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A Blockchain Energy Trading Platform For Microgrids

by

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MSc Artificial Intelligence

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Abstract

The ongoing decarbonisation of the electricity sector is causing an increase in the renewable energy sources integration as they are seen as a way to reduce our dependency in fossil fuels. The current energy system networks were not originally designed for a high integration of variable generation technologies. These therefore cause problems due to their volatility and non-controllable generation. This work will investigate the use of peer-to-peer energy market platform to be used within microgrids as a contingency to solve these problems. The rise of prosumers, both consumers and producers, has been caused by the increasing affordability to invest in domestic solar systems. Hence, consumers and prosumers can trade within their communities to better manage their demand and supply as well as providing socio-economic benefits. The use of blockchain technologies is implemented to develop a energy trading market platform while following a micromarket setup based on the Brooklyn Microgrid project use case. The Ethereum blockchain technology is used and a cost analysis comparing to the current energy system to the blockchain micromarket setup is presented. The continuous double auction and uniform-price double sided auction mechanisms are implemented with two different architectures. A simulation of these are experimented on the micromarket setup and differences are discussed. It is observed that the continuous double auction yields a more favourable mechanism to be implemented within the smart contract limitations of the blockchain, and offers a cheaper solution than using the current energy systems. Finally, it is concluded that blockchain technologies are an eligible technology to be used within the microgrid energy markets, as they provide a decentralised, trustless and secure information system, that fits the requirements for smart-grid integration.

Acknowledgements

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Abbreviations

P2P - Peer-to-peer

RE - Renewable Energy

RES - Renewable Energy Sources

PV - Photovoltaic

EV - Electric Vehicles

DNO - Distributed Network Operators

DSO - Distributed System Operators

DER - Distributed Energy Sources

PoW - Proof-of-Work

PoS - Proof-of-Stake

PoA - Proof-of-Authority

ICT - Information Communications Technology

EMTS - Energy Management Trading System

IoT - Internet of Things

Chapter 1

Introduction

1.1 Introduction

Recently the world's electricity systems and energy market have been driven by decarbonisation, decentralisation and democratisation. The trend of the "three Ds" stems from the growing problems of the electricity grid. Decarbonisation has been an increasing issue with the need to move away from fossil fuel energy sources in order to reduce CO2 emissions in the fight to mitigate climate change – this is happening both in the way we generate electricity and heat. Decreasing dependency on fossil fuels is part of the regulatory plan in the UK. The first regulatory act was the Climate Change Act that was passed in 2008, committed to reduce greenhouse gas emission to at least 80% by 2050 compared to 1990 levels, determined by 5 yearly carbon budgets [1]. This was followed by the recent 2015 Paris Agreeement which was signed in an attempt to unite over 90% of the global economic activity to agree in keeping the global temperature rise below two degrees. Furthermore, the current centralised system causes large amount of energy losses in power transmission due to long physical distances between generation and consumptions sites [2]. Thus leads us to the need for decentralisation to avoid these inefficiencies and transition from a centralised system to a more decentralised way of generating and locally controlling our demand and supply requirements.

The increasing integration of renewable energy sources (RES) has a deep impact on the national grid due to the variable nature of these sources. This is a problem that will only get accentuated, as there is an exponential growth of installed solar capacity worldwide (Fig. 1.1), providing a dramatic decrease in the prices of technology (Fig. 1.2). With the research development of areas such as electric vehicle and energy storage within the grid and also solar PV along with onshore wind, have been driving down the prices of battery storage exponentially, opening up the doors to new opportunities for domestic investment. Individuals are no longer just consumers, but are actively taking part in the productions of their own energy and collectively feeding electricity into the grid. These are what can be called prosumers, both consumers and producers of energy. The inevitable rise of the number of prosumers will increase over the years in line with the decentralisation and democratised reformation of the energy space, in which large companies will no longer be the only ones with a stake in the energy space, but the public as well. This new movement creates a range of opportunities to reform the centralised way of managing today's grid, one of which is the possibility to introduce the ability to react in real time to the intermittent generation and volatility of the RES in the current wholesale market. The way these prices are determined does not reflect scarcity and surplus of energy at a local level.

Microgrids can be constructed by agglomerating small-scale participants, whether they are prosumers or consumers, to form a local energy market and trade energy within their community. This scenario can help with reflecting the real-time prices of energy, and facilitate a sustainable, reliable way of locally balancing generation and consumption. Additionally, these initiatives can help communities become more self-sustainable, ecologically and economically.

These systems need a secure, reliable and transparent information system to manage these markets, helping with their local energy balancing needs and providing a user friendly application for people to use. This enables customers with a choice in which technology is being used to generate their energy while providing a reduced energy price in comparison to the existing grid prices. This dissertation will investigate the use of blockchain technologies to build a peer-to-peer energy trading system to explore their applicability in this domain as well as providing insights in their associated costs and limitations.

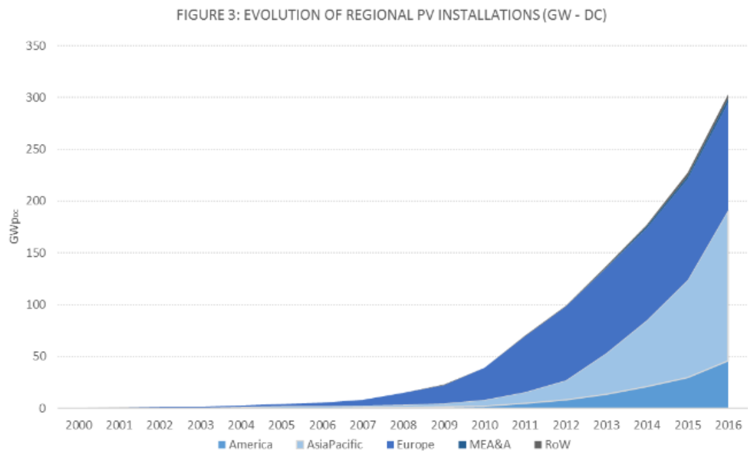


Figure 1.1: Illustration of growth of photvoltaic installed capacity across the world [3].

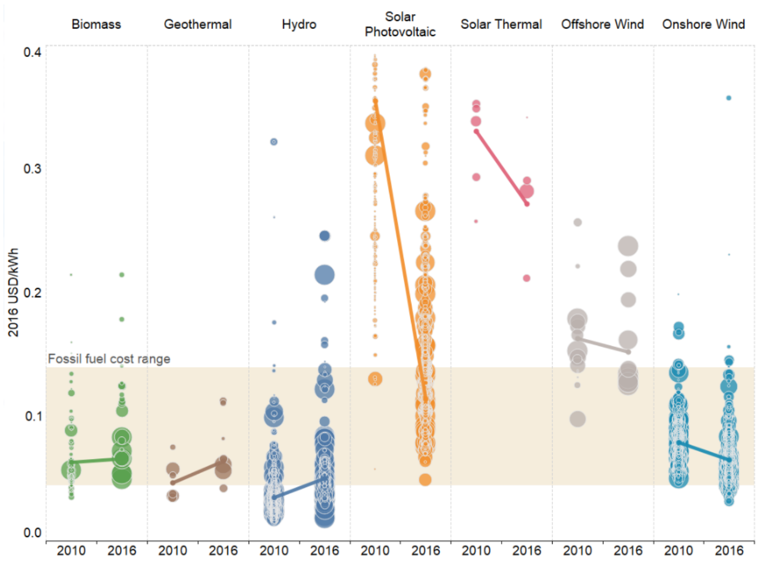


Figure 1.2: Shows the decline in prices for different renewable energies from 2010-2016[4].

1.2 Overall Research Aim and Individual Objectives

This project aims to design and develop a decentralised application that would allow energy trading in a peer-to-peer fashion. The aspiration lies not on trying to develop a ready for deployment product, but to design it in a way in which different architectures and methods can be implemented and simulated. The development of this application could therefore provide some insights into the potential benefits and limitations of using blockchain technologies along with its effectiveness as an information system to integrate different subsystems involved in microgrids. Finally, this work will also discuss the economic benefits of using a microgrid P2P trading platform in the point of view of the customer. This will then be compared with the costs of using the current energy system.

The objectives of this work include:

- Development of the two main components of a micromarket setup:
  - Information System.
  - Market Mechanism.
- Development of a simple Energy Management Trading System to enable the functionality of performing a trading simulation over real household data.
- Perform a cost analysis of using a decentralised approach compared to a centralised approach.
- Identification of benefits and limitation of using a decentralised approach.

This area of research brings together a large number of disciplines and topics, therefore, there will be a number of areas that this dissertation will not covered. This work will try to set the scene of a microgrid blockchain-based implementation, however, it will not try to accurately represent all the factors that are part of the microgrid energy management, costs and distribution. Lastly, the volatility of cryptocurrencies will not be considered in the design of this system as it is outside of the scope of this project.

1.3 Project Management

A Gantt Chart was made to outline a planned schedule at the early stages of the project, providing an idea of the order in which tasks were tackled - can be found in [Appendix A]. It is constituted of four main phases, research, design phase, integration and optimisation and deliverables preparation.

Firstly, three weeks were spent on research energy market design and market mechanisms, while researching into using the Ethereum's blockchain and learning about solidity (smart contract programming language) and how to use it.

The design phase was supposed to last around 4 weeks in order to choose appropriate market mechanisms along with the way the pricing of energy was going to be decided. The pricing of energy and applicable market mechanisms were the tasks in which some time was lost as they required more thought than initially planned.

The implementation and optimisation phase comprised of developing the actual application in which the market mechanism, the blockchain technology, the energy management trading system as well as the simulation algorithm were developed and integrated. This phase required slightly more time as some time was lost in the design phase, which could've been used to attempt to fix the problems with the continuous double auction mechanism and testing.

Finally, the deliverables preparation involved writing necessary notes along the duration of the summer project and was scheduled to be done along the completion of each phase.

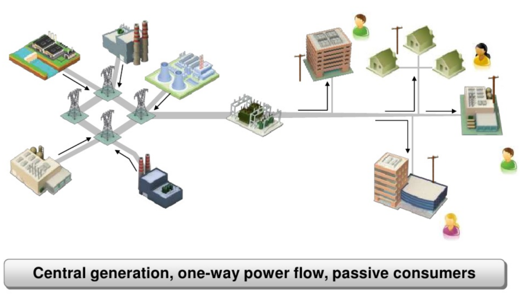
Overall, the plan was correctly followed as planned, with some minor delays in relation to design phase of this system of which the time could've been useful for the implementation phase.

Chapter 2

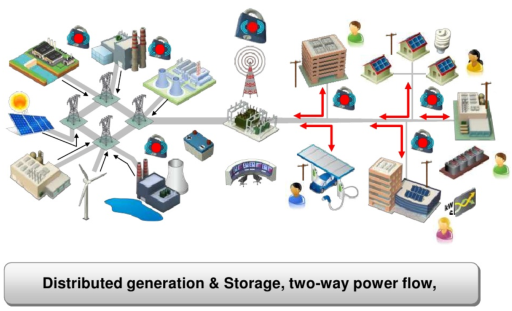
Background

2.1 Current state of National Grid

The current state of the national grid in following a massive reformation due to new technological advancements and distributed intermittent generation. The current infrastructure of the national grid is ageing and has been mainly built to support one way power flow. It is a centralised system where energy is generated in power plants, transmitted over long distances to consumptions sites, where consummers are majorly passive (Fig. 2.1(a)). We're moving to a more distributed network (more complicated), in which generating will no longer only come from power plants, but houses with solar photovoltaic panels (PV), electric vehicle(EV) charging stations (that can act as storage), locally produced wind power, and other RE technologies. This causes a situation in which power will flow bidirectionally, something the current network/infrastructure was never designed to do. This presents a particular problem in ancillary services at major transmission link levels [5]. However, this doesn't only entail existing wires and transformers exists, but the need for a new control architecture. This control architecture requires to be able to intelligently integrate different generator entities (producers of energy) and consumers in order to efficiently allocate the electricity supplies in an sustainable, secure, and economic way.



(a) Illustration of today's power system, mainly comprised of central generation, with one-way power flow from generation to consumption [4].



(b) Illustration of tomorrow's power system, a system that would need to adapt to a more distributed generation and storage which would have to handle the capability of two-way power flow[4].

Figure 2.1: Figure illustration comparing today's power system compared to what tomorrow's power system will look like.

Discussed heavily in the smart grid debate, there's an interest in enabling flexible trading which optimises the supply and demand of RE as locally as possible. Opening up the market for domestic consumers to participate in the whole sale market in half hour intervals so the prices of energy can be reflected to the consumers. A shift is in an attempt to achieve the goal of having a smart grid, is the part of the UK plan to transition from Distributed Network Operators (DNO) to Distributed System Operators (DSO). The definition is stated as:

- "A Distribution System Operator (DS) securely operates and develops an active distribution system comprising networks, demands, generation and other flexible distributed energy resources(DER)."
- "It acts as a neutral facilitator of an open and accessible market, enabling competitive access to markets, and the optimal use of DER on distribution networks to delivery security, sustainability an affordability in the support of the whole system optimisation."
- "It enables customers to be both produces and consumers; enabling customer access, customer choice and great customer service [6]."

Redefining these changes to local electricity networks will enable new opportunities for households and businesses to engage in the energy market. This will provide them with greater control over their electricity and unlock the possibilities of introducing new technologies such as battery storage and electric vehicles into their lives [7]. This shift and redefinition has been really important as the current infrastructure and architecture experiences large inefficiencies in the transmission and distribution of energy. An excellent figure was produced by the UCL RCUK Center for Energy Epidemiology which illustrates these large inefficiencies in the network using a Sankey Diagram (Fig. 2.2).

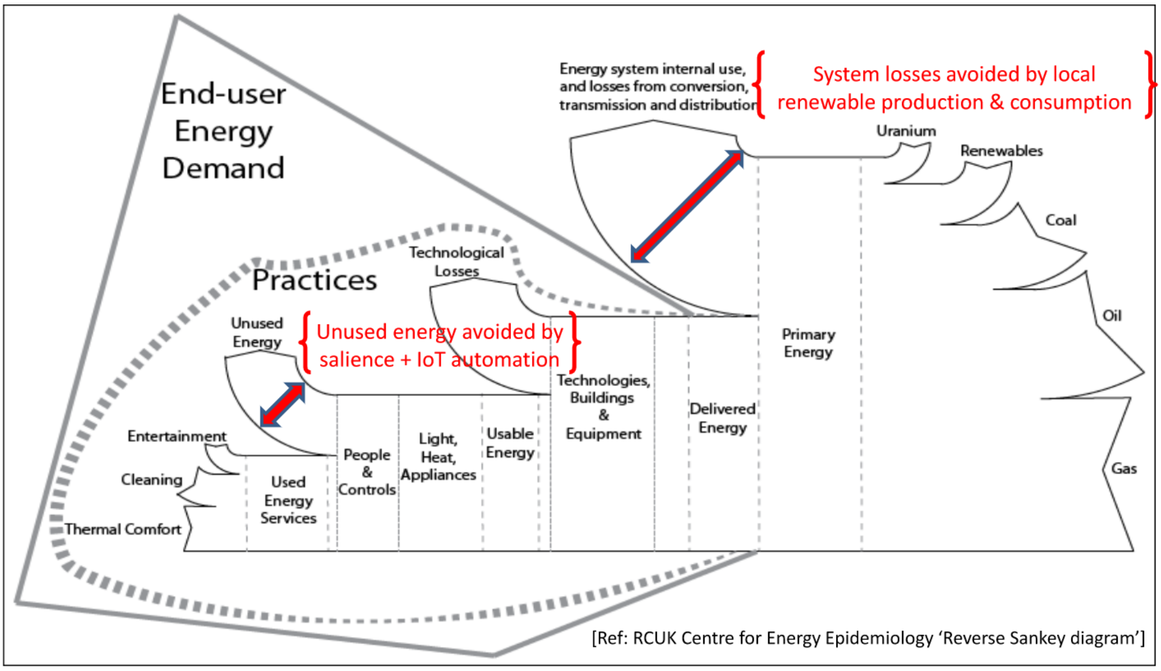


Figure 2.2: Illustration of current inefficiencies in the energy grid today with the end-user energy demand perspective. [2].

The large losses experienced on the primary energy side are associated with the combustion of fossil fuels through their conversion to electricity as well as the transmission and distribution of the power on to the network. By matching demand and supply locally, it could drastically minimise that portion of energy losses.

Furthermore, the unused energy on the end-user side could be reduced by energy salience - a term coined within the field of social science which highlights awareness and mindfulness in people's actions. This is a phenomenon that is noticeable when people start producing their own energy and become more aware and careful of the energy they are using, therefore, starting to shift their energy consumptions to times in which it serves to meet their respective supply. Along with that factor, the introduction of automation through internet of things (IoT) devices - e.g. sensors that automatically turn lights/electrical devices off when people are not around - can be a big driver in reducing energy consumption across the network.

A different perspective on the problem of the balancing services is shown in Figure 2.3. The increasing generation of solar, introduces large amounts of generation in times there is low demand, thereby causing this duck shape curve that has been recorded in the California's electric grid [8]. More extreme cases have also been recorded in Germany, which has been at the forefront of solar generation adoption. The increase amount of investment into solar and wind from the German iniciatives as been beneficial for the reduction of environmental damage but has come with a caveat attached to it. Germany has experienced unexpected negative prices for electricity, where they produce too much when there is not enough demand, causing them to have to pay to be able to 'sell' their product. These negative prices can be blamed by the addition of RES, however, the inflexibility of conventional power plants are equally responsible [9]. Changes to power plants need to be implemented in order to be more responsive to changing conditions on the power market, improve forecasting operating capability and incetivise large-scale consumer to ramp up demand when prices are low . Ultimately, these situations would be met by energy storage capabilities, however although the prices of this technologies are quickly decreasing, their capability to handle such large amount of energy are still far from being met [8]. These situations also highlight the need for a more interconnected grid following the IoT mind set. One day, when the infrastructure is in place, they can work to be part of the solution.

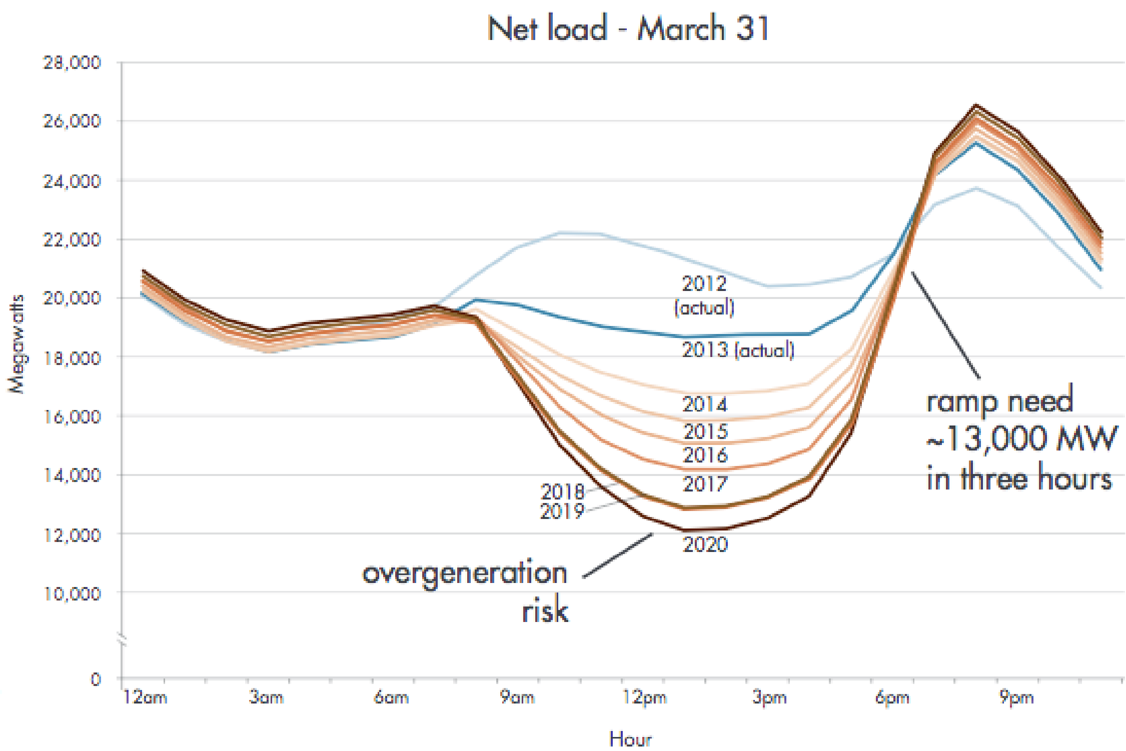


Figure 2.3: Illustration of how the demand curve has been changing over the years - forming a duck shape. [8].

Smart grid hardware such as smart meters have been a large catalyst for potential benefits in moving to more semi-autonomous networks, as they enable the possibility of automatically feeding real-time data of load and supply relating to end-user customers - whether domestic or industrial. They can be used for more complex information, such as optimising energy consumption patterns, adapting to them and using these to optimise the price of energy as well as controlling the parameters of the applicances in their houses by using the customer generated energy profile [10]. These will play a large role in the desired ecosystem and framework that the UK planned to achieve, hence, this dissertation will base itself on the existence of this infrastructure to design it's own architecture.

A bigger picture of the current state of the regulatory environment and outstanding issues with the current control architecture and infrastructure of the national grid have been outlined, leading to an investigation of what microgrids are and what potential benefits they can bring to the discussed issues.

2.2 Microgrids

The use of microgrids have been mentioned in academia for quite some time, however, currently there have been an emerging amount of demonstration sites and research into testing it's authenticity and utility in its introduction to the current energy system [11]. The U.S. Department of Energy by the Microgrid Exchange Group have defined microgrid as:

"A group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode [12]."

There are three main concepts presented in this definition. It makes a clear distinction from the distribution system comprising a microgrid and the rest of the grid. The resources produced and consumed within the microgrid are controlled within it, but can be connected and integrated within the grid. Finally the microgrid can also function regardless of whether it is connected to the grid or not. These concepts help understand what value a microgrid can bring to the current energy systems. To touch on the first concept, a microgrid satisfies the possibility of connecting various distribute energy resources (DER) in different areas of the grid as one single controllable entity. The second concept identifies that microgrid can help with the balancing of demand and supply locally, as they can manage and control themselves, which satisfies the need for the national grid to manage this as locally as possible and to produce energy located close to points-of-use. Although they are able to do this, they may require external help to fulfill their energy requirements, which can be satisfied by their integration to the grid. Lastly, it is important to note that the definition doesn't declare which types of sources are needed, or the size, which means that any DERs could apply.

Microgrid can help with resilience, reliability and power outages of the superordinate grid in situations where an electrical microgrid is built in addition to the existing distribution grid. They can also help reduce the latency for managing congestion, the distribution faults while reducing the losses involved in energy transportation by satisfying demand locally [13]. Furthermore, the decentralisation structure of a microgrid can helps with cyber attack resilience, as it is more difficult to the attack the main infrastructure. Finally, there are studies showing that interconnecting multiple microgrids can contribute to an even more reliable balance of supply and demand, whilst providing a more active market than an isolated microgrid[14].

The decrease in prices and incentives in the regulatory environment have lead to an increased adoption of the DERs which create a rise in prosumers within communities. In this scenario, it is beneficial for communities to create microgrids where these small scale participants can take part in a peer-to-peer market in which the local prices of electricity can be reflected and the demand and supply can be locally balanced. This is especially important with RES due to their intermittent nature. Hence, there is a need for flexibility of the demand and generation which can be provided by storage capacities [15], otherwise the microgrids would not be able to operate in island-mode for extended periods of time. This emphasises the importance of the lower prices of energy storage in its contribution to making microgrids a more common reality. In addition, the introduction of smart devices such as smart meters is key for the control architecture, as these devices are able to relay information from the consumers to the microgrid in real-time. Therefore, the control systems can be aware at all times of what energy is available, whether in instant generation or storage, as well as the levels of demand across the different interconnected parties.

The concept of exchanging energy within communities has been put forward as "Transactive energy" from the U.S. GridWise Architecture Council - as you actively transact energy between parties. Similarly the French initiative of 'Community self-consumption' introducing a regulatory framework to make it so that people are allowed to consume their energy locally. The distributed network operators will therefore need to facilitate people consuming their own energy and incentivise communities installing new systems under a certain capacity by receiving a feed-in-tarrif mechanism [16][17]. Aside from the reasons already stated, these concepts have some additional humanitarian benefits. By building such local markets, it builds stronger communities, and provides skills, training and experiences for people to learn how to use their energy (local energy resilience). This would cause them to shift their use of energy to match their local production, thereby helping with the self sufficiency and sustainability of the system. Lastly, these markets can help improve the local economy as the money is kept within the community as it is exchanged internally.

The successful operation of a microgrid market require the implementation of innovative, secure and smart information systems. As this movement of distributed generation and decentralisation is underway, it makes sense to have look at decentralised information system to support these markets. This is where blockchain technologies can be of benefit to the energy space, and this dissertation will investigate the possibility of integrating blockchain technologies to exploit some of its desired capabilities.

2.3 Blockchain Technologies

In this section an introduction to blockchain architecture will be presented along with the features that it offers, and how they fit in with the smart grid use case. Blockchain technologies are an emerging information technology that offer a trustless, fully decentralised peer-to-peer data storage system. The first use of Blockchain came around with Bitcoin in 2008, by Satoshi Nakomoto (pseudonym), following the 2008 market crisis [18]. This decentralisation movement has grown immensely over the years, as people are starting to want to gain back control over their data, diverging control from distributed participants rather than central authorities [19].

2.3.1 Blockchain Architecture

Blockchain is formed by a series of blocks which contain a record of transactions similar to a traditional ledger. Each of these blocks reference the previous block, or parent block, via its hash value (256-bit hash) thereby creating a chain of transactional records which can be traced back to the very first transaction ever made. Each of these blocks consist of a block header with the block version indicating the rules that are to be followed, the reference to the previous block, a Merkle tree root hash (used in Bitcoin) containing all the transaction processes within the said block, a timestamp, the current hash target and a nonce value which varies depending on the difficulty set by the blockchain at that point in time.

The blockchain, however, is not provided from a single server, but is a distributed transactional database with globally distributed nodes which are linked by a peer-to-peer communication network. These nodes are virtual machines that communicate via TCP and identify each other over IP addresses which reference each other via a public key. The corresponding private key is then used to cryptographically sign messages or transactions. Transactions, once included in a block and mined, according to the rules of the consensus algorithm are then validated by every node in the network in order to be finally added to the chain. The most trusted and reliable chain is the longest chain, thereby guaranteeing the validity of it because if nodes were to include invalid transactions, these would be ignored by the remainding nodes of the system [20].

2.3.2 Blockchain Features

Blockchain comes with a number of key features:

- Decentralisation - centralised systems control everything from one central system where they validate transactions and update their database accordingly, this causes bottlenecks in terms of security as it is easier to attack one server than multiple ones. Decentralisation in the blockchain means that there thousands of computers around the globe with a copy of the same database which synchronise at every set time interval to agree on the new state of the database, by a means of consensus mechanism (Proof-of-work in Bitcoin). This not only guarantees a more trustworthy version of the data, but also offers an increased resilience to hackers [21].
- Trustless - this characteristic provides a restlessness in the technology, as one no longer needs to rely on a third-party to validate/verify transactions, thereby reducing the costs associated with relying on these intermediary entities and increasing trust in the system for the user.
- Security - Due to the distributed architecture of the blockchain parts of the system can be attacked without putting the systems in jeopardy, providing a level security unforeseen in databases before, due to mining energy and scale, it becomes nearly impossible to tamper with in its public form. Falsification or double-spending is easily detected as blocks are validated by other nodes, and reference each other back in time.
- Privacy - Blockchain is privately secure with public/private key encryption. By using this mechanism; one that has a private key only known by himself, will have a unique identifier which can be compared to a notion of identity in the blockchain. The concept is that it provides privacy in the network as other people don't necessarily know who is being the keys that represent identity in the blockchain. However, with the rise of data analytics there are examples in the literature of privacy leakage using transaction graph analysis [22].
- Immutable - the architecure of the blockchain provides an elegant mechanism to prevent anyone from changing what has been agreed in the past. If someone tries to include or change data, or a transaction

from the past, the hash functions will change and it will cascade over the blockchain, thereby creating a fork. This is quickly rejected by the fact that people always follow the longest chain. Hence, unless some entity would have the computing power to mine the whole chain from the point of change, up the current block quicker than the rest of the world, the blockchain cannot be modified.

2.3.3 Blockchain Evolution

Blockchain technologies have over the last year gone through a tremendous hype cycle, this has brought what bictoin and cryptocurrencies into the attention of the public. This can be well visualised through the common Gartner Hype Cycle graph which describes the different steps in which a new technology goes through until it becomes productive [23]. Figure 2.4 illustrates where Gartner Group has placed blockchain technologies in this hype cycle, which explains that the technology has already gone through the peak of inflated expectations, and entering through of disillusionment. This indicates that we are at the point in which people have been brought to the attention of the technology, and are identifying and developing use cases in which it is applicable to use it in. It is important to highlight the origins and developments of technology to ensure that these developments are productive in the goal of mass-adoption rather than based on emotional hype and media coverage.

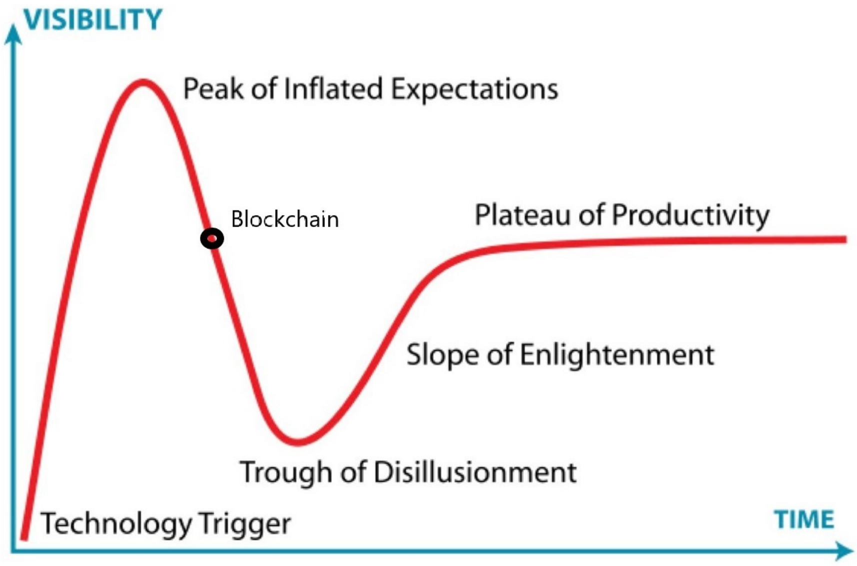


Figure 2.4: Illustration of where blockchain is within the Gartner's Hype Cycle [23].

Blockchain could be stated to having 'three phases' of evolution:

- Cryptocurrencies (e.g. Bitcoin [18])
- Smart Contracts (e.g. Ethereum [24], EOS [25], NEO [26])
- Decentralised Autonomous Organisations (DAOs [27])

Since the creation of Bitcoin, more networks and protocols have emerged that can process much more than just peer-to-peer transactions. New networks such as Ethereum, can execute complex business logic in the full security network. The pieces of code that can perform these operations are called smart contracts, which open up a range of new applications for blockchain. A smart contract can be described as a computerised transaction protocol that executes the terms of a contract. In essence, it is a piece of code which can contain data, its own balance of ether (Ethereum coins) and functions that can be triggered if the conditions/terms are fulfilled within it. Just like a participant in the blockchain, it has an address providing it a unique identifier [28]. Smart contract enables a more vast range of applications that can be built on top of the Ethereum network where they can interact with each other and achieve what has been referenced as a 'smart economy' [26]. These systems can revolutionise current transaction systems and enable fully decentralised market platforms [29]. The introduction of these smart contracts to the blockchain space is the kind of capability this dissertation will exploit, in order to investigate its utility for the energy space.

Blockchain 3.0 applications are attempting to go an extra step, and use the idea of intelligent contracts to create DAOs which operate and govern themselves with a high degree of autonomy. These projects aim to solve challenges such as, interoperability, scalability, governance and sustainability. The most well known project attempting to tackle these problems is Cardano which focuses on a research-first approach, in contrast to other cryptocurrencies where it aims at publishing their ideas and peer reviewing them before attempting to implement them. This provides a more robust process in advancement of these technologies, creating a platform for agreement and discussion in relation to these matters [30]. It will be interesting to see how these technologies unfold in the near future and if they can fulfill their very ambitious ideas that they have set themselves.

2.3.4 Blockchain types

It is worth mentioning that blockchain technologies come in different types, the blockchain that has and will continue to be referred up to this point, has been the public blockchain. However, there are also the existence of consortium and private blockchains. They differ by who is responsible to run the system and their permission capabilities for users. Public blockchains (e.g. Bitcoin and Ethereum) are run and can be accessed by anyone in the world, which offers a high level of decentralisation, security and immutability. These is however a con of having lower computational efficiency as so many computers have to agree upon incoming data, thereby making the mining difficulty harder. The consortium blockchain is a hybrid between public and private blockchain in the sense that some participants will have different rights than others. It requires fewer validators in the system, hence, it has a higher level of efficiency compared to the public blockchain. This kind of blockchain can be quite desirable for companies that work in the same domain as different entities, but require to access and share the same information (e.g. financial sector) - blockchain can provide a database that represents a single truth (avoids conflicts). Lastly, the private blockchain is only applicable for closed ecosystems in which a company/entity does not desire other people to have access to their database. Therefore, only participants that belong to this organisation, have access to it. This situation can be very close to being centralised, as it allows for the organisations to maintain a certain degree of control and offers a much higher level of efficiency for having even less validators, of which, in this scenario are known. It this scenario blockchain, there is no risk of a 51% attack, cheaper transactions, faster consensus algorithms and potentially a greater level of privacy [31]. However, this type of blockchain has the disadvantage of being less secure than the its public blockchain counterpart [21].

2.3.5 Blockchain Consensus Mechanisms

The blockchain verifies written information of its distributed ledger data according to a system-wide common consensus mechanism followed by all the nodes. The three mainly discussed algorithms in the microgrid implementation are Proof-of-Work (PoW), Proof-of-Stake (PoS) and Proof-of-Authority (PoA) [31]. The PoW consensus, reqruires miners to provide computational power in order to solve a "computational puzzle". This puzzle involves hashing the block data in combination with a nonce value in order to find a hash value to be below a targe value determined by the mining difficulty at that point in time. The miner that is able to find the solution to this puzzle first, gets to propose the new block, hence, this mechanism requires proof of computational work for the block to be accepted. It serves to verify the legitimacy of the included transactions as well providing an incentive mechanism to the miners. This process ensures a high degree of security but comes with a high energy inefficiency noted by [22] in which not everyone that put efforts in gets a reward, resulting on large amounts of electricity being expended.

The PoS mechanism, doesn't require miners to compete, instead, anyone stakes their blockchain coins by locking them in a deposit. These validators will then participate in the block creation process. In Chained-based PoS, the validator is pseudo-randomly assigned to create a block. In Byzantine-fault-tolerant PoS, randomly assigned validators are allowed to propose blocks which are then put up for a vote across the validators that agree or disagree. Block creators are then rewarded with the transactions fees included in the block. This consensus algorithm has the advantage of using less energy and being less prone to attacks. Disadvantages lie on the fact that the amount of stake, i.e. amount of wealth, affects the stake that the validator will have in the system, which can pose to be a problem. However, the algorithms in place such as the forthcoming CASPER, suggest that it will prevent this from being a problem by punishing malicious nodes (validators) [32].

The PoA mechanism, uses simple hash-based identification verifications to validate transactions and prevent corrupted agents entering the system. This authentification mechanism requires that every single identity to be confirmed and known. Hence, identities could potentially be verified by a centralised entity or authority in order to verify their existence and validity to participate in the market [15].

Chapter 3

Literature Review

3.1 Related Work

There is a large repertoire of literature relating to microgrids, their architectures, benefits and trials done around the world [11][33], however, this section will focus on projects in which the outcome was P2P energy trading platforms - a comparison is given in Table 3.1. Some of the following projects have different approaches, some similarly act as a supplier's role as others target more the local control and information and communications technology (ICT) layer for microgrid systems. Many of these projects are based around P2P trading, however, the following subsections will briefly cover the existing projects in which the outcome came as a P2P trading platform.

3.1.1 Piclo

Piclo is a UK based project. It comprises of a collaoration between the renewable energy supplier "Good Energy" and the technology company "Open Utility", where business consumers gain access to electricity directly from local renewable sources. Every half an hour electricity demand and supply is matched through the information given by meter data, generator pricing and consumer preferences. Businesses can select and prioritise which sources to buy electricity from, giving them the choice and knowledge of where their consumption comes from. On the other hand, the producers are also given the capability of seeing where and to who the electricity they are selling is going. Good Energy then provides the contracts, billing, meter data, and is responsible of balancing the market place [34].

3.1.2 Vandebron

Vandebron is a green energy company based in Amsterdam, Netherlands that has a platform which enables the direct trade between independent producers (focuses on farmers) that may have wind turbines, solar panels or even biomass. Producers can set their own prices, and customers can choose which energy source they want to be supplied by. By removing out the utility company, producers make more and consumers pay less. Important to note that vandebron doesn't produce energy itself, it simply provides the market platform for it. Similarly to Piclo, it acts as an energy supplier that links generators to consumers and offers balancing services for the market [35][36].

Project Name	Country	Year	Objectives	Network Size	P2P Layers	Outcome
Piclo	Uk	2014	P2P energy trading platform from suppliers perspective	National	Business	A P2P energy trading platform
Vandebron	Netherland	2014	P2P energy trading platform from suppliers perspective	National	Business	A P2P energy trading platform
PeerEnergy Cloud	Germany	2012	Cloud-based P2P energy trading platform, smart home	Microgrids	energy network, ICT	Cloud-based platform for smart homes
Smart Watts	Germany	2011	Optimising energy supply via ICT	Regional	Energy Network, ICT	A smart meter gateway as interface to Internet of energy
Power Ledger	Australia	2016	P2P energy trading platform using blockchain	National and Regional	Energy Network, ICT, Business	A P2P energy trading platform
SonnenCommunity	Germany	2015	P2P energy trading with storage system	National	Energy Network, Business	A P2P energy trading platform
Lichtblick Swarm Energy	Germany	2010	IT platform for energy markets and customers	National	energy Network, ICT	Plenty of services provided by the energy supplier
Community First! Village	US	2015	Energy sharing from donations	Community	Business	Saving energy bills for poor people
TransActive Grid	US	2015	P2P energy trading within microgrid using blockchain	Grid-connected Microgrids	Energy Network Control, ICT, Business	Automatic Energy trading platform within Microgrids
Electron	UK	2016	Energy metering and using billing platform using blockchain	Unknown	energy network, ICT, business	Not started yet

Table 3.1: A comparison between existing peer-to-peer existing projects [37]

3.1.3 SonnenCommunity

The sonnenCommunity is developed by the renowned battery company sonnenBatterie, from Germany. They have a reputed name as a battery manufacturer in the energy space and took the initiative of enabling their community to share self-produced energy with others. This concept is similar to Piclo and Vandebron with the additional factor of recognising the importance of having a storage system. This allows the users to generate enough energy from solar panels, and when there is a surplus they feed it into a virtual energy pool that can then be used by other members that may need it when weather conditions don't suffice for generating enough for their needs. SonnenCommunity provides the software that links all the monitors and provides energy supply and demand services [38].

3.1.4 PowerLedger

PowerLedger is an already deployed system used internationally, that enables peer-to-peer trading between prosumers and consumers within microgrids or existing electricity distribution networks (grid). They provide hardware (smart meters) and an easy to use application that enables the trade of electricity using the trading unit called Sparks to use as monetary units within the blockchain. The application provides in-built useful statistics to their users such as return on investment of their solar system, where the electricity is coming from or where is it being sold to. Additionally, customers without solar systems, are also allowed to participate in the market. Power Ledger trials have shown to result in consumers getting a smaller price for the energy bought and prosumers selling their energy at a better deal than feeding it back into the grid [39].

3.1.5 Electron

Electron introduced blockchain technology into the energy sector in the UK, and it is targeting advanced billing platform for energy suppliers. It is still under development, but it is planning to offer a platform for gas and electricity metering and billing systems. It markets itself as trying to follow the trend of 'Decarbonisation, Decentralisation, Digitasiation and Democratisation'. It claims to offer a completely secure, transparent, dencetralised platform running on the blockchain, which enables the functionality of honest metering, billing and switching services using Smart Contract functionality of Ethereum and the power of Distributed Consensus [37][40]. It is ambitious and if successful, should contribute to a large change in the way the UK energy sector could operate.

3.1.6 TransActive Grid

TransActive Grid is a project located in Brooklyn, New York, which combines software and hardware to enable the creation of a community market in which participants can buy and sell energy to each other securely, and automatically, through the Ethereum blockchain using smart contracts. Similarly to other discussed projects, consumers can choose where to buy renewables from. This initiative does not restrict the trading to occur between solar system owners, but also allows to sell to neighbours that are devoid of solar systems themselves - neighbours can benefit of cheaper electricity this way. Additionally, this system also enables the storage of energy in their energy accumulators(i.e. batteries) which can then be sold to other energy companies enrolled in the trading platform. This adds another level of reliability as the grid may also have the choice of acquiring their energy from energy companies in case of a shortage within the microgrid. This project also matches the demand and supply of electricity, regulating the energy price in real-time and reducing the costs of transmission and distribution infrastructures [41]. Interestingly enough, TransActive Grid decided to not only add a virtual layer but a physical layer to their system, providing additional interconnections on top of the existing distribution grid. The thought process behind this was that if there are any severe weather conditions or unforeseen circumstances that could cause a power outage, this system could decouple from the existing distribution grid and operate in island mode.

3.2 Microgrid Energy Market Framework

This case study is mentioned quite frequently in the literature as an example for blockchain-based microgrids. Due to the extensive information and detailed use case study provided by [15] this dissertation will therefore look into it with more detail as it will be base itself on some of the components that constitutes this working system. Based on research done in [15], the authors derived seven components needed for the efficient operation of a blockchain-based microgrid energy market and analysed them in the context of the TransActive Grid case study. A schematic of these is presented in Fig. 3.1. for a micromarket setup to function, which are identified to be the information system (C3), the pricing mechanism (C4) and market mechanism (C5). However, the pricing mechanism is part of the market mechanism, hence, in this work, they will be addressed as a single component. An extra component to the microgrid market setup will be mentioned due to the need for automated bidding in the simulation process, a simple energy management trading system (EMTS) is attempted, and therefore will also be discussed.

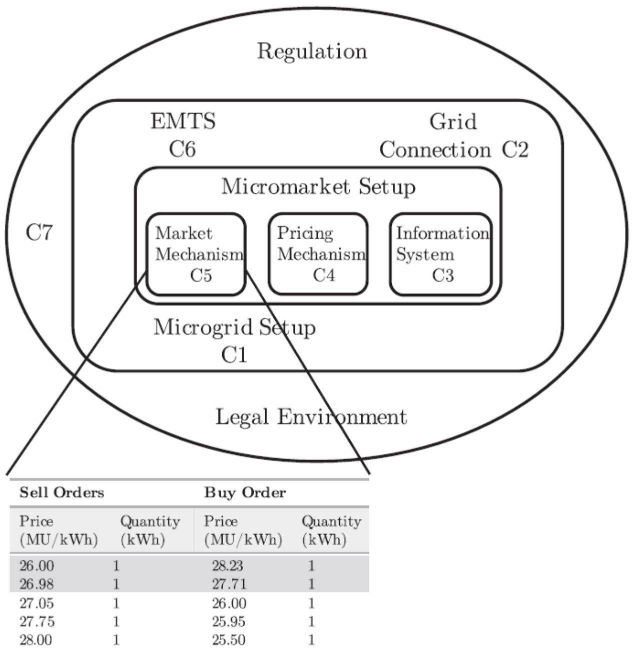


Figure 3.1: A schematic overview of the seven derived market components needed for the efficient operation of blokchain-based microgrid energy market. The market mechanism illustrates that the two top orders of the order book (prices determined by the pricing mechanism) should be matched and subsequently paid by the use of monetary units (MU) - blockchain case, tokens [15].

3.2.1 Distributed Ledger System

It is essential to have a high-performing information system that runs the entire market and integrates all market participants. It should adequately monitor market operations and provide a secure and easy market access. The information system that will be used for this market is a distributed ledger system (i.e. blockchain technology), however, its applicability to smart grids will firstly be discussed.

A smart grid requires the three main concepts. They require a data infrastructure that is able to have mutually competing and distrustul entities (energy and distribution companies), as well as providing integrity, authenticity, commercial secrecy while providing some level of customer privacy. This data infrastructure should also be resilient to hacking, thereby not being compromised by a single entity. Furthermore, the information system should allow for a financial transaction layer that enables the transaction of value while minimising the transaction costs involved. This is important in order to exchange electricity for value, in this case, a digital asset. Moreover, an IoT control architecture should be employable by the mean of smart-controls which are distributed to minimise latency and energy delivery [2].

Blockchain protocols in this case fits the mentioned requirements, as they provide a distributed, shared global infrastructure, where intelligent software applications - using smart contracts - can be implemented without a centralised control. This provides the necessary requirements of the IoT control architecture, while enabling the secure, trustless and decentralised necessary data infrastructure that the blockchain architecture provides. Additionally, blockchain coins can be used for the exchange of value necessary in the financial transaction layer. Finally, blockchain also provides a secure connection from smart meters (infrastructure layer) into the respective user blockchain accounts (virtual layer) where real-time data such as the amount of production and demand can be obtained.

The blockchain consensus mechanism depends on the microgrid setup . This can depend on the microgrid size, it's defined objective, i.e. increasing security of energy supply or increased the integration of RE in the energy supply, and if there is a separate physical microgrid infrastructure built along with the existing distribution grid [15]. These may all be factors contributing to the three mainly discussed algorithms, Proof-of-Work (PoW), Proof-of-Stake (PoS) and Proof-of-Authority (PoA). It is suggested in the literature that in a private blockchain, PoW becomes more a formality and is less necessary, as the different parties within that system will be known, and therefore PoA and PoS can be desirable to reduce the computational costs and energy requirements. However, this comes with the caveat of losing the same level of resilience and security that PoW can offer. Within the reviewed existing projects, the most predominant consensus mechanism used is still PoW, with the exception of Power Ledger which uses a self-developed Ecochain with PoS [31].

3.2.2 Market Mechanism

The market mechanisms aims to define how the bids and asks are allocated, what are the payment rules and the standardised bidding format[42]. It is implemented through the information system and it is defined by [42] its main objective is to efficiently match the buy orders to the sell orders, done in real-time to the best of its capability. The study also states that there should be the functionality of having a predefined minimum and maximum amounts of allocated energy configurable within bids/asks - they cannot be matched unless they fulfill those constraints. Additionally, there should be different pre-defined market times depending on their goal, (e.g. intraday trading and day-ahead market). For example, there could be the availability of a customer buying a set amount of energy for a defined interval of time in order to guarantee its energy reliability during that period of time. Alternatively, these bids could be limited to a certain amount of time slots during the day, in which every offer is cleared at the end of each time slots. This is named as single-bid, or uniform-priced double-sided auction in the literature [43][44][45], that consists of a uniform price at the end of each time interval, that is decided by the instersection of the aggregated demand and supply curve. In the case of a continuous double auction, bids/asks can be carried on to the next step if not filled. Finally, [15] also suggests that there can be P2P bilateral negotiation markets, in which the two parties can negotiate for a price and amount for a determine time horizon in the future, which can be better suited for over-the-counter trades.

The pricing mechanism is implemented via the market mechanism. It aims at efficiently allocating energy suply and demand [15]. In uniform price auctions, common in energy markets, already serve as a pricing mechanism [44][45]. In contrast to traditional energy pricing, microgrids with RE have a zero marginal cost [46]. They do not consist of surcharges taxes and additional fees that the physical microgrid is composed of. As this is the case, prosumers should guarantee their minimal revenue by pricing their energy above their base costs, fees or any existing taxes within the ecosystem that they operate in. It is also assumed, that price signals should reflect scarcity and surplus of energy respectively. Overall, an effective pricing mechanism, should benefit both the producers and consumers with a reduced price compared to the traditional grid price.

3.2.3 Energy Management Trading System (EMTS)

The EMTS's aim lies in formulating a biding strategy in order to automatically secure the energy supply necessary for a market participant. It needs to be able to have direct access to the participants energy profile in real-time, in order to forecast its future consumption and generation with the intent of optimising a bidding strategy for that individual. The demand is slightly more predictable although eradic due to the human behaviour, however, supply depends on weather conditions which proves to be more challenging. Numerous different forecasting algorithms have been implemented in the literature in order to achieve this, discussing the use of Neural Networks (NN), Non-Linear Autoregressive Neural Networks (NAR) and Support Vector Machines (SVM) [47][48]. Furthermore, the EMTS component should be able to have access to the markets platform data, so it can react to variable prices and act accordingly to the strategy devised. It should have pre-defined limit prices that it wouldn't go under or exceed, whether that is on the buy or sell side - e.g. a seller shouldn't place asks at a price that is below its production price. Simple strategies for an EMTS could be that it always buys energy when it falls below a certain price and always sells when it market price is above a certain threshold (if it has energy surplus). Ideally these thresholds should differ depending on the time of day, as a microgrid will have a demand profile and supply profile in which prices will be reflected. This gives the opportunity for the intelligent bidding strategies of each agent to have some strategic thinking that will benefit the participant itself. Self-interested rational market participants should aim to maximise their revenue and minimise their energy costs [15].

Similarly to reviewed existing P2P Trading projects, an EMTS should have the capability of choosing a preferred local renewable generation source. Finally, the EMTS should have complete access to the participants blockchain account in order to automate its process without requiring any supervision - decreases the burden of energy trading while increasing social acceptance of the community energy market [49].

Chapter 4

Implementation

4.1 Methodology

The methodology taken for this dissertation was an engineering one, following the concept of learning by doing. The ordered approach was the following:

- Set up of an information system
  - Creation of a simplified blockchain application for energy trading
  - Testing the limitations of created smart contracts
- Acquire a dataset of real household generation and consumption data
- Formulate a market mechanism
- Formulate the pricing of energy
- Develop a market simulation algorithm
  - Design suitable architectures
- Analysis of results
- Identify system limitations and potential benefits

4.1.1 Set up of the information system

At the start of this project, very little was known about the information system modelling language and how the interactions with the blockchain would be done. The three main contenders that enabled smart contracts were Ethereum, Hyperledger Fabric (IBM) and NEO. Hyperledger Fabric offered a good framework and resources to get started and testing the application, however, it had the caveat of not enabling cryptocurrency transactions which was essential for this project to enable the financial transaction between microgrid participants. Between NEO and Ethereum, even though NEO could be programmed in quite a few known languages to the author, it provided less resources and documentation than Ethereum did, therefore, Ethereum was the chosen blockchain technology. The project started by familiarisation with the information system by creating a simplified blockchain application to get familiar with the technologies functionality. To develop this application, a wide range of technologies were used, these include: 'Solc', 'Mocha', 'React.js' Next.js', 'Ganache-cli', 'Metamask' and 'Web3'. Out of these, the most important technologies to mention are Ganache-cli and Web3. 'Ganache-cli', an Ethereum development tool, that simulated full client behaviour by running a personal blockchain on your own local machine. This was essential to make the testing faster and easier as it can run transactions very quickly compared to the online ethereum test networks. Lastly, Web3 enabled an interface to communicate between the application and the ganache provider, i.e. sending transactions, creating contracts, requesting blockchain accounts information.

The initial step taken was the creation of adequate smart contracts which would enable the storage of information and added bidding functionality to the households, name household contracts. These would then communicate to a smart contract that served the function of decentralised exchange/market. The smart contracts were then tested using the 'Mocha' library to check if they were working as desired and to learn about the contracts limitations - i.e. memory limitations, computational cost optimisation, functionality of transaction between contracts and between ethereum accounts. Once the smart contracts were sufficiently refined, the simplified UI application was developed using 'React.js' and 'Next.js'. It's functionality can be tested by following the instructions of the read me file that will be submitted with this work, and some snapshots of can be found in the appendix [Appendix B].

4.1.2 Dataset acquisition

Subsequent to the UI application, working towards the development of a simulation algorithm was needed to achieve the defined goals of the project. To achieve this, a dataset was needed. This was acquired through the Pecan Street website, a research network with data of over a thousand homes out of which 250 were households with installed solar systems [50]. This dataset was comprised of houses mainly located in Austin, Texas, USA, providing plenty of solar coverage and with information available about their energy profile, load, demand, how much was required from the grid, and which utilities constituted the total demand.

4.1.3 Market Mechanism

The market mechanism is one of the most important component of the system as it defined all the conditions and rules in which energy will be traded. The two main market mechanisms identified in the literature, the continuous double auction [15], and the single-bid, or uniform-priced double-sided auction [44][45][43], hence, both will be investigated in this work, following the guidelines in which each are defined. The details of the mechanisms are explained in the section 4.3.

4.1.4 Pricing of Energy

The data was preprocessed using Python to isolate the households into separate csv files and calculating their respective levelised cost of energy (LCOE), defined simply as the sum of the system cost over a year (considering system life cycle to be 25 years) over the sum of generation that system produced - giving a £/kWh metric. The cost of system was derived by taking the UK national average of price per kWh of installed solar capacity applied to the different tiers of installed capacity - e.g. 0-4 kWp, 4-10 kWp and 10-50 kWp [51]. Additionaly, battery prices were included in the derivation of LCOE, by introducing a 8 kWh battery (Powervault Lithium-ion G200) cost for every system that had a capacity between 2 and 4 kWp [52], one or two Tesla powerwall batteries for systems with capactiy of 4 to 6 kWp or 6 kwp and above respectively [53]. At the end of this process, each household ended up having their two individual LCOE derived for a system without a battery, and another one with. Finally, a large biomass producer was introduced as it is a controllable RES that can be used to generate a more stable supply than solar - LCOE prices ranging from 5-12 p/kWh to emulate different type of biomass used, taken from [54][55]. This provides the microgrid with self-sustainability by increasing its generation capability. How these will be utilised is discussed in section 4.3.1.

4.1.5 Market Simulation

The market simulation was programmed in Javascript as the underlying UI application to match the stack of technologies that were used to code the front-end of the application. The method employed in the simulation starts by importing the respective csv files containing each household's hourly load and demand into separate class instances (data structures) called agents. Each of these agent instances, represents a household, in which all its data (e.g. amount of battery charge, load, demand, ether balance, historical bids/asks, etc.) is stored, along with functions representing the functionality that the agent is able to perform. These were used to interact either with it's own data structures or to interact with the smart contracts. The agents were coded to take independent actions based on on the most attractive conditions in the market and following their own self-interest. No coordination mechanism between the agents was built into to the system. From the start of the simulation, for each time step, each agent was given the chance of acting according to these set of actions; these actions were recorded and the market mechanism took care of the rest. At the end of the simulation, the data is collected from the separate agent data structures, and written to a csv file to be examined by a Python script (better visualisation and mathematical tools). Finally, to properly develop a market simulation, a market architecture needed to be developed which defines how the different components are interconnected and how they interact between the application layer and the blockchain layer of the system. Two architectures were designed, one more centralised than the other, these will be discussed in section 4.4.

4.1.6 Analysis of Results

The analysis of the results will be undertaken by calculating the aggregated costs of all the households if they were to always pay to the national grid when they lack energy or not generating enough from their PV systems. In contrast, this data will be compared to the results obtained from the two separate market mechanisms. This analysis will be done predominantly from an economic point of view as well as an electrical point of view. These results will be discussed to assess whether using microgrids is economically beneficial for both consumers and producers, as well as providing an insight into whether blockchain technologies are effective in intergrating necessary components to constitute a micromarket setup.

4.2 Information System

4.2.1 Ethereum Blockchain Costs and Considerations

Ethereum blockchain was chosen as an information system for this project, and therefore it's important to establish a base knowledge of how it works. Any transaction that changes state in the blockchain database will have to wait to be mined, in Ethereum, this block time interval lasts around 15 seconds. Reading data from the blockchain can be considered as an immediate process and is free of cost, however, transactions that change state infer a cost, which is paid in gas, the unit of computation in the ethereum blockchain. Each operation (e.g adding, multiplying) have a pre-defined cost of gas, therefore, the overall gas necessary to complete a transaction amounts to the amount of operations it needs to perform up to its completion. The total cost of a transaction is defined as:

$$\textit{Cost of Transaction} = \textit{Gas Limit} * \textit{Gas Price}$$

Gas limit is a parameter that is defined in any transaction, it aims to set a maximum limit of gas in that the user is willing to pay for said transaction. Gas price is the price per unit of gas and this generally influence the speed in which the transaction will be included in the next block. Miners will subsequently use these parameters to decide which transactions to include in the next block so they can maximise their transaction fee profit. However, since the simulation will be run in a local network using Ganache-cli, the gas price will be set to 2e10 Wei. Wei is the smallest portion of Ether possible, each Wei is equivalent to 1e-18 Ether and it is the unit that is used to make transactions. Ether will be considered to cost £250 for the entirety of the analysis, however, all these parameters can be customised in the simulation file. Laslty, each transaction between user accounts have a set fee of 21,000 gas, however, transactions to a contract has higher fees, which depend on the code, computation required and size of contract. These considerations are important as they will be referred back to, with the intent of explaining the re-iterative process in the contract and architecture design.

4.3 Market Mechanism

In this section, the two different market mechanisms will be discussed, the continuous double auction and the uniform-price double sided auction. The continuous double auction is a mechanism often used in financial market exchanges and its functionality is relatively simple. There are two sides, the buyer (bids) and sellers (asks) side. Each participant bids their value and quantity of the desired good, and if any bid surpasses the lowest priced ask, they are matched and a trade occurs.

The uniform-priced double-sided auction is more common in day ahead energy markets. These markets intend to buy and sell energy for defined time intervals for the following day. This process, prevents volatility in prices of energy along with providing reliability of energy availability for the buyer. It also serves for producers to better schedule their generation capacity. The auction works in discrete intervals, in this case, set to be one hour, where all the bidders and sellers submit offers. At the end of this hour, a uniform price is defined by the intersection between the aggregated demand and supply curve (Fig. 4.1). Trade occurs between all the participants at the equilibrium price and the market is reset for the next hour. This mechanisms shows that when there is an increase in demand, consequently the demand will shift to the right which will cause an intersection of the curves to be at a higher price - represented in Figure 4.1 as the demand shifted. Hence, an increase in demand reflects an increase in price.

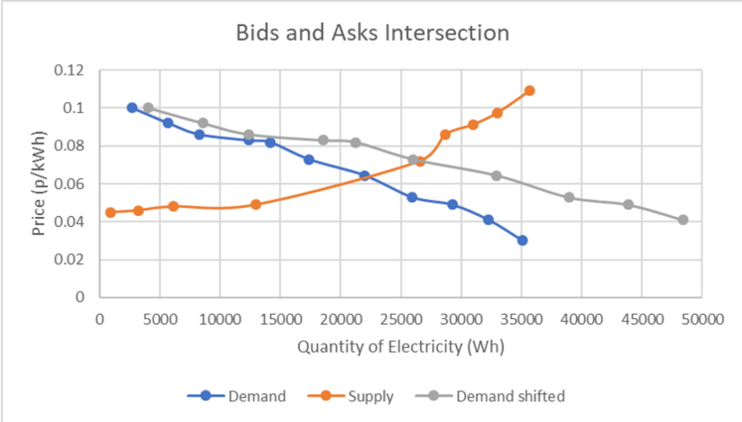


Figure 4.1: An example of the uniform price taken from intersection between aggregated demand and supply curve.

4.3.1 Pricing of Energy

The pricing of energy was suggested to be set at a price that benefits both the producer and consumer. That is, a pricing the energy above the sellers base costs, but also setting a maximum price for the buyer which did not exceed the national grid price. If any energy was to be sold at higher than the grid price, there would be no incentive for consumers to use the microgrid market. Hence, these two constraints were taken in consideration and a normal distribution was attributed to each agent. The minimum price, i.e. the LCOE for each agent (base electricity cost) was set a two standard of deviations below the mean, and the national grid price at two standard of deviations above the mean - resulting in a truncated normal distribution (Fig. 4.2).

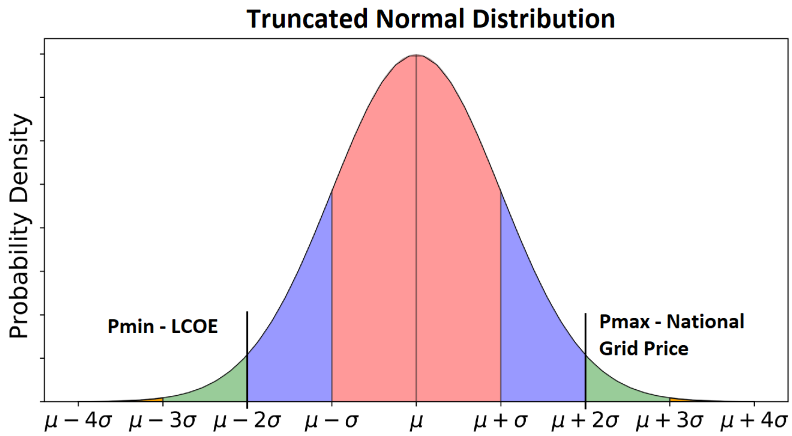


Figure 4.2: Trucanted normal distribution showing where the LCOE and national grid price constraints were placed.

4.4 Market Simulation

4.4.1 Architectures

The market simulation required a definition of how the market mechanisms were going to be implemented and how the application was going to interact with the blockchain. For this reason, two architectures were designed, one taking full advantage of the blockchain technology platform, and another slightly less decentralised and requiring a component to be off-chain in order to alleviate the computational work from the blockchain.

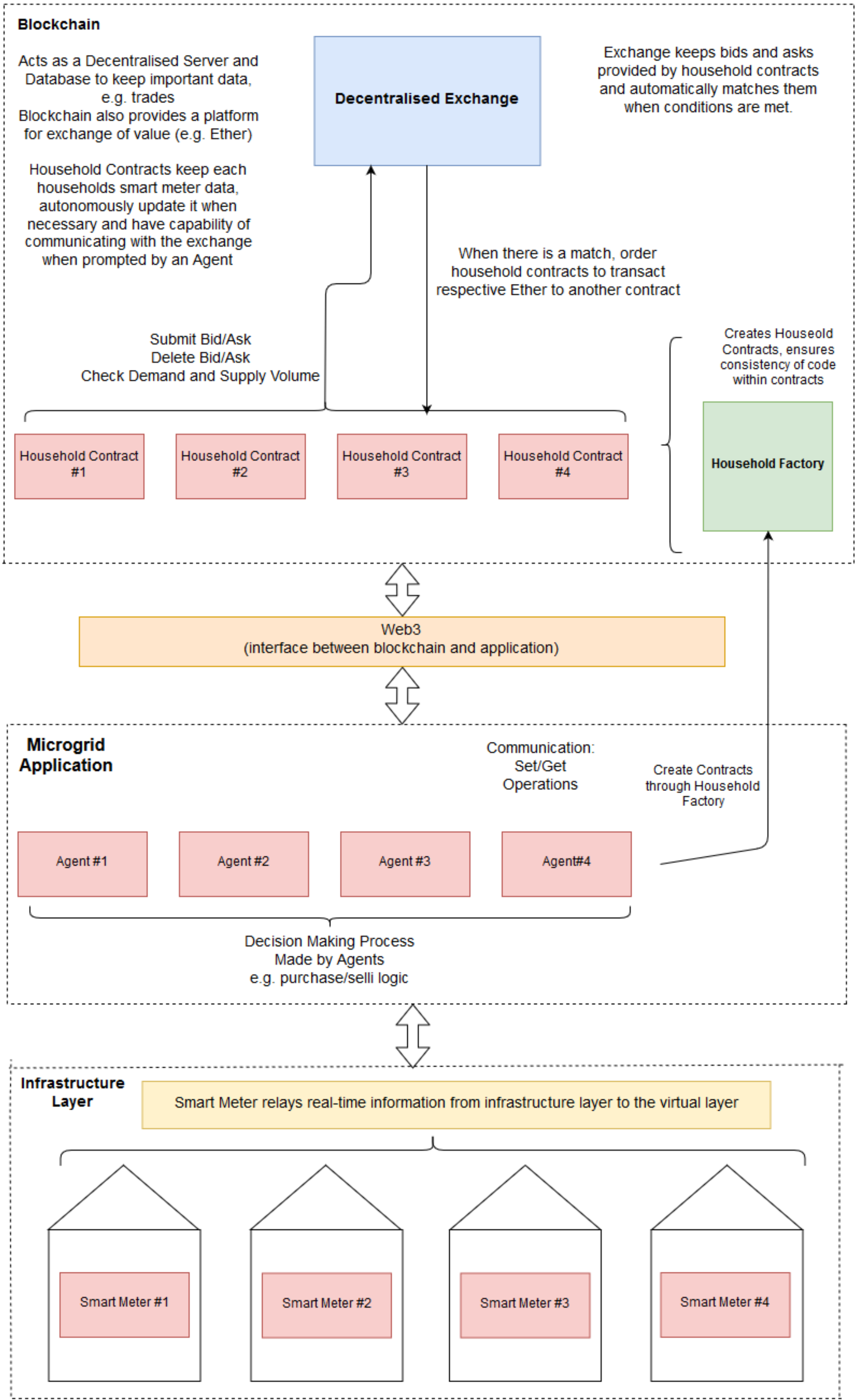


Figure 4.3: Diagram showing showing how the infrastructure layer is connected to the virtual layer (i.e.application and blockchain) and demonstrating the flow of information between different system components.

The first architecture (Fig. 4.3) was devised to use the full functionality of the blockchain, using it as a server in which people can connect to, a database with immutable information that can people can access and write to, as well as a platform for exchange of value. The bottom of the diagram indicates that each household, holding a smart meter, connects and relays information in real-time to its representative agent in the microgrid application. This connection is of restricted access to the smart meter that corresponds to the respective household owner and provides all the information the agent needs in order to make rational decisions on his behalf. If this is the first time the agent is connecting to the blockchain, the agents will request a creation of household contract to the household factory through the Web3 interface technology, which enables you to communicate to the blockchain. This household factory creates the household contracts on the agents behalf and attributes their Ethereum address respectively. The reason for this is to guarantee consistency of the smart contracts code, i.e. no malicious code can be inserted by any participant if all have to be created by this factory. Additionally, it creates the contracts with the decentralised exchange address automatically configured and it is a useful point of access to request statistics about every participants readable information. Household contracts now have a direct restricted channel to their agent, which provides and updates all the necessary information - serving as a repository of information. These are then allowed to submit bids/asks, delete them from the exchange, and make calls to the exchange when triggered by the agents logic. The decentralised exchange takes all the bids/asks and orders them in ascending and descending order of price respectively. This way, it automates the matching process of the offers and relays the appropriate transaction commands between household contracts. All these trades are stored in the blockchain and the accountability of each entities balance is taken care off by the consensus mechanism.

The second architecture shown in Figure 4.4 works similarly to the first architecutre with a few minor changes in order to implement a uniform-price double-sided auction. The household contracts and factory was removed to reduce an intermediary layer of transactions in order to get information onto the exchange. This enables a reduction in the amount of transactions the agents have to make. Moreover, the decentralised exchange no longer automates the matching of offers coming from the agents, instead, the smart contract is used to simply store the information relayed from all the different participants of the microgrid. At the end of each time step, the application collects the offers from the decentralised exchange, consequently calculating the regression curves of the supply and demand side in order to find the interception - uniform price. The matching algorithm is then initialised which relays the respective matching with their respective prices to each agent. This triggers their payment functionality, thereby transacting the necessary amount of Ether from one account to the other through the Web3 interface.

Architecture 1 (Continuous Double Auction)	Architecture 2 (Uniform-price double sided auction)
Computation is done in the blockchain	Computation is done externally to the blockchain
Uses more transactions = more gas expenditure	Uses less transactions = less gas expenditure
Less flexible - can not implement heavy computation procedures	More flexible - can implement more complex procedures, (e.g.more type of auctions)
Slower system	Quicker system
More secure	Less secure

Table 4.1: A comparison of the main differences between two implemented architectures.

A comparison of the main differences between the two architectures is given in Table 4.1. Overall, architecture 1 uses the storage, computation and exchange of value functionality of the blockchain whereas architecture 2 does the computation externally. It takes advantage of the fact that reading information is quicker and free of costs, hence vastly reducing the amount of transactions used within its operation. The caveat is that this computation has to be done in a centralised server, which is prone to attacks as it is less secure than the blockchain. However, one could assume that the current centralised servers have the same level of security. The necessity for this was that the computation required to calculate the uniform price was too great to implement in a smart contract. In contrast, architecture one is more secure as all the information is within the blockchain, yet slower due to the larger amount of transactions is has to execute. In addition to this, it can only run the continuous double-auction. The architecture one is therefore more decentralised as every participant pays his share of computation of the decentralised exchange when placing a bid/ask. More details about the results of the implementation of these two architectures in the Result section.

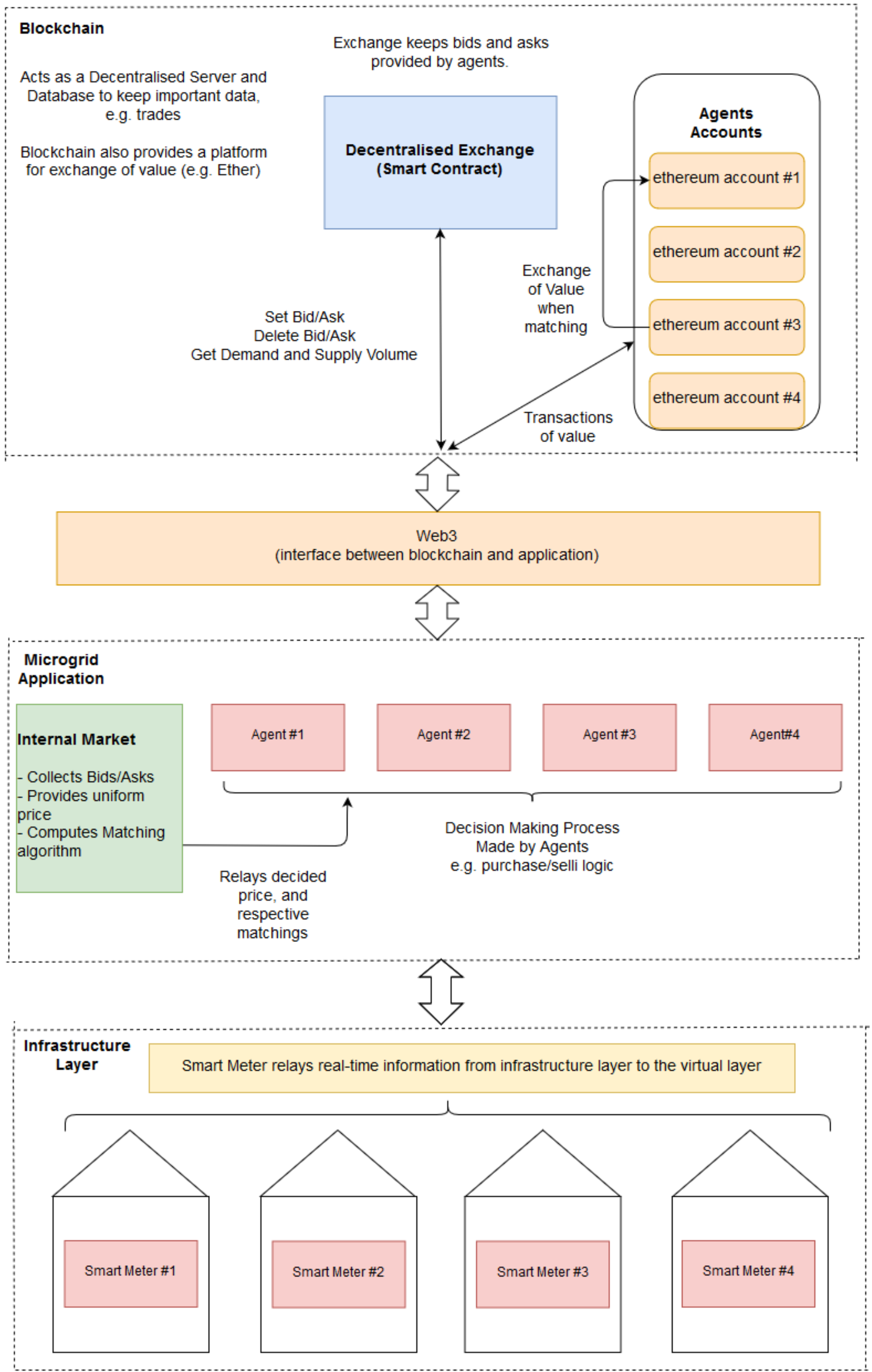


Figure 4.4: Diagram showing showing the second architecutre, demonstrating the flow of information and components functionality.

4.4.2 Agent Bidding Strategy Logic / EMTS

This section aims at describing the simple EMTS implemented in the market simulation. In order to better visualise its functionality, a diagram is shown in Figure 4.5. The diagram should be read from the top to bottom, starting at the excess or lack of energy instances. It is constituted of several threshold of batteries in which the agent makes a decision to sell/buy energy or to charge/discharge the batteries. This mechanism results in a behaviour in which energy is sold when prices are high and bought when prices are low. Furthermore, it has some level of 'forecasting' capability in which it checks the necessary energy that is going to be needed for the following 10 hours (configurable). This attempts to emulate the actual forecasting done in energy markets in order to predict how much demand and supply individuals will need in the upcoming day. Forecasting provides a more reliable level of energy supply as suppliers can be aware of the amount of necessary energy that will be required at different times of day, and control systems can prepare accordingly. Preprocessed data was prepared by acquiring weather data from the National Renewable Energy Laboratory (NREL) within the same time frame and location, which is included in the files of the application [56]. Forecasting predictions were attempted to be implemented, however using Javascript machine learning packages, the regression problems did not function appropriately with large datasets, hence, since it was out of scope for this project, actual data was used instead. This 'forecasting' function, is what permitted agents to reduce the amount of transactions they would have to do a day, by filling their batteries with the necessary energy they will need for that time interval, otherwise, they would have to bid almost every hour resulting in a system that would be very costly just in transactions fees. Finally, there is a safety net mechanism in which the agents will buy energy from the national grid if the batteries fall under 20% of their total capacity.

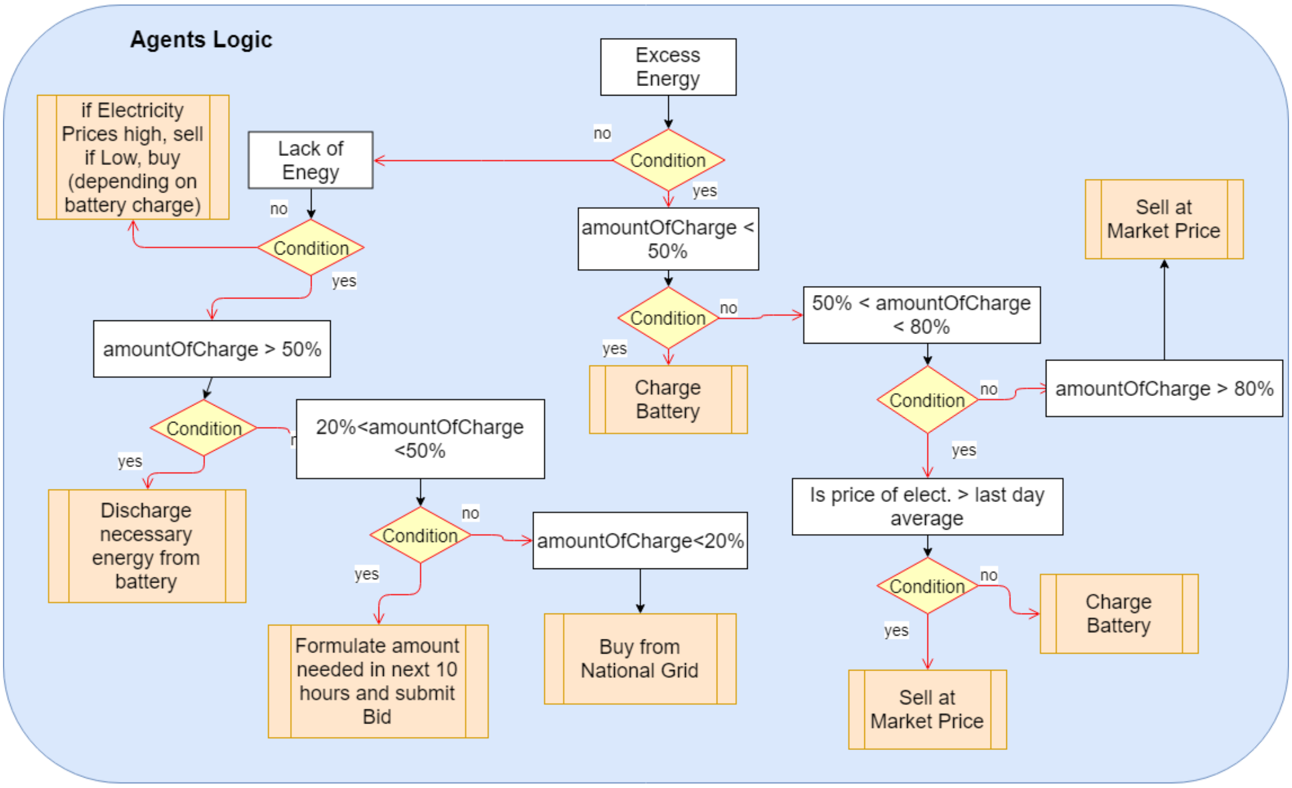


Figure 4.5: Diagram showing the logic behind the agents strategic bidding or selling.

Chapter 5

Results and Discussion

This section will comprise of presenting and discussing the results. A comparison between the two different types of auctions will be presented for a weekly simulation, and the uniform-price auction for longer periods of time can be found in [Appendix C]. Unfortunately, the results for longer simulations have not been acquired due to a malfunction in the Ganache tool after long periods of run-time. It should also be noted that the architecture one was used with the continuous double auction mechanism and the architecture two was used for the uniform-price double sided auction mechanism.

Observing Fig 5.1 and 5.2 indicates the prices over time, in which the times when there was no activity in the market (more supply than demand) the values were replaced with the previous ones - can be seen by the flat line instances - to allow for better visualisation of the prices, raw data graph can be found in [Appendix D].

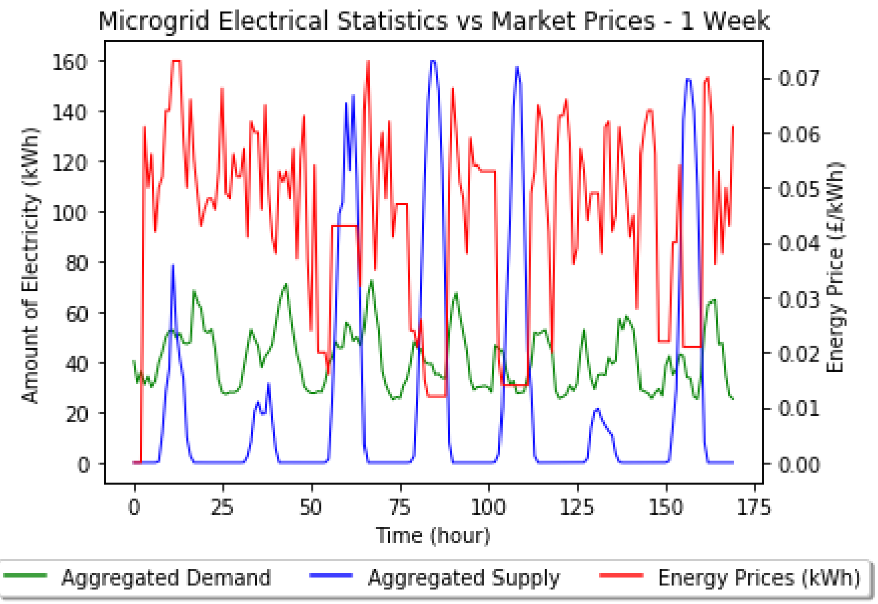


Figure 5.1: Uniform-price double sided auction comparing aggregated demand and supply to energy prices.

These graphs (Figure 5.1 and 5.2) show that the continuous double auction results in higher price average of around 8 p/kWh, whereas the uniform-price auction results in an average of 4.4 p/kWh as well as exhibiting a more volatile range of prices. This is caused by the mechanism used in the latter, as the interception between demand and supply curve may be found at lower prices than the private value of the producers (averaged at 7 p/kWh), which doesn't follow individual rationality of auction mechanisms. Perhaps introducing more producers present in the market would add a stronger supply side, thereby pushing the interception of the curves to a higher price, causing more reasonable prices to be observed.

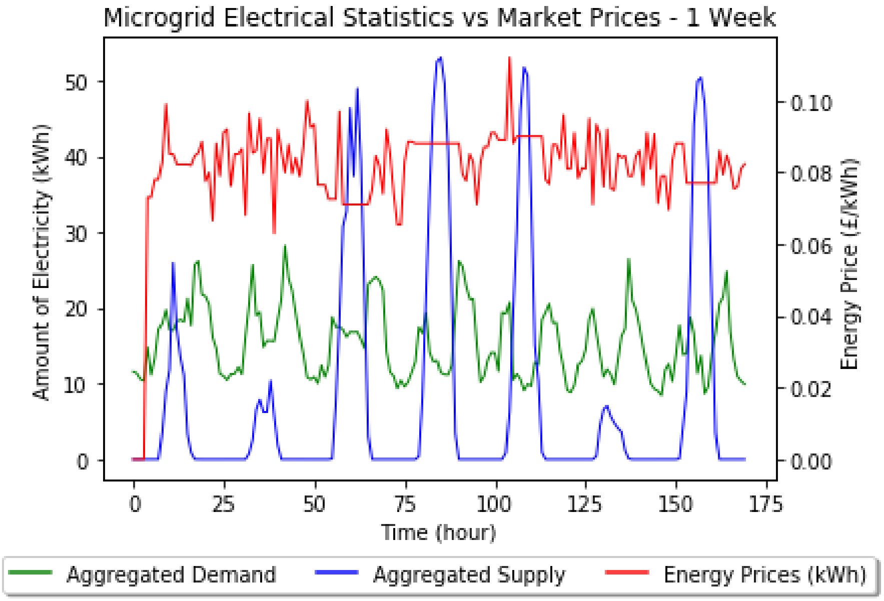


Figure 5.2: Continuous double auction comparing aggregated demand and supply to energy prices.

The continuous double auction follows individual rationality, as consumers are paying less than they would be paying with the national grid, and producers are selling at a higher cost than their LCOE value, resulting in a beneficial situation for both parties. Furthermore, the uniform-price auction demonstrates a larger amount of electricity volume being traded, with 3.69 MWh compared to 2.7 MWh with the continuous double auction. This characteristic is due to the fact that some orders do not get filled for not having a high enough price tag in relation to the sell side in the continuous double auction.

Observing Figure 5.3 and Figure 5.4, a comparison can be drawn between the two average battery charge percentages. A periodic pattern can be seen in the uniform-price double auction in times when the battery charge gets to 50%, as this triggers the EMTS mechanism of the agents to purchase enough energy to cover their needs for the following 10 hours. This also coincides with the supply going up during daylight, meaning that the EMTS mechanism correctly manages the agents needs on a day-to-day basis. It regulates its purchases in order for the energy storage to cover its demand needs up to the following day at early hours in the morning when the sun is present, when it knows it will be able charge its battery. One can also notice that this battery charge doesn't tend to go over 80%, due to the selling mechanism put in place at that threshold of energy. Similar patterns can be observed in Figure 5.4 representing the continuous double auction mechanism, where the battery charge does not tend to drop much below 50%. The difference in volume traded in both mechanisms is reflected in the differences of these two Figures, as the spikes of battery charge in Figure 5.4. tend to be less abrupt, showing that some of the bids were not filled in the order book due to their lower price. Finally, the correct functionality of the EMTS system can be seen to work well, with the battery charge being kept at safe levels between 50 and 80% as designed to promote supply reliability and trading opportunities.

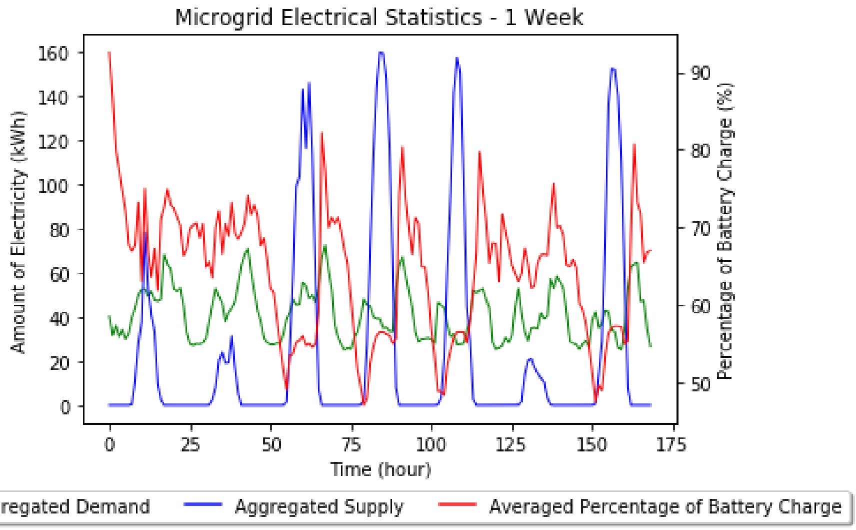


Figure 5.3: Uniform-price double sided auction comparing aggregated demand and supply to aggregated averaged percentage of battery charge.

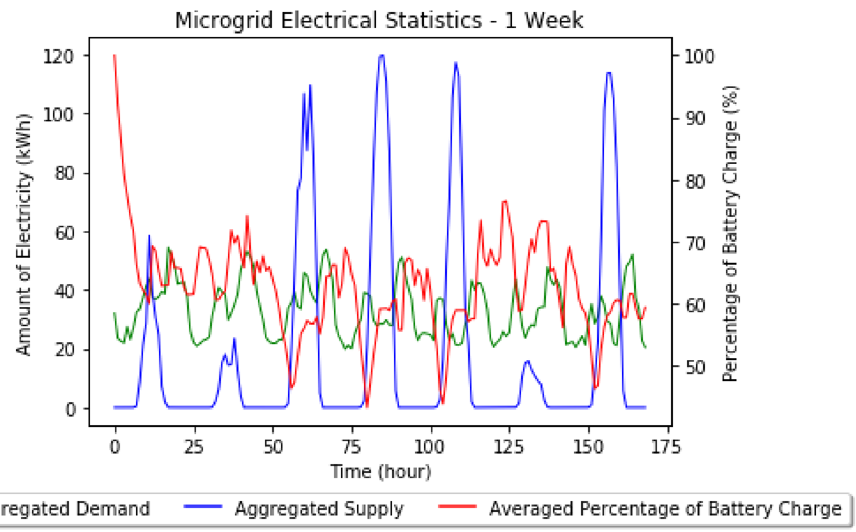


Figure 5.4: Continuous double auction comparing aggregated demand and supply to aggregated averaged percentage of battery charge.

In regards to the amount of transactions performed, Figure 5.5 shows that around half of the total amount of transactions in the blockchain system, actually constitute of successful market trades, while showing a very infrequent necessity to buy from the national grid. In contrast, Figure 5.6 exhibits a much larger amount of transactions per time step, where only 5-10% of the transactions are from actual market trades. The reduction of market transactions is only observed when there is less activity in terms of market trades. The tremendous differences between the two is not due to the market mechanism, but to do with the differences in architectures, as the first architecture requires much more transactions to update the middle layer of household contracts. This results in quite a drastic difference in transaction costs shown between Figure 5.7 and Figure 5.8, where the continuous double auction implemented in architecture one, exhibits larger transaction costs than actual trading volume, whereas the uniform-price auction shows the contrary. Large spikes of trading volume are caused by large amounts of electricity being bough at one time, due to the forecasting capability implemented in the simple ETMS, which aims to reduce the amount of transactions by buying larger volumes of energy at

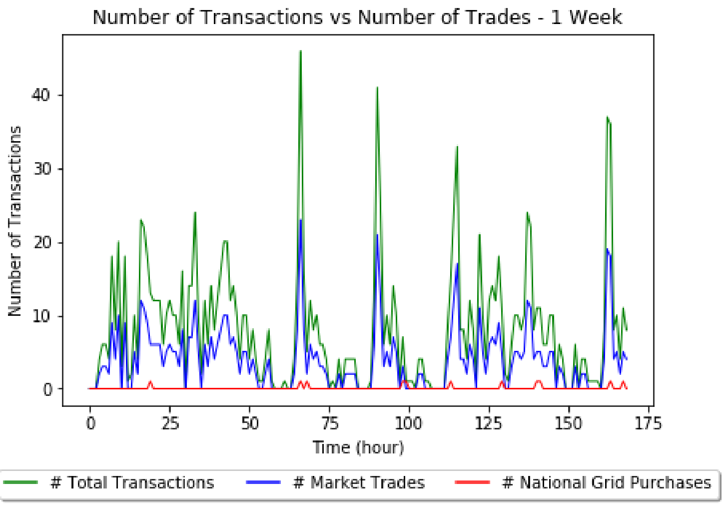


Figure 5.5: Uniform-price double sided auction comparing the number of total transactions, to the amount of market trade transactions and national grid purchases.

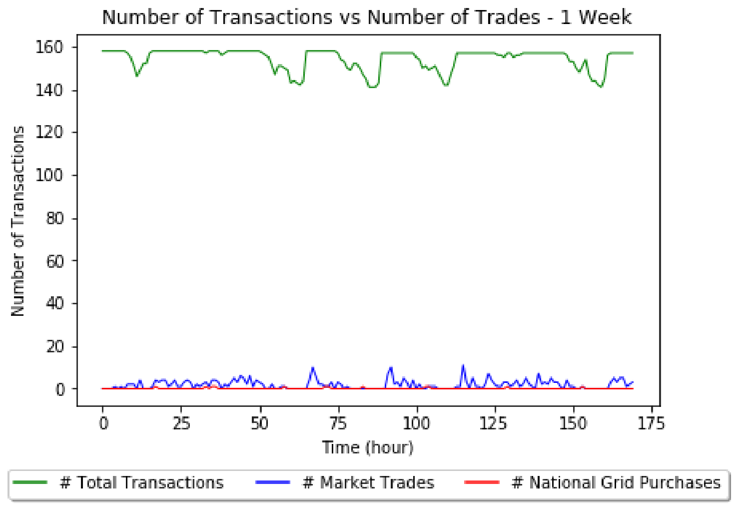


Figure 5.6: Continuous double auction comparing the number of total transactions, to the amount of market trade transactions and national grid purchases.

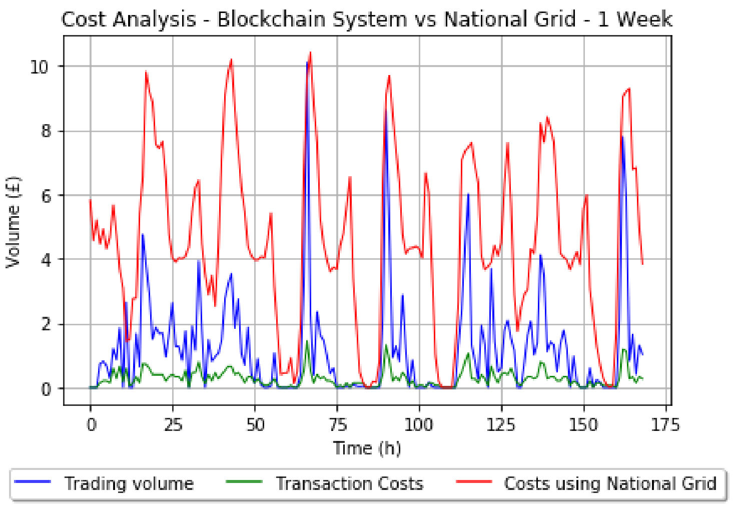


Figure 5.7: Uniform-price double sided auction comparing costs of using blockchain trading platform with only using national grid instead.

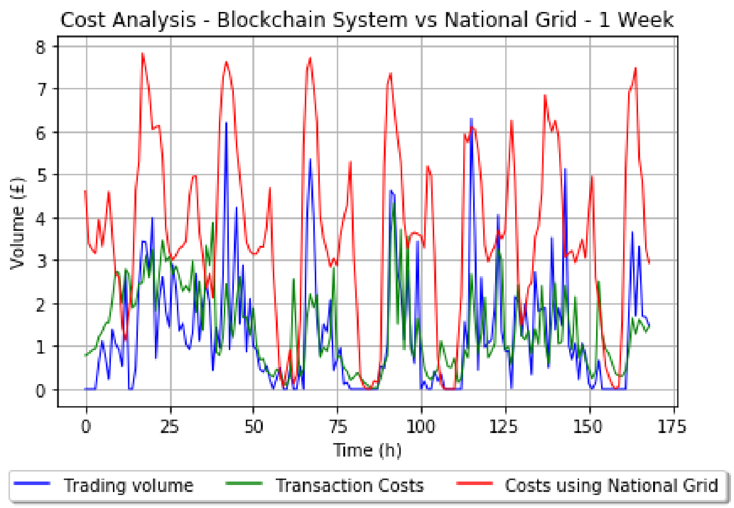


Figure 5.8: Continuous double auction comparing costs of using blockchain trading platform with only using national grid instead.

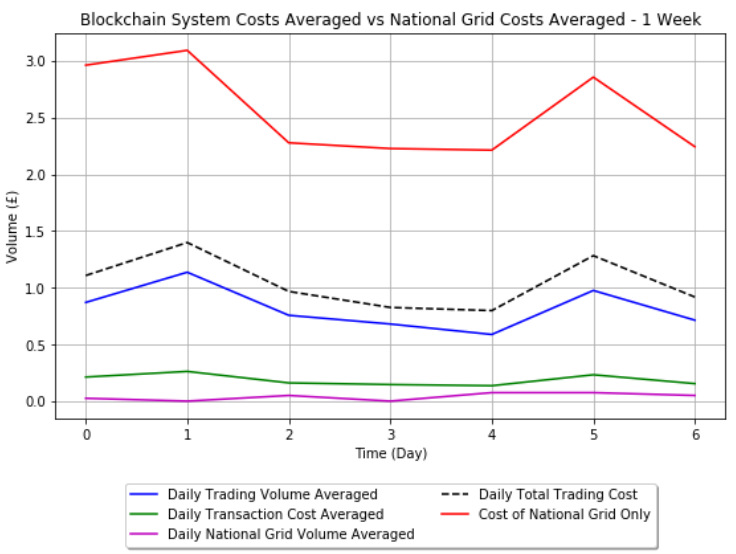


Figure 5.9: Unifrom-price double sided auction comparing average costs of using solely national grid against average costs of using blockchain P2P trading platform.

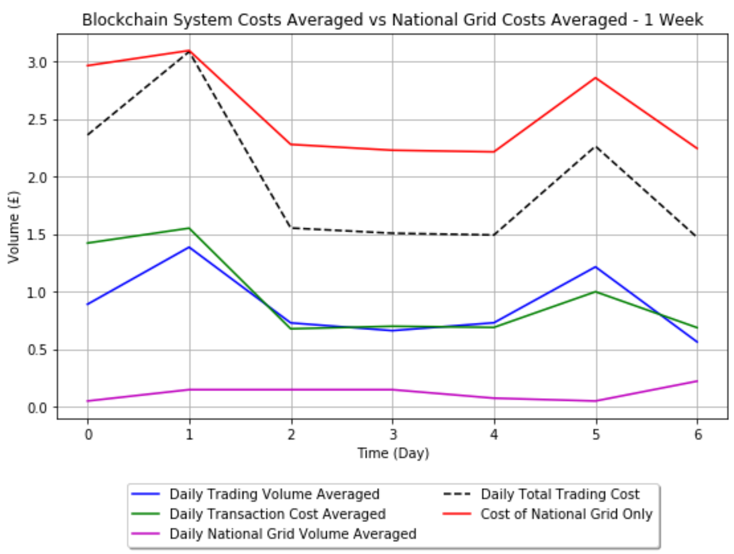


Figure 5.10: Continuous double auction comparing average costs of using solely national grid against average costs of using blockchain P2P trading platform.

one time. These spikes happen coincidentally to the spikes observed in the curve representing the costs of using national grid as these are the periods with larger demand, i.e. at the end of the day. This matches with the highest levels of electricity consumption of peoples domestic behaviour.

A more broken down view of the costs can be found in Fig 5.9 and 5.10 in which the costs have been averaged for each day and household. It can be seen that in the uniform-price auction situation, 79% of the costs, on average, originate from the trading volume, whereas 18% originate from transaction costs and the remaining 3% on national grid purchases. On the other hand, the continuous double auction results show that around 48% of the costs originate from the transaction costs alone, while 45% from the trading cost with the remaining 7% coming from the national grid purchases. This demonstrates that using the first architecture requires far too many transactions and therefore would not be applicable to use in a microgrid P2P energy trading scenario, while architecture two seems to offer reasonable breakdown of costs that one would expect. Additionally, the increase in national grid purchases is due to the bidders having to recur to buying from the grid since their lower priced bids were not filled in the microgrid market. Finally, it can be seen that from both trading scenarios, one can achieve an economic benefit by locally trading using a microgrid with local prices in contrast to using the national grid for supplementary energy, confirming claims made by [15].

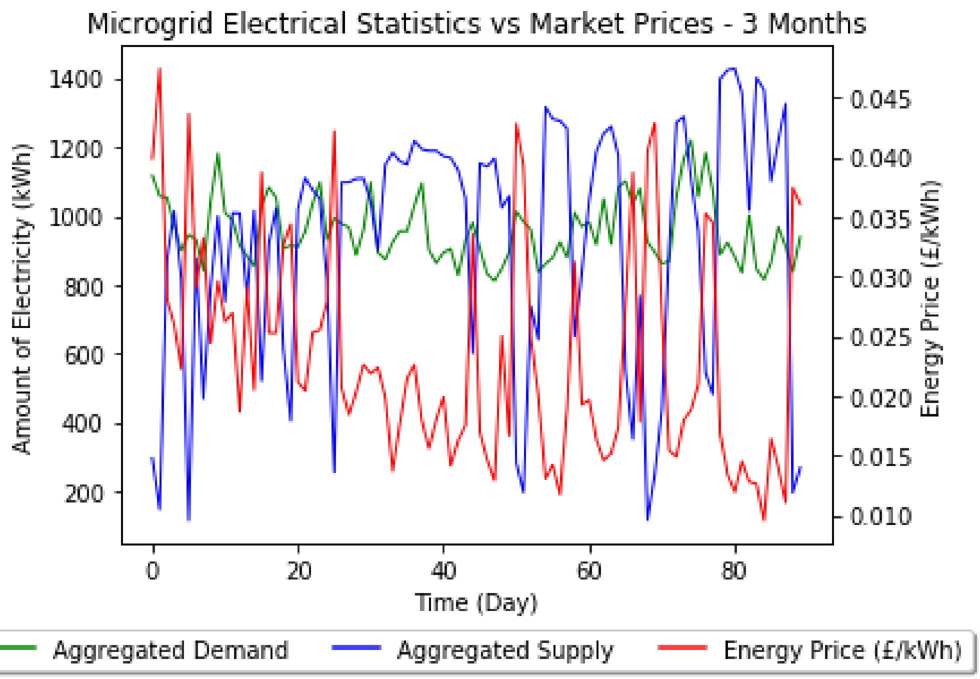


Figure 5.11: Uniform-price double sided auction comparing aggregated demand and supply to energy prices.

Simulations of longer time periods were only achieved using architecture two, in which the uniform-price double sided auction was implemented. Hence, the results of a three month period are presented (Fig. 5.11, Fig. 5.12, Fig. 5.13). The prices seen in Figure 5.11, demonstrate that the prices of energy spike up in situations of lower supply, which remains consistent with the previous week long results. Furthermore, a much lower price range in the graph is observed due to the fact that it takes a daily average over the hourly prices, including times in which there is no activity in the market. Times of no activity are represented by a cost of 0, hence exhibiting false prices. By removing instances of zero activity, and calculating the average according these changes, a real average of prices is shown to be 4.2 p/kWh which matches with previous results. Figure 5.12 demonstrates that over a 3 month period, the proportion of total transactions to market trades continue to be around 50% with very infrequent amount of national grid purchases.

Finally, Figure 5.13, the costs comparison between using the blockchain P2P trading platform and the costs of using solely the national grid are presented for a 3 month period. The averaged of the total trading cost per household comes to around £0.74 per day, whereas the averaged cost of using the grid per household is of £2.18 a day. These remain consistent with the previous week long results which show that national grid costs are around three fold as much as the blockchain P2P trading platform. Finally, it should be reiterated that this disparity between the two systems is due to the uniform-price double sided auction having a mechanism that results in energy prices that are lower than they should be. Further reflection and possible improvements to these results are discussed in section 6.2.

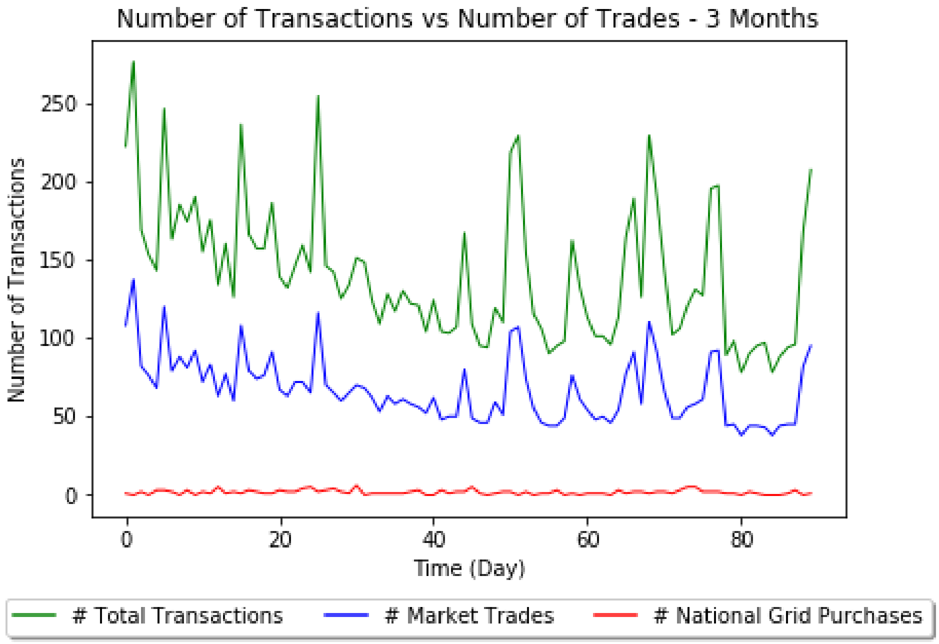


Figure 5.12: Uniform-price double sided auction comparing the number of total transactions to the amount of market trade transactions and national grid purchases.

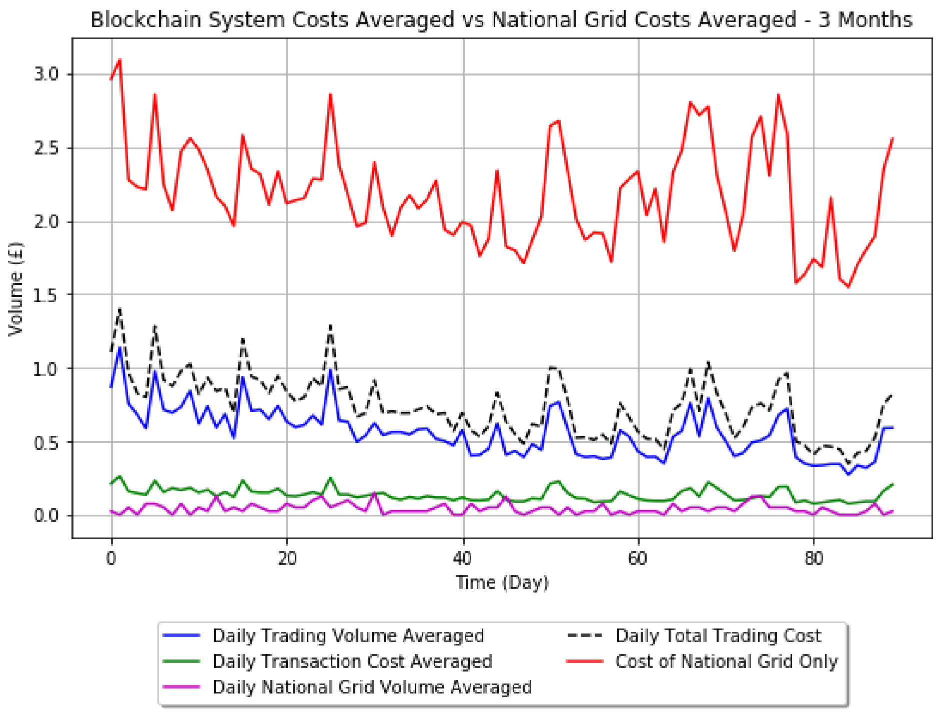


Figure 5.13: Uniform-price double sided auction comparing average costs of using solely national grid against average costs of using blockchain P2P trading platform.

Chapter 6

Limitations and Critical Reflection

6.1 Limitations

This section will outline the limitations of this dissertations work. Firstly, the application wasn't able to run simulations for long periods of time, which was found to be due to the Ganache development tool slowing down and eventually crashing after processing too many transactions. Longer simulations could have provided more useful insights of the two market mechanisms and their respective architectures. Additionally, the simulation capability was not available in a UI which would have been more user friendly. It also has the limitation of not being able to simulate over a specific time frame (e.g. only the summer weeks), as the simulation is programmed to start from the beginning of the dataset (indexing problems). Furthermore, the smart contract limitations prevented the introduction of more complex logic in order to introduce the uniform-price double sided auction. The transaction costs and efficiency of the system could have been improved by an optimising EMTS algorithm, to choose the optimal pricing and time to place offers in order to manage the systems energy more efficiently. Moreover, some assumptions were made in calculating the prices of solar energy systems. National averages were used, which may infer some errors as well as not considering transmission, distribution costs and battery charging/discharging inefficiencies. Lastly, the second architecture has some security flaws due to its centralised server characteristic, however, this security concern can also be applied to the current state of the centralised system of the grid.

6.2 Critical Reflection

This section will comprise of a critical reflection over results presented, the architecture designs implemented, along with some observations about the applicability of blockchain technologies in the microgrids use case. Lastly, some possibilities of further work will be discussed.

Two market mechanisms have been implemented showing quite different results. The uniform-price auction has shown to result in more amount of volume being traded but with reduction in prices that fall below most private values (LCOE) of the producers (average of 7 p/kWh). However, a change to this could be observed by adding more participants to the market on the selling side, in order to push the intersection point upwards and have more realistic energy prices. Similarly, an increase on the supply side could help increase the trading volume observed in the continuous double auction, as it would have provided a larger range of energy prices for consumer to buy from.

However, this mechanism seems to indicate a less volatile pricing, with a more realistic pricing range.

A more sophisticated ETMS could be developed with an optimisation algorithm comprised of a minimisation problem that would provide the best solution to reducing costs. This could be done by optimising the times of placing offers, charging or discharging the battery, along with an optimised price decision making process - implemented in [44]. This could take into account a larger amount of parameters and conditions from the market in order to make its decision, along with constraints related to the household owners components, such as batteries depth of discharge and inefficiencies associated with them. Further testing would be required with more extensive simulations and a consistent architecture across both market mechanisms to come to a solid conclusion about which one is most applicable. However, considering the experimental results, one has to conclude that the continuous double auction results is a more realistic and viable option for this use case due to its resulting price range and inexpensive computation.

In relation to the architectures used, it was clear from the results that the first architecture required too many transactions to operate, superseding the trading volume. It was understood that the middle layer of household contracts became an unnecessary step to store smart meter data of the agent, and this could be attempted to be stored within the smart meter processing unit along with its operating agent that would be integrated in the microgrid application. This way, the agent would be operating in the same device as the stored information, and could potentially also provide some computational work for the consensus mechanism of the blockchain.

The correct functionality in integrating all the necessary subsystems involving the microgrid setup have proven blockchain technology to be a high-performing information system to utilise in a microgrid use case. It provides a decentralised, transparent, immutable secure database server that enables a financial layer for exchange of value that does not require any intermediaries. It provides the data infrastructure, the financial and IoT control infrastructure necessary to integrate with smart-grids. However, it should also be stated that it is unlikely that this use case would be applicable in the form of a public blockchain, as people and business would not desire their data to be publicly available. Hence, consortium or private blockchain should be the preferred choice.

A new attempt could be constructed using the best approaches of both architectures in which agents would communicate directly to the decentralised exchange smart contract that uses the continuous double auction (for its preferable price range and being computationally cheap) in order to reduce transaction costs. The only caveat of that approach is that the smart contract would not be able to automate the transaction from one party to another when it found a matching. This is due to the inability of a contract to trigger transactions from a user account to another as it only has the capability to do that with contract addresses. Alternatively, a contract could be created for each successful matching/trade that would contain a balance sufficient to fill the desired amount being bought. This way, when a match would be found, the market would automatically trigger the smart contract to exchange value between the two participants and return the remaining balance. This seems like quite an intuitive way of trading as a contract would be devised for each trade between two parties representing an agreement between them. This would prevent the agents from updating unnecessary information to the blockchain, however, further work would have to be done to test if the creation of said contracts for each trade would be more costly than the current approach. An illustration of this can be found in the [Appendix E]. Some extensions to this could also include the ability to add sophisticated functionalities such that producers could giving the possibility of renting partition of their batteries to other participants that do not have storage capabilities. Finally, there are also some interesting questions that should be considered and pursued as further work:

- Is it a concern that a user could leave the blockchain when has certain knowledge of the private data in the blockchain?
- What is the procedure to enter and leave the blockchain as a user?
- Can there be interoperability between different blockchain networks?
- Can there be exchange of tokens across different blockchain networks?

For this specific scenario in a closed testing environment, ethereum's transaction throughput was not a concern as this market would be trading every hour, and therefore the amount of data to process wasn't a problem. As ethereum has 15s block interval, there could be plenty of block times to insert all the necessary transactions for an hours increment, however, this could become more of a problem as trading intervals shorten (e.g. 1 or 5 minutes). In this scenario not all transactions would be processed in time for the time interval to finalise, leaving the network congested and the market with incomplete information. Furthermore, there are still substantial transaction fees implied in the system when trading very frequently. In a smart-grid future scenario, millions of small transactions with very small value will have to be processed which would be unfeasible with the existence of transaction fees. There are still many challenges facing blockchain technologies, however, new and innovative solutions to some of these problems are being developed. An example of these is the IOTA project. This is not a blockchain, but a 'ledger of things' involving the use of a tangle framework, which is computationally lighter, very low energy, highly scalable and has zero transaction fees [57]. However, this is a highly academic and untested framework, which does not have the same level of reliability and research that the blockchain has. Taking that into account, this technology is very promising as these characteristics are ideal for a rising IoT driven world and would fall very well within the use case of microgrids. Lately, news that the IOTA Foundation is working on additional smart contracts layer on top of their existing tangle framework [58], which could open new doors to a more effective, low cost alternative solution to the problems that the blockchain faces today.

Chapter 7

Conclusion

In this dissertation, the use of blockchain technologies in the microgrid market use case was investigated. Research was done in the current energy systems, microgrids and blockchain technologies to provide a background basis of knowledge along with research into related work in relation to P2P energy trading platform. Using the TransActive grid case study, a microgrid market setup framework was followed in order to devise the most important components to setup an energy market using Ethereum blockchain technology. Two different market mechanisms were experimented and applied to two newly created architectures tailored to Ethereum's blockchain and smart contracts constraints. Real world data was used to individually price energy for each household in order to provide a basis in which energy is priced. A simple EMTS was designed to emulate the agents' biddings behaviour within a simulation environment. Various new technologies were used to develop a simulation algorithm in order to integrate the different micromarket setup components, yielding useful results about energy prices in a microgrid P2P market environment, the different architectures, market mechanisms and blockchain technology capabilities and limitations. These fulfilled the desired research aims and objectives by demonstrating that a significant reduction in prices can be achieved by using a microgrid market in contrast to solely using the existing national grid prices average. These results are consistent and reaffirm the claims made by research done according to the benefits that microgrid can bring to the current energy systems, by providing a cheaper, sustainable, reliable and efficient way of consuming electricity closer to their point-of-use, while balancing the demand and supply as locally as possible.

The two different market mechanisms have shown to generate different results relating to the amount of volume traded over the course of the simulation, with significantly different market prices. The uniform-price double sided auction has shown to result in a higher volume traded, but lower market prices due to its curve intersection uniform price mechanism. It was concluded that the continuous double auction demonstrated more realistic energy prices, following the individual rationality of market participants, while proving to be a more applicable mechanism for the computational constraints of smart contracts.

Considering the current state of Ethereum's blockchain technology, it was concluded that the continuous double auction market mechanisms was more applicable to implement as it is computationally cheaper and therefore possible to implement within the Ethereum's blockchain environment. Moreover, insights into it's limitations were obtained through the experimentation of both architectures designed, specifically into how the flow of information should be optimised and reduced in order to reduce the amount of transactions performed. The transactions fees and its associated costs have shown to have not be hindering to the possible implementation of such a system in the real-world considering the existing costs of the current energy system. Concerns about possible security flaws were outlined, while recommendations were proposed in how this system could be redesigned in order to eliminate them for future work. Some unanswered questions about private data while using blockchain technologies, their interoperability and exchange of tokens are left as food for thought in future work. Finally, the work is concluded by outlining an upcoming future technology - IOTA tangle framework - that could help tackle some of the existing blockchain technology limitations for this use case.

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Chapter 8

Appendix

Appendix A

Gantt chart of the project, is presented in the next page due to its size.

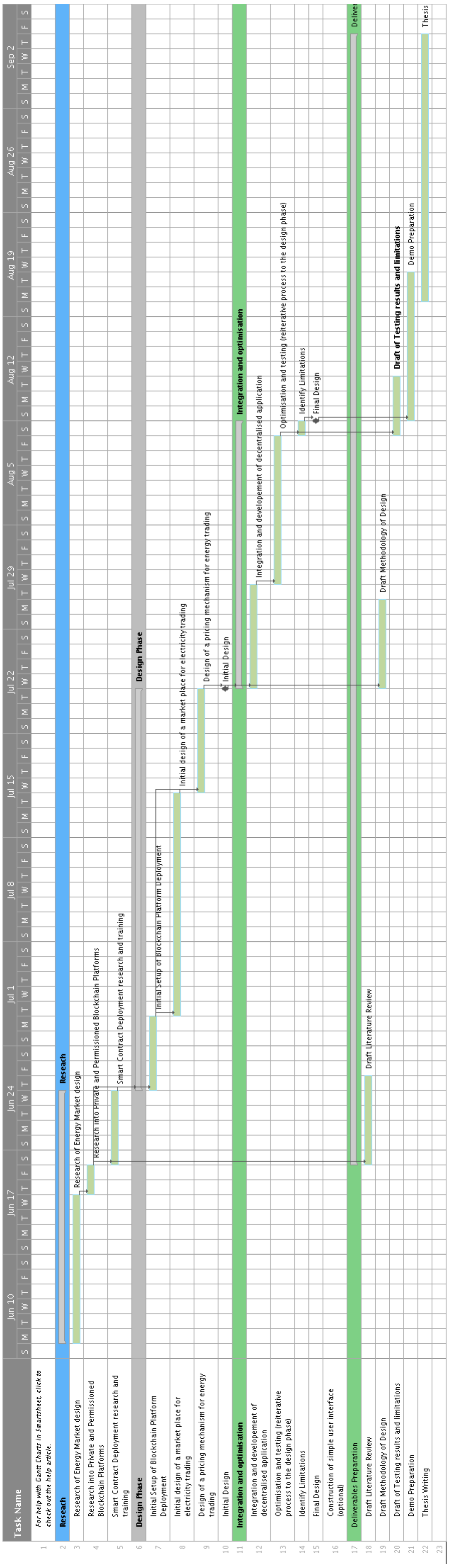

Figure 8.1: Gantt chart of the project plan for the dissertation.

Appendix B

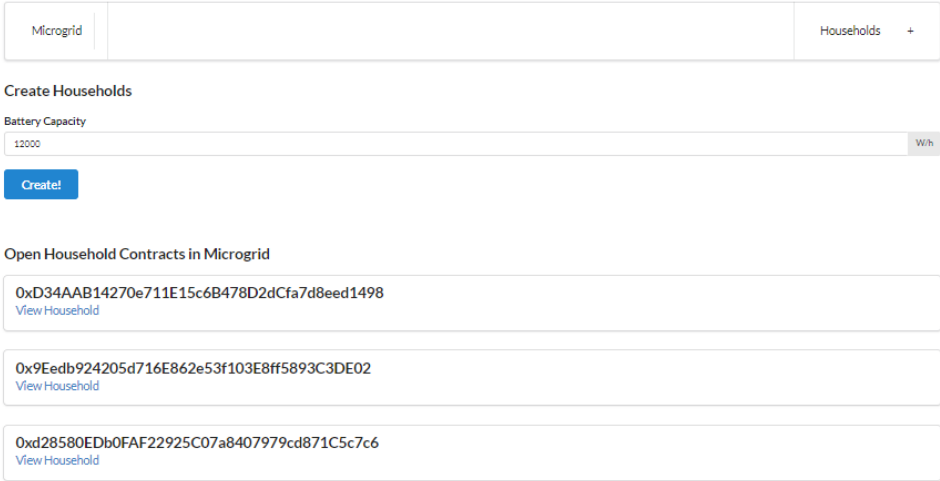

Figure 8.2: Snapshot of the home page of the application UI.

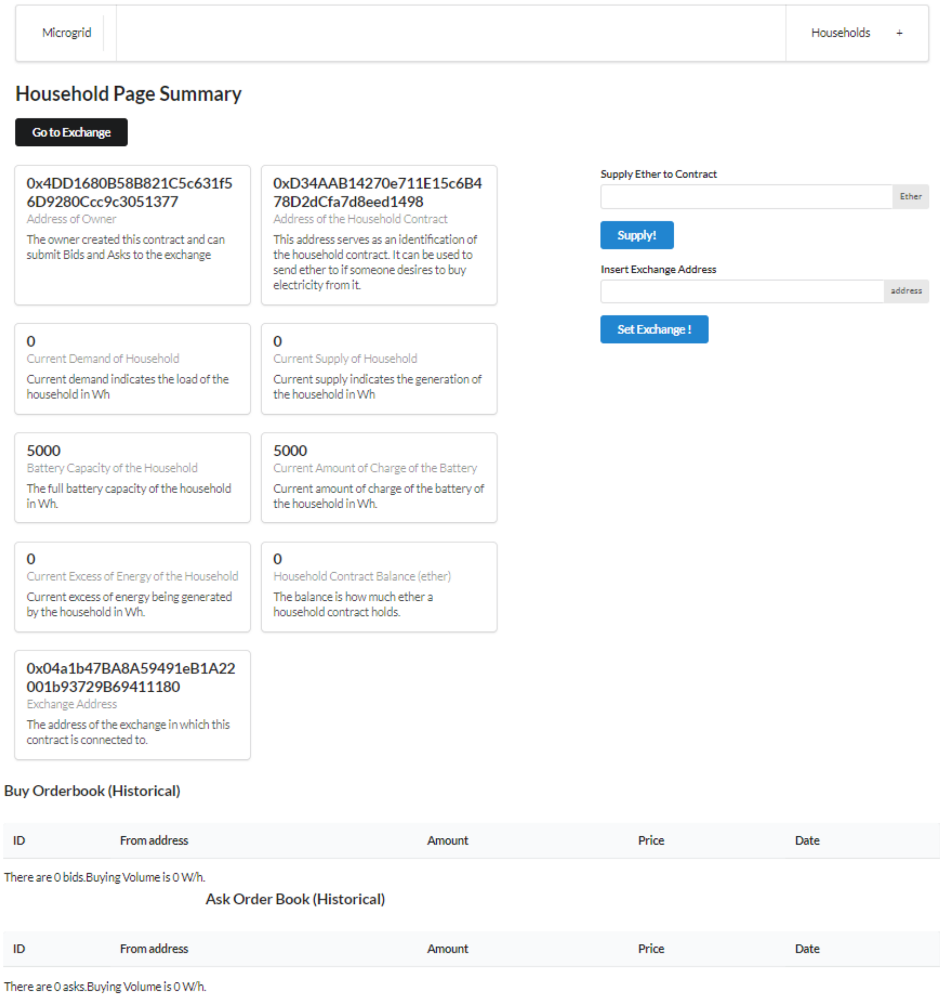

Figure 8.3: Snapshot of the household contract information page.

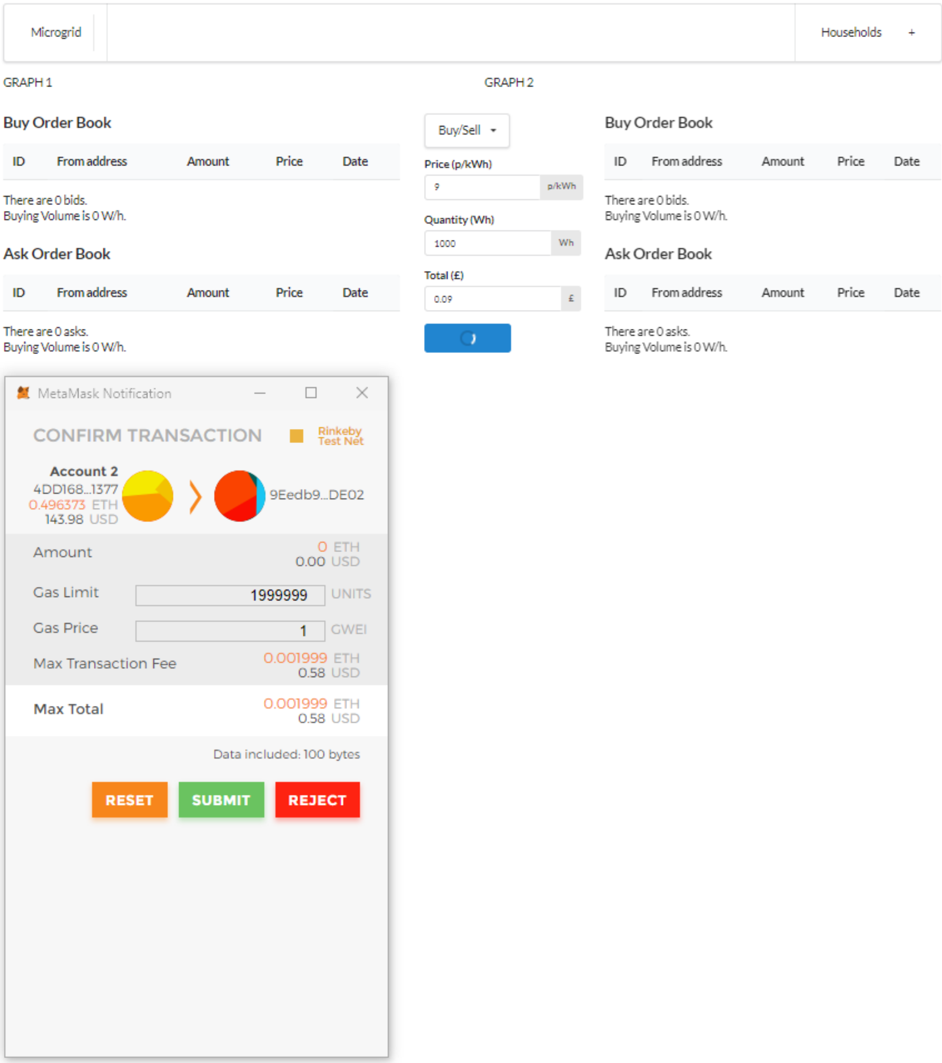

Figure 8.4: Snapshot of the exchange page where a bid is being submitted with the respective Metamask confirmation window.

Appendix C

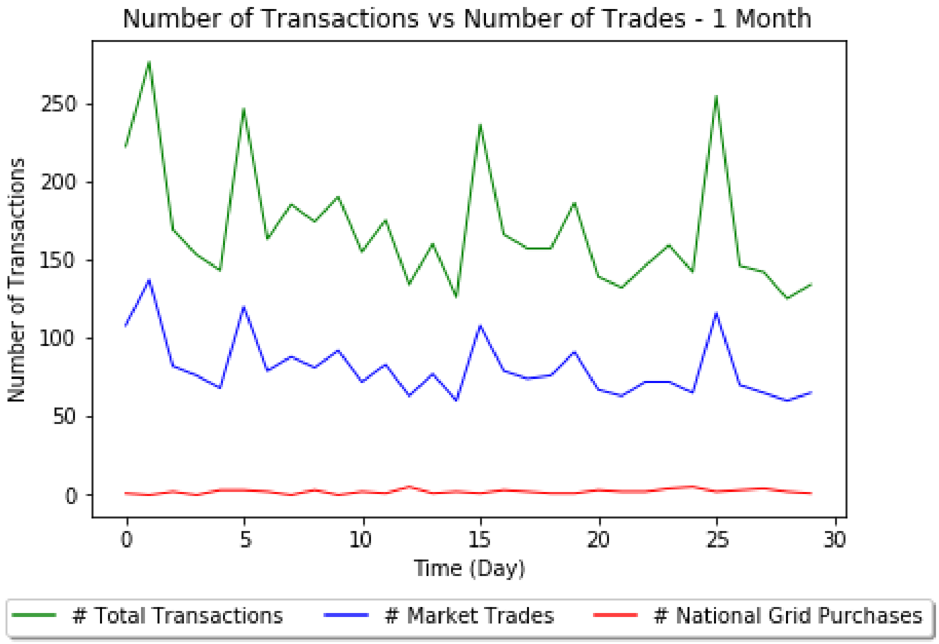

Figure 8.5: Uniform-price double sided auction comparing the number of total transactions, to the amount of market trade transactions and national grid purchases.

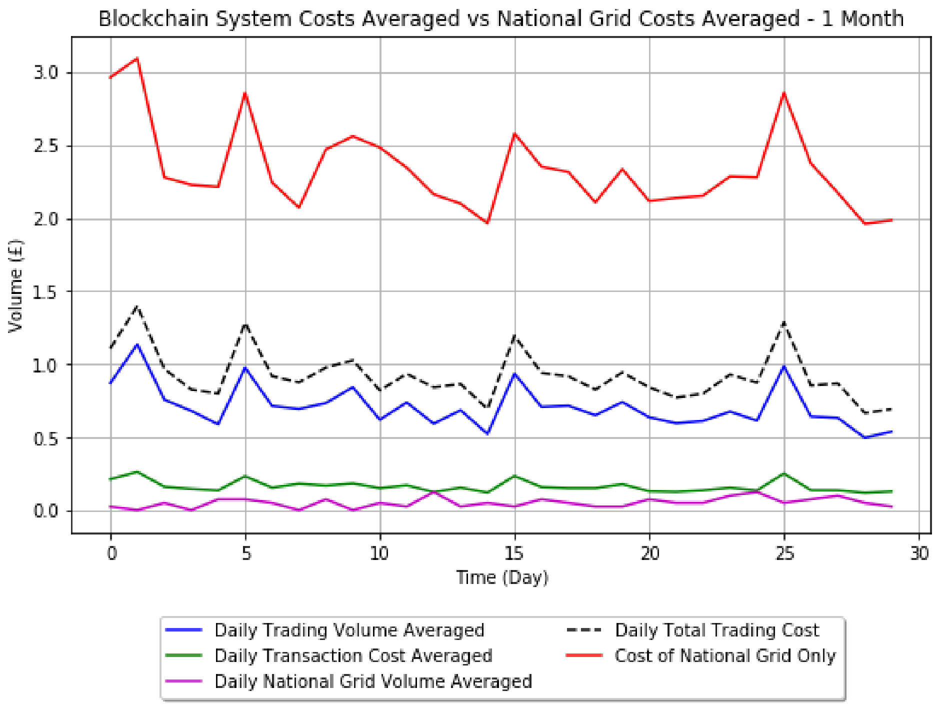

Figure 8.6: Uniform-price double sided auction comparing the average costs of using solely national grid against average costs of using blockchain P2P trading platform.

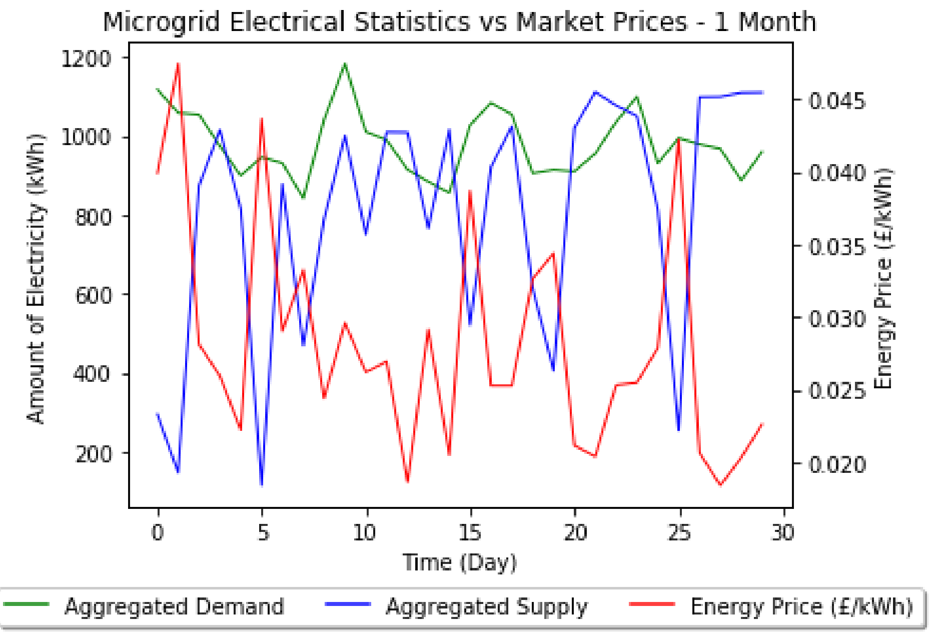

Figure 8.7: Uniform-price double sided auction comparing aggregated demand and supply to energy prices.

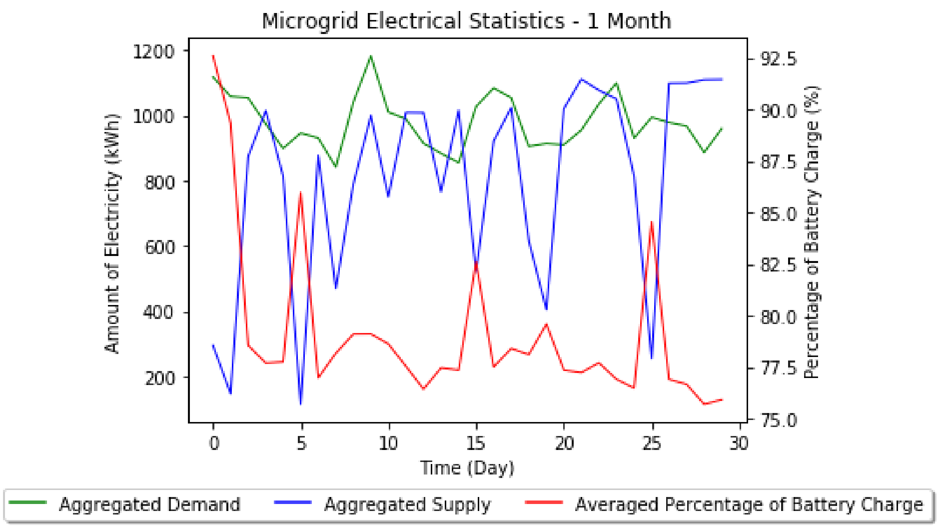

Figure 8.8: Uniform-price double sided auction comparing aggregated demand and supply to aggregated averaged percentage of battery charge.

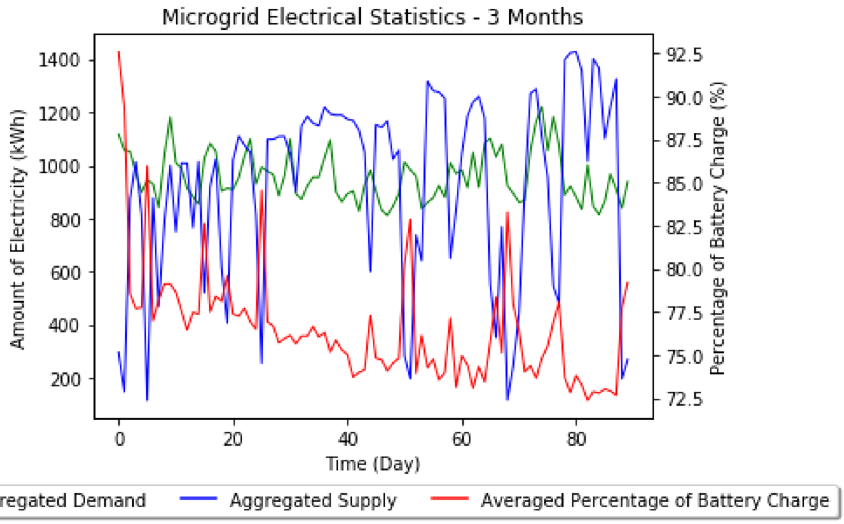

Figure 8.9: Uniform-price double sided auction comparing aggregated demand and supply to aggregated averaged percentage of battery charge.

Appendix D

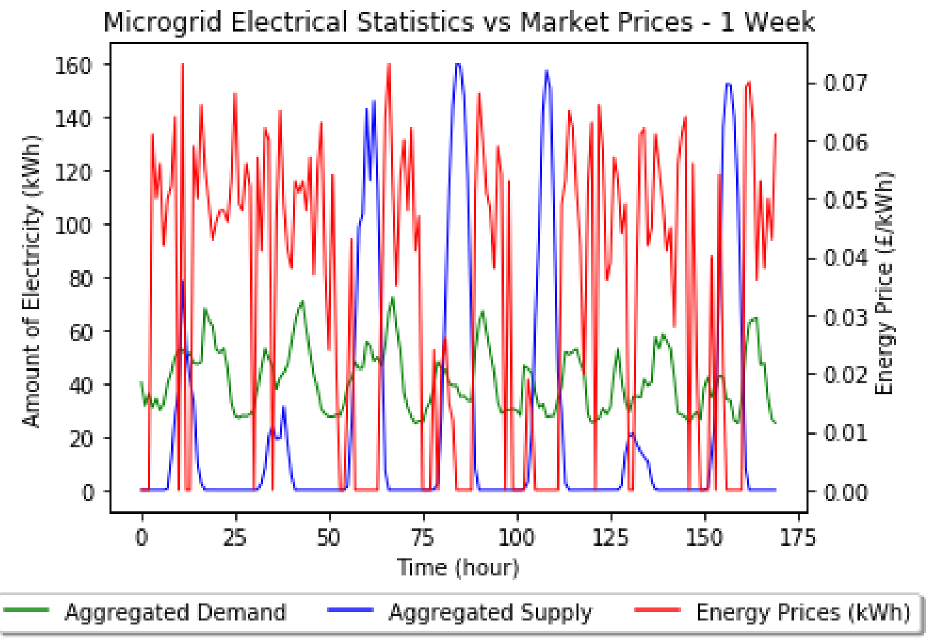

Figure 8.10: Uniform-price double sided auction comparing aggregated demand and supply to energy prices - raw data.

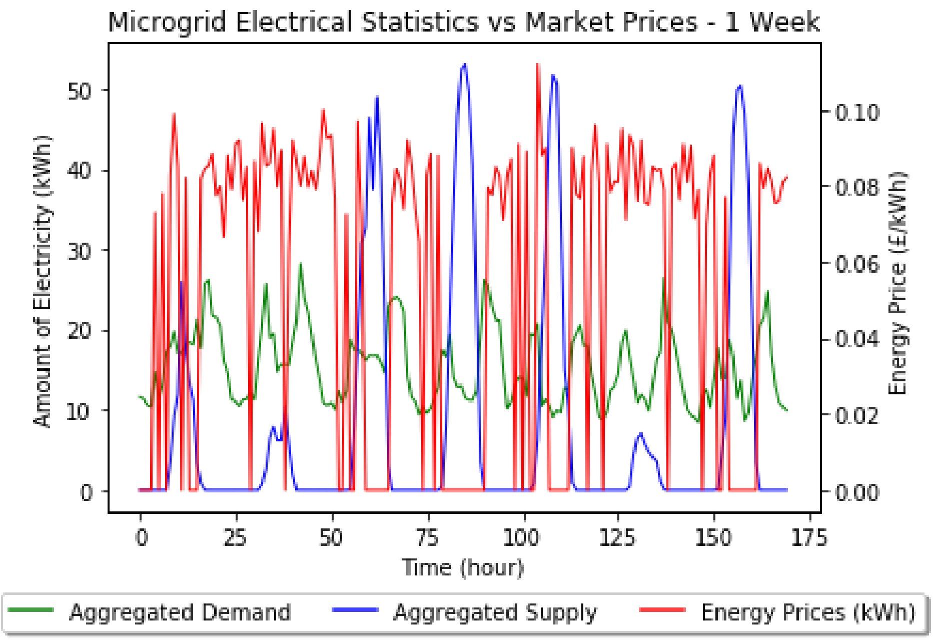

Figure 8.11: Continuous double auction comparing aggregated demand and supply to energy prices - raw data.

Appendix E

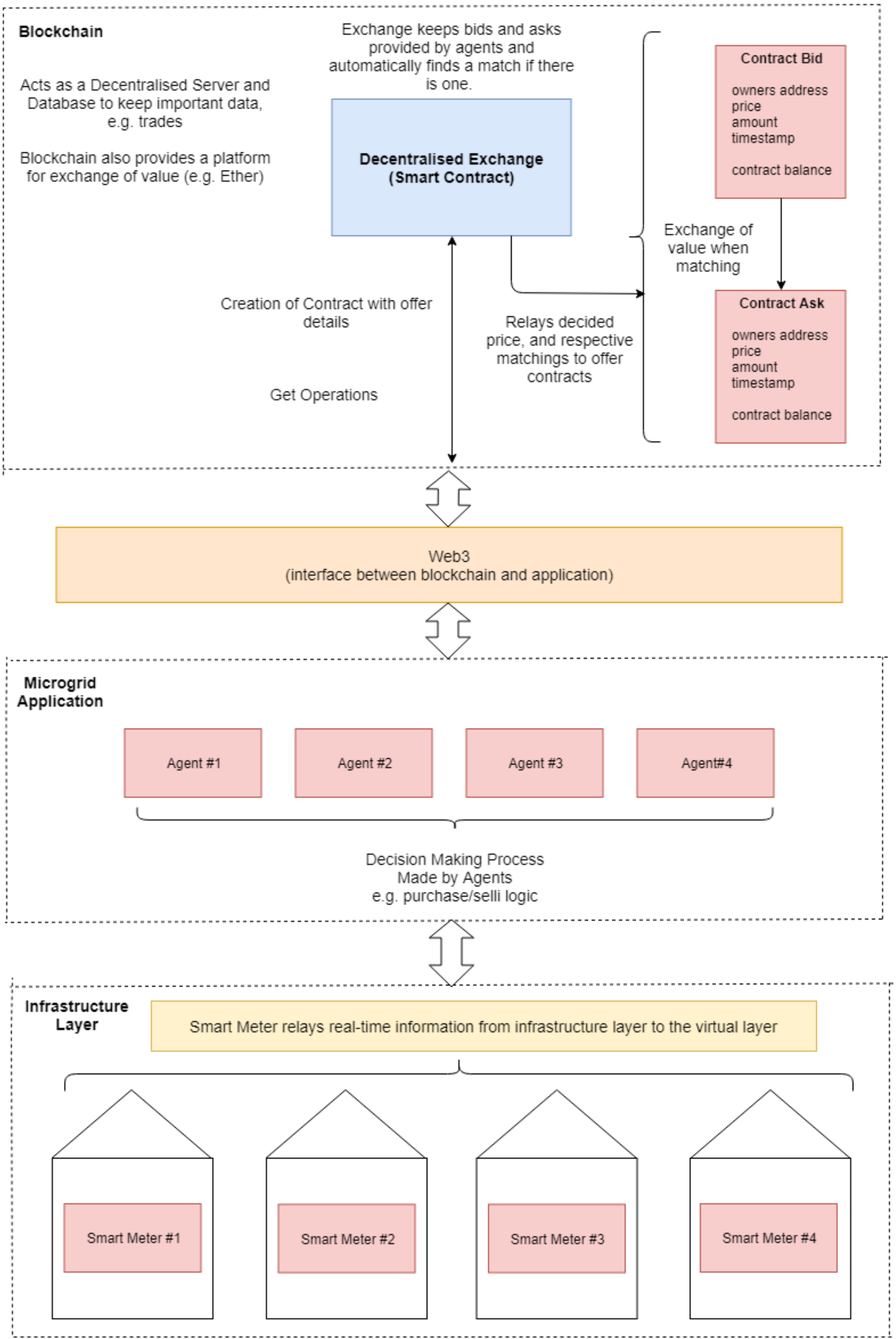

Figure 8.12: Diagram illustrating the proposal of a new architectures which uses a continuous double auction mechanism within the decentralised exchange smart contract. This architecture, creates contracts for each bid/ask, resulting in the possibility of automating the entire process while reducing the transaction costs substantially.