electricity Trading System (SNIPPETS) for EVs [98]

The system addresses benefit conflicts between electricity traders, as well as price competition among neighbouring regions, thereby improving overall social welfare. However, the Ethereum module of SNIPPETS only supports transaction payments and data storage and lacks the protection of transaction information during the trading process.

Blockchain-Enabled Robust-Game Electricity Transaction Model of Multi-Microgrid System (MMS) Considering Wind Power Uncertainty [99]

The presented blockchain-enabled robust-game electricity transaction model can achieve transparent and decentralized electricity transactions without the intervention of a trusted third party, improve the overall economy of MMS, promote the wind power generation (WPG) consumption, handle the conflict of interest between different trading microgrids and effectively cope with the WPG uncertainty.

V2X blockchain power trading and energy management platform [100]

This presents an overall study of the V2X blockchain power trading and EMS platform. The platform was tested with only 30 charging piles simulated for EV charging stations in commercial buildings. The authors hope this platform will meet demands for charging and discharging transactions when the number of EVs increases rapidly and solve the real-time supply and demand imbalance problems caused by the high proportion of renewable energy. The blockchain platform is designed as public; however, it uses an SQL database as a buffer to store transaction data that comes from the distributed ledger, which is then displayed on the user interface.

Trading Management Platform based on permissioned blockchain with Paillier algorithm [101]

The proposed trading management platform was constructed and deployed utilising the permissioned blockchain Hyperledger Fabric. The trading management platform devised a homomorphic encryption scheme that provides an exceptional level of privacy protection without compromising trading efficiency to better safeguard users' privacy in the trading platform.

P2P energy trading model with fast-PBFT and Stackelberg game theory [102]

The type of market is determined based on energy supply and demand, then uses cooperative and noncooperative games to construct the protective effect between buyers and sellers while using the fast PBFT as the underlying consensus algorithm for P2P trading in the blockchain environment.

Energy trading scheme based on consortium blockchain and game theory [103]

A game model is established to transform the competition of energy trading into the solution of game equilibrium. The scheme can ensure that all energy entities obtain maximum benefits and achieve a mutual benefit for both sides of supply and demand. On their Consortium blockchain, all nodes must be authorized by certificate authority when participating in the transaction, and each energy node has the same trading rights.

A localised P2P Electricity Trading system with COnsortium blockchaiN (PETCON) method [104]

This system focuses on localised P2P electricity trading that should maximize social welfare and achieve effective market equilibrium. The model is predicated on an iterative double auction mechanism for charging and discharging plug-in hybrid electric vehicles (PHEVs) to maximize social welfare. The local aggregators work as auctioneers to conduct the double auction among PHEVs according to their bid prices, which does not require private information about PHEVs.

BEST: a blockchain-based secure energy trading scheme for electric vehicles [105]

The miner nodes are selected to validate the requests based on energy requirements, time of stay, dynamic pricing, and connectivity record, such as other factors crucial for the operator at the time of operation. The scheme presents a design of an SDN-based vehicular networking architecture to transfer energy trading requests from EVs to the global controller and vice-versa for improving the quality of service in the network.

A Multi-Agent System based electricity trading architecture [106]

This system proposes a set of multi-agent coalition formation and electricity trading negotiation protocols to enable prosumers to form coalitions and negotiate the electricity amount and trading price. The consensus proposed consists of a contract chain, a ledger chain, and a high-frequency verification module. The high-frequency verification mechanism is designed to inspect any inconsistencies between the smart contract and ledger to detect malicious manipulation from cyber attacks.

SURVIVOR: blockchain-based Edge-as-a-Service Framework for Secure Energy Trading [107]

EVs select an edge node (from all available edge nodes) based on utility functions. This selected edge node serves the EVs for handling their energy trading computational load. Using this edge-as-a-service platform, EVs trade for the required energy with the CSs deployed in the smart city. The edge nodes (other than the one responsible for the computation load of an EV) act as approver nodes for transaction authentication.

The proliferation of systems, platforms and projects clearly makes comparisons between them problematic. The most significant elements introduced in Chapter 2.3.1 are used as a base for comparison in this research, and a more detailed analysis of the previous projects is presented in the following subsection.

2.3.3.1 Type of blockchain used in the research projects

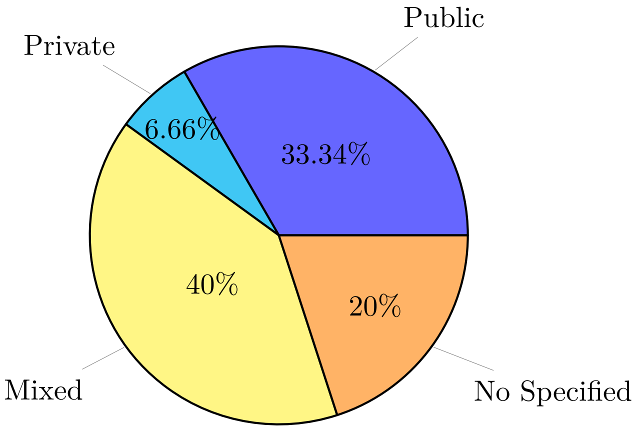


Figure 2.12: Type of blockchain used by research projects described in Table 2.5

Figure 2.12 represents the percentage of types of blockchain used. The difference between Mixed (Federated) and Public (Permissionless) blockchain stands out in this figure. A possible reason could be that Mixed types may be less susceptible to individual influence, or perhaps public types are less likely to be scalable.

2.3.3.2 Type of Consensus Algorithms used in the research projects

The pie chart in Figure 2.13 shows the proportion of different categories of consensus algorithms used. As shown, the PoW algorithm reported significantly more use than the other algorithms. One reason for this difference may be the high latency of transaction validation that PoW consensus has, even though the amount of energy

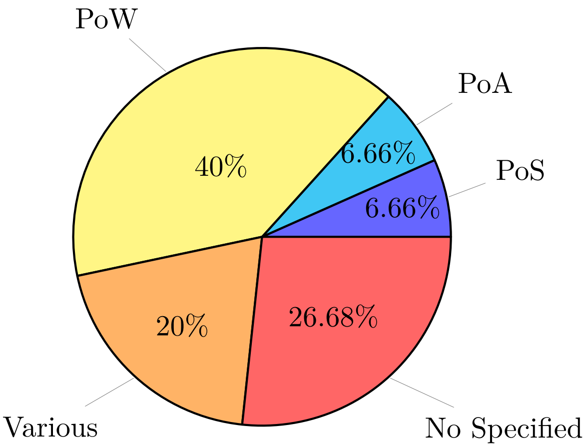


Figure 2.13: Type of Consensus Algorithm used by research projects described in Table 2.5

must be used. The most exciting aspect of this graph is that PoA and PoS consensus algorithms have less use than PoW. For PoA consensus, it might be attributed to the use of authorities to create blocks and secure the ledger, which gives a less distributed view of the ledger. PoS consensus may be associated with how validators are chosen by the number of stakeholders, which might severely influence the ledger.

2.3.3.3 Type of Transaction

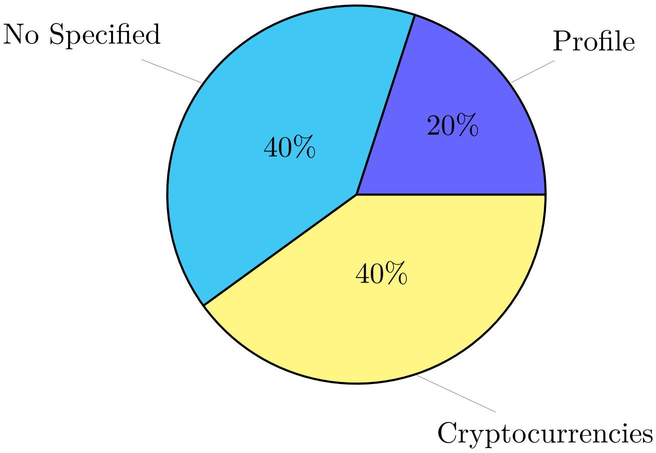


Figure 2.14: Type of Transaction used by research projects described in Table 2.5

Figure 2.14 represents the ratio on types of transactions used. There was no significant difference between projects were did not specify their type of transaction and the use of cryptocurrencies. A possible explanation for these results may be the lack of adequate state-of-the-art of these projects. There are, however, other possible explanations.

2.3.4 Hyperledger Fabric

Hyperledger Fabric was used in this research as the blockchain Network to perform the present research due to its modular design, highly scalable flexibility and flexible components such as the ledger, smart contract, consensus authority management, and digital certificate. Hyperledger Fabric is the first distributed operating system for permissioned blockchains built specifically for business[97]. This research takes permissioned blockchain's advantages, such as a high level of privacy and security. Given the type of user on the P2P Energy trading (untrusted parties), without a verified set of credentials and access, no user can access or alter transaction information without permission. For detailed reference of Hyperledger Fabric structure see Appendix A. Hyperledger's main attributes are:

- **Hyperledger Fabric is modular, extensible and scalable.** Each component built on Hyperledger Fabric has the quality of a plug-and-play component; distributed ledgers, consensus protocols, membership services, smart contracts, and others run independently of each other. This built-in modularity enables system privacy and resiliency.
- **Hyperledger Fabric is Open Source.** Blockchain technology aims to share community assets whose direction is determined by the users instead of being controlled by a single user. Hyperledger Fabric is the first framework to run applications written in general-purpose programming languages without depending on a particular currency. Hosted and governed by The Linux Foundation with more than 180 companies behind Hyperledger, 28 different companies and 159 engineers participated in the release of Hyperledger Fabric 1.0.

- **Hyperledger Fabric is permissioned.** A permissioned framework means that all participants in a blockchain network are known to one another. Permission contrasts with permissionless blockchain platforms, where network members can remain anonymous. In the case of a private permissioned network, membership may be by invitation only.

- **Hyperledger Fabric does not rely on cryptocurrency or mining.** The way of participation from users in a blockchain network differs from each other. In Hyperledger Fabric, participants work together around a common cause or goal; moving goods more efficiently, sharing patient data more securely, ensuring food safety and much more. Therefore, systems design in Hyperledger Fabric requires fewer resources: time, computing power and energy.

Research by Androulaki et al.[117] presents an Unspent Transaction Outputs (UTXO) model to track the balances of a purely conceptual token minted. This research aimed to put Hyperledger Fabric Framework's performance in the context of other permissioned blockchains often derived from Bitcoin or Ethereum. Hyperledger Fabric performed at a rate of more than 3500 transactions per second with 300 to 400-millisecond latency[118–120].

2.3.5 General findings

Through a low-cost settlement system, P2P refers to the ability to trade electricity with one another (consumer or prosumer), earn income for extra power, cut electricity bills, and improve returns on distributed generating investments. P2P trading enables the incorporation of blockchain technology in the microgrid operation quickly and automatically. It allows direct communication between market players without needing a third party. A P2P system may employ blockchain technology to track the amount of electricity traded and provide a transparent and automatic payment process. Users can switch energy suppliers regularly and buy-sell electricity according to their preferences using P2P trading. Local consumers can acquire low-cost energy supply through this energy trading automation through their microgrids[121]. More of this application will be discussed later.

Together these results provide important insights into using blockchain for P2P Energy Trading. One interesting finding is the slight difference between Mixed and Public types of blockchain. Another important finding is that cryptocurrencies might be an excellent solution to ensure transactions between peers. The most exciting finding was the high use of PoW as a consensus algorithm even though the energy is consumed too high.

Very little was found in the literature about the type of transaction used by the projects. This finding is unexpected and suggests that more research in this area be performed.

These results may be limited to public information available for each project. These results further support the hypothesis that blockchain can be used as a platform for P2P Energy Trading. However, further work is required to establish its viability regarding the energy balance in the transmission/distribution line.

Chapter 3

Demand-Prioritised Double Auction Mechanism

The role of prosumers in supplying energy is becoming increasingly essential and is significantly impacting power systems. Prosumers, individuals or organizations that generate their energy are becoming more active in trading energy and influencing the trading process. Prosumers can sell their surplus energy, which they have generated but are not consuming, or energy that has been stored, in the local market. However, this has created new challenges for P2P energy trading, such as ensuring fairness while approving trades and managing the increased proportion of distributed energy.

To address these challenges, a mechanism called the Demand-Prioritised Double Auction Mechanism (DPDA) has been proposed for the peer-to-peer trading model. The DPDA mechanism is based on a double auction system where buyers and sellers submit their reserved price and quantity of energy to trade to an auctioneer, who then decides on the price for the trade and which buyers and sellers will be involved in the trade. The DPDA mechanism ensures buyer satisfaction by ensuring each winning buyer purchases their total energy requirement. This factor will also determine the number of winning buyers and sellers for each trade.

The DPDA mechanism also promotes cooperative behaviour among prosumers by ensuring they receive the most reasonable price for the energy they are trading.

This is achieved by calculating the prosumers' interests during the matching phase and defining their welfare, as described in Chapter 4. By encouraging cooperative behaviour, the mechanism aims to prevent prosumers from taking advantage of the situation. Finally, the chapter discusses the effects of cooperative and non-cooperative behaviour in energy trading.

3.1 Introduction

The energy market has two primary objectives: generating and transmitting electrical power[42]. Challenges of local market operators and their fundamentals were discussed in Section 2.2.1. These operators control power transmission to meet system-wide demands[122]. The central control authority or market operator determines the amount of energy produced by a given power plant. The transmission service market considers issues such as scheduled outages, power flows including losses, the price offered by each generator for supplying electricity, and a prediction of aggregated demand. The process is then balanced through small changes to dispatch and ancillary services, which control the frequency and voltage[123]. Adding users as active prosumers requires the whole process to be redefined to encourage distributed energy, which previous trading mechanisms cannot achieve.

P2P trading aims to remove intermediaries from transactions, especially as platforms that allow prosumers to benefit from higher rates of return than they would receive on conventional trading channels. Blockchain is an example of such technology[5]. The idea is to facilitate access to trade at cheaper rates, especially for retail consumers, because of the reduced operational and intermediation costs of P2P platforms. However, a method to enable this trading is necessary.

The standard Double Auction Mechanism (DAM) presented in Chapter 2.2.3, also known as McAfee's mechanism, helps determine the winners in energy trading. Buyers and sellers who can trade based on their amount of energy and the price proposed are considered winners. Buyers and sellers submit their private reserved price and quantity of energy to trade to an auctioneer. The auctioneer decides the price for the trade and the subsets of sellers and buyers who will be part of the trade. The double auction mechanism features an absence of strategic behaviour among prosumers without reference to bidding behaviour. Equilibrium properties can be established purely on the characteristics of the underlying distribution of bids/offers.

Nash equilibrium states nothing is gained if parties change their strategy while others maintain it[124]. In contrast, the Dominant strategy asserts that a party will choose a strategy that will lead to the best outcome regardless of the other parties' chosen strategies. As shown by Wang et al.[125], Nash Equilibrium exists to determine such winners, and efficient algorithms are proposed to guide the buyer and the seller to converge to an approximate Nash Equilibrium quickly.

The proposed method aims to formulate a centralised local auction process in a distributed fashion without investigating such strategies (behaviours) for all prosumers with a Dominant strategy. The main focus is to incentivise prosumers to participate in the trade while supporting their community by keeping the energy local and promoting the use of DERs in the area, prioritising buyers' demands to achieve this.

This research focuses on buyers as the primary objective. Understanding their needs will build trust and ultimately influence the prosumer's purchasing decision. The proposed DPDA aims to obtain the subset of participating buyers and sellers for the trading while ensuring that the buyers receive the amount of requested energy. To get the needed amount is necessary to ensure enough energy to sell. In order to achieve buyers' satisfaction, the mechanism proposed aims to cover their energy asked by adding a condition to the Double Auction Mechanism. When the mechanism gets an oversupply, the excess energy is divided among the subset of all participant sellers to keep the trade fair.

3.2 Formulation of Problem

In a microgrid, buyers and sellers aim to trade energy (measured in kWh) while being truthful. The microgrid is defined from the substation to end-users. The total number of buyers and sellers are denoted by $\mathcal{B}$ and $\mathcal{S}$, respectively. Each seller i has a private reserved price, $\mathcal{P}(\mathcal{S}_i)$, in pounds per kWh, to sell a certain amount of energy, $\mathcal{E}(\mathcal{S}_i)$, in kWh. Similarly, each buyer j has a private reserved price, $\mathcal{P}(\mathcal{B}_i)$, in pounds per kWh, to buy a certain amount of energy, $\mathcal{E}(\mathcal{B}_i)$, in kWh.

The proposed mechanism determines the subset of buyers and sellers participating in the trading by defining the equilibrium point. To ensure that buyers are satisfied, the subset of sellers needs to ensure that the total amount of energy from the buyers is met.

In case of oversupply, the proposed mechanism ensures that the excess energy is distributed among all the sellers in the participating subset. This excess energy can be used to cover any power loss or can be utilised by the DSOs when performing power balance.

3.3 Proposed Behavioural Data for Users

Two different analyses were performed to prove the benefits of the proposed DPDA mechanism. The first analysis examines the participants allowed to trade while considering the buyer's satisfaction. The second analysis demonstrates the use of the proposed DPDA mechanism as a means to incentivise participants to be more cooperative.

For the first analysis, case studies were conducted to demonstrate the efficacy of the proposed trading mechanism. Reserved prices and volume of goods to trade were generated randomly and are not based on actual trade values. The reserved prices range from £2.0 to £30.0, and the volume of goods ranges from $5kWh$ to

Scenario	Number of Sellers vs Buyers	Amount of energy $\sum \mathcal{E}(\mathcal{S}_i)$ vs $\sum \mathcal{E}(\mathcal{B}_j)$
1	$8 > 7$	$268 > 259$
2	$8 > 7$	$268 < 341$
3	$8 > 7$	$268 = 268$
4	$7 < 8$	$198 > 150$
5	$7 < 8$	$198 < 268$
6	$7 < 8$	$198 = 198$
7	$8 = 8$	$268 > 150$
8	$8 = 8$	$268 < 341$
9	$8 = 8$	$268 = 268$
10	$8 > 7$	$268 = 268$
11	$7 < 8$	$198 > 150$
12	$8 = 8$	$268 < 341$
13	$8 = 8$	$268 < 341$

Table 3.1: Conditions for each scenario simulated.

$100kWh$. The total number of participants for the first analysis was 15 or 16 users, and the ratio of buyers and sellers changed for each scenario in both analyses. In addition, the total amount of energy between buyers and sellers was also changed for each scenario. Finally, scenarios 10 to 13 were added to analyse the impacts on the trades while having similar prices on the sellers and/or buyers. Table 3.1 summarises the parameters described, where $\mathcal{E}(\mathcal{S}_i)$ and $\mathcal{E}(\mathcal{B}_j)$ represent the total amount of energy that sellers and buyers want to trade at the point of submission, respectively.

Table 3.2: Condition for each scenario simulated to test performance.

Scenario	Number of Sellers vs Buyers	Amount of energy $\sum \mathcal{E}(\mathcal{S}_i)$ vs $\sum \mathcal{E}(\mathcal{B}_j)$	Total Number of participants
P-10	$5 = 5$	$155 < 163$	10
P-20	$11 > 9$	$382 > 322$	20
P-30	$14 < 16$	$524 < 658$	30
P-40	$22 > 18$	$841 > 713$	40
P-50	$25 = 25$	$1003 = 1003$	50

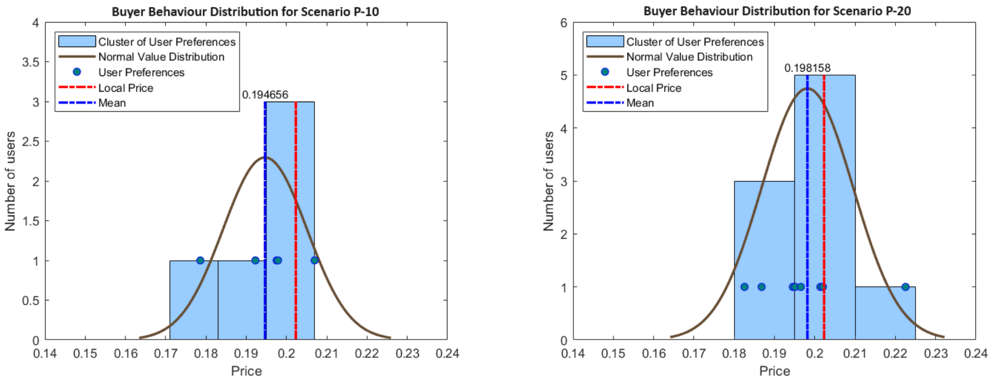
For the second analysis, another set of scenarios was defined, where the number of participants was increased, intending to test the proposed trading mechanism's performance and behaviour. Reserved prices are normalised random values based on a local price of $£0.2023$; by 2021, the price was $£627.18$ for $3,100kWh$ [40], and the volume for tradings of energy ranges from $30kWh$ to $200kWh$. The total number of participants was incremented for each scenario, starting with 10 participants and up to 55 participants; these increments simulate off-peak and peak demand. The correlation between the number of buyers and sellers changed for each scenario, and the total amount of energy to trade had a similar change in ratio. Table 3.2 summarises these criteria. These scenarios are used as a base for cooperative and non-cooperative behaviour comparison.

Figures 3.1 and 3.2 present the normalised behaviour of buyers and sellers. These data sets show cooperative behaviour, with a standard deviation for buyers of 0.01 and 0.025 for sellers. Meanwhile, Figures 3.3 and 3.4 show the normalised behaviour of buyers and sellers, respectively, with no cooperative behaviour. The standard deviation for buyers is 0.02 and 0.045 for sellers.

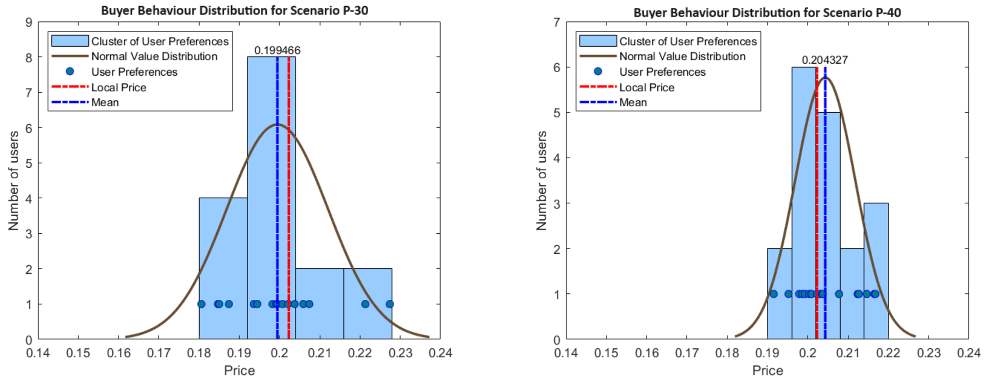
3.4 Proposed Mechanism

The proposed DPDA mechanism is designed to satisfy buyers' requirements while meeting the conditions of the standard Double Auction Mechanism. It achieves this by ensuring that the sum of the energy supplied by the sellers in a subset is greater than or equal to the sum of the energy requested by the buyers in another subset. If this condition is met, any oversupply is distributed among the sellers in the subset.

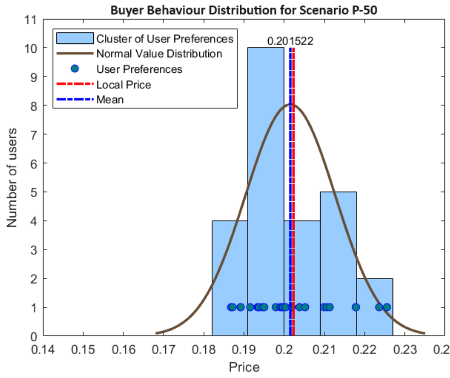
The Algorithm 2 presents the proposed DPDA mechanism and is based on McAfee's work, which produces a curve representing the buyers' and sellers' energy bids. The point where these curves intersect is the equilibrium point and determines the proposed price to trade. The proposed algorithm has four cases covering all possible scenarios based on the previously defined conditions. These cases prioritise meeting the condition where the sum of the energy supplied is greater than or equal to the sum of the energy requested.



(a) Scenario P-10 (b) Scenario P-20

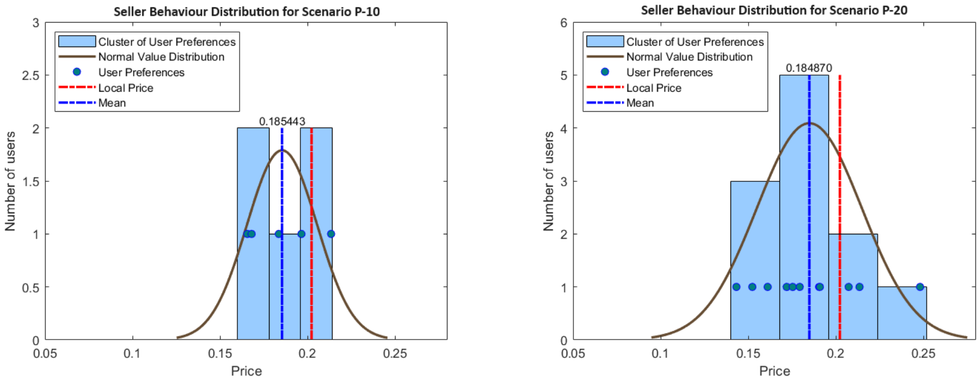


(c) Scenario P-30 (d) Scenario P-40



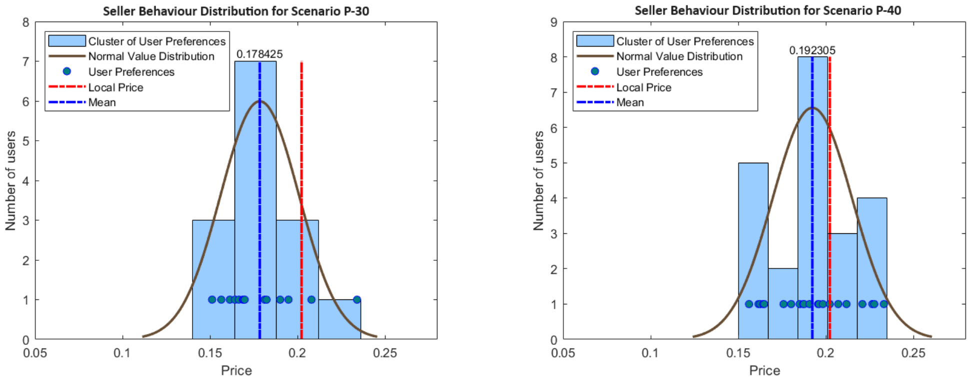
(e) Scenario P-50

Figure 3.1: Normalised Behaviour for buyers with cooperative behaviour for Scenario a)P-10, b)P-20, c)P-30, d)P-40, and e)P-50; see Table 3.2.



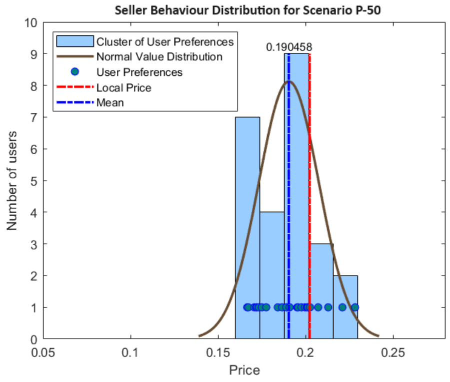
(a) Scenario P-10

(b) Scenario P-20



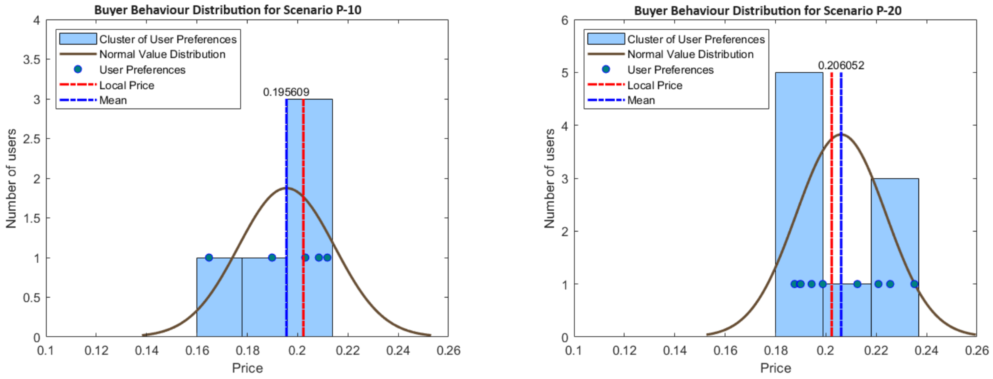
(c) Scenario P-30

(d) Scenario P-40

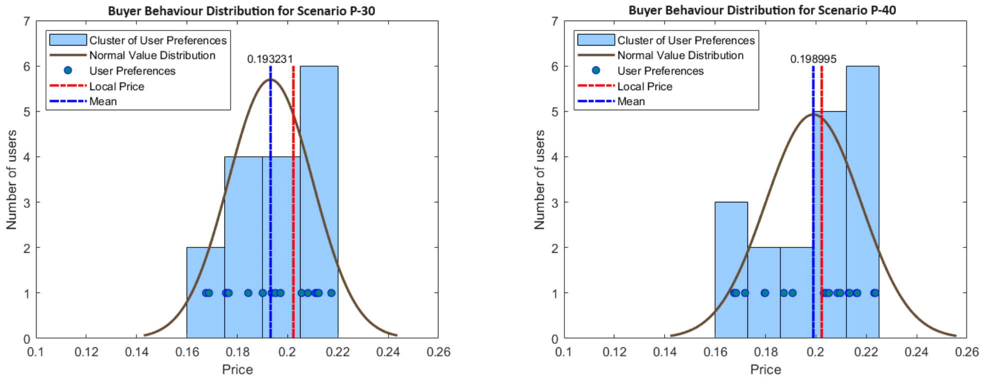


(e) Scenario P-50

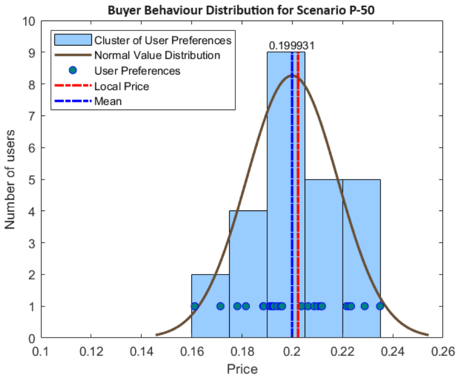
Figure 3.2: Normalised Behaviour for sellers with cooperative behaviour for Scenario a)P-10, b)P-20, c)P-30, d)P-40, and e)P-50; see Table 3.2.



(a) Scenario P-10 (b) Scenario P-20

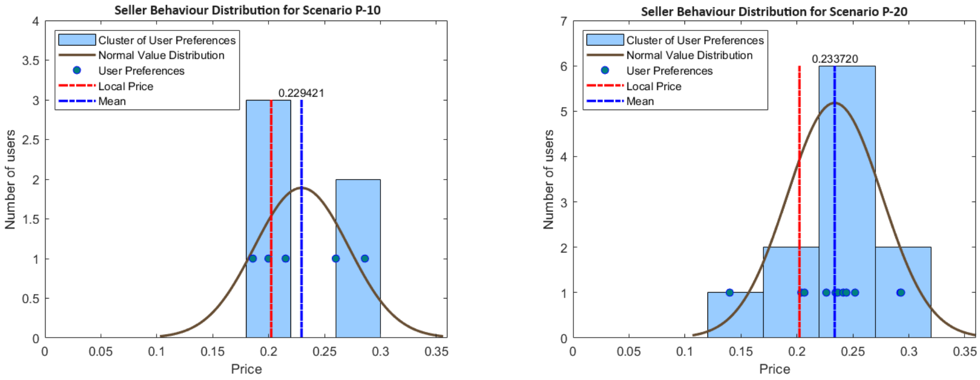


(c) Scenario P-30 (d) Scenario P-40



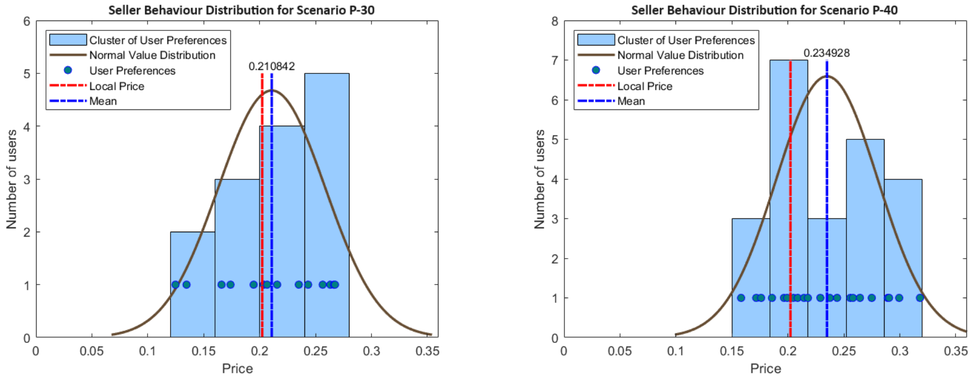
(e) Scenario P-50

Figure 3.3: Normalised Behaviour for buyers with no cooperative behaviour for Scenario a)P-10, b)P-20, c)P-30, d)P-40, and e)P-50; see Table 3.2.



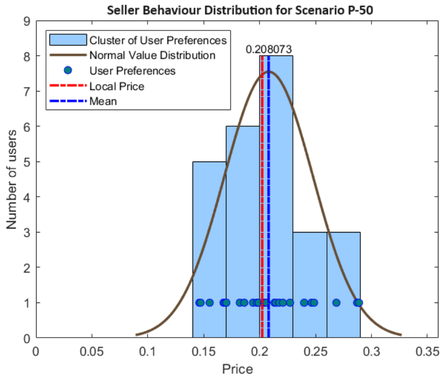
(a) Scenario P-10

(b) Scenario P-20



(c) Scenario P-30

(d) Scenario P-40



(e) Scenario P-50

Figure 3.4: Normalised Behaviour for sellers with no cooperative behaviour for Scenario a)P-10, b)P-20, c)P-30, d)P-40, and e)P-50; see Table 3.2.

Algorithm 2 Proposed DPDA Algorithm

```
Require: Seller curve $\mathcal{P}(\mathcal{S}_1) \leq \mathcal{P}(\mathcal{S}_2) \leq \cdots \leq \mathcal{P}(\mathcal{S}_{\mathcal{S}})$
Require: Buyer curve $\mathcal{P}(\mathcal{B}_1) \geq \mathcal{P}(\mathcal{B}_2) \geq \cdots \geq \mathcal{P}(\mathcal{B}_{\mathcal{B}})$
Ensure: $(x, y) \in \left\{ \begin{array}{ll} [\mathcal{P}(\mathcal{B}_x) \ \geq \ \mathcal{P}(\mathcal{S}_y)] & \& \\ [\sum^y \mathcal{E}(\mathcal{S}_i) \ \geq \ \sum^x \mathcal{E}(\mathcal{B}_j)] & \end{array} \right\}$
  if $\left[\frac{\mathcal{P}(\mathcal{S}_{y+1})+\mathcal{P}(\mathcal{B}_{x+1})}{2}\right] \in [\mathcal{P}(\mathcal{S}_y), \mathcal{P}(\mathcal{B}_x)]$ then
      if $\sum^x \mathcal{E}(\mathcal{B}_j) \leq \sum^y \mathcal{E}(\mathcal{S}_i)$ then
          $Sellers = [\mathcal{S}_1, \mathcal{S}_2, ..., \mathcal{S}_y]$
          $Buyers = [\mathcal{B}_1, \mathcal{B}_2, ..., \mathcal{B}_x]$
          $p_0 = \frac{\mathcal{P}(\mathcal{S}_{y+1})+\mathcal{P}(\mathcal{B}_{x+1})}{2}$
          $oversupply \ = \ \frac{\sum^y \mathcal{E}(\mathcal{S}_i) \ - \ \sum^x \mathcal{E}(\mathcal{B}_j)}{y}$          ▷ Case 1
      else
          $Sellers = [\mathcal{S}_1, \mathcal{S}_2, ..., \mathcal{S}_{y-1}]$
          $Buyers = [\mathcal{B}_1, \mathcal{B}_2, ..., \mathcal{B}_{x-2}]$
          $p_0 = \frac{\mathcal{P}(\mathcal{S}_y)+\mathcal{P}(\mathcal{B}_{x-1})}{2}$
          $oversupply \ = \ \frac{\sum^{y-1} \mathcal{E}(\mathcal{S}_i) \ - \ \sum^{x-2} \mathcal{E}(\mathcal{B}_j)}{y-1}$          ▷ Case 2
      end if
  else
      if $\sum^{x-1} \mathcal{E}(\mathcal{B}_j) \leq \sum^{y-1} \mathcal{E}(\mathcal{S}_i)$ then
          $Sellers = [\mathcal{S}_1, \mathcal{S}_2, ..., \mathcal{S}_{y-1}]$
          $Buyers = [\mathcal{B}_1, \mathcal{B}_2, ..., \mathcal{B}_{x-1}]$
          $p_0 = \frac{\mathcal{P}(\mathcal{S}_y)+\mathcal{P}(\mathcal{B}_x)}{2}$
          $oversupply \ = \ \frac{\sum^{y-1} \mathcal{E}(\mathcal{S}_i) \ - \ \sum^{x-1} \mathcal{E}(\mathcal{B}_j)}{y-1}$          ▷ Case 3
      else
          $Sellers = [\mathcal{S}_1, \mathcal{S}_2, ..., \mathcal{S}_y]$
          $Buyers = [\mathcal{B}_1, \mathcal{B}_2, ..., \mathcal{B}_{x-1}]$
          $p_0 = \frac{\mathcal{P}(\mathcal{S}_{y+1})+\mathcal{P}(\mathcal{B}_x)}{2}$
          $oversupply \ = \ \frac{\sum^y \mathcal{E}(\mathcal{S}_i) \ - \ \sum^{x-1} \mathcal{E}(\mathcal{B}_j)}{y}$          ▷ Case 4
      end if
  end if
  $\mathcal{E}'(S_i) = Max(0, \mathcal{E}(\mathcal{S}_i) - oversupply)$
```

In **Case 1**, all conditions are met, and the subsets of buyers and sellers participating are defined based on the intersection point. The proposed price to trade is taken from the seller and buyer at indices $y + 1$ and $x + 1$, respectively. In **Case 2**, the energy submitted by the buyers is insufficient to supply all the sellers from the subsets of buyers and sellers participating. In this scenario, the number of buyers is reduced by two, and the number of sellers is reduced by one, making the new intersection point $(x-2, y-1)$. The proposed price to trade is taken from the seller at index y and the buyer at index $x-1$.

Case 3 describes a scenario where the Double Auction Mechanism's condition has not been met. Hence, the subsets of sellers and buyers are reduced by one each, giving the new intersection point $(x-1, y-1)$. For the proposed price to trade, the seller at index y and the buyer at index x are used. Finally, in **Case 4**, the worst-case scenario is defined, where all conditions are not met. For this case, the subset of buyers is modified and reduced by one participant, producing the new intersection of $(x-1, y)$. The proposed price to trade is based on the seller at index $y+1$ and the buyer at index x.

Before submitting a request, the DPDA mechanism checks the prosumer's state to ensure that the requested energy can be produced or is already stored. This check helps the prosumer submit quantities of energy that can be committed to the trading. However, the system can change such quantities if the amounts need to be corrected. The mechanism also has penalty charges for prosumers who fail to complete the transaction, as discussed in Chapter 4.

3.5 Case Study Results

The following subsections present the key findings for both analyses using the data set defined in section 3.3. First, an ideal scenario is presented to demonstrate the application of the proposed DPDA mechanism. Then, the different possible outcomes regarding the cases defined in Algorithm 2, finalising with an analysis of the two types of prosumers' behaviour, cooperative and non-cooperative.

3.5.1 Analysis of an ideal scenario for the proposed DPDA mechanism

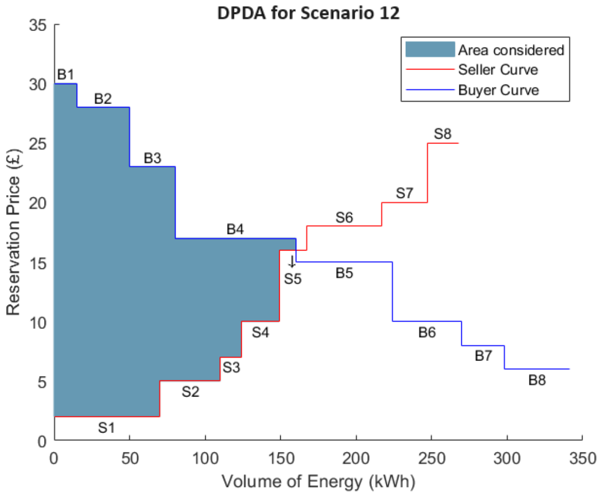


Figure 3.5: Proposed DPDA mechanism to determine winners for Scenario 12, see Table 3.1.

Table 3.3: Parameters used in Scenario 12, see table 3.1.

Parameter	Value
Set of sellers (ID)	[73,44,11,32,53,6,45,4]
Set of buyers (ID)	[116,110,10,9,95,48,42]
Set of amount of energy to sell (kWh)	[30,25,18,40,50,21,14,70]
Set of amount of energy to buy (kWh)	[80,35,43,15,28,64,30,46]
Set of reserved prices from sellers (£)	[20,10,16,5,18,25,7,2]
Set of reserved prices from buyers (£)	[17,28,6,30,8,15,23,10]

Scenario 12 is used to demonstrate the process of the proposed DPDA Mechanism; see Figure 3.5. The values for the energy demand (in kWh), energy production (in kWh), reservation price for both sellers and buyers in (£) and distance preference for buyers and sellers (in km) are randomized. For this scenario, there are eight sellers and seven buyers, some sellers have similar prices, and the total amount of energy to sell is greater than the total amount of energy to buy. Table 3.3 presents the parameters submitted for this scenario and are displayed in order of submission. Following Algorithm 2:

1. Once the values are reported, the new set of reservation prices for sellers is arranged in ascending order:

   $\mathcal{P}'(\mathcal{S}) = \{2, 5, 7, 10, 16, 18, 20, 25\}$

   And the new set of reservation prices for buyers is arranged in descending order:

   $\mathcal{P}'(\mathcal{B}) = \{30, 28, 23, 17, 15, 10, 8, 6\}$

2. Then, the intersection is found between the prices of 17 and 16 for buying and selling, respectively. On this point $x = 4$ and $y = 5$, see Figure 3.5. Ensuring that the conditions mentioned above stated in Algorithm 2 are met by using the values of $x = 5$ and $y = 6$:

   $$\frac{18 + 15}{2} = 16.5 \in [16, 17]$$

   Then, the total energy considering the intersection point is calculated:

   $$\sum_{i=1}^{y} \mathcal{E}(\mathcal{S}_i) = 167, \; \sum_{j=1}^{x} \mathcal{E}(\mathcal{B}_j) = 160$$

3. Since $\sum^{x} \mathcal{E}(\mathcal{B}_j) < \sum^{y} \mathcal{E}(\mathcal{S}_i)$ then the next seller and the next buyer in the intersection are considered as the based price. The subset of seller's IDs considered to trade is $[24, 20, 45, 4]$, and for the subset of buyers is $[39, 9, 12]$.

   The price proposed for the trading is 16.5 as previously calculated, and the oversupply shared between the 5 sellers as:

   $$Oversupply = \frac{167 - 160}{5} = 1.4$$

4. Each seller on the subset of prosumers will trade the following amount of energy: $\mathcal{E}'(\mathcal{S}) = \{0.0, 24.25, 0.0, 39.25, 0.0, 0.0, 13.25, 69.25\}$

   the order of the values is similar to the order submitted to the system at the beginning of the process.

Scenario 12 presents an ideal situation because there is no need to discard any additional values at the intersection due to the total amount of energy sold compared with the total amount of energy bought; this is Case 1 of Algorithm 2. However, scenarios where the intersection is not directly obtained, are covered by Cases 2 to 4 of Algorithm 2. The following subsections will discuss such cases in further detail.

3.5.2 Further analysis of the proposed DPDA mechanism

This subsection will present different outcomes found while analysing the scenarios described in Table 3.1. These outcomes exemplify Cases 2 to 4 from Algorithm 2 and cover subjects such as discarding a participant at the intersection, price value for buying and selling overlapped, gap before the intersection is found and lack of an apparent intersection between both curves. These outcomes focus on the values at the intersection while considering the oversupply needed for each scenario.

3.5.2.1 Case 2 of Algorithm 2

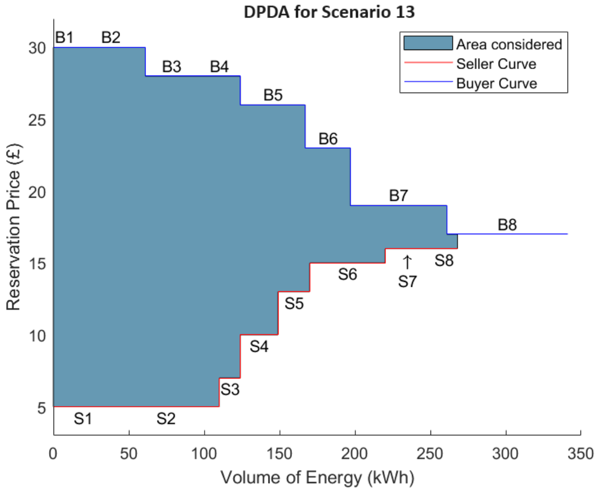


Figure 3.6: Proposed DPDA mechanism to determine winners for Scenario 13, see Table 3.1.

Scenario 13, see Figure 3.6, have eight sellers and eight buyers; some buyers and sellers have similar prices, and the total amount of energy to sell is less than the total amount of energy to buy. Table 3.4 presents the parameters used for this scenario in order of submission. Following Algorithm 2:

Table 3.4: Parameters used in Scenario 13, see table 3.1.

Parameter	Value
Set of sellers (ID)	[53,44,11,72,63,6,51,4]
Set of buyers (ID)	[46,41,10,9,75,80,12,77]
Set of amount of energy to sell (kWh)	[30,25,18,40,50,21,14,70]
Set of amount of energy to buy (kWh)	[80,35,43,15,28,64,30,46]
Set of reserved prices from sellers (£)	[16,10,16,5,15,13,7,5]
Set of reserved prices from buyers (£)	[17,28,26,30,28,19,23,30]

1. The new set of reservation prices for sellers is arranged in ascending order:

   $\mathcal{P}'(\mathcal{S}) = \{5, 5, 7, 10, 13, 15, 16, 16\}$

   And the new set of reservation prices for buyers is arranged in descending order:

   $\mathcal{P}'(\mathcal{B}) = \{30, 30, 28, 28, 26, 23, 19, 17\}$

2. It is impossible to identify a point of intersection based only on the reservation prices submitted to the system. However, it is possible to deduce a virtual intersection using the considerations of prices and the amount of energy. In Figure 3.6, the virtual intersection occurs between the prices of 17 and 16 for buying and selling, respectively. On this point $x = 8$ and $y = 8$, see Figure 3.6. Since these values are the last members of the sets, they can not be considered, and the prices used as intersections are 19 and 16 for buying and selling, respectively, having $x = 7$ and $y = 7$. Checking the conditions from Algorithm 2:

   $$\frac{16 + 17}{2} = 16.5 \in [16, 19]$$

   The prosumers proposed can be considered as the intersection point. Therefore, the total energy regarding the intersection point is calculated:

   $$\sum_{i=1}^{y} \mathcal{E}(\mathcal{S}_i) = 250, \ \sum_{j=1}^{x} \mathcal{E}(\mathcal{B}_j) = 261$$

3. Since $\sum^{x} \mathcal{E}(\mathcal{B}_j) > \sum^{y} \mathcal{E}(\mathcal{S}_i)$, then the previous buyer before the intersection point and the current seller are taken as the based price. The subset of seller's IDs considered to trade is $[44, 72, 6, 51, 4]$, and for buyers is $[41, 9, 75, 77]$.

The price proposed for the trading is:

$$p_0 = \frac{15+26}{2} = 20.5 \in [16, 23]$$

and the oversupply shared between the 5 sellers is:

$$Oversupply = \frac{170-139}{5} = 6.2$$

4. Each seller that participates will trade the next amount of energy:

   $$\mathcal{E}'(\mathcal{S}) = \{0.0, 18.8, 0.0, 33.8, 0.0, 14.8, 7.8, 63.8\}$$

   the order of the values is similar to the order they were submitted to the system at the beginning of the process.

Scenario 13 presents two curves with no clear intersection point due to the reservation prices chosen by the prosumers. Since there was no apparent intersection, it was necessary to define a virtual intersection to calculate the subsets of sellers and buyers to participate in the trading. Despite considering buyers' satisfaction, the subsets of sellers and buyers in this scenario have not been affected.

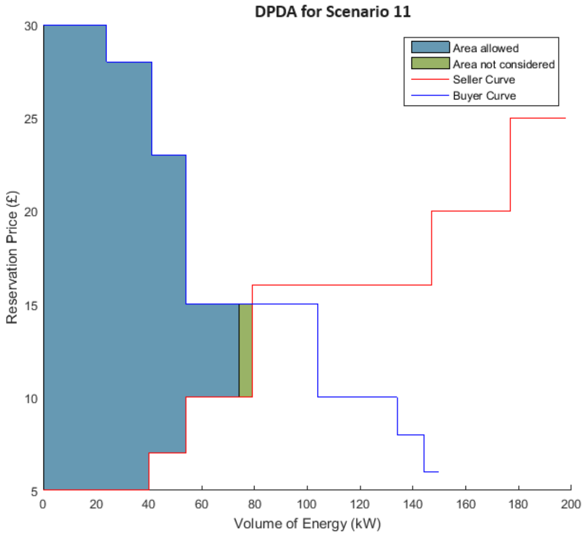


Figure 3.7: Proposed DPDA mechanism to determine winners for Scenario 11, see Table 3.1.

Like Scenario 13, Scenario 11 presents an example of Case 2 of Algorithm 2, see Figure 3.7, but with an intersection at $x = 5$ and $y = 3$. In this scenario, there is no oversupply shared by the sellers. Therefore, the energy submitted to trade will be the same as they will be allowed to trade. Due to the lack of energy despite meeting the price range, the scenario ends with only three buyers and two sellers.

3.5.2.2 Case 3 of Algorithm 2

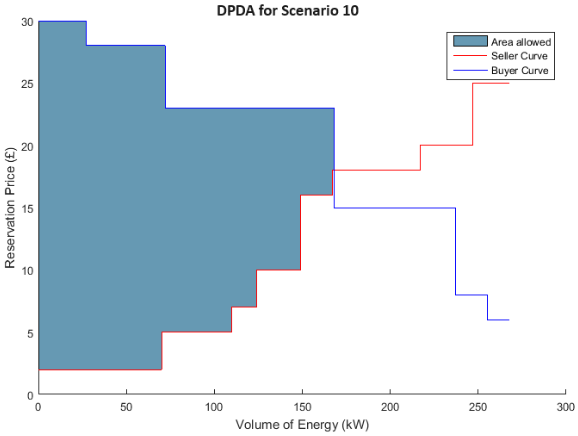


Figure 3.8: Proposed DPDA mechanism to determine winners for Scenario 10, see Table 3.1.

Table 3.5: Parameters used in Scenario 10, see table 3.1.

Parameter	Value
Set of sellers (ID)	[3,14,11,2,13,6,15,4]
Set of buyers (ID)	[16,1,10,9,5,8,12]
Set of amount of energy to sell (kWh)	[30,25,18,40,50,21,14,70]
Set of amount of energy to buy (kWh)	[30,45,13,27,18,39,96]
Set of reserved prices from sellers (£)	[20,10,16,5,18,25,7,2]
Set of reserved prices from buyers (£)	[15,28,6,30,8,15,23]

Scenario 10, see Figure 3.8, has eight sellers and seven buyers; some buyers have similar prices, and the total amount of energy to sell equals the total amount to buy. Table 3.5 presents the parameters used for this scenario and are shown in order of submission. Following Algorithm 2:

1. The new set of reservation prices for sellers is arranged in ascending order:

$$\mathcal{P}'(\mathcal{S}) = \{2, 5, 7, 10, 16, 18, 20, 25\}$$

And the new set of reservation prices for buyers is arranged in descending order:

$\mathcal{P}'(\mathcal{B}) = \{30, 28, 23, 15, 15, 8, 6\}$

2. The intersection happens between the prices of 23 and 18 for buying and selling, respectively. On this point $x = 3$ and $y = 6$, see Figure 3.8. All sellers cover the amount of energy the buyer requests with the price of 23. Therefore, both prices are used as the intersection. Using the values of $x = 4$ and $y = 7$ to ensure that the conditions mentioned above stated in Algorithm 2 are met:

$$\frac{15 + 20}{2} = 17.5 \notin [18, 23]$$

However, the prosumers in the intersection can not be considered. Therefore, the total energy without regarding the intersection point is calculated as:

$$\sum_{i=1}^{y-1} \mathcal{E}(\mathcal{S}_i) = 167, \ \sum_{j=1}^{x-1} \mathcal{E}(\mathcal{B}_j) = 72$$

3. Regarding $\sum^{x-1} \mathcal{E}(\mathcal{B}_j) < \sum^{y-1} \mathcal{E}(\mathcal{S}_i)$, then the seller and buyer in the intersection are considered as the based price, and then they will not be part of the trading. The subset of seller's IDs assumed to trade is $[14, 11, 2, 15, 4]$, and for buyers is $[1, 9]$.

The price proposed for the trading is:

$$p_0 = \frac{23 + 18}{2} = 20.5 \in [16, 28]$$

and the oversupply shared between the 5 sellers is:

$$Oversupply = \frac{167 - 72}{5} = 19$$

4. Each seller that participates will trade the next amount of energy:

$\mathcal{E}'(\mathcal{S}) = \{0.0, 6.0, 0.0, 21.0, 0.0, 0.0, 0.0, 51\}$

the order of the values is similar to the order they were submitted to the system at the beginning of the process.

The point of intersection in Scenario 10 presents a gap between both prices. However, the buyer with a reserved price of 23 and the seller with a reserved price of 18 are considered. Therefore, the consideration of oversupply does not influence the subsets of sellers and buyers in this scenario.

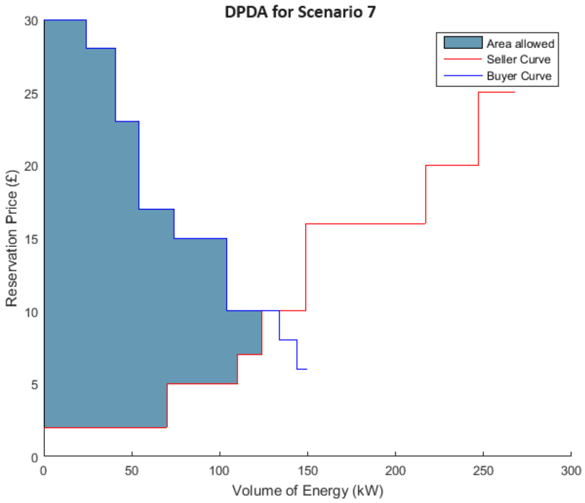


Figure 3.9: Proposed DPDA mechanism to determine the winners for Scenario 7, see Table 3.1.

Similar the Scenario 10, Scenario 7 presents an example of Case 3 of Algorithm 2; see Figure 3.9. With an intersection at $x = 6$ and $y = 4$, the subsets of prosumers trading were not influenced despite presenting an overlap in the prices at the point of intersection. Even though the oversupply was considered, this did not affect the outcome, and the intersection was taken as the base to calculate the price for the trade.

3.5.2.3 Case 4 of Algorithm 2

Scenario 4, see Figure 3.10, has seven sellers and eight buyers; some sellers have the same price, and the total amount of energy to sell is more significant than the total amount of energy to buy. Table 3.6 presents the parameters submitted for this scenario in order of submission. Following Algorithm 2:

1. The new set of reservation prices for sellers is arranged in ascending order:

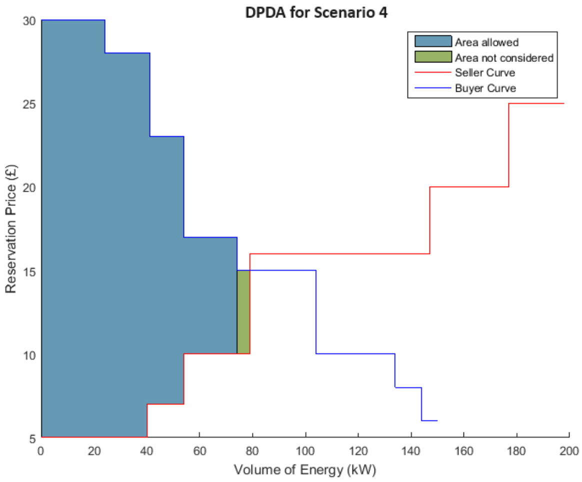


Figure 3.10: Proposed DPDA mechanism to determine winners for Scenario 4, see Table 3.1.

Parameter	Value
Set of sellers (ID)	[16,1,10,9,5,8,12]
Set of buyers (ID)	[3,14,11,2,13,6,15,4]
Set of amount of energy to sell (kWh)	[30,25,18,40,50,21,14,70]
Set of amount of energy to buy (kWh)	[20,16,50,70,24,19,60]
Set of reserved prices from sellers (£)	[20,10,16,5,16,25,7]
Set of reserved prices from buyers (£)	[17,28,6,30,8,15,23,10]

Table 3.6: Parameters used in Scenario 4, see table 3.1.

$$\mathcal{P}'(\mathcal{S}) = \{5, 7, 10, 16, 16, 20, 25\}$$

And the new set of reservation prices for buyers is arranged in descending order:

$$\mathcal{P}'(\mathcal{B}) = \{30, 28, 23, 17, 15, 10, 8, 6\}$$

2. The intersection happens between the prices of 15 and 10 for buying and selling, respectively. On this point $x = 5$ and $y = 3$, see Figure 3.10. However, since the amount of energy for the buyer with price 15 will not be fulfilled by the sellers, the subsequent price is higher than the reserved price for the last buyer. Therefore, the last buyer is not considered during the process. Thus, the prices used as intersection are 17 and 10 for buying and selling, respectively, having $x = 4$ and $y = 3$. Therefore, the values of $x = 5$ and $y = 4$ are used to

ensure that the conditions mentioned above stated in Algorithm 2 are met:

$$\frac{15+16}{2} = 15.5 \in [10, 17]$$

Since the conditions are met, the prosumers in the intersection can be considered. Therefore, the total energy, including the intersection point, is calculated:

$$\sum_{i=1}^{y} \mathcal{E}(\mathcal{S}_i) = 79, \ \sum_{j=1}^{x} \mathcal{E}(\mathcal{B}_j) = 74$$

3. Considering $\sum^x \mathcal{E}(\mathcal{B}_j) < \sum^y \mathcal{E}(\mathcal{S}_i)$ then the seller and buyer in the intersection are considered as part of the prosumers for the trade. The previous price calculated by the prosumers on $x = 5$ and $y = 4$ is set as the base price. The subset of seller's IDs considered to trade is $[1, 9, 12]$, and for buyers is $[3, 14, 2, 15]$.

   The oversupply shared between the 3 sellers is:

   $$Oversupply = \frac{79-74}{3} = 1.67$$

4. Each seller that participates will trade the next amount of energy:

   $\mathcal{E}'(\mathcal{S}) = \{0.0, 23.33, 0.0, 38.33, 0.0, 0.0, 12.33\}$

   the order of the values is similar to the order submitted to the system at the beginning of the process.

One of the first outcomes of considering oversupply is presented in Scenario 4. Analysing the point of intersection at $x = 5$ and $y = 3$, the buyer at five with a reserved price of 15 will not get the total amount of energy asked. Therefore, this buyer is not considered in further calculations, and the feedback sent to this participant is that the lack of energy supply is not enough to provide sufficient energy for it to participate in this trading.

Like Scenario 4, Scenario 5 presents an intersection between prices 17 and 16 for buying and selling, respectively. On this point $x = 4$ and $y = 5$, see Figure 3.11.

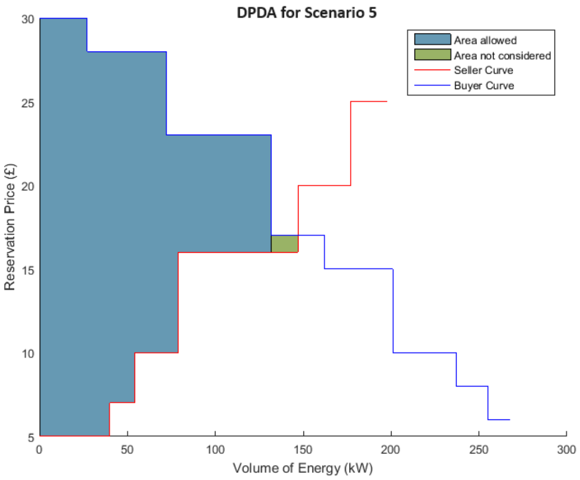


Figure 3.11: McAfee's mechanism to determine the winners of a double auction for Scenario 5, see Table 3.1.

However, the last buyer is not considered based on the considerations to fulfil all buyers' demands. Thus, the prices used as intersection are 23 and 16 for buying and selling, respectively, having $x = 3$ and $y = 5$. Furthermore, in consideration of the condition $\sum^{x} \mathcal{E}(\mathcal{B}_j) < \sum^{y} \mathcal{E}(\mathcal{S}_i)$, the seller and buyer in the intersection are considered part of the trade participants.

It can be concluded from the first analysis that while considering the buyers' satisfaction, the total number of buyers could be reduced when calculating the oversupply once the intersection has been defined. This reduction is entirely independent of the type of intersection. It only affects the outcome if the total amount of energy to buy at the intersection is less than the total amount of energy to sell. Moreover, once the procedure described on Algorithm 2 is performed, the result will achieve the buyers' satisfaction of the subset of prosumers.

The following subsection will illustrate the second analysis based on cases presented in Table 3.2. The first two parts will focus on cooperative behaviour followed by non-cooperative behaviour and finalise with a comparison between both behaviours.

3.5.3 Cooperative and non-cooperative behaviour on proposed DPDA mechanism

In this research, non-cooperative behaviour is defined when the reserved price submitted by the sellers surpasses the 15% of the average market price or the reserved price submitted by the buyers forfeits the 15% of the average market price. This subsection aims to analyse the effects of such behaviours on the subsets of buyers and sellers participating in the trade while applying the proposed DPDA mechanism. For both behaviours, the parameters used are presented in Table 3.2.

3.5.3.1 Cooperative Behaviour

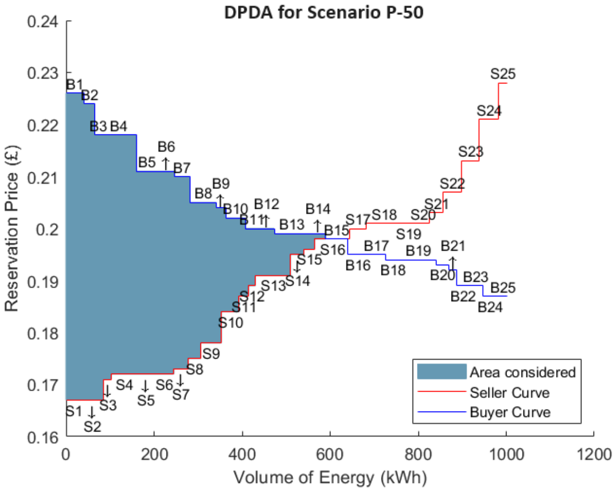


Figure 3.12: Proposed DPDA mechanism to determine the subset of participant sellers and buyers to trade for Scenario P-50 with cooperative behaviour, see Table 3.2

Scenario P-50 with cooperative behaviour, see Figure 3.12, have twenty-five sellers and twenty-five buyers; some buyers and sellers have similar prices, and the total amount of energy to sell is less than the total amount of energy to buy. Table 3.7 presents the parameters used for this case in order of submission. Following Algorithm 2:

Table 3.7: Parameters used in Scenario P-50 with cooperative behaviour, see table 3.2

Parameter	Value
Set of sellers (ID)	[76,20,114,56,33,72,41,9,97,112,6,115,65,83,12,77,61,32,116,93,38,73,103,66,107,46,106,88]
Set of buyers (ID)	[10,53,87,23,81,48,28,36,59,110,39,4,80,45,96,24,51,113,101,11,95,63,29,44,102,49,75]
Set of amount of energy to sell (kWh)	[80,45,37,30,25,30,40,30,35,28,33,47,34,80,22,50,40,43,15,20,60,37,44,18,80,30,40,35]
Set of amount of energy to buy (kWh)	[80,45,37,30,25,30,40,30,35,28,33,47,34,80,22,50,40,43,15,20,60,37,44,18,80,35,65]
Set of reserved prices from sellers (£)	[0.198,0.172,0.172,0.195,0.196,0.203,0.213,0.201,0.167,0.175,0.173,0.178,0.201,0.201,0.187,0.167,0.184,0.207,0.189,0.228,0.172,0.200,0.221,0.171,0.191]
Set of reserved prices from buyers (£)	[0.199,0.202,0.199,0.189,0.224,0.200,0.226,0.193,0.200,0.189,0.194,0.211,0.210,0.194,0.204,0.198,0.211,0.195,0.218,0.187,0.205,0.187,0.195,0.192,0.218]

1. The new set of reservation prices for sellers is arranged in ascending order:

$$\begin{aligned}\mathcal{P}'(\mathcal{S}) = \{&0.198, 0.172, 0.172, 0.195, 0.196, 0.203, 0.213, 0.201, 0.167, 0.175, 0.173,\\ &0.178, 0.201, 0.201, 0.187, 0.167, 0.184, 0.207, 0.189, 0.228, 0.172, 0.200,\\ &0.221, 0.171, 0.191\}\end{aligned}$$

   And the new set of reservation prices for buyers is arranged in descending order:

$$\begin{aligned}\mathcal{P}'(\mathcal{B}) = \{&0.199, 0.202, 0.199, 0.189, 0.224, 0.200, 0.226, 0.193, 0.200, 0.189, 0.194,\\ &0.211, 0.210, 0.194, 0.204, 0.198, 0.211, 0.195, 0.218, 0.187, 0.205, 0.187,\\ &0.195, 0.192, 0.218\}\end{aligned}$$

2. The intersection occurs between prices both at 0.198. On this point, $x = 15$ and $y = 16$, see Figure 3.12. However, the amount of energy from the subset of sellers participating can not fulfil buyers' demands. Therefore, the last buyer is not considered. Thus, the prices used as intersection are 0.198 and 0.200 for buying and selling, respectively. Using the values of $x = 14$ and $y = 16$ to

check the conditions mentioned above stated in Algorithm 2 are met:

$$\frac{0.198 + 0.200}{2} = 0.199 \in [0.198, 0.199]$$

Therefore, the total energy regarding the intersection point is calculated:

$$\sum_{i=1}^{y} \mathcal{E}(\mathcal{S}_i) = 645, \sum_{j=1}^{x-1} \mathcal{E}(\mathcal{B}_j) = 590$$

3. Since $\sum^{x-1} \mathcal{E}(\mathcal{B}_j) < \sum^{y} \mathcal{E}(\mathcal{S}_i)$, then the buyer and seller in the intersection are considered as part of the subset of prosumers to trade. The previous price calculated by the prosumers $x = 14$ and $y = 16$ is set as the based price. The subset of seller's IDs considered to trade is $[76, 20, 114, 56, 33, 97, 112, 6, 115, 12, 77, 61, 116, 38, 66, 107]$ and for buyers is $[10, 53, 87, 81, 48, 28, 59, 4, 80, 96, 51, 101, 95, 102]$.

   The oversupply shared between the 16 sellers is:

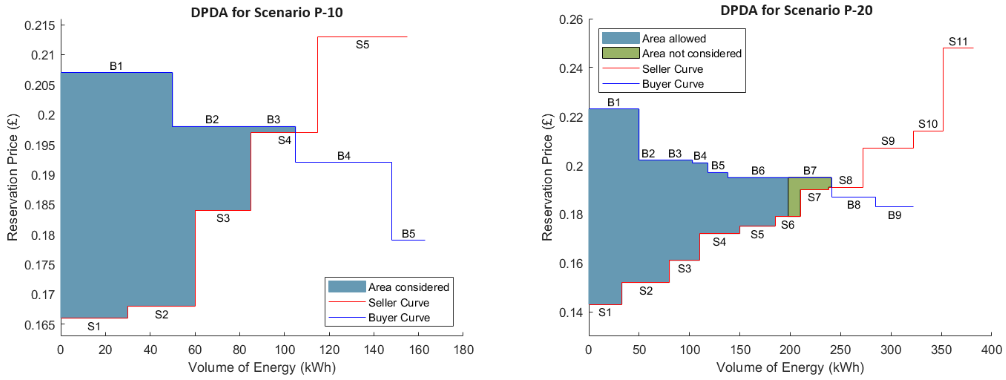
$$Oversupply = \frac{645 - 590}{16} = 3.438$$

4. Each seller that participates will trade the next amount of energy:

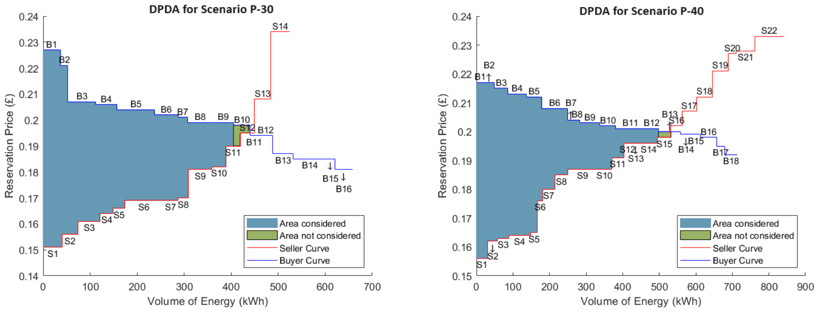
$$\begin{aligned} \mathcal{E}'(\mathcal{S}) = \{&76.562, 41.562, 33.562, 26.562, 21.562, 31.562,\\ &24.562, 29.562, 43.562, 18.562, 46.562, 36.562,\\ &11.562, 56.562, 14.562, 76.562\} \end{aligned}$$

   the order of the values are similar to the order they were submitted to the system at the beginning of the process.

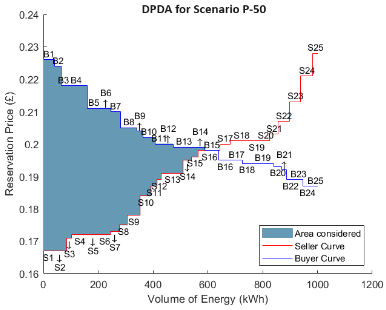
Case P-50 with cooperative behaviour is an example of the Case 4 defined in Algorithm 2, where the condition $(\sum^{y} \mathcal{E}(\mathcal{S}_i) - \sum^{x} \mathcal{E}(\mathcal{B}_j)) \geq 0$ is considered when obtaining the subset of prosumers. The average price for this trading is £0.199, analysing Figure 3.12, the prices submitted for both sets of prosumers are close to the average, allowing more prosumers to be able to trade. However, it is not only the price that influences the number of prosumers but also the total amount of energy offered.



(a) 10 prosumers in total (b) 20 prosumers in total



(c) 30 prosumers in total (d) 40 prosumers in total



(e) 50 prosumers in total

Figure 3.13: Proposed DPDA mechanism to determine the subset of participant sellers and buyers for the trading for a case of cooperative behaviour with a) 10 prosumers in total, b) 20 prosumers in total, c) 30 prosumers in total, d) 40 prosumers in total, and e) 50 prosumers in total, see Table 3.2.

Figure 3.13 summarises each case's results based on Table 3.2 considering cooperative behaviour when the proposed DPDA mechanism is applied. Figures 3.13(a), 3.13(b), and 3.13(c) demonstrate the application of Case 3 from Algorithm 2. For these cases, most prosumers can partake in the trading, while the ones left out were mainly due to the price difference. Figures 3.13(d) and 3.13(e) show the application of Case 4, where the energy submitted by the sellers is not enough to reach buyers' satisfaction in the first subset obtained.

3.5.3.2 Non-Cooperative Behaviour

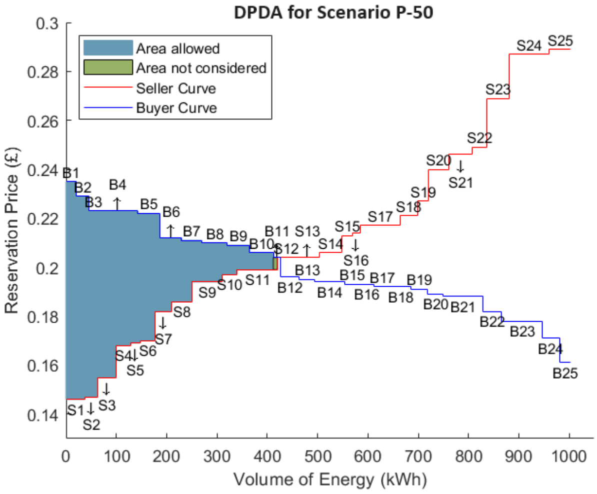


Figure 3.14: Proposed DPDA mechanism to determine the subset of participant sellers and buyers to trade for Scenario P-50 with non-cooperative behaviour, see Table 3.2

Scenario P-50 with non-cooperative behaviour, see Figure 3.14, has the same number of prosumers as Scenario P-50 with cooperative behaviour previously described. The difference is the sets of reserved prices for buyers and sellers and the amount of energy to trade submitted by buyers and sellers. Table 3.8 presents the parameters used for this case in order of submission. Following Algorithm 2:

Table 3.8: Parameters used in Scenario P-50 with non-cooperative behaviour, see table 3.2

Parameter	Value
Set of sellers (ID)	[76,20,114,56,33,72,41,9,97,112,6,115,65,83,12,77, 61,32,116,93,38,73,103,66,107,46,106,88]
Set of buyers (ID)	[10,53,87,23,81,48,28,36,59,110,39,4,80,45,96,24,51, 113,101,11,95,63,29,44,102,49,75]
Set of amount of energy to sell (kWh)	[80,45,37,30,25,30,40,30,35,28,33,47,34,80,22,50,40, 43,15,20,60,37,44,18,80,30,40,35]
Set of amount of energy to buy (kWh)	[80,45,37,30,25,30,40,30,35,28,33,47,34,80,22,50,40, 43,15,20,60,37,44,18,80,35,65]
Set of reserved prices from sellers (£)	[0.287,0.206,0.155,0.168,0.147,0.170,0.240,0.197, 0.221,0.249,0.182,0.246,0.204,0.199,0.227,0.204, 0.186,0.289,0.214,0.213,0.194,0.146,0.269,0.169, 0.2175]
Set of reserved prices from buyers (£)	[0.188,0.209,0.182,0.189,0.229,0.195,0.211,0.193, 0.171,0.193,0.191,0.206,0.192,0.223,0.161,0.210, 0.192,0.222,0.204,0.235,0.194,0.196,0.212,0.223, 0.178]

1. The new set of reservation prices for sellers is arranged in ascending order:

$$\begin{aligned}\mathcal{P}'(\mathcal{S}) =\{&0.287, 0.206, 0.155, 0.168, 0.147, 0.170, 0.240, 0.197, 0.221, 0.249, 0.182,\\ &0.246, 0.204, 0.199, 0.227, 0.204, 0.186, 0.289, 0.214, 0.213, 0.194, 0.146,\\ &0.269, 0.169, 0.217\}\end{aligned}$$

   And the new set of reservation prices for buyers is arranged in descending order:

$$\begin{aligned}\mathcal{P}'(\mathcal{B}) =\{&0.188, 0.209, 0.182, 0.189, 0.229, 0.195, 0.211, 0.193, 0.171, 0.193, 0.191,\\ &0.206, 0.192, 0.223, 0.161, 0.210, 0.192, 0.222, 0.204, 0.235, 0.194, 0.196,\\ &0.212, 0.223, 0.178\}\end{aligned}$$

2. The intersection happens between the prices of 0.204 for buying and selling. On this point $x = 10$ and $y = 11$, see Figure 3.14. Since the amount of energy from the subset of sellers can supply the subset of buyers, these values are considered the intersection point. Checking the conditions from Algorithm 2:

$$\frac{0.196 + 0.204}{2} = 0.2 \notin [0.204, 0.204]$$

Considering that the condition is not met, the prosumers in the intersection are not considered in the subsets of prosumers. Calculating the total energy without contemplating the intersection point:

$$\sum_{i=1}^{y-1} \mathcal{E}(\mathcal{S}_i) = 420, \sum_{j=1}^{x-1} \mathcal{E}(\mathcal{B}_j) = 412$$

Since $\sum^{x} \mathcal{E}(\mathcal{B}_j) < \sum^{y} \mathcal{E}(\mathcal{S}_i)$, then the seller and buyer in the intersection are not considered part of the subset of prosumers. The subset of seller's IDs considered to trade is $[114, 56, 33, 72, 9, 6, 83, 61, 38, 73, 66$ and $[53, 81, 28, 4, 45, 24, 113, 11, 29, 44]$ for buyers. All prosumers trade with a based price of:

$$p_0 = \frac{0.204 + 0.204}{2} = 0.204 \in [0.196, 0.204]$$

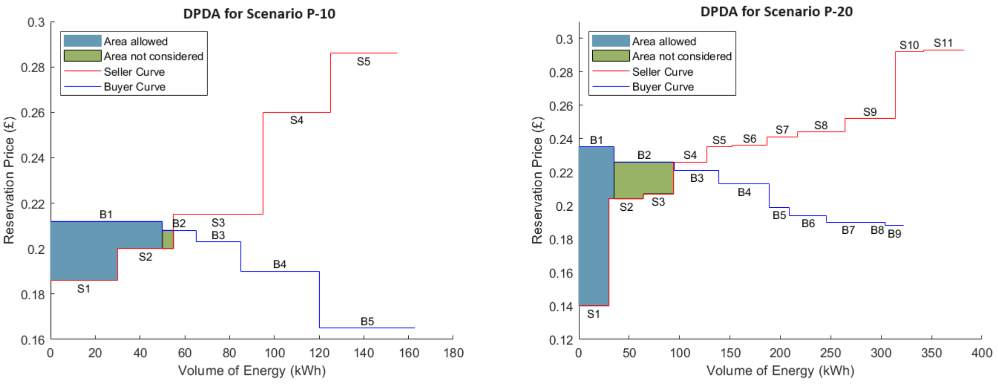
In this scenario, there is no oversupply shared by the sellers. Therefore, the energy submitted to trade will be the same as they will be allowed to trade.

3. Each seller that participates will trade the next amount of energy:

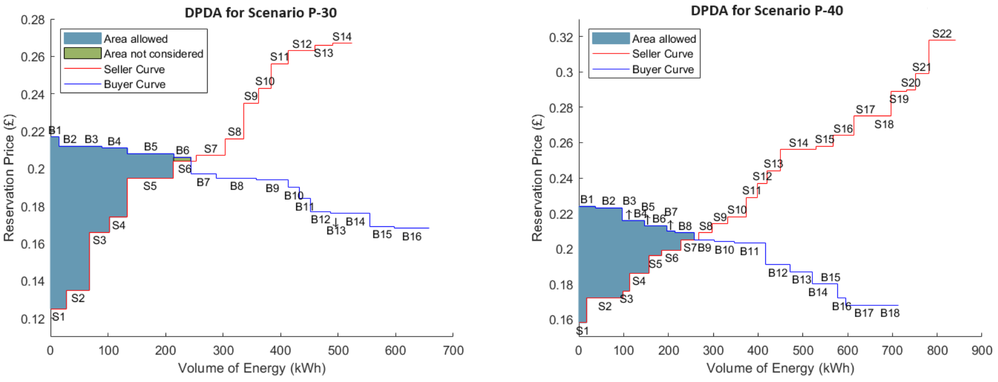
$$\begin{aligned}\mathcal{E}'(\mathcal{S}) =& \{36.273, 29.273, 24.273, 29.273, 29.273, 32.273, 79.273, \\ & 39.273, 59.273, 36.273, 17.273\}\end{aligned}$$

   the order of the values is similar to the order submitted to the system at the beginning of the process.

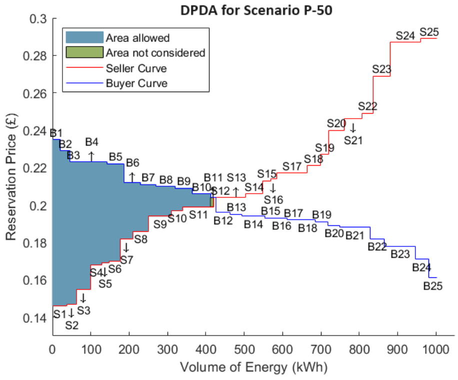
Figure 3.15 summarise the results for each scenario based on Table 3.2 considering non-cooperative behaviour when the proposed DPDA mechanism is applied. Figures 3.15(a), 3.15(d), and 3.15(e) emphasise the consequences when prosumers try to take advantage of other prosumers and do not cooperate with the system. While in Figures 3.15(b) and 3.15(c), the impact of the non-cooperative behaviour is not emphasised like in the previous two figures. Many prosumers were left out due to the reserved price rather than the energy submitted to trade.



(a) 10 prosumers in total (b) 20 prosumers in total

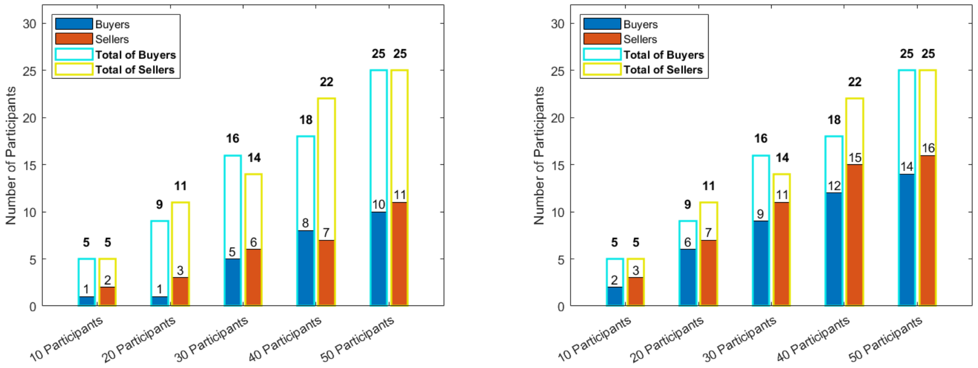


(c) 30 prosumers in total (d) 40 prosumers in total



(e) 50 prosumers in total

Figure 3.15: Proposed DPDA mechanism to determine the subset of participant sellers and buyers for the trading for a case of non-cooperative behaviour with a) 10 prosumers in total, b) 20 prosumers in total, c) 30 prosumers in total, d) 40 prosumers in total, and e) 50 prosumers in total, see Table 3.2.



(a) Non-cooperative (b) Cooperative

Figure 3.16: Comparison of prosumers on DPDA between the total number of buyers and sellers a) without cooperation and b) with cooperation, see Table 3.2.

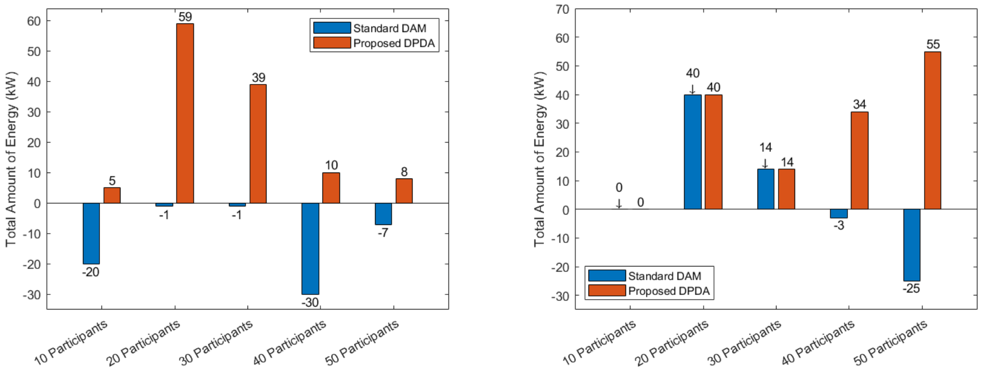
3.5.3.3 Cooperative vs Non-Cooperative Behaviour

Based on the analysis performed in the previous two sections, the reserved prices in Figure 3.15 have a direct impact on the final number of buyers and sellers trading. While in Figure 3.13, some prosumers are not part of the final subset of prosumers, the effects on the price are fewer, and the amount of energy to trade has more impact on the final results.

Figure 3.16 presents the number of sellers and buyers trading against the total number of bids and asks received by the trading mechanism on each scenario from Table 3.2. Figure 3.16(a) displays the scenario when prosumers are not cooperating and focus more on their benefit, resulting in fewer prosumers trading. In contrast, in Figure 3.16(b), prosumers are willing to cooperate with everyone, and their reserved prices are within the average market price. This comparison demonstrates the effects on the number of prosumers for each subset based on their willingness to cooperate.

3.5.4 General Findings

Figure 3.17 shows the amount of energy the sellers cannot trade. On DAM-based results, see Figure 3.17(a), the amount of energy will affect the last seller directly;



(a) Non-cooperative

(b) Cooperative

Figure 3.17: Comparison of the amount of energy seller(s) can not trade on a) without cooperation and b) with cooperation, see Table 3.2.

negative results mean that the amount of energy from sellers is not enough to secure that all buyers will receive energy.

Examples of this are the scenarios of 40 and 50 prosumers with both non-cooperative behaviour and all scenarios with cooperative behaviour. In contrast, Figure 3.17(b) presents a clear example of DPDA-based results, where no buyer is affected, and the amount of energy sellers cannot trade is distributed among all, not only the last, as in DAM. Moreover, even though the maximum amount of energy that sellers cannot trade on DPDA-based scenarios is higher than DAM, there is no case of a deficit in the amount of energy sent to the buyers.

These results prove that prosumers can be incentivised to use DPDA because their earnings impact is lesser than with DAM.

Figure 3.18 presents the individual amount of energy sellers will not trade on DPDA-based scenarios for both behaviour, cooperative and non-cooperative. The scenario of 20 prosumers with non-cooperative behaviour presents the highest amount of energy each seller will not trade due to the number of sellers in the subset of prosumers. Compare to the scenario of 50 prosumers with cooperative behaviour, see Figure 3.17(b), which is the second case with a high total amount of energy that sellers will not be able to trade, following the individual analysis, each seller, in this scenario, will be reduced only 3.438 kW. These two examples demonstrate the impact of

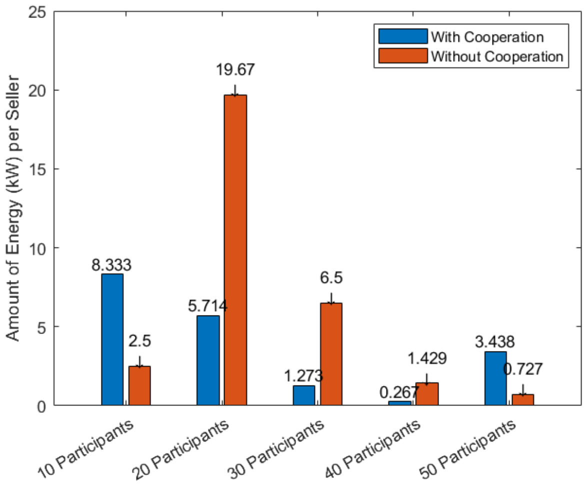
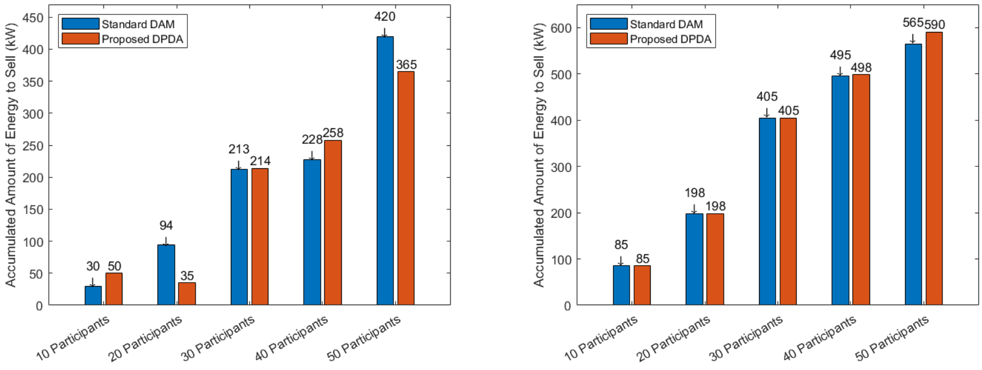


Figure 3.18: Comparison of the individual amount of energy each seller loses based on DPDA between cooperative and non-cooperative behaviour, see Table 3.2.

cooperative behaviour compared to non-cooperative behaviour for each seller.

Based on the past two comparisons, promoting prosumers' cooperative behaviour is vital so all prosumers trading can benefit from local energy. The number of prosumers participating in the trades does not affect as much as their willingness to trade. Using DPDA, buyers can benefit by fulfilling their requests while all sellers will share any oversupply on the trade. This oversupply can be used later by the DSOs to balance the power on the distribution lines or to compensate for the power loss due to the trade; this can be explored in the future.



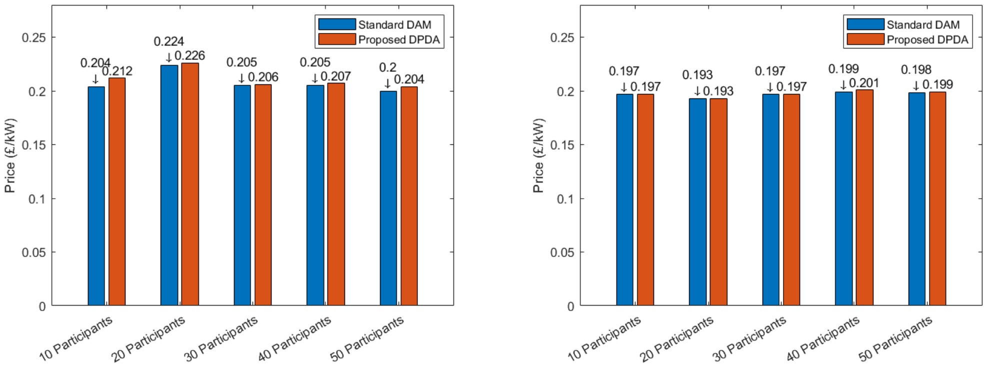
(a) Non-cooperative

(b) Cooperative

Figure 3.19: Comparison of the total accumulative amount of energy to sell a) without cooperation and b) with cooperation.

Figure 3.19 compares the accumulative energy to trade from the sellers for both types of behaviours based on DAM and DPDA. For scenarios based on DPDA, the total amount of energy buyers asked will be traded on DPDA compared to the scenarios on DAM. Meanwhile, the total amount of energy from the sellers trading on DAM will not be able to fulfil the buyer's demand, except for the scenarios with cooperative behaviour with 10, 20, and 30 prosumers, resulting in a loss for the last seller.

In comparison, DPDA ensures that all sellers will trade, and in case of a loss due to less energy traded, all participant sellers will take the loss. These results demonstrate that DPDA aims for a fair share of losses among all sellers.



(a) Non-cooperative (b) Cooperative

Figure 3.20: Comparison of price settled a) without cooperation and b) with cooperation, see Table 3.2.

As a result of the difference of energy traded previously shown in Figure 3.19, Fig 3.20 shows the impact on the price settled for each scenario for both behaviours, non-cooperative and cooperative.

Except for the scenarios of cooperative behaviour with 10, 20, and 30 prosumers, all other scenarios show a small increment in the price (with a maximum of £0.008 for the scenario of 10 prosumers with non-cooperative behaviour) from DPDA scenarios compared to DAM. However, this small increment ensured that all buyers participating in the trading would fulfil their energy demands.

All scenarios with non-cooperation behaviour present a higher price settlement than those with cooperative behaviour; this is an expected result for DPDA. The scenario of 20 prosumers shows the highest increase in the price settlement by £0.033 difference compared to non-cooperative behaviour due to fewer prosumers and more energy. Meanwhile, the other scenarios differ from £0.005 to £0.009.

This variance is related to the amount of energy the prosumers can trade. In comparison, DPDA ensures that all sellers will have equal opportunity to earn from the trading. However, even if the sellers get a high price for their energy, they might only get some of the energy sold, impacting how much they will earn.

3.6 Conclusion

Based on the first analysis, the proposed DPDA mechanism will affect the number of prosumers trading due to buyers' satisfaction. However, all buyers on the subset of prosumers will be ensured to receive the energy requested with this condition. A side effect of ensuring buyers' satisfaction is that the final number of prosumers could be reduced to achieve this condition. One assumption for this analysis is that prosumers will always want to trade and will not be discouraged from future trading. Future benefits of ensuring that the energy sold on the tradings is more significant than the amount requested are reducing the loss of power due to its transmission or performing power balance.

Regarding the second analysis, with the system's feedback based on the proposed DPDA mechanism results, prosumers who cannot trade due to their choice of the reserved price will be able to make an informed choice behaving more cooperatively. This behaviour is an assumption that all prosumers are working together for a whole benefit instead of an individual.

Therefore, the proposed DPDA mechanism obtains the subset of participating buyers and sellers trading while ensuring buyers' satisfaction. In addition, incentivising prosumers to behave cooperatively has proved to benefit all prosumers when defining the subsets of buyers and sellers.

Chapter 4

Consortium Blockchain Network

The Demand-Prioritised Double Auction Mechanism now allows prosumers to trade energy within their community, giving them more control over their energy sources. However, automating the matching process is crucial to maintaining prosumer interest in P2P energy trading.

By using blockchain technology, P2P energy trading can be automated, allowing prosumers to set their prices and energy amounts. The transactions are recorded and monitored on the decentralised and distributed system. This technology enables DSOs to monitor energy trading and grid usage.

The adoption of blockchain technology in P2P energy trading promotes a shared economy that utilises DERs. As this growth continues, companies are exploring ways to incorporate this technology. However, the successful adoption of blockchain technology in P2P energy trading is yet to be widely observed[126].

4.1 Introduction

In the preceding chapter, the subset of sellers and buyers who will be participating in P2P energy trading was defined. However, the matching process still needs to be determined. The goal is to encourage prosumers to participate in this type of trading by ensuring their welfare. The proposed Score Matching Mechanism considers all participants' welfare while pairing each trade. The matching process defined in the works of Murkin et al.[66] offers a price and generation type choice, with some participants even considering the distance between them. With this in mind, a similar score-matching mechanism is proposed.

Furthermore, this proposed research aims to establish a Consortium Blockchain Network for P2P energy trading. This network will allow prosumers to submit their requests for selling or buying and provide DSOs with transparency on all transactions.

This chapter will introduce the Score Matching Mechanism, which will handle the pairing process and encourage prosumers to trade energy generated by DERs in their community. The Consortium Blockchain Network is further introduced, automating the entire P2P energy trading process. Using such a network will eliminate the need for prosumers to invest time or acquire knowledge related to trading if they choose to trade manually.

4.2 Formulation of Problem

Blockchain technology provides an automated mechanism for matching buyers and sellers, considering prosumers' preferences. More details on the architecture of this technology are presented in Chapter 2. The DPDA Mechanism generates a subset of buyers and sellers who participate in trading based on their preferences regarding the price and quantity of energy to trade. Prosumers can submit their preferences using a GUI designed for this purpose. Further details regarding the GUI will be presented in this Chapter.

Table 4.1: Preferences used for sellers and buyers

	Seller	Buyer
Price Preference	Minimum acceptable $\mathcal{P}(\mathcal{S}_i)$	Maximum acceptable $\mathcal{P}(\mathcal{B}_j)$
Distance Preference	Value acceptable $\mathcal{D}(\mathcal{S}_i)$	Value acceptable $\mathcal{D}(\mathcal{B}_j)$
Welfare Preference	Value calculated $\mathcal{W}(\mathcal{S}_i)$	Value calculated $\mathcal{W}(\mathcal{B}_j)$

The Score Matching Mechanism utilises a list of preferences based on price, distance, and quantity of energy to trade, as presented in Table 4.1. By incorporating welfare considerations, this mechanism creates a rank-ordered list for each prosumer based on their preferences. The mechanism proposed by Murkin et al. [66] incentivises prosumers by considering their preferences, which allows the market to prioritise specific trades. This mechanism differs from the traditional commodity market, which treats each unit as identical.

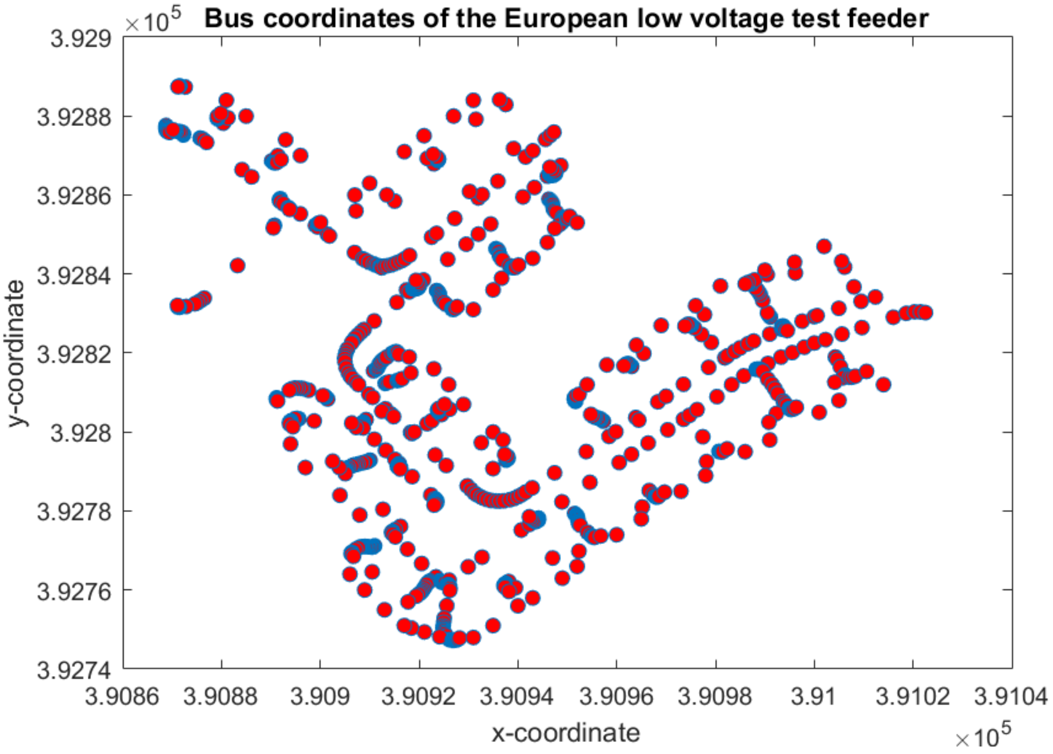


Figure 4.1: Distribution Network test case layout of the IEEE European Low Voltage Test Feeder[1]

Calculating the grid distance for each trade is necessary to determine the distance charges associated with using the power grid distribution network. The IEEE European Low Voltage Test Feeder[1] is utilised as a typical European suburban distribution network configuration; see Figure 4.1.

In previous work by PankiRaj [127], an optimisation method for peer-to-peer energy trading in smart grids was presented. The model considered transmission costs, buyers' bid offers, and operating costs, ensuring that transmission capacities were not exceeded and each buyer's demand was met. However, the power grid company imposes costs associated with using the power grid line, varying according to the amount of energy a supplier transfers.

Furthermore, different network topologies will lead to different distances among microgrids, which could result in different trading decisions. The Transactive Energy path between nodes i and j in the distribution network is dynamically calculated based on the latest distribution system topology. The proposed Transactive Energy path search method produces an equivalent electrical distance between microgrids[128].

Finally, the Consortium Blockchain Network is introduced in this research to implement the entire process described in Chapter 3 with the addition of the Score Matching Mechanism. The proposed Consortium Blockchain Network will include state channels, which will be in charge of the communication between the different users of such network.

4.3 Proposed Score Matching Mechanism

The primary goal of this mechanism is to create a system that encourages prosumers to participate in local trading while considering their preferences. To clarify, the Price and Distance preferences outlined by Murkin et al. [66] in Chapter 2.2.4 are used. Then, the welfare of participants is also included as a preference parameter, as previously defined in Chapter 2.2.6. These preferences of sellers and buyers are presented in Table 4.1.

To implement this system, the Score Matching Mechanism involves generating a rank list based on each participant's trading score within the subset of sellers and buyers. Using this rank list, trades are then matched according to the highest score. The result is a list of trades pairing each prosumer so that they know whom they are trading.

4.3.1 Proposed Score Algorithm

To design the proposed Score Algorithm effectively, it is imperative to define each preference precisely and subsequently amalgamate them to formulate the final proposed Score Algorithm. This process demands a meticulous approach that ensures the accuracy and validity of the algorithm's output.

4.3.1.1 Price Preference

Price preference is the first preference used to create an initial score between participants. A base score reflects the maximum price a buyer is willing to pay for the given transaction. By using this preference for both subsets of buyers and sellers and the distance charge based on the physical distance for each trade:

$$score_{\mathcal{B}_j \to \mathcal{S}_i} \ = \ \mathcal{P}(\mathcal{B}_j) \ - \ (d \ \times C_d) \tag{4.1}$$

where $d \ = \ d_{\mathcal{B}_j} \longmapsto d_{\mathcal{S}_i}$ represents the physical distance from Buyer j to Seller i for the given trading. C_d is the charge for using the main grid. And $\mathcal{P}(\mathcal{B}_j)$ the Price preference from the buyer, see Table 4.1.

Algorithm 3 Price Preference Algorithm

```
Require: Seller minimum price preference $\mathcal{P}(\mathcal{S}_i)$
Require: Buyer maximum price preference $\mathcal{P}(\mathcal{B}_j)$
Require: Charge imposed by DSO for the use of grid $C_d$
  $score_{\mathcal{B}_j \to \mathcal{S}_i} \ = \ \mathcal{P}(\mathcal{B}_j) \ - \ (d \ \times C_d)$
  if $\mathcal{P}(\mathcal{B}_j) \geq \mathcal{P}(\mathcal{S}_i)$ then
      $score_{price} = score_{\mathcal{B}_j \to \mathcal{S}_i}$
  else
      $score_{price} = 1.0$                    ▷ Discard of score calculated
  end if
```

However, the score calculated by (4.1) only considers the buyer's preference. To incorporate the seller preference, $\mathcal{P}(\mathcal{S}_i)$, it is necessary to ensure that the maximum price that a buyer is willing to pay is above the minimum price offered by the seller. This process is presented in Algorithm 3.

4.3.1.2 Distance Preference

The second consideration is the distance preference between buyers and sellers in a trade. It is necessary to determine whether the distance preference is within the physical distance range for both subsets of sellers and buyers. Suppose the prosumer is farther than the distance preference. In that case, a multiplier is applied to the score to reduce the score more as the distance increases. Lowering the score allows prosumers outside the preferred area to be considered while avoiding creating an exact range within which a prosumer can search for trades.

A breadth-first search (BFS) is employed in this research to calculate the grid distance first, as the power grid distribution network has a radial distribution network configuration; this search proves helpful.

Therefore, the calculation of both scores for the subset of buyers and sellers are given a specific trade is determined by:

$$score_{\mathcal{B}_j \rightarrow \mathcal{S}_i} = \begin{cases} score_{\mathcal{B}_j \rightarrow \mathcal{S}_i} & if \quad d \leq \mathcal{D}(\mathcal{B}_j) \\ score_{\mathcal{B}_j \rightarrow \mathcal{S}_i} \times \left(\frac{\mathcal{D}(\mathcal{B}_j)}{d}\right) & if \quad d > \mathcal{D}(\mathcal{B}_j) \end{cases} \tag{4.2}$$

$$score_{\mathcal{B}_j \rightarrow \mathcal{S}_i} = \begin{cases} score_{\mathcal{B}_j \rightarrow \mathcal{S}_i} & if \quad d \leq \mathcal{D}(\mathcal{S}_i) \\ score_{\mathcal{B}_j \rightarrow \mathcal{S}_i} \times \left(\frac{\mathcal{D}(\mathcal{S}_i)}{d}\right) & if \quad d > \mathcal{D}(\mathcal{S}_i) \end{cases} \tag{4.3}$$

where $\mathcal{D}(\mathcal{B}_j)$ and $\mathcal{D}(\mathcal{S}_i)$ are the distance preference for buyer j and seller i, respectively. And d is the physical distance between each other. The consideration of distance preference allows participants to trade with people in their community or support their local area.

4.3.1.3 Welfare Preference

The last consideration is the welfare of the subsets of sellers and buyers participating. Since the motivation for using welfare preference is to incentivise prosumers to participate, the average of the buyer and seller for a given trade is considered.

Following the system's fairness, an average of both welfare is used to modify the current score. This average is added as a multiplier to increment the score; therefore, the score will rise if the average of welfare increments.

The updated value for the score considering the welfare preference is determined by:

$$score_{\mathcal{B}_j \to \mathcal{S}_i} \;=\; score_{\mathcal{B}_j \to \mathcal{S}_i} \times \frac{1}{2}\left[\mathcal{W}_{\mathcal{S}_i} \;+\; \mathcal{W}_{\mathcal{B}_j}\right] \tag{4.4}$$

where $\mathcal{W}_{\mathcal{B}_j}$ and $\mathcal{W}_{\mathcal{S}_i}$ are calculated based on (2.9) and (2.8), respectively.

Algorithm 4 Proposed Score Algorithm

```
Require: Seller minimum price preference $P(S_i)$
Require: Buyer maximum price preference $P(B_j)$
Require: Charge imposed by DSO for the use of the grid $C_d$
Require: Physical Distance $d$
Require: Seller distance preference $D(S_i)$
Require: Buyer distance preference $D(B_j)$
Require: Welfare of buyer $W_{B_j}$
Require: Welfare of seller $W_{S_i}$
  if $P(B_j) \geq P(S_i)$ then
      $score_{price} = P(B_j) \; - \; (d \; \times C_d)$
  else
      $score_{price} = 1.0$
  end if
  if $d \leq D(B_i)$ & $d \leq D(S_j)$ then
      $score = score_{price}$ x $\left(\frac{W_{S_j} \; + \; W_{B_i}}{2}\right)$
  else
      if $d \leq D(B_i)$ & $d > D(S_j)$ then
          $score = score_{price}$ x $\left[\frac{\left(\frac{W_{S_j} \; + \; W_{B_i}}{2}\right) + \left(\frac{D(S_j)}{d}\right)}{2}\right]$
      else
          if $d > D(B_i)$ & $d \leq D(S_j)$ then
              $score = score_{price}$ x $\left[\frac{\left(\frac{W_{S_j} \; + \; W_{B_i}}{2}\right) + \left(\frac{D(B_i)}{d}\right)}{2}\right]$
          else
              $score = score_{price}$ x $\left[\frac{\left(\frac{W_{S_j} \; + \; W_{B_i}}{2}\right) + \left(\frac{D(B_i)}{d}\right) + \left(\frac{D(S_j)}{d}\right)}{3}\right]$
          end if
      end if
  end if
```

Once each preference has been outlined, the price preference from Algorithm 3, as well as the distance preferences from (4.2) and (4.3), and the welfare preference from (4.4), are all factored into a final score calculation. To generate the rank list for each participant on the subsets of sellers and buyers involved, giving the proposed score algorithm described in Algorithm 4.

4.3.2 Proposed Matching Mechanism

Once the scores are calculated based on Algorithm 4, each trade is paired with its corresponding score, creating a rank list for the tradings. The highest score from the rank list is assigned as the first trade matched. The details for this trade are saved, including the participants' ID, the charge for distribution, and the amount of energy traded. Finally, the energy for the seller and buyer trading is updated, such as:

$$\mathcal{E}(\mathcal{B}_j) \;-\; \mathcal{E}'(\mathcal{S}_i) \tag{4.5}$$

There are three possible results from (4.5):

1. (4.5) is $<\ 0$. The updated values are 0 for $\mathcal{B}_j$ and $|\mathcal{E}(\mathcal{B}_j) \;-\; \mathcal{E}'(\mathcal{S}_i)|$ for $\mathcal{S}_i$,
2. (4.5) is $>\ 0$. For $\mathcal{B}_j$ is assigned the result of (4.5) and for $\mathcal{S}_i$ the value is 0.
3. (4.5) is $=\ 0$. Both values for $\mathcal{B}_j$ and $\mathcal{S}_i$ are 0.

The matching process will continue based on the highest score from the rank list and end when all the energy is traded. Future work could optimize this process, but this research uses an individual-based optimization.

4.3.3 Update on Transaction charges

An important factor to take into account is the settlement of payments. While the Score Matching Mechanism offers an optimal solution, there could be instances where the prosumer is unable to fulfill the trade. In such cases, the system will adjust the charges accordingly.

After all matches are defined, the proposed charge for each participant per match is calculated as follows:

For Buyer

$$Quote_{bill} \;=\; [p_0 \times \mathcal{E}(\mathcal{B}_k)] \;+\; \frac{(C_d \times d)}{2} \tag{4.6}$$

For Seller

$$Quote_{income} \;=\; [p_0 \times \mathcal{E}'(\mathcal{S}_k)] \;-\; \frac{(C_d \times d)}{2} \tag{4.7}$$

The mechanism is aware that sometimes the prosumer might not send/receive the energy settled in the trading. Therefore, it is necessary to update the charges.

For Buyer

$$bill_{\mathcal{B}_k} \;=\; (p_0 \times \mathcal{E}_{meter}) \;+\; tariff_{\mathcal{B}_k} \;+\; credit_{\mathcal{B}_k} \tag{4.8}$$

where $credit_{\mathcal{B}_k}$ is the compensation for any difference in the energy trading and is defined as:

$$credit_{\mathcal{B}_k} = \begin{cases} \mathcal{E}_{diff-\mathcal{B}} \times penalty & if\ \mathcal{E}_{ref\mathcal{B}_k} > \mathcal{E}_{meter} \\ 0.0 & if\ \mathcal{E}_{ref\mathcal{B}_k} = \mathcal{E}_{meter} \\ |\mathcal{E}_{diff-\mathcal{B}}| \times penalty & if\ \mathcal{E}_{ref\mathcal{B}_k} < E_{meter} \end{cases}$$

with $\mathcal{E}_{diff-\mathcal{B}}$ defined as $\mathcal{E}_{diff-\mathcal{B}} = \mathcal{E}_{ref\mathcal{B}_k} \;-\; \mathcal{E}_{meter}$, and $tariff_{\mathcal{B}_k}$ is the total cost for all the distribution charges to complete the trading and is defined as:

$$tariff_{\mathcal{B}_k} \;=\; \textstyle\sum_{t=1}^{Total-trades} \left(\frac{C_d \times d}{2}\right)_t$$

For Seller

$$income_{\mathcal{S}_k} \;= (p_0 \times \mathcal{E}_{meter}) \;-\; tariff_{\mathcal{S}_k} \;-\; credit_{\mathcal{S}_k} \tag{4.9}$$

where $credit_{\mathcal{S}_k}$ is the compensation for any difference in the energy trading and is defined as:

$$credit_{\mathcal{S}_k} = \begin{cases} \mathcal{E}_{diff-S} \times penalty & if\ \mathcal{E}_{ref\mathcal{S}_k} > \mathcal{E}_{meter} \\ 0.0 & if\ \mathcal{E}_{ref\mathcal{S}_k} = \mathcal{E}_{meter} \\ |\mathcal{E}_{diff-S}| \times penalty & if\ \mathcal{E}_{ref\mathcal{S}_k} < \mathcal{E}_{meter} \end{cases}$$

with $\mathcal{E}_{diff-S}$ defined as $\mathcal{E}_{diff-S} = \mathcal{E}_{ref\mathcal{S}_k} \;-\; \mathcal{E}_{meter}$, and $tariff_{\mathcal{S}_k}$ is the total cost for all the distribution charges to complete the trading and is defined as:

$$tariff_{\mathcal{S}_k} = \sum_{t=1}^{Total-trades} \left(\frac{C_d \times d}{2}\right)_t$$

The aggregate quantity of trades conducted by individual participants is denoted as $Total - trades$. The readings from the smart meter of either the buyer or seller are represented by $\mathcal{E}_{meter}$, while $\mathcal{E}_{ref\mathcal{B}_k}$ and $\mathcal{E}_{ref\mathcal{S}_k}$ correspond to the energy amounts that have been mutually agreed upon by the buyer and seller, respectively. The DSOs stipulate the penalty incurred by both parties.

The subsequent section aims to introduce the Consortium Blockchain Network, a platform that automates all the requisite processes to implement P2P energy trading defined previously. This innovative network provides a secure, transparent, and efficient way for participants to engage in energy trading without the need for intermediaries.

4.4 Proposed Consortium Blockchain Network

The proposed model in this research aims to achieve a Consortium blockchain-based P2P energy trading system using the Smart Grid Architecture Model (SGAM) framework; see Chapter 2 for more details. The model defines a prosumer as an individual household, and the goal is to work with the data after the substation point (low-voltage grid). The proposed model exhibits characteristics of a decentralised architecture, and prosumers are independent of how they use the energy obtained from their Distributed Energy Resources (DERs).

To enable P2P energy trading, the model uses data acquired from smart meters and smart relays, which communicate through ZigBee. Each prosumer uses this information to submit transactions on the blockchain, where a new operation will be generated if the prosumer wants to buy or sell energy. The proposed model also employs interoperability layers to allow each prosumer access to distribution network parameters, such as connections to specific busses, type of bus agent (transmission or feeder), and location within the grid.

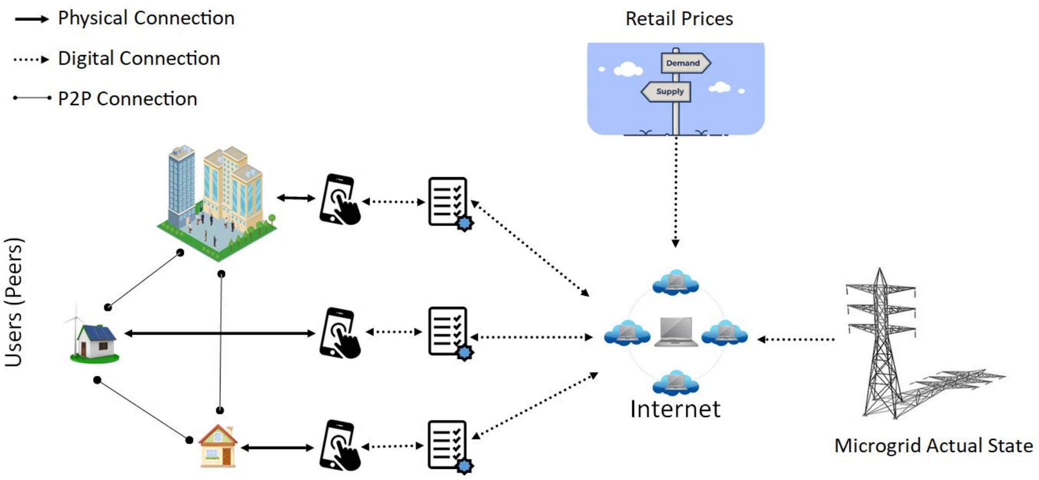


Figure 4.2: Proposed model for the P2P Energy Trading.

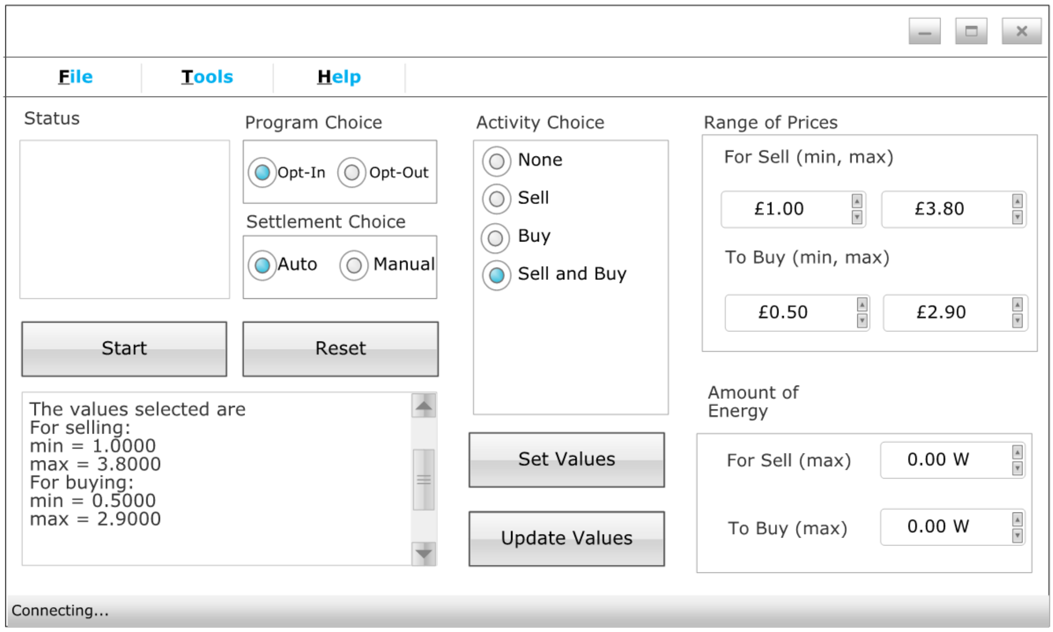
Once the decision to buy or sell energy is made, the transaction is submitted to the blockchain, utilising the Smart Contract defined in the network. The final result of the transaction is returned to each prosumer, taking into account the feedback from the actual state of the network and previous prosumer consumption/production. The proposed network model is presented in Figure 4.2.

The proposed model consists of several components, including a Graphical User Interface (GUI), Smart Contract, and a Consortium blockchain network configuration. The GUI allows prosumers to communicate with the blockchain, while the Smart Contract performs all the operations to implement P2P energy trading. The blockchain network configuration provides the channels to complete the P2P energy trading transactions. The following subsections will present more particulars of these components of the proposed model presented in Figure 4.2.

4.4.1 Data Acquisition using the GUI on Raspberry Pi

A Raspberry Pi is utilised to analyse the data submitted by each prosumer by comparing their preferences with the values obtained from the smart relays or smart meters. Raspberry Pi can interact with ZigBee devices, making data acquisition more flexible [129].

The configuration between Raspberry Pi and ZigBee devices will define each prosumer, communicate different data from the house to the blockchain, and submit the corresponding transactions. Defining each prosumer's behaviour is critical since data sharing always has disadvantages. It is important to note that the energy data submitted through the GUI is considered available, and the proposed research does not consider the intermittent nature of DERs.



Program Choice: ● Opt-In ○ Opt-Out

Settlement Choice: ● Auto ○ Manual

Activity Choice:
○ None
○ Sell
○ Buy
● Sell and Buy

Range of Prices
For Sell (min, max): £1.00 £3.80
To Buy (min, max): £0.50 £2.90

Amount of Energy
For Sell (max): 0.00 W
To Buy (max): 0.00 W

```
The values selected are
For selling:
min = 1.0000
max = 3.8000
For buying:
min = 0.5000
max = 2.9000
```

Connecting...

Figure 4.3: GUI design implemented on Raspberry Pi

Figure 4.3 presents the GUI implemented in Raspberry. The GUI is displayed using a seven-inch screen connected to the Raspberry Pi. The GUI has two windows that display helpful information to the prosumer: the *Status* area and the left bottom section (*Information* area). There are a set of different choices that the prosumer can select, such as *Program Choice*, *Settlement Choice*, *Activity Choice*, *Range of Prices*, and *Amount of Energy*. The GUI also includes four buttons: *Start*, *Reset*, *Set Values*, and *Update Values*. All of these elements will be explained next.

The *Information* area displays the data chosen by the prosumer, and after a transaction has been submitted, the blockchain results are shown. The *Reset* button clears all choices and returns the program to its initial state. The initial state of the program will wait until the prosumer selects the *Start* button. However, if a transaction is submitted to the blockchain, it will not be cancelled, and the results will be presented in the *Information* area.

The *Status* area informs the prosumer of the current state of their energy consumption/production. The system checks the state of the generation and usage of energy and then compares them. Depending on the result, this area will display either a *green state* or *red state*. Once the program has started, the *Program Choice* section will be enabled. The *Opt-in* option allows the prosumer to participate in the trading platform and enables the other parameters to be edited. However, if the prosumer does not select this option, the parameter will not be allowed for editing, and the prosumer will not participate in any tradings.

After the prosumer has chosen to participate in the trading, the next step is to select the activity they want to perform. Unless the prosumer chooses a different option apart from the *None* option, all the other options will enable the next set of parameters that the prosumer needs to submit, i.e., price and amount of energy. If the parameters are set for selling, the GUI will confirm that the prosumer's current status is adequate to submit a sell transaction; if the prosumer is on a *green status*, then the *Settlement Choice* is enabled. For the case of buying, the *Set Values* button is used to submit the parameters.

The *Settlement Choice* section lets the prosumer choose between manually submitting the amount of energy or letting the GUI decide them. Suppose the prosumer manually sets these values by updating the *Amount of Energy* section. In that case, the GUI will check that the prosumer can achieve (in the case of sell) or needs (in the buy case) the amount of energy submitted to trade. Once these values are accepted by the GUI or decided by it, the *Set Values* button will be enabled so that the prosumer can submit the desired transaction. The *Set Values* button verifies the parameters input on the prosumer's choices. Additionally, the *Update Values* button is used to re-validate the data in case the first validation fails. These two buttons perform the same validation and update the information section, but the

Update Values button is enabled if the first validation is unsuccessful.

Once the data is ready to be submitted to the blockchain, the prosumer can select the *Set Values* button to submit the transaction. The GUI will send all the details to the blockchain network and wait for the results of this submission. The prosumer is notified after the blockchain network has returned the trading results.

4.4.2 Smart Contract Design

This research proposes a novel approach to implement P2P energy trading using smart contracts. The proposed smart contract-based trading mechanism is designed to enable prosumers in a neighbourhood to trade energy with each other securely, efficiently, and transparently. The research presents a detailed description of the smart contract, including the three aspects that define it: type of data, type of goal, and consensus[26]. The first aspect includes the type of transaction (sell or buy), the amount of energy, the reserved price, the prosumer ID, and the timestamp of transaction submission. The second aspect is the type of goal, which is promoting the use of local energy. The consensus is on the implementation of trading, and the Proof of Stake (PoS) consensus would be tested on a Public Blockchain with different channels within the identical network blockchain.

The proposed smart contract is intended to be executed within a period of fifteen minutes. The smart contract has a period of fifteen minutes to perform the whole trading process, which is divided into six steps: initialisation, distance calculation, DPDA, score-matching, supply service, and pay-to-seller. The initial three minutes are devoted to receiving submissions from prosumers. The following seven minutes involve completing the DPDA mechanism and matching. Then, all prosumers are informed of the trading results in the following three minutes. During the last two minutes, the prices are settled based on the trades performed, and the values from previous trades are updated based on the feedback received from the smart meters. Table 4.2 defines each process and describes its activities.

Algorithm 5 Smart Contract procedure

```
Require: $C_d$
function INITIALISATION
    Obtain all data from prosumers
    return $\mathcal{G}, \mathcal{P}(\mathcal{B}_j), \mathcal{P}(\mathcal{S}_i), \mathcal{E}(\mathcal{B}_j), \mathcal{E}(\mathcal{S}_i), \mathcal{D}(\mathcal{B}_j), \mathcal{D}(\mathcal{S}_i), \mathcal{ID}(\mathcal{B}_j), \mathcal{ID}(\mathcal{S}_i)$
end function
function DISTANCE-CALCULATION($\mathcal{G}, flag_{\mathcal{G}change}$)
    if $flag_{\mathcal{G}change} = 1$ then
        Update graph of grid $\mathcal{G}$
    else
        Calculate distance based on Algorithm 6
    end if
    return $PeerDist$
end function
function DPDA($\mathcal{G}, \mathcal{P}(\mathcal{B}_j), \mathcal{P}(\mathcal{S}_i), \mathcal{E}(\mathcal{B}_j), \mathcal{E}(\mathcal{S}_i), \mathcal{ID}(\mathcal{B}_j), \mathcal{ID}(\mathcal{S}_i), PeerDist, C_d$)
    Obtain the pool of participant prosumers based on Algorithm 2
    Calculate welfare of participant prosumers by (2.9) and (2.8)
    return $p_0, \mathcal{E}'(S_i), \mathcal{ID}_p(\mathcal{B}_j), \mathcal{ID}_p(\mathcal{S}_i), \mathcal{W}(\mathcal{B}_j), \mathcal{W}(\mathcal{S}_i)$
end function
function SCORE-MATCH($\mathcal{E}'(S_i), \mathcal{E}(\mathcal{B}_j), \mathcal{ID}_p(\mathcal{B}_j), \mathcal{ID}_p(\mathcal{S}_i), \mathcal{W}(\mathcal{B}_j), \mathcal{W}(\mathcal{S}_i)$)
    for $j = 1; j < B_x$ do
        Calculate Score based on Algorithm 4
    end for
    Match trades by process described in 4.3.2
    return $PairMatch(\mathcal{ID}_p(\mathcal{B}_j), \mathcal{ID}_p(\mathcal{S}_i), \mathcal{E}), p_0$
end function
function SUPPLY-SERVICE($PairMatch(\mathcal{ID}_p(\mathcal{B}_j), \mathcal{ID}_p(\mathcal{S}_i), \mathcal{E}), p_0$)
    Submit results of trading
    Feedback to unsuccessful prosumers
    return $Quote_{bill}, Quote_{income}$
end function
function UPDATE-PAYMENT($\mathcal{E}_{meter}, tariff_{\mathcal{B}_k}, tariff_{\mathcal{S}_k}, \mathcal{E}_{ref\mathcal{B}_k}, \mathcal{E}_{ref\mathcal{S}_k}$)
    Update payment by 4.8
    Update charge by 4.9
    return $bill_{\mathcal{B}_k}, income_{\mathcal{S}_k}$
end function
```

Table 4.2: Smart Contract schedule process

Duration	Process
$0 \sim 3$ minutes	*Quotation Period* prosumers declare the demand of energy production or consumption and reserved electricity price for the next trading cycle T_{i+1}.
$3 \sim 10$ minutes	*Matching Period* Smart contract matches the transaction demand of prosumers.
$10 \sim 13$ minutes	*Feedback Period* Any prosumers who were not part of the trading are informed. If the prosumer is accepted, the information about the trading is sent.
$13 \sim 15$ minutes	*Transaction settlement and reward* Smart contract settles trades according to the transaction results in the current cycle T_i, and the actual energy consumption or production in the previous cycle T_{i-1}. The smart meter inputs the data of actual energy production or consumption of prosumers in the previous trading cycle T_{i-1}.

The proposed smart contract-based trading mechanism applies to all prosumers under the standardised negotiation and self-enforcing of the smart contract. A smart contract function performs each step. As shown in Algorithm 5, the algorithm is written in C++ and stored in the Hyperledger Fabric blockchain. Let $\mathcal{S}_k$ denote the index set of sellers, and $\mathcal{B}_k$ denote the index set of buyers. The detailed steps for executing the auction are described below:

Step 1: The DSOs will submit any change to the main grid graph, and each prosumer calls the initialisation function from the smart contract to specify their ID, price preference, amount of energy to trade, and distance preference to sell (line 1-4 in Algorithm 5). Where $\mathcal{G}$ denotes the graph of the Grid, $\mathcal{ID}(\mathcal{B}_j), \mathcal{ID}(\mathcal{S}_i)$ denotes their ID, $\mathcal{P}(\mathcal{B}_j), \mathcal{P}(\mathcal{S}_i)$ denotes their reserved price, $\mathcal{E}(\mathcal{B}_j), \mathcal{E}(\mathcal{S}_i)$ denotes the amount of energy they can schedule to trade, and $\mathcal{D}(\mathcal{B}_j), \mathcal{D}(\mathcal{S}_i)$ denotes the distance preference to trade for buyer and seller, respectively for each term.

Step 2: If the DSO submits a new version of the main grid graph, the endorsing peers will call the distance calculation function from the smart contract to obtain the distance between all prosumers (line 5-12 in Algorithm 5). Where $PeerDist$ represents the matrix of the distances.

Step 3: The DPDA function enables endorsing peers to obtain the pool of buyers and sellers participating in the trading and calculate the welfare for each of them (lines 13-17 in Algorithm 5). Where p_0 denotes the price for the trade, $\mathcal{E}'(S_i)$ is the updated amount of energy each seller can trade, $\mathcal{ID}_p(\mathcal{B}_j), \mathcal{ID}_p(\mathcal{S}_i)$ are the IDs of the participant sellers and buyers, respectively, and $\mathcal{W}(\mathcal{B}_j), \mathcal{W}(\mathcal{S}_i)$ is the welfare calculated for each buyer and seller. Before the auction ends, all the bids are frozen by the smart contract, which means that the participant buyers cannot withdraw their bids back to their accounts.

Step 4: The score-matching function obtains the pair of buyer and seller with the amount of energy they will trade at a price received previously (lines 18-24 in Algorithm 5). Where $\mathcal{ID}_p(\mathcal{B}_j), \mathcal{ID}_p(\mathcal{S}_i)$ is the ID for each pair of buyer and seller, $\mathcal{E})$ is the amount of energy trading between the given pair at a price p_0.

Step 5: The supply service function updates prosumers with the result of the trading, giving them the price settled and the amount of energy they will be trading; for those who are unsuccessful in trading, they will get a message to encourage them to trade at a price closer to the base price(lines 25-29 in Algorithm 5). $Quote_{bill}$ is the expected charge buyers will get and $Quote_{income}$ is the expected payment sellers will receive.

Step 6: Once the smart contract confirms that the energy is delivered by querying the smart meter, the charge to the buyer and the payment to the seller is updated by the pay-to-seller function (lines 30-34 in Algorithm 5).

According to the information presented in Table 4.2, steps 1 and 2 will take place during the quotation period, steps 3 and 4 during the matching period, and step 5 will be implemented during the feedback period. Finally, step 6 will be executed during the transaction settlement and reward period.

A select group of authorised prosumers is responsible for carrying out the consensus process. These prosumers audit the block submitted and share their results for mutual supervision and verification. After all prosumers have received the results, they compare them with one another. Once each prosumer has compared the results, they each submit their agreement on the block. If all prosumers agree with the block submitted, the block is broadcasted to the network for storage. However, suppose some prosumers do not agree with the block submitted. In that case, one prosumer is assigned to review the audit results and send the data back to the prosumers for further verification.

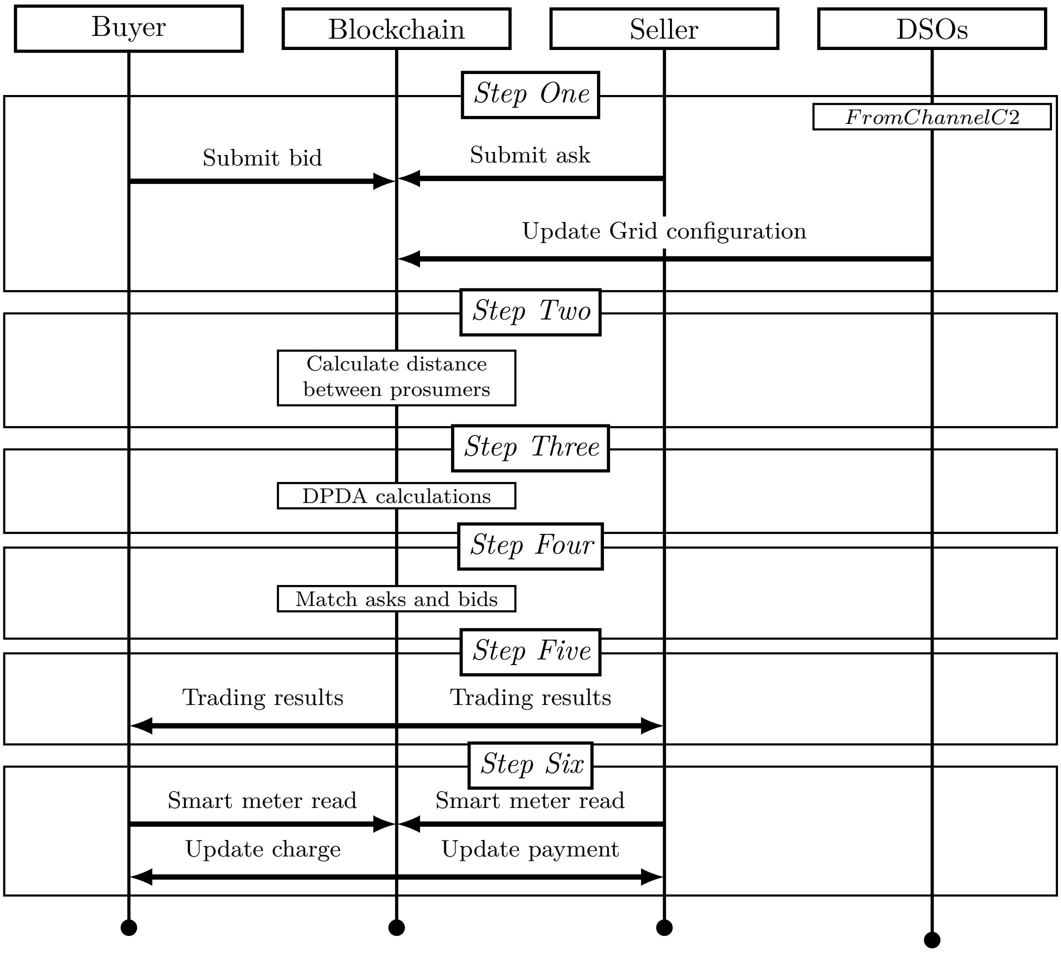


Figure 4.4: The protocol for P2P trading via smart contract

The protocol for selling/purchasing energy through the smart contract is depicted in the sequence diagram in Figure 4.4. The actors involved in this process are prosumers offering or demanding energy, DSOs providing updates on the distribution network configuration, and blockchain, which keeps track of the transactions. As shown in the diagram, the protocol follows the steps described above.

4.4.3 Blockchain Network configuration

The proposed blockchain network has been designed to operate as a public network but has been transformed into a consortium blockchain network consisting of two different channels. The prosumers' channel allows data to be shared to obtain DPDA results, but not recorded. On the other hand, the DSOs channel is a restricted channel where the DSOs can access the information of the DPDA results without monitoring each prosumer's behaviour or influencing how the trades are settled. This design allows for two different channels, where the data submitted from each prosumer is shared only among them, and the DSOs are only interested in the results of the DPDA.

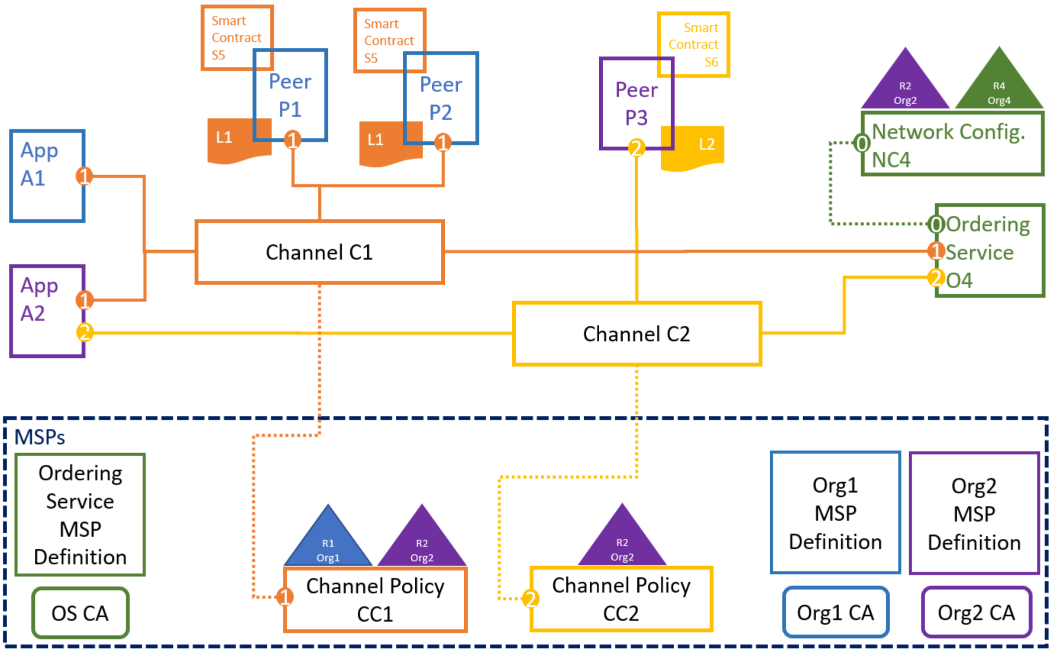


Figure 4.5: Blockchain Network design

Figure 4.5 presents the blockchain network based on the proposed model of Figure 4.2 implemented in the blockchain. The network comprises two channels, namely *Channel C1* and *Channel C2*. *Channel C1* allows all prosumers to submit transactions and perform smart contracts, whereas *Channel C2* is a restricted channel for all DSOs that need to know the results of the tradings. The configuration of *Channel C1* is such that only a few designated prosumers will be *endorsing peers*, determined based on their past behaviour and willingness to support transactions, and the *leader peer* will be chosen among this pool. *Channel C2* allows all peers to be *endorsing peers*, and future research can consider different types of peers.

The DSOs can use the information obtained through *Channel C2* to balance the grid based on the results of the DPDA and the extra supply and demand from prosumers who do not partake in the trading. This income refers to the transmission and distribution costs included in the (4.6) and (4.7). One of the most significant contributions of this proposed Blockchain Network is the use of State Channels such as *Channel C1* and *Channel C2*. State Channels have the lowest cost per transaction, making them suitable for streaming micropayments, and can drastically reduce the costs and increase the speed compared to Ethereum[130]. A more detailed description of other elements from the blockchain network can be found in Section 2.3.1.

4.5 Simulation Results

It is worth noting that the microgrid used in this research is based on the IEEE European Low Voltage Test Feeder model[1]. As such, the results of computing physical distance are presented. Additionally, the hypothetical charge imposed by DSOs for using the grid is fixed at 0.002 $\pounds/km$ and does not reflect any actual charge.

Three separate analyses were conducted to analyse the impact of each preference on the matching results. The first analysis involved a change in the submitted price preference, as shown in Table 3.1. In contrast, the second analysis varied the submitted distance preference. Cooperative and non-cooperative behaviour was observed for the final analysis based on the cases presented in Table 3.2.

The blockchain implementation utilised the Network definition depicted in Figure 4.5. The Network consists of a maximum of fifty-five prosumers in *Channel C1* and one DSO in *Channel C2*. Subsequent subsections will detail the results of the P2P energy trading platform implementation performance.

4.5.1 BFS implementation for Distance calculation

Algorithm 6 resumes the steps needed to search on a given Graph $\mathcal{G}$. Every time a vertex is visited, the new distance is calculated and compared with the previous distance. If the first distance is shorter than the previous saved, then this distance is considered the shortest path to that node; if not, then this distance is not considered. A double-ended queue records the vertices that need to be visited; this allows more flexibility when deciding on the next vertex to consider.

Algorithm 6 BFS Algorithm

```
Require: $\mathcal{G} = (\mathcal{V}, \mathcal{E})$
Require: $\mathcal{A}$
  let $\mathcal{Q}$ be a double ended queue
  $dist[\mathcal{A}] = 0.0$
  $\mathcal{Q}.push\_back(\mathcal{A})$
  $Vertex * ptr$                                  ▷ Pointer to a vertex
  while $\mathcal{Q} \neq \emptyset$ do
      $v = \mathcal{Q}.front()$                   ▷ Access the first element of the queue
      $\mathcal{Q}.pop\_front()$                  ▷ Removes the first element of the queue
      $ptr = head[v]$                             ▷ Point to the begining of the node
      while $ptr \neq nullptr$ do
          if $dist[ptr \rightarrow id] > dist[v] + ptr \rightarrow dist$ then
              $dist[ptr \rightarrow id] = dist[v] + ptr \rightarrow dist$
          end if
          if $ptr \rightarrow dist = 0$ then
              $\mathcal{Q}.push\_front(ptr \rightarrow id)$;
          else
              $\mathcal{Q}.push\_back(ptr \rightarrow id)$
          end if
          $ptr = ptr \rightarrow next$
      end while
  end while
```

The BFS algorithm was applied to the tree diagram in Figure 4.6, and the resulting

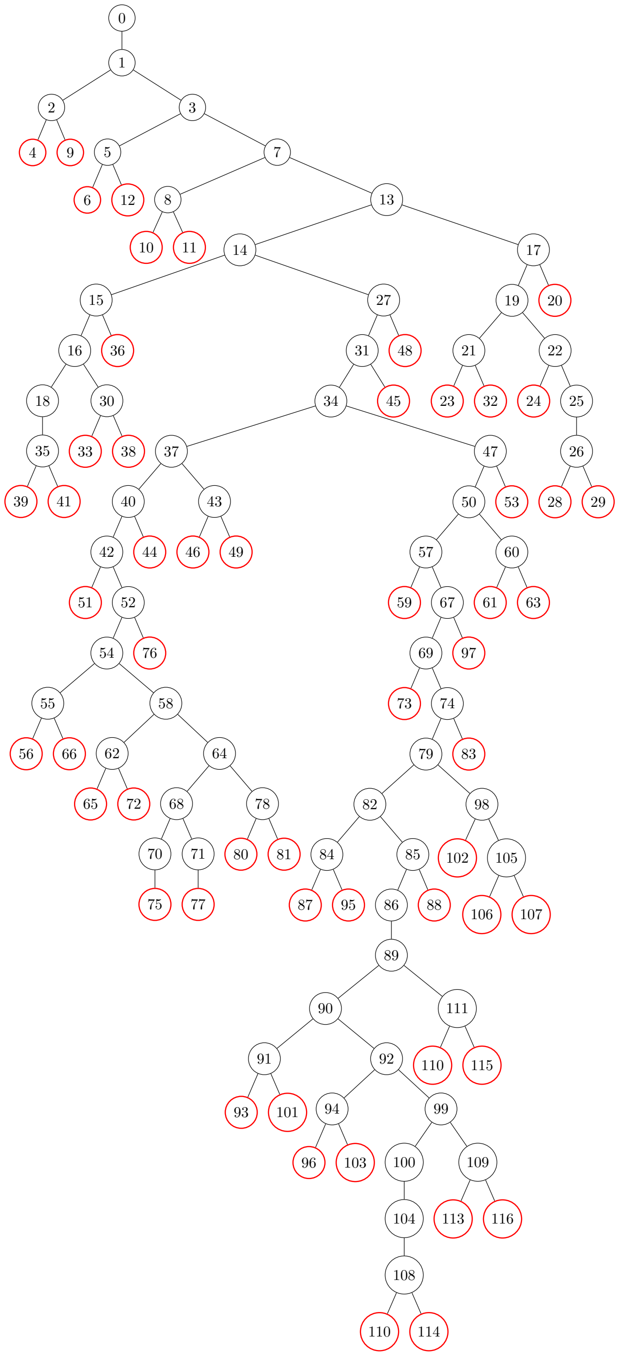


Figure 4.6: Graph representation of the conversed Reduce Distribution Network layout from IEEE European Low Voltage Test Feeder[1]

Table 4.3: Conversion list of Nodes from the IEEE European Low Voltage Test Feeder[1] to the Tree diagram shown in Figure 4.6

Node #	New Vertex #
1	0
25	1
27	2
32	3
34	4
36	5
47	6
59	7
66	8
70	9
73	10
74	11
83	12
101	13
114	14
127	15
145	16
155	17
166	18
171	19
178	20
188	21
196	22
208	23
225	24
226	25
241	26
247	27
248	28
249	29
261	30
263	31
264	32
276	33
280	34
283	35
289	36
310	37
314	38
320	39
325	40
327	41
332	42
336	43
337	44
342	45
349	46
373	47
387	48
388	49
391	50
406	51
453	52
458	53
475	54
484	55
502	56
505	57
508	58
522	59
530	60
539	61
544	62
556	63
559	64
562	65
563	66
578	67
587	68
594	69
596	70
604	71
611	72
614	73
615	74
619	75
629	76
639	77
651	78
666	79
676	80
682	81
686	82
688	83
690	84
691	85
697	86
701	87
702	88
707	89
718	90
739	91
745	92
755	93
763	94
778	95
780	96
785	97
786	98
794	99
802	100
813	101
817	102
835	103
839	104
854	105
860	106
861	107
868	108
884	109
886	110
891	111
896	112
898	113
899	114
900	115
906	116

distances between all vertices, including itself, were stored in a matrix. This process aimed to find the shortest path between each vertex. Whenever a shorter path was found, the distance was saved. However, only the distances between the red vertices, representing the users' locations in the network, are necessary. These distances can be accessed using their renamed ID from Table 4.3.

This process must only be completed once and saved in the Blockchain, provided that the distribution network configuration does not change. Adding new users to the network will only affect the results if they are connected to a simplified node. In this case, a new tree diagram must be defined, and the same procedure must be followed.

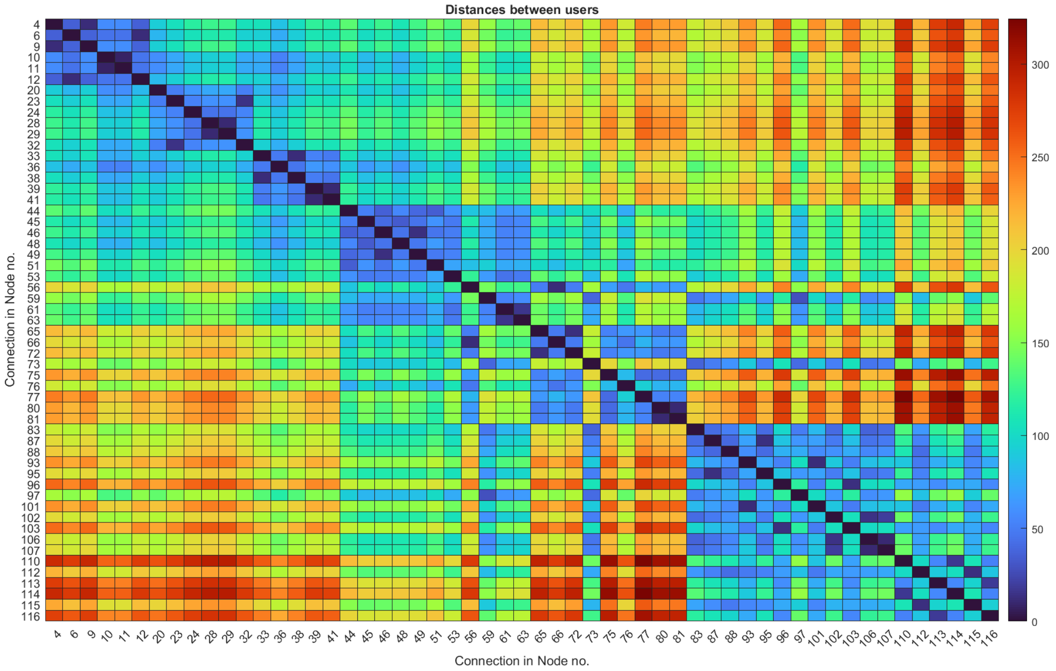


Figure 4.7: Distance for all Participants

The results of implementing the BFS method on a reduced model are presented in Figure 4.7. The analysis focuses on the distances between vertices that have users on the network, and these values will be used in the future. The BFS calculates the shortest path between two vertices, and the final distance is the one that matters. Each line corresponds to one vertex and shows the distance, in meters, to the other vertices. The distances from vertices without users on the network are not displayed, but the BFS has calculated them.

It is essential to note that the vertex name does not determine the distance significance. For example, the distance to Vertex 110 and 113 is more important than the distance to Vertex 112. The Tree diagram in Figure 4.6 confirms that the path to Vertex 112 is shorter than the path to Vertex 110 or Vertex 113, which supports the BFS results.

Suppose a user on Vertex 51 defines a radius of 100 m to trade within their location. In that case, users on Vertices 36, 44, 45, 46, 48, 49, 53, 56, 59, 61, 63, 66, and 76 meet the criteria and will be the first option for the user on Vertex 51. Users on Vertices 65, 72, and 97 are the second option, while the rest are the last option for the user on Vertex 51 to trade.

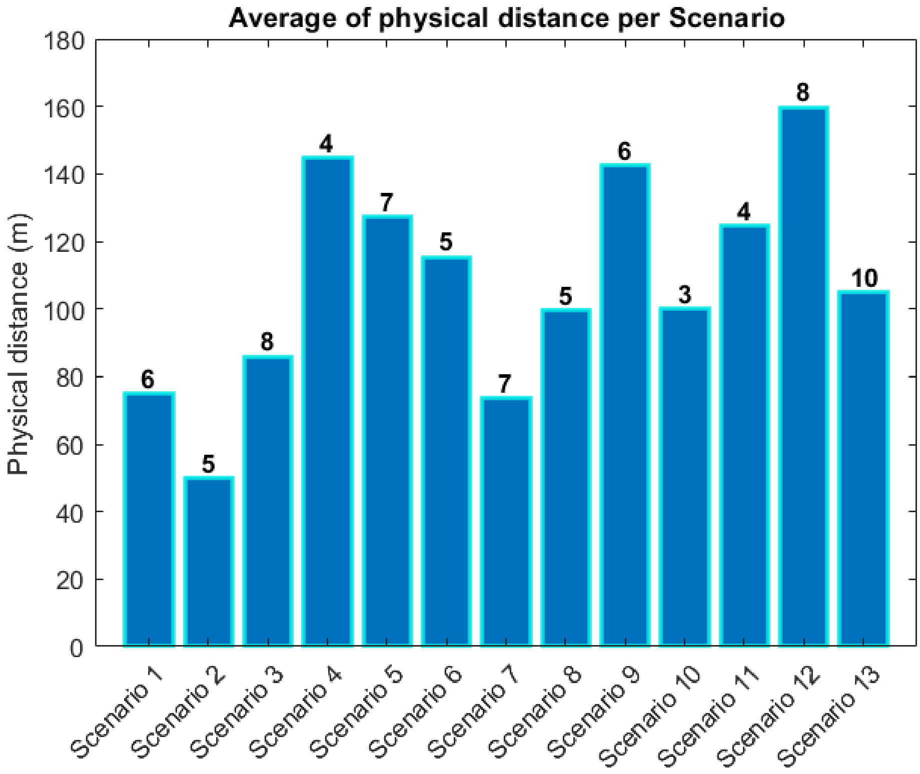


Figure 4.8: Average distance per scenario

Figure 4.8 displays the average distance per scenario, with the number of tradings performed at the top of each bar. It is important to note that the number of trades completed does not impact the average distance per scenario.

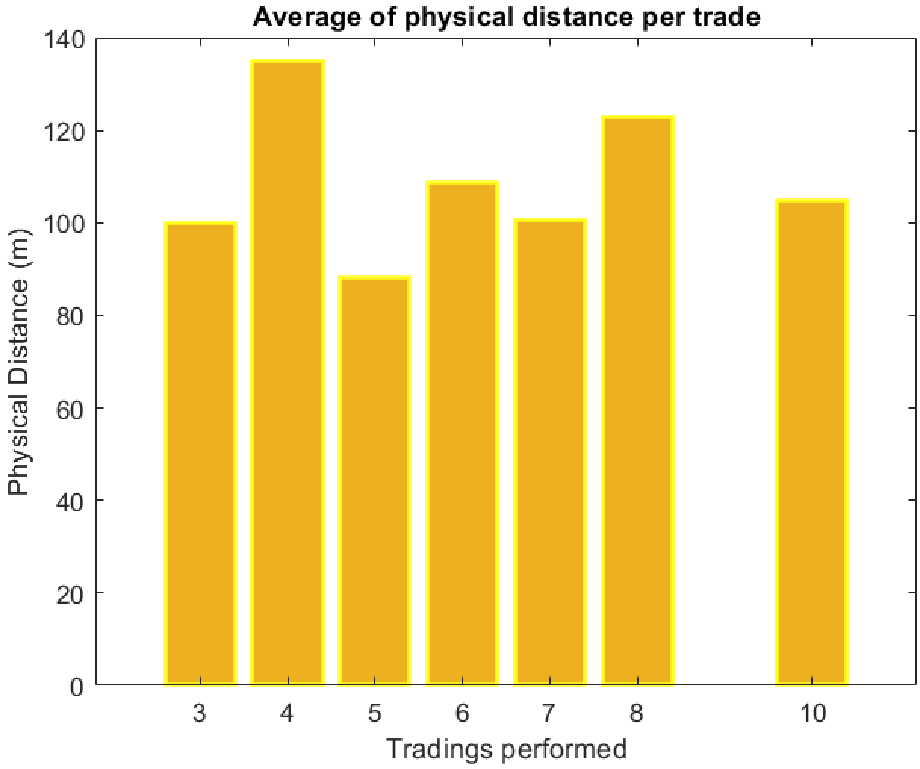


Figure 4.9: Average distance per trade performed

Moving on to Figure 4.9, compares the number of tradings performed and the average distance. It is worth emphasising that the number of tradings does not determine the average distance, but rather the distance between users.

Finally, Figure 4.10 highlights a comparison between two types of user behaviours: cooperative and non-cooperative. Non-cooperative behaviour is defined as users submitting prices that are far from the average during trading. However, it is essential to note that the type of behaviour users exhibit does not affect the average distance per trade.

In summary, the distance between users during each trade is independent of the number of trades completed or the type of user behaviour. Instead, the distance is influenced solely by the users' availability during the trade and their location on the power grid.

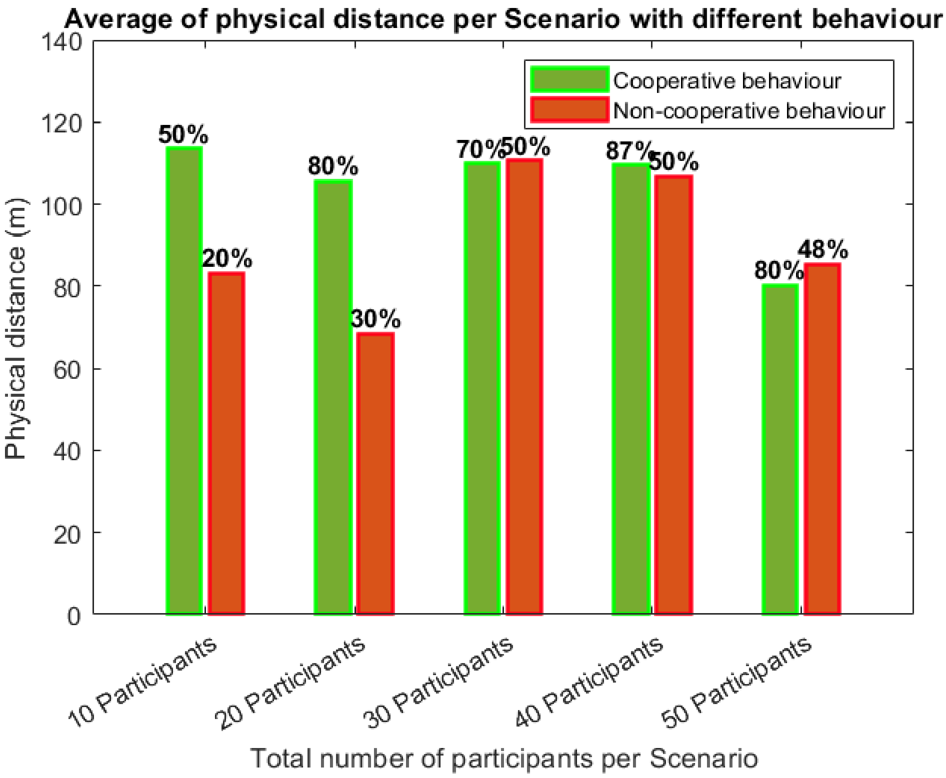
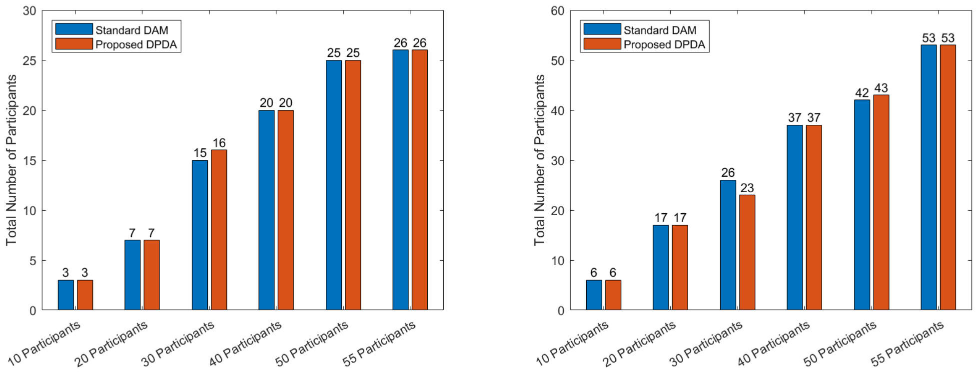


Figure 4.10: Average distance based on cooperative and non-cooperative behaviour

4.5.2 Effects of the use of preferences previously defined on P2P energy trading

This subsection will analyse how the matching results are affected by each preference that has been put forth in the previously defined Score Matching Mechanism. Table 3.1 outlines the cases that have been employed to conduct these analyses. The results have been compared to a standard double auction mechanism, and a subset of participant buyers and sellers using (2.3) has been defined. The matching process is determined by the position in the curve and the amount of energy the prosumer can trade. To better understand how to implement the proposed Score Matching Mechanism, please refer to Appendix B.

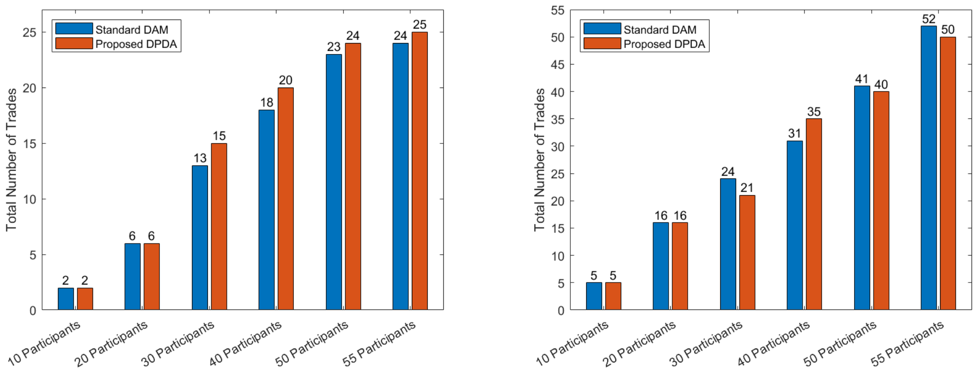
Figure 4.11 compares the total number of participants that can participate based on the mechanism implemented. Changes in these numbers are presented in Figure 4.11(a) only for the cases of thirty and fifty prosumers, and Figure 4.11(b) for the case



(a) Without cooperation (b) With cooperation

Figure 4.11: Comparison of total number of participants for both DAM and DPDA a) without cooperation and b) with cooperation.

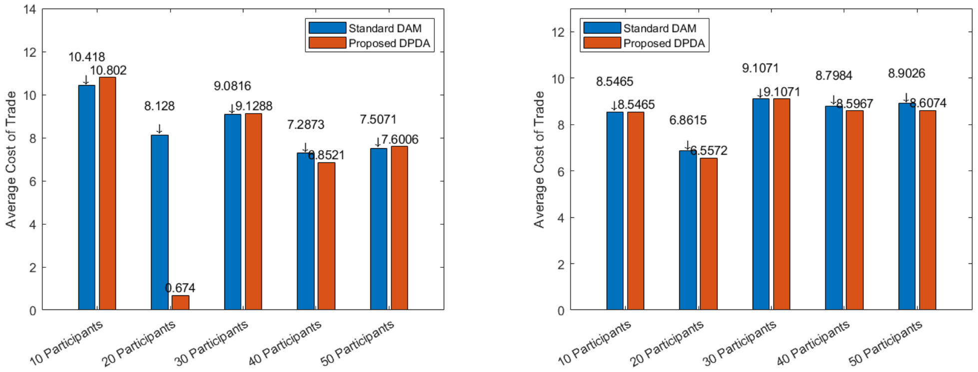
of thirty prosumers. These changes can be attributed to the condition of oversupply that the proposed DPDA needs.



(a) Without cooperation (b) With cooperation

Figure 4.12: Comparison of the number of trades for both DAM and DPDA a) without cooperation and b) with cooperation.

Figure 4.12 shows how the total number of trades for all cases in both behaviours, with and without cooperation, changed. Figure 4.12(a) shows a slight decrease in the last four cases, except for the forty prosumers. These decrements are due to the participants' cooperative behaviour, making meeting the proposed Score Matching mechanism's conditions easier. In comparison, Figure 4.12(b) presents a slight increment in the last four cases, which is the effect of having non-cooperative behaviour, making it more challenging to find the lower costs of the trades.



(a) Without cooperation

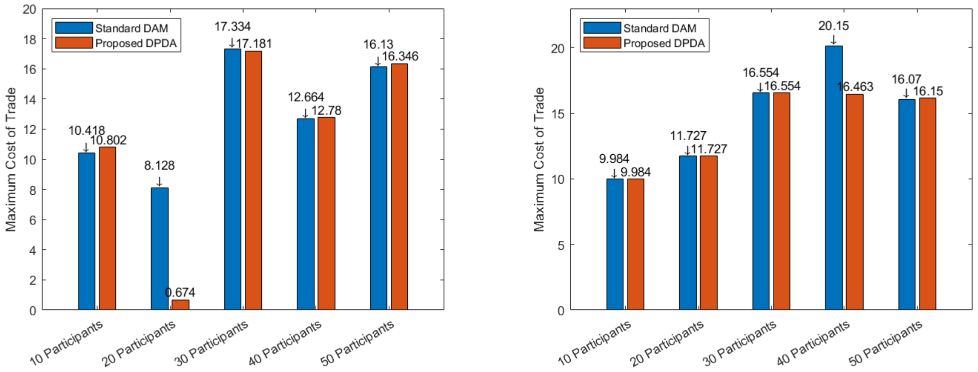
(b) With cooperation

Figure 4.13: Comparison of average cost of trade for both DAM and DPDA a) without cooperation and b) with cooperation.

Figure 4.13 compares each case's average cost per trade. Figure 4.13(a) shows that in most cases, there is a decrement of at least 19% compared to a standard double auction mechanism. The case with thirty prosumers presents a small increment in the average price compared to its homonym. However, it is essential to note that for the DPDA, the number of participants is less than the standard, as shown in Figure 4.12(a). For non-cooperative behaviour, see Figure 4.13(b), there is a decrement of at least 15% in a standard double auction mechanism price. The case with ten prosumers has similar costs. The DPDA generally helps participants save on their trades, regardless of their behaviour.

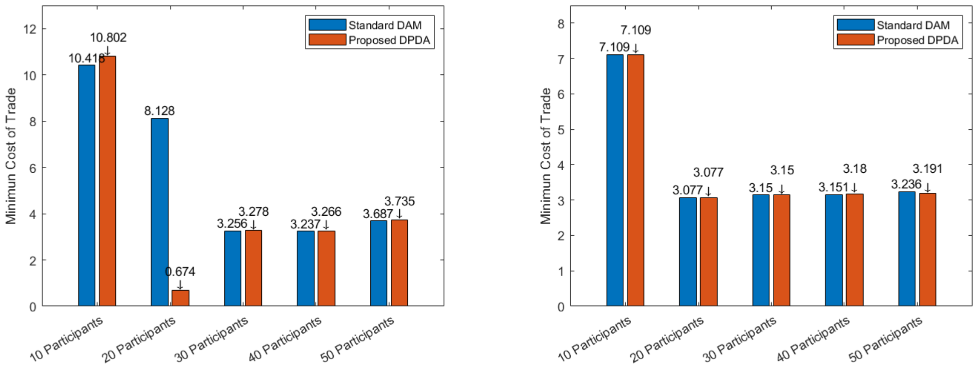
Two analyses were performed to prove that participants save money in their trades. These analyses focus on each case's highest and lowest prices when trading. Then, the standard and the DPDA are presented for both types of behaviours. The results of these comparisons are shown in Figure 4.14 and Figure 4.15.

Figure 4.14 presents the analyses for the highest price in each case for both types of behaviours. For cooperative behaviour, see Figure 4.14(a); most cases show a decrement compared to the standard double auction or have similar prices. While for non-cooperative behaviour, see Figure 4.14(b), the trend is similar except for the case of fifty-five prosumers, where the number of trades on DPDA is less than the standard double auction, causing an increment in this comparison.



(a) Without cooperation (b) With cooperation

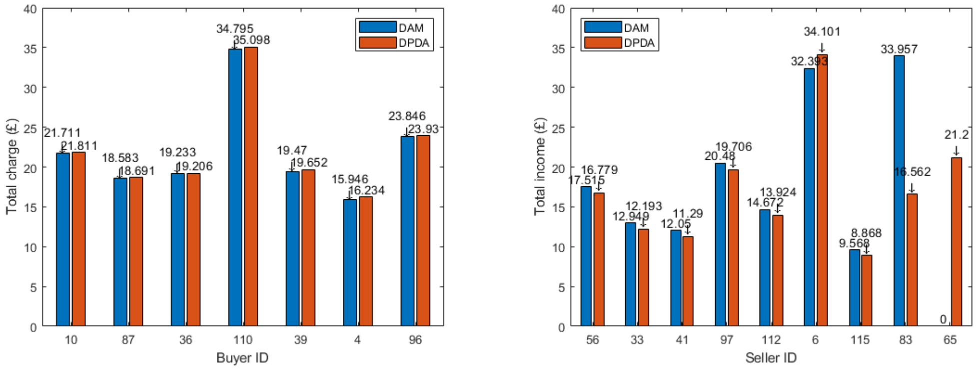
Figure 4.14: Comparison of maximum cost on trade for both DAM and DPDA a) without cooperation and b) with cooperation.



(a) Without cooperation (b) With cooperation

Figure 4.15: Comparison of minimum cost on trade for both DAM and DPDA a) without cooperation and b) with cooperation.

Figure 4.15 shows the other analyses for the lowest price in each case on both types of behaviours. For non-cooperative behaviour, see Figure 4.15(b); there is a considerable decrement in the last three cases of at least 63% of a standard double auction price. These decrements start once the number of participants increases despite the non-cooperative behaviour. Compared with cooperative behaviour, see Figure 4.15(a), most cases present a decrement of at least 37%, except for the case of thirty prosumers where the price is similar. In general, the cases with cooperative behaviour will show a relatively minor price decrease compared to non-cooperative ones. This difference is because participants are more willing to trade in cooperative behaviour, and the price difference is minor when submitted.

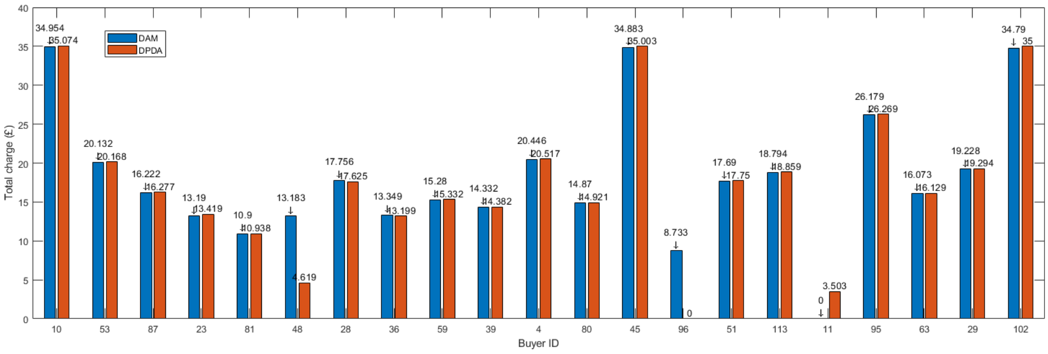


(a) Total costs for buyers (b) Total income for sellers

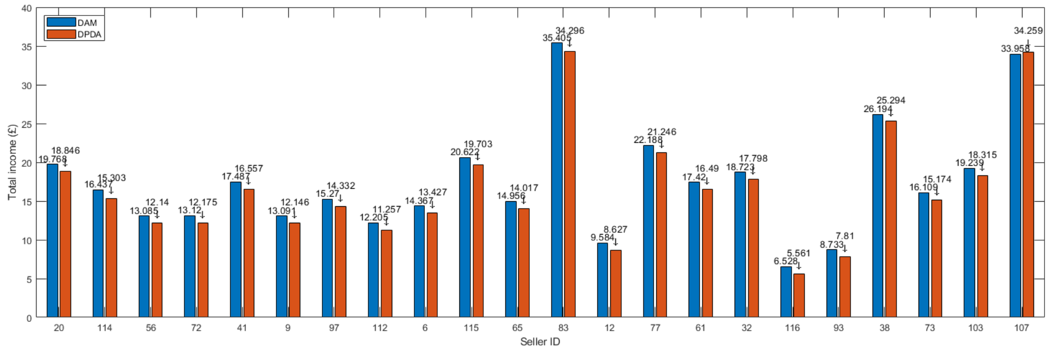
Figure 4.16: Comparison of costs (Case B-30 non-cooperative behaviour) for both DAM and DPDA a) for buyers and b) for sellers.

Figure 4.16 compares buyers' total costs and income for sellers for DAM and DPDA based on case B-30 with non-cooperative behaviour. The total amount of energy traded is 354 kW between 15 trades in both cases. Buyers using DPDA have a slight increment in the costs compared to DAM, as shown in Figure 4.16(a). Sellers using DAM have a small increment in their income compared to DPDA, except for seller 6, who cannot trade the whole amount of energy, and seller 65, who cannot sell any energy, as shown in Figure 4.16(b). On the other hand, seller 83 sells all the energy on DAM. In contrast, in DPDA, the excess energy is divided among all sellers, allowing all available participants to trade.

Figure 4.17 also compares the total costs for buyers and the total income for sellers for DAM and DPA, this time for the case B-50 with cooperative behaviour. In the case of DAM, the energy traded is 878 kW with 41 trades, while in DPDA, the energy traded is 830 kW with 40 trades. The difference in the total costs for the buyers using both methods is minimal. However, three buyers are affected, as shown in Figure 4.17(a). Buyer 96 does not participate in the DPDA but does not trade the whole amount in DAM. Buyer 11 participates in both; however, the sellers' energy is insufficient, and this buyer does not trade. Lastly, the difference in costs for buyer 48 is more significant than for the rest of the buyers, resulting from the distance of this trade. Due to the difference in energy trade between both cases, sellers using



(a) Total costs for buyers



(b) Total income for sellers

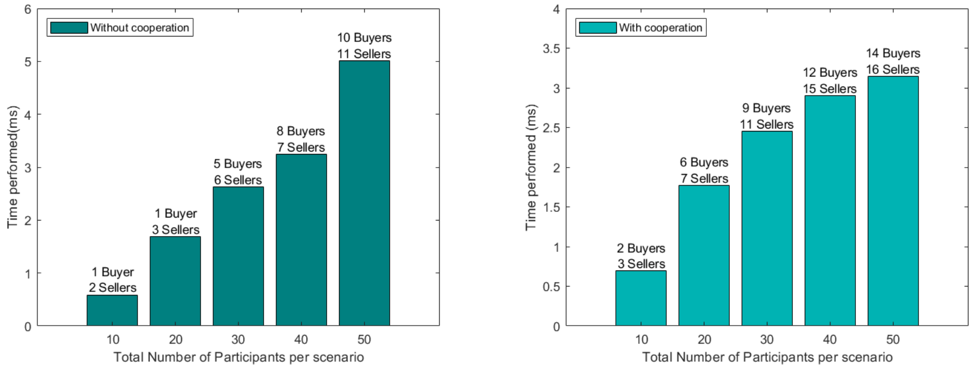
Figure 4.17: Comparison of costs (Case B-50 cooperative behaviour) for both DAM and DPDA a) for buyers and b) for sellers.

DPDA have less income than DAM, as shown in Figure 4.17(b).

4.5.3 Blockchain performance results

This section uses the cases outlined in Table 3.2 to evaluate the DPDA's performance with the proposed score-matching mechanism.

Two figures are presented to analyse the performance under different scenarios: Figure 4.18(b) for cooperative behaviour and Figure 4.18(a) for non-cooperative behaviour. Both figures demonstrate that the time to complete the task increases proportionally with the number of participants. This behaviour can be described as quadratic, providing advantages as more participants are added. Additionally, when considering a P2P energy trading smart grid system in a radial low-voltage distribution network under a mid-decentralised scheme, as described in [1], it took *0.007639 seconds* with 55 participants trading. Please refer to Figure 4.18 for more information.



(a) Without cooperation (b) With cooperation

Figure 4.18: Performance of the algorithm for different number of participants a) without cooperation and b) with cooperation, see Table 3.2.

4.6 Conclusion

The present research proposes a novel approach to microgrid energy trading by implementing a blockchain-based consortium network. The proposed network consists of two channels, with data submitted by each prosumer shared only among them, and the DSOs are interested only in the results of the DPDA. This approach offers several advantages, including increased security, reduced costs, and enhanced speed compared to Ethereum.

The analysis also presents the results of testing the proposed DPDA mechanism, which demonstrated its effectiveness in facilitating microgrid energy trading, particularly in scenarios with limited participants. Using the algorithm to determine the distance between nodes in the network allows DSOs to charge customers when they trade between nodes, covering the grid's usage and any necessary upgrades. Users can decide the radius within the network they want to trade, giving them flexibility.

The model presented in this research has balanced lines to make computation more convenient, and all tested loads are in the same phase. However, further work is needed to assess the voltage balance in the whole network. Using these distances can lead to more accurate power balance control when trading users. The distance calculation must only be performed once and saved into the blockchain for further use.

In the current analysis, there is no consideration of contract enforcement for either prosumer on each trade, with the exception of a penalty while updating the transaction fees. In future work, the consideration of demand and supply forecasting so that the trades have more chance to be fulfilled.

Overall, the analysis highlights the potential impact of the proposed mechanism on DPDA participants, demonstrating significant savings and incentivising prosumers to participate in trading energy locally. However, the study also notes that third parties, such as supplier companies, may be affected for a long time.

Chapter 5

Conclusions and Future Work

The research was conducted on a radial low-voltage distribution network within smart grids. The analysis aimed to facilitate energy trading for all participants while prioritising their well-being; to accomplish this, the proposed DPDA mechanism, which emphasised local consumption and production while considering the expenses associated with energy distribution, was utilised. The research's primary contribution was developing and testing the DPDA mechanism and Consortium Blockchain Network configuration in the deployment setting.

5.1 Addressing the Research Objectives

The objective of the research was to establish a mechanism for Peer-to-Peer Energy Trading using a Consortium Blockchain. Chapter 1 identified the following research objectives to achieve this goal:

- RO1: Create a Double Auction Framework to facilitate local trading of renewable energy by prosumers.
- RO2: Deploy a Consortium Blockchain Network for energy trading.

5.1.1 RO1: Create a Double Auction Framework to facilitate local trading of renewable energy by prosumers

Chapter 3 commences by addressing the crucial aspect of calculating the grid distance between participants trading based on their connection in the power grid distribution network configuration. This distance computation is used further by the DSOs to compute the cost associated with using the distribution grid. Furthermore, the proposed matching mechanism compares this distance with the distance preference submitted by each participant to define their welfare.

The proposed algorithm automatically calculates the distances between all the nodes. This process must be performed only once, and the results are saved on the Blockchain. Unless there is a change in the physical configuration of the distribution lines, there is no need to compute these values again.

DSOs can greatly benefit from automating distribution charges, which are applied directly to the trades. These charges are designed to cover the grid's usage while helping the grid receive the necessary upgrades. Moreover, each trade is based on the radius defined by the user.

Later in this Chapter, the Score Matching Mechanism is presented. This mechanism aims to obtain the subset of participating buyers and sellers trading while ensuring buyers' satisfaction. Buyer's satisfaction is ensured by securing each winning buyer's purchase total energy requirement: this condition affects the number of winning buyers and sellers for each trade. Additionally, all sellers shared any oversupply consequences.

The proposed Score mechanism matches each participant based on the score obtained based on their preferences. This mechanism incentivises users to participate in P2P energy trading by considering welfare. Encouraging users to have cooperative behaviour has delivered more benefits to all users when defining the subsets of participating buyers and sellers.

Local energy can be traded by appealing to each participant's social contribution to the community. If the users can count on their community to obtain the energy needed, the DSOs can promote local energy, which is reflected in the trading prices.

Several analyses were performed in Chapter 4 to compare the effectiveness of the proposed DPDA mechanism against a typical DAM. A side effect of ensuring buyers' satisfaction is that the final number of participants could be reduced to achieve this condition. However, by ensuring that the amount of energy asked is fully covered, buyer satisfaction is achieved, and future research could use this condition to reduce the effects of power loss due to transmission.

5.1.2 RO2: Deploy a Consortium Blockchain Network for energy trading

Chapter 4 proposes a novel approach to implementing P2P energy trading through a Consortium Blockchain network. The chapter introduces an automated P2P energy trading process that allows users to determine their reserved price and the amount of energy to trade.

The significant contribution of this research is the transparency that Blockchain technology provides for all transactions. With the proposed system, users are free from the required time commitments and the need to acquire trade-related domain knowledge if they choose to trade manually. The proposed Consortium Blockchain's two channels enable users to share necessary information to trade while allowing DSOs to monitor energy trading and grid usage. The second channel is designed explicitly for this purpose.

The research evaluates the performance of the proposed DPDA mechanism against the standard DAM in a microgrid scenario implemented through the Consortium Blockchain network. The analysis focuses on the impact of the DPDA on the number of participants, the number of trades, the average cost per trade, and the highest and lowest prices for each trade in both cooperative and non-cooperative behaviours.

The research's findings show that the DPDA mechanism can effectively increase the number of participants in the microgrid when they behave cooperatively, allowing more prosumers to participate in trading. Additionally, the DPDA mechanism leads to a decrease in the average cost per trade as compared to the standard DAM. However, the number of trades is slightly less in the DPDA mechanism, particularly in the non-cooperative behaviour. These findings are under the assumption that no participant will be discouraged from participating in trading but will try to participate in future trades.

Furthermore, the analysis reveals that the DPDA mechanism effectively ensures that all available participants can trade, even with excess energy. This is achieved by dividing the excess energy among all sellers. The research highlights the impact of the DPDA on buyers' and sellers' total costs and income, which varies depending on the specific case study analysed. In addition, DSOs benefit from each trade by getting the fee for usage of the distribution network, but they are not allowed to decide or influence the trades between prosumers. All payments are assumed to be settled using the blockchain and a predefined wallet for each prosumer.

The proposed Consortium Blockchain network presents good scalability due to the type of consensus, which is based on a predetermined number of authorised users. As the number of participants in the network increases, new users can submit their computing power and storage resources. Based on the performance analysis, the total time needed to reach a consensus is steady despite the network's number of users and participants. Overall, this research presents a promising approach to implementing P2P energy trading through the use of a Consortium Blockchain network that provides transparency and scalability while increasing the participation of prosumers in energy trading.

5.1.3 Limitations of the Research

It is important to note that the balance in the power lines is not considered when settling trades. Instead, the assumption of having balanced lines during trading is made. This can result in sudden increases or decreases in the voltage level. Therefore, proposing and implementing a suitable method to reduce this possibility is necessary.

Chapter 3 assumes that the proposed energy to trade by each prosumer to the blockchain is ready to be used, and it does not consider any forecast of the availability of energy and the type of renewal energy source. Additionally, when the matches have been computed, the system does not consider contract enforcement and assumes that prosumers will want to participate in future trades. Thus, more research must be performed to address these topics.

Chapter 4 provides a general overview of a Consortium Blockchain network used to evaluate the performance of the proposed P2P energy trading mechanism. However, it is essential to conduct further analysis of different consensus algorithms and the energy expended on them.

5.2 Future Directions of the Research

The increasing availability of information about the state of the grid presents future challenges, especially with more frequent and real-time data on critical network components. Smart technology is poised to help manage a bi-directional energy grid, but existing blockchain-based energy trading solutions have challenges. As presented in this research, future challenges that can be investigated include:

- blockchain overheads due to negotiations being broadcast to all participants
- lack of trade regulations

- potential privacy concerns due to transaction patterns revealing energy consumption and production
- problematic ownership of data
- high energy consumption from using certain consensus such as PoW (Proof of Work).

Moreover, the type of renewal energy sources and their forecast must be considered before the system computes the matching process. In addition, the system should be able to consider all constraints related to energy trading on the distribution lines, such as power balance.

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Appendix A

Hyperledger Fabric Structure

A blockchain network is a technical infrastructure offering ledger and smart contract (chaincode) services to various applications. Primarily, smart contracts are utilised to define transactions within the network. These transactions are then distributed to every peer node in the network and recorded immutably on their copy of the ledger. The users of these applications can either be end-users utilising client applications or blockchain network administrators.

Often, multiple organisations collaborate as a consortium to form the network, and their permissions are determined by a set of policies agreed upon by the consortium during the network's initial configuration. Additionally, network policies can be changed over time, provided that the organisations in the consortium agree.

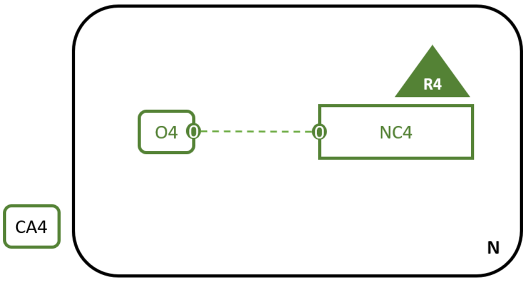

Figure A.1: First definition of Hyperledger Network

The Hyperledger Network has an ordering service called "N", which includes a single node "O4". The node is configured according to a network configuration called "NC4" that grants administrative rights to the organisation "R4"; see Figure A.1. The Certificate Authority (CA), "CA4", provides identities to the administrators and network nodes of "R4".

The ordering service is the initial administration point for the network. It is initially configured and started by an administrator in the organisation "R4", and the configuration "NC4" contains the policies that describe the starting set of administrative capabilities for the network. Initially, only "R4" had rights over the network.

The Certificate Authority "CA4" issues certificates to administrators and network nodes. It plays a crucial role in the network by dispensing X.509 certificates that can identify components belonging to "R4". Certificates issued by CAs can also be used to sign transactions, indicating that an organisation endorses the transaction result, which is a precondition for it being accepted onto the ledger.

Different organisations often use different CAs, and certificates are mapped to member organisations via a Membership Services Provider (MSP) structure. The network configuration "NC4" uses a named MSP to identify the properties of certificates dispensed by "CA4", which associates certificate holders with "R4". "NC4" can use this MSP name in policies to grant nodes from "R4" particular rights over network resources. For instance, identifying the administrators in "R4" who can add new member organisations to the network.

Certificates issued by CAs are crucial to the transaction generation and validation process. Specifically, X.509 certificates are used in client application transaction proposals and smart contract transaction responses to sign transactions digitally. Subsequently, network nodes that host copies of the ledger verify those transaction signatures' validity before accepting transactions onto the ledger.

A consortium is a group of companies or people who work together to achieve a shared goal. On Hyperledger Fabric, a consortium is defined as a "group with a shared destiny". In the context of Network N, a network administrator has defined a consortium called X1, which has two members, organisations R1 and R2. Each organisation has its respective Certificate Authority, CA1 and CA2. This consortium definition is stored in the network configuration NC4 and will be used in the next stage of network development.

Consortium X1 has been created to allow R1 and R2 to transact with each other. Since they share a common goal, forming a consortium makes sense. However, R2 does not have any network administrator rights. More information on how R1 and R2 integrate will be provided in Chapter 4.

Once a consortium has been defined, the next step is to create a channel. A channel is a primary communication mechanism through which consortium members can communicate. There can be multiple channels in a network, which will be addressed

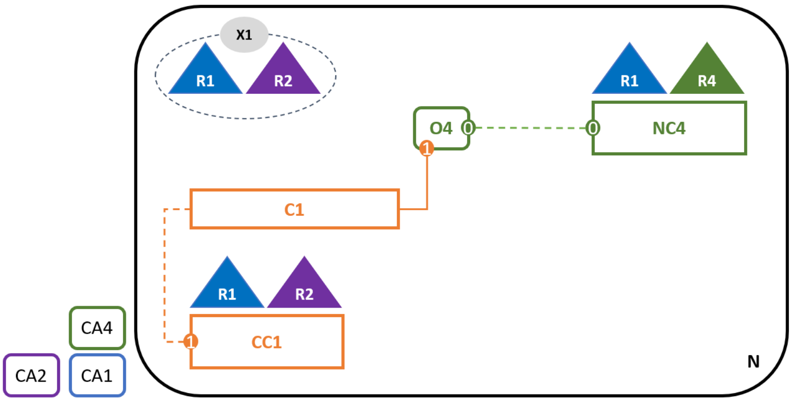

Figure A.2: State channel **C1** created for **R1** and **R2** using the consortium definition

in this research as State Channels. Figure Y presents the creation of State Channel C1 for R1 and R2 using the consortium definition X1. The State Channel configuration CC1 governs State Channel C1, separate from the network configuration NC4. R1 and R2 have equal rights over C1, which they manage. R4 has no rights in CC1 whatsoever.

State Channel C1 serves as a private communication mechanism for consortium X1. It is connected only to the ordering service O4 and has no other connections. However, in future stages of network development, C1 will be connected to other components like client applications and peer nodes. At present, the channel only represents the possibility of future connectivity.

C1 has a separate configuration called CC1, which governs the rights of R1 and R2 over the state channel. For instance, it sets rules on who can add a new organisation to the channel. It is important to note that organisations other than R1 and R2 have no permissions over C1. They can only interact with it if R1 or R2 adds them to the appropriate policy in the channel configuration CC1. Furthermore, R4 cannot add itself to C1 unless authorised by R1 or R2.

State Channels provide a convenient way for consortium members to share infrastructure while maintaining data and communications privacy. These channels are entirely separate from the network; only organisations defined in the channel configuration can control them. Updates to the network configuration NC4 will not directly impact channel configuration CC1. In addition, State Channels offer privacy from other state channels and the network.

Overall, State Channels are an efficient mechanism for sharing information and processes among different consortia within the network. They allow for private communications and data sharing between consortium members and ensure that the data within a state channel is entirely isolated from the rest of the network.

In Hyperledger Fabric, a specific system channel is designated for use by the ordering system. This channel functions similarly to a standard state channel but is referred to as an application channel. While it is not being used in the current research, it could be a potential focus for future investigation, as all transactions on the system channel pertain to either configuration or the creation of new channels. The ordering service nodes are connected via a mini-blockchain through the system channel to distribute network configuration transactions that help maintain consistent copies of the network configuration for each node. Similarly, peer nodes in an application channel can distribute state channel configuration transactions, ensuring that the channel configuration exists uniformly across all nodes. This balance between logically singular objects is a typical pattern in Hyperledger Fabric due to the network's physical distribution. Objects like network configurations and state channel configurations are logically singular but physically replicated among a set of ordering service nodes. The same applies to ledgers and smart contracts, which exist logically at the channel level but are installed in multiple locations.

In a blockchain network, peer nodes host copies of the blockchain ledger. One of these peer nodes, P1, has the specific role of hosting a copy of the ledger instance L1 for others to access. While L1 is physically located on P1, it is logically hosted on state channel C1. To be a part of the network, P1 must have an X.509 identity issued by CA1, which associates it with organisation R1. When the R1 administrator joins P1 to state channel C1, and the peer starts pulling blocks from orderer O4, the orderer uses the channel configuration CC1 to determine P1's permissions on this state channel. For example, the policy in CC1 determines whether P1 (or the organisation R1) can read and/or write on the state channel C1.

In Hyperledger Fabric, all peer nodes are equal but can take on different roles depending on the network configuration. The two prominent roles are committing peer and endorsing peer. Every peer node in a state channel is a committing peer. It receives blocks of generated transactions, which are subsequently validated before they are committed to the peer node's copy of the ledger as an appended operation. Only peers with a smart contract installed can be endorsing peers. Each endorsing peer takes the transaction proposal inputs as arguments to invoke the chaincode function, and depending on the result, the transaction is approved or rejected.

An endorsement policy for a smart contract identifies the organisations whose peer should digitally sign a generated transaction before it can be accepted onto a committing peer's copy of the ledger. Additionally, a peer can take on two other roles:

- **Leader peer**. When an organisation has multiple peers in a channel, a leader peer is a node responsible for distributing transactions from the orderer to the other committing peers in the organisation. A peer can choose to participate in static or dynamic leadership selection. It is helpful to think of two sets of peers from a leadership perspective: those with static leader selection and those with dynamic leader selection. Zero or more peers can be configured as leaders for the static set. For the dynamic set, one peer will be elected leader by the set. If a leader peer fails in the dynamic set, the remaining peers will re-elect a leader. An organisation's peers can have one or more leaders connected to the ordering service. This configuration can help improve resilience and scalability in large networks that process high transaction volumes.
- **Anchor peer**. When a peer needs to communicate with a peer in another organisation, it can use one of the anchor peers defined in the state channel configuration for that organisation. An organisation can have zero or more anchor peers defined for it, and an anchor peer can help with many different cross-organisation communication scenarios.

State channels play a crucial role in facilitating communication between different components of a network and organisation. In the upcoming development phase of the Hyperledger network, the client application A1 can leverage the state channel C1 to connect with specific network resources. In this case, A1 can connect with peer node P1 and orderer node O4. Like peers and orderers, a client application has an identity that links it with an organisation. In this example, client application A1 is associated with organisation R1, and although it is not a part of the Fabric blockchain network, it can still connect via state channel C1.

At first glance, it may seem that A1 can directly access the ledger L1 via P1, but all access is managed through a specific program called smart contract chaincode, S5. S5 defines all the expected access patterns to the ledger and provides a well-defined set of ways to query or update the ledger L1. In short, client application A1 has to go through smart contract S5 to access the ledger L1.

State channels are beneficial in the energy industry because they allow each organisation to be on a different channel and manage the information shared between peers within their organisation. Additionally, DSOs can benefit from these channels by adding privacy layers and sharing essential data related to energy trade without revealing consumer behaviour. More advantages of state channels in the energy industry are discussed in Chapter 4.4.3.

Developers can create smart contracts for each organisation to implement a business process shared by the consortium members. Smart contracts help generate transactions that can be distributed to every network node. To make this possible, two operations must be performed on the smart contract: installation on peers and definition on a channel.

Hyperledger Fabric users often use the terms "smart contract" and "chaincode" interchangeably. However, in general, a smart contract defines the transaction logic that controls the lifecycle of a business object contained in the world state. The smart contract is then packaged into a chaincode deployed to a blockchain network.

Smart contracts are like governing transactions, whereas chaincode governs how smart contracts are packaged for deployment.

When an organisation has multiple peers in a channel, it can choose the peers upon which it installs smart contracts. Therefore, the organisation can install a smart contract on some peers. Each organisation needs to approve a chaincode definition, a set of parameters that establish how a chaincode will be used on a channel.

An organisation must approve a chaincode definition to use the installed smart contract to query the ledger and endorse transactions. A majority (by default) number of organisations need to approve a chaincode definition before the chaincode definition can be committed to the channel and used to interact with the channel ledger.

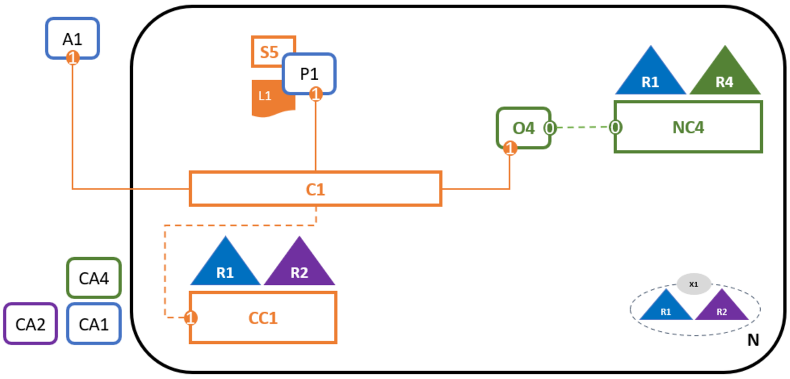

Figure A.3: Operational Network example using application **A1**

In the example shown in Figure A.3, which only has a single peer node, an administrator in organisation R1 must approve a chaincode definition for S5. Because the channel only has one member, the administrator of R1 can commit the chaincode definition of S5 to state channel C1. Once the definition has been committed, S5 can now be invoked by client application A1.

Although every component on the state channel can now access S5, they cannot see its program logic. The chaincode remains private to those nodes who have installed it. Conceptually, this means that the smart contract interface is defined and committed to a state channel, in contrast to the installed smart contract implementation.

The endorsement policy is the most crucial information supplied within the chaincode definition. It describes which organisations must approve transactions before others accept them onto their ledger copy. In the sample network, transactions can only be accepted onto ledger L1 if R1 or R2 endorse them. Committing the chaincode definition to the state channel places the endorsement policy on the channel ledger, enabling the policy to be accessed by any channel member.

Once a smart contract has been committed to a channel, it can be invoked by a client application. Client applications do this by sending transaction proposals to peers owned by the organisations specified by the smart contract endorsement policy. The transaction proposal serves as input to the smart contract, which uses it to generate an endorsed transaction response, which the peer node returns to the client application. These transaction responses are packaged together with the transaction proposal to form a fully endorsed transaction, which can be distributed to the entire network.

Now, organisation R1 is fully participating in the network. Its applications, starting with S5, can access the ledger L1 via smart contract S5 to generate transactions that R1 will endorse and, therefore, be accepted onto the ledger because they conform to the endorsement policy.

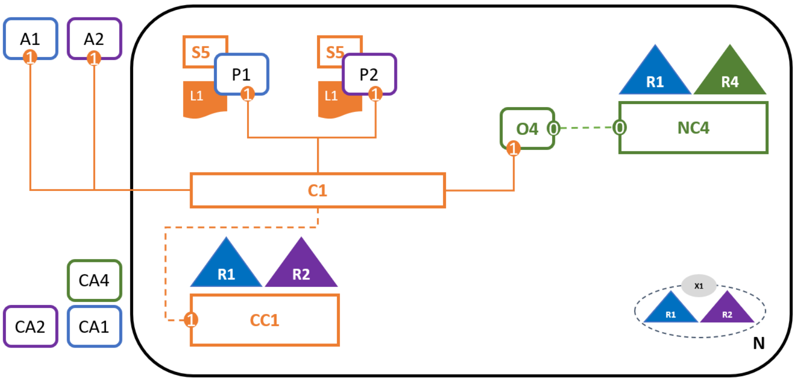

Figure A.4: Operational Network example using applications **A1** and **A2**

The diagram presented in Figure A.4 shows that **R2** has integrated a new peer node, **P2**, onto channel **C1**. Additionally, **P2** is responsible for hosting a copy of smart contract **S5** and ledger **L1**. Organisation **R2** has also included client application **A2**, which can connect to the network through the state channel **C1**. To accomplish this, an administrator within **R2** has established peer node **P2** and connected it to state channel **C1**, following the same steps as the administrator in **R1**. The administrator must also approve the precise chaincode definition as **R1**. At this point in network development, there is a state channel where organisations **R1** and **R2** can conduct whole transactions with each other. Specifically, this implies that applications **A1** and **A2** can produce transactions utilising smart contract **S5** and ledger **L1** on channel **C1**.

In order to run a smart contract, a peer must be installed on the state channel and connected to it. There are two types of peer nodes: those that host smart contracts and those which do not. In the example network, every peer hosts a copy of the smart contract, but in more extensive networks, many peer nodes will not host a copy of the smart contract. Peer nodes with smart contracts have extraordinary power - they can help generate transactions. However, only peer nodes with a smart contract installed can participate in the transaction endorsement process, which is central to generating valid transactions. All peer nodes can validate and subsequently accept or reject transactions onto their copy of the ledger L1.

The network example includes state channel C1, which connects two client applications, two peer nodes and an ordering service. Since there is only one channel, there is only one logical ledger with which these components interact. Peer nodes P1 and P2 have identical copies of ledger L1. Copies of smart contract S5 should be implemented identically using the same programming language. If not, they must be semantically equivalent. However, network and channel policies can help govern even large networks. Organisations can add peer nodes to the network if they conform to the agreed policies. Network and channel policies balance autonomy and control, characterising a decentralised network. Therefore, it is possible to configure sophisticated topologies that support various operational goals. There is no theoretical limit to how big a network can become. Moreover, the gossip protocol, which is the technical mechanism by which peers within an organisation efficiently discover and communicate with each other, can accommodate many peer nodes supporting such topologies.

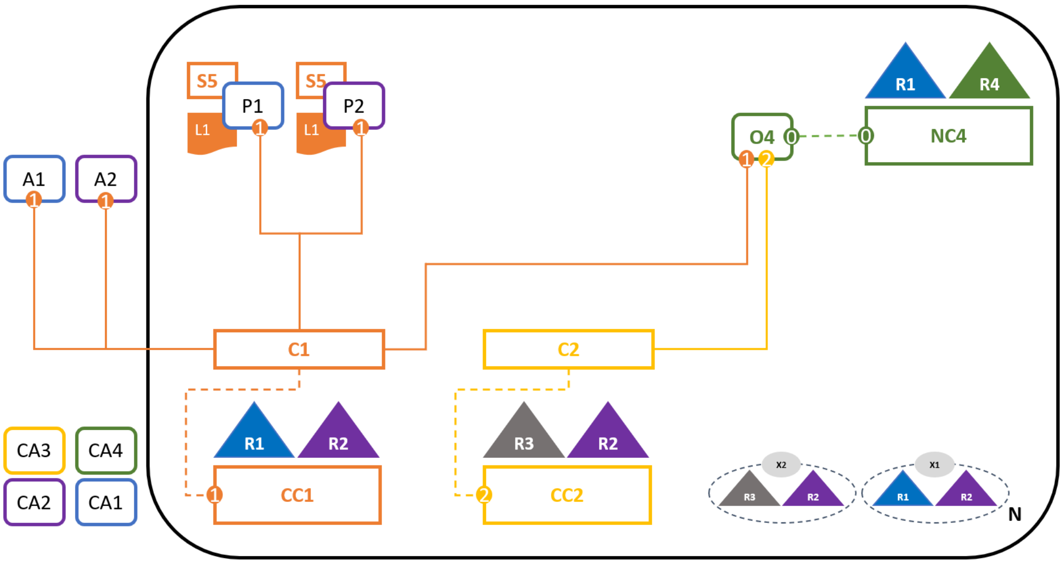

Figure A.5: Addition of a second state channel **C2** to an operational network

Figure A.5 shows that a second state channel has been added, labelled as **C2**. It is important to note that the state channel configurations **CC1** and **CC2** remain separate from each other and from the overall network configuration **NC4**. Consortium **X2**, which includes organizations **R2** and **R3**, manages state channel **C2** independently from other network elements. It is worth mentioning that state channel policies always remain separate, and only authorised organisations can change them in the state channel. As the network and state channels evolve, their configurations will change accordingly. This process is regulated through configuration transactions that capture any changes made to these configurations. Each configuration change generates a new configuration block transaction.

State channels serve as a dual-purpose infrastructure, enabling organisations to function independently while facilitating collaboration. This system is maintained and utilised by a group of autonomous entities. Each node's conduct on a state channel is governed by specific regulations outlined in the corresponding state channel policies. These guidelines are essential for ensuring proper behaviour across all components of a state channel, as previously agreed upon.

Appendix B

Example of implementing the proposed Score Matching Mechanism

Scenario 1, see Figure 2.8, demonstrates the implementation of the proposed Score Matching Mechanism. Based on the parameters showed in Table 2.2, the results from Algorithm 2 are:

1. The price for the trading is:

   $p_0 = 16.5$

2. The subset of seller's IDs considered to trade is $[24, 20, 45, 4]$, and for the subset of buyers is $[39, 9, 12]$.

3. Each Seller that participates will trade the following amount of energy

   $E'(S) = \{0.0, 24.25, 0.0, 39.25, 0.0, 0.0, 13.25, 69.25\}$

   the order of the values is similar to the order received at the beginning of the process.

Parameter	Value
Subset of sellers (ID)	[24,20,45,4]
Subset of buyers (ID)	[39,9,12]
Subset of the amount of energy to sell (kWh)	[24.25,39.25,13.25,69.25]
Subset of the amount of energy to buy (kWh)	[16.000,70.000,60.000]
Subset of reserved prices from sellers (£)	[10.000,5.000,7.000,2.000]
Subset of reserved prices from buyers (£)	[28.000,30.000,23.000]
Subset of distance preference from sellers (km)	[100.000,35.000,280.000,390.000]
Subset of distance preference from buyers (km)	[80.000,100.000,400.000]

Table B.1: Parameters used for Case 1 (based on DAM results), see table 3.1.

Table B.1 summarise the data used for the following calculations. All data is displayed in order of submission to the system.

The first step is to calculate the welfare for the subsets of buyers and sellers participating. Based on Table B.1 and implementing (2.8) and (2.9), the welfare for each seller is $[250.685, 403.422, 137.247, 702.147]$ and for each buyer is $[-57.920, -518.000,$

Buyer (ID) \Seller (ID)	24	20	45	4
39	976.531	1683.731	669.259	4586.524
9	-1309.318	-848.397	-2820.745	2759.977
12	-851.3	13.120	-3017.459	3440.873

Table B.2: Scores for Case 1

-402.000]. Then, following Algorithm 4, the scores for each participant are displayed in Table B.2.

Once the scores are obtained, following the matching procedure previously described, the highest score is 4586.524, between the buyer ID 39 and seller ID 4, each with $E(B_{39}) = 16$ and $E'(S_4) = 69.25$, respectively.

Buyer (ID) \Seller (ID)	24	20	45	4
39	976.531	1683.731	669.259	4586.524
9	-1309.318	-848.397	-2820.745	2759.977
12	-851.3	13.120	-3017.459	3440.873

Following (4.5): $E(B_{39}) \ - \ E'(S_4) = 16 \ - \ 69.25 = -53.25$

The amount of energy requested by the buyer is completed, and the new amount of energy for seller ID 4 is $E''(S_4) = 53.25$. Since buyer ID 39 has no more requests, the remaining scores are not considered further.

Buyer (ID) \Seller (ID)	24	20	45	4
39	~~976.531~~	~~1683.731~~	~~669.259~~	4586.524
9	-1309.318	-848.397	-2820.745	2759.977
12	-851.3	13.120	-3017.459	3440.873

Continue with the matching procedure, the new highest score is 3440.873, between the buyer ID 12 and seller ID 4, each with $E(B_{12}) = 60$ and $E''(S_4) = 53.25$, respectively.

Following (4.5): $E(B_{12}) \ - \ E'(S_4) = 60 \ - \ 53.25 = 6.75$

The amount of energy provided by the seller is reached, and the new amount of energy for buyer ID 12 is $E'(B_{12}) = 6.75$. Since seller ID 4 has no more supply, the remaining scores are not considered further.

Buyer (ID) \Seller (ID)	24	20	45	4
39	~~976.531~~	~~1683.731~~	~~669.259~~	4586.524
9	-1309.318	-848.397	-2820.745	~~2759.977~~
12	-851.3	13.120	-3017.459	3440.873

Following the matching procedure, the new highest score is 13.12, between the buyer ID 12 and seller ID 20, each with $E'(B_{12}) = 6.75$ and $E'(S_{20}) = 39.25$, respectively.

Based on (4.5): $E'(B_{12}) \; - \; E'(S_{20}) = 6.75 \; - \; 39.25 = -32.5$

The amount of energy requested by the buyer is completed, and the new amount of energy for seller ID 20 is $E''(S_{20}) = 32.5$. Since buyer ID 12 has no more requests, the remaining scores are not considered further.

Buyer (ID) \Seller (ID)	24	20	45	4
39	~~976.531~~	~~1683.731~~	~~669.259~~	4586.524
9	-1309.318	-848.397	-2820.745	~~2759.977~~
12	~~-851.3~~	13.120	~~-3017.459~~	3440.873

Continue with the matching procedure, the new highest score is -848.397, between the buyer ID 9 and seller ID 20, each with $E(B_9) = 70$ and $E''(S_{20}) = 32.5$, respectively.

Following (4.5): $E'(B_9) \; - \; E'(S_{20}) = 70 \; - \; 32.5 = 37.5$

The amount of energy the seller provides is reached, and the new amount of energy for buyer ID 9 is $E'(B_9) = 37.5$. Since seller ID 20 has no more supply, the remaining scores are not considered further. However, this seller has no more scores, so the omission is unnecessary.

Buyer (ID) \Seller (ID)	24	20	45	4
39	~~976.531~~	~~1683.731~~	~~669.259~~	4586.524
9	-1309.318	-848.397	-2820.745	~~2759.977~~
12	~~-851.3~~	13.120	~~-3017.459~~	3440.873

Following the matching procedure, the new highest score is -1309.318, between the buyer ID 9 and seller ID 24, each with $E'(B_9) = 37.5$ and $E'(S_{24}) = 24.25$, respectively.

Based on (4.5): $E'(B_9) \; - \; E'(S_{24}) = 37.5 \; - \; 24.25 = 13.25$

The amount of energy provided by the seller is reached, and the new amount of energy for buyer ID 9 is $E''(B_9) = 13.25$. Since seller ID 24 has no more supply, the remaining scores are not considered further. However, this seller has no more scores similar to the previous case, so the omission is unnecessary.

Buyer (ID) \Seller (ID)	24	20	45	4
39	~~976.531~~	~~1683.731~~	~~669.259~~	4586.524
9	-1309.318	-848.397	-2820.745	~~2759.977~~
12	~~-851.3~~	13.120	~~-3017.459~~	3440.873

Continue with the matching procedure, the new highest score is -2820.745, between the buyer ID 9 and seller ID 45, each with $E''(B_9) = 13.25$ and $E''(S_{45}) = 13.25$, respectively.

Following (4.5): $E''(B_9) \; - \; E'(S_{45}) = 13.25 \; - \; 13.25 = 0$

Sellers			
ID	Income	Amount of Energy	Charge for Distribution
24	400.244	24.5	0.119
20	647.798	39.25	0.173
45	218.741	13.25	0.116
4	1142.782	69.25	0.157

Table B.3: Information sent back to each seller.

Buyers			
ID	Bill	Amount of Energy	Charge for Distribution
39	264.121	16	0.121
9	1155.328	70.25	0.328
12	990.116	60	0.116

Table B.4: Information sent back to each Buyer.

Once there is no more energy to trade, the process ends, and the results from the Score Matching Mechanism are sent back to the system. Table B.3 presents the information sent to the subset of sellers participating, while Table B.4 refers to the subset of buyers participating.

Colophon

This thesis is based on a template developed by Matthew Townson and Andrew Reeves. It was typeset with LaTeX 2$_{\varepsilon}$. It was created using the *memoir* package, maintained by Lars Madsen, with the *madsen* chapter style. The font used is Latin Modern, derived from fonts designed by Donald E. Kunith.