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Empowering individuals with low-level control using preference-based automated matching

By

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Abstract

As the uptake of microgeneration continues, the topology of the electricity network is changing with the reliance on large-scale electricity generation being reduced and replaced with distributed energy resources (DERs). This change though has not yet been reflected in the market model that is used to organise the market. This project explores an alternative model wherein producers and consumers are able to directly trade with one another, without the need for an intermediary supplier, increasing the control and transparency of each individuals electricity supply. This model, known as a peer-to-peer (P2P), has been seen as one possible future for the electricity system, but for domestic householders, the benefits of this market are limited by the time commitment and knowledge necessary to participate in this market and the little reward that it could provide.

Through this research, we present a blockchain-based infrastructure for enabling P2P markets with the objectives of incentivising the purchase of locally generated electricity, incentivising the uptake of microgeneration to local demand capacity and providing increased control to the householders. This infrastructure demonstrates the viability of blockchain as an enabler for this market model providing a modular, flexible and adaptable solution to the various P2P business models. The feasibility of this infrastructure is assessed through the integration of two alternative trading models within the same platform: a local trading model providing automated preference-based trading across the market and a community-focused trading model integrating various sharing models within a microgrid. An early-stage empirical study is then used to validate the platform through a preliminary live customer trial in a residential flat building and a demonstration deployment within a university campus.

Dedication and acknowledgements

This work would not be possible without the support of my supervisors, friends and colleagues that have been there throughout the process providing encouragement and guidance. I would like to specifically thank Ruzanna Chitchyan (academic supervisor), Charles Delalonde (first industrial supervisor), Alastair Byrne (second industrial supervisor), David Ferguson (third industrial supervisor) and Christopher Weeks for their advice, intellectual discussions and patience. I would also like to thank all of the people in academia and EDF Energy that I worked with throughout my PhD, especially Adrien Nivaggioli, Albane Julia, Alexandre Nicol, Alice Calliger, Baptise Ingrand, Camille Roux, Emmanuel Dupriez, Hippolyte Coste, Huma Arif, Irena Yanachkova, Jacques Folleas, Jean-Francois Hullo, Jean-Michel Daignan, Konstantins Afanasjevs, María del Carmen Campos Varillas, Marius Vaitkevicius, Mathieu Vu, Matthew Carver, Mohamed Hadri, Nguyen Nguyen, Pedro Monteiro Carvalho da Costa, Pierre Dupuy De La Grand'Rive, Rim Kaddah, Thibaut Possompes, Thomas Erlebach, William Selby and Yushi Chen. A special thank you is also greatly deserved by my partner Vanessa Lenormand whom provided continual support from beginning to end.

Author's declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

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Acronyms

BSUoS balancing services use of system. 16

dApp decentralised application. 22, 126

DCA distributed consensus algorithm. 24

DER Distributed Energy Resource. 2, 3, 38–40, 44, 45, 47, 48, 126, 129, 137

DLT distributed ledger technology. 5, 19, 140

DNO Distribution network operator. 119

DSO Distribution system operator. 16, 37, 41, 49

DUoS distribution use of system. 16, 17

ETP electricity trading platform. 60, 64, 68, 71, 115–117, 120, 121, 123, 124

FIT Feed-In-Tariff. 2, 18

GWp gigawatt peak. 2

HH half-hourly. 11, 15, 90

IoT Internet of Things. 3

MPP Major Power Producer. 1, 10, 16, 17

P2P peer-to-peer. xi, 3–7, 9, 12–19, 30, 32, 37, 45–47, 51, 52, 55, 56, 82, 116, 124, 125, 130, 131, 137–139

PV photovoltaic. 31, 90, 115, 117, 127

TNUoS transmission network use of system. 17

UK united kingdom. 1–3, 6, 9, 13, 138

VPP Virtual Power Plant. 40, 66

Glossary

domestic supplier (also **household supplier**) A household able to market its electricity exports directly to others. 3, 74

embedded generation The production of electricity from generation sources directly connected to the distribution network. 16

microgeneration Small-scale generation resources that produce heat or electricity. 2, 3, 7, 10

microgrid A group of interconnected buildings with only a single connection to the electricity grid. 28, 29, 37, 68, 69, 115, 116

power purchase agreement A long-term contract in which electricity is purchased directly from an electricity generator. 118

prosumer An individual that is both the consumer and producer of some good. 3, 14, 15, 18, 20, 90, 91, 94, 98, 131

technological trust The belief that a piece of technology will guarantee a result, as opposed to the reliance on another person. 60, 66, 140

transactive A broader term often used to refer to peer-to-peer trading. 12, 29, 138

Chapter 1

Introduction

The opening chapter of this thesis will provide context of the research area and introduce the problem we are addressing. It will present the research objectives, core research contributions and provide a structure to the thesis to improve readability for the reader.

1.1 Problem statement

In the UK, electricity generation is primarily undertaken by large corporations - known as Major Power Producers (MPPs) - that feed electricity through the grid to end users. These MPPs have supplied over 80% of the electricity in the UK for the past 70 years [1, 2], and as such the electricity system has been designed around this model of electricity generation. The electricity grid, the markets and the regulation have been shaped over time to best suit this system and while we have used the UK as an example, this model of the energy sector is used throughout the developed world as a traditional default solution to electricity supply.

However, this long established method of generating our electricity is beginning to change, due to a number of drivers:

1. National and international concerns for climate change motivate the move to clean energy sources.

In recent years the electricity landscape has begun changing from its centralised state into a more distributed environment in which electricity is increasingly generated through smaller scale sources. There are numerous factors responsible for this, including social perception, global need and regulation changes. One of the most impactful changes has been the increasing concern for climate change that has sparked major international agreements such as The Paris Agreement [3] - requiring that countries involved attempt to minimise global temperature rise - and the EU

2020 [4], 2030 [5] and 2050 [6] frameworks - requiring broad quantitative changes to emissions, renewable generation and energy efficiency. These agreements, along with national government objectives have resulted in significant regulatory changes to meet these goals including the introduction of incentive schemes to encourage consumers to act. These include schemes such as the Green Deal [7] that provides discounts and finance plans for making energy-saving improvements to houses and the Feed-In-Tariff (FIT) [8] that pays owners for any electricity they generate or export to the grid.

2. Technical feasibility of economically viable DERs at household level and their increasing physical installations

The incentives put in place have proved successful, and consequently we have seen a significant rise in the installations of Distributed Energy Resources (DERs), specifically microgeneration - small-scale generation resources that produce heat or electricity. The FIT scheme alone has registered over 800,000 installations since its inception in 2010 with a total capacity of 6.2 gigawatt peak (GWp) [9]. This increase in the number of energy resources in the network provides increased stability to the grid through the reduced reliance on single large-scale generation resources and reduced transmission losses by moving the generation closer to the end-users. However, this growth has also called into question the ability of the current electricity system to accommodate this alternative model [10].

The grid was designed as a one-way electricity flow, but by moving the generation to a household level the grid is increasingly being used as a two-way system putting extra strain on the infrastructure. Similarly, the current market model (i.e., how energy is bought and sold) was designed to be underpinned by large-scale generation and does not provide facilities for individuals to join the market. The UK electricity system is currently based upon a supplier hub model, in which suppliers act as an intermediary between consumers and generators. For microgenerators, this means that they must either use their own production or sell it to a supplier for resale. While this arrangement simplifies the market, it relies on government incentive schemes to increase the uptake of microgeneration and guaranteed payments from suppliers to handle excess production. As the number of microgenerators continues to rise, this model becomes an ineffective way of managing the small-scale generation, and providing little to no control to the owners of the generation devices over their produced electricity. These issues have been raised by the energy regulator of the UK that has determined that there is a "strong case for considering fundamental reforms" to the current market model [11].

3. UK-wide increased availability and connectivity of digital infrastructure at a household level

Concurrently, as these infrastructure changes are taking place, the integration of energy-related digital technologies in domestic setting has also been significantly increasing. Metering is seeing widespread change with the advent of smart meters, i.e. electricity meters that send their data to remote servers and provide local connectivity for real-time monitoring. The UK has already begun the rollout of these new meters, and there are currently just over 14.9 million smart meters installed in domestic properties [12]; smart meter coverage is planned to increase to all domestic and small business customers by the end of 2020 [13]. The concept of smart home has also begun to gain traction with the number of smart home devices and Internet of Things (IoT) devices growing rapidly [14], providing an increasing amount of data and connectivity to residential properties. This data enables significant insights into occupant behaviour and enables development of more personalised digital tools for the energy domain.

4. An opportunity for a new kind of energy market

The combination of increasing DER installations and data availability has the potential to completely alter the energy industry into a model of both decentralised production and sale. This change though would require industry-wide changes and an alternative model that better supports small-scale interactions with the market. This project explores one model that is currently studied by both business and academia: the idea of a peer-to-peer (P2P) electricity market, in which individuals can interact directly with one another without the need for an intermediary to act as a provider. The emergence of this P2P market would see energy generated, sold, and consumed by individuals households. Instead of the current centralised system, we could see microgenerators selling their excess electricity on a P2P network to other individuals or organisations on the grid. This would introduce a new role within the energy market, which goes beyond the concept of current prosumers (where a prosumer is a producer of some good as well as its consumer). Whereas a prosumer sells their excess electricity production to an energy supplier for resale, this new role would see individuals trading directly without the need for this intermediary supplier. In this new market structure a household with microgeneration can also independently trade its produced electricity on the market. Such households would become small energy suppliers and are henceforth referred to as household or domestic suppliers.

Due to the small amounts of electricity produced by such domestic suppliers and the likely supply intermittency due to their renewables-based production, there would be significant differences between the current system of energy supply and consumption and the one envisioned in this project:

- Instead of consumers having their electricity sourced from one single energy supplier, they would buy and sell electricity across an open market from anyone, swapping their energy supplier on a minute-by-minute basis.

- This would allow them to buy electricity based on their own personal preferences, whether that be the distance from the generator, type of microgeneration or just to buy for the best price.

1.2 Research objectives

To enable this market, a platform would need to be created, in which any household could market their electricity exports, and any other household could buy this from them. This platform would need to access individual household data to provide accurate, real-time electricity exports which could then be listed on a market where others could purchase it. With a platform such as this, the market would then be able to:

- Develop optimisation mechanisms that automate the trading process
- Increase the monetary benefit to consumers
- Support local generators
- Provide demand response services to the grid

This research project sets out to demonstrate the feasibility of a platform such as this, understanding the technological barriers, market design and regulatory issues that it would face. To this work the primary motivation of such a platform is to *improve the control that individuals have over both the purchase and sale of electricity*. This dissertation is specifically setting out the address the following questions:

1. How can a peer-to-peer market be designed to provide maximum control to its participants?
2. How can a software platform and a trading algorithm be implemented to enable and encourage localised renewable-based microgeneration within a P2P electricity market?
    a) Is blockchain a viable solution for the creation and deployment of this market?

To address these questions, a platform that provides a decentralised trading mechanism which maximises individuals control was developed and evaluated. This platform not only provides control to individuals, but also simultaneously remains adaptable to the differing requirements of various other groups that operate in the energy system and its market. The work on this platform is presented in two parts: first is a software solution to enable decentralised interactions and, secondly, as a matching algorithm to automate the trading process. The software solution demonstrates a generic platform architecture that can provide automated trading between individual participants using blockchain technology as a means to enable decentralised interactions and maintain trust. This choice to explore blockchain as the underlying technology for this solution sought to validate speculation of its benefits by other researchers. Given the history of inefficient energy usage and computational resource waste, this research focused on the capabilities that blockchain provides with the expectation that the technology itself will enable this functionality within less wasteful non proof-of-work implementations. This dissertation will focus on blockchain specifically, as the focus is on the properties that a ledger built of cryptographically linked blocks provides, rather than the more generic distributed ledger technology (DLT) or block-free DLT solutions. Meanwhile, the algorithm implements the design for a P2P market and incorporates a many-to-many matching procedure, designed to provide a wholesale market solution for P2P and a scoring mechanism that creates a localised preference-based matching system.

1.3 Research contributions

This research explored multiple areas and has a number of core contributions to the academic community, as are outlined below.

1.3.1 Systematic review of P2P trading models

A systematic review of the current research into P2P trading models within the energy industry was completed (i) providing an integrated perspective on the objectives, mechanisms, algorithms, and assumptions that underpin the implementation of the current peer-to-peer energy trading platforms, and (ii) reflecting on the transition paths envisioned from the current centralised energy system to the future peer-to-peer model proposed in the recent peer-reviewed publications.

We observe that, so far, the research has mainly focused on two objectives for the peer-to-peer markets: direct transactions as means to optimise potential utility of the distributed energy resources, and peer to peer interaction to provide demand response services to the energy network. The main mechanisms proposed are use of real-time energy monitoring integrated with energy management systems. These mechanisms provide an automated trading system to the users, with the algorithms focused on minimising the cost of electricity, increasing resource sharing and providing optimal scheduling of energy resources. The ability of the energy users to express their preferences in these systems are extremely limited (to price), if at all present. Finally, we found that the transition paths to the proposed peer to peer markets is a severely under-researched topic.

1.3.2 An extensible blockchain-based P2P trading infrastructure

A generic platform in which any number of P2P trading mechanisms can be deployed was designed and implemented to provide a modular, flexible and adaptable approach to P2P market development and deployment. The platform incorporates blockchain as the underlying technology with the intention to remove third-party intermediaries (such as large supplier utilities), enforce market rules while remaining publicly auditable. The design uses control delegation to simplify trading for users and enable automation and multi-level markets. This platform demonstrates the viability of blockchain to encourage and support P2P market deployments.

1.3.3 Preference-based matching mechanism for enabling localised trading

To support localised electricity trading, we present a new approach to buyer and seller matching in a P2P electricity market using a distance-focused matching mechanism. This is presented as a combination of a preference-based scoring mechanism, whereby participants may specify the energy type, distance and price of the electricity they wish to trade, and a many-to-many stable matching algorithm. This mechanism incentivises the purchase of locally produced electricity while providing users with an increased choice over the electricity that they use. This mechanism is validated through an agent-based simulation over some real geographical areas in the UK, to ensure that preferences are matched fairly and the objectives of the system are met.

1.3.4 Publications

Through the duration of this research, the work conducted has resulted in the publication of three research papers:

Enabling peer-to-peer electricity trading

This poster paper was published at the 4th International Conference on ICT for Sustainability and presented at ICT4S 2016 detailing the initial concepts and architecture of the ETP platform. Content from this paper is not included within the dissertation, instead this has been included as Appendix D to separate it and allow the dissertation to remain focused on the topic. This paper was written by Jordan Murkin and reviewed by the PhD supervisors, Ruzanna Chitchyan and Alastair Byrne, prior to submission.

Goal-based automation of peer-to-peer electricity trading

A research paper was published in From Science to Society 2018 and presented at EnviroInfo 2017 detailing the scoring mechanism and providing an overview of the algorithm design. This paper includes initial performance analysis not included within the dissertation and is incorporated as Appendix C to remove duplication within the dissertation and to allow the dissertation to remain focused on the topic. This paper was written by Jordan Murkin and reviewed by the PhD supervisors, Ruzanna Chitchyan and David Ferguson, prior to submission.

Review of Blockchain Technology and its Expectations: Case of the Energy Sector

A draft paper was written for a journal that had invited Ruzanna Chitchyan to submit a paper. This paper contains a review of the existing solutions and mechanisms using blockchain within P2P systems and a background to the technology itself. It was co-authored between Jordan Murkin and Ruzanna Chitchyan and published on arXiv. Sections of this paper have been used within the dissertation to provide additional background of the uses of blockchain within the energy sector and an overview of blockchain technology. The paper has also been included in full in Appendix B

1.4 Summary: Research introduction

This dissertation is focused on the creation of a future peer-to-peer electricity trading market built upon blockchain that provides participants with complete control over their electricity purchases while incentivising the use of locally generated electricity. This objective seeks to encourage the uptake of microgeneration and improve the integration of these assets within the market.

The report will begin with a look at the context and vision of P2P electricity trading in Chapter 2. This will be followed by a background review in Chapter 3 that provides a systematic review of the academic research, details the businesses that are already working in this area, and discusses blockchain as a potential technology to underpin the market. It will then document the methodology followed through this research in Chapter 4 before discussing the platform developed in Chapter 5 the trading algorithm created in Chapter 6 and the evaluation of this algorithm in Chapter 7. The report will then finish with the case studies investigated in Chapter 8 and a final discussion in Chapter 9.

CHAPTER 2

Context and Vision for Peer-to-peer electricity system

For a P2P electricity trading system to become widely used there are not only challenges facing the participants, but also changes needed to the market as well. This chapter first presents the current structure of the UK electricity market, then, considering the P2P alternative, discusses the market design, structure and regulatory aspects of a P2P model and the changes that will be required for it to gain traction and how these could assist the network to run more effectively.

2.1 UK's Current electricity system

In order highlight the changes that a P2P electricity system will address, we must first understand the current structure of the electricity system. This section presents an overview of the infrastructure, architecture and pricing mechanisms of the current electricity market in the UK.

2.1.1 Infrastructure

The UK electricity infrastructure was designed around the model of large-scale electricity production whereby electricity is primarily provided by a small number of generation sources spread across the nation. To move this electricity from the generation sources to the end-users, it is passed through the electricity grid. The grid is a system made up of two layers: transmission and distribution. Thus the system works as a pipeline, starting with the generators producing electricity, flowing through the transmission and distribution networks and ending with users consuming the electricity at the end. Each of these layers has its own operator(s), and the network

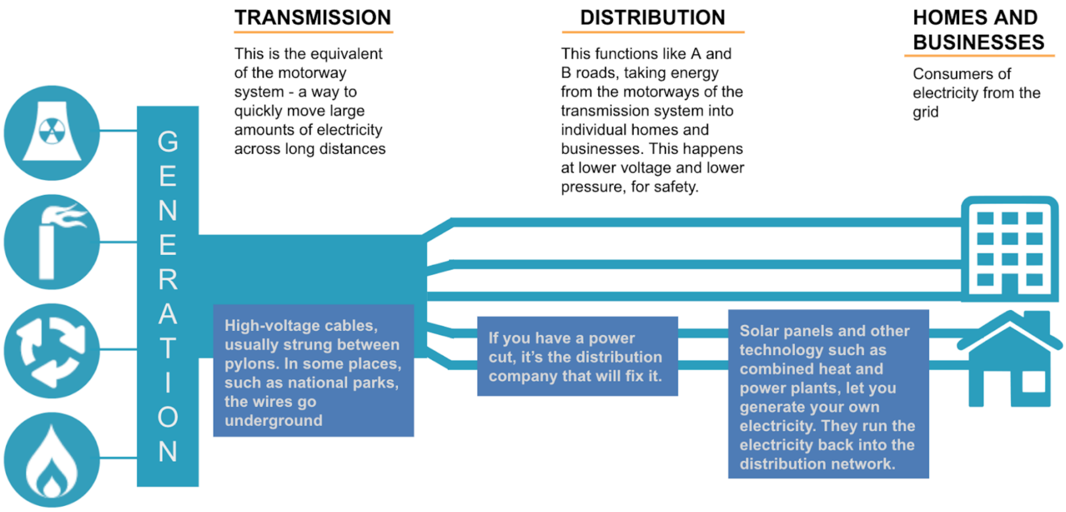

FIGURE 2.1. The layers of the UK electricity system. Figure reproduced from [16].

as a whole is managed by the system operator, National Grid plc [15]. This structure is shown in Figure 2.1 and explained below:

Generation: The generators are the large-scale electricity producers, such as nuclear, gas and coal power plants, solar and wind farms and hydroelectric dams. They are operated by MPPs and generate electricity as required by the system operator and feed it into the transmission network.

Transmission: The transmission network takes this electricity and transports it across large distances to deliver electricity where it is needed. This network is divided into four regions, each maintained by its own regional transmission company.

Distribution: This electricity is then transferred from the transmission network into the distribution network, which lowers the voltage and acts as the 'last mile' transport to deliver electricity to the users. This network is made up of 14 areas each with their own distribution network operator.

End-users: The last layer is made up of households, business and other entities who consume electricity. However, recently with the uptake of microgeneration this layer has also started to generate its own electricity that is either used by themselves or supplied back into the distribution network.

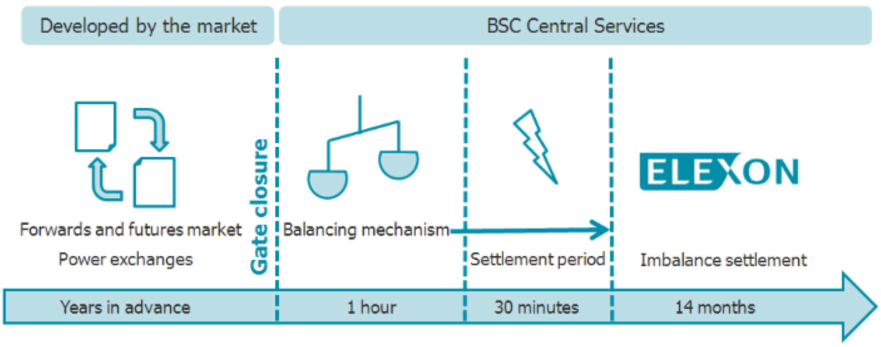

FIGURE 2.2. Trading settlement in the UK electricity market [17].

2.1.2 Wholesale electricity market

The wholesale electricity market differs from traditional commodity markets due to the nature of electricity. Electricity consumption and generation must be balanced within the electricity grid at all times; excess generation will overload the infrastructure and excess consumption will result in blackouts. The balancing condition requires a market structure where balancing takes place in real-time. To accommodate this balancing, the trading periods at the market are structured into discrete sections, shown in Figure 2.2. Trading takes place for each half-hourly (HH) period, referred to as a settlement period, and can be negotiated at any time up to one hour prior to the time of that settlement period. This one hour window is known as gate closure, after which trade information is given to National Grid who uses this information to perform balancing actions. Once the settlement period has expired, any remaining imbalance will pass to Balancing and Settlement Code (BSC) Central Services which will bill each party responsible for this imbalance (the so-called imbalance settlement).

The result of these mechanisms is that trading electricity is a complicated endeavour. Consumers though do not see this. To shield the consumers from the complexity of the energy market, UK regulators established energy suppliers as an intermediary between consumers and the energy system. This design, often referred to as the *supplier hub model*, requires that consumers purchase their electricity from a supplier, who in turn purchase this from the wholesale market. Structuring the market in this way simplifies access to the electricity network for consumers, with any issues on infrastructure charges, trade negotiations or policy obligations handled by the suppliers.

2.1.3 Non-energy costs

The charges that are handled by suppliers are known as non-energy costs. These "costs" ensure that the network infrastructure, maintenance and management services have the finances required to keep the system in good functional state and fund network's evolution and improvement.

Name	Description
Capacity Market Charges	Investment in new capacity, maintaining existing capacity, developing more active demand management
Transmission Network Use of System (TNUoS)	Maintaining and upgrading the high-voltage power lines that carry electricity from power stations to local distribution stations
Distribution Use of System (DUoS)	Maintaining and upgrading the substations and power lines that carry electricity from the high-voltage transmission network to businesses and homes
Balancing Services Use of System (BSUoS)	Reflects the costs incurred to balance the electricity network
Renewables Obligation (RO)	Support for renewable electricity generators
Contracts for Difference (CfD)	Support for low-carbon electricity generators
Feed-in-Tariff (FIT)	Encouraging more small-scale renewable electricity generation, such as solar panels on houses

TABLE 2.1. Non-energy costs and their responsible parties.

These charges fund a wide range of network services. For transparency, contribution to each element of the network is reflected separately in the structure of these changes. The different components for the charges are listed in Table 2.1, along with a description of their purpose. The whole set of components for the charges is composed together only at time of use. As a result, each participant in the system pays differing charges, depending on their role in the market, the infrastructure they require and their interactions with the network.

With these charges applied, only 36.3% of the price that consumers pay for their electricity goes towards the wholesale market costs of that electricity (Figure 2.3).

Challenge: The P2P electricity infrastructure of the future (as researched is this dissertation) will have the bulk of the energy produced and consumed at the end-user sites. While the distribution and transmission infrastructures and balancing services will remain critically important, their roles are likely to change substantially. Thus, the service charges, as calculated today could block the adoption of P2P trading, and make price calculations overly complicated or unfair to some market participants. A re-imagined pricing structure will need to be developed that better suits the nature of the new market.

2.2 P2P Trading Concept

The concept of creating a more open, P2P electricity trading market has been investigated from many viewpoints (see Chapter 3), but while referring to different ideas it is still discussed as a single concept. These differences are due to the broad nature of the terms P2P and transactive

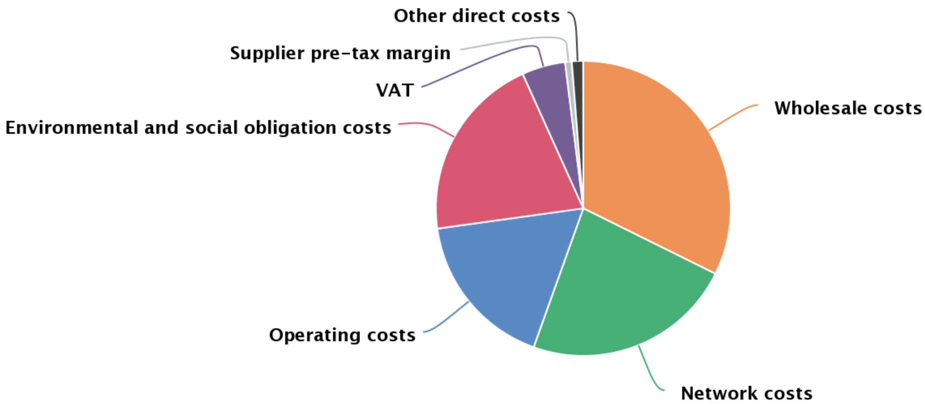

FIGURE 2.3. The breakdown of a UK electricity bill [18].

- outlined in Section 3.3. To overcome this, researchers have suggested breaking the concept into more representative groups. For example Sousa *et al.* suggested classifying the various P2P market types into three overarching groups:

Full P2P market Peers directly negotiate with each other without centralised supervision;

Community-based market A central manager manages trading between participants in a group and acts as the intermediator to the wider system

Hybrid P2P market A combination or layering of the community-based and full P2P market approaches

These classifications, however, remain a high-level separation and discuss only the physical interactions between participants and overlook the market design that they incorporate. To accurately discuss P2P systems going forward we propose a transition level based classification system that incorporates the different concepts and the transition states into these new markets.

This level-based approach incorporates both current and future concepts of peer-to-peer by relating instead to the service they provide rather than the structure of the market. Each level would require progressively greater changes to the electricity market and regulation. While the majority of examples that we see today fall into level 1, we have already seen examples of systems at level 3 and researchers have investigated up to a level 5.

2.2.1 Market design

We discussed in 2.1 the current infrastructure and market design of the UK electricity network. One of the points to note was that the UK is based around a supplier hub model in which suppliers act as an intermediary between consumers and the wholesale electricity market. While this structure provides a simplified access to electricity for consumers, it has also caused multiple

Level	Description
1	Trading takes place outside of the national energy market, participants are members of a microgrid. This trading may be completed in advance using a home energy management system and a battery, or post-consumption as a means of settlement.
2	Trading takes place on the national energy market through an intermediary, such as an aggregator. This transition level sees prosumers using a service to sell their production for them and consumers buying their electricity as usual from the electricity grid.
3	Trades are manually arranged in advance between generators and consumers and backed by a third party. The third party ensures that trades are fulfilled by settling any imbalance with the grid.
4	Trading takes place directly between the individuals and are manually negotiated in advance. Due to unpredictable generation and consumption, this level requires a home energy management system and a battery to guarantee import/export for each trade.
5	Automated trading solution built on top of level four.
6	Real-time trading solution built on top of level five. A home energy management system and battery would not be necessary here due to only the required consumption / generation being traded.

TABLE 2.2. Transition levels for a peer-to-peer electricity market.

controversies. These are discussed in [10], which notes that there have been concerns that the supplier hub limits competition and favours suppliers in regards to new policies. These concerns are also shared by Ofgem, who have stated that the model has "reinforced the dominance enjoyed by large suppliers and has stifled competition in the retail market" [11]. These controversies are not the only concerns with the current model. When we start to envision future network requirements, the model becomes even less applicable. The supplier model imposes restrictions on market access, requiring that a generator must have a supplier license before they could market their generation on the wholesale market. This restriction would prevent household suppliers from trading their excess directly to others, thus immediately preventing the appearance of a P2P market. The restrictions of the current model also impact consumers. At the moment, consumers may only have one supplier at a time. This limitation works well for the current market in which a supplier has access to an essentially infinite supply of electricity in the wholesale market that they can provide to their customers. In a P2P environment, household suppliers will not have this kind of supply available to them, only having their own excess to market. Due to these small quantities of generation, a single household will often require multiple suppliers to fulfil their demand for a single settlement period. This restriction, therefore, prevents any P2P model of level four or above. These limitations have already called into question the future of the supplier hub model. In November 2017, Ofgem published a call for views, requesting opinions regarding the suitability of the supplier hub model in the future market, specifically addressing the limits it brings to alternate models such as P2P.

This project would suggest that for a P2P market to appear, reform is needed in the market structure and regulation that is currently in place, specifically addressing the following:

- Consumers would require the ability to purchase their electricity from multiple suppliers at one time
- Consumers would require the ability to switch suppliers for each settlement period
- Prosumers would require the ability to act as suppliers, directly interacting with the buyers of their generation

2.2.2 Market structure

Along with changes needed to the market design, we must also discuss the trading and settlement structure of a P2P market. As introduced in 2.1.2, the current electricity market divides each day into half-hourly (HH) periods in which electricity can be traded. This structure accounts for the need to continually balance the generation and consumption of electricity. A P2P trading structure would also need to account for this requirement.

Theoretically a P2P market would be able to function on a shorter settlement period due to the increased automation in trading which could result in more accurate pricing and less imbalance settlement. However, with data sources required for a P2P market (i.e. smart meters) currently providing only HH data and the significant impact of adopting a shorter settlement period (discussed in [19]) on the rest of the parties in the sector it is unlikely that the benefits would outweigh the implementation costs. A P2P market would therefore retain current market structure until it can be demonstrated that a longer or shorter settlement period would be beneficial to the market or balancing actions. This project maintained the HH settlement period for these reasons.

2.2.3 Non-energy costs

Non-energy costs are designed to pay for the infrastructure of the electricity network as well as incurred costs to maintain and expand it. These costs inside today's market were discussed in 2.1.3, detailing the purpose of the different charges and whom is responsible for each. This section will discuss the necessary changes to these charges that are required to support a P2P market.

2.2.3.1 Current model

If we were to apply the current methodology for calculating these costs to the concept of household suppliers, it would result in an overly complicated, difficult to manage and unfair charging system. This is due to the calculation methods used and the settlement logistics. Charges such as the Capacity Market Charges, have been designed with the current supplier model in mind and do not factor in the idea of a small scale supplier whom only supply their own generation. Setting monthly charges in advance based upon projected demand for the future year would be inaccurate due to the difficulty of predicting their generation. This would result in regular over/under payments, multiply this by the number of potential household suppliers that could exist and the result would be a significant increase to the Settlement Costs Levy Payment.

The TNUoS, which pays for the transmission network, would also encounter an issue for a different reason. The current charging mechanism would be able to function in a P2P environment, but this is primarily due to an exemption for embedded generation of less than 100MW. While the reason for this is simple, as these generators are directly connected to the distribution network and therefore don't use the infrastructure of the transmission network for their generation, as the number of these generators increases, the exemption would, at some point, not provide the transmission network with enough investment to cover its costs. While this would be a viable option if decentralised generation were able to replace all MPPs, it is likely that a backup of some MPPs will always be necessary and therefore the infrastructure as well.

The BSUoS, however, has a charging model that is supportable by a P2P market. It is currently calculated ex post and charged per MWh, in a P2P market the number of trades taking place would be vastly increased, thus the execution of this charge would be the primary concern. One simple implementation would be to hold trades in escrow until this charge can be applied, or alternatively as the charge is simply per MWh for a given period, this could be applied automatically per trade.

Lastly, DUoS, again has a charging model that is more readily able to support a P2P environment. The calculation of this charge is undertaken differently for those connected to the extra-high voltage lines and those connected to the high-voltage and low-voltage lines. The charges differ by DSO, but have a fixed pricing structure that dependant on the time of use and the type of metering available at the building. These charges are calculated per kWh and an additional charge per day can also be applied. Applying these per trade is then a viable option for a P2P market except the per day pricing which could be integrated as an access fee.

2.2.3.2 P2P model

To address these issues, the current charging models would need to be altered while also retaining their original intent. This project looked to identify the changes necessary such that the charging model would be capable of handling the future requirements of the electricity network.

A significant shift in the way that individuals view electricity would be needed for a P2P market to emerge. At present, individuals are effectively shielded by their suppliers, such that they view electricity as a standard commodity - in that each unit is identical regardless of source. This view is impractical in a P2P environment and would result in a market that enables inefficiency. Instead it should be understood that the location of the generation affects the networks efficiency. This would require the removal of this commoditization, instead pricing electricity based on the location of the generator and the location of the buyer. Pricing this way expands upon the current geographical charges that suppliers and generators currently pay through TNUoS and DUoS by embedding these costs directly into trades of electricity. This geographical element serves two purposes. Firstly, incorporating the infrastructure costs necessary for the electricity network to function including any other obligations that need to come through the sale of electricity. Secondly, to differentiate each sale from one another allowing each market participant to see the complete cost of trading with each other participant and therefore use this as a basis for their trading decisions. This change would also help to address the settlement overhead of a P2P market discussed in 2.2.3.1. With non-energy costs charged separately for each trade this would mean that instead of consumers and generators being charged based on predicted values, a cut would be taken from each trade directly. This would have a number of implications on the network.

1. **Settlement would be reduced.** Provided that money is held in escrow until electricity is exchanged, settlement would be ensured as part of the trade.

2. **Non-energy cost avoidance would become more difficult.** Combining the energy and its associated costs together ensures that an individual's non-energy costs are always paid.

Along with these, this project envisions that this trade-level charging could be used as a means to achieve other objectives. For instance, using non-energy costs as a means of balancing the network, through monetary incentives to trade at less congested times. As this would be at trade-level, this control could also be targeted, allowing costs to be more reflective of the current network state.

This project also concludes that it is unlikely a P2P market would ever completely eliminate the use of MPPs, rather that their role will slowly change to that of a backup provider and balancer. To account for this, non-energy costs would need to be redesigned such that individuals still support the infrastructure necessary for them to exist through an 'insurance payment' embedded into the TNUoS such that even trades purely within the distribution network still contribute to the backup of the transmission network.

These changes aim to redesign the charging model with the intent to redistribute network charges, rather than to allow P2P traders to avoid network charges which is mentioned in many other papers on this topic. This distinction results in the mechanism that this project proposes being focused purely on consumer choice and not prosumer profit, such that household suppliers may earn less in this P2P market than from FIT, but the model is more sustainable and applicable for the future. While individuals will have more control over whom they would want to trade, the trading system would need to enforce rules to ensure that these trades are fairly compensating the services that provide the network for them to take place.

In conclusion, this project envisions that non-energy costs inside a P2P market would need to be vastly different from that of today, but the necessary changes provide a means to improve the efficiency of the network and achieve objectives for the benefit of the grid:

- creating an incentive for the purchase of locally generated electricity
- enabling charging that would fairly distribute infrastructure charges to more accurately represent the costs of use
- further using non-energy charges as a method to incentivise the installation of generation where needed
- repurposing network charges as a means to assist balancing the network

2.3 Summary: Context and vision for P2P electricity trading

For a P2P market to be realised, changes are needed from both a regulatory and householders point of view. The obfuscation of electricity through energy suppliers be removed, allowing participants in the market to see the true cost of the electricity they are trading. Limitations within the current model must be removed, allowing householders to receive electricity from multiple suppliers, switch suppliers in real-time and directly interact with one another. These changes will allow a P2P market to develop and provide householders with more control and visibility over the electricity they are using.

We will now look into the previous research that has been undertaken within this area and the technologies that are currently in use to support these markets.

Chapter 3

Background Technology and Related Work

In this chapter, we will provide an in-depth background review of both the P2P models that exist in academia and industry and an understanding of blockchain as a technology for creating P2P markets. This chapter is divided into three sections: an overview of blockchain technology; a systematic review of the P2P trading models researched in academia; and a look at the existing P2P trading platforms that have been developed by the practicing industry.

3.1 Background technology: Blockchain [1]

As a part of this project, we also set out to investigate the technological innovations that are emerging that may be required or beneficial to the development of a future P2P electricity trading market. The primary technology that we investigated was a distributed ledger technology (DLT) known as blockchain that has been seen by many as a clear choice for creating decentralised peer-to-peer systems. This chapter will provide a background on blockchain and discuss its role inside a P2P electricity system.

3.1.1 Why Blockchain?

Blockchains are able to fundamentally shift the manner in which entities digitally interact with one another and are expected to impact a wide range of industries and introduce new business models that were previously unachievable. They first appeared as a mechanism to underpin digital currencies, specifically Bitcoin, and are unique in that they facilitate decentralised interactions and storage without the need for a third-party intermediary to act as a guarantor. To achieve this,

[1] This section is built upon a working paper written in collaboration with Ruzanna Chitchyan [20].

blockchains use consensus mechanisms to establish a decentralised ledger that is managed by the participants themselves wherein they both use and maintain the network. This alternative means of interacting digitally has the potential to bring about major changes to all areas of society.

Changing the way business is conducted. Until now societies needed trusted intermediaries to mediate most types of business transactions: for instance, individuals entrust their savings to a bank for safekeeping and interest accumulation and the bank loans these savings out to other individuals at a higher interest rate; farmers deliver their produce to supermarkets who resell these to consumers at higher prices; energy generators sell their outputs to suppliers who resell the energy to end users. As blockchains provide cryptographic trust through technology design, whereby anonymous parties can transact without the possibility of cheating, the role of intermediaries will be shifted towards platform provision, with some functionality externalised and a greater focus placed on ancillary functions. This phenomenon has already commenced to some degree with the internet, whereby virtual organisations (such as Airbnb and Uber) deliver the platform for individuals to transact with each other. These platforms, however, monopolise their respective markets and impose substantial intermediation costs. Blockchain technology facilitates the creation of decentralised platforms able to replicate these business models, whilst removing the need for an intermediator and the associated costs.

Changing the way business is regulated. Until now societies have required regulators to ensure that businesses operate within legal frameworks: for instance, land registry authorities are to assure correct record-keeping for land ownership, financial auditors are to assure proper fund handling and absence of embezzlement, competition authorities oversee fair pricing and so on. As blockchain, along with its smart contracts, provides transaction record transparency, as well as imposing rules defined within contracts upon all transactions, regulatory and legal compliance checks, become a prerequisite for any transaction completion.

Changes the role of individuals within society. Today we view ourselves as "consumer societies", where individuals are generally passive consumers. However, the peer-to-peer transactive nature of blockchain encourages individuals into both productive and consumptive roles. The individuals are no longer passive consumers but are active prosumers (i.e., producers and consumers). This again, is an ongoing process already today, with such examples as music production crowdsourcing by individual artists [21], microlending by peers [22], peer-to-peer file sharing, and micro-generation in the energy sector [23]. The common adoption of blockchain platforms would transform such activities from niche to norm.

3.1.2 Structure

To provide this alternative to traditional digital interactions, blockchains are structured in a particular manner. They exist as a ledger managed by a network of nodes, wherein anyone may

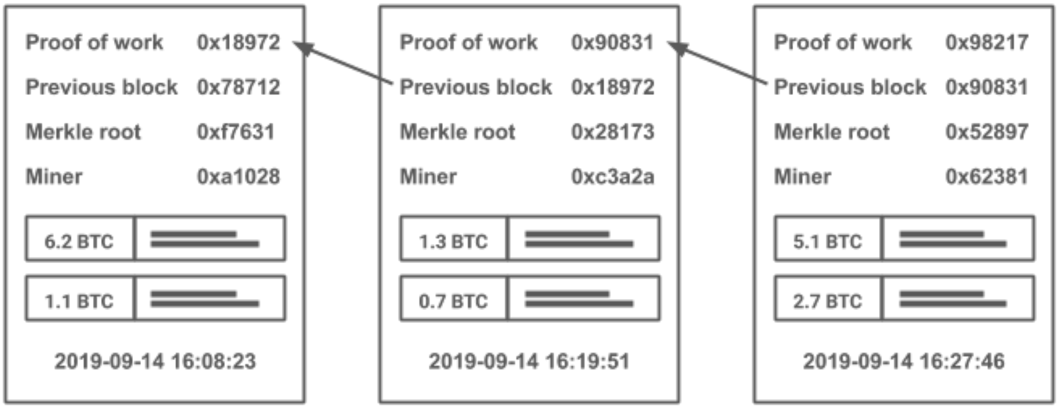

FIGURE 3.1. Simplified view of the block chaining process.

operate a node, each of which has a complete duplicate of the ledger. This ledger stores a historical record of the state changes that have taken place, from which a current network state can be determined. These state changes are the transfers of data between blockchain addresses, which are public keys and as such managed by the owner(s) of the corresponding private key. The data transferred can be arbitrary and may also be appended to a value, which is sent in the form of the blockchain network's cryptocurrency. These addresses act as the user accounts of the network and are referred to as wallets and may be freely created such that a user may have any number of wallets. This structure allows for users to remain pseudo-anonymous during their interactions with the network.

At any time, a network participant may sign data with their private key and send this to another address on the network. This is known as a transaction and is then validated by the network and appended onto the chain along with a set of other transactions validated at the same time. This validation process is known as mining and allows the network to come to an agreement on which transactions are valid. Once validated, these sets of transactions - known as blocks - are then appended to one another linearly, each referring to the previous (as shown in Figure 3.2), ensuring that any change to the history will be instantly identified.

While this concept was initially designed as the backbone of decentralised currency, its scope was quickly expanded with the introduction of smart contracts. In addition to the transfer of cryptocurrency, many blockchains now provide custom programming languages which allow for arbitrary code storage and execution within the blockchain. This addition allows users to send code into the network, creating a blockchain address that owns this code, these are known as smart contracts. Once sent to the network, this code adopts the same features that are intrinsic with blockchain, meaning that the code may not be altered and that the result will be agreed upon by the network whenever executed. These smart contracts allow applications to be developed that are made up of discrete, deterministic functions and storage, such that participants can trust that the application will function in a consistent manner. These applications are referred to as decentralised applications (dApps).

Blockchains are then fundamentally a distributed database managed by a network of peers in which data is stored in an ever-growing ledger. This structure introduces characteristics that make blockchains an attractive solution for digital interactions including:

- *Cryptographic immutability and verifiability* making it quite impossible to modify transaction records once committed, thus ensuring secure transactions;
- *Distributed consensus* allowing anonymous individuals across a peer-to-peer network to come to an agreement on the state of the network, thus removing the need for a centralised agreement mediator/organisation.

3.1.2.1 Cryptographic immutability and verifiability

The immutability and verifiability incorporated into blockchain are provided by pairing two existing technologies: hash functions (such as SHA256 [24]) and Merkle trees [25]. A hash function is an algorithm that takes arbitrary data and outputs a fixed-sized bit string known as a hash. Hash functions are one-way mapping functions, i.e., given the output of the function, there is no simple way of reverse-engineering the input that generated the given bit-string[2]. They are also quick to compute and deterministic, i.e., given the same input, the function will always produce the same output. Moreover, a small change in the input will dramatically change the output. In a blockchain, a hash function is used to represent the data content of a block with a fixed-length bit-string. Merkle trees are then used to structure the records in blocks and support efficient verification of the chain's data authenticity. In a simple Merkle tree, all data is contained in leaf nodes. Each data record is then hashed, and a parent node created from the pairing of two hashes of the lower-level nodes. This procedure is then followed until a single top-level hash is created at the top of the tree, this is known as the Merkle root. This mechanism provides an easy verification of the presence of a given record within the chain [26] using the so-called Merkle proof. Given a Merkle root, the transaction, and the set of hashes that are used to integrate the current data with the rest of the tree, a Merkle proof allows any interested party to verify that the given transaction is correctly and uniquely integrated into the chain without the party requiring knowledge of every individual child node (e.g., by comparing the newly calculated Merkle root for the data record of interest with the initial Merkle root).

These two technologies are then integrated into the block creation process to provide a system for ensuring that the history of transactions are not altered and that transactions can be easily verified. Inside each block, a hash of the previous block is stored, along with the Merkle root,

[2]Except through "brute force": searching through (the infinite) set of possible inputs, hashing them, and comparing the results, in the hope that (at some point) a match would be found. This, however, is an infinitely expansive process in terms of time and computational resources.

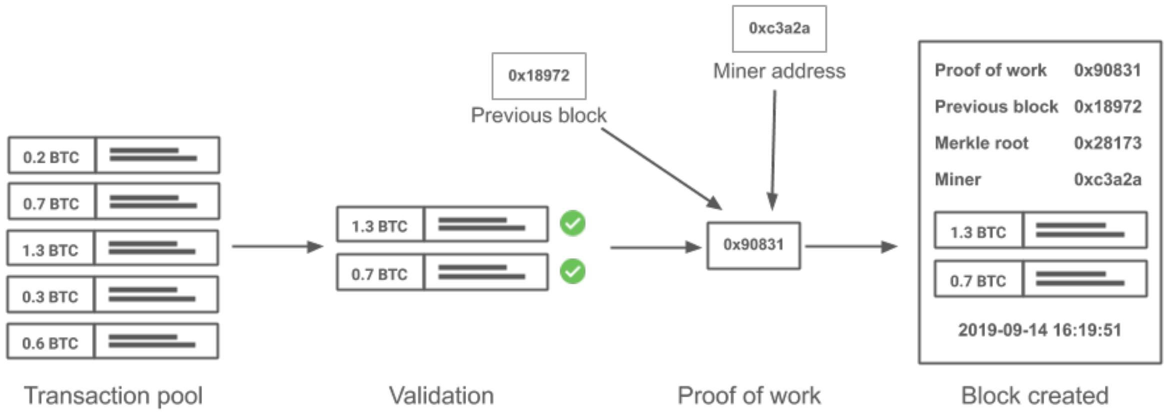

FIGURE 3.2. Simplified view of the block creation process.

the transactions included, a timestamp and the creator of the block (the *miner*). By storing a reference to the previous block, the new block becomes inseparably connected to its predecessor: should any part of the records in any of the recorded blocks change, the whole blockchain from that point onwards will diverge from its previous version.

While this immutability is one of the most important and valuable features of blockchains, this also presents itself as a challenge when smart contracts are considered. Writing a classic piece of software, no matter how well thought out will at some point require an alteration to be made. In traditional technologies, this doesn't pose a problem as developers can alter the code and redeploy it to users as an update. However, in a blockchain, this idea of updating has to be considered at the time of development, and if something is missed, there is no way to alter it retrospectively. Due to this, before we see any complex large scale projects, changes will need to be made that allow more flexibility, while also retaining this feature. This importance of design in smart contracts is not only limited to the introduction of immutability to code, but also to the public nature that they have within the blockchain. This means that a flaw in a contract may be unresolvable and visible to anyone and therefore remain publicly exploitable. An instance of this has already taken place, where a multi-signature wallet library written by Parity [27], the second largest Ethereum client developer was completely disabled by a rogue actor. In this example, an individual experimenting with smart contract development managed to accidentally self-destruct one of the library contracts. This simple act was virtually free to perform, irreversible and resulted in all multi-signature wallets using that library code to become locked along with the $280m stored in them [28]. This illustrates both the features of immutability and verifiability that can make blockchain such a revolutionary technology along with the downfalls that this approach introduces.

3.1.2.2 Distributed consensus

Distributed consensus is the process of coming to an agreement between individuals distributed across a network. In a blockchain, this is required for agreeing that a block validated by some miner should be added to the chain. Since miners are rewarded when their block is added to the chain, they compete against each other and a number of candidate blocks could be available at any given time. The agreement is achieved through distributed consensus algorithms (DCAs) [29]. Each blockchain platform uses its own flavour of DCA. Some examples are:

Proof of Work (PoW) [30, 31] is a method of ensuring that sufficient work has been completed by the validator. It works by providing a challenge for each participant that is labour intensive to solve, but simple to verify by others. Within a blockchain, PoW operates by setting a target value, which must not be exceeded by the value of the hash for a given block, if that block is to be acceptable for addition to the blockchain (e.g., in Bitcoin and Ethereum). This target is adjusted so that on average one node in the network will find a block with such value within a given time interval (e.g., every 10 min. in Bitcoin network). The node that finds such a block can add this to the chain. This creates competition between miners to be the first to find an acceptable hash value.

Proof of Stake (PoS) [32, 33] works by choosing the node that will be able to form the next block on the basis of 'staked' currency within the network. Miners will lock cryptocurrency into a smart contract that defines the rules for the miners. The amount staked is then proportional to the power of this miner and contravening any of the rules will result in the loss of this cryptocurrency. The PoS implementation can vary however, with some also using a random selection amongst the nodes that have maintained unspent currency within the blockchain network for the longest period of time (e.g., in Peercoin [34]) or of the largest size deposit (e.g., BlackCoin [35]).

Proof of Burn (PoB) [36] where the next block creating node is chosen from amongst those who demonstrate burning some of their coins by sending these to a verifiably unspendable address (e.g., in Slimcoin [37]).

Whichever flavour of DCA is used, each is structured to incur a demonstrable cost to the miners. Those who complete a block formation task are rewarded with a payment comprised from the fees that each blockchain participant pays to ensure completion of their transactions and a predetermined amount of the network's cryptocurrency. Thus, the consensus mechanism aims to ensure that for a given node it is very expensive to attack the network and more profitable to help maintain it. Should a malicious node wish to alter a transaction committed to some previous block, it must recreate the block to-be-changed, as well as all the subsequent blocks (else the change will be immediately marked as invalid due to broken hashes). Such a malicious node would thus need to incur the cumulative cost for change, including the cost of generation of the newest block, to become the current longest chain and have this accepted by the network. This, however, is prohibitively expensive in terms of processing power and the costs (imposed by a given DCA) that a node would have to amass.

This method of deciding which block should next be added to the chain, also ensures that the network nodes contain a consistent state. While multiple blocks may be created simultaneously, nodes will always use the longest chain available. This means that while the network may fork temporarily, at the point when a block is created on one of these divisions which makes it the longest chain it will take precedence. Due to this the more blocks added to a chain since a transaction is appended, the higher the likelihood it will not be removed and thus a transaction is only considered ‘confirmed’ once it is at a sufficient depth within the network.

3.1.3 Permissioning

Blockchains were initially open, permissionless networks, wherein any interested entity can operate a node and act as a miner. This property has generally made blockchains a relatively slow and restricted system due the mechanisms required to maintain the network (i.e DCA). Alternatives, however, have appeared over time that compromise this open nature to provide additional capacity or privacy while remaining within the blockchain context. This section will provide an overview of the alternative types of blockchain available. While distinct types are presented, the level of permissioning can be seen as a scale and the lines can be blurred between each level.

Public blockchains are fully open to everyone; anyone may inspect and participate in the network, viewing transactions, creating transactions and mining blocks. The original blockchain concept was a public blockchain, and this was important to provide the transparency and immutability required for trustless, intermediary-free, decentralised transactions to take place.

Consortium blockchains add a layer of permissioning, such that only selected organisations can validate transactions. Access to transaction history may also be restricted, but is in some cases kept public for full transparency. These blockchains are quicker and scale more easily, but at the cost of trust. Unlike public blockchains, validators must be trusted by the users to validate transactions correctly. Consortium chains are primarily used to increase automation of transactions between organisations, reduce cross-organisation transaction fees, improve standardisation, reduce fraud and increase auditability. For example, automatic settlement of trades between banking institutions could be handled by a blockchain using smart contracts where the validators in the network are the banks themselves. The Energy Web Foundation [38] have already began developing a consortium chain aiming to accelerate the use of the blockchain infrastructure in the energy sector.

Private blockchains as the name suggests, are the most restrictive. These reserve validation tasks to a single organisation. Similarly to consortium chains, viewing of the transaction history may either be restricted or left public, depending on the use case.

3.1.4 Applicability

As with any technology, blockchain cannot be seen as a solution to all problems, its applicability is dependent on each particular situation. It is generally recognised [39–41] that to be well suited for the blockchain, a business case should require:

- Use of a database, as the basic purpose of the blockchain is still to order and record transactions;
- This database must be shared amongst multiple users wishing to write to it to commit their own transactions;
- The transactions are interdependent, i.e., the order of the transactions matters (e.g., the investor must pay money before the borrower pays interest on it);
- The writers do not trust each other as they may have conflicting interests (e.g., investors may wish to gain interest without paying, while borrowers may wish to get money without paying interest); or simply have no sufficient information about each other;
- There is a need for disintermediation, i.e., when no third party (such as a bank for investment and borrowing) is suited to act as a trusted intermediary for all writers for one reason or another (e.g., cost and/or speed of intermediation under micro-lending schemes [22], ideology, etc.).

Alongside the business case itself, the technical requirements and implications of blockchain must also be considered. Functionality that may be considered expected within traditional technology stacks must be reasoned for each particular case.

One such group of functionality is the ability to create, read, update, and delete (CRUD) records in storage. As a blockchain provides only a ledger, an append-only record of transactions, the concepts of updating and deleting information are quite different. Each only appends a new transaction stating that the record has been changed. Whilst this affects the data read from the storage interface as expected, it does not remove the previous value from storage entirely. This means that the previously stored values will always remain available regardless of any update or deletion. The implications of this can be significant if the application requires the storage of sensitive information, or if it is possible for sensitive information to be stored by mistake.

Another factor often considered in the selection of a storage mechanism is the ability of that mechanism to provide atomic, consistent, isolated and durable (ACID) transactions. These properties determine the ability for a given storage system to ensure data integrity throughout transactions that alter the state of the storage. In the context of blockchain, we can see that atomicity is present, with transactions being all-or-nothing, such that a change will only be made if the entire transaction it is within succeeds. However, the presence of the remaining properties is more ambiguous as the mining process used within blockchains introduces elements that go against these ACID principles. As miners effectively determine the transactions that are included in any given block, the order in which transactions take place may not match the order in which they were created. Whilst the final blocks created through the mining and chaining process may be consistent and isolated once created, their creation process undermines these properties. Lastly, while the durability of the blockchain is often regarded as an integral property, with transactions being stored within an immutable ledger, this is not always the case. The consensus approaches used by blockchains, as discussed in Section 3.1.2.2, allow for blocks to be created and later removed if multiple blocks are created simultaneously. The creation of multiple blocks at the same time, results in a temporary divergence of the chain that will be resolved once one of these divergences grows larger than the other. However, this can result in a block being appended that is subsequently removed and the order of transactions within the affected blocks altered. Along with this, as blockchains rely on consensus based approaches, it is also possible for the collective mining community to intentionally alter history if they choose to, as was seen when a hack took place on the Ethereum blockchain in 2016 [42]. The ACID transactional properties of blockchain along with the applicability of BASE (a set of properties relating to distributed big data systems) and the introduction of an alternative set of properties (SALT) that apply more relevantly to blockchain systems was discussed further by Tai *et al.* [43].

The transaction throughput and speed is another factor that must be considered when determining the applicability of blockchain to a particular solution. As briefly discussed in Section 3.1.5, blockchains generally have a significantly lower transaction throughput than traditional database mechanisms. Coupled with the delay introduced into transactions by the mining process, this has immediate impacts on the user experience and scalability of the applications built upon blockchain.

3.1.5 Blockchain Platforms

There are numerous blockchain platforms available, each aiming to provide a different level of functionality. Many options could be sufficient for this project, but Ethereum [44] was chosen due to its position in the market at the start of this project and the capability of the smart contract system it incorporates. The Ethereum blockchain was introduced in 2013 with the objective of providing a platform for decentralised applications. It took the concept of blockchain and incorporated a Turing-complete scripting language with it. This allowed for applications themselves to be stored inside the blockchain where they can be used by anyone connected to the network.

The cryptocurrency in this network is Ether, which is used as a means to store and transfer value, as well as to pay for computation and transaction costs. Since Ethereum allows arbitrary code to be stored and executed inside the blockchain, there can be an infinite number of methods each requiring a different amount of computation and storage. To pay for this, Ethereum introduces the notion of *gas*. Each opcode inside the Ethereum virtual machine is assigned a different amount of gas [45]. Each transaction sent to the blockchain must then specify: (i) a gas limit - the maximum computation the user is willing to incur; and (ii) a gas price - an amount of Ether the user will pay per gas unit. The gas price is used by the miners to prioritise transactions: those with the higher gas price are preferred by miners. If the user does not specify enough gas for their requested transaction, the transaction will fail and, conversely, any excess gas provided will be refunded to the user.

This use of gas means that the computation performed by any given transaction can vary greatly and as such could result in significant variations in block sizes. To control this, a gas limit was set on a network level that determines the maximum amount of gas that can be used in each block. Whilst this block gas limit is integral to controlling the network, it introduces a computational limit to the system. As every single operation performed within a smart contract (e.g. an addition or a modification of memory) has a gas cost there will always be a finite number of calculations possible before this block gas limit is reached. This limits the complexity and scale of algorithms that can be handled within one transaction.

The Ethereum protocol currently uses PoW, but plans to move to a hybrid proof-of-work/proof-of-stake system [33] shortly and finally to a purely proof-of-stake mechanism in the future. The network can currently process ~15 transactions per second. Scalability measures are under discussion through planned integration with the Raiden network [46] for off-chain processing, and efforts to implement sharding [47].

3.2 Related work: P2P trading models

The concept of a decentralised electricity grid has been around for some time now [48] and industry, academia and regulators across the world have quickly moved this area forward, pushing pilots, trials and microgrid solutions into consumers hands. This section will detail a number of the previous projects that have been completed in both academia and industry.

Coordinating distributed energy resources and providing two-way communications with consumers is considered an important step into the concept of smart grid and many projects have taken place exploring these ideas. The PowerMatcher project in the Netherlands presented a study exploring real-time supply and demand matching as a means to reduce imbalance settlement from intermittent generation and smooth the profile of electricity in the network [49]. This project used home energy management (HEM) devices that provided a means to set energy preferences and coordinated trading with a central auctioneer on behalf of the users and could shift flexible demand as necessary. They demonstrated that this concept could result in reduced fluctuations within the network, thus reducing pressure on the grid. In the USA, a significantly larger scale project took place investigating this concept of a transactive electricity grid across multiple states with a number of utility companies [50]. The project was able to manage a large number of DERs, demonstrating how automated individual on-premise equipment can be coordinated to provide wide-scale control to assist in managing the electricity system.

Other researchers have focused on exploring the different methods of household trading inside the electricity market. The authors of [51] and [52] used a modified regret matching as a method to match buyers and sellers individually, allowing for price preferences and taking into account transmission losses in the network. However, in [51] each buyer can only receive energy from one seller and price is the only consideration. Another game-theoretic approach was used in [53] which focused primarily on the increased utilisation of energy storage using an auction based approach to determine price. A microgrid focused trading mechanism [54] has also been suggested that relies on sharing energy schedules between participants so as to match producers and consumers at the correct time to ensure electricity is utilised fully.

The rise of blockchain has been seen by many as a mechanism to foster innovative changes and facilitate the transition to the smart grid and as such, research has began to investigate its potential. Blockchain has been used to eliminate fraudulent behaviour in emissions trading with the creation of an alternative Emissions Trading Scheme (ETS) backed by a blockchain to ensure reliable, secure transactions and embed a reputation system to encourage investment into ETS in the long-term [55]. It has also been considered as a means to tokenise Guarantee of Origin (GoO) certificates [56–58]. Since these certificates could act as a proof that a specified amount of electricity was generated through renewable sources, they could also form part of the emissions trading market. Thus, blockchain can support trade in such standardised certificates, as well as foster removal of the intermediaries from the market.

With the introduction of blockchain, the research in this area has only increased and the concept focused more heavily on the idea of P2P interactions. With P2P trading systems, the units of generated electricity themselves are recorded inside a blockchain, allowing the owner of this generation to market it to others. This enables energy generators and consumers (both large and small) to take ownership of their product, choices, and preferences, rather than solely rely on the grid or another entity as an intermediary. Some researchers focused on the P2P energy market creation, demonstrating that blockchain-based intermediary-free energy trading is possible and beneficial to the generators and consumers alike whereas others studied the optimisation of energy resources using P2P trading as a means.

In [59], the authors have developed a smart contract based closed double auction market mechanism wherein individuals could submit bids and sale orders for each market period and an automated contract would decide a market clearing price for the period. A prototype trading platform was developed in [60] focusing on privacy and anonymity of users while also removing a single point of failure. This platform opted to remove a central price setting algorithm, instead of providing users with encrypted channels to directly negotiate a price between a buyer and a seller.

The Scanergy research project [61] is taking a different approach of incorporating blockchain into the electricity network. Here participants are provided with an incentive to export electricity and assist with the balancing supply and demand on the grid. For every kWh a household export to the network that is consumed by another household, the exporter is credited with an NRGCoin [62, 63]. These NRGCoins can then be traded on a separate market like any other cryptocurrency. This system works using smart meter data and street-level substation data. The substation sees the total consumption and generation for the group of houses connected to it and smart meter data provides individual household information for the same period. Using the consumption and generation values from both the individual smart meters and the substation they are connected to, it is determined whether the exports of each house were consumed by another household. The producers are then credited with NRGCoins corresponding to the exported amounts. The smart meter data and substation data is also used to prevent tampering by ensuring the totals from the smart meters is the same as the totals from the substation.

To further explore the area of blockchain, an in-depth review of blockchain, its expectations and its impacts within the energy sector was completed and can be found in Appendix B. An overview of the companies found through this review can be seen in Table 3.1, providing insight into the commercially available blockchain-based energy sector applications that are currently available. As well as understanding the research from a blockchain point of view, a systematic review of P2P trading models was also completed and can be found in 3.3.

3.3 Systematic review of P2P trading models [3]

To understand the current state of research, a systematic review was undertaken to provide a clear view on what a P2P electricity market is conceived to be within peer-reviewed published research. The key contribution of this review is in providing a deeper insight into the P2P energy trading research: looking at how this research segments energy market; how the trading models are structured, what assumptions are made about these models, how is the transition to such models envisioned.

[3] This section is in submission with Renewable & Sustainable Energy Reviews.

Company	Blockchain Use	Operation at/since
Alliander [64]	A smart energy company which has piloted a P2P energy trading platform. The energy production tokens (Juliets) are also exchangeable for goods and services within the piloting community.	The Netherlands, since 2017.
Bankymoon [65]	A blockchain solutions company that introduced prepaid blockchain-enabled smart meters in Africa to help energy suppliers collect payment, as well as to enable humanitarian aid to be sent as energy via direct payments to smart meters at schools.	South Africa since 2015
Conjoule [66]	Platform to support P2P trading among rooftop PV owners and interested public-sector or corporate buyers.	Germany: 2 pilots running since 2016
Drift [67]	Retail energy provider that uses blockchain, machine learning and high-frequency trading to provide better prices to customers and promote green energy use.	New York, USA since 2014
Greeneum [68]	P2P energy trading platform that incentivises renewable-based generation through GREEN tokens, global data collection and AI-based processing for energy industry optimisation.	Beta release in Cyprus, UK, Israel, Germany, Guinea, Argentina, US, India, Australia. Expects a product release by mid-2018
Grid+ [69]	Retail provider (i.e.,buys on behalf of its customers at wholesale prices from outside) and P2P trading platform between Grid+ customers	Texas, USA since 2017
Grid Singularity [70]	Developing a blockchain-based core technology for the energy sector, focused on B2B provision; this technology is to underpin EWF	Internationally since 2016 (?)
Electron [71]	Automated energy supplier switching platform; also aims to to support P2P energy trading and grid-balancing	UK, since 2016
Energy Web Foundation [38]	Non-profit alliance between major energy players internationally, aimed at accelerating blockchain technology across energy market, and building an ecosystem around blockchain for energy.	Projects in preparation at Somaliland, Haiti, India, Argentina, since 2017
LO3 Energy (Exergy) [72]	P2P energy trading platform, aiming also at grid-level service provision (e.g., DER aggregation, balancing, wholesale trading).	NY, USA, since 2017
MyBit [73]	P2P investment into IoT hardware, such as connected solar panels. An investor can own a portion of tokenised hardware and get return per owned portion.	Alfa launch of platform in 2018
Ponton's [74] Enerchain	A B2B solutions integration company that runs the Enerchain platform used for peer to peer blockchain-based energy trading at wholesale energy market by energy sector businesses. The traders anonymously send orders to a decentralised order book, which can also be used by other organisations. Enerchain does not require a central authority.	The platform is used by some 30 European companies since 2016
Power Ledger [75]	P2P energy trading (individuals and wholesale for utilities), EV charging, transmission grid monitoring, P2P asset funding and asset ownership token trading.	Australia and New Zealand, since 2016
SolarCoin Foundation [76]	The foundation aims to foster solar energy generation installations. It awards crypto-coins (for free, similar to air miles) to registered and verified solar energy producers. Each coin represents 1 MWh of produced solar energy.	Used in more than 13 countries since 2014
Sun Exchange [77]	P2P funding of solar PV installations in return for income on investment. Installations are for specific projects in Southern Africa to supply energy to schools, hospitals, and similar businesses.	Southern Africa since 2015
Veridium Labs [78]	Veridium is a financial technology firm aiming to create a new asset class that tokenizes natural capital. Each token will represent removal of 1 ton of greenhouse gases from the atmosphere, or equivalent natural capital preservation activities (e.g., conserve 1 sq. meter of biodiverse tropical forest). Tokens will be issues for validated projects. This would be used by firms to conform with environmental impact mitigation regulations, and more generally embed environmental replacements into the cost of their products.	First project to commence in 2018 for Rimba Raya Biodiversity Reserve in Borneo, Indonesia, tokens will be traded internationally.
WePower [79]	A platform for P2P trading of renewable energy, as well as fund raising for renewable projects by pre-sale of energy to be generated in the future.	To commence in 2018 in Lithuania and Spain

TABLE 3.1. Blockchain companies currently working in the energy sector (adapted from [80])

3.3.1 Study design

The study followed the established systematic review procedures and guidelines established by Kitchenham [81]. The objective of the review was to provide insight into the control mechanisms envisaged by research that will be provided to market participants through the implementation of these P2P models. This includes outlining the market structure and algorithms used to enable these models and the objective of the models. More generally this review also seeks to understand the barriers that research has identified before these models can become a reality and the scope of models that have been presented. To this end a set of ***research questions*** were established to interrogate the various facets of this topic, namely:

RQ1 How is P2P trading research segmenting the energy market?

RQ2 What is the make up of the peer-to-peer electricity market models?

- RQ2.1 What are the objectives of these new models?
- RQ2.2 How are these models implemented?
- RQ2.3 What increased control do these models provide to the participants in the market?
- RQ2.4 What assumptions/requirements have been stated by the researchers for peer-to-peer markets to exist?
- RQ2.5 How have these models been evaluated?

RQ3 How do researchers envision a peer-to-peer market integrating into / transitioning from the current market?

RQ4 What role does blockchain play in enabling these markets?

A systematic search for and analysis of research published on this topic was carried out. The research papers for analysis were collected following the search criteria, as discussed in Subsection 3.3.1.1. The selected papers where then filtered using the selection criteria detailed in Subsections 3.3.1.2 and 3.3.1.3. Upon filtering, the papers deemed relevant to our research questions were analysed, as explained in Subsection 3.3.1.4.

3.3.1.1 Search strategy

Since the term "peer to peer" is often used with different spellings and abbreviations, we used all the various spellings of this term that we could identify. For the search term formation, the numerous spellings of P2P were each appended with both ’energy’ or ’electricity’.

To incorporate as many relevant papers as possible, the term *transactive* was also included as synonymous to P2P. *Transactive energy* is defined by the Gridwise Architecture Council as "a set of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter". Thus, in reality this term is somewhat broader than P2P energy. Yet, some authors use it to refer to the same notions as P2P energy. Consequently, we expect that inclusion of the term "transactive" as a synonym for "P2P" will ensure that relevant publications are not missed, but will also bring up a set of papers that are not directly relevant to our research scope. These broader papers would have to be excluded during the filtering process.

The final set of *search terms* used in this study comprises: "peer-to-peer energy", "peer-to-peer electricity", "p2p energy", "p2p electricity", "transactive energy".

Some similar search terms (namely: "peer to peer electricity", "peer to peer energy" and "transactive electricity") were excluded as they returned only a subset of papers selected by the above listed final terms.

We used the following digital libraries as *information sources*: Scopus, IEEE Xplore, and ACM Digital Library. These sources were chosen as they are the most widely referenced Computer Science and Engineering indexing systems for peer-reviewed publications.

3.3.1.2 Selection criteria

To identify publications relevant to our research questions, the following inclusion/exclusion criteria were used:

1. *Inclusion criteria:* We established the following criteria to identify relevant publications that would answer the research questions:

    - **Publication Year:** All years were included, with papers published in online repositories as October 2018
    - **Publication Type:** All peer-reviewed papers were included.
    - **Content:** Papers must discuss the market design or implementation of a *direct electricity trading mechanism between any number of parties*

2. *Exclusion criteria:*

    - **Publication Language:** All papers written in a language other than English were excluded
    - **Publication Type:** All non-peer-reviewed were excluded and the following types of paper were excluded: reviews; abstracts; opinion pieces; panels; reports; tutorials; presentations.

3.3.1.3 Selection procedure

In the first instance our term-based search returned 87 papers. All of these were then downloaded and checked for relevance in accordance with the inclusion/exclusion criteria. Out of these 87 (as detailed in [82]):

- 11 discussed a different field of research
- 24 were related to the energy field, but unrelated to the topic of peer-to-peer electricity markets
- 15 were high-level papers, discussing briefly only the concept of peer-to-peer electricity trading
- four were review papers
- one was unobtainable due to a paywall
- two were duplicates
- two discussed the evaluation of a P2P model, rather than the implementation

With these removed, 29 papers remained to be included in the review.

3.3.1.4 Analysis

The 29 relevant papers were analysed using thematic analysis. The analysis was carried out with a mixed approach of inductive category development and deductive category application [83, 84]:

1. The researchers first familiarised themselves with the data, for which deep reading of a subset of the papers was carried out.
2. The researchers then set out a number of initial codes that reflected the kinds of information needed to address the aforementioned set of research questions (e.g., the type of P2P model used, the solution evaluation method, etc.),
3. The work then progressed by coding the contents of each paper in accordance with the initial set of categories. Yet, the code set was also intentionally kept open, and was extended with new categories, as these emerged from the data during analysis.
4. Once the initial coding was complete, the set of themes and their codes were reviewed and finalised. The resulting final set of codes used in this analysis is shown in Appendix A.

To mitigate the individual coder's bias and ensure consistency of the analysis, two researchers were engaged with this study. They together discussed and agreed upon the initial code set (as per point 2 above). Then the primary researcher analysed all papers, while the secondary researcher independently analysed every third paper. For the subset of the double-coded papers, the results of the independent analyses were thereafter compared (as part of point 4 above). Several discrepancies (such as the need for a new sub-code, perspectives on the paper contents etc.) were identified, discussed, and resolved. Finally, the agreed upon code set with its respective data extracted from the set of 29 relevant articles was produced.

The full set of the analysed data can be found in this Google spreadsheet [82].

3.3.2 Threats to Validity

Although this study has been carried out in accordance with the best academic practice, we note several points that could threaten the validity of our findings:

Construct Validity: While carrying out this study we have observed that there is a lack of consistency in the terminology used to refer to P2P energy trading in the published papers. For instance, [85–87] refer to P2P trading as simply 'energy trading', [88] refers to it as 'direct trading', [89] calls it 'energy markets' and [90] calls it 'energy scheduling'. Such terms refer to a much broader set of activities than P2P trading, and so it is infeasible to include all of them into a well scoped literature review on P2P energy trading. Yet, it is also likely that some relevant papers, which use divergent terms for P2P trading, were not found through our search process.

Researcher expectations bias Furthermore, keeping in mind that qualitative coding could be impacted by researchers expectations and views, the 1st author analysed all papers, while the 2nd author independently analysed every 3rd paper. Independent coding, qualitative annotations, and discussions between both authors were carried out to ensure consistency and construct validity.

Internal Validity Whilst we followed Kitchenham's guidelines for systematic literature reviews, a few minor deviations from the protocol should be noted:

- We did not explicitly evaluate the quality of the published papers. Instead, we chose the peer-reviewed publications, which provides a level of certainty that other academics and professionals have commented upon the soundness of the published work.
- Our review protocol was not evaluated by an external reviewer. However, the protocol was developed in mutual agreement, and followed the process previously by the 2nd author in a similar study [91].

External Validity The searches were limited to three databases, and no snowballing was conducted. This limits the external validity of our findings. However, the databases we used are commonly considered the main sources in the Engineering Discipline.

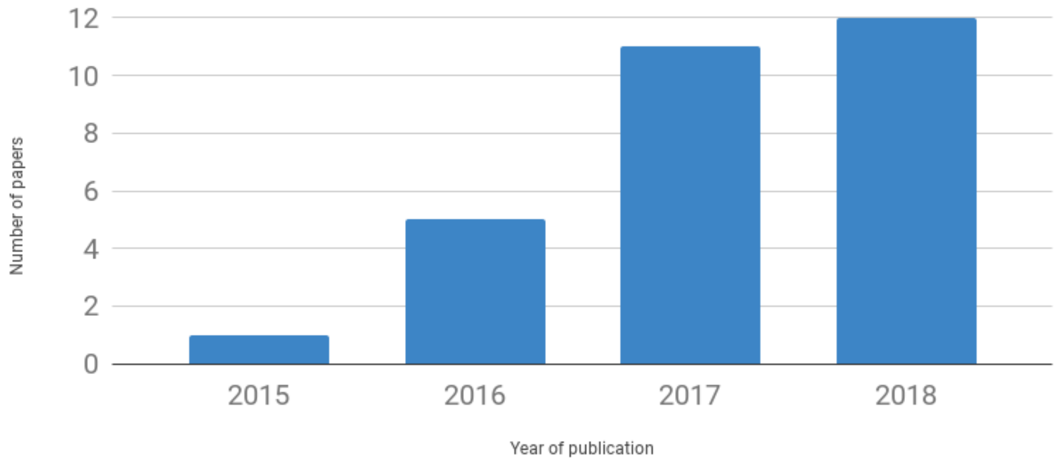

FIGURE 3.3. Number of papers covered in this review, by year of publication.

The search for data extraction was performed in October 2018. Thus, very recent work will be missed from this report, which could threaten the up-to-date generalisability of the work.

3.3.3 Findings

Below we discuss how the findings from this analysis answer the research questions stated in Section 3.3.1. It should be noted that all data presented below is only in relation to the 29 reviewed papers; where any of the presented graphs does not sum to 29, it is because some of the the papers have been unclassifiable for a specific field.

Looking at the number of papers per publication year (Figure 3.3), one can immediately see that P2P energy trading is an emerging topic of research. The earliest relevant papers were published in 2015, with the number of such papers increasing in each subsequent year.

RQ1 How is P2P trading research segmenting the energy market?

The papers reviewed in the present study can be differentiated on basis of the market **scope** (i.e., if they are addressing the wholesale market level trading, trading within a microgrid, or provide an additional service outside of the wholesale market), the specific **aspect of energy trading** addressed (e.g., pricing, resource use optimisation, etc.), and the actors engaged into the direct interaction (e.g., individuals or businesses) which define the **sector** for which P2P trading is delivered.

Scope: The majority of papers (62%) included in this review focused on trading mechanisms that interact directly with the *wholesale market* without entirely replacing it. For instance [92] discusses the interaction between load aggregators, distributed generation and storage devices in a day-ahead market using the DSO to determine the optimal matching between parties.

The second largest group of papers (28%) discussed models that related to the interaction between individuals entirely disconnected from the wholesale market, who form their own *microgrid*. Prinsloo *et al.* [93] for example, demonstrated the potential of a P2P energy management solution in rural islanded microgrids.

The remaining three papers were not categorised into any specific group, they discussed: the optimal *control of energy storage devices* within a transactive framework [94], an assessment of the *reliability services* that microgrids could provide under a transactive market structure [95], and a standardised approach to *communication between devices* to improve interoperability and enable transactive system to serve [96] as a mechanisms of market organisation.

None of the papers discussed an entire replacement of the wholesale market.

Trading Aspects: The two biggest aspects of trading considered by the reviewed research were the *optimisation of distributed energy resources* (DER) and *demand response* (DR) mechanisms. The remaining papers were split between *matching mechanisms* and *complete models* or both.

None of the reviewed papers discussed either the regulatory or social implications of these new models. Yet, it must be noted that these issues are addressed by the ongoing research elsewhere. For instance, Fell *et al.* [97] detail a protocol to understand the social impacts of P2P energy trading with a focus on the use of distributed ledger technology as an enabler. Glorioso *et al.* [98] investigate more broadly the social impact of P2P systems without a specific focus into the energy sector. Such research was not included into our search results as it was either not yet a peer-reviewed publication (e.g., [97]) or was not focused on energy sector ([98]).

Sector: The key actors considered for P2P trading are individuals, businesses, and microgrids. Depending on which of these actors are peered in a trading model, a variety of trading sectors emerge:

- Domestic - addressing the individual to individual trading;
- Commercial - addressing trading between individuals and businesses;
- Industrial - addressing trading between business;
- Microgrid to grid - addressing trading of microgrids to the whole grid;
- Microgrid to microgrid - addressing trading between microgrids;
- Peer-to-peer - Anyone to anyone trading (a superset of all others).

In this review, 14 (48%) of the papers were focused on the *domestic market*. This group being the largest is as expected due to the concept of P2P inferring a low-level interaction with the market, typically individual households. These models often focused on the means to use and integrate the DERs possessed by the households into the wider market for demand response or network balancing/optimisation.

The second largest group was that of *microgrid-to-microgrid* interactions. These models primarily foresee the market becoming a network of networks - in this case, microgrids - that can operate independently or be interconnected to each other as necessary.

Two further models [99, 100] considered purely the *industrial*, i.e., intra-business aspect of P2P. The three remaining papers [92, 101, 102] undertook development of *generic P2P* platforms through which any party can interact with any other party in the market.

RQ2 What is the make up of the peer-to-peer electricity market models?

To study the make up of the P2P models, we consider their objectives, implicit assumptions that must be in place before these models could become operational, implementation mechanisms/algorithms proposed, additional controls/power expected to be given to the peers in the models, as well as the evidence of the model evaluation. Each of these aspects is detailed upon below:

RQ2.1 What are the objectives of these models?

The objectives of the papers included in this review can broadly be divided into four categories, with a few papers focusing on other topics of their own. These objectives are:

- Cost minimisation
- Network balancing
- Resource management
- Integration into the wholesale market

Often a model falls into several of these categories, as one category can be seen a means to provide another (for instance, resource management could be carried out to provide network balancing, or to enable integration of these resources into the wholesale market, etc.).

Cost reduction is one of the key themes interwoven throughout the reviewed models. Yet, it was often not the primary objective of the models, but the end result of another objective. This came through multiple streams, e.g., due to:

- **Optimal generation scheduling** objective [103], which aimed to ensure that local generation was maximised, which led to a reduced reliance on the main grid and the cut costs that come with that.
- **Reduced imbalance costs** [104] due to the increased accuracy of forward-market predictions by using transactive methods to meet these predictions, as necessary.

- **Reduced network costs and transmission losses** [105] as a result of a decreased usage of the main grid.

- **Resource sharing** [106] to maximise the use of DERs.

Such cost reduction is promoted to the potential users as one of the key selling points of a peer-to-peer approach.

The *network balancing* objective was also quite prevalent [105, 107–109], with multiple approaches incorporating demand response programs [110, 111] alongside with it. This objective is particularly relevant where the DERs are considered as main generation sources within the P2P market. The DERs inevitably introduce intermittency of supply, thus necessitating provision of a network balancing support. The reviewed papers focused on the *trading of flexibility* between either groups of microgrids or the individuals inside these microgrids, such that minimum imbalance is submitted to the grid. Thus, *demand response programs* allow individuals to demonstrate that they are acting as stated in their flexibility trading agreements. Similarly, Prinsloo *et al.* [93] study the security of supply to rural islanded microgrids through use of an auction strategy with a clearing price.

Resource management aimed to make better use of the available resources is another prominent theme emerging from the review. This theme is comprised of two sub-groups:

- **Sharing:** Allowing one resource to be used by multiple individuals'

- **Scheduling:** Managing the on/off times for flexible load and generation.

The studied research noted that while individual ownership of DERs is increasing, the full potential of such energy generation and management devices is not yet utilised. This potential arises due to the economies of scales, when a large number of small appliances are *managed in coordination*. To incentivise device owners to provide access to their resources for scale-based management and optimisation, the literature proposes setting monetarily rewards to the resource providers. Thus, Broering *et al.* [106] explored the concept of an "energy storage cloud" whereby the excess capacity of small-scale batteries could be sold to others that have excess generation. This resource sharing model sought to maximise the self-consumption of all participants as well as maximising the utilisation of the available resources.

Alvaro-Hermana *et al.* [112] integrated both a sharing and scheduling model, in which drivers were provided an optimal schedule for their electric vehicle charging requirements from which battery sharing was then used to minimise the cost of charging. The *sharing models* here could provide another revenue stream for the owners of DERs, further increasing the return on investment.

The *scheduling models* however provide benefits to either the individual, the grid or both. This makes them more sustainable for the long-term but gives them the potential to result in reduced revenue due to the owners being asked to reduce generation for the benefit of the network.

Due to the intermittency of generation from DERs, some researchers identified that the integration of these resources into the wider market could become challenging. Models were therefore designed with the objective of providing the small-scale generation/flexibility providers with a **simplified process to access the wholesale market**. This is realised through *virtual power plants (VPPs) and load aggregators (LA) acting as* ***intermediators***. Qiu *et al.* [104] focused on the management of a VPP in which the participants exchange electricity to guarantee the trades to the market. This approach saw the participants scheduled by the VPP owner, *maximising profit in the day-ahead market and minimising any imbalance costs*. A similar VPP approach was taken in [113], with additional ability to exercise *control over price* given to the peer-participants participants.

Khodayar *et al.* [114] instead focused on load aggregators. The model they present splits the market into two levels, wherein generation companies and load aggregators continue to act as presently in the wholesale market, yet a **secondary market** exists in which load aggregators and DERs interact. This sees load aggregators act as the intermediators between the two markets.

Hu *et al.* [100] introduced a new **independent body to resolve scheduling issues** between retailers who are coordinate DERs and distribution network operators.

Finally, Hong *et al.* [115] considered risks of exposing energy data when setting up P2P markets and focused on demonstrating a **privacy-preserving trading mechanism** that allowed the participants to come to an optimal trading outcome without disclosing private information.

While the topic of privacy was not considered in other reviewed papers, it is clear that this is an area that will require further research before peer-to-peer trading solutions could become more widely accepted.

RQ2.2 How are these models implemented?

While the implementation of each platform was specific to its objectives, the platforms were often built using existing methodologies. To understand the implementation approach taken for each platform, this research question sought to understand what are the **design decisions** and **techniques** identified as suitable for creating a P2P market.

Design Decisions

Of the 29 papers included in this review, 16 (55%) papers introduced platforms that performed the matching of the participants **automatically**, using a combination of *real-time monitoring*, *energy management systems* and/or a *central controller* to coordinate the participants and run the algorithms. The remaining platforms required **direct interaction of some entity** (a *controller* or the *participant themselves*) within each market period.

The entity managing this direct interaction or automated matching was an important factor of the implementation. Throughout the implementations many entities were suggested, yet two groups of papers emerged: those relying on **centralised control** and those that were **decentralised**.

Centralised Control: Olivella-Rosell *et al.* [99] and Hu *et al.* [100] each suggested the introduction of a *new party into the market* to schedule flexible energy resources and resolve scheduling issues respectively.

The authors of [92, 103, 116, 117] instead chose *current market players* to assume this new responsibility, using the DSO, the market operator, the utility companies and a distributor respectively to manage and maintain the platform.

Alvaro-Hermana *et al.* [112] employed an *aggregator* to manage the trading inside the platform.

The author of [118] used a *centralised processing* unit to provide the platform to the users The platforms designed for VPPs [104, 119] were managed by their *owners*.

Decentralised Control: Only two papers suggested platform that was not centrally controlled. Giotitsas *et al.* [120] sees each microgrid system acting *independently through their own energy management systems*.

Pop *et al.* [110] went even further decentralised, moving all *management inside a blockchain allowing the platform to manage itself*.

Mechanisms

Software Mechanisms include actions, optimisation algorithms, and game-theoretic solutions:

Auctions weree the most used mechanism, utilised in seven of the reviewed papers. These auctions were used to *perform the matching* between bidders and *establish the clearing price* within the market. Chen *et al.* [102] suggested four alternative auction mechanisms that could be used to perform the matching between bids, selecting a sealed-bid second-price auction as the most appropriate. Auctions were also used to find an optimal matching between participants in [92, 101, 107, 121, 122], and as a means to find a clearing price in [93].

We also saw a number of *optimisation algorithms* used to determine the optimal trades to take place between participants to meet a given objective. Alam *et al.* [118] and Qiu *et al.* [119] formulated the problem as a *Mixed Integer Nonlinear Programming (MINLP) problem*. Whereas Prinsloo *et al.* [107] structured their solution as a *Mixed Integer Linear Programming problem (MILP)*.

Lastly, *game theoretic approaches* were also seen as a method to determine trades by formulating a game and establishing a Nash equilibrium between the participants. Zhang *et al.* [108] structured this as a *non-cooperative game* using the demand of the participants as the input. Whilst Park *et al.* [117] instead formulated a *Stackelberg game amongst* the retailers to find a stable solution.

Hardware Mechanisms were not considered by the vast majority of the reviewed papers, which assumed that data was available or would become available to enable these markets to exist, *without additional specialised hardware*.

Only Mengelkamp *et al.* [122] required that participants installed a *specialised meter to take part in the market*. This meter would sign the data at source and add it directly to the blockchain ensuring that it could be trusted. This would resolves a much of the potential fraudulent behaviour that could arise in a P2P market, but the implementation costs of such an approach could make it unviable.

RQ2.3 What increased control do these models provide to the market participants?

As the peer-to-peer model of electricity trading brings about the idea of individuals interacting directly with one another, it could be assumed that this would result in increased control passed on to these individuals. Surprisingly, many of the models used centralised control with little input from the participants. Nevertheless, a range of controls was seen through the presented models.

Price was the most common control mechanism provided to the participants and allowed them to control the price they are willing to pay for the energy they receive. The models allowed this configuration in different manners. Mengelkamp *et al.* [122] provided a means to set a *maximum price for which the participant is willing to pay*. Alvaro-Hermana *et al.* [112] required participants to *negotiate directly with one another to determine the price to pay*, within bounds set by a central controller. Park *et al.* [117] allowed *buyers to state a reward for the energy provided to them and presented an algorithm for calculating the optimal reward*. Alam *et al.* [118] had *participants configure the disutility cost* for each of their appliances such that demand-side management could work effectively. Whereas, Olivella-Rosell [99] required that the *pricing was set out in advance on a per-contract basis with the DSO*.

While often participants were given only price or even no direct control, they generally retained the **ability to manage their own demand** and thus impact the result of their trading except in the case of dispatchable load trading. This is not a direct input to the control mechanism, yet it allows the participant to decide whether a price is acceptable to them for participation or not.

In only one paper was preference seen to expand beyond price. Mengelkamp *et al.* [122] also included choice over the **generation type** that the user wished to receive resulting in increased control and transparency.

RQ2.4 What assumptions/requirements have been stated by the researchers for peer-to-peer markets to exist?

It was widely assumed that a P2P market would require a significant increase in **real-time monitoring and communication of energy data** between the participants of such a market. This generally came in the form of *increased internet-of-things devices* and *improved metering*. Babar *et al.* [96] focused on this requirement, creating a new hardware solution for monitoring and controlling energy devices, proposing a standardised interface for communicating between them.

Along with this increase to energy monitoring, models often required **energy management systems to be present for each of the participants** (individuals or microgrids) to manage their interaction with the market or the central controller of the system. These were used for a range of purposes, such as to:

- Determine energy schedules: Either configured directly by the user or determined by the consumption/generation patterns of the participant;
- Control dispatchable devices;
- Bid by submitting requests to buy and sell
- Manage preferences: the device would take in user preferences and share these as necessary.

This assumes that the P2P market participants would have **committed to an upfront investment** for either/or energy generation devices and (smart) controllable appliances and are also **willing and able to become a part of the market**. However, the factors that would foster willingness to invest and take part in the market are yet to be researched.

Furthermore, many of the papers assumed that **accurately predicted energy generation and consumption schedules** up to a day-ahead will be calculated for each participant [92, 105]. This is to be carried out either by the central controller or the energy management system. Given the assumption of the continuous communication between devices, all papers assumed that there was **perfect connectivity** between the different devices as well as parties in the market. Yet, given the complexity due to poor interface implementations and lack of standardisation across most IoT devices, such assumption could be somewhat premature for an at-scale P2P market set up.

Most authors assumed that the existing market structure of **using defined trading periods**, for which individuals could trade either in advance or in real time, would persist. Only Park *et al.* [117] instead chose to restructure the market into an *event-driven trading mechanism* in which energy is requested as required. Event-based trading would be a significant change from the existing market, but the effects on the resilience of the energy system were not investigated.

It was assumed that the **energy data is valid** and the **systems worked without failures**, though in the reviewed set of papers there was no discussion as to how data would be validated at source or what would happen in the case of a connectivity interruption or other persistent failures. We note that periodisation of the market (i.e., the above mentioned fixed trading period structure) should somewhat facilitate resolution of the connectivity gaps by providing a large window for the interaction to take place. Nevertheless, research is required to understand the impact of large scale connectivity loss or other failures on the functioning of such markets.

Many papers assumed that to **simplify the interactions of peers in the market, it is acceptable to introduce a central controller** primarily to act as a scheduler to optimise the usage of DERs within a network. Decision making would then be moved to a third-party that would be able to make collective decisions based upon the predictions and preferences of the participants. This was considered for electricity sharing between electric vehicles at charging stations [112], establishing fair congestion pricing [100] on the network, and , managing interactions within a VPP to minimise the power deviations of individual inputs/outputs [104, 119].

RQ2.5 How have these models been evaluated?

The proposed models were primarily evaluated through **software simulations**, with 23 (79%) of papers using this approach. This was to be expected as a simulation has few barriers and provides a reasonable demonstration of the potential of a given model.

Three of the authors [102, 114, 120] introduced their model in a **purely theoretical** manner, using no means of evaluation to demonstrate their approach .

Only one paper had undertaken an evaluation using **hardware in a simulated environment**: Babar *et al.* [96] implemented their flexometer using a Raspberry Pi device along with domotic agents to demonstrate its effectiveness in a multi-agent system.

Two authors evaluated their model through **case studies with users**. Mengelkamp *et al.* [122] evaluated their model through a *live trial* in Brooklyn, NY proving the potential for its use. Good *et al.* [123] *used data from a district of commercial buildings* in France to evaluate six business cases to understand the impact of different optimisation objectives and market conditions.

RQ3 How do researchers envision a peer-to-peer market integrating into / transitioning from the current market?

The process of **transitioning into a P2P marketplace was not explicitly discussed** throughout the papers in this review.

Yet, the platforms based upon intra-microgrid interactions are able to act independently of the grid and could appear today **without a transition required**.

Many of the other authors worked under the prerequisite of the **existing market remaining and interacting directly with the new P2P market**. Olivella-Rosell *et al.* [99] presumed *existence of flexibility contracts* between distribution system operators and flexibility providers to determine the pricing inside their market. Marzband *et al.* [101] envisioned a new retail market structure inside the current distribution network. They use a market operator to manage the market and its participants and suggest this could be performed by either a separate entity overseen by the distribution network operator, a distribution system operator or a distribution management system. Zhang *et al.* [108] incorporated *current energy suppliers as passive users* in the system that are able to provide energy with less attractive prices. Some trading schemes instead created actors in the market to act as *intermediaries between the current and the P2P market* such as VPPs and LAs which were discussed in RQ2.1.

The integration of P2P markets into the current market structure would have an *impact on the network costs* within the market as a whole. With a reduction in reliance on the wholesale market, costs would still need to be met to ensure that the large scale producers can provide their services as a backup when required. This again was primarily overlooked, although some authors did consider alternative network charging strategies and factor in losses and network costs into their calculations [105].

RQ4 What role does blockchain play in enabling these markets?

Only two of the reviewed papers integrated blockchain as a part of their solution, and only one chose to use it as a **means to trade**. Pop *et al.* [110] used blockchain as a means to *manage a demand response program*. Once a user had stated their consumption/generation profile, data would be polled every ten minutes to ensure that this matched their claim. Smart contracts were used for this claim validation and also to calculate the rewards/penalties due.

Mengelkamp *et al.* [122] however, used blockchain as a *complete solution for electricity trading* with data stored directly from custom meters into the blockchain. Using the data stored inside the blockchain, users were able to set preferences for the price they wish to pay and the generation type they wish to purchase from.

While blockchain was explicitly used only in the above two papers, an investigation of it as a potentially relevant technology was suggested in eight more [93, 107, 124–129].

3.3.4 Ongoing literature review

This systematic review was conducted during the initial stages of this research to identify open areas and direct the focus of the work. As the work progressed, the topics identified were monitored to remain inline with current research areas. This section will detail the relevant research that took place since this review with researchers further exploring the transitional aspects of P2P markets and looking to resolve issues caused by increased DER uptake.

A key issue facing P2P markets is the uncertainty introduced by the small, unpredictable loads of prosumers. Sundararajan *et al.* [130] used a hybrid-model of historical photovoltaic data and modelling to improve the accuracy of generation estimations. Their work provided a model that responds more quickly to generation fluctuations and the reduction of error measures. This aspect of P2P systems was also considered by Ghorani *et al.* [131] who sought to incorporate the risks associated with uncertain generation within the market settlement process. They handled this using coordination by the DSO and the operation of two transactive markets. A day-ahead market is created that allows for bids to be submitted in advance by market participants such that the DSO can factor these in within their interactions with the day-ahead wholesale market. Once the final consumption and generation values are known they are submitted to a secondary real-time market allowing the DSO to use actual values in their interactions with the wholesale market. A new penalty scheme is then introduced that favours lower risks rather than directly punishing those that fail to fulfil their bids. Ghorani *et al.* [132] discuss the implications of penalty mechanisms from unfulfilled transactive energy contracts in an earlier paper whereby they introduce the concept of price changing to meet the associated risk. When a participant fails to meet their market obligations, their associated risk is increased which in turn results in them having to submit lower offers to sell generation and higher bids to satisfy their demand.

Researchers are also investigating the social and policy aspects of P2P markets. Kirchhoff *et al.* [133] focused on the incentives needed to encourage prosumers to participate and remain active within transactive markets in the long-term. The authors map user values to specific measures that seek to address these values, including additional tariffs, improved technology, training and financing options for microgeneration. They concluded that to encourage uptake, there is a need for tariffs that guarantee a minimum price for their electricity (e.g. a feed-in tariff), backup generation to increase reliability and technology to improve ease-of-use. Moura *et al.* [134] discussed attribution of network charges within P2P trading environments, stating that the current grid charges do not correctly reflect the network usage of those involved. This is due to grid charges compensating for all voltage levels of the grid, even if the trades taking place are only within a distribution network. To address this, they suggest that we should instead use 'local network charges' that recognise different grid usage levels. Similarly, Baroche *et al.* [135] suggests that a future P2P system allows us to move away from socialised grid-related costs, and instead use these charges to meet alternative objectives. The authors investigate three alternative cost allocation policies: unique cost (sharing costs equally); distance (charges proportional to the electrical distance between trade partners); and zonal (priced per zone at any given time). They go on to state that these charges could be used to influence participant behaviour and should be transparent to allow participants to better anticipate costs prior to trading.

In the initial systematic review, only one paper was seen to provide controls other than price to the market participants. Since then, multiple other researchers have now explored this area. Sorin *et al.* [136] explores making electricity a heterogeneous good and the benefits this could have to consumers and the grid itself. They see this differentiation between electricity sources implemented to factor in external factors (e.g. grid costs, environmental aspects) and consumer preferences (e.g. generation type, distance from seller). Morstyn *et al.* [137] similarly explores this idea to treat electricity as a heterogeneous product, focusing on prosumer preferences as a driver for the optimisation. The authors expand the concept further, introducing the concept of 'energy classes' that provide more granular information about each source. This information includes generation type and location within the market as has been previously seen, and also includes the participants reputation and the ability to state preference for individuals within the network.

Further research has been undertaken into the integration of DERs into the network and transition from our current structure into the future network. Meena *et al.* [138] discusses the benefits of small-scale microgrids with high penetration of DERs with flexible loads and demand response programs referred to as 'community microgrids'. They focus on the design and optimisation of these microgrids to minimise operating costs and allow for operation islanded from the grid for extended periods of time. Liu *et al.* [139] focuses on transactive energy controls within networked microgrids to again minimize operating costs and increase utilisation of renewable generation. Their proposed control mechanism facilitates increased collaboration between microgrids whilst retaining the privacy of the individuals in the network to operate in both grid-connected and islanded scenarios. Ning *et al.* [140] explores the concept of the 'energy internet', made up of three layers: power (energy resources); information (servers, data, communication); and business (the network controllers). The authors again suggest that this structure, built on networked microgrids allows for efficient coordination of DERs within the distribution networks. Lastly, they suggest the need for a backup energy source for P2P activities to take place, handled by the DNO within their examples. This need for current suppliers to be retained is reiterated by Morstyn *et al.* [137], who state that suppliers remain important to the market to provide invoicing, metering and local energy management. The authors also suggest that prosumers may additionally wish to directly establish contracts with suppliers to reduce price fluctuations of a P2P market.

3.3.5 Related work

Several previous reviews into the P2P energy trading have already been undertaken. Here we summarise the previous reviews and discuss the distinctions between the present and previous reviews.

The present review focuses on the specific implementation details of the P2P market structures proposed in the published research. It provides an implementation-level comparison between the projects, incorporating the market design, algorithms used and control systems provided. This is in contrast to the previous reviews, which have focused mainly on comparative study of P2P systems' objectives and market roles required by such systems.

For instance, Sousa *et al.* [141] carried out a comprehensive review of P2P and community-based markets. They classified P2P markets into three overarching designs:

- Full P2P market - Peers directly negotiate with each other without centralised supervision;
- Community-based market - A central manager manages trading between participants in a group and acts as the intermediator to the wider system;
- Hybrid P2P market - A combination or layering of the community-based and full P2P market approaches.

These broad categories match closely with what was found in our review, although the control aspect (e.g. who is making the final decisions) is overlooked in Sousa's definitions. We found that central managers, for example, can either act as purely decision makers or also as managers that perform the dispatch of the DERs. These get further differentiated when the role of the individuals is considered. For example, in a VPP [104] model the manager decides the basis on which to make decisions and enacts these decisions itself, while in an input-based model [117] individuals state what they need and the central controller finds the required sale/purchase provision on the individuals' behalf.

Sousa and colleagues [141] also identified the need to study the coupling of P2P and existing markets and understand the role that system operators can play in these markets. The issues of scalability and asynchronous interactions were also mentioned as unresolved challenges of P2P markets. Our review found only one paper (46) that looked to address these issues and thus we can conclude that this area is still in need of further investigation. Lastly the authors discussed the need for research into the human dimension of P2P markets, which again was found to be an underdeveloped area within our review.

Zhang *et al.* [142] investigated the commercial P2P projects that were taking place worldwide, detailing their objectives and comparing the approaches that each was taking. The authors found that projects were primarily focused on the business models and marketplace design but overlooked local markets appearing inside microgrids and the control mechanisms required to power these markets. Our review shows that since the time of writing, the community has expanded further, with academia now heavily incorporating these areas. The authors also noted that blockchain was a "very promising technique" at the time. This thinking appears to remain the same with eight papers suggesting the potential and two researchers actively providing blockchain solutions for P2P, but there still remains to be significant research into the topic.

The topic of blockchain has also been incorporated specifically into some reviews. Andoni *et al.* [143] undertook a wide scoped research project looking broadly at blockchain in the energy sector to understand the problems it can solve and the drawbacks that it brings with it. In general they found that while blockchain has now past the proof of concept stage it still needs to prove itself in regards to scalability, security and transaction speed. Along with this the choice to use blockchain comes with high development costs and in integration into the metering and grid infrastructure would have significant implementation costs. Specifically focusing on the P2P findings of the paper, they found that P2P is still in the early stages with limited adoption and that it still faces challenges in regards to coordination with central controls and balancing mechanisms. They concluded that P2P is likely to change the role of current actors in the energy industry and that P2P coordinated by the DSO could deliver greater benefits than those that were fully decentralised. Wang *et al.* [86] provided an in-depth look into the mechanisms used in both commercial and academic blockchain solutions for P2P markets detailing the matching and pricing mechanisms as well as the blockchain specific implementation details. Ahl *et al.* [144] explored the challenges that a blockchain based P2P approach may have and the practical implications this has. They again identified computational costs and scalability concerns need to be addressed and that further research is needed to encourage institutional development.

3.3.6 Discussion

Empowering Peers vs Business Objectives: When undertaking this review, we had a preconceived perception that the primary concern of these systems would be supporting the interests of the individuals in this market by changing the way that individuals interact with and understand their electricity. Yet, as discussed in 2.3 the majority of the reviewed models provided little extra control to the participants, beyond the ability to flexibly change their load in order to achieve an improved price. This stems from the objectives that these P2P models had set, i.e., their focus on resource optimisation, cost minimisation and grid balancing (see RQ2.1). These objectives are easier to meet when the outcome is determined by a single party, rather than by integrating the collective objectives of many individuals. This, then results in a use of centralised controllers and the reliance on dedicated third-parties to manage the interactions between the individuals (see RQ2.2).

Little focus on blockchain: We observe that use of blockchain was limited in the reviewed papers (see RQ4). This too links directly to the lack of objectives focusing on decentralisation and personalised control (see RQ2.1).

Significantly, the use of blockchain in P2P projects appears to be far more prevalent [20] in the commercial environment as opposed to the academic research. For instance, Power Ledger [75] provides P2P energy trading for individuals and utilities, as well as EV charging, and grid monitoring services over blockchain infrastructure. A smart energy company, Alliander [64] provides a blockchain-based platform for P2P energy trading and supports own tokens (Juliets) which are exchangeable for goods and services within the project's member community. MyBit's

[73] blockchain supports investment into connected solar panels where investors own a portion of tokenised hardware and get return per owned portion. Yet, the vast majority of the research community has limited research evaluation to theoretical and simulation environments (see RQ2.5).

Clearly, the startup environment has been quicker in spotting the interest in decentralisation and personalisation appetite within the energy systems. Understanding the outcomes from such industrial projects would also allow researchers to focus their efforts more effectively.

On the Road from Research to Practice: As detailed in RQ2.4, the published research assumes that a number of conditions have been met for the said P2P trading models to be viable. These assumptions vary from the infrastructure (both hardware and software) availability at the participants' side to the willingness and ability of the intended peers to engage with these trading models. In fact a substantial research, training, investment, and policy and regulatory change for all of these assumption areas is yet to be carried out.

Some of such work is already underway. For instance, while this review found no academic researchers investigating the needed regulatory changes for a P2P market to exist, in practice regulators have started work on this topic. French regulators in 2017 passed a law to support the self-consumption of electricity from distributed energy resources and allow it to be shared with the local community [145]. Regulators in the UK have reported on the need to alter market structure to enable services such as P2P [10, 11, 146]. Here too, it appears that the practitioners are leading the change, while the academic colleagues have paid little attention to the imminent systems transition (see RQ3). Thus, we suggest that the research community must redouble its efforts to support research into the said assumptions across the variety of disciplines and in partnership with the practitioners.

3.4 Summary: Literature Review

This review has provided an in-depth look into the current state of the research into peer-to-peer electricity trading mechanisms. It has detailed the current assumptions required for a P2P market to exist and identified gaps that research is yet to investigate.

While some of the papers provided a means for control to the participants in the market, this was often limited or deferred entirely to a third-party. In the systems that provided control we also found no validation mechanisms available to the participants to ensure that they were receiving what they had requested. Through the various controls given to participants, the most common control was over the price paid and the individual's flexibility with only one including a choice of the generation type that they were purchasing. We can conclude that further research is required to investigate other control that can be provided to participants and the mechanisms that can be used to ensure that they are being treated fairly in the market.

It was also found that while peer-to-peer systems provide more control to the individuals, there was still a reliance on third-parties in many of the systems. Similarly to the preferences, research is needed to create - and understand the implications of - moving the control into the hands of the participants, whether that involves removing the third-parties entirely or providing proof mechanisms to ensure that they are acting in the best interest of the individuals.

The possibility of a P2P market emerging and the impact it would have was also generally overlooked. The majority of papers focused on inter or intra-microgrid interactions, which would require significant modifications to current infrastructure and regulatory framework to become widespread. Only one paper was seen to consider the privacy and security implications of a P2P market emerging. These would each need significantly more research to understand fully the policy, infrastructure and social implications of such a market.

To expand upon the background research and understand the values of the future users of P2P systems, the research in this dissertation was discussed with fellow researchers that explored the design characteristics of a future P2P platform through the use of qualitative interviews [147]. These interviews helped to inform the design of the platform and the control provided to users. Participants expressed concerns about the lack of trust in large energy companies and the desire for local decision making in regard to energy-related activities. This requirement reiterated the need for a generic platform that doesn't provide only a single model, instead supporting the self-organisation of the platform users. Participants also expressed their desire for increased control within the market, specifically for those with their own generation. They went on to state the concerns that a P2P market will further exacerbate the exclusion of those that were financially disadvantaged or those with low computer literacy. These concerns highlight the importance of providing autonomy to market participants through the use of user preferences.

The following chapters will discuss the research that this project completed to address open issues found through this review.

- It was found that previous researchers had focused on specific implementations of a P2P market, but not considered the integration of this market with the existing or alternative market structures. In Chapter 5, a generic platform-first approach to P2P markets is presented that demonstrates a platform to support any number of market structures, including multi-level market structures whilst retaining control to the individual participants

- Research has focused on P2P models reliant on a central control mechanism where participants are provided little control over their desired trading. In Chapter 6, an algorithm is presented to maintain decentralisation of the P2P market whilst providing increased control to market participants. This control is provided in the form of a preference-based algorithm where participants are able to state the generation type, price they are willing to pay and the location of their trade partners.

- Where control mechanisms besides price have been presented, there is a lack of analysis to demonstrate that these preferences effectively modify the trading result in accordance with the preference configured. Chapter 7 evaluates each preference included within the presented algorithm to validate its effectiveness.

- In previous research, simulations have been the preferred method of evaluating P2P platforms, with only one paper found in the systematic review using a live trial to demonstrate their model. To explore further the real-world complications of deploying a P2P platform with real participants, Chapter 8 presents two preliminary live deployments to evaluate the social, policy and technical implications of a P2P system.

Chapter 4

Methodology

In this chapter, we will discuss the methodology followed by this project to design and develop both a flexible platform for P2P project and a preference-based locality-focused trading algorithm.

4.1 Technique Used

The methodology followed in this work is a variation of the Design Science approach [148, 149] widely used for information systems. Here the focus is on addressing a practically relevant challenge identified by the researchers through a cycle of development of design solutions, their testing and evaluations against the set criteria, and repeated re-design to address issues identified through the evaluation and testing process.

Here four dosing-evaluation cycles were used, upon identification of the challenge to *support user-preferences based P2P solution for electricity trading* from the background literature review and informal consultation with energy system practitioners.

The design work naturally divided into two co-related work packages:

- development of a generic platform for the creation of P2P markets, and
- an algorithm to demonstrate the potential of a locality-focused market that put user control at the forefront.

While previous researchers focused on the design of independent case studies for single business models, the platform designed through this research intended to provide a backbone for any number of current or future business models. Alongside this platform infrastructure, a separate business case was explored for re-envisioning the current electricity market. This business case saw the development of an automated preference-based locality-focused matching algorithm that intends to remove the barriers to entry for a P2P market while providing increased control to its users.

The four design cycles each saw saw a functioning proof-of-concept (PoC) developed during each iteration that provided a tangible platform to assess the capability and applicability of this design such that we could better understand the changes required to better support the market it would be maintaining. This approach allowed for a natural evolution of the platform, while also providing an understanding of the limitations and capabilities of the emerging blockchain technology that it incorporates. The **criteria against which the platform was tested** upon each iteration are:

- accessibility of the platform to users
- control provided to the participants in the market
- removal of third-party trust
- flexibility of the platform to adapt to alternative market models

The algorithm was developed in a similar fashion, exploring different algorithm designs and testing the outcome of each. The algorithm is composed of two parts; a scoring mechanism that takes user preferences as an input and determines their favoured matches within the market; and a many-to-many matching algorithm that uses these scores to determine the final matching between trading partners. An agent-based evaluation of this mechanism was then completed using a real dataset to simulate individual postcode sectors of the UK. This evaluation assessed each facet of the scoring and algorithm design ensuring that preferences set were provided and that the matching is not biased towards any particular group. The **criteria against which the algorithm was tested upon in each iteration are**:

- scalability of the matching mechanism
- retention of technological trust throughout the trading process
- choice afforded to trading participants
- ensuring a fair trading outcome to all trading participants
- provides an incentive to purchase locally generated electricity

Initially, the development of the algorithm and platform architecture were completed separately from one another, allowing the algorithm to escape any potential platform limitations and the platform architecture could freely expand without the constraint of a specific business case.

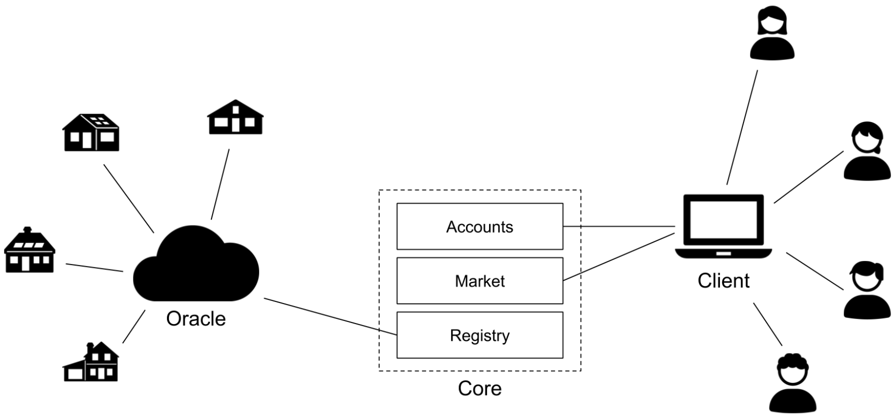

FIGURE 4.1. Initial platform architecture used in iteration 1 and 2.

These consecutive developments were then merged, using the algorithm as a means to validate the platform architecture.

Finally, two empirical studies were undertaken to assess the real-world use of the platform. A deployment was completed inside the University of Bristol, testing the ability to integrate within existing monitoring infrastructure and a customer trial was undertaken with EDF Energy to assess the flexibility of the platform architecture to handle an alternative market structure.

4.2 Notes on iteration process

There were four design cycle iterations of the platform and algorithm architectures each building upon the previous. This section will briefly detail the process that was followed through each iteration, the issues that were uncovered and the solutions that were chosen going forward.

4.2.1 Proof-of-concept

Initially, this project set out to demonstrate the concept of P2P electricity trading within a blockchain environment without the need for intermediary control. A proof of concept was developed that incorporated the minimum requirements needed to establish a trading environment which could then be expanded upon to further meet the needs of the project. This design for the platform set out to use blockchain as the only technology requirement and used a purely manual trading approach with little flexibility. In this design, generation and consumption data was fed via an Oracle into a registry and associated with user accounts, this data set the trading limits for the users who could then list this as trades within the market for another user to purchase. The architecture of this design can be seen in Figure 4.1.

This iteration was tested through the input of dummy data which was used to evaluate trading from a user perspective. It was clear that this design had a number of flaws that would need to be addressed within a real-world P2P market. Trades in this market were 'first come, first served' meaning that the first buyer to offer the asking price for a sale would receive it. This system gave the maximum choice to users, allowing complete control over the electricity they were purchasing but meant that latency within the network or on a user's connection could dictate the final trades that take place. This system also gave an incentive to purchase the first acceptable trade, rather than achieving an optimal (most preferential for all participants) result. Along with this, a considerable time commitment would be required by the users of the system to effectively purchase and sell their electricity.

To resolve the issues found during this iteration, numerous options were considered. These options included:

Incorporating a listing period Establishing a period within each trading period that sellers may list their sales but purchasers may not yet make offers on these sales. This would provide buyers with visibility of all available sales to make an informed decision.

Embedding an auction mechanism on trades Altering the trading system from 'first come, first served' into an auction system such that multiple users may bid on any particular sale.

Automating the trading process Using an algorithm based trading mechanism to remove the time commitment required by users.

While initially, an auction mechanism seemed appropriate, it was superseded by an automated trading algorithm which would remove the need for this system. The next iteration then would incorporate these decisions such that a listing period is included and an automated system constructed.

4.2.2 On-chain automation

The second iteration of the platform intended to remain entirely within the blockchain environment to retain the properties that it introduces. To incorporate the learnings from the previous design, this iteration then attempted to incorporate an algorithm for automated matching as a smart contract. As discussed in the first iteration, this design included a listing period within the trading period such that purchasers may make more informed choices. The architecture, however, remained unchanged from the initial design (Figure 4.1).

To incorporate an automated trading solution, this design moved away from the idea of listing sales and initiating trades into a preference-based solution. Users would input their trading preferences at any time which were then used during trading periods on their behalf to find their best match and complete a trade. This moved the control away from the users, instead, relying on the algorithm to perform as expected by the user.

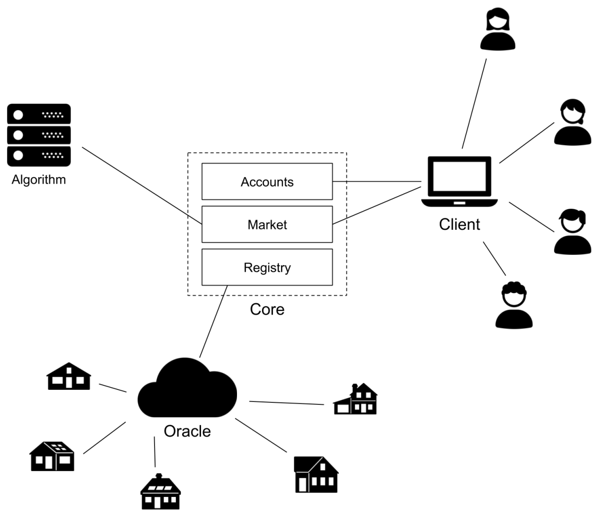

FIGURE 4.2. Platform architecture used in iteration three.

Using these preferences, an algorithm was written into the Market smart contract that would look through all available sales, assess the applicability of each, select the best match and complete the trade. This algorithm was only used as an initial test of the automation system and did not intend to resolve the 'first come, first served' issue. Before an algorithm was integrated that would resolve this, it became apparent that an on-chain trading algorithm was not feasible. The constraints of the blockchain environment greatly restrict the possibility of automating the trading process. Due to the processing limits introduced with the concept of gas, any process-intensive algorithm would not be possible. These limitations are further discussed in 5.3.1. As a resolution to this, a solution was considered that would move the processing outside of the blockchain while attempting to retain the blockchain characteristics which were integral to the system.

4.2.3 Off-chain processing

With the knowledge that a blockchain only automated trading solution was not a viable solution, the third iteration investigated the alternative options for providing an algorithm-based trading mechanism to users. An additional module was added to the architecture that would provide additional processing power outside of the blockchain environment (Figure 4.2).

The concept of on-chain sales was removed in this design. Instead, the Market contract would enforce rules using known electricity generation and consumption rather than enforcing them on the sales created by users themselves. This change meant that the off-chain module could initiate trades between any two users at any time, and the blockchain would determine whether this trade was acceptable or not. The purpose of this change was to remove any remaining unnecessary user actions inside the blockchain to further simplify the trading process while also increasing the flexibility of the automated trading solution.

At each trading period, the off-chain module would use on-chain user preferences and available electricity data to determine optimal trades between users. This module was the first to use the algorithm designed as part of this project which is further detailed in Chapter 6. This solution was able to provide users with the automated trading solution that we had desired, but restricted the blockchain characteristics that were integral to the success of the platform. Specifically, the trust between users was altered from a technological trust of blockchain to a social trust in the entity operating the off-chain module. Alongside this, the element of free choice that we had intended had been removed, with only a single solution available. To address these concerns, the final design expanded upon off-chain processing through the incorporation of a delegated control mechanism to reintroduce the element of choice to users and protocol was introduced that attempted to reestablish technological trust. These, along with the final iteration design are discussed in Section 5.3.

4.3 Summary: Methodology

This chapter introduced the design science approach taken by this research and established the assessment criteria by which the final components were assessed. The work was broken down into two primary components, which would each follow the design, evaluate, iterate cycle to address the challenges faced by a P2P market. The iteration cycles were then detailed, providing insight into the reasoning behind the design choices taken throughout the project.

The following chapters will now expand upon these initial designs to discuss the finalised implementation details of the platform in Chapter 5 and the algorithm in Chapter 6.

CHAPTER 5

PLATFORM

This chapter will discuss the platform developed through this research to provide a modular, adaptable and extensible architecture built upon blockchain to support the deployment of P2P business models in the energy market.

5.1 Purpose

To enable a peer-to-peer trading marketplace in which individuals may negotiate and trade directly, a software platform is required that facilitates their interactions. This platform would rely on the rapidly increasing availability of energy data to provide a means to validate electricity consumption and production such that it can provide near real-time trading and settlement for the participants in the market. For a peer-to-peer electricity market of level 4 2.2 or above to exist, this platform would need to remain provably independent, such that users may exercise free choice during the purchase and sale of electricity whilst also ensuring that the necessary regulatory procedures are upheld and non-energy costs paid. Given that the supplier and consumer of each trade can be different, the users can no longer rely on the established and trusted/reputable generators or suppliers for continuity of their energy provision and payments. In this constantly changing environment of per-transaction partner matching, the participants need to be able to trust that the transactions will be honoured and trade contracts enforced. The platform would therefore be responsible for maintaining the trust between the users, allowing them to feel confident that their purchases will be fulfilled and that the other party can uphold their side of the agreement or that there will be a system in place to handle this if they do not.To provide this level of functionality, the platform would need to be designed in a generic and flexible manner allowing it to incorporate a wide range of business cases and remain extensible for future requirements. In addition to the assessment criteria introduced in 4.1, the requirements of this platform is then to also:

- Verify electricity production, recording the generation time, amount and location. This is required as the price of electricity varies over time based on supply and demand.
- Ensure that each unit of electricity is sold only once.
- Provide traceable and auditable trading history to enable electricity suppliers (domestic or otherwise) to accurately calculate bills and allow the network operators to understand the current state of the system to accurately perform balancing.

To develop a platform that meets these requirements, blockchain is suggested as the technological solution to underpin the system. This is due to the characteristics of the platform meeting the requirements discussed in 3.1 regarding the applicability of blockchain technology to solve a problem. The platform requires an underlying database to record and verify both the electricity data and the trades themselves. This will need to be shared amongst the users that will each need the ability to initiate trades, thus writing records into this database. Each of the trades is independent and must be actioned in a specified order, allowing us to ensure that electricity is sold only once. The participants in this platform would be competitive and thus have conflicting interests, as they would each prefer to get the cheapest price available for themselves. Blockchain, therefore, is well suited to this platform and provides a means for direct interaction between users without the need for mediation by a third-party in a transparent manner while also allowing us to incorporate rules in the system that enforce pricing structure and prevent bad behaviour.

To demonstrate the feasibility of a platform such as this, we developed an electricity trading platform (ETP) built upon blockchain to enable both manual and automated trading to take place while maintaining the level of control needed for a P2P market.

5.2 Architecture

As discussed in Section 3.3, peer-to-peer trading mechanisms have become a wide-ranging concept each with their own objectives. When designing our platform, we attempted to create an architecture that could be used to **underpin the various trading mechanisms** (as noted in 4.1, 4.2). To achieve this the system was constructed with the intention of **flexibility** and **pluggability**, maximising the reuse when being applied to a new concept and incorporating easily into existing systems. An important component of this was to incorporate trust within the system rather than within the other market participants. This shift in the trust of the user would provide a means to remove the potential for bad actors and allow trades to be made with confidence. This concept - hereby referred to as technological trust - however would require a change in the mindset of the users themselves in order to function. This project did not focus on

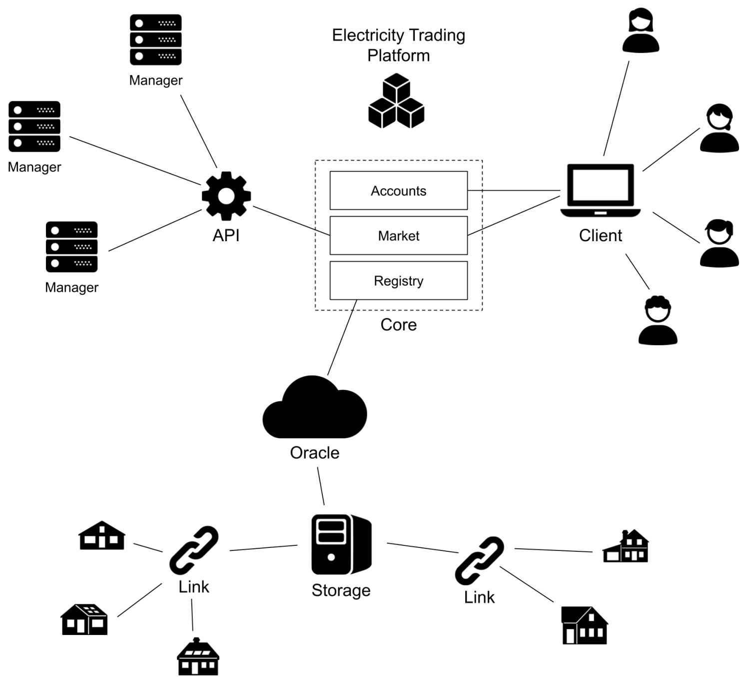

FIGURE 5.1. Electricity trading platform architecture.

this from a psychological standpoint, instead attempting to provide a platform that could foster this trust.

The platform was therefore designed as a series of modules, each providing a defined external interface. This results in modules acting as black-box components with defined input/outputs, decoupling them from one another to maximise the modularity of the system. While the basis of this platform used blockchain to enable this market, there are a number of other components that interact with it to make up the complete solution. These components can be seen in Figure 5.1 and an explanation of each is provided below. The data flow through each component is shown in Figure 5.2, with an additional validation tool included as described in Section 5.3.1.

5.2.1 Core

At the centre of the platform is the Core module (shown in Figure 5.3) that contains all of the blockchain functionality within the system and acts as the central coordinator for storage and interactions throughout the platform. It is important to understand that this centralisation refers only to the architectural role of this module within the system, not to the ownership or control of the system itself. This module is implemented through the use of smart contracts, meaning that all functionality and storage takes place across the blockchain. The operation of this module is dictated by publicly readable and immutable code, the storage is provided by the maintainers of blockchain nodes and all transactions that it performs are auditable and must be verified by the

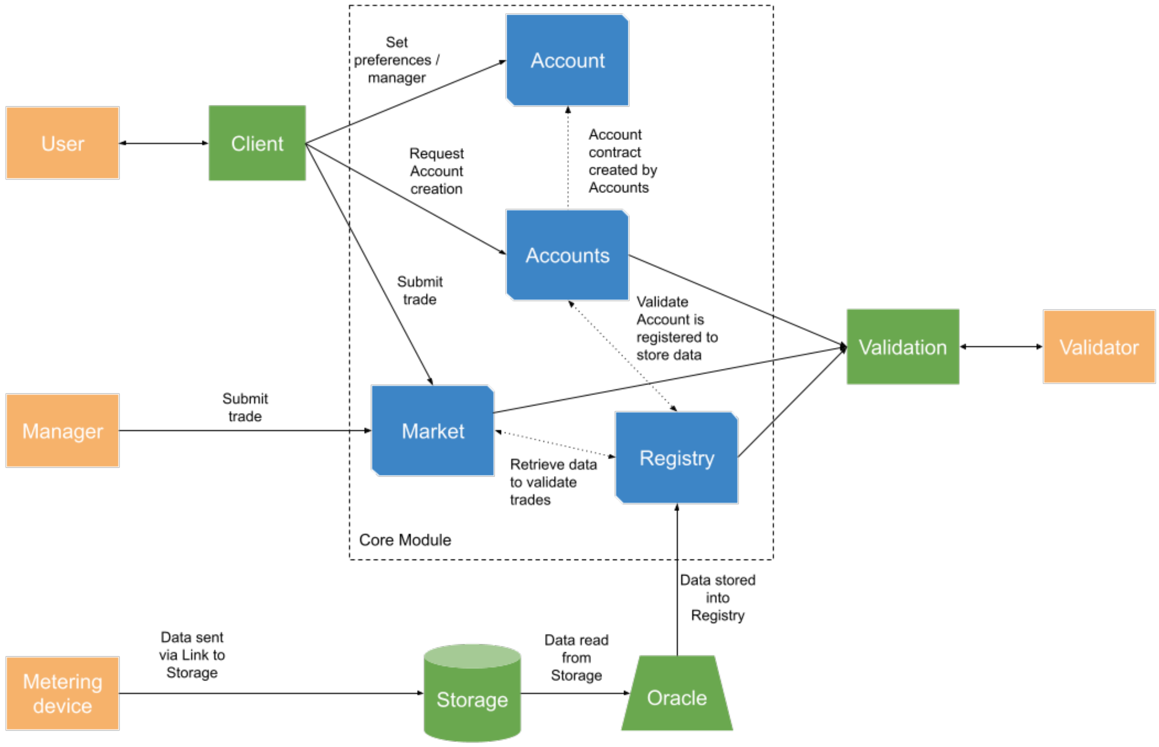

FIGURE 5.2. Electricity trading platform data flow.

blockchain's miners before taking place. The Core stores all user accounts and contains a registry mechanism to link off-chain data from smart meters and manages all trading activity. This module is also responsible for enforcing all market rules which ensure that necessary restrictions are in place throughout user interactions.

To build this module, Ethereum[44] was selected as the blockchain platform due to its market position, maturity and Turing-complete smart contract language. To incorporate this functionality, the module was divided into three overarching smart contracts to manage the system.

5.2.1.1 Accounts

The Accounts contract maintains a directory of all Account contracts that have been created by users. These Account contracts represent one energy asset owned by a user inside the system and contain the basic asset information required for others to make informed trading decisions. As this information is public a number of privacy concerns are raised by these contracts and as such the data required was kept to a minimum. Information about the asset was required to enable user choice during the trading process but could be used as a means to determine user behaviour (e.g. a burglar identifying that a resident of a given property is on holiday). As a solution, the

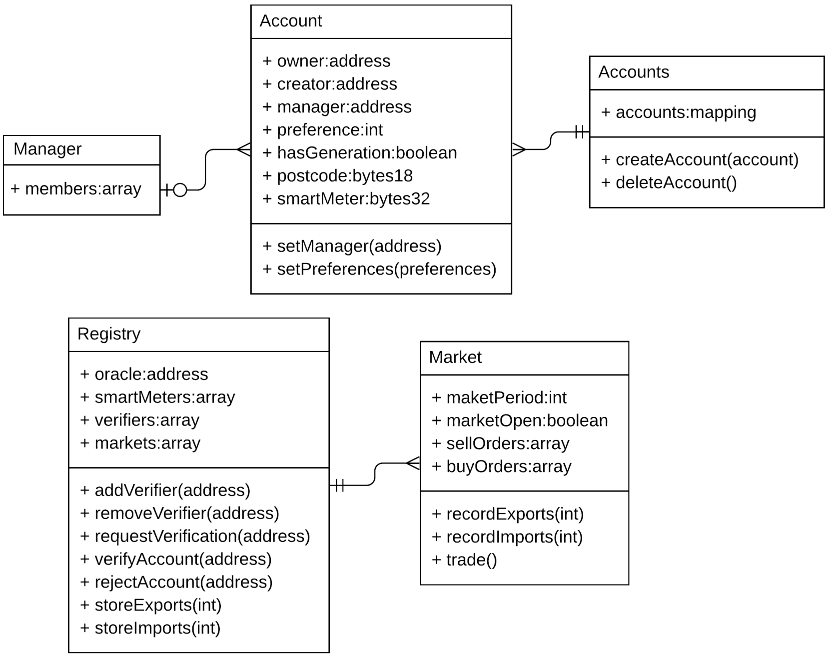

FIGURE 5.3. Electricity trading platform core contract architecture (simplified for brevity).

geographical information was restricted only to postcodes which are not identifiers of individual residential buildings but retain the locality necessary to provide localisation of energy resources during trading. However, this privacy concern requires further investigation, for example, the incorporation of P2P privacy research such as that by Hong *et al.* [115], but for the purposes of our feasibility demonstration will suffice. A user may create as many Account contracts as they wish, but to begin trading with this account it must be verified by a system administrator inside the Registry contract.

5.2.1.2 Registry

The Registry contract manages the verification process of Account contracts, the storage of electricity data and the creation of Market contracts. Any user may apply for an Account to be verified, which then allows system administrators to validate the information provided by the user and verify the Account. Once verified, a mapping is recorded between electricity data identifiers (e.g. meter point administration numbers to identify a specific smart meter) and the Account to which they relate. This information is used by the Oracle to correctly store incoming data streams.

The requirement of a system administrator inside this contract is a rather contentious issue for the creation of a fully P2P system designed to remove the need for intermediators. To address this, it is suggested that this process is handled by the current installation certification schemes (e.g. MCS [150]) or by a consortium of members within the energy industry. This would ensure that the system remains at least as trustworthy as the system currently in place. The separation of the platform from the current energy industry is discussed further in 5.4.3 which details further how this may need to be addressed.

5.2.1.3 Market

The trading mechanism and rule enforcement are handled by the Market contract. As electricity data is fed into the Registry by the Oracle, a Market contract is created for each trading period which contains all data pertaining to that period. This Market contract then handles the input from traders and managers which is recorded as trades into storage within the contract. The reason that the trading was separated in this way was to ensure that the accessibility of data remained the same as the number of trades continues to grow (i.e separating the trades into blocks that can be quickly searched, rather than needing to search the entire history). This structure also allows the trading to be opened and closed for a given trading period by manipulating a flag within each Market contract.

5.2.2 Oracle

An Oracle is the name given to an entity that relays information from the real world into a blockchain platform and is currently required as part of any blockchain application dealing with real data. Inside the ETP, the Oracle component provides this service to provide electricity data to the smart contracts. Import and export data is retrieved from market participants and relayed by this component into the Registry contract to ensure that settlement inside the platform is accurate and reflects the real world.

5.2.3 Client

The Client component is an interface allowing participants to interact with the ETP. This is a decentralised web application that abstracts the smart contracts inside the Core. It provides participants with account management and data exploration tools, including preference configuration, balance top-up and withdrawal, manager settings, trade history and market period summaries.

5.2.4 Managers

In order to allow for automation of matching inside the market and the processing requirements this brings, the Managers component was added to allow processing to take place outside of the blockchain, while also attempting to retain as many of the blockchain benefits as possible. There can be any number of managers inside the system, and participants can select which they would like to use, or even create their own. Managers provide a smart contract for users to provide any preferences available within their system which can be extended to incorporate any manager specific requirements or settings. During each market period, managers perform matching of accounts based on their preferences and execute the trades between these accounts. The purpose and limitations of this component will be discussed further in Section 5.3.

5.2.5 Storage

A standardised data storage mechanism was added to act as a central repository for import and export data. This abstraction of the data sources provides a unified format for the Oracle to use, allowing new data sources to be added without the need for modification to other components. While providing this abstraction, the storage system also provides the data aggregation necessary for defined trading periods.

5.2.6 Links

To receive data and process it into a standardised format, link modules were integrated that provide a means for incorporating multiple data sources. Each module pulls data from one data source and pushes this into storage. These modules are the result of smart meter data not yet being accessible, requiring that data is pulled from home energy management and monitoring solutions.

5.3 Design decisions

This architecture was developed to provide an open platform in which buyers and sellers of electricity are given complete autonomy to interact and achieve their electricity objectives with the knowledge that these interactions are trusted and enforceable. To achieve this, the platform was built using blockchain as the underlying technology to provide transparency, enforce trading rules and guarantee the interactions that take place. While it was initially considered that blockchain was feasible as a complete solution for establishing this platform, hurdles were encountered during the initial proof-of-concept phases of this development and alternative measures were integrated to overcome these. These initial phases, along with an overview of these issues is discussed in 4.2 and this section will expand upon these decisions.

5.3.1 Off-chain processing

During the design stages of this architecture, it was identified that the act of manually interacting with the system was a significant time commitment which would greatly outweigh any potential benefit of the system to small-scale actors such as household suppliers or consumers. To address this concern the system was built instead to incorporate automated trading mechanisms, which would allow users to trade using only preferences. These automated mechanisms consist of either delegating trading to another entity (i.e inside a VPP) or implementing an algorithmic trading system to trade on the user's behalf. While manual trading on behalf of another user is an important feature that is needed in the platform, the focus was initially placed on the algorithmic trading approach due to the increased difficulty of maintaining technological trust in an algorithmic environment.

To ensure that blockchain characteristics were retained, an initial algorithmic approach was developed using Solidity and deployed within the Market smart contract. While a limited algorithm was possible, we quickly exceeded the processing limitations inherent in blockchain systems. Specifically we exceed the gas limit of a block. This limit, as explained in 3.1.5, is designed to prevent coding mistakes and limit the processing required by miners, thus it is unlikely that a solution can be found that will overcome this within the blockchain environment. Along with this technological limitation, this approach would also become increasingly expensive on a public blockchain as the number of users in the system increased due to the payments for this processing to the network.

With the knowledge that a fully on-chain solution was not possible, an off-chain approach was investigated with the intention to retain the blockchain characteristics within the platform. This approach used a traditional server as a means to provide processing power to the on-chain mechanisms, hereby referred to as off-chain processing, that would provide the power needed to perform automated trading algorithms while attempting to retain technological trust within the platform. This solution was a hybrid, in which all storage was contained within a blockchain as well as all interactions between participants and the input and output of the algorithm itself. While this mechanism can't guarantee that the off-chain processing functions as stated, using the on-chain data its result can be verified externally due to the transparency of the system. Therefore a requirement of this off-chain processing would be that it remains open source such that independent third-parties could validate the output is as expected.

To achieve this hybrid solution, all data inputs and outputs are retained within the blockchain, with only the computation offloaded. Information regarding each individual is retained within their Account contract. Data from smart meters is fed directly from Oracles into Registry to act as the source of truth for blockchain transactions. Trades are performed through the Market contract using the Registry data to determine the validity of trades. The creation of these trades though is moved outside of the blockchain, whether this be a manual trade or an algorithm acting on behalf of the participant.

This method removes the processing limitations encountered when operating within a blockchain but removes the possibility of the public to see the runtime code of the algorithm used to determine the final trades. This obfuscation of the algorithm introduces the potential for bad actors when using a delegated trading manager (discussed further in Section 5.3.2) and as such could compromise the trust within the system.

Whilst some trading managers may see this as a way to protect the intellectual property of their proprietary trading algorithms, which is also provided by this method, it must still be possible for the system to retain technological trust if demanded by users of a particular manager. To address this, it is sufficient for an external validation tool to be created alongside each algorithm. This validation tool must provide an implementation of the algorithm in a publicly visible and executable manner (such as open source), such that any interested party can execute the algorithm themselves. With all inputs, and outputs remaining publicly visible within the blockchain, it can be determined if a particular output matches the given inputs for any given market period that was computed by a third party and thus that the algorithm used is as stated in the validation tool.

5.3.2 Delegated control

While off-chain processing addressed implementation of algorithmic trading systems, another objective of the platform was to provide users with autonomy within the system. This objective required that users could completely control the way that they trade and not purely rely on the manual system or algorithmic approach that was created for them. To address this, we introduced the concept of control delegation to the platform, allowing users to delegate the control of their account to any other blockchain account.

This delegation was integrated in the form of a manager, which users may set within the Account contract. Each manager has a single blockchain account from which all interactions of that manager will be executed with the control mechanism of each decided by the owner of the manager. Alongside this, managers may also provide smart contracts in which their users may provide settings and trading preferences. This allows managers to either manually trade on behalf of their users or implement an off-chain processing system to provide their own algorithmic trading system. Delegating control in this way increases both the control of the user and the range of functionality that can be supported by the platform. Additionally this allows anyone in the market to implement additional trading mechanisms if they are not satisfied with the current offerings.

The minimum requirements for control delegation are shown in Listing 5.1 where an account is given both an owner (the user themselves) and a manager (the delegated owner) that can be checked during transactions. In this example, the Market contract defines a modifier that can be applied to any function that only the owner and manager may perform. A modifier is used to modify the behaviour of a function and reduce code duplication. When applied to a function, the existing function body is inserted at the position of the '_;' symbol, allowing the modifier

```
contract User {
    address public owner;
    address public manager;
}

contract Market {
    modifier onlyOwnerOrManager() {
        require(msg.sender == user.owner() ||
                msg.sender == user.manager());
        _;
    }
}
```

Listing 5.1: Basic requirements of control delegation

to append code before and after the function. This modifier is implemented using the require function in Solidity that will revert all changes if the requirement is not met, or continue with the existing function body otherwise. However, in practice, the implementation would likely more complex, such as allowing multiple delegated owners and requiring registration systems to track which users have subscribed to which manager.

The off-chain processing and control delegation mechanisms described above are design-focused approaches to this problem and require that the implementation restricts the potential for bad actors. The manager's permission must not be overextended and users should be provided with tools to restrict this access as required. Inside the ETP, these restrictions could include:

- limiting trading to only future half-hourly periods
- limit trading quantity through incoming Oracle data
- allowing users to set a price cap which they are willing to pay

5.4 Solution

5.4.1 Framework

The architecture presented above provides a generic framework in which P2P electricity trading systems can be integrated. Designing the platform in this manner means that this single platform may contain any number of alternative business cases or markets, resulting in a **standardised approach to the development and deployment of new P2P markets**.

This structure also enables the **existence of sub-markets**, in which the participants interact purely between themselves such as a microgrid or a VPP. In this case the coordinator is able to act as a manager for this sub-market and an actor in the greater market. This sub-market

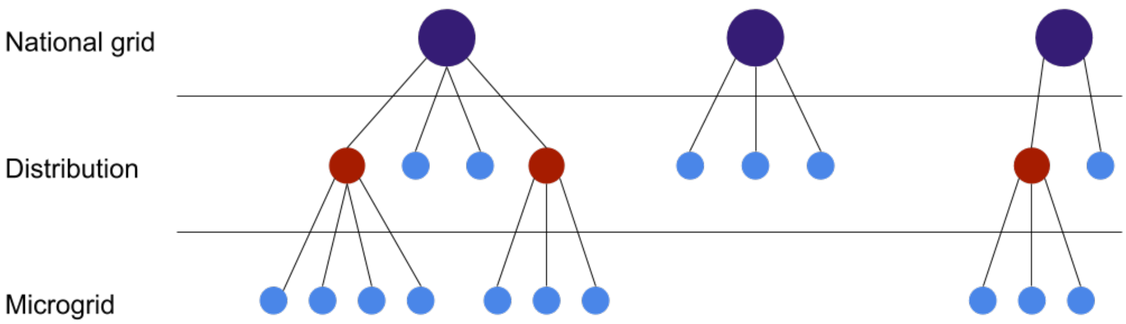

FIGURE 5.4. Example multi-level electricity market architecture.

mechanism is also extensible, giving rise to multi-level market structures incorporating the concept of a grid of microgrids (discussed in 3.3) and expanding further to any number of layers contained within layers. An example of this is shown in Figure 5.4 where the national market is made up of a set of distribution-level markets, each of which is made up of a number of individuals and microgrids.

This approach reflects the current structure of electricity market, wherein microgrid and VPPs currently interact independently with a single point of entry into the wider market, but standardises the process of operating and integrating these sub-markets. This flexibility is provided by the use of **managers that allow for segregated markets to exist** that are managed by a different entity. This entity may be a manual trader acting on behalf of the participants or an algorithm automating the trading procedure. In the feasibility demonstration, these managers are kept independent, but going forward this market structure allows for a *standardised manner for cross-market interaction through the interaction between managers*. For instance, these cross-market interactions between sub-markets could enable members of separate VPPs to trade with one another. However, further investigation is needed to explore the possibilities and implications of this.

5.4.2 Blockchain

The use of blockchain as the underlying technology in this platform intends to maximise the decentralised nature of the system and further increases the extensibility of the functionality. While third-parties may develop their own managers as discussed above, they may also extend the platform itself. As the Core module handles the necessary rule enforcement while also remaining public, additional smart contracts can be created to develop additional functionality, e.g. managers may wish to create rule enforcement contracts such that the participants of a specific manager may be restricted or monitored to ensure they meet specific group values. This flexibility and transparency brought by blockchain also allows individuals to build additional integrations without restriction such as additional client frontends for specific groups or as complete alternatives.

The decision to use blockchain though also comes with certain implications and limitations. For instance:

- There is a **trade-off** to be made at the design time between the need to **design for future** (e.g., allow for expansion to business cases which may not exist yet) **and security**. A balance then needs to be found between the increased flexibility to allow for the future and the security of the platform as anything missed during the design stage will be difficult to correct;
- An added complication with the choice of blockchain is that the system has a relatively **steep learning curve** (compared to traditional systems) and the impact of a mistake has greater consequences;
- Many prospective users of the system may not have any technical knowledge, and therefore the **private key management may be daunting** to them. This is particularly concerning as the notions of 'Forgot your password' mechanisms are currently non-existent in the blockchain space.

To combat this, the client built for the demonstration includes multiple authentication systems, ranging from a traditional system to a fully decentralised authentication. This integration of traditional technologies decreases the decentralised nature of user interaction by incorporating a reliance on a third-party provider. This again results in the *need for a balance to be struck between the traditional but less secure and the new but more complicated approaches*.

For a blockchain system to be used on a large scale with the general public it is suggested that we would need a similarly large learning system to be deployed alongside for users to understand the implications of their decisions and the risk that each option poses.

5.4.3 Deployment

The question of reliance on third-party providers is also important for the deployment of the platform. As mentioned in 5.2.1, the demonstrator was built for the Ethereum [44] blockchain, but the platform itself could be deployed onto any blockchain network that supports smart contracts (e.g. Hyperledger Fabric [151], NEO [152], etc). The factor that must be considered is the intention to remain decentralised. In the demonstrator, there are two components that require third-party interaction and subsequently trust. The Oracle module is responsible for relaying electricity data into the blockchain and the Registry contract incorporates a registration mechanism to correctly match Oracle data with the on-chain accounts. Ensuring that these components may be trusted is then of great importance within the platform.

When deployed, it is envisioned that the electricity data inside this platform would be retrieved from smart meters, providing accurate and billable information to the system. This would put a large reliance on the role of the Oracle, which would equate the trust of the platform solely to this entity. The most reliable solution to this would be to feed data directly from smart meters into the platform removing the need for an Oracle entirely, similar to the third-party meters which Lo3Energy [72] deployed for their P2P trials in Brooklyn [127]. This, however, would require alterations to be made to the smart meter specifications and incur significant expense to implement for every household. Instead, we suggested that the encryption tools for signing and encrypting transmissions that are already built into smart meters [153] are used for this task. The ownership and operation of the Oracle modules would then not impact the trust of the system as they would simply be relaying signed information which if changed would be immediately noticeable. In certain scenarios (e.g. inter-site trading) smart meter data may not be available, but we foresee that in these instances, trust in a single Oracle is an acceptable outcome due to the purpose of the trading (i.e. an energy management inside a company).

Registration within the Registry contract, however, is more of an obstacle. At some point in the system, a link needs to be made between physical devices (smart meters in this case) and the blockchain contracts (user accounts). This cannot be resolved using an alternative means, and as such will have to be performed by another entity. This action is currently performed by a group of actors, with metering installers informing utilities which in turn inform government. To retain the current level of trust this registration should be handled by the same entities within the system, but could expand upon this to a consortium of approvers.

While it would be ideal that deployment of this platform take place on a public blockchain to reduce the need for trusted entities and increase the independence of each participant, these considerations may instead favour a consortium blockchain. As an entity is needed to manage the registration process and government regulation is a requirement for the final trading, this could be handled solely by the government itself, but this would fully centralise the platform. A consortium of members from the energy industry (i.e. The Energy Web Foundation) would therefore be the preferred deployment option until a solution for registration could be found.

5.5 Summary: P2P trading platform

In this chapter we provided detail of the underlying components of the ETP platform architecture. We discussed the design choices made to maximises the control provided to participants, providing means to trade manually and through the use of an automated trading system. This automation is provided through the addition of delegated control, allowing third-parties to provide further trading options, additional market models and multi-level structures within the same platform. This expands upon previous research which had focused on single-objective mechanisms to enable

P2P markets. Whilst providing this, we also introduced off-chain processing systems to address the limitations currently inherent with blockchain solutions. Chapter 6 will now introduce one possible automated trading solution that can be deployed within this platform to both automate and retain control with the market participants.

Chapter 6

Algorithm

The algorithm developed during this project aims to provide an automated means for P2P electricity trading that maximises the control of participants in the market with a focus on encouraging the use of locally generated electricity. This chapter will discuss the creation and subsequent evaluation of this algorithm.

6.1 Overview

This project set out to provide participants in a P2P market with complete **autonomy** on their trading while simultaneously encouraging the use of locally generated electricity. The platform architecture (presented in 5.2) enables this market, allowing participants to choose the method through which they interact with the market while remaining independent. To expand upon this and provide a mechanism for **encouraging growth of locally generated electricity**, we have also designed a trading algorithm. As discussed in Chapter 1, a focus of this research was to provide increased control to users inline with the values of users discussed in [147]. To incorporate this control, the algorithm enables participants to exercise a **preference-based control** over their trading activities. These preferences provide users with choices over the electricity generation technology, the location of the seller and the price they intend to pay. The selection of these non-price energy preferences was inline with the objectives to encourage the use locally generated electricity as discussed in Section 2.2.3.2 and change the perception of electricity to a non-commoditized good as discussed in Section 9.2.

As detailed in 5.3.1, while a manual approach to trading would provide optimal control, it would be prohibitive for small-scale market participants due to the required trade-related domain knowledge and high time commitments. This, along with the small amounts of electricity traded by domestic suppliers, and therefore small monetary reward, would likely outweigh the benefits of the platform for the majority of the domestic users. This concern and the potential for a manual approach to alienate those that are less digitally abled was also raised in the interviews undertaken by Wilkins *et al.* [147]. To address this, the algorithm presented in this chapter will instead focus on providing an automated trading mechanism that maximises the benefit of P2P trading with only minimal input required from domestic participants.

In short, as discussed in Section 4.1, the criteria that the algorithm is aiming to meet are that it:

- supports user preferences (i.e., their autonomy);
- provides fair outcome form to all trade participants;
- scale up as number of participants increases.
- fosters local energy generation and consumption.

This trading mechanism is made up of two components: a scoring mechanism (detailed in 6.4) that takes the preferences of each participant and creates compatibility scores between each; and an algorithm that provides a matching process (detailed in 6.5) using the compatibility scores between participants. Along with this component division, each is further divided into a set of modules. This structure allows the trading mechanism to remain flexible and extensible, such that alternative modules or complete components can be developed and integrated in future. The design presented through this chapter has been developed to provide a demonstrative individual matching process, but future designs may explore alternative objectives such as grid optimisation or group optimisation.

Since the algorithm must operate with our P2P trading platform, it has to support the same market view as the platform (discussed in 5.2 and 5.3). In particular, this refers to the trading periods and user preferences.

6.2 Periods

To represent the trading environment of the market, the platform has been created to support the interaction between buyers and sellers, and enabling the use of automated trading systems. This platform is designed to perform a matching for every trading period, treating each period as an independent event. These trading periods were discussed in 2.2.2, in which it was concluded that a half-hourly settlement to match the current market structure was currently most applicable. In future, these periods may need to be altered, or even non-existent in which trading would take place in real-time, for which a new mechanism would need to be designed.

For each trading period, each participant in the market will take a single role - buyer or seller. This will be determined based on their electricity import/export during that period. Those that are net importers will be *buyers* and those that are net exporters will be *sellers*. This structure means that the role of an individual may change from period to period.

6.3 Preferences

To provide control to market participants while also minimising the input required, a preference system was added, that provided them with a number of configurable choices that indicated their trading objectives. These objectives were then used by the trading mechanism to determine which trades should be made on their behalf. The preferences given to participants, included a choice over the electricity generation source (e.g., photovoltaic, wind, etc.), the distance between the generator and the end-user and the price of the electricity. These preferences were dependent on the role of the participant during a given trading period and in each role had a separate purpose. These are indicated in Table 6.1 describing how each was used, to whom they apply and the limitations that they incorporate. Whilst these preferences provide extra control to the participants, they also allow the system to achieve alternative objectives. Allowing participants understanding the impact of buying locally and the different generation sources available changes the concept of electricity away from a commodity product as discussed in Section 9.2. Participants are expected to provide their preference for both roles when they join the market and may then alter these at any point as they choose. The trading mechanism will then use the configured preference at the start of each trading period, such that modifications will come into effect at the start of the following trading period.

6.4 Scoring

The scoring mechanism uses the preferences described in the previous section to calculate an individual compatibility score between any two participants in the market. The objective of incentivising locally generated electricity is used as a basis to create these scores into which other preferences are then added, resulting in a score that can be used for each potential match within the market to allow the matching algorithm to determine the best trades to be completed. This section details the calculations used to incorporate each preference and the reasoning behind each.

6.4.1 Charges

The basis of the scoring is determined by the charges to be paid for a successful trade between the buyer and the seller. The purpose of this module is to incorporate the necessary non-energy

Preference	Buyer	Seller
Distance	The maximum distance that they would prefer to buy from. Trades may exceed this distance if this or other preferences cannot be satisfied.	The maximum distance that they would prefer to sell to. Trades may exceed this distance if this or other preferences cannot be satisfied.
Price	The maximum price that they are willing to pay for electricity in a trade. This preference is definitive; a trade will never be found at a higher price than set.	The minimum price that they are willing to accept for their electricity. This preference is definitive; a trade will never be found at a lower price than set.
Generation Type	The types of generation production that they would prefer. A preference is set for each type of generation. Trades may be found from least preferred types if this or other preferences cannot be satisfied.	n/a

TABLE 6.1. Available preferences, their purpose and to whom they apply.

costs discussed in 2.2.3, that must be paid to maintain the system infrastructure and balancing mechanisms. This mechanism is a hybrid method, incorporating both a distance rate and flat rate charge. The purpose is to demonstrate a basic incentive to encourage the purchase of locally generated electricity and not necessarily to create a final mechanism to be used in the live market. Regulatory discussions would first be needed regarding the integration of non-energy costs into a P2P market, and this charges module would then need to be replaced to reflect these.

Equation 6.1 calculates the total charge – i.e., non-energy costs – to be paid for any given trade between buyer b and seller s. This uses a distance charge C_d, priced per km for the distance d_{sb} between s and b, and a fixed charge C_f, priced per trade.

$$totalCharge_{sb} = (distance_{sb} \times distanceCharge) + fixedCharge \tag{6.1}$$

6.4.2 Price

The price module uses the charges module as well as the buyer and seller price preferences to determine the maximum price that could be paid. It must be noted that this is not the final price that will be used in the trade. The price preference is used as a means for both the buyer and the seller to express their acceptable trade prices in the matching: the buyer states the maximum they are willing to pay, and the seller states the minimum they are willing to receive. As these are hard limits, such that a trade will never take place outside of these limits, this must be designed into the system.

Equation 6.2 uses the total charge from the charges module and the buyer's price preference P_b to determine the maximum price that the buyer is able to pay for this trade.

$$baseScore_{sb} = maximumTradePrice_{sb} = pricePreference_b - totalCharge_{sb} \tag{6.2}$$

This calculation ensures that the maximum trade price includes the buyer's hard limit for maximum price while also incorporating the necessary charges for each trade. To then include the seller's price preference P_s we must simply ensure that this maximum trade price exceeds the minimum price that the seller is willing to accept. The module thus discards all potential matches in which $maximumTradePrice_{sb} < pricePreference_s$.

Alongside incorporating price preferences into the scoring mechanism, the $maximumTradePrice_{sb}$ acts as an initial score for other modules to expand upon such that $baseScore_{sb} = maximumTradePrice_{sb}$.

6.4.3 Generation type

The generation type preferences are used by buyers to state which types of electricity generation they prefer (e.g. solar, wind, anaerobic digestion, etc.). Each generation type preference is set independently on a scale from zero to one, which are then normalised to one to allow them to be used correctly within the calculations. These preferences are not guarantees, and alternative generation types will be considered if there is a lack of availability or if other preference settings favour an alternative source.

As the generation type preference is normalised, it can be incorporated as a factor

$$energyPreference_b(generationType_s)$$

against the base score, where $energyPreference_b$ is a function used to access the buyer's preference for the generation type $generationType_s$ being used by the seller s.

$$energyScore_{sb} = baseScore_{sb} \times energyPreference_b(generationType_s) \tag{6.3}$$

6.4.4 Distance

The distance module uses the distance preferences defined by both the buyer and the seller to apply a modifier to the score based on the distance between the trade partners. These preferences are defined as the radius within which they would prefer to trade and are expressed in kilometres. To remove the potential for an abrupt barrier at the limit, this preference does not apply a hard

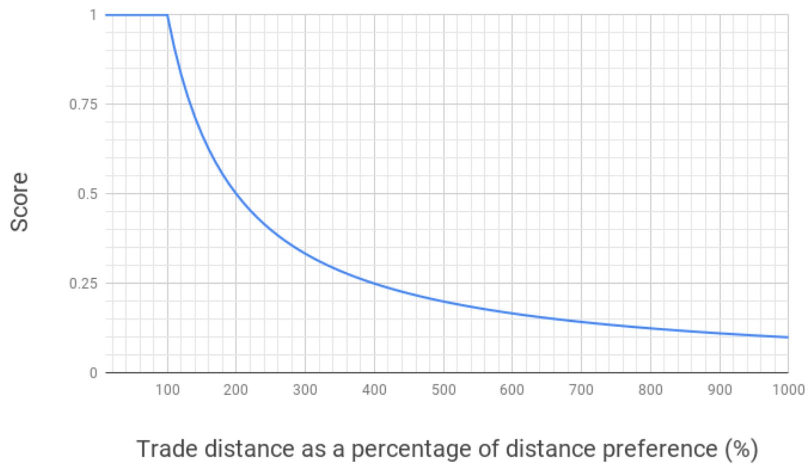

FIGURE 6.1. Distance score relative to trade distance.

limit beyond which trades are no longer acceptable. Instead, the score is reduced steadily as the distance passes the preference. This reduction was applied relative to the preference set, rather than a discrete reduction, regardless of the preference as shown in Figure 6.1.

To incorporate this preference into the score, checks are added to determine if the trade falls within the desired radius of both the buyer and the seller. If the trade is within this range, the score will be unaltered, and if it falls outside of this area, a modifier is applied for each participant whose distance preference is not satisfied. The modifier is set to

$$distancePreference_s / distance_{sb}$$

for the seller s, where $distancePreference_s$ is the seller's distance preference and $distance_{sb}$ is the distance between s and b. The modifier for the buyer is

$$distancePreference_b / distance_{sb}$$

where $distancePreference_b$ is the buyer's distance preference.

(6.4)
$$distanceScore_{sb} = \begin{cases} baseScore_{sb} & distance_{sb} \le distancePreference_b \\ baseScore_{sb} \times \frac{distancePreference_b}{distance_{sb}} & distance_{sb} > distancePreference_b \end{cases}$$

(6.5)
$$distanceScore_{sb} = \begin{cases} baseScore_{sb} & distance_{sb} \le distancePreference_s \\ baseScore_{sb} \times \frac{distancePreference_s}{distance_{sb}} & distance_{sb} > distancePreference_s \end{cases}$$

Variable	Meaning
b	Buyer
s	Seller
d_{sb}	Distance between s and b
C_d	Distance charge per km
C_f	Fixed charge per trade
E_s	Generation type of seller s
P	Price preference (with subscript b or s)
D	Distance preference (with subscript b or s)
$EP_b(e)$	generation type preference of the buyer b for generation type e

TABLE 6.2. Summary of ETP algorithm notation

6.4.5 Compatibility score calculation

The above sections describe how each of the preferences available to buyer and seller is converted into a score. These must now be combined to provide a complete scoring mechanism that can provide a single compatibility score between any buyer and seller. This calculation uses each of the modules described above and merges them into a single modifier that is applied to the base score. The final base score calculation is given in Equation 6.6 and the final score that is calculated from this is given in Equation 6.7, while the notation is summarised in Table 6.2.

$$baseScore_{sb} = P_b - ((d_{sb} \times C_d) + C_f) \tag{6.6}$$

$$finalScore_{sb} = \left\{ \begin{array}{cc} baseScore_{sb} \times EP(E_s) & d_{sb} \le D_b, d_{sb} \le D_s \\ baseScore_{sb} \times \frac{\frac{D_s}{d_{sb}} + EP(E_s)}{2} & d_{sb} \le D_b, d_{sb} > D_s \\ baseScore_{sb} \times \frac{\frac{D_d}{d_{sb}} + EP(E_s)}{2} & d_{sb} > D_b, d_{sb} \le D_s \\ baseScore_{sb} \times \frac{\frac{D_s}{d_{sb}} + \frac{D_d}{d_{sb}} + EP(E_s)}{3} & d_{sb} > D_b, d_{sb} > D_s \end{array} \right\} \tag{6.7}$$

6.5 Matching

The matching component then uses an algorithm along with the scoring component described above to determine the outcome of trading within each trading period. The design of the algorithm was greatly influenced by the environment in which it will operate and the challenges this introduces. This section details the design, implementation and optimisation of the algorithm used to perform this matching.

6.5.1 Design

The matching performed by this algorithm considers all parties in the electricity market, including domestic suppliers and consumers. The intermittency of the generation and the unpredictability of the usage patterns of these actors results in a likely imbalance between electricity production and consumption within each trading period. Alongside this, the preference-based scoring system and the incorporation of distance-based network charging results in some matches being completely unviable. These challenges mean that the algorithm must allow for an incomplete matching to take place, such that not all parties have been matched even if they still have electricity to market.

Another challenge faced by the algorithm is the low level of marketable generation available from microgeneration and similarly the low level of consumption that householders may have during any given trading period. The algorithm therefore needs to provide a many-to-many matching such that participants may trade with any number of participants to fulfil their needs. This requirement also ensures that the algorithm can maximise the use of the available resources.

The problem therefore presents itself as a many-to-many matching problem between two groups, in which each party may express their preferences over all parties in the other group. There are multiple types of algorithms that could be considered for such a problem, each presenting a different approach and having a different applicability to our problem:

Game theory (Regret matching) Matches between participants are found through a trading game in which historical actions are used to assess the current offerings and minimise the regret of each participant's future actions. An approach for applying this to energy trading has been presented by Yaagoubi and Mouftah [51].

Schedule sharing Participants in the trading share their energy production and consumption schedules in advance. These schedules are used to determine the optimal trades to take place. This energy trading strategy is discussed by Luo *et al.* [54].

Stable matching Members of two groups indicate their preferences over members of the other group, and these preferences are used to determine a complete and stable matching between the two groups. A complete matching means that there is no one left unmatched and a stable matching means that no pair of members of the two groups would prefer to be matched to each other over the matches assigned to them.

Schedule sharing provides a solution for ensuring the balance of the grid, but our objective of providing maximum control to participants would be superseded by the scheduling mechanism.

The regret matching approach relies upon a reinforcement learning technique, building upon previous decisions to ensure that each participant will not regret its next action. However, the continually changing nature of each trading period and our intention to maintain fairness throughout (such that no particular participant is favoured due to reasons outside of their preference choices) do not provide a provision to maintain a record of positive/negative historical trades.

A stable matching approach is the most applicable to the problem, wherein each of the buyers and sellers has a preference over one another, given by the score assigned to a potential trade. Stable matching, however, may quickly become computationally unviable and as such the scalability of such a system will need to be managed. Nevertheless, this option was chosen due to the applicability of this mechanism to the objectives of this platform, and it was considered that a suitably modified stable matching mechanism could minimise the computational inefficiency.

6.5.2 Approach

Stable matching, or more generally matching under preferences, is a well-researched topic with substantial literature covering the many different problem variants that it presents [154]. The objective of this approach is to create matches between two groups in such a way that the resulting matching is stable, i.e., no unmatched pair exists that would each prefer to be matched to the other over their current match. Ensuring this property persistently within the algorithm is crucial to ensure that it provides matches that are acceptable by the participants involved.

The solution presented uses the Gale–Shapley (GS) algorithm [155] as a basis. This algorithm uses an iterative process in which in each round every unmatched member of one group attempts to create a match with their preferred member of the second group. The member of the second group then either accepts this as a provisional match if they are currently unmatched or the offer is better than their current match, or rejects if the offer is worse. This continues until all parties have been included in a provisional match, at which time the matches are then finalised as the result. This method produces a complete matching in a one-to-one fashion.

For our purpose we modify the GS concept into an incomplete many-to-many approach. To first alter GS from one-to-one to many-to-many, we incorporate the concept of volume. Each participant is assigned a volume representing the amount they are able to either buy or sell, which is modified as necessary to represent their remaining volume throughout the process. An additional loop is also added during each iteration in which all current provisional matches are finalised and the participant's volume modified to represent the amount exchanged between them. When a match is finalised, this is their optimal trade, and as such the participants exchange as much as possible between them, leaving either both parties with no remaining volume or only one of the parties with some remaining volume. Participants with no remaining volume are then removed from the process, and those with a remaining volume are included again in the next iteration.

To then alter the GS algorithm to allow for an incomplete matching, we change the end criterion. GS continues to iterate until there are no remaining unmatched participants, but this might continue indefinitely for our problem. To resolve this, we instead set the end criterion such that once an iteration completes without forming a new final match, we can determine that there are no more matches possible. This requires only one additional iteration of the process once the final matching has been found. Our basic matching algorithm is given in Algorithm 1, including the modifications discussed.

At the time of development, the use of a modified GS algorithm to provide a preference-based matching system incorporating choice over price, distance and generation source within a P2P electricity market had not yet been seen. However, since this time, researchers have begun to incorporate further preference-based controls as described in Section 3.3.4. For example, Morstyn *et al.* [137] consider the same preferences within their system and Sorin *et al.* [136] include preference-based approaches within their matching mechanism as well. However, in each case there remains a key differentiator. Morstyn *et al.* retain a platform agent acting as an auctioneer that defines a set price for each energy class within the network. The algorithm presented in this dissertation instead allows price to be determined on an individual trade basis. Sorin *et al.* focus on a decentralised approach, wherein they rely on each market participant to perform all computation and negotiations independently. This design choice results in an approach that is difficult to scale both computationally and from a communications perspective between market participants.

6.5.3 Implementation

The modified version of the GS algorithm provides a solution to the matching problem in our market, but to optimise it for our particular task, additional steps were taken during the implementation. This section details the process taken to fit this algorithm to our use case and the scalability measures introduced.

6.5.3.1 Details

To incorporate the scoring component from Section 6.4, the internal representation of the current market period was given an object-based structure. The algorithm takes the sell and buy orders of a given market period and represents the sell orders as *Sales* and the buy orders as *Interest* against these Sales. This interest is calculated using the scoring mechanism, and the result is an array of Sale objects, each containing a number of Interest objects. This structure allowed the implementation to follow object-oriented programming (OOP) standards to help structure and organise our code.

During the completion of each trade an the final pricing is determined. With the intention of our system being to change the way that energy is viewed in the market such that consumers understand the impact of distance and time on the price of electricity (see 2.2.3.2), this pricing was determined using the maximum price the buyer is able to pay using the calculation in

Algorithm 1 Modified Gale-Shapley algorithm to compute an incomplete many-to-many matching

Input: Sellers S, Buyers B
Output: Matches (b,s)

```
Given V_s is the volume of electricity to sell for seller s
Given V_b is the volume of electricity to buy for buyer b
n ← 0 {rounds}
t ← 0 {total matches}
while T_n > T_{n−1} do
  for s ∈ 𝒮 do
    p ← most preferred match for seller s
    if p has no provisional match then
      (s,p) created as provisional match
    else
      (s′,p) exists as provisional match of p
      if p prefers s to s′ then
        (s′,p) removed
        (s,p) created as a provisional match
        move s′ to the end of S
      else
        remove p as possible match for s
        move s to the end of S
      end if
    end if
  end for
  for b ∈ ℬ do
    if exists a provisional match (s,b) then
      (s,b) created as a final match
      if V_b > V_s then
        V_s = 0
        s removed from S
        V_b = V_b − V_s
      else
        V_s = V_s − V_b
        V_b = 0
        b removed from B
      end if
    end if
  end for
  all provisional matches removed
  n = n + 1
end while
```

Equation 6.2, which incorporates the non-energy costs of the system. This price is not a clearing price and will differ for each trade that is made. On top of this a second-highest price approach was applied with the result being that trades on Sales with multiple buyers interested would be charged based on the maximum price to pay of the second highest Interest at the time of the trade (if the second highest Interest had a lower maximum price) and charged the maximum price to pay of the first Interest if the Sale only had one interested buyer. The reason for this is to ensure that it is in the buyer's best interest to set their price preference as an amount they are willing to pay, while also ensuring that the buyer pays a fair price. It is worth noting that the price paid is calculated during each iteration and not when all trades are completed. This means that there is also not a clearing price for each specific Sale, and two trades with the same Seller may pay different prices. This decision was made to more accurately reflect a free market.

6.5.4 Optimisation

Implementing the algorithm directly into a working solution provided the functionality that was necessary for the market, but proved to slow down quickly as the number of households and percentage of sellers in the market increased. To address this, a number of optimisation steps were performed to increase the scalability of this algorithm through the removal of unnecessary computation, reduction of rounds, and the avoidance of unnecessary provisional matches.

The final implemented algorithm can be seen in Algorithm 2, incorporating the additional steps taken to increase the efficiency of the algorithm:

Sorting The most impactful modification was the addition of a sorting mechanism (step 3) which orders the Interest for each Sale such that the best match is always found at $I_s(0)$. This alteration removes the need to search the entire array during each round, instead processing the entire array only once to perform the sorting.

Interest exclusions To further reduce the computation, exclusions were added, preventing Interest from being added to Sales that would not be successful. For example, ensuring that the price to pay exceed the minimum requested by the seller.

Multi-threading The algorithm does not consider the runtime environment available and as such used only one thread, disregarding modern processors that would compute the result. Multi-threading was implemented during steps 2 and 3 with mixed results, as can be seen in Figure 6.2. The extra computation necessary to manage the threads resulted in a worse performance in some scenarios, but provided a generally faster solution in more situations.

Along with these optimisation alterations, further modifications were made to ensure the result was optimal:

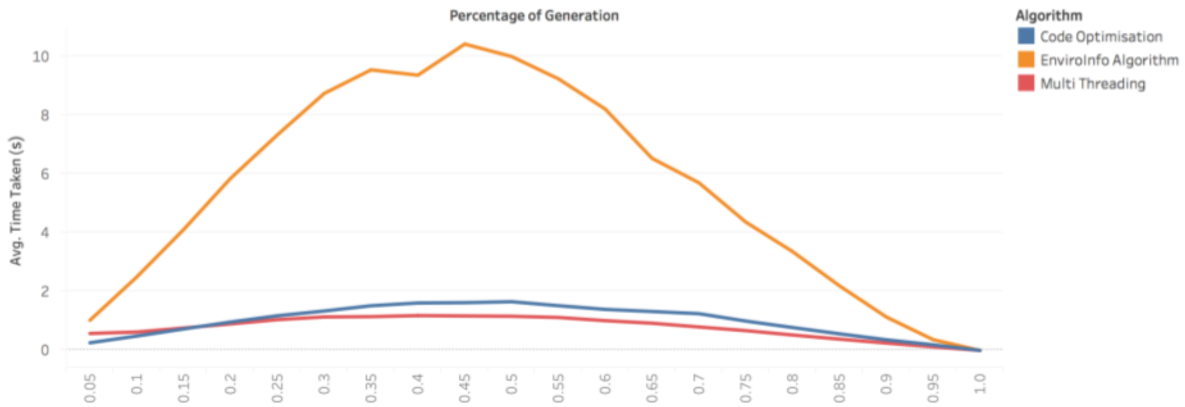

FIGURE 6.2. Algorithm performance before and after optimisation (evaluated on postcode sector SS11 7).

Deemed unacceptable As a result of the zero-order problem, presented in 7.5.1.1, an additional check was added to determine whether a trade was unacceptable during each trade loop. This step was only impactful when the scores of a Sale were all zero, and determined whether $I_s(0)$ had a better match elsewhere. This prevented consumers being provided with matches to which their score was zero, unless this was their highest score.

Stability A requirement of this algorithm is to provide a stable result, and the initial design presented one case in which this could be compromised. As only one match can be made in each round, a consumer may be excluded as they have already found a better match. If this match does not completely satisfy their demand, the Sale will have finalised a match with a less favourable consumer than the one with remaining demand. To resolve this, an additional check was incorporated, which stopped Sales from finalising a match if $I_s(0)$ had a better match which would not satisfy their demand.

6.6 Summary: P2P trading algorithm

This chapter presents an automated trading algorithm that provides participants in a P2P market with granular control over the electricity they wish to purchase. This preference-based algorithm allows participants to manage the distance to trading partners, the type of generation they wish to receive and the price they are willing to pay. While providing these preferences to users, this algorithm acts as a means to incentivise the purchase of locally generated electricity and encourage the uptake of microgeneration to local demand capacity. In Chapter 7 we will continue with an evaluation of this algorithm against the assessment criteria presented in Chapter 4.

Algorithm 2 Final implementation of the matching algorithm

Input: Sellers S, Buyers B

Output: Matches $[(b, s, q, r, p)]$

With trade volume q, score r and price p

Given V_s is the volume of electricity to sell for seller s
Given V_b is the volume of electricity to buy for buyer b
for $b \in \mathscr{B}$ **do**
  for $s \in \mathscr{S}$ **do**
    Calculate score r_{sb} and using the scoring mechanism (1)
    Calculate maximum price to pay p_{sb} using the pricing mechanism (2)
    $i_{sb} \leftarrow (b, r_{sb}, p_{sb})$
    Push i_{sb} into I_s
  end for
end for
Sort interest arrays, descending on r
$M \leftarrow []$ {Final matches set}
$PM \leftarrow \{\}$ {Provisional matches set}
$n \leftarrow 0$ {round number}
while $length(M_{n-1}) \neq length(M_n)$ **do**
  for $s \in \mathscr{S}$ **do**
    if length(I_s == 0) **then**
      skip to next s
    end if
    Search for the highest scoring match that has not found a better match elsewhere
    $m \leftarrow null$ {most suitable match}
    while $m == null$ **do**
      if buyer in $I_s(0)$ has no more volume **then**
        delete $I_s(0)$
        if length(I_s == 0) **then**
          skip to next s
        end if
      end if
      if buyer in $I_s(0)$ has a better match which will not satisfy their volume **then**
        Await next round for another chance to match
        skip to next s
      end if
      if if buyer in $I_s(0)$ has a better match which will satisfy their volume **then**

delete $I_s(0)$
if length(I_s == 0) **then**
skip to next s
end if
end if
$m \leftarrow I_s(0)$ {most suitable match}
end while
if m is not deemed acceptable by the matching mechanism (3) **then**
skip to next s
end if
if length(I_s == 1) **then**
Only one interest, create provisional match to the buyer ($m.b$)
$b \leftarrow m.b$ buyer
$r \leftarrow m.r$ highest interest score
$p \leftarrow m.p$ highest interest price
$PM_b \leftarrow (s, m, r, p)$
else
More than one interest, create provisional match to the buyer (m.b) with the final pricing of the second highest
$b \leftarrow m.b$ buyer
$r \leftarrow m.r$ highest interest score
$p \leftarrow I_s(1).p$ second highest interest price
$PM_b \leftarrow (s, m, r, p)$
end if
end for
for $b \in \mathscr{B}$ **do**
if $PM_b \neq null$ **then**
$s \leftarrow PM_b.s$ seller
$r \leftarrow PM_b.r$ match score
$p \leftarrow PM_b.p$ match price
if $V_b > V_s$ **then**
$q = V_s$
$V_s = 0$
$V_b = V_b - V_s$
else
$q = V_b$
$V_s = V_s - V_b$

```
        V_b = 0
      end if
      Push (b, s, q, r, p) into M
      Delete I_s(0)
    end if
  end for
end while
```

CHAPTER 7

ANALYSIS OF P2P TRADING ALGORITHM

To evaluate the algorithm presented in Chapter 6 a series of agent-based simulations were undertaken to assess each aspect. This chapter presents the undertaking of these simulations and an analysis of the results to determine the success of the algorithm.

7.1 Introduction

To validate that the algorithm developed for matching individuals inside a peer-to-peer market performs as expected, simulations for a number of scenarios examining each aspect individually were performed. These scenarios used data from a historical dataset of real domestic electricity imports and exports that was extrapolated to represent a complete uptake of a peer-to-peer electricity trading platform in a single area of the UK. Each scenario was created as static input for a simulation, thus allowing each trading period to be exactly reproduced so that the effects of changes to individual aspects could be observed.

The scenarios investigated were designed to address the objectives of the trading mechanism: providing increased control to market participants, matching fairly based on user preferences, and incentivising the purchase of locally generated electricity. This resulted in six properties being examined:

Localisation Ensuring that distance based charging is effectively localising trading

Distance preference Understanding the impact of an individual's distance preference on their trading outcome

Price preference Understanding the impact of an individual's price preference on their trading outcome

Generation type preference Understanding the impact of an individual's generation type preference on their trading outcome

Energy matching Ensuring that an individual's preferred energy type is correctly prioritised

Fairness Ensuring that matching is performed fairly for similar individuals

In the following, we give a detailed description of the data preparation and scenario design methodology. Section 7.4 then presents the results from each scenario tested.

7.2 Data preparation

In an attempt to mitigate any time-of-day or data-related issues when running our scenarios, it was decided that each scenario would be extrapolated from a real dataset of domestic electricity exports and imports and would simulate a whole day of trading. It is important to note that while an attempt was made to use data representative of normal households, this should not change the conclusions of the testing. The scenarios were designed purely to test the algorithm itself, and not to demonstrate accurate profitability or differentials from the current market.

The real dataset used was gathered by Sunplug as part of a trial with EDF Energy from 76 households with photovoltaic panels installed. Data was recorded through a home energy management system at intervals of one second and aggregated into half-hourly periods. The location of the houses in the dataset were unknown due to data privacy considerations, and as such it was decided that the data from these houses would be averaged to provide some concept of the average prosumer household.

This average prosumer household was computed as import and export curves for each month of the year. These curves were calculated independently, averaging each half hourly period of each month into a single 24 hour period for that month with any household missing any half hourly period in the month excluded from the calculation. The import curve from this calculation was also used separately to provide a representation of an average consumer household as well.

Using these import/export curves, the households for the scenarios could then be built. As real households would not follow identical curves, two layers of randomisation were added:

- Each household was assigned a scale factor between 0.8 and 2.8 that acted as a way to represent household size. This factor was then multiplied to each of their imports and exports.
- In each half-hour period, imports and exports were randomised by $\pm 10\%$. This simulated weather variations between the households.

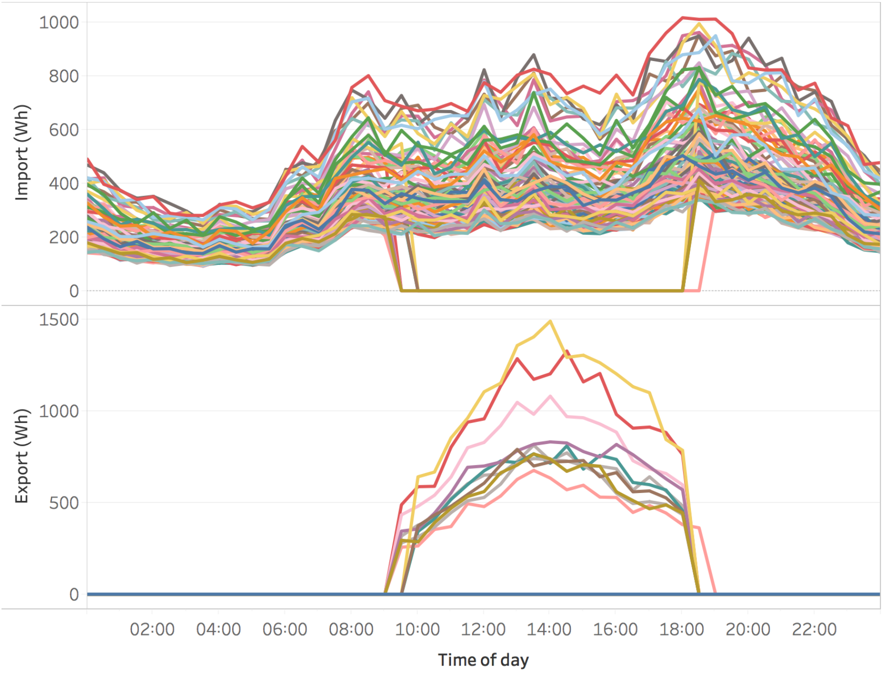

FIGURE 7.1. Simulated export and import curves for 100 households in July.

Once these randomisation layers were added, household usage curves were more representative of normal households[1]. The imports and exports of 100 households (10% prosumers) after this process are shown in Figure 7.1. The figure shows each household as a single colour, and it can be seen that the prosumers' imports decrease to zero during some parts of the day in which their exports outweigh their consumption.

7.3 Scenario design

With a data preparation method allowing for the generation of simulated household data, it was then possible to create our scenarios. A base scenario was created that represented 100% usage of a peer-to-peer trading platform in one postcode district of the UK. This was created from the July curves, as this was the month in which export was greatest, allowing the algorithm to be fully tested. This base scenario could then be varied to create our test scenarios.

The district used was SS11, an area in the south-east of England, with 6968 households and a mix of urban and rural households (see Figure 7.2 for a visual representation of their locations and density). For the purposes of analysis, 10% were randomly assigned as prosumers and the type of generation these prosumers were using was evenly distributed amongst them. These

[1]While more representative, this simulated data is not an accurate representation of all households in the grid

households were then given randomised preferences and simulated for one day, and the data stored into files to provide reproducibility.

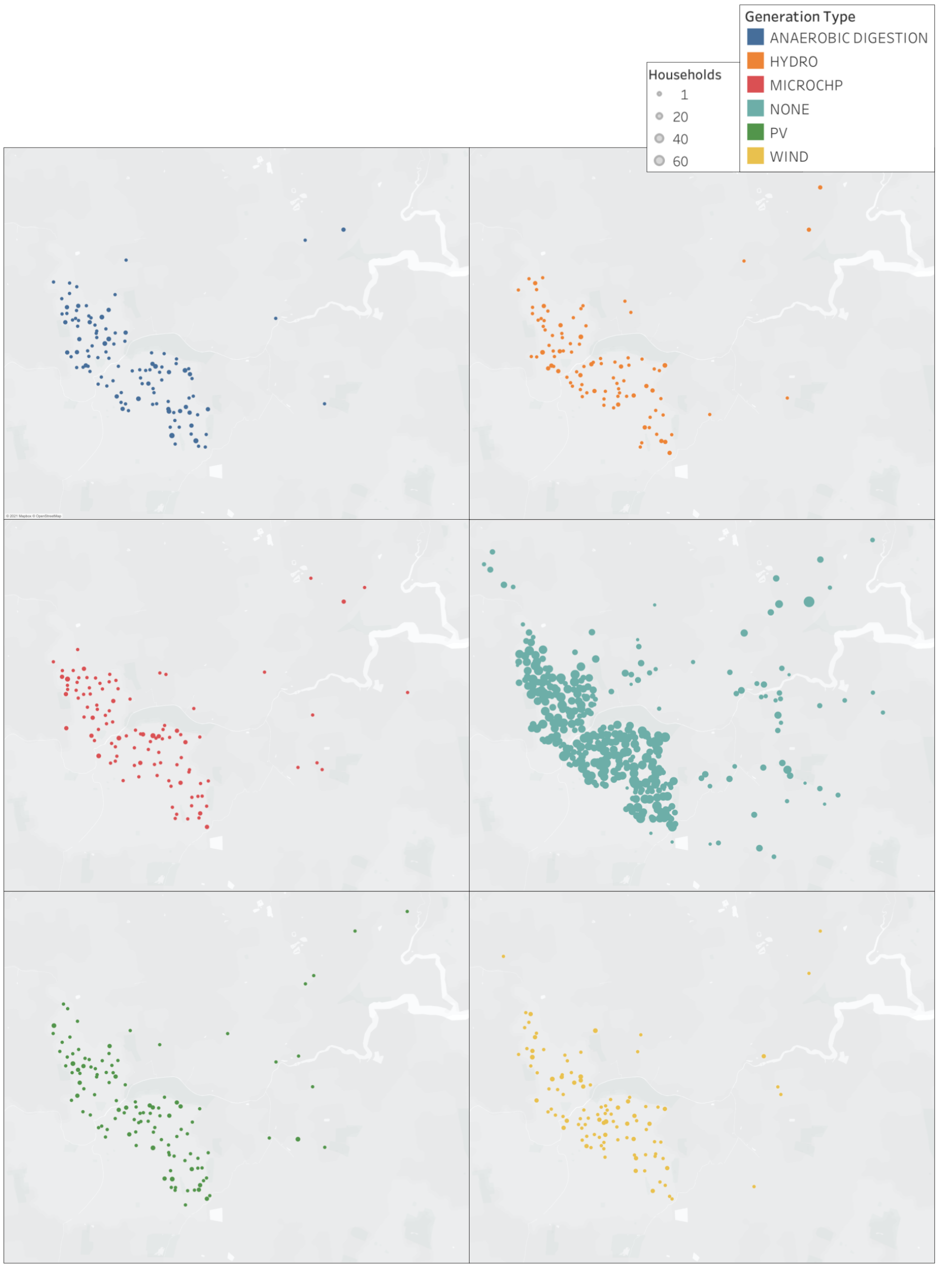

FIGURE 7.2. Base scenarios household locations and density inside SS11.

7.4 Simulations

Agent-based simulations were then created using this base scenario to evaluate the impact of each independent variable on the trading result. Throughout the simulations, the variation of the network charges and preferences had no discernible impact on the computation time taken. Periods in which trading took place consistently converged in 1-2s and periods in which there was no generation to be traded converged in 0.25-0.4s.

However, whilst the computational time remained consistent throughout the simulations, the number of rounds needed to converge did not. In nearly all simulations in which trading took place, the number of rounds needed to converge was consistently ~20. There was one scenario in which this did not hold true; when no network charges were present in the Localisation simulations, the rounds to converge was ~160, significantly higher than needed for all other simulations. This increase is due to the lack of differentiation between market participants, such that participants are given more similar match scores with one another. This increased number of similar scores results in the algorithm waiting for another round to create a more favoured match at lines 29-32 in the algorithm presented in Algorithm 2 and had no impact on the computational time or the outcome of the trading.

7.4.1 Localisation

Objective: Assess the effectiveness of the network charging mechanism to incentivise localisation of trading.
Variation from base scenario: The base scenario was unaltered for this test. Instead, the distance-based non-energy costs were altered for each variation.

The distance based non-energy costs, hereby referred to as network charges, for each simulation were set between 0p and 2p per km in increments of 0.5p, and the distance between trades was observed to understand the correlation between the two.

As can be seen in Figure 7.3 and Figure 7.4, even a small network charge has a significant effect on the localisation. The distance between trades drops from an average of 1.492km between trade partners for no network charges to 0.153km for 0.5p/km. The reason for this is that without network charges, trades only vary from one another by their preferences, and thus individuals will be assigned their best match regardless of distance.

We notice that the first and last trading period of each day also vary from all other periods. This difference can be seen in increased values when no network charge is present and decreased values when network charges are present and can be attributed to the reduced generation at the start and end of the day. When no network charge is present, the best matches will be found regardless of distance, but with a reduce number of generators available, it is more likely that the best match would be further away purely due to the average distance between generators

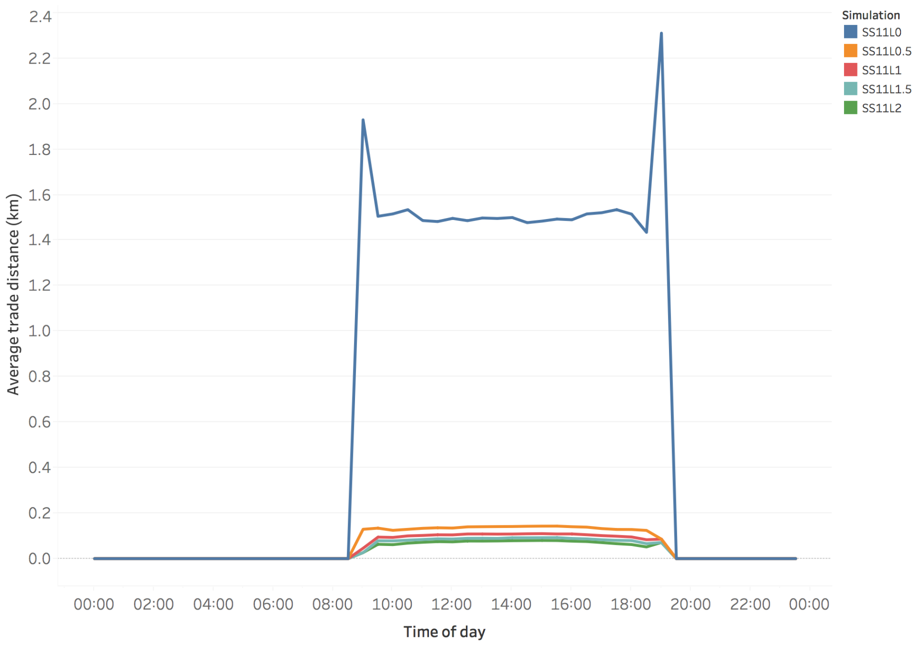

FIGURE 7.3. Localisation: Trade distance (km) as network charges were varied.

and consumers increasing. Conversely, when a network charge is present, the reduced number of generators available mean it is less likely for a viable match to be found.

Throughout the remaining simulations, as the network charges continue to increase, the average trade distance continues to fall and the distribution of trade distances reduces. This demonstrates that a charging mechanism that increases network charges along with the distance between trade partners provides an effective localisation mechanism for the market participants.

7.4.2 Distance Preference

Objective: Examine the impact of an individual's distance preference on their trading result.
Variation from base scenario: Accounts were selected randomly from the base scenario as test subjects, and five simulations were conducted in which the subject's distance preference varied between 0km and 0.4km in increments of 0.1km. This test was completed for 20 consumers and 20 prosumers.

Through the consumer distance preference scenario we can see from Figure 7.5 that, as the test subjects increased their preferred maximum distance, they were able to purchase a higher percentage of their desired quantity. This is because the scoring algorithm was designed so that an increase in a preference will provide higher scores to more market participants, resulting in a higher likelihood that they will find a match. The result is that as individuals increase the distance they would prefer to purchase within, the amount of their demand that can be satisfied increases.

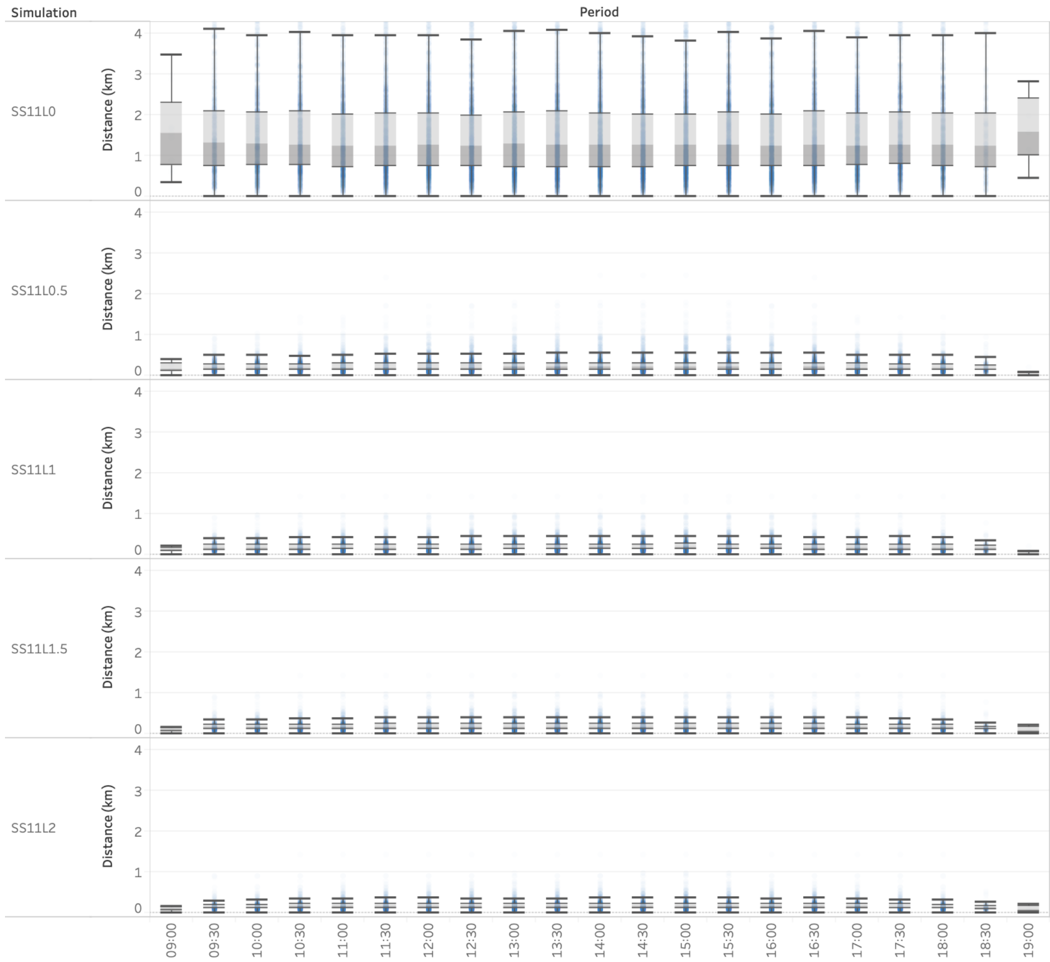

FIGURE 7.4. Localisation: Distribution of trade distance (km) for each simulation.

The effect of the distance preference on trade distance and price paid is shown in Figure 7.6 and Table 7.1 and the distribution of values for each are shown in Figures 7.7 and 7.8, where all test subjects that did not make a trade were excluded to prevent those that weren't able to find a match from reducing averages. We can see that, as expected, the average distance of the trades made increased along with the test subject's distance preference. This is a result of the increased distance preference allowing them to find more suitable matches at a further distance, widening their opportunities for matches.

We note that as their distance preference increased, they also managed to pay less per kWh. This shows again that the increased opportunities for matches allow them to find more suitable matches, in this case finding a better price. While the change was only small, reducing from an average of 15.79p/kWh at 0km to 15.76p/kWh at 0.4km, it demonstrates an important property of the algorithm: for an individual to have increased control over a single property (i.e., purchasing more locally) they must sacrifice other properties (i.e., price).

FIGURE 7.5. Consumer distance preference: Percentage of test subject imports that were bought through the platform.

FIGURE 7.6. Consumer distance preference: Average price paid per kWh and trade distance for test subjects that executed a trade.

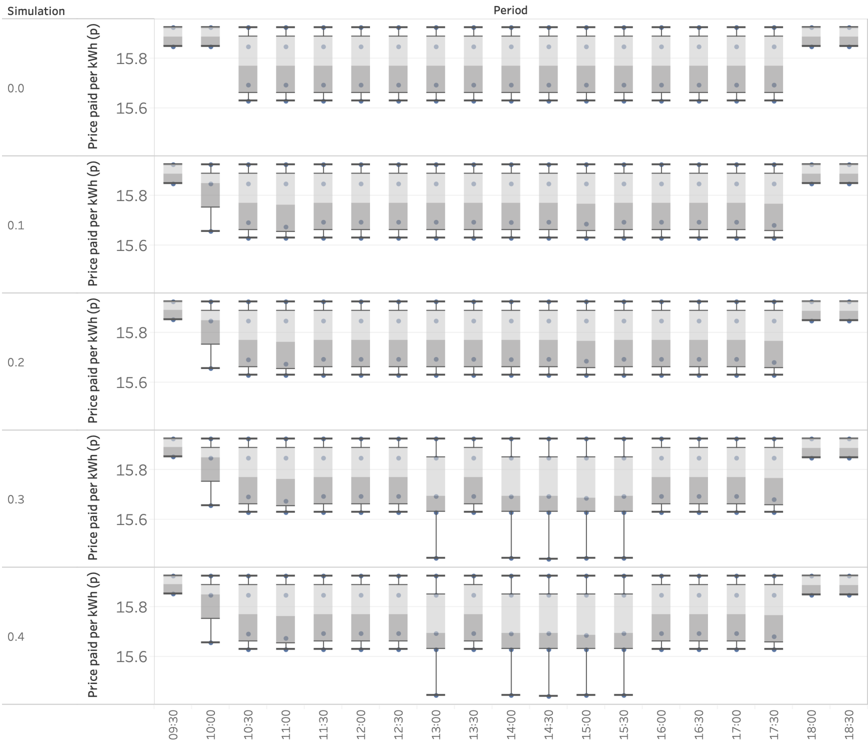

FIGURE 7.7. Consumer distance preference: Distribution of price paid per kWh as distance preference was varied.

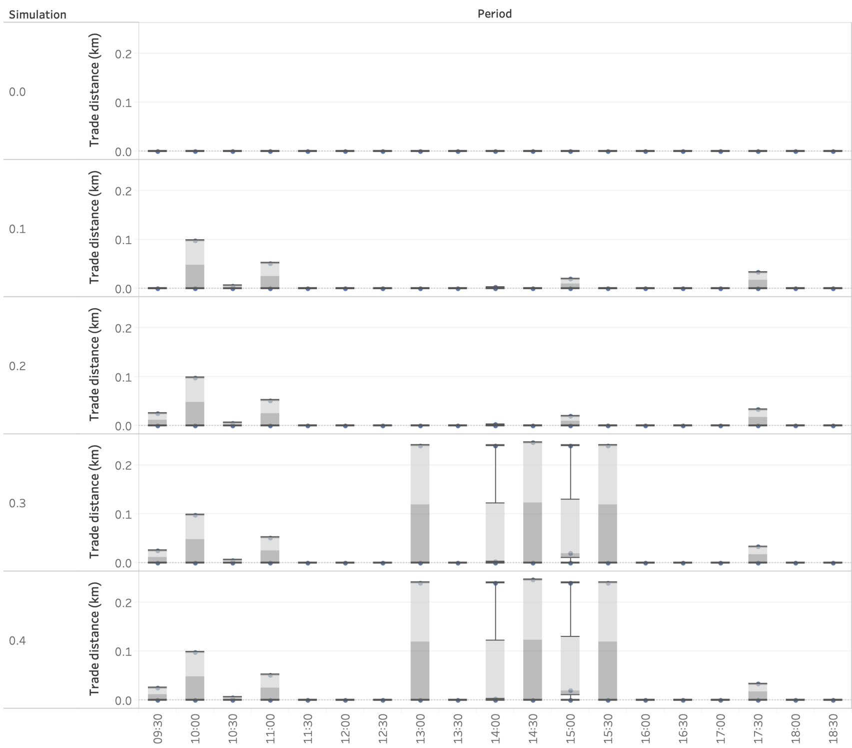

FIGURE 7.8. Consumer distance preference: Distribution of trade distance as distance preference was varied.

Simulation	Average price paid per kWh (p)
0.0	15.78604
0.1	15.78356
0.2	15.78363
0.3	15.76089
0.4	15.76089

TABLE 7.1. Consumer distance preference: Average price paid per kWh for consumers that executed a trade.

Figure 7.11 shows the average price paid and distance of trades when prosumer preferences were varied, and Figures 7.9 and 7.10 show the distribution of each. Similarly to the consumer scenario, we can see that the trade distance of prosumers also increases along with the test subject's distance preference. While the trade distance increases, however, an effect opposite to that for consumers arises, in that the price paid per kWh also increases. The matching mechanism is designed in such a way that prosumers prefer matches with a higher price, as this directly relates to the profit they make from the trade. This again shows that an increase in control may result in a less optimal outcome; in this case, restricting the distance over which they prefer to sell results in lower profits.

As the generation in this scenario did not satisfy buyer demand, all sellers were able to fully sell their exports. Another test could be completed in the future where generation is in excess, in order to understand the effect this would have on the impact of preference changes.

7.4.3 Price preference

Objective: Examine the impact of an individual's price preference on their trading result
Variation from base scenario: Consumers were selected randomly from the base scenario as test subjects, and five simulations were conducted in which the subject's price preference was varied between 14p and 16p at increments of 0.5p. This range was chosen to match the initial dataset, which had price preferences randomised between the same values.

In Figure 7.12 we can see that the first two price preferences (14p–14.5p) resulted in no trades, this was due to there being excess demand and thus better matched individuals took priority with the generators. At 15p we can see that while some trades were found, these were only during high generation periods of the day (12:30pm–4:00pm). This trend continues with 15.5p, finding trades in a larger period of the day (10:30am–17:30pm), and with 16p, finding trades in all periods of the day in which generation is available (9:30am–18:30pm). This occurs due to the generation available throughout the day not remaining constant. When little generation is available, those offering higher prices will take all that is available, whereas in high generation periods, there will still be remaining generated energy to sell after the higher bidders have been fulfilled.

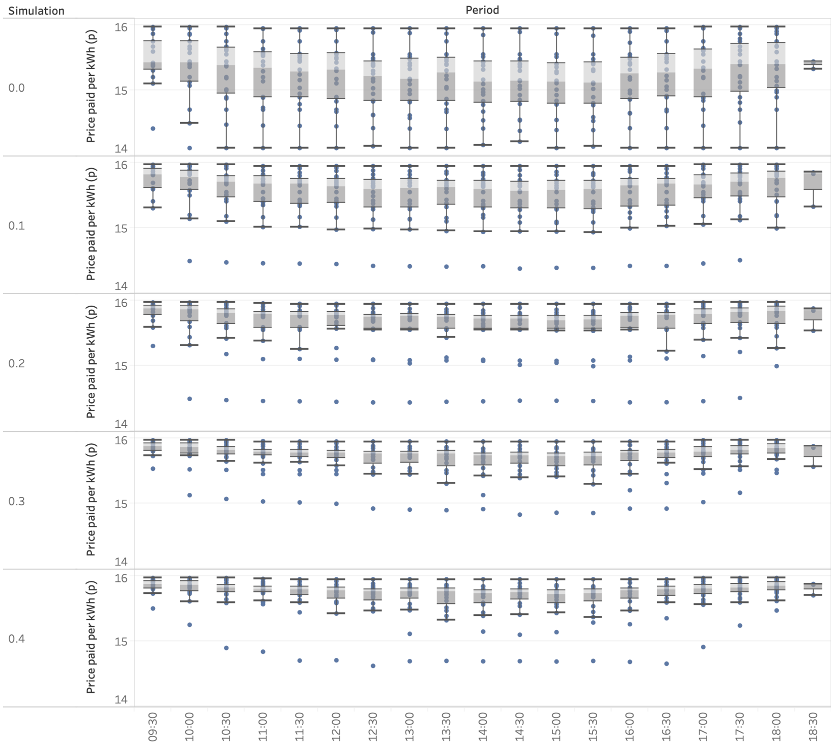

FIGURE 7.9. Prosumer distance preference: Distribution of price paid per kWh as distance preference was varied.

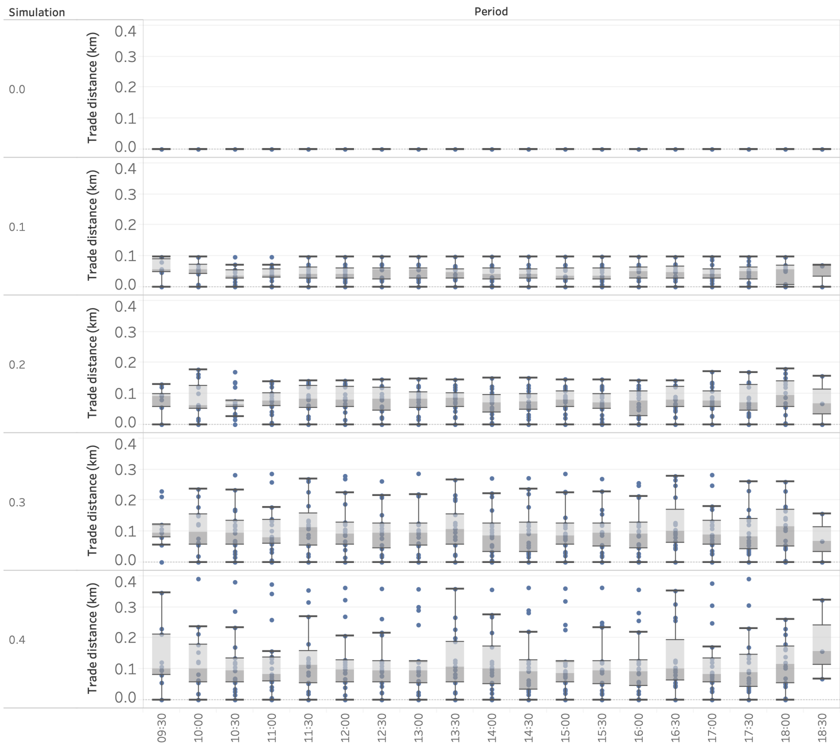

FIGURE 7.10. Prosumer distance preference: Distribution of trade distance as distance preference was varied.

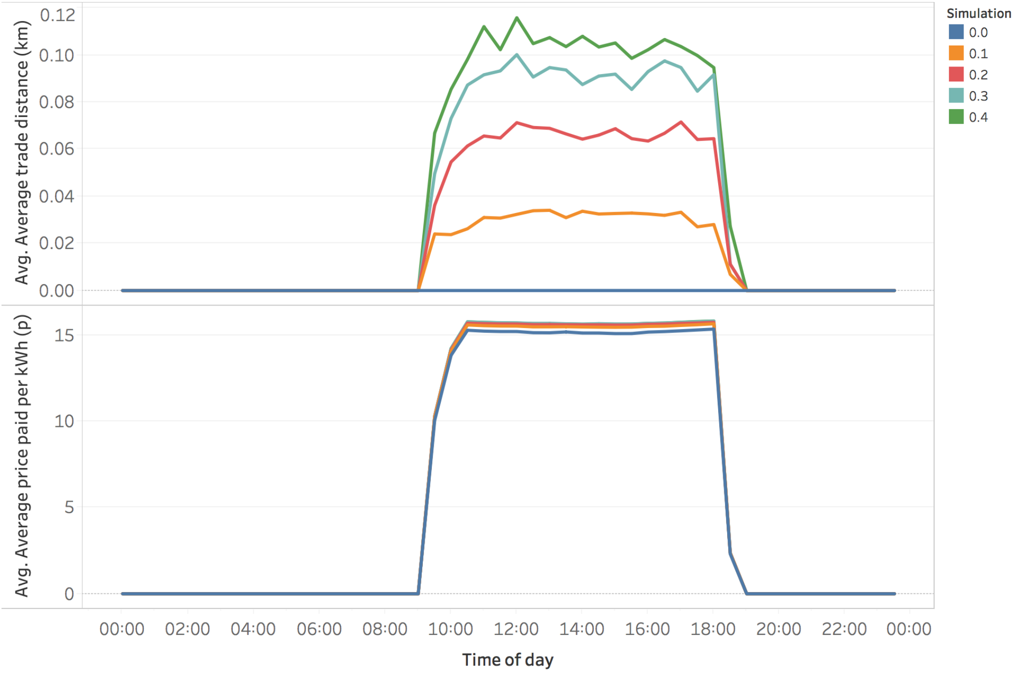

FIGURE 7.11. Prosumer distance preference: Average price paid per kWh and trade distance for test subjects that executed a trade.

FIGURE 7.12. Consumer price preference: Average trade distance and percentage of demand satisfied for test subjects.

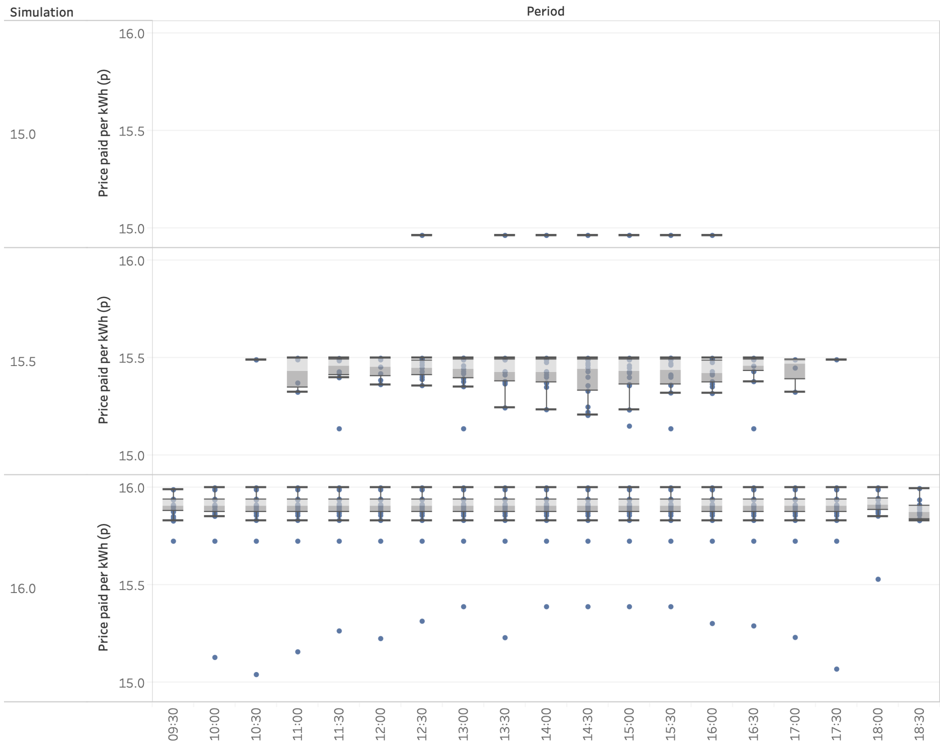

FIGURE 7.13. Consumer price preference: Distribution of price paid per kWh as price preference was varied.

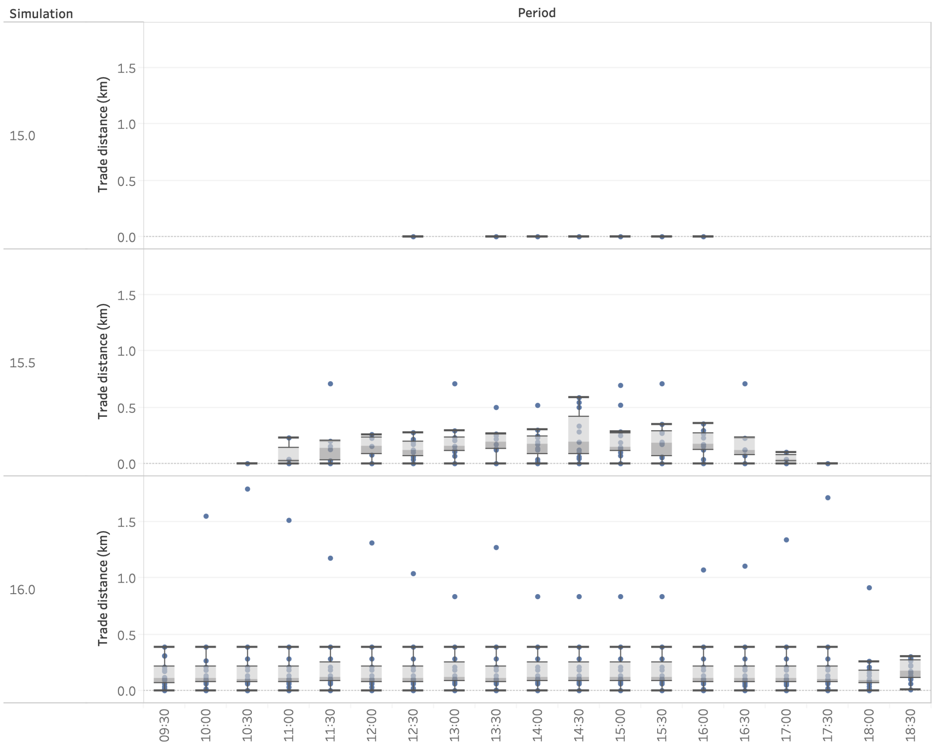

FIGURE 7.14. Consumer price preference: Distribution of trade distance as price preference was varied.

Simulation	Average price paid per kWh
15.0	14.9643
15.5	15.4219
16.0	15.8770

TABLE 7.2. Consumer price preference: Average price paid per kWh for consumers that executed a trade.

We can also see from Table 7.2 that, as the price they are willing to pay increases, they are charged more for their electricity, paying an average of 14.96p/kWh, 15.42p/kWh and 15.88p/kWh for 15p, 15.5p and 16p price preferences, respectively. This is a trade-off between achieving more of their objectives and spending more, and it again shows that to increase their control over one property they must sacrifice other properties.

7.4.4 Generation type preference

Objective: Ensure that the type of energy requested is prioritised for each market participant
Variation from base scenario: Consumers were selected randomly from the base scenario as test subjects and five simulations were conducted in which the test subject was assigned a specific generation type preference as their preferred option and all other generation type preferences were set to zero interest.

As shown in Table 7.3, in each test the trades found for the test subject were as expected, only matching them with their preferred generation type. We can also see, from Figures 7.15, 7.16 and 7.17 that although the individual was matched to their preferences, these trades were not necessarily equivalent for each. Anaerobic digestion saw test subjects match the highest percentage of their requirements, whereas solar saw test subjects purchasing from further distances. The design of the scoring mechanism enables this functionality through integration of the energy preference as a scaling factor into the score of the match. When an energy preference is set to zero, the final score will always be zero, prioritising any other match. Nevertheless, even a score of zero could be matched if there were to be no match of the preferred type available.

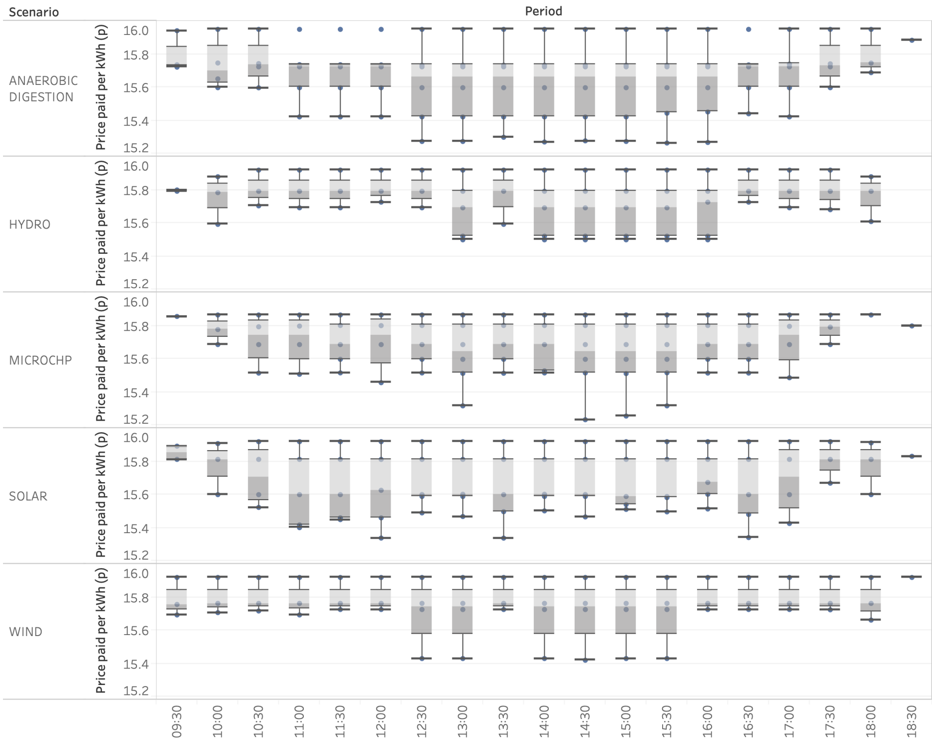

FIGURE 7.15. Generation type preference: Distribution of price paid per kWh for each energy scenario.

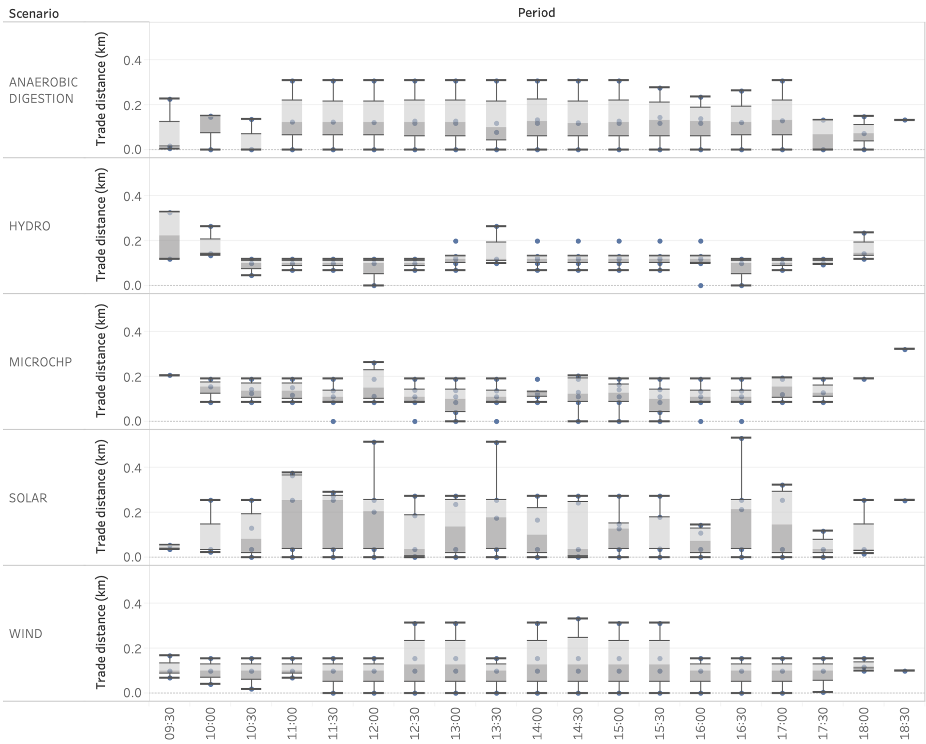

FIGURE 7.16. Generation type preference: Distribution of trade distance for each energy scenario.

Scenario	AD Trades	Hydro Trades	CHP Trades	Solar Trades	Wind Trades
ANAEROBIC DIGESTION	148	0	0	0	0
HYDRO	0	71	0	0	0
MICROCHP	0	0	118	0	0
SOLAR	0	0	0	127	0
WIND	0	0	0	0	73

TABLE 7.3. Generation type preference: Trades made for each energy scenario.

FIGURE 7.17. Generation type preference: Price paid, distance between traders and amount traded for each energy scenario.

7.4.5 Energy matching

Objective: Examine how well market participants are matched to their preferred type of energy
Variation from base scenario: To control as many variables as possible, the base scenario was not used for this. Instead, a unique scenario was generated with the following properties:

- All households were generated inside one postcode to remove distance effects.
- Prosumers were given excess production to ensure that availability was not a factor.
- Consumers were given one type of energy generation that was preferred, and the preferences for all other energy generation types were set to zero.

	Minute of Period																						
Simulation	08:30	09:00	09:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30	16:00	16:30	17:00	17:30	18:00	18:30	19:00	19:30
SS11EXCESS	0.0	41.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	46.4	0.0
SS11EXCESSNOAD	0.0	80.3	80.3	80.3	80.3	80.3	80.3	80.3	80.3	80.3	80.3	80.3	80.3	80.3	80.3	80.3	80.3	80.3	80.3	80.3	80.3	39.2	0.0
SS11EXCESSNOHYDRO	0.0	39.9	80.4	80.5	80.4	80.4	80.4	80.4	80.4	80.4	80.4	80.4	80.4	80.4	80.4	80.4	80.4	80.4	80.4	80.4	80.4	61.2	0.0
SS11EXCESSNOMICROCHP	0.0	78.9	79.1	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	78.8	78.9	0.0
SS11EXCESSNOSOLAR	0.0	80.2	80.3	80.2	80.2	80.2	80.2	80.2	80.2	80.2	80.2	80.2	80.2	80.2	80.2	80.2	80.2	80.2	80.2	80.2	80.3	71.3	0.0
SS11EXCESSNOWIND	0.0	80.3	80.4	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.4	71.3	0.0

FIGURE 7.18. Energy matching: Percentage of preferred trades found.

Whereas the energy preference scenario was created to look in depth at an individual's outcome as a result of changing their preference, this scenario was created to assess the market as a whole. Six variations of this scenario were created, one evenly spread between each type of generation and a further five that were each missing one type of generation but had other types evenly spread. The purpose of the first was to assess the energy matching, whereas the others were used to assess how the matching is handled when a participant's preferred energy generation type is not available.

The results are shown in Figure 7.18 and are as expected. All periods in which all types of energy generation were present were matched to 100% of an individual's preference. The first and last period of the day did not meet this level due to sellers having a significant excess, but not all sellers generating electricity at those times. This meant that sellers and buyers would be matched out of their preference until sellers had sold all production. The same applies in the five scenarios that had a missing energy production type. With five types of energy preference evenly spread and only four types of generation, we would expect 4/5 (80%) of the consumers to achieve their preference and the remaining 1/5 (20%) to receive any excess. This can be seen in Figure 7.18, with 80% being matched to their preferred energy type in each scenario.

7.4.6 Fairness

Objective: Examine the outcome of the matching to ensure that those with similar preferences and household properties were matched similarly
Variation from base scenario: This scenario used a variation of the base scenario in which generators produced excess generation, the purpose being to exclude variations caused by consumers being unable to find a match for their demand.

As the algorithm performs an automated matching, it is important that it performs in a fair manner for all participants using it. To assess the fairness of the matching, market participants were grouped on a number of factors, and the trade results of each group were then analysed. The factors determining the grouping are shown in Table 7.4.

Property	**Groups**
Price preference	14-14.5p | 14.5-15p | 15-15.5p | 15.5-16p
Distance preference	0-0.5km | 0.5-1km | 1-1.5km | 1.5-2km | 2-2.5km
Distance to preferred sellers	0-1.4km | 1.4km+
Generation type preference	Solar | Wind | Hydro | Micro CHP | Anaerobic digestion

TABLE 7.4. Factors used to group market participants to assess fairness.

Identifier	**Generation Type Preference**
5	Solar
6	Micro CHP
7	Anaerobic digestion
8	Wind
9	Hydro

TABLE 7.5. Reference table to match identifiers with the respective generation type preference.

This grouping was performed on all buyers and resulted in 200 groups of buyers with similar properties. To assist with readability, the analysis groups will be referred to throughout the evaluation by a name defining the properties of the group using 7.5 as a reference:

```
<price>-<distance>-<distance_to_sellers>-<generation>
```

For instance 15.5-0.0-1.4-6 would be a group with a price preference between 15.5-16p, a distance preference of 0-0.5km, an average distance to their preferred sellers of 1.4km+ and a generation type preference for Micro CHP. To then understand whether the members of these groups had been matched similarly, a score was calculated for each buyer to indicate how well they achieved their objectives. These scores provide overall statistics about each group, namely the mean, standard deviation and median, that could be used to decide whether members of each group had been matched similarly.

This score was calculated using a scoring algorithm designed such that it would provide an individual score for each of the elements of the scoring and matching mechanism. The result was scores from zero to one indicating the accuracy of the energy match (E), price match (P), distance match (D) and demand match (R). An overall score (S) was also computed by weighing each evenly. Alongside the scores, the variation of each property value was also recorded, allowing a quick look into the variance of prices paid, trade distances and quantity traded. The equations used to calculate these scores for one particular buyer are as follows, using the notation shown in Table 7.6.

Variable	Meaning
T	Set of trades made by the buyer
T_i	A single trade
T_{i_q}	The quantity traded in a given trade
T_{i_p}	The price paid for a given trade
T_{i_e}	The energy type for a given trade
T_{i_d}	The distance between the buyer and seller for a trade
B	Buyer
B_p	Buyer price preference
B_d	Buyer distance preference
B_r	Buyer total demand
n	Number of trades made by the buyer
$EP(e)$	Energy preference of buyer for given production type

Table 7.6: Notation used for fairness scores

The total quantity traded by the buyer is:

$$Q = \sum_{i=1}^{n} T_{i_q} \tag{7.1}$$

The energy match score is the average of the energy preferences of all trades, weighted by quantity:

$$E = \frac{\sum_{i=1}^{n}(T_{i_q} \times EP(T_{i_e}))}{Q} \tag{7.2}$$

The price match score is obtained by dividing the total volume traded at prices $\leq T_{i_p}$ by the total volume of all trades for that buyer. We expect that score to be one for all buyers as our algorithm interprets the price preferences as hard limits.

$$P_i = \begin{Bmatrix} T_{i_q} & B_p \geq T_{i_p} \\ 0 & B_p < T_{i_p} \end{Bmatrix} \tag{7.3}$$

$$P = \frac{\sum_{i=1}^{n} P_i}{Q} \tag{7.4}$$

The distance match score is obtained by multiplying each proportion of the traded volume with one if $T_{i_d} \leq B_d$ and with B_d/T_{i_d} otherwise.

$$D_i = \begin{Bmatrix} \frac{B_d}{T_{i_d}} \times T_{i_q} & B_d < T_{i_d} \\ T_{i_q} & B_d \geq T_{i_d} \end{Bmatrix} \tag{7.5}$$

$$D = \frac{\sum_{i=1}^{n} D_i}{Q} \tag{7.6}$$

The demand match score is obtained by dividing the quantity traded by the total demand of the buyer.

$$R = \frac{Q}{B_r} \tag{7.7}$$

The final score is the average of the four score components above:

$$S = (E \times 0.25) + (P \times 0.25) + (D \times 0.25) + (R \times 0.25) \tag{7.8}$$

Alongside the scores, the variation of each property value was also recorded, allowing a quick look into the variance of prices paid, trade distances and quantity traded.

7.4.6.1 Price

The price match score for all groups was one with no variation. This is a result of the scoring and matching mechanism working effectively to prevent participants paying more than their preference.

Examining the final prices paid directly shows that some variation is present, but this is expected to an extent due to each group containing price preferences in a range of 0.5p, thus a variation of ±0.25p. The standard deviation we find is an average of 0.18p for all groups. However, there are groups with significantly higher standard deviation, with a maximum of 0.53p for the group 15.5-0.0-1.4-6. Looking further to understand the cause of this variation we can see in Figure 7.19 that 19 of the 26 standard deviations that are above the 0.25p threshold are from groups with a distance preference of 0.0–0.5km. From this we can understand that the algorithm is struggling to match those with more restrictive preferences, causing them to be matched more unevenly. This distance preference variance will be further examined while observing results for other fairness scores. Figure 7.19 also shows that while this is more variation than expected, the variation relates to a coefficient of variation of less than 3.5% for all groups.

7.4.6.2 Distance

The variation observed earlier for buyers with restrictive distance preferences can be seen again when examining the distance match scores. The mean score for all groups was 0.9897 with a standard deviation of 0.03706, which is a higher standard deviation than all other fairness scores under consideration. Figure 7.20 shows that the distance preference is the culprit of the high mean standard deviation: Those with a distance preference of 0.0–0.5km achieve a mean of only 0.95737 with a standard deviation of 0.1477, while all other groups attain a minimum mean of 0.996 and a maximum standard deviation of 0.0167. These scores related to a coefficient of variation of 0.1571 for those in the 0.0–0.5km distance preference group.

To understand the root cause of this issue, the individuals in the groups were investigated further. Figure 7.21 shows the distance match score in relation to the distance preference of

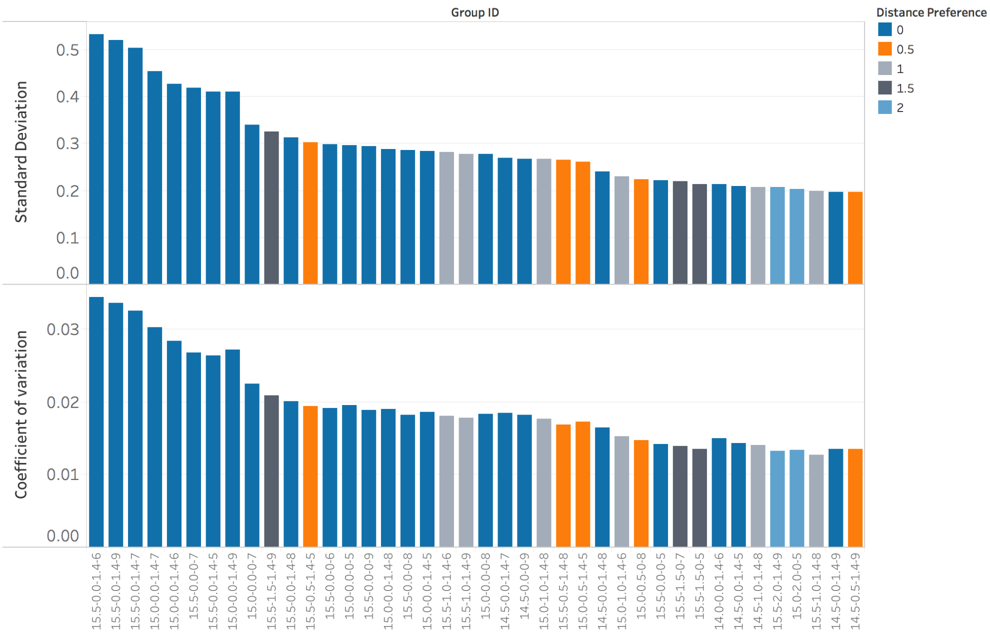

FIGURE 7.19. Fairness: The 40 highest standard deviations and their coefficient of variation for price paid.

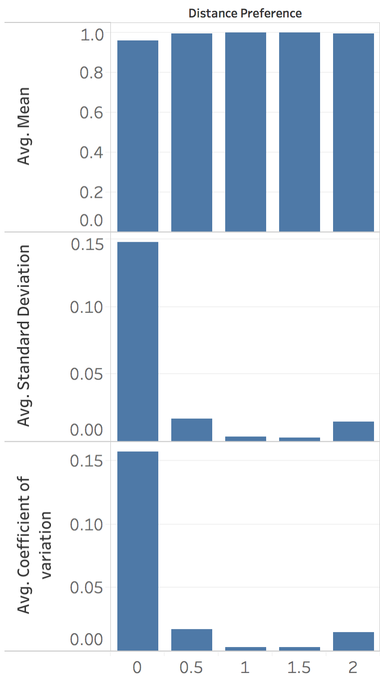

FIGURE 7.20. Fairness: Standard deviation, mean and coefficient of variation for distance scores broken down by distance preference.

each individual in the four groups with the highest standard deviations in their distance match scores. We notice that in each group, there are only few individuals scoring much lower than others, greatly affecting the mean. Each of these have a very low distance preference < 0.1km, and investigating further we find that for all of them the closest seller of their preferred energy type is outside of their distance preference. This allows us to conclude that the issue is caused by the restrictive nature of their preference and the lack of availability to meet their requirements. The preferences of these individuals cannot be met, and the algorithm performs poorly for these buyers as a result.

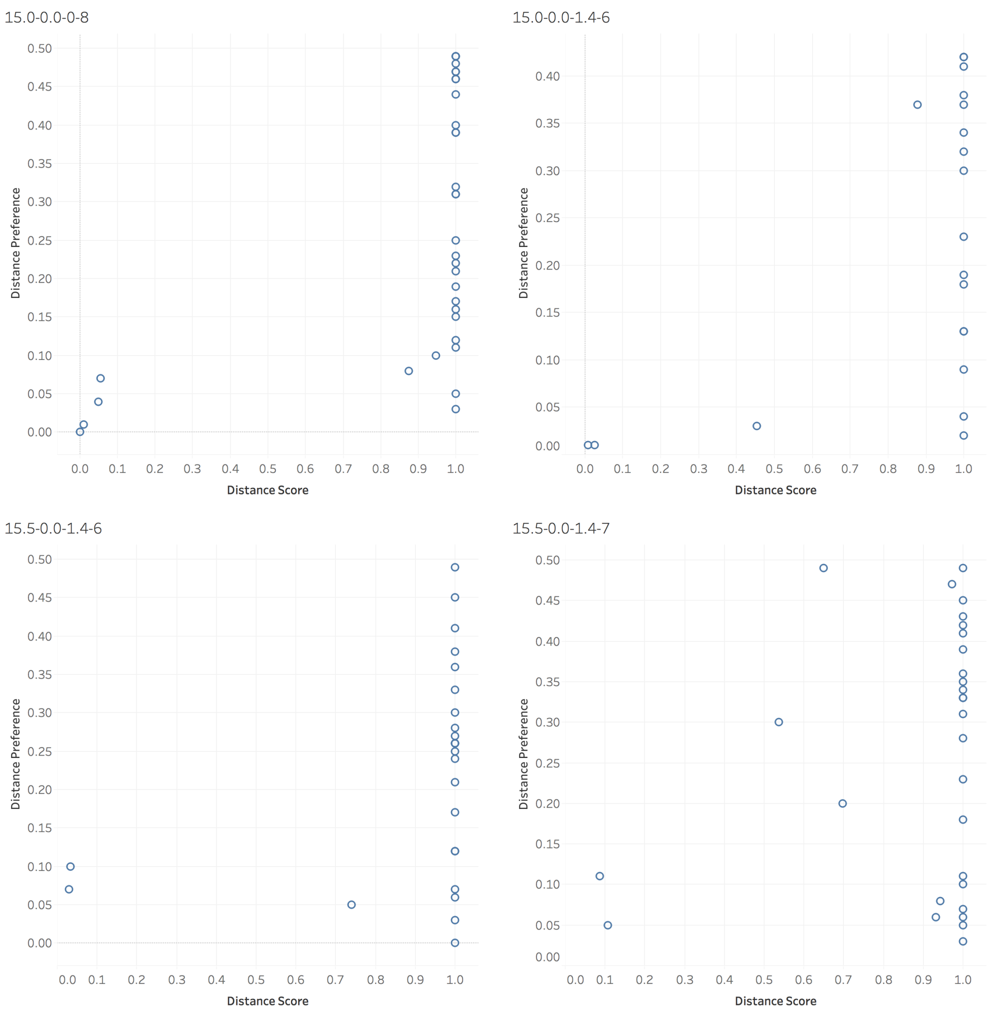

FIGURE 7.21. Fairness: Distance match score versus distance preference in the four groups with highest standard deviation.

7.4.6.3 Energy

The energy match score for a buyer indicates the percentage of preference for the trades made with respect to the energy type that was traded. The mean score of all groups was 99.28% with a standard deviation of 2.26% and we notice that the effect of restrictive distance preferences is still visible, but to a lesser extent. The mean standard deviation of the 0.0–0.5km group is 4.712%, in comparison to a maximum of 1.91% for any other group. In this case there is no threshold that we would expect the matching to produce, but it can be seen that in some groups this standard deviation increased up to 10.04%. Similarly to the analysis of distance match scores, these groups contain only few individuals with significantly lower scores that greatly affect the average. The same method was used to understand why some participants scored so differently. The four groups with the highest standard deviations were picked and the individuals in the groups analysed. It was found once again that those scoring poorly were those that had preferences that were unattainable, namely having a distance preference lower than the minimum distance of a seller of their preferred energy type. We can again conclude that the algorithm performs unfairly in scenarios where some participants have preferences that cannot be met.

7.4.6.4 Overall

This investigation into the fairness of the scoring and matching algorithm has allowed us to determine that the algorithm produces fair outcomes regarding price match score for all groups, and regarding distance match score and energy match score for most groups.

The distance preference was shown to cause variance in groups with restrictive preferences. Individuals in groups with the lowest distance preference were not able to be matched evenly by the algorithm. This is caused by a lack of sellers available within the buyer's range that meet their requirements and thus trades over a larger distance, but with a more closely matched seller were found. This issue does not require an alteration to the algorithm, as it is caused by an unavailability of an individual's preference.

7.5 Discussion

The evaluation allows us to conclude that the matching and scoring algorithms are performing as intended with some small limitations regarding fairness. The automated algorithm provides control to the participants, with each component of the scoring mechanism – price, distance and energy – working effectively to find matches within an individual's preference. Throughout the evaluation it was noticed that all preferences come with a sacrifice, an intended consequence of an individual's increased control. This sacrifice comes in the form of altering the price or quantity traded as preferences are changed and ensures that those who are looking to achieve a specific objective must be willing to accept a consequence.

	Minute of Period																						
Simulation	08:30	09:00	09:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30	16:00	16:30	17:00	17:30	18:00	18:30	19:00	19:30
SS11EXCESS	0.0	100.0	99.5	99.4	99.5	99.4	99.4	99.4	99.4	99.4	99.4	99.4	99.4	99.4	99.4	99.4	99.4	99.4	99.4	99.3	99.4	100.0	0.0

FIGURE 7.22. Energy matching: Percentages of preferred trades found in initial test.

The caveat regarding fairness is a result of the algorithm being unable to produce fully fair outcomes when an individual's preferences are unachievable, which results in these individuals being matched outside of their preferences. It is expected that an algorithm cannot find a match where it does not exist, but limits may be required to the granularity of control that is given to participants to ensure that an expected result can be guaranteed.

It was also noticed that even small implementation errors could result in significant errors in the matchings produced. This will be discussed in Section 7.5.1 and demonstrates that any system like this, were it to be made available to the public, would need a large amount of scrutiny to ensure that it functions as intended or designed.

7.5.1 Issues encountered

When the energy matching scenario was first run, it gave results that were unexpected, with only ~99.4% achieving their preferred matches in the majority of periods as shown in Figure 7.22. It was initially suspected that this was a design issue, as it was designed that after initially matching for score, matches were subsequently compared by price. The reason this was significant is that due to the scoring mechanism, those with zero preference for a given type of energy would be given a match score of zero, but their price offering could still be higher than the other matches to that seller.

7.5.1.1 The zero order problem

This was discovered to only be part of the problem, however. After further investigation, it turned out to be primarily an ordering problem resulting from both design and implementation. The algorithm was designed to go through each of the initial matches, select the best, and start the process of a sale. There was an oversight, however, in that when this sale process was started it would disregard other sellers that are also trying to create a sale with that individual. This resulted in the last seller to interact with a buyer taking priority on the sale. This scenario exacerbated this problem by effectively giving all sellers excess production, meaning that a single seller could satisfy a large number of buyers. The combination of these resulted in the last sellers to interact with their preferred matches winning every sale in every round, continuing to win even when only their worst matches (scores of zero) remained.

After correcting for these issues, all tests were completed again to ensure that the solution had not affected the other properties of the system.

7.6 Limitations

The testing performed in the evaluation was limited to the pricing, scoring and matching mechanisms that are described in Chapter 6, and any change to any of these modules would require a retest to conclude that no element has been affected by the alteration.

The evaluation performed used a small district of the UK and thus these results are not validated at a larger scale. When scaling measures are implemented into the system, a large-scale evaluation would therefore need to be conducted.

The dataset on which the household imports and exports were based was taken from purely solar households and as such, while the conclusions are valid, the timings discussed are likely to be different when based on multiple generation sources.

To generate the base scenario, preferences were randomly generated and may not reflect the way that real market participants would act when given control of their trading.

7.7 Summary: Algorithm analysis

Chapter 7 evaluated the performance and effectiveness of the algorithm presented in Chapter 6. Real geographical data and electricity data was used to produce scenarios in which the algorithm could be simulated to assess each aspect. This evaluation demonstrated that the algorithm provides an effective trading mechanism that matches uses fairly based upon the preferences they have set. In Chapter 8 we will further evaluate both the algorithm and the platform through the use of real-world case studies.

Chapter 8

Case studies

With the platform developed and tested within a simulated environment, it was necessary to evaluate it in a realistic setting. This was completed using two preliminary case studies, each assessing a different feature of the platform's design. A customer trial was established involving multiple stakeholders and residents from a flat building in Brixton that assessed the flexibility of the architectural design of the platform as well as demonstrating the technology in a real setting. A deployment was also completed inside the University of Bristol, assessing the systems capability to integrate within existing monitoring infrastructure.

8.1 Validating deployability of the ETP: University of Bristol case

The UoB case study was designed to evaluate the integration of the ETP into a live setting while providing validation of the preference-based trading algorithm. The University of Bristol (UoB) was used as a testbed for this deployment, using their existing building management systems to provide data. UoB has a number of generation assets, including a Combined Heat Power (CHP) system and multiple photovoltaic arrays throughout the campus, as well as significant energy consumption. This allowed the campus to be modelled as a self-contained village for the purposes of this study.

8.1.1 Objective

The assets within UoB are connected as a microgrid, with a large number of buildings, it's own generation and a single point of connection to the grid. This is currently managed through the use of energy monitoring on each device in the network, feeding data to a central building management system. This case study explores the use of the ETP as a means to provide a commercial energy management solution built upon their existing infrastructure and providing increased transparency from source to end-user within their site. This implementation within a commercial environment allows us to demonstrate the deployment of a P2P market to provide additional capability without disrupting any existing infrasturecture.

While a traditional approach to building management systems provides only a view of the generation and consumption across a site, the integration of trading managers allowed for direct interactions to take place between buildings. This provides the site owners with a view of how the generated electricity is being used and would assist with improving the efficiency of the site.

8.1.2 Trial

The ETP platform as described in Chapter 5 was used within this trial representing each building within the site as an individual household. Buildings from the UoB site were selected and their information collected from the existing building energy management system and fed into the ETP platform. Each was provided an account within the market, allowing preferences to be set as to the electricity that it wished to receive. This configuration allowed live trading to take place between the buildings and represented the site as a full deployment of the ETP platform assessing the deployability and pluggability of the system into existing infrastructure.

To further test the system, two managers (see 5.2.4) were deployed which were randomly assigned to each building. This allowed the system to evaluate the deployment of multiple models within a single trading platform.

8.1.3 Outcome

To integrate the ETP within the existing infrastructure an ETP-link module was developed that retrieved information in half-hourly intervals and provided it to the platform for use within trading. As the algorithm described in Chapter 6 was used to determine the trading, no further changes were necessary for the deployment to take place. The ease at which the ETP system may be integrated within a microgrid network like this, built upon the existing commercial energy monitoring systems demonstrates the potential for blockchains use as an institutional energy management solution. The addition of blockchain into these environments provides an additional layer of transparency and the integration of managers as a means to interact between buildings using set trading rules provides flexible control over energy sharing between buildings.

8.1.4 Learnings

During the course of this case study, a number of problems were encountered regarding accessibility of data and the reliability of the infrastructure in place to transmit data. The sensors installed throughout the site use the mobile network to transfer data to remote servers from which we were able to access it. However, the location of the photovoltaic arrays in rural fields results in an unreliable mobile network and as such data blackouts occur frequently. During these times, we are unable to automatically trade on behalf of these generation assets, and in a deployment interacting with the market this could cause both issues with trading and in balancing the grid. These issues were repeated in the CommUNITY case study and will be discussed further in 8.2.8.

8.2 Assessing adaptability of the ETP: CommUNITY case

The second case study assessed the adaptability of the ETP which was used to enable local consumption of the electricity generated within a single building. This building generates energy through a roof-mounted PV array. However, the building inhabitants cannot consume the generated energy due to the building's wiring limitations.

8.2.1 Study

The CommUNITY project brought with it a business case in which the ETP can be used to enable peer-to-peer trading between households within a single building. While the platform was initially designed for trading between independent households, this project required support for trading amongst a community that shared a single generation source. This trading model allowed us to evaluate ETP for:

- Flexibility: can the ETP cater for sub-markets with their own trading rules?
- Deployability: can the ETP be deployed to address a real world business case?

This study used real participants, allowing us to understand the social dynamics of a peer-to-peer environment, including the potential interest in such a market becoming a reality and the interactions that participants wish to have within this market. This deployment within a live environment also meant that the ETP had to account for and overcome the regulatory barriers to such a market, as well as consider the problems that need to be addressed for community-based and market-scale peer-to-peer solutions deployments.

8.2.2 Context

The self-consumption of electricity is simple to achieve in individual households and commercial properties that are able to install their own microgeneration. However, in residential buildings where tenant and landlord wiring is kept separate to enable individual billing, self-consumption would often involve rewiring the property. When multiple tenancy properties are built, each resident is given a separate connection to the electricity grid to provide accurate billing to each of the residents. Shared areas of the building are then given a separate connection, which is managed by the owner of the building. When a generation resource is installed in the building (such as a photovoltaic array), it will be connected to the owner's system, wiring it into the shared system of the building. As each resident is separately metered, this means that while the generation is in the same place geographically, the generated electricity may only be used by the shared consumption of the building and not by the individual flats themselves. The CommUNITY project - community urban neighbourhoods internal trading of energy - aimed to investigate, design and pilot a local P2P energy market that enabled residents to benefit from this generation.

8.2.3 Scope

The specific case that was used for the pilot study was a block of 62 two-bed properties in Brixton that had had a 37kWp photovoltaic array retrofitted by the building owner. The array was also part-owned by some of the residents (from now on the term *owner* will be used to refer to both the *primary owner* (i.e., main owner of the array and the building) and the *part-owners* for brevity). As shown in Figure 8.1, the wiring of the building was separated for each resident and in this particular case the generation was further restricted, solely powering the building's elevator with the remaining electricity exported to the grid. This wiring meant that over 90% of the generated electricity was exported directly to the grid. While the owner had established a power purchase agreement with an electricity supplier for 7p/kWh this setup did not maximise the value of the generation asset. The owner of the generation received only the minimum monetary value from each unit generated and the residents received no benefit at all. Therefore the objective of this project was to better utilise the available generation, maximising its benefit to both parties while also providing increased control and sense of community to the participants.

As the CommUNITY project involved interacting with the public and deploying an experimental technology, a number of partners were involved. The project was managed by EDF Energy and granted a regulatory sandbox status by Ofgem [156], i.e., the project could act outside of the current regulatory framework and access knowledge and guidance from Ofgem as necessary. The project partnered with Repowering London [157] - a not-for-profit organisation specialising in community-owned renewable energy projects - that worked with the community during the construction of the photovoltaic array and facilitated interactions with the residents. The project also partnered with University College London to provide additional academic input during the design and development.

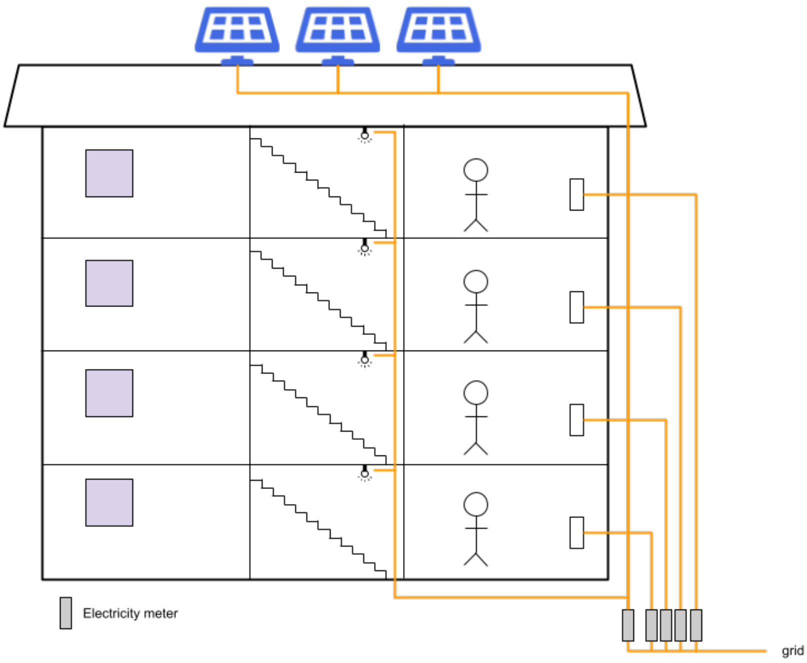

FIGURE 8.1. Current wiring within the CommUNITY flat building.

8.2.4 Solution

To provide the CommUNITY project with the generation sharing capability they had envisioned, they had initially considered the various rewiring options that would allow the generation to be distributed amongst the residents prior to reaching the grid. Using a rewiring approach would avoid any regulatory issues, but would introduce limitations and cost to the project. Minimising any changes necessary to the building's wiring infrastructure was therefore considered vital to ensure the system retained flexibility whilst also maximising the applicability to other buildings in similar scenarios if it were determined to be a successful model.

The ETP presented an alternative, non-wire option, using the concept of "virtual trading" whereby residents would trade as if direct wires existed, instead using a platform to record and settle these trades at a later date. This allowed for the simplest installation by removing the need for altering the wiring in the building but is not considered by current regulation. A DNO would be required to operate and maintain the network, but residents would retain the flexibility to join and leave the community as necessary. In this system, electricity meter data would be collected at source and fed into a separate trading mechanism that would determine the distribution of excess electricity generation amongst the residents. At predetermined intervals, this trading information would then be used to adjust customer bills to reflect their interactions in this secondary market. This structure was named as NW1, and the final wiring structure used in the CommUNITY project is shown in Figure 8.2.

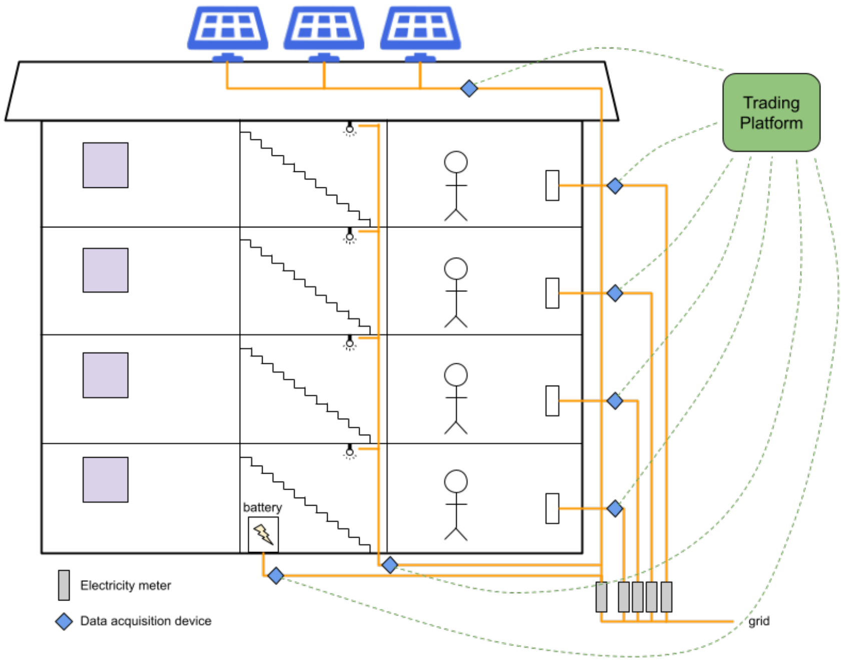

FIGURE 8.2. Wiring required in the CommUNITY flat building for model NW1.

8.2.5 Research objectives

To support this model within the building, the ETP was used as the infrastructure on which to build a P2P market that would support automated trading between the residents using preferences as a means to determine trading outcomes. To achieve this, the project set out to address a number of objectives:

- To design a replicable, local energy market model which can help deliver future community energy schemes
- To deliver savings to consumers while providing wider community benefits
- To demonstrate the efficacy of a peer-to-peer local trading platform
- To demonstrate the application of blockchain in enabling local energy markets
- To conduct research on the key drivers and enablers for consumers to engage into a local energy market based on peer-to-peer trading
- To assess the impact of community self-consumption and peer-to-peer energy trading schemes on energy salience and engagement with energy and energy services
- To test consumer engagement and response in a peer to peer energy trading trial and provide robust evidence outputs for government and industry

To ensure that the project would meet these objectives a number of research questions were also established that the trial would set to answer. These were divided into two main areas: technological, investigating the applicability, deployability of blockchain technology, and the use of the ETP system to provide this secondary market; and social, understanding the social implications of a community peer-to-peer trading scheme:

1. Technological:
   a) What are the implications of using blockchain within a real world application?
   b) What considerations must be made when deploying a P2P trading market?
   c) What changes are necessary to the ETP infrastructure support the CommUNITY trading model?
2. Social:
   a) Do participants alter their behaviour when provided increased control over their electricity? What do they change & why?
   b) Do participants in this P2P market feel more direct ownership over the photovoltaic array?
   c) What are the co-benefits? Is there an impact on social cohesion or well being?
   d) What are the particular opportunities for urban communities?

To answer these questions, a platform was required that enabled the residents to interact with one another to use and share the excess electricity to benefit both the owner and the residents. This involved establishing reliable data connections to each property, developing a pricing model that would result in both parties profiting, creating an algorithm that simplified the process of trading amongst each other and deploying the platform in a live environment.

The platform that was required to enable the trading inside this project had quite separate requirements from that of the ETP. The ETP system was designed as a wholesale market replacement platform that would maximise control to the participants by removing intermediaries between themselves and the market. The CommUNITY project, on the other hand, was an intermediary driven project using a facilitating supplier to determine the final outcome of trading and to bill users based on their interactions. This allowed the ETP to be tested for its architectural flexibility, demonstrating that community markets could exist within the same framework.

8.2.6 Platform

This section will discuss the requirements of the CommUNITY project along with the changes required by the ETP to meet the needs of the project and allow the platform to exist inside the current market structure with a discussion on the factors that were discovered that would need to be addressed on a wider scale for peer-to-peer trading to be realised.

8.2.6.1 Trading

As part of the ETP, pricing was used as a control mechanism, to determine the trading that will take place within the market and as such, the market would be competitive. CommUNITY, however, used a fixed pricing structure which focused on the social-element of peer-to-peer interaction where participants were only given the options to 'share' or 'sell' their electricity. This pricing mechanism therefore means the trading decisions will be purely based upon user decisions.

Trading will be divided into half-hourly trading periods to remain inline with the wholesale market and reflect the time-based nature of the electricity being traded. In each trading period, the generation of the photovoltaic array will be allocated equally to each of the participants, with any remainder exceeding total participant demand being exported to the grid. Participants will then first use the maximum amount possible of this allocation to meet their own demand. Any remaining allocation that is not consumed by the participants demand may then be traded within the market. Participants can elect to either share this excess to a particular individual or into a community pot that any participants may use or to sell their excess to another participant. To ensure that this platform remains beneficial for all involved, the pricing is fixed such that participants pay 7p/kWh (equal to the PPA price) to the PV owner for each unit allocated to them, each share within the system is then also fixed at 7p/kWh, such that a share is providing the electricity at cost to the receiver. A sell on the other hand is priced at 8p/kWh so the participant with excess earns a small profit.

8.2.6.2 Algorithm

The algorithm developed as part of the ETP was therefore not applicable to the CommUNITY project. The algorithm designed for the ETP was designed to provide individuals with a means to source locally generated electricity from specific generation sources within their preferred price range. Inside the CommUNITY project, residents were located within the same building with only one generation source to share amongst themselves. Along with this, the pricing model that had been developed was unique to this business case. The CommUNITY algorithm was thus developed as a separate manager implementation allowing it to be easily plugged into the platform.

This provided confirmation that the manager structure was a viable means of providing individuals with a choice of algorithm within the system and also demonstrated a feature that was not intended. In scenarios such as this, the individuals are able to use a separate manager to determine their internal trading outcome, while the building as a whole was still able to register

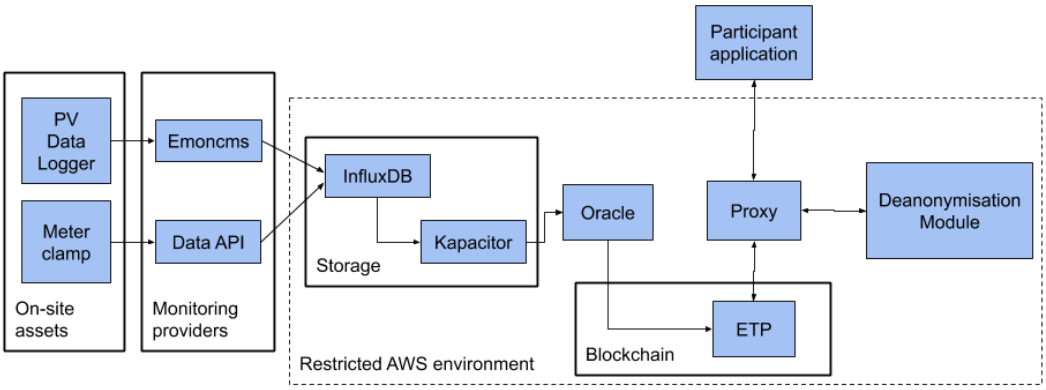

FIGURE 8.3. Final architecture used within the CommUNITY project.

with another manager to interact with the wider network. Using the manager system in this way allowed tiered structures to appear inside the platform and was discussed in 5.4.1.

8.2.6.3 Anonymisation

One of the major additions to the CommUNITY system which was not present within the ETP was the objective to provide a sense of community. When designing the ETP it was considered that privacy was a key factor when interacting with a peer-to-peer market, and as such, the system was built to minimise the possibility of identifying an individual. Instead, relying on participants to interact purely based on their energy preferences.

Alone this could be simply addressed by the addition of a deanonymisation module that would essentially work as a lookup table, mapping a user's identifier with their personal information. While providing this personal information though, data anonymity was required in order to be compliant with the privacy regulations. This requirement was primarily due to the "right to erasure" that came into force with Article 17 of General Data Protection Regulation (GDPR) [158]. Typically, deleting the entry in the lookup table would suffice, as the data would be moved from pseudo-anonymous status to anonymous status. This was not possible within this system, as data inside the ETP is only pseudo-anonymised and the data is stored using a blockchain thus removing the possibility of deletion, this meant that revealing a blockchain address at any point throughout the process would make the deletion from our lookup table worthless. To resolve this problem for the project, two methods were used. Firstly, an intermediary module was built that ensure that all interactions between accounts were performed using an off-chain identifier which was then mapped into their on-chain address. Secondly, the blockchain used was made private to prevent individuals from looking into this history of any participants in the market. The final architecture used within the CommUNITY project is given in Figure 8.3.

This solution would not suffice inside a live ETP system and this issue of "right to erasure" would need to be further investigated for blockchain-based trading mechanisms. Other researchers have begun this, through studies into anonymous peer-to-peer trading interactions [74, 115].

8.2.6.4 Data

The ETP was designed around the use of smart meter data to minimise the barriers to entry for participants, however in practice using smart meter data within a live environment was not possible at this stage of the smart meter rollout. Along with rollout still ongoing, the use of smart meter data is also heavily restricted and as such would also introduce a number of data privacy limitations. This issue of using live smart meter data within the platform also extends to the ETP system as a whole and will be discussed further in 8.2.8. The project instead chose to use third-party electricity meters (hereby referred to as clamps) and an additional ETP-Link module was developed to provide this data to the Oracle.

8.2.7 Pre-trial

An internal pre-trial was conducted prior to the public trial going live in Brixton and due to time constraints will be the only experiment documented within this dissertation. The full trial will be documented at a later date once launched.

The pre-trial was operated as two periods of two months and consisted of six participants providing real-time electricity data using the same devices that would be installed as part of the final trial and the real-time electricity data from the PV panels installed on the building in Brixton. This pre-trial replicated the final version of the system with the only difference being that the participants were not located within the building and thus any trades were theoretical. Unfortunately due to the nature of a pre-trial, the social interactions that took place are not representative of a real-world environment and as such outcomes regarding the preferences are limited.

8.2.8 Discussion

Throughout the process of designing, constructing and trialling this P2P platform, numerous hurdles were discovered that will have an impact on P2P markets going forward. This section will detail how these were overcome for the purposes of the CommUNITY project and the questions that this will introduce to the ETP system.

Access to real-time smart meter data would be mandatory for a P2P market to become widespread but data privacy concerns will need to be addressed.

Access to electricity consumption and generation data and the usage of this data to provide a P2P market was identified as a major blocker. In this trial, we provided trial participants with electricity clamps to provide access to their electricity meter data due to the unavailability of smart meter data. This alternative is not scalable, and the use of smart meter data would be necessary for a large-scale deployment to be successful, removing any barrier to entry for participants and therefore encouraging wide spread use. However, when this smart meter data is to become available, accessing and using this data may prove difficult. Energy suppliers that do have this data available are sensibly restrictive of this data to provide data privacy to their customers.

This question of data privacy will be the most significant question to answer in regards to P2P markets. For the market to provide complete transparency and control, electricity data would need to be visible along with the respective building that it relates to in real-time and also likely within future predictions. As briefly mentioned above, researchers are already investigating the means by which this participant interaction can be facilitated while retaining privacy, but in all cases this comes at a cost to flexibility, transparency or control.

While a public blockchain would provide the most trust and transparency, the concept is not compatible with government policy.

As with the smart meter data question above, this data privacy concern extends to the storage of the data and preferences due to the nature of the personal data they contain. A public blockchain would be the clear choice for providing a public platform such as this, to guarantee trust and transparency to the participants. However, the classification of electricity data as personal data means that it must comply with the EU GDPR [158] regulation including the 'right to erasure' allowing participants the ability to have their information deleted upon request.

Due to the design of blockchains, a traditional approach will remove this possibility of deletion and make all data within the system public. Unless an alternative solution can be found, a consortium blockchain managed by a government approved group or the government themselves. Alterations will still be necessary to the blockchain mechanism to allow compliance with the GDPR right to erasure, but this may come simply in the form of an obfuscation layer to prevent personal data being exposed.

Data is not always available, data blackouts must be handled effectively.

The presumption within many P2P platforms, as found in the systematic review in 3.3, is that perfect data access is provided to inform the trading. In practice, data will not always be available for all participants during each market period. A simple equipment failure or the data transmission network having an outage will result in 'data blackouts' for participants.

Data blackouts could cause major issues. Within this trial, the impact of a data blackout for one or all of the participants was severely limited, as the trading mechanism could be envisioned as a settlement mechanism (balancing does not need to be considered), thus the settlement can be completed at a later date when data is available and electricity supply and the grid will not be affected. In a complete P2P market, however, data blackouts could have a major impact on the settlement of the market. Without the data required for market participants to effectively trade with one another, the system reverts back to the state of the current energy system whereby settlement is completed at a future date using aggregated data. Handling these blackouts will be key to a robust deployment of a P2P market, and may result in the requirement for underlying contracts with energy suppliers to remain as backup.

Additionally, data blackouts will reduce the predictability of the system, which as the network becomes further reliant on DERs and real-time data could result in difficulties balancing the system. This again will require a backup in place to ensure stable supply throughout data shortages.

The addition of blockchain affects user experience and limits analytics.

While blockchain provides vital characteristics to provide users with increased control and ensure transparency throughout the system, its use within a live environment imposes limitations that affect both analytics and user experience. In a perfect world, blockchain users would each operate a node which would contribute to the network as a whole and provide local high-speed data retrieval. In practice, however, the majority of blockchain applications used by the general public will implement only a remote connection to a blockchain node, simplifying the system for its users but reducing functionality.

This decision has an immediate consequence on the benefits that blockchain introduces. While the blockchain component remains robust, using a remote connection places the reliance for the application back into the traditional computing environment. This can be partially negated with the use of backup connections built into the application itself, but does not completely mitigate the concern. However, solutions to this problem are being explored, such as mobile phones that are designed specifically to act as a node [159], and protocols such as the light client protocol [160] which see the phone remain directly in communication with the network without the need to maintain a duplicate state.

Additionally, the use of blockchain itself also introduces limitations to the capability of applications which may not be in line with a modern user's expectations. Current software that the public are used to interacting with use large data centres to store, analyse and serve large quantities of content quickly to users upon demand. This use of cloud infrastructure allows significant amounts of computation to be removed from the user's device, with devices acting purely as a display for this pre-computed information they receive. To provide a fully fledged dApp, this computation would instead need to be performed within the device itself. This problem is twofold: retrieving the data; and processing the data. Firstly, due to the aforementioned remote blockchain connections used in these applications, the retrieval of large scale data would over-time become increasingly expensive. In our trial of only four months, on-chain trading data for the participants as a whole grew to 70 megabytes, which can typically be considered a reasonably small amount of data, but when sent over the internet each time a user would like to compute analytics is both slow and expensive in regards to data transfer over mobile networks. Secondly, once received, the processing of this ever-growing data can also prove computationally expensive when compared to the traditional approach of simply displaying the information that is received. This is partially due to the data structures used within smart contracts and the block-based nature of a blockchain. For instance, analytics within the trial required retrieving all trades within a given market period. Whilst there is no complexity to the coding of this, by default blockchains will search all blocks within the chain for related data. As the chain grows, this search becomes increasingly slower, such that additional information must be stored to efficiently limit the search space.

To resolve these issues, we provided a proxy server between the blockchain layer and the application layer which handled this computation on behalf of the users and incorporated a caching mechanism to reduce computation and drastically improve the speed of data retrieval. This solution again works against the benefits associated with blockchain, relying on the traditional approach to maintain the interactions with the blockchain. This introduces another question that will need further research, whether users will understand the value of blockchain enough to cope with the limitations imposed by it.

The regulatory aspect of P2P is more flexible than originally thought, but also significant changes are still needed

Implementing this solution into a live trial allowed for an investigation to take place into the current regulatory system and the potential for NW1 to exist. It was concluded that there are a number of ways that NW1 could be implemented that regulation would allow depending on the desire for collective switching or the need for residents to retain their existing energy suppliers. This section highlights three of the most suitable methods for implementing NW1 that all fall within existing licence exemptions but would require changes to the Balancing and Settlement Code (BSC) as described.

8.2.8.1 Electricity facilitator umbrella

This option would require two electricity supplies to be present in the building (one for residents and one for the shared areas and the PV system). As the building is not considered as a “site” by the BSC, "netting" is only allowed on the energy costs. Instead, the building is considered a “complex site” and thus would require a "facilitating" energy supplier which the residents participating in peer-to-peer trading would be required to have meters registered with. This would allow NW1 to take place without the need for BSC changes.

8.2.8.2 Multiple electricity suppliers

The requirements of this option would be the same as for the ’Electricity facilitator umbrella’ but would also use multiple electricity suppliers. This would allow each resident to select their own supplier (host supplier) while the building as a whole would be managed by another supplier (facilitating supplier). The facilitating supplier would be required to submit an allocation schedule for metering purposes and cooperation between the different suppliers would need to be facilitated due to the increased consumption uncertainty that the host suppliers would be exposed to. This option is partly covered by the meter splitting / sharing arrangement but BSC changes would be required. While this would allow the residents to retain their current suppliers this would complicate the peer-to-peer trading due to the imbalance management and charges recovery that would need to take place between suppliers.

8.2.8.3 Deemed trading

This option would again require multiple electricity suppliers, allowing each resident to retain their current supplier but instead of suppliers managing allocation schedules, residents would freely interact and suppliers would then use deemed trades during the settlement period to handle balancing. This follows the current participation of customers into the provision of grid services directly to National Grid or through aggregation. With this option, residents would trade amongst themselves and the facilitating supplier would then be responsible for balancing through the submission of aggregated deemed trades between suppliers. The advantage of this method is that deemed trading can also be extended to other buildings and does not involve metering but transactions only.

Chapter 9

Discussion

This project set out to explore the creation of a future P2P electricity trading market and demonstrate the viability of blockchain as a means to enable this trading to broaden user choice and ease the creation and deployment of alternative markets. This chapter discusses the various concerns and open issues that the present research has encountered. These are the hurdles that remain on the path towards a P2P energy trading market.

9.1 Market Structure

The P2P electricity market envisioned by this project would redesign the current structure of the system so that each participant can act independently and directly with one another. This design would have significant impacts on both the interactions that individuals have with the energy system and the underlying model that is in place. The platform architecture and preference-based matching algorithm presented expand upon previous research and provide a contribution to the future of the energy system with the intent to provide a system that is: cost representative; transparent and demonstrably fair and collusion free.

Structuring the market in this way lessens the need for incentive mechanisms, allowing the owners of DERs to more easily integrate and trade their resources within the market. The generic nature of the architecture also allows the future market to support any number of trading models, including sub-markets such as community energy schemes and their connection into the wider market. However, prior to P2P electricity trading replacing the current market structure, there remain numerous hurdles before it will become a widely used mechanism for householders to manage their electricity.

9.2 Social Concerns

As discussed in 2.2.3.1, the current electricity system has been designed to minimise the knowledge necessary and effort required for end-users to manage their electricity and instead, the burden of pricing, balancing and regulation is the responsibility of the electricity suppliers. This design ensures that the public has the simplest means of accessing electricity, but results in a lack of knowledge, inefficient use of electricity and increased difficulty to balance and reduce the carbon intensity of the network. As discussed in 2.2.3.2, the commoditization of electricity is set to change and knowledge of one's own electricity will be increased. This can already be seen with the introduction of time-of-use tariffs from suppliers such as Bulb [161] and Octopus [162], which provides a monetary incentive to the general public for shifting their electricity consumption to lesser demand periods.

A P2P electricity market will extend further than any existing mechanism and require that the perception of electricity undergo a fundamental shift. Participants in the market will be provided with control schemes that are not currently available and an understanding of the exact source of their electricity along with each associated cost of receiving and using this electricity. This increased choice and knowledge will move domestic participants from their current passive consumer role to an active role in the market. This role change will have an impact on their perception of electricity consumption, allowing them to take charge of their electricity whilst also allowing the market to be more cost representative and have a more fine-grained approach to efficient management. However, with this shift, participants will require significantly more information and time to make effective use of this new market. The resulting impact is an increased burden to manage their electricity usage which could overwhelm participants, reducing the accessibility of the electricity system and limiting any benefits a P2P market introduces.

To counteract this increasing burden, this project proposes that any future P2P market will incorporate an automated approach to interactions within the system to reduce the complexity and barriers to entry for participants such as the algorithm described in Chapter 6. This automation though introduces risk, removing some individual control afforded to participants and returning to central points of control that determine the trading outcome. Further to this, each algorithm will, in turn, have proportionate control over the market itself such that owners of a widely used algorithm may be able to dictate the market. Ensuring that control remains within the participant's hands is vital to ensuring that the market remains collusion free and that a P2P market proves beneficial over the current approach. It should, therefore, be possible that algorithms may be developed by any interested party to ensure competition, are public and monitored such that they remain impartial and that participants may change freely between algorithms acting on their behalf to ensure control.

9.3 Pricing Concerns

Along with the consideration of social impact, P2P electricity markets will also greatly impact the pricing structure in place within the energy sector. While today, pricing for consumers is primarily determined in advance at a fixed-rate, a P2P market will instead see costs vary in line with the current market state during each market period and geographical location of the generating assets. This change will come in two main areas: the price charged by generators; and the non-energy costs associated with the maintenance and future development of the network.

Throughout this project, pricing has been considered as a means to determine matches between participants in the market. In a complete P2P market, little will change from this concept except for the need for generators to determine the price they wish to receive. As the market will be competitive between both domestic suppliers and the wider market, determining this price will fall to the automated systems in place for prosumers and again the solutions discussed above will be needed to prevent collusion or algorithmic monopolies. The fluctuations in the dynamically determined prices changing from one market period to the next however may have a larger impact. The previously discussed knowledge requirement in a P2P market will be expanded here, including the need to provide consumers with future price predictions within the market to adjust their demand accordingly.

The non-energy costs within a P2P market will undergo significant changes. In this project, they were used as a means to more accurately represent the costs of the network infrastructure and the resulting incentive to locally purchased electricity was used to assist the trading algorithm presented. As discussed in 2.2.3.1, the complexity of the current non-energy costs calculation is not compatible with the P2P concept, resulting in excessive post-trade settlement mechanisms. Instead, this project incorporated only a basic representation of this cost into the system, using the combination of a fixed charge per trade and a fixed charge per kilometre between trading partners. The final non-energy cost calculation will be significantly more complex and will play a crucial role within any P2P market that will be deployed.

The approach by which the non-energy costs are distributed will directly impact the final pricing between trading partners and therefore impact the incentive mechanism for encouraging the use of locally generated electricity. Determining these costs will, therefore, be related to the objective of the P2P market implemented. To maintain our objective of reflecting network usage more accurately, further research will be required to determine the most effective distribution model. Table 9.1 presents numerous high-level options that may be used moving forward.

These options would each have a different influence on the trading outcome. A *flat-rate* approach would see each trade considered as equal, which provides completeness to the list but does not achieve our primary objective of incentivising the purchase of locally generated electricity. *Infrastructure-based charging* would be the most accurate method for achieving our objective of fairly distributing infrastructure costs. However, while it is fair in regard to infrastructure

Method	**Description**
Flat rate	Distributing the costs evenly amongst all sales, applied per kWh. (£/kWh)
Distance rate	The charge paid for a trade increases linearly with the distance of the trade. (£/kWh/km)
Scaled distance rate	The charge paid for a trade changes non-linearly with the distance of the trade. (For example, £/kWh/km^x)
Infrastructure-based	Direct charging based on the infrastructure used in a given trade. For example, a charge paid for each trade as a calculation of the number of substations that electricity must travel through for a given trade.
Boundary-based	Boundary-based charging, incorporating multiple pricing structures, one inside that boundary, one outside.
Hybrid	Any combination of other charging methods. For example, a hybrid solution using a flat rate (base rate) + an additional charge per km, calculated using one of the other distance rate methods. (£/kWh + £/kWh/km)

TABLE 9.1. Non-energy cost distribution methods

cost, it has the potential of going further than intended in regards to incentivising local trades by creating arbitrary boundaries. For instance, an individual's next-door neighbour may be connected to a different substation than themselves such that they are not the best match. This type of distribution could result in discrepancies between different demographics, where more affluent areas - anticipated to have more microgeneration - are given a disincentive from trading to an adjacent poorer community. A *distance-based charging* approach provides a solution to some of these issues, creating a more open trading space wherein closer neighbours will always be the cheapest to trade with, but comes with the tradeoff of less accurately representing infrastructure costs. The final distribution model would likely be a hybrid solution that achieves a balance between each of the system objectives.

Alongside the method used to distribute non-energy costs within the market, the calculation of these costs must also be decided. While the distribution method tries to fairly portion the network charges to each participant in the network, the total network charges that are due must first be calculated or estimated. As the network charges are applied per trade, the method of calculating these could help to control and balance the network. An example of this would be to alter network charges throughout the day so as to give increased monetary benefit to those that generate in beneficial periods.

9.3.1 Fixed Pricing Option

The most simplistic approach for consumers would be to define the pricing structure in advance, such that the total cost may always be calculated for a given sale. This approach, however, would be significantly more difficult to establish and removes the possibility of using charges as an incentive mechanism, resulting in the non-energy costs not accurately representing the current market state.

9.3.2 Predictive Pricing Option

An alternative would be to make a prediction in advance of each trading period, essentially defining a dynamic but fixed for consumers pricing structure. In contrast to a fixed structure, this would require less upfront input, but would need continual involvement and distribution to participants. This would remain straightforward to consumers while also more accurately representing the current market state.

9.3.3 Post-calculated Pricing Option

A more accurate approach is to calculate the total network costs once the trading has completed. This would require that each trade made during a market period remain provisional until a later time in which an adjustment can be made to meet the infrastructure costs for that period.

9.4 Blockchain Concerns

The use of blockchain was suggested throughout previous research (see 3.3) as a promising technology that may enable future P2P electricity markets but limited research was conducted to evaluate its potential. This project set out to investigate the technology further and determine its viability to underpin these markets.

As detailed in 3.1, the design of blockchain technology enables it to provide truly P2P mechanisms in which the interaction between participants requires no additional input from a third-party to guarantee or provide escrow to those interacting. Using blockchain as the technology to underpin the platform provides characteristics not currently possible using traditional techniques, such as automated contract creation and enforcement. These characteristics form the basis of technological trust, in which participants may rely wholly on the technology itself to guarantee and enforce the trading between one another, rather than require the reliance on trust between each of the trading partners. Alongside this, the structure used by blockchain to store data also provides us with other beneficial characteristics. Maintaining a record of each transaction with the network and duplicating this record across nodes in a publicly visible network ensures that the network is difficult to manipulate by bad actors and ensures that there is no single point of failure within the system. These benefits make blockchain appear as a mechanism that is suited perfectly to the deployment of a P2P market.

To assess the viability of this technology in practice, a demonstratory blockchain-based platform was developed to provide an open market in which complete control is provided to the participants. The platform enforced the rules of the market, allowing trades to be made directly between participants while incorporating an automated settlement mechanism. The presented platform provides an insight into what could be representative features of a future P2P market in which blockchain is used as the underlying technology.

Unlike previous researchers who focused on providing a single solution, we focused on the provision of a **generic platform architecture** in which third-parties can provide their services and generate competition within the automation choices. We observe that **no single trading algorithm is suitable for all contexts**, as demonstrated by the needs of the University of Bristol vs CommUNITY projects, where the trading peers had varying goals and priorities. Instead, a plethora of algorithms within the same space should be provided to *allow rapid switching and alterations, such that control is retained by the peer trading participants with minimal input and effort* required from them.

Similarly to the addition of automated trading to simplify the process for users, a consideration must be made to account for the complexity of the technology itself. Blockchain proves to be a complicated system for both designers and the users of the final product and to provide the maximum benefit, it must first be understood. To provide this, guides must be given alongside any blockchain deployment to inform users of the technological concepts and the means of best interacting with it. This may however not be enough, as the **technology is not yet user friendly** and typical features that users will expect, such as 'password resets' do not yet exist. This blocker may reduce the use of blockchain in the future to simply an alternative backend database system that users need no knowledge of for the benefits to be realised.

Upon evaluating our blockchain platform within both simulated and empirical studies, the features it provides were found to bring with them additional limitations that could also hinder its future use. The use of a **public consensus protocol severely impacts the scalability** and throughput of the system, such that a public blockchain in its current form would not suffice if the market were to be used on a wide scale. The publicity of the data stored within a blockchain also proved to introduce issues along with the benefits discussed above. While complete **auditability prevents collusion** and removes bad actors, data privacy concerns are raised due to the **lack of a deletion process** along with the **public storage of personal data**. The complexity of the mechanism also proves to become a barrier to entry for the average user along with limiting the user experience of the final system. This complexity makes retaining the beneficial properties of a blockchain in a full deployment with users difficult as a **balance must be struck between usability and user control**.

In its current form blockchain does provide a viable solution for the creation and deployment of a P2P electricity market, however the design of the system must be carefully controlled to retain the benefits it provides while also following regulations and remaining scalable. In the domain of energy trading, currently use of a public blockchain is not a viable option for practical use due to **throughput required** by a large scale market and data privacy concerns. Even with a non-public blockchain, the current data privacy **regulations limit the potential functionality** of the P2P trading systems.

Before blockchains can be used within a practical large scale deployment, further improvements are necessary to address the technology's **scalability concerns**.

Chapter 10

Conclusion

In this final chapter, we return to the original objectives of this research, reiterate the core contributions from this research and provide recommendations on the future work necessary to establish P2P electricity markets.

10.1 Contributions

This research project set out to investigate one potential future of the electricity market, a P2P trading system in which the end-users of electricity are able to negotiate and trade directly with the electricity generators. This alternative approach to the electricity market aims to address issues that are arising due to the supplier hub model proving to be an ineffective means of integrating small-scale generation sources into the market. The use of a P2P mechanism is thus seen as a design to better integrate DERs into the wholesale market and provide an incentive for the uptake of further renewables-based generation to meet worldwide climate objectives.

To explore this model, the objective of this research was then to understand how it will work in practice, and how it can be used to provide additional benefits to the market. Specifically, we aimed to maximise the control provided to participants in this new market and to provide an incentive to encourage the use of localised renewable-based microgeneration. Further exploring the underlying technicalities of the model, we looked to understand the viability of blockchain as a technology to underpin the new system as a truly P2P market.

A review of the current state of research was conducted, including a systematic review of academic literature, a review of the existing industrial solutions and an investigation into blockchain and its usage within this field. This review highlighted that previous research had focused on the objectives of balancing the network, optimising the use of available resources and cost minimisation using transactive approaches. The solutions to achieve these objectives consisted of single-objective mechanisms that provided little additional control to their users relying on dedicated third-parties to manage interactions within the market. It was also seen that while many researchers had suggested the use of distributed ledger technology, only limited research was conducted into its potential to provide the necessary mechanism to enable this market. We concluded that large areas within the field of P2P electricity markets had been overlooked and did not provide the necessary investigation into the participant benefits, transition period, social and regulatory aspects, and pricing mechanisms needed for a P2P market to be deployed. To begin to address these areas, this research focused its efforts into two interconnected streams. A blockchain-based platform that provides an environment in which any number of P2P models can co-exist and a preference-based many-to-many matching algorithm to provide user control and encourage the use of locally generated electricity.

The generic blockchain-based P2P electricity market architecture presented in Chapter 5 demonstrates the viability of blockchain as a technology to underpin the future market while also addressing issues identified through our literature review. This platform shifts the focus from single-objective mechanisms into a generic architecture in which multiple P2P models can operate simultaneously. This allows both manual and automated trading mechanisms to operate and provides additional control to the participants of the market whilst also enabling multi-level market architectures to exist. The design presented can act as the base of a future P2P market, enforcing trading rules while remaining extensible and adaptable to the numerous current and future P2P trading models.

The many-to-many trading algorithm presented in Chapter 6 provides one trading model that operates within this platform to address the need for automated control while providing an incentive mechanism to encourage the use of locally produced electricity. This algorithm provides participants with control over the generation type, price and location of the electricity they receive while removing the need for continual interaction with the market. This mechanism was evaluated through an agent-based simulation of regions in the UK using real electricity data. We demonstrate that this algorithm provides participants with the electricity preference they require without introducing bias to any particular group.

10.1.1 Research questions

To conclude this research, this section will now refer back to the original research questions posed in 1, provide an answer to each and detail how they have been addressed within the project.

1. How can a peer-to-peer market be designed to provide maximum control to its participants?

These components work in parallel to answer our initial research questions. To provide maximum control to the participants of the market, they must be able to trade freely and fairly.

The platform presents an approach that allows an individual to manually interact with the market, use an existing trading mechanism or develop and use their own. This allows complete control over the trading approach that participants may have with the market. In addition to this, we foresee that the average domestic participant will not have the time or knowledge to make effective use of a P2P market given the small monetary benefit it can provide. To address this further, the algorithm we have presented intends to provide participants with control over the price, location and generation type of the electricity they receive whilst minimising the necessary interaction with the system. This ensures that the benefits of a P2P system can be easily accessed. The trading algorithm was evaluated through agent-based simulations to ensure that it matches participants using the preferences given without introducing bias to any particular group. In addition, the market can provide a number of alternative trading models allowing the participants to choose which suits them best. For instance, the algorithm discussed in Chapter 6 or the model used within the CommUNITY case study in Chapter 8.

2. How can a software platform and a trading algorithm be implemented to enable and encourage localised renewable-based microgeneration within a P2P electricity market?

To provide a P2P market that encourages the use of locally generated electricity requires a combination of two elements. Firstly, as discussed in 2.1, the non-energy costs in a future P2P system must provide its participants with insight into the detailed costing of the electricity they are purchasing. This will require that the market changes the perception of electricity for its users such that trades within the system can be differentiated by the cost to the network they introduce. Secondly, to make the purchase of local generation accessible to the average user within the system, an automated approach must be provided that incorporates an incentive scheme based upon these differentiated electricity sources. The platform and algorithm presented through this research incorporate these components providing market participants with a trading system that embeds this distance-based incentive.

2a. Is blockchain a viable solution for the creation and deployment of this market?

The discussion regarding the applicability of blockchain within a future P2P market was concluded within 9.4. This project used blockchain as a means to provide an extensible, modular platform that enabled third-party mechanisms to be incorporated and provided to participants while enforcing underlying trading rules in a transparent manner. To provide this mechanism without the use of blockchain would require vetting mechanisms for the third-party solutions and the trust of the participants in these third-parties. This project demonstrates that blockchain is a viable solution to creating and deploying these markets and provides additional functionality that would be difficult to reproduce by traditional means.

10.2 Future research

This work has built upon the current state of research and provided contributions to address a number of the issues identified through our initial literature review. There are, however, many outstanding issues that remain to be addressed by further research in the field.

This project did not consider the regulatory implications of the changes needed to support a P2P market. We briefly considered the means by which a P2P system could appear within the current legislation (see 8.2.8) but the empirical studies were performed within environments that were either exempt (in the case of UoB) or inside a regulatory sandbox (in the case of CommUNITY). Investigations into the necessary regulatory changes are underway, including legislation in France that has already begun to allow community-based trading schemes [145]. This area still remains under-researched and further research will need to be completed to better understand the changes needed to support a P2P market and the environments in which these markets will be allowed to exist. This discussion will need to take place alongside government bodies and industry members to demonstrate the need for this future market and to regulate not only the direct impacts but also the secondary implications, e.g. increased electricity data sharing.

Throughout this project, we have discussed the need for the perception of electricity to change, allowing the participants to better understand the electricity they are using and the costs to the network this introduces. With the introduction of smart meters, the use of demand response schemes and the introduction of 'smart' tariffs [161, 162], this change is already underway. The impact of this change to the average household, however, is not yet seen due to the opt-in nature of these programmes. Deploying a market with a completely alternate approach to electricity purchase that requires users to make the move to a more cost representative market will accelerate this change and the social impact of this is not yet known. Understanding the market participant's reactions to increased choice and alternative pricing structures will be vital before a P2P system can become widespread in the market.

Similarly, using blockchain to underpin these future markets will have further impacts on both the social and regulatory aspects. As identified through our case studies, the characteristics of blockchain that we hope to employ within the market introduce complexity to the user that may reduce any benefit they receive. Further research is required into the user interaction with DLT systems to retain these benefits whilst not introducing confusion or complexity that outweighs the possible return. This will need to include understanding the perception of blockchain as well as research into additional tools to simplify its usage. Furthermore, a key contribution that blockchain provides is the ability to introduce technological trust, removing the need for trust between the participants and providers of the market. Ensuring that this trust can be understood will be necessary for the market to be successful and beneficial to the users.

The use of data to operate our future electricity markets will allow us to provide additional services to end-users and create a more efficient energy network. However, this use of data to underpin our infrastructure brings with it numerous concerns. Data privacy, for instance, is becoming increasingly important as large scale data breaches [163] and unwanted personal data analytics [164] continue to make headlines throughout the world. Ensuring that a P2P market does not also compromise its user's rights is essential and as such researchers will need to explore methods to guarantee privacy of both interactions and data within the system. This is especially of note with the use of blockchain that is currently incompatible with this need for data privacy and with regulation such as GDPR [158]. To address this, researchers will need to continue work into mechanisms to provide private interactions [74, 115, 165] within the market whilst retaining the functionality afforded by the P2P approach.

The algorithm explored through this project presents one possible trading mechanism for a future P2P market, but as discussed in 4.1 we feel that a complete P2P system should provide numerous alternatives to participants. This open platform mechanism ensures that control remains in the hands of the users, allows for multi-level markets to exist and promotes competition between the algorithm providers. In our current platform architecture, this choice also introduces segregation within the market, such that each manager (see 5.2.4) acts independently thus separating their members. Further research will be required to address this division such that algorithm monopolies do not form and discourage the creation of smaller groups. This research will need to provide some form of inter-manager trading while retaining the original intentions of the participants in each trading group.

Lastly, we identified through the literature review that whilst numerous P2P models have been investigated, little research has been conducted into the transition paths to introduce these into the sector. A P2P market will have impacts for all parties involved within the energy sector and ensuring a smooth transition to the future market will require coordination from each.

APPENDIX

A

Final set of categories and codes used within the systematic literature review

Category: Sector of research	
(c2c)	**Domestic** - Individual to individual trading
(b2c)	**Commercial** - Business to individual trading / Individual to business trading
(b2b)	**Industrial** - Business to business trading
(m2g)	**Microgrid To Grid** - Microgrid to grid trading
(m2m)	**Microgrid To Microgrid** - Microgrid to microgrid trading
(p2p)	**Peer-to-peer** - Anyone to anyone trading (a superset of all others)

Category: Area of research	
(reg)	**Regulation** - Understanding the regulatory changes required
(opt)	**Optimisation** - Optimisation of energy resources
(mat)	**Matching** - Matching mechanisms between buyers and sellers
(pri)	**Pricing** - Designing pricing structures
(soc)	**Social** - Assessing the social impact
(dsr)	**Demand Response** - Trading as a means to balance the network
(mod)	**Model** - A complete alternate model of the energy system

Category: Scope of research	
(mcg)	**Microgrid** - Trading takes place inside a microgrid
(wmr)	**Wholesale market replacement** - Trading mechanism is a replacement for the wholesale market
(wms)	**Wholesale market service** - Trading mechanism is a service that sits outside of the wholesale market

Category: Transition	
free text	**How do researchers envision a peer-to-peer market integrating into / transitioning from the current market?**

Category: Model - Overview	
free text	**Which market models have been suggested to create peer-to-peer electricity markets?**

Category: Model - Objective	
free text	**What is the objective of this model?**

Category: Model - Assumptions	
free text	**What assumptions have been made for this model to exist?**

Categoryd: Model - Control	
free text	**What control does this model provide to its users**

Category: Trading - Type	
(man)	**Manual** - Participants manage trades themselves
(atm)	**Automated** - Participants are matched automatically. The specific mechanism used to match participants should be recorded in the notes.

Category: Trading - User control	
(pri)	**Price** - Participants are only able to state the price at which they wish to sell or buy (no other preferences)
(prf)	**Preferences** - Participants have a number of preferences that they can set (including price)
(non)	**No control** - Participants are matched on a predefined mechanism

Category: Trading - Network Charges	
(cur)	**Current** - Network charges are unchanged from the current market
(alt)	**Alternative** - Network charges are changed but remain charged on aggregates
(dyn)	**Dynamic** - Network charges are applied per trade
(non)	**None** - Not considered/discussed
(na)	**Not applicable** - It is not necessary to consider (microgrids for example)

Category: Blockchain - Used	
(yes)	Uses blockchain
(no)	Does not use blockchain

Data extraction field 7b: Blockchain - Level	
(cpl)	**Complete** - Mechanism resides completely on-chain
(hyb)	**Hybrid** - Mechanism uses a combination of on-chain and off-chain processing (Describe the hybrid mechanism)

Category: Scale	
(grd)	**Grid** - Modelled to grid scale
(lcl)	**Local** - Modelled for 100% usage in a given region (>1000)
(tst)	**Test** - <100% usage in a given region
(sml)	**Small** - An area of fewer than 1000 participants (<1000)
(mcg)	**Microgrid** - Tested to microgrid level (<100)

Category: Evaluation	
(sim)	**Simulation** - Evaluate through simulation, software only
(lab)	**Laboratory experiments** - Evaluated through lab experiments with hardware
(ana)	**Analytical** - Evaluated through analytical discussion
(user)	**Case studies with users** - Evaluated through practically implemented case studies
(non)	**None** - Not considered/discussed

Appendix B

Review of Blockchain Technology and its Expectations: Case of the Energy Sector

A working paper was published on arXiv with Ruzanna Chitchyan investigating blockchain technology and its impacts within the energy sector. This paper is included in its entirety as an appendix here for completeness, although sections of it have been re-used in the main body of the thesis. This paper was co-authored by Jordan Murkin and Ruzanna Chitchyan.

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Review of Blockchain Technology and its Expectations: Case of the Energy Sector

Ruzanna Chitchyan · Jordan Murkin

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Abstract This article suggests that the worldwide relevance of blockchain technology is motivated by the changes that it is expected to cause in: (i) the way that business is organised and (ii) regulated, as well as (iii) by the way that it changes the role of individuals within a society. The article presents an overview of the features of blockchain technology. It then takes a closer look into the developments within the energy sector across the world to gain a preliminary indication of whether the stated expectations are coming to reality. As a result of this review, we remain cautiously optimistic that blockchain technology could deliver the expected impact.

Keywords blockchain · distributed ledger technology · energy sector · peer-to-peer energy trading

1 Introduction

In recent years academia and industry alike have been excited about blockchain. Blockchain has been proclaimed to be the next biggest technological breakthrough since the invention of internet. It is expected to revolutionise not only the technical structure of our communication and information technology, but also the very fabric of societies. The list of the changes expected to come through the blockchain are many, including:

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Changing the way business is conducted. Until now societies needed trusted intermediaries to mediate most types of business transactions: for instance, individuals entrust their savings to a bank for safekeeping and interest accumulation and the bank loans these savings out to other individuals at higher interest rate; farmers deliver their produce to supermarkets who re-sell these to consumers at higher prices; energy generators sell their outputs to suppliers who re-sell the energy to end users. In all these cases both producers and consumers know and trust the intermediary (e.g., the bank has good reputation, farmers know this supermarket which is likely to work with other farmers around the given area, the energy distributor has green credentials) but do not know or trust each other. As blockchain provides cryptographic trust through technology design, whereby anonymous parties can transact without the possibility of cheating, intermediaries will no longer be necessary beyond the technical platform provision. This phenomenon has already commenced, to some degree, with the internet whereby virtual organisations (such as Airbnb and Uber) deliver the platform for individuals to transact with each other. Yet, presently, these organisations are monopolising platform delivery and still imposing substantial intermediation costs. As blockchain gets integrated into the ICT infrastructure, such monopolisation would become impossible.

Changing the way business is regulated. Until now societies have required regulators to ensure that businesses operate within legal frameworks: for instance, land registry authorities are to assure correct record keeping for land ownership, financial auditors are to assure proper fund handling and absence of embezzlement, competition authorities to oversee fair pricing and so on. As blockchain, along with its smart contracts, provides transaction record transparency, as well as imposing rules defined within contracts upon all transactions, regulatory and legal compliance checks become a prerequisite for any transaction completion.

Changes the role of individuals within society. Today we view ourselves as "consumer societies", where individuals are generally passive consumers. However, the peer-to-peer transactive nature of blockchain encourages individuals into both productive and consumptive roles. The individuals are no longer passive consumers, but are active prosumers (i.e., *pro*ducers and con*sumers*). This again, is an ongoing process already today, with such examples as music production crowdsourcing by individual artists [1], microlending by peers [2], peer-to-peer file sharing, and micro-generation in the energy sector [3]. Common adoption of blockchain platforms would transform such activities from niche to norm.

As discussed, a diverse set of changes are expected across all walks of society, all of which are driven by the ***secure decentralisation of social and technical structures*** enabled through blockchain technology.

In this paper we first present the makeup of blockchain technology, discussing what exactly distinguishes it and how (sections 2 and 3). We then review the academic and industrial state of the art with respect to blockchain technology for a specific industry - the energy sector - to analyse how blockchain technology has affected it (section 4). We finally consider how the present findings stand up against the stated expectations, and if there are any indications of realisability of these expectations (section 5). As a result of this exercise, we remain cautiously optimistic that the blockchain technology could deliver the expected impact.

2 Technology Review

2.1 The makeup of the blockchain technology

A blockchain is a distributed database in which transaction records are collected into groups - called blocks - and stored with a reference to the previous block, forming an ever growing chain of blocks. These blocks are created by members of the network, known as *miners*, who validate the transactions and are rewarded for their contribution.

Blockchains provide two characteristics that make them attractive as a transaction recording solution:

1. **Cryptographic immutability and verifiability** making it quite impossible to modify transaction records once committed, thus ensuring secure transactions;
2. **Distributed consensus** allowing anonymous individuals across a peer-to-peer network to come to agreement on the state of the network, thus removing the need of a centralised agreement mediator/organisation.

2.1.1 Cryptographic immutability and verifiability

Blockchains provide immutability and verifiability by pairing two existing technologies: hash functions (such as SHA256 [4]) and Merkle trees [5].

A *hash function* is an algorithm that takes arbitrary data and outputs a fixed-sized bit string known as a hash. Hush functions are one-way mapping functions, i.e., given the output of the function, there is no way of reverse engineering the input that generated the given bit-string[1]. They are also quick to compute and deterministic, i.e., given the same input, the function will always produce the same output. Moreover, a small change in the input will dramatically change the output. In a blockchain, a hash function is used to represent the data content of a block with a fixed-length bit-string.

Merkle trees are then used to structure the records in blocks, and support efficient verification of the chain's data authenticity. In a simple Merkle tree all data is contained in leaf nodes. Each record is then hashed, and the parent nodes are layered upon the leaves by combining pairs of hashes of the lower level nodes and calculating a new hash node, as shown in Fig. 1.

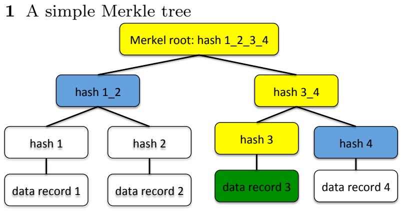
Each block of a blockchain contains the top level hash of this tree, known as the *Merkle root*, along with all the transactions that the block includes. Each block also contains the record of the hash of the previous block in the chain. When the hash of a new block is calculated, the new block becomes inseparably connected to its predecessor: should any part of the records in any of the recorded blocks change, the whole blockchain from that point onwards will diverge from its previous version.

Thus, use of Merkle trees ensure that no change can go unnoticed to previously agreed upon and recorded transactions. They also provide easy verification on the presence of a given record within the chain [6] using the so called *Merkle proof*. Given a top level hash (e.g., the Merkle root in Fig.1), the node of data (e.g., *data record 3* in Fig.1), and the set of hashes that are used to integrate the current data with the rest of the tree (e.g.,

[1] Except through "brute force": searching through (the infinite) set of possible inputs, hashing them, and comparing the results, in the hope that (at some point) a match would be found. This, however, is an infinitely expansive process in terms of time and computational resources.

hash1_2 and *hash 3* in Fig.1), a Merkle proof allows any interested party to verify that the given data (e.g., *data record 3* in Fig.1) is correctly and uniquely integrated into the chain without the party requiring knowledge of every individual child node (e.g., by comparing the newly calculated Merkle root for the given data record with the given one).

Fig. 1 A simple Merkle tree



2.1.2 Distributed consensus

Distributed consensus is the process of coming to an agreement between individuals distributed across a peer-to-peer network. In a blockchain this is required for agreeing that a block validated by some miner should be added to the chain. Since miners are rewarded when their block is added to the chain, they would compete against each other and a number of candidate blocks could be available at any given time. The agreement is achieved through distributed consensus algorithms (DCA) [7]. Each blockchain platform uses its own flavour of DCA. Some examples are:

1. *Proof of Work* (PoW) [8,9], which operates by setting a target value, which must not be exceeded by the value of the hash for a given block, if that block is to be acceptable for addition to the blockchain (e.g., in Bitcoin [10] and Ethereum [11]). This target is adjusted so that on average one node in the network will find a block with such a value within a given time interval (e.g, every 10 min. in Bitcoin network). The node that finds such a block can add this to the chain. This creates competition between miners to be the first to find an acceptable hash value.
2. *Proof of Stake* (PoS) [12,13] works by choosing the node that will be able to form the next block on basis of random selection from amongst the nodes that have maintained unspent currency within the blockchain network for the longest period of time (e.g., in Peercoin [14]) or of the largest size deposit (e.g., BlackCoin [15]).
3. Proof of Burn (PoB) [16] (e.g., in Slimcoin [17]) where the next block creating node is chosen from amongst those who demonstrate burning some of their coins by sending these to a verifiably unspendable address.

Whichever flavour of DCA is used, they all are structured to incur a demonstrable cost to the mining nodes. Those who complete a block formation task are rewarded with a payment comprised from the fees that each blockchain participant pays to ensure completion of their transactions and a preconfigured amount of the network's cryptocurrency. Thus, the consensus mechanism aims to ensure that for a given node it is very expensive to attack the network and more profitable to help maintain it.

Blockchains are maintained and operated by the blockchain network - an open membership peer-to-peer network of computers which redundantly store the data logs. This redundancy ensures that the network has no single point of failure or target for attacks. But it also necessitates a process by which all nodes on the network are able to ensure a consistent state of the blockchain copies [18]. This process too is furnished though the above discussed DCA, by which all nodes on the network (or at least the clear majority, i.e., 51% of them) accept that the longest blockchain (i.e, the version with the largest number of signed blocks) is the valid one. As noted above, the DCA imposes a cost upon miners for signing blocks, thus the longest chain is also the one which has the largest accumulated cost. Should a malicious node wish to alter a transaction committed to some previous block, it must recreate the block to-be-changed, as well as all the subsequent blocks (else the change will be immediately marked as invalid due to broken hashes). Such a malicious node would thus need to incur the cumulative cost for change, including also the cost of generation of the newest block, to become the current longest chain and have this accepted by the network. This, however, is prohibitively expensive in terms of processing power and the costs imposed by a given DCA that a node would have to amass.

In summary, blockchains are distributed, decentralised, multi-access databases with cryptographic security of data records. Yet, the very nature of these databases requires a peculiar operating environment, such as dedicated network of peers to support it and a cost to committing transactions. So when are these databases to be preferred over the more traditional ones?

2.2 To blockchain or not to blockchain?

As any technology, blockchain too has a specific set of use cases where it is particularly well suited. It is generally recognised [19, 20, 21] that to be particularly well suited for the blockchain, a business case should require:

1. Use of a database, as the basic purpose of the blockchain is still to order and record transactions;
2. This database must be shared amongst multiple users wishing to write to it to commit their own transactions;
3. The transactions are interdependent, i.e., the order of the transactions matters (e.g., the investor must pay money before the borrower pays interest on it);
4. The writers do not trust each other as they may have conflicting interests (e.g., investors may wish to gain interest without paying, while borrowers may wish to get money without paying interest); or simply have no sufficient information about each other;
5. There is a need for disintermediation, i.e., when no third party (such as a bank for investment and borrowing) is suited to act as a trusted intermediary for all writers for one reason or another (e.g., cost and/or speed of intermediation under micro-lending schemes [2], ideology, etc.).

2.3 And if to blockchain, will it scale?

Securing decentralised transactions was the primary goal of blockchain technology, which is now sufficiently resolved. However, the mass adoption of this technology requires a resolution to one other challenge - that of scaling up the volume and speed of transaction processing over a blockchain infrastructure. There presently is an unresolved tension between scalability, security, and decentralisation concerns [22], as only two of them at a time can (so far) be addressed satisfactorily with blockchain technologies. The established PoW DCA, for instance, is extremely secure and fully decentralised, as the computational resources (in terms of processing power and expended energy) required to falsify the records on the accepted chain are completely prohibitive. Yet, the very costs required to guarantee security (e.g., resources and time expended on hashing, consensus, and competition between miners) inhibit its scalability.

To address the tension within the scalability, security, and decentralisation trilemma, a number of solutions have been proposed that relax the requirements of the blockchain mechanisms. Such relaxations come with their own tradeoffs.

2.3.1 Permissioning

To start with, blockchain began as an open, so-called *permissionless* network, where any interested entity can act as a miner. Yet presently blockchains are used with varying degree of *permissioning*, which helps to reduce the competition between miners and latency of consensus at the expense of decentralisation and security.

Public blockchains are fully open to everyone; anyone may inspect and participate in the network, viewing transactions, creating transactions and mining blocks. The original blockchain concept was a public blockchain, and this was important to provide the transparency and immutability required for trustless, intermediary-free, decentralised transactions to take place.

Consortium blockchains add a layer of permissioning, such that only selected organisations can validate transactions. Access to transaction history may also be restricted, but is in some cases kept public for full transparency. These blockchains are quicker and scale more easily, but at the cost of trust. Unlike public blockchains, the validators must be trusted by the users to validate transactions correctly.

Consortium chains are primarily used to increase automation of transactions between organisations, reduce cross-organisation transaction fees, improve standardisation, reduce fraud and increase auditability. For example, automatic settlement of trades between banking institutions could be handled by a blockchain using smart contracts where the validators in the network are the banks themselves. The Energy Web Foundation [23] is already developing a consortium chain aiming to accelerate use of the blockchain infrastructure in the energy sector.

Private blockchains, as the name suggests, are the most restrictive. These reserve validation task to a single organisation. Similarly to consortium chains, viewing of the transaction history may either be restricted or left public, depending on the use case.

2.3.2 Off Chain Transactions

Moving some portion of transaction processing between account holders on a blockchain away from the chain itself is another currently popular direction for improved scalability. This is done by using (a portion of) the assets currently present in the accounts of the transacting parties (say A and B) as fenced off payment guarantee for a specified time period (referred to as the *funding transaction* [24]; lets say A and B each commit 10 coins for 1 week). The transacting parties can then undertake two way transactions within the agreed funding transaction limits (say A pays 5 coins to B, B pays

12 to A, then A pays three lots of 2 coins to B). At the end of the agreed time period the final account between participants is settled[2] (e.g., now A has 10-5+12-2-2-2=11 coins and B has 10+5-12+2+2+2 = 9 coins) and recorded into the blockchain (a single summative transaction of B paying 1 coin to A instead of 5 actual transactions).

This solution could be adapted to support not only bi-lateral, but also multilateral off-chain transactions, which guarantees fast transaction processing time for large volumes of translations without need for any intermediary, but for an account availability on the chain. It is also claimed to support privacy and anonymity of the transaction participants. Yet, the transparency of the whole transaction history between participants is lost, along with the trust and full accountability (e.g., for regulatory compliance and business practices).

There are presently a few implementation efforts (e.g., Raiden [25] and Lightning [26] networks) on the way to integrate off-chain transaction handling into blockchain systems. The Lightning Bitcoin [27] fork of the Bitcoin blockchain for example, already runs with Lightning support.

2.3.3 Sharding

Sharding - the process of partitioning the blockchain into smaller sub-chains (termed *shards*) is another direction of tackling the trilemma. Shards can be defined on basis of some specific criteria, such as account address space, use of specific applications, or geographical location, etc. With sharding [28] most validator nodes would need to store and process transaction history data for specific shards only, not the full chain. Only a relatively small number of nodes would keep history of the full chain.

If validators are randomly assigned to the shard that they would validate for each block validation, and the result that the majority agrees upon is accepted and the current true state of the chain, the security of the transactions is still (mostly) assured, with improved throughput of the transaction processing.

Some of the main challenges to be address under sharding are, for instance: (i) slow cross-shard communication; (ii) complications in synchronisation of user requests that require atomic translation over two or more shards; (iii) risk of validator collusion in some consensus models where validators non-randomly choose what to validate (e.g., PoW), etc.

2.4 Contractual Transactions

The appeal of blockchain technology is magnified by the addition of *smart contracts*[3] to the blockchain infrastructure. A *smart contract* [29] is a piece of code (running inside a blockchain platform) that represents and enforces the protocol and any terms of a contract agreed upon by the contractual parties (e.g., seller and buyer of a product). The contracts can store arbitrary logic, such as restricting execution until a predefined criteria is met (e.g., a contract that only allows the sale of an item once a specific date/time has passed). A smart contract is identified by an address with the contract's code housed within a blockchain. The contract is executed by sending transactions to its identifier address.

The transactions executed via the contracts are secure (as these are recorded in a blockchain and enforced through the DCA), automated (and so are cheap and quick), and deterministic (always delivering the expected outcome, the code of the contract cannot be changed as it is also a part of the blockchain). All these properties foster dis-intermediation within businesses using such contracts (e.g., no need to have a broker to sell an item), and promise faster transactions at better price.

Yet, the smart contracts are also rigid and inflexible, which may cause difficulties (e.g., difficult to fix bugs identified in the code [30], or accommodate changes in context of the parties).

3 Blockchain Platforms

A number of blockchain platforms are currently in development and use, each targeted for a specific use case.

3.1 Bitcoin

Bitcoin [10] was the first to use blockchain and is subsequently the first cryptocurrency [8]. Its intention is to act as a decentralised electronic transaction system, in which individuals can store and transfer value between one another without the need for central authorities [1]. This value is represented by in Bitcoin tokens; with an issue limit of 21 million Bitcoins to provide scarcity of supply. Transactions on the network are paid for using Bitcoin. The platform operates under the PoW consensus mechanism and miners are rewarded in Bitcoin generation and through fees of the transactions they

[2] This is a simplified explanation, in reality each individual transactions will also be cryptographically signed by both parties; parties will be able to redeem their funds before end of set time; penalties will be payable by non-cooperating parties for violating the transaction agreements [24].

[3] The name is somewhat misleading, as smart contracts do not (need to) have any real built-in intelligence.

process. The transaction fees are specified by the transaction senders and transactions with the higher fees are prioritised by miners due to the increased profit from their processing. Thus users can reduce transaction fees for low priority transactions and vice versa. Each block size is limited to 1MB and the network intends to produce one block every 10 minutes, giving a maximum potential of ~7 transactions per second. Scalability improvement measures are under development, including increasing the block size (though this would reduce decentralisation as smaller miners would be unable to handle larger block mining) and integration of the Lightning network [26] for off-chain processing.

3.2 Ethereum

Ethereum [11] was introduced in 2013 with the objective of providing a platform for decentralised applications. It took the concept of blockchain and incorporated a turing-complete scripting language with it. This allowed for applications themselves to be stored inside the blockchain where they can be used by anyone connected to the network.

The cryptocurrency in this network is Ether, which is used as a means to store and transfer value, as well as to pay for computation and transaction costs. Since Ethereum allows arbitrary code to be stored and executed inside the blockchain, there can be an infinite number of methods each requiring a different amount of computation and storage. To pay for this, Ethereum introduces the notion of *gas*. Each opcode inside the Ethereum virtual machine is assigned a different amount of gas. Each transaction sent to the blockchain must specify: (i) a gas limit - the maximum computation the user is willing to incur; and (ii) a gas price - an amount of Ether the user will pay per gas unit. The gas price is used by the miners to prioritise transactions: those with the higher gas price are preferred by miners (similarly to Bitcoin). If the user does not specify enough gas for their requested transaction, the transaction will fail and, conversely, any excess gas provided will be refunded to the user.

Ethereum currently uses PoW protocol, but plans to move to a hybrid proof-of-work/proof-of-stake system [13] shortly and finally to a purely proof-of-stake mechanism in the future. The network can currently process ~15 transactions per second. Scalability measures are under discussion through planned integration with the Raiden network [25] for off-chain processing, and efforts to implement sharding [28].

3.3 Ripple

Ripple provides a real-time cross-border settlement and remittance network to banks, payment services providers, and corporates for the transfer of assets and money globally. The network is a permissioned blockchain with a consortium of approved validators, but the ledger is public. The network uses its own Ripple Protocol Consensus Algorithm [31]. This is a vote-based consensus algorithm in which each validator has a vote and at least 80% of voters must vote in favour for a transaction to be successful.

The network uses own currency (called XRP) for imposing anti-spam transaction fees and as a currency for value exchange.

3.4 Iota

Iota [32] is not a blockchain, it is stated as a cryptocurrency for the IoT industry. Instead of using a blockchain, it is built upon the Tangle [33], a mechanism that "succeeds the blockchain". The tangle does not have miners, instead opting for a user driven network; whenever a transaction is sent, the sender must authenticate two previous transactions. This allows the network to remain decentralised while also reducing transaction time and removing fees completely. As there are no miners, the computation required to run the network is significantly reduced, allowing nodes to run on devices with little computational power. This design choice also means that as more transactions are made, the network transaction time reduces further.

4 Blockchain in Energy Sector

Many - both in academia and industry - believe that the rise of blockchain could potentially foster innovative changes and facilitate the transition to the smart grid [34]. The concept of a decentralised electricity grid has been around for some time now [35]. Recently, the integration of energy storage devices as well as electric vehicles into the future electricity grid [36] has initiated a wide discussion, as have studies on new control schemes for both energy storage and demand side response programmes [37].

The idea of using blockchain in the energy sector is gaining an increasingly large interest. For instance, some researchers propose to integrate blockchain with electric vehicles (EV) [38] so that EVs could use blockchain to find a nearby charging stations, while charging stations could bid for the opportunity to charge EVs. This mechanism would help find the best price and location for both EV users and charging stations, while at the same time providing privacy and security to the EVs.

Use of blockchain for IoT and, subsequently, energy efficiency in the smart homes is another area of active research [39]. Here, blockchain could play a key role in data control and decision support for large scale IoT using smart contracts as means to communicate, automate and enforce rules between devices. As mentioned before (see 3.3), a dedicated blockchain platform for IoT is already under development.

Blockchain was used to eliminate fraudulent behaviour in emissions trading [40]. Here an alternative Emissions Trading Scheme (ETS) backed by a blockchain was developed. Blockchain helped to ensure reliable, secure transactions and embed a reputation system to encourage investment into ETS in the long-term.

In a related work [41] [42] the tokenisation of Guarantee of Origin (GoO) certificates [43] was considered. Since these certificates could act as a proof that a specified amount of electricity was generated through renewable sources, they could also form part of the emissions trading market. Thus, blockchain can support trade in such standardised certificates, as well as foster removal of the intermediaries from the market.

Expanding on these certificate trading systems is the concept of peer-to-peer (P2P) electricity trading. With P2P trading systems the units of generated electricity themselves are recorded inside a blockchain, allowing the owner of this generation to market it to others. This enables energy generators and buyers (both large and small) to take ownership of their product, choices, and preferences, rather than solely rely on the grid as an intermediary [44]. Some researchers on p2p energy trading focused on the P2P energy market creation [45] [44], [46], demonstrating that blockchain-based intermediary-free energy trading is possible and beneficial to the generators and buyers alike. Others studied the optimisation of energy resources [47] in P2P trading. In [48], the authors have developed a smart contract based closed double auction market mechanism wherein individuals could submit bids and sale orders for each market period and an automated contract would decide a market clearing price for the period.

A prototype trading platform was developed in [49] focusing on privacy and anonymity of users while also removing a single point of failure. This platform opted to remove a central price setting algorithm, instead providing users with encrypted channels to directly negotiate price between a buyer and a seller.

Scanergy [50] [51] research project is taking a different approach of incorporating blockchain into the electricity network. Here participants are provided with an incentive to export electricity and assist with the balancing supply and demand on the grid. For every kWh a household exports to the network that is consumed by another household, the exporter is credited with an NRGCoin [52] [53]. These NRGCoins can then be traded on a separate market like any other cryptocurrency. This system works using smart meter data and street-level substation data. The substation sees the total consumption and generation for the group of houses connected to it and smart meter data provides individual household information for the same period. Using the consumption and generation values from both the individual smart meters and the substation they are connected to, it is determined whether the exports of each house were consumed by another household. The producers are then credited with NRGCoins corresponding to the exported amounts. The smart meter data and substation data is also used to prevent tampering by ensuring the totals from the smart meters is the same as the totals from the substation.

Despite blockchain being a hot topic for energy researchers, the industry has taken the real lead in championing this technology (see Table 1).

There is a quickly growing number of startups as well as established energy players who are already tackling energy sector issues using blockchain technology. Table 1 (expanded from [54]) presents a summary of some of the most prominent companies currently active in this space.

As Table 1 demonstrates, there is a real breadth of the areas and purposes within energy sector where blockchain is being actively employed. Some, for instance, utilise blockchain for p2p energy trading aiming to eliminate retail intermediaries [71, 72, 73]; others, quite the opposite, use it for themselves becoming more competitive and affordable energy retail intermediaries [58, 60]; some utilise it to support non-for-profit and charitable causes [56], while others base wholesale B2B energy trading solutions on it [74, 61]; some promote industry standardisation [23], others set out to monetise environmental resources and even their protection [69].

Several observations (be it preliminary) surface from the review of the current blockchain-based businesses (summed up in Table 1):

– Blockchain is used for *starting up a new business structure and ecosystem* within the energy sector, competing against the incumbents. Thus, some businesses, like myBit [64] foster investment into renewable generation hardware in such a way that, even if an individual is unable to purchase a whole device, he/she can invest into a portion of a tokenised hardware and get return per owned portion. Once generated, the energy production is recorded into a blockchain, over which software (acting as a whole-

Table 1 Blockchain companies currently working in energy sector (adapted from [54])

Company	Blockchain Use	Operation at/since
Alliander [55]	A smart energy company which has piloted a P2P energy trading platform. The energy production tokens (Juliets) are also exchangeable for goods and services within the piloting community.	The Netherlands, since 2017.
Bankymoon [56]	A blockhain solutions company that introduced prepaid blockchain-enabled smart meters in Africa to help energy suppliers collect payment, as well as to enable humanitarian aid to be sent as energy via direct payments to smart meters at schools.	South Africa since 2015
Conjoule [57]	Platform to support P2P trading among rooftop PV owners and interested public-sector or corporate buyers.	Germany: 2 pilots running since 2016
Drift [58]	Retail energy provider that uses blockchain, machine learning and high-frequency trading to provide better prices to customers and promote green energy use.	New York, USA since 2014
Greeneum [59]	P2P energy trading platform that incentivises renewable-based generation through GREEN tokens, global data collection and AI-based processing for energy industry optimisation.	Beta release in Cyprus, UK, Israel, Germany, Guinea, Argentina, US, India, Australia. Expects a product release by mid-2018
Grid+ [60]	Retail provider (i.e.,buys on behalf of its customers at wholesale prices from outside) and P2P trading platform between Grid+ customers	Texas, USA since 2017
Grid Singularity [61]	Developing a blockchain-based core technology for the energy sector, focused on B2B provision; this technology is to underpin EWF	Internationally since 2016 (?)
Electron [62]	Automated energy supplier switching platform; also aims to to support P2P energy trading and grid-balancing	UK, since 2016
Energy Web Foundation [23]	Non-profit alliance between major energy players internationally, aimed at accelerating blockchain technology across energy market, and building an ecosystem around blockchain for energy.	Projects in preparation at Somaliland, Haiti, India, Argentina, since 2017
LO3 Energy (Exergy) [63]	P2P energy trading platform, aiming also at grid-level service provision (e.g., DER aggregation, balancing, wholesale trading).	NY, USA, since 2017
MyBit [64]	P2P investment into IoT hardware, such as connected solar panels. An investor can own a portion of tokenised hardware and get return per owned portion.	Alfa launch of platform in 2018
Ponton's [65] Enerchain	A B2B solutions integration company that runs the Enerchain platform used for peer to peer blockchain-based energy trading at wholesale energy market by energy sector businesses. The traders anonymously send orders to a decentralised order book, which can also be used by other organisations. Enerchain does not require a central authority.	The platform is used by some 30 European companies since 2016
Power Ledger [66]	P2P energy trading (individuals and wholesale for utilities), EV charging, transmission grid monitoring, P2P asset funding and asset ownership token trading.	Australia and New Zealand, since 2016
SolarCoin Foundation [67]	The foundation aims to foster solar energy generation installations. It awards crypto-coins (for free, similar to air miles) to registered and verified solar energy producers. Each coin represents 1 MWh of produced solar energy.	Used in more than 13 countries since 2014
Sun Exchange [68]	P2P funding of solar PV installations in return for income on investment. Installations are for specific projects in Southern Africa to supply energy to schools, hospitals, and similar businesses.	Southern Africa since 2015
Veridium Labs [69]	Veridium is a financial technology firm aiming to create a new asset class that tokenizes natural capital. Each token will represent removal of 1 ton of greenhouse gases from the atmosphere, or equivalent natural capital preservation activities (e.g., conserve 1 sq. meter of biodiverse tropical forest). Tokens will be issues for validated projects. This would be used by firms to conform with environmental impact mitigation regulations, and more generally embed environmental replacements into the cost of their products.	First project to commence in 2018 for Rimba Raya Biodiversity Reserve in Borneo, Indonesia, tokens will be traded internationally.
WePower [70]	A platform for P2P trading of renewable energy, as well as fund raising for renewable projects by pre-sale of energy to be generated in the future.	To commence in 2018 in Lithuania and Spain

sale or retailer trader) [55,57,62,58,60] buys and sells energy. Software companies [71,61,62] (rather than the traditional distribution network operators and retailers) cater for the (increasingly more and

more automated and optimised, e.g., with AI [59]) delivery of and accounting for the energy generation and consumption. To facilitate the emergence and operation of this new ecosystem, a standardisation effort is already under way (e.g.,[23]).
- Driven by this newly emerging ecosystem, *new kinds of energy services* are also beginning to emerge (e.g., balancing the supply and demand within the grid or remotely scheduling consumer device operation, such as EVs charging, running washing machines, etc., in response to the generated every availability) [63].
- *Renewable forms of energy are very much the core* of the products delivered via a blockchain infrastructure. Some businesses foster trading of the generated renewable energy [55,57,71,58,59], while others support adoption [64,68] and better utilisation [60] of the household-level generation assets;
- Many of these businesses are *end-user focused*, aiming to obtain better energy prices for the end users [55,57,62,58,60], or access to/participation in the energy generation endeavour [64,68];
- Finally, the incumbent energy businesses have also identified blockchain as a potent technology, and have started using it for business process optimisation and inter-business communication [23,61].

5 Concluding Thoughts

This article presents an overview of the basic features of blockchain technology. In the introduction to this article we suggested that the high relevance of blockchain technology is motivated by the changes that it is expected to cause in: (i) the way that business is organised and (ii) regulated, as well as (iii) by the way that it changes the role of individual within a society. We then took a closer look into the developments within the energy sector (see section 4) across the world, to gain a preliminary indication of the effects that blockchain has caused within this sector and assess whether the current trends within energy sector confirm or refute the stated expectations.

As noted above (section 4), blockchain has indeed initiated a change of business ecosystem and organisation within the energy sector. For instance, by

- removing the need for intermediaries (currently often played by the established energy utility providers) through direct p2p energy trading and even allowing wholesale generators to trade directly with the end users/consumers (e.g., [55,57,62,60]);
- enabling individuals and communities to initiate energy production projects that require expensive investment which they could access through crowdfunding (e.g., [64,68]);
- transposing a number of energy services (e.g., billing, supplier switching) form established retailers and utilities to software platform providing companies which automate these services and deliver them at a fraction of the “normal” costs;
- allowing for a number of new, previously non-existent services to emerge, e.g., to optimise the price of a household’s energy consumption by scheduling such tasks as washing and vehicle battery charging; or balancing energy grid.

We also observe a change of the role that the households play in energy sector: these are not simply consumers, but active owners and/or investors into energy hardware and software infrastructure, generators and sellers of energy, as well as buyers and consumers. In the past intermediated market, the capacity of an individual household would be considered too small for acting as either a viable energy seller or investor. Now, with no intermediaries and a low barrier to market entry, households and individuals not only can assume new roles, but are also actively encouraged to do so by the new businesses that rely on active household investors and prosumers.

Regulation of businesses through blockchain technology in energy sector is currently somewhat underdeveloped. This has largely to do with blockchain-based energy businesses being a relatively novel phenomena. However, recent developments worldwide indicate that regulators recognise the potential of this technology in both enabling more efficient energy systems, and facilitating their regulation. For instance, a law enabling self-consumption by individuals and small communities has already been passed in France [75] and there is regulations support for (limited) P2P energy trading in Germany, Netherlands, and USA [76]. Furthermore, most businesses discussed in Table 1 (e.g., [62,63,66]) already use smart contracts over blockchain for specifying and enforcing energy trading contracts to support efficient trading, as well as business transparency and trustworthiness.

In summary, looking at the trends within the energy sector, we suggest that the impacts expected from blockchain technology have already started to manifest in practice, and seems to be grounded in reality, though there still is a long way to go for its full-scale rooting with the energy sector. Thus, we remain cautiously optimistic that these expectations will be realised in not-so-distant future.

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Appendix C

Goal-based automation of peer-to-peer electricity trading

A research paper was published in From Science to Society 2018 and presented at EnviroInfo 2017 detailing the scoring mechanism and providing an overview of the algorithm design. This paper includes initial performance analysis not included within the report and is incorporated as an Appendix to remove duplication within the dissertation and to allow the dissertation to remain focused on the topic.

Goal-based automation of peer-to-peer electricity trading

Jordan Murkin, Ruzanna Chitchyan, and David Ferguson

Abstract As the uptake of microgeneration increases, the centralised model of electricity generation will be significantly altered. One of the new models that is being investigated is the notion of a peer-to-peer electricity market in which prosumers can market their electricity exports to any other household. This paper investigates this model and proposes a new algorithm for automating the sale and purchase of electricity in this market aiming to optimise the market while providing increased control to householders.

Key words: p2p electricity trading, trading automation, goal optimisation

1 Introduction

Microgeneration is the generation of small amounts of electricity by individual households (e.g., via solar panels) and non-energy specialist small businesses (e.g., farmers via wind turbines). Uptake of the microgeneration in the UK is steadily increasing [1] and with it new market models are necessary to make full use of this newly available generation capability. One of the new models that has gained a lot of research and practical interest with increased *distributed generation* (i.e., generation by other than centralised power plants) is the concept of *peer-to-peer (P2P) electricity trading* [2, 3, 4] in which excess microgeneration can be sold by the producer directly to another consumer instead of to the grid.

A P2P market model would bring a number of benefits over the current system; prosumers would be able to market their excess generation, possibly providing an extra income stream. While consumers would see a far greater choice over their

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energy source, with the ability to pick the exact source of their supply. However, should the microgenerators be required to manually manage sales, the required time commitments and need to acquire trade-related domain knowledge would likely outweigh any benefit for the majority of users. Consequently, it is necessary to automate the trading process, and with automation also comes potential optimisation.

This paper will explore the methods of automation with the objective to provide increased choice to consumers and incentivise the purchase of locally generated electricity to increase the value proposition of microgeneration. The intent being to reduce transmission losses caused by long distance energy distribution and increase the use of renewable technologies, both aiming to increase energy efficiency in the energy industry. Thus the contribution this paper provides is to propose:

- An electricity market structure that enables the automation of p2p trading;
- A new algorithm to automate p2p electricity trading;
- Evaluation of performance of this algorithm using simulations.

This paper investigates the different ways in which electricity trading over a P2P market could be automated, and the different optimisations it makes possible. It will start with a background of the current research has taken place in this area, the ways that a peer-to-peer market may appear and ends by proposing a new matching algorithm that could be used to optimise this future market.

2 Background

Previous research has explored different methods of household trading inside the electricity market. The authors of [5] and [6] used a modified regret matching as a method to match buyers and sellers individually, allowing for price preferences and taking into account transmission losses in the network. However, in [5] each buyer can only receive energy from one seller and price is the only consideration. Another game theoretic approach was used in [7] which focused primarily on the increased utilisation of energy storage using an auction based approach to determine price. A microgrid focused trading mechanism [8] has also been suggested that relies on sharing energy schedules between participants so as to match producers and consumers at the correct time to ensure electricity is utilised fully. This research expands on these with the addition of multiple preferences for each participant in the network, the ability for buyers to purchase from multiple sellers and vice versa and proposes a new market matching approach designed to find an optimal solution while reducing overheads.

While automation is the focus, it is important to first detail how the market would be structured and function in a P2P trading environment. The structure of the market will also inform the choice of trading algorithm type.

The current electricity market divides each day into 30 minute periods which electricity can be traded for. This research kept the same approach in which trading is separated into clearly defined periods allowing for regular trading to continue as well as providing a structure to the automation. It is currently undecided whether these fixed trading periods will remain at 30 minutes or whether a shorter time period will be used. To decide this, a number of simulations will be run with different trading periods to identify if there is a benefit to shortening these periods.

2.1 Structure

To begin, it is necessary to define the structure of these trading periods and the trading procedure. In the current electricity market trade contracts are determined in advance between parties and controlled by the parties involved. To remove the complexity of the electricity market and make this accessible to the average consumer, these instead will be organised by the market itself. This means that from a consumer point of view the only interaction with the system is the setup of their account and the configuration of their preferences.

With the market establishing contracts between participants, there are two main approaches that can be taken. The first and more traditional is to automate each participant individually, so that their contracts are negotiated for them with other participants in the market. The second is to have a single entity that performs a matching of all buyers and sellers together, negotiating all contracts at the same time. The first serves to benefit individuals to the maximum potential, but may not find the optimal solution for the network as a whole. The second allows for matching to be decided on a market level, reducing overheads. This method though, is generally more open to abuse by having a single entity that controls all contracts being created. As this research is centred on the concept of distributed ledger technology (DLT) which allows for a platform to be created in such a way that it can never be altered it is not an issue for this research. Due to this, the second option was chosen. This left a number of choices available, summarised in Table 1:

Table 1: Market design options

Option	Seller	Buyer	Market	Notes
1	List sales	List buy orders	Match buy orders to sales	Overheads for matching all buyers against all sellers
2	List sales	Directly assign buy orders to sales	Determine which buyer gets which sale	Reduced overheads for matching buyers against specific sellers
3	List sales	Bid on sales	Bids are frozen at the end of trading and the highest bids win	High bidding overheads under large-scale trading
4	List sales	Purchase sales	First come first served basis	Network latencies will have large effect on sales

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

While option 4 supports a truly open market, where a product can be listed for any price and any buyer can instantly purchase that product, it does not apply well to electricity mainly due to network latencies playing such a large role in sales.

An auction mechanism as described in option 3 would likely allow significant control to users of the system, but was removed due to the overhead that would be created if used on a large scale.

The final options, 1 & 2, are quite similar, but again due to possible increased overhead for minimal improvement, option 1 was removed and the project settled on a variation of rank order list matching to fit option 2.

This type of matching typically sees two groups, each member of each group has a list defining their preference over the other parties in the other group. These two lists are then used to determine how the participants from each group are matched. This will be detailed further in the algorithm section.

With the trading process defined, it is then possible to structure the trading periods by splitting it into defined sections. As the system is planned to use a DLT approach, a number of sections were also needed to allow for this. The final sections that were defined are shown below:

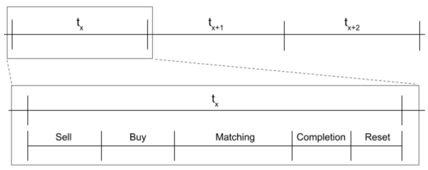

Fig. 1: Proposed structure for p2p trading periods

The purpose of these sections is described below:
Sell: In this period participants will place their sell orders.
Buy: In this period buyers would list interest against the sales created in the Sell 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 time period.

3 Algorithm design

With a market structure in place and an algorithm picked for the matching procedure the next stage was to implement it. This section will take you through the design decisions that took place while implementing this algorithm and the considerations that need to be made when automating trades for a peer-to-peer electricity market.

3.1 Considerations

An integral element of this system is the distance charge. It was added to the system to serve two purposes. Firstly, to pay for the infrastructure necessary for the electricity network to function including any other obligations that need to come through the sale of electricity. Secondly, to differentiate each sale from one another. Whereas in a traditional commodity market, from a consumer's point of view each unit is thought of to be identical to enable the market to function correctly. The distance charge serves the opposite purpose, intending to differentiate each sale. The reason for this is that while electricity is identical from all sources, transmission loss and other associated costs are largely dependant on the distance it travels.

3.2 Preferences

A primary objective of this research is to provide a mechanism to increase choice over electricity source. The current system already allows choice over price, but there is limited choice that accurately reflects real-time wholesale prices. Generation type is already partially supported with suppliers selling products that are backed by renewable sources. Distance is not supported at all, as in the current system electricity is seen as a commodity in which each unit is identical from a consumer's point of view.

To incorporate these into the algorithm, each participant was given a method to specify a number of preferences that allowed them to control the way in which they were matched by the market. In the same way, sellers were also given a number of preferences to allow them to control the way in which their sales were matched. The preferences included **for sellers** are (i) Minimum price preference and (ii) Distance preference. Preferences **for buyers** are (i) Maximum price preference, (ii) Distance preference, and (iii) Energy type preference.

These preferences are used as a means to create scores between the market participants creating the rank order lists for each.

3.3 Scoring

The scoring module of the algorithm dictates how matches are made and so was designed as an independent module allowing it to be replaced whenever needed allowing easy testing of different calculation methods. Below, the calculations used for the current implementation are shown.

In this section a number of letters will be used throughout to improve readability of equations. Firstly, B and S will be used to represent buyer and seller respectively and these letters may be appended to other letters, such as P_b referring to buyer's price preference and P_s referring to sellers price preference.

Other letters:

P	Price preference
D	Distance preference
E	Energy generation type
C_d	Distance charge
EP()	a function returning the energy type preference given an energy type E
d	distance

The scoring system used needs to incorporate the preferences that were previously mentioned. For each of these preferences a different method was used, this section will go through each. To begin it is first necessary to calculate the distance between the participants to allow for the score to be calculated. This was implemented by adding a latitude and longitude to each participant and then using a great-circle calculation to determine the distance between the two points.

3.3.1 Price preference

The price preference is used as a method to create an initial score between the participants. By using the price preference of both the buyer and seller and including the distance charge we can create a basic score that also reflects the maximum price that the buyer is willing to pay for the given sale.

$$score = P_b - (d \times C_d)$$

This current score only takes into account buyer preference. To incorporate seller preference as well, a check is added to ensure that the maximum price that a buyer is willing to pay is above the minimum price they are looking for. This means discarding all scores in which $score < P_S$.

3.3.2 Energy type preference

Allowing householders to specify the energy type they prefer provides a significant benefit over the current system in which electricity sources are indistinguishable. This preference allows individual preference to be given for each microgeneration energy type: solar, micro CHP, wind, hydro, and anaerobic digestion. Each of these individual preferences is normalised to 1, thus the energy type preference is included by multiplying the score by $score = score \times EP(E_s)$

3.3.3 Distance preference

To incorporate distance preference a simple check is added to determine if the seller is outside of the buyer distance preference. If it is farther than the preference, then a multiplier is added to the score so as to reduce the score more as the distance increases. The reason for this is to not create an abrupt range within which a buyer searches for sales, instead allowing sellers outside to still be considered.

$$score = score, d \leqslant D_b$$
$$score = score \times (D_b \div d), d > D_b$$

Again, to incorporate the seller preferences we must add a second stage. This can be added by reversing the buyer distance preference system.

$$score = score, d \leqslant D_s$$
$$score = score \times (D_s \div d), d > D_s$$

3.3.4 Final score calculation

After each section described above had been incorporated this gave a final method for calculating the score between two participants as:

$$score = (P_b - (d \times C_d)) \times EP(E_s), d \leqslant D_b, d \leqslant D_s$$
$$score = (P_b - (d \times C_d)) \times ((D_s \div d) + EP(E_s)) \div 2, d \leqslant D_b, d > D_s$$
$$score = (P_b - (d \times C_d)) \times ((D_b \div d) + EP(E_s)) \div 2, d > D_b, d \leqslant D_s$$
$$score = (P_b - (d \times C_d)) \times ((D_b \div d) + (D_s \div d) + EP(E_s)) \div 3, d > D_b, d > D_s$$

3.3.5 Implementation

As noted, our algorithm is adapted from a traditional rank order list matching. Here:

1. Seller exports are listed as sales
2. Buyers are assigned to all sales for which their preferences suit and a score is assigned between the two. This score acts as a method to create rank order lists for both the buyer and the seller. For buyers, this is the list of sales they are assigned and their respective scores and for sales this is the list of interested buyers and their respective scores.
3. The highest scoring buyer for each sale is assigned as an initial match to this sale.
4. The highest score of all initial matches for each buyer is chosen to realise a sale.
5. The algorithm then repeats from step 3 until there are no buyers assigned to a sale, no more sales or there is no remaining consumption to satisfy from buyers.
6. This algorithm performs an individual based optimisation but can easily be modified to incorporate other types of optimisation (e.g. a score maximising algorithm to allow for market level optimisation).

4 Preliminary evaluation

To assess the performance of this algorithm a JavaScript simulation was implemented. As we aim to assess the performance of the algorithm (and not to accurately simulate an electricity market) a number of generators were created to automate the creation of the accounts and simulate their generation and consumption
Simulation configuration: The accounts were randomly generated for each simu-

lation to ensure that the algorithm functioned correctly regardless of the accounts it used. They were assigned a random location inside an arbitrary area in the UK, with latitude between 50.956870 and 52.438562 and longitude between -2.386779 and 0.292914. A percentage of these were assigned to be prosumers. Price preferences were randomised; for prosumers, minimum sell price set between 4-6p/kWh and for consumers maximum purchase price set between 14-16p/kWh. Distance preference was set for all accounts between 5-10km. Energy type preferences for consumers were randomised between 0.5-1 and then normalised to 1 between all preferences with the highest preference being set to 1. Lastly generation type for prosumers was randomised to reflect figures from UK microgeneration installations [1].

Simulations were run for 16 different scenarios, where the percentage of prosumers in the market ranged from 5% to 20% in 5% increments, and the number of participants ranged from 500 to 2000 in increments of 500. In all scenarios the prosumers generated between 5-10 kWh of electricity and consumers consumed between 1-6 kWh and the distance charge was set to 0.2p/km/kWh. Each scenario was run 50 times and then averaged and the results can be seen below.

Simulation results: Here we assess the algorithm and its performance.

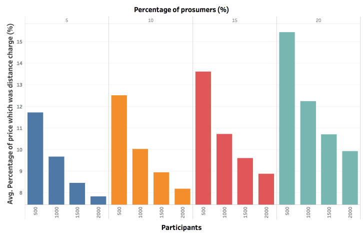

Fig. 2: The percentage of the price paid which was distance charge for each scenario

Figure 2 demonstrates how the distance charge is affected as the market changes. It is important to note that the percentage of distance charge is directly related to distance during this simulations and therefore an increased percentage of distance charge directly relates to an increased distance between sales. It can be seen that an increase in the number of participants in the market decreases the average distance between sales. This is likely due to a decreased average distance between participants through increased density and shows that the algorithm is performing as expected, incentivising the use of local generators.

A point to be noted is that with an increase in the number of generators, there is an increase in the distance between sales. This was a more surprising result, but could explained by a decrease in the average price paid shown in figure 3.

Another important characteristic of the algorithm can been seen in Figure 3, which shows how the price per kWh is affected through each scenario. This figure shows that the algorithm reflects the standard economic model of supply and demand. As the number of participants (demand) increases, competition increases and this increases the average price paid. At the same time it can be seen that with an increased number of prosumers (supply) a decrease in the average price occurs.

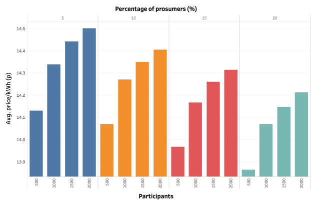

Fig. 3: The average price paid per kWh in each scenario

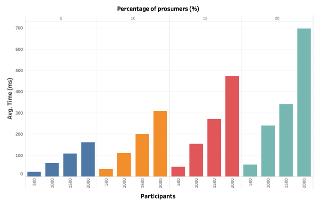

Fig. 4: Average time taken to converge for each scenario

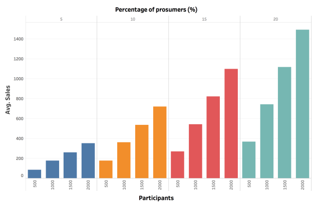

Fig. 5: The number of sales that took place in each scenario

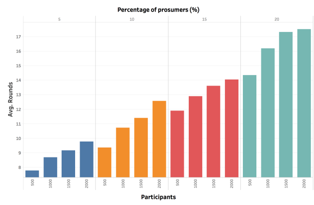

Fig. 6: Average number of rounds taken to converge for each scenario

Figures 5, 4 and 6 assess the performance of the algorithm. It can be seen that as the number of participants increases, the number of sales, the number of rounds and the time taken all increase linearly. The time taken though increases with a significant gradient and thus could pose a problem with a large number of participants. As the current simulation is running synchronously it may be possible to reduce through parallelisation and caching mechanisms to reduce calculations per round if it was to be scaled to millions.

The final important piece of information is the amount of unsold generation throughout the simulations. With 5%, 10% and 15% of participants as prosumers there was no unsold generation, but as the share of prosumers increased to 20% a small amount of generation was unsold (Fig.7). Yet, as the number of participants increased further, this unsold generation again dropped to zero. This is likely due to the large area used in simulation, leading to large distance between participants, with some generation unsold due to high distance charge effect.

These evaluations allow us to conclude that the algorithm is functioning as originally intended, incentivising the purchase of locally produced electricity, minimising the electricity that is left unsold and encouraging competition. We have also seen that while at a low number of participants (thousands) the algorithm will converge in acceptable times, large scale use (millions) would likely require some alterations.

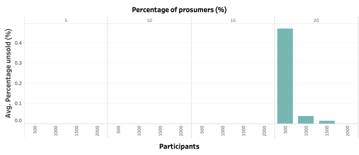

Fig. 7: Average percentage of unsold generation for each scenario

5 Conclusion and future work

This paper has presented a new approach to buyer and seller matching in a p2p electricity market. Through simulations we have shown that the algorithm performs acceptably, reducing unsold electricity to almost zero, incentivising the use of locally produced electricity, accounting for individual preferences and encouraging local purchases, but may require alterations for large-scale implementation.

As this research continues: real locational data will be added to the simulation to help locate areas that would benefit most from this type of trading mechanism and remove the unrealistic spacing between households; and energy data will be added to conclude the quantitative benefits to both buyers and sellers that can be achieved using this algorithm.

The next stage of this research will investigate alternative algorithms to look beyond purely individual optimisation to allow for group based optimisation and optimisation of the market itself.

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Appendix D

Enabling peer-to-peer electricity trading

A poster paper was published at the 4th International Conference on ICT for Sustainability and presented at ICT4S 2016 detailing the initial concepts and architecture of the ETP platform. Content from this paper is not included within the report and is separated to allow the dissertation to remain focused on the topic.

4th International Conference on ICT for Sustainability (ICT4S 2016)

Enabling peer-to-peer electricity trading

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***Abstract*—Due to the recent advances in household-level renewable electricity generation technology, a new type of market based on peer-to-peer (P2P) electricity trading between households will emerge. This poster presents a technical platform which will enable such a market to function.**

***Index Terms*—Blockchain, peer-to-peer electricity, smart grid, microgeneration.**

I. Introduction

Electricity production and supply has traditionally been, and still remains, a majority centralised system, with Major Power Producers (MPPs) making up 94% of electricity production [1]. In this system, MPPs generate electricity that is fed through the grid to individual households. However, this situation has already begun to change with the increased adoption of *microgeneration* [2], i.e., production of heat or electricity on a small, local scale, with domestic energy producers taking a much more active role.

Instead of the current centralised system, we could see consumers with microgeneration selling their electricity on a peer-to-peer (P2P) network to other individuals or organisations on the grid. Here, households are more than *prosumers*, as while they do produce and consume their own electricity, they also sell it to others on a free market. Essentially, households become small energy suppliers, hereafter referred to as *household* or *domestic suppliers*.

This poster provides a deeper insight into such a P2P market and outlines a design of a technical platform to support it.

II. Changes to the electricity system

Because of the small amounts of electricity produced by domestic suppliers and their likely supply intermittency, due to their renewable-based production, there would have to be significant differences between the current system of energy supply and consumption and the one envisioned with a greater installed capacity of microgeneration:

- Instead of sourcing their electricity from a single supplier, consumers would buy and sell electricity across an open market, essentially *swapping their energy supplier on a minute-by-minute basis*.
- Households will be able to buy electricity based on a their own personal preference, whether it be distance from the generator, type of generation, or just to buy at the best price.

To enable this, a P2P trading platform (hereafter referred to as *the platform*) would need to be created in which households could market their electricity exports for other households to buy. Once the platform is in place, optimisation methods could be developed to automate the trading process to either increase monetary benefits, support local generators, or even to smooth load curves on the grid as a whole.

Electricity transmission causes energy losses, and the further electricity travels, the more of it is lost [3]. If the true cost of losses were reflected in sale price then generators would be able to offer a better price to nearby customers. This could benefit both the environment and customers. Thus, the **key benefits** for domestic suppliers using this platform are:

- Ability to exercise independent choice on the purchase and sale of electricity according to their personal preferences and needs;
- Added monetary benefits through optimising for the most favourable energy transactions at any given time;
- Increased independence from the grid in case of power supply issues from MPPs.

III. Requirements of a peer-to-peer market

In order to develop and enable P2P trading of electricity, a number of steps need to take place:

- Microgenerated electricity needs to be verified, with the generation time and amount recorded. This is required, as the price of electricity varies over time based on supply and demand.
- Each unit of electricity must only ever be represented by one token on the network.
- Trades must be traceable and auditable to enable electricity suppliers (domestic and otherwise) to accurately calculate bills.

IV. Platform design

We have selected blockchain technology as the solution of choice for the platform, as it provides a decentralised, distributed ledger in which all transactions are immutably recorded. It relies on cryptography to ensure transactions are secure, authenticated and accurate [4]. Thus, it could support the delivery of an energy trading mechanism that meets the above requirements.

The platform is comprised of a number of components that work together to enable a decentralised, open market. These

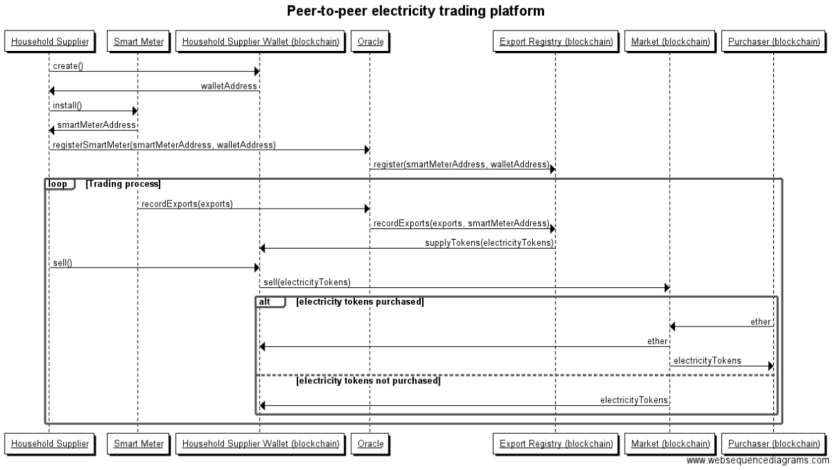

Fig. 1. Trading process sequence diagram

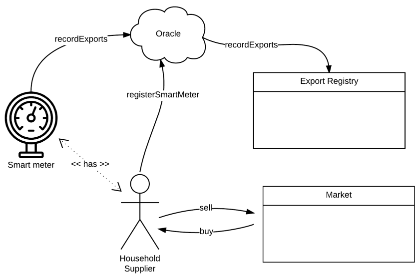

Fig. 2. Platform structure from a household supplier's perspective

components and how they communicate with one another are shown in Fig. 1 and Fig. 2.

Here, a **household supplier** is a micro-generator that produces electricity, uses some of its own product, sells excess and purchases electricity on the market when its own generation falls short. Each household supplier has a **smart meter** installed which records electricity consumption and generation data. This data is then passed to an **oracle** that manages the movement of content from the real-world on to the blockchain. In this case, the oracle tokenises their electricity generation and associates it to a household supplier's address on the blockchain ledger. This tokenisation would allow the generation to be represented as a sub-currency on the network so it could be traded (e.g., 1 token per kWh generated). For the oracle to perform this task, householders would first need to register to the oracle to associate their microgeneration equipment with their **wallet** address. During this process the oracle would also perform a quality assurance check to ensure their equipment was installed by a registered installer and has been certified. It would do this by checking scheme's such as the Microgeneration Certification Scheme [5].

Each household supplier that trades on this platform must have a **wallet** on the blockchain which provides an address to identify that supplier on the network.

The trade balance of each participant on the platform is maintained by a smart contract known as the **export registry**, and the electricity trading is enabled through a smart contract called the **market**. In Fig.1, the selling household is represented as the supplier, while another participant that is looking to purchase electricity is called the **purchaser**.

V. Conclusion

As the uptake of microgeneration increases, there is a possibility to provide significantly more control to consumers on the grid. This paper explored one way this could be achieved through the development of a new peer-to-peer electricity trading platform.

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