AN EFFICIENT PEER TO PEER ENERGY TRADING SYSTEM USING BLOCK CHAIN

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A Thesis submitted to the Department of Electrical and Electronic Engineering Of BRAC University, in partial fulfillment of the requirements for the degree of Bachelor of Science in Electrical and Electronic Engineering

Department of Electrical and Electronic Engineering
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October, 2020

Declaration

We hereby declare that

1. The thesis submitted is our own original work while completing degree at BRAC University.
2. The thesis does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The thesis does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.
4. We have acknowledged all main sources of help.

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Abstract

The energy sector of Bangladesh is highly dependent on fossil fuels. This situation has led to increased carbon dioxide emission over the years. However, the government is strongly advocating for the installation of green renewable energy sources. This has fostered an increased adoption of PV generation systems. The net-metering system has been deployed in the country to allow PV owners to sell their excess energy generated. The P2P model, however, is gaining significant interest. Dhaka is one of the largest electricity consumers in the country. Therefore, an analysis has been conducted with Uttara, Dhaka being the case study region. The rooftop PV generation capacity of the region has been investigated and showed that with 50% of the available rooftop area used for installing solar panels of average capacity, solar power provided a feasible complement to the main grid power. A model was developed to facilitate information exchange leading up to a trade of excess energy for money using the Multichain blockchain and implemented successfully to demonstrate asset transactions. A physical layer design was proposed, synthesized and simulated. The design achieved the basic functionalities to allow energy consumption using local SHS utilities available by the owner, import external power from the grid, and export excess power to other peers. The design, however, still exhibited faults, that necessitated future work. Finally, the economic impact of establishing a blockchain-enabled P2P market for energy trade was investigated. It was projected that the system had the potential of reducing a consumer's electrical expenditure by 17%.

Acknowledgment

We would like to extend our sincere gratitude to our supervisor Dr. A. S. Nazmul Huda, Assistant Professor, Department of Electrical and Electronics Engineering, Brac University for his guidance, continuous support, motivation, patience and crucial suggestions during the entire process of research which helped us in completing this thesis. We would also like to thank the thesis committee for their continuous encouragement. We are grateful to Brac University for providing us with all the necessary materials required for the successful completion of the thesis.

Table of Contents

List of Tables

List of Figures

Acronyms

AC	Alternating Current
API	Application Programming Interface
CLI	Command Line Interface
CSV	Comma Separated Value
DER	Distributed Energy Resource
DC	Direct Current
DoS	Denial of Service
FiT	Feed-in-Tariff
GIS	Geographic Information System
ICT	Information and Communications Technology
JSON	Java Script Object Notation
kWh	kilo Watt hour
LDR	Light dependent resistor
MWh	Mega Watt hour
NASA	National Aeronautics and Space Administration
P2G	Peer-to-Grid
P2P	Peer-to-Peer
POWER	Prediction of Worldwide Energy Resources
PV	Photo-voltaic
QoS	Quality of Service
SHS	Solar Home System

Chapter 1

Introduction

1.1 Background of the Study

The energy sector in Bangladesh is highly dependent on fossil fuels. About 62.9% of the country's generated electricity comes from natural gas, 10% from diesel, 5% from coal, 3% heavy oil and only 3.3% from renewable sources. As of September 2019, the country had an installed capacity of 21, 419 MW (Nabi, 2019). However, the demand still exceeds the supply. As such, power shortages are a common phenomenon in the country (Malek, Hossain, & Sarkar, 2015).

The energy-related carbon dioxide emission in Bangladesh was 74.5 tons in 2016. However, the country, which is also a signatory of the Kyoto Protocol, is heavily advocating for the promotion of clean green energy. Bangladesh aims at making renewables contribute to producing 10% of Bangladesh electricity by 2020 (Hossain, 2015).

As such, the country has seen increased undertakings aimed at increasing production of green energy. Distributed energy resources (DERs) are being adopted even more into homes, offices and industrial complexes, making use of renewable energy sources such as solar power, wind power and small hydro. This has exposed the country toa paradigm shift from the mainstream centralized energy production and distribution to a decentralized system, fueled by alternative renewable sources.

Bangladesh is highly favorable for solar energy production due it's tropical location. Insolation levels in Bangladesh vary from 3.8 kWh/m^2/day to 6.4 kWh/m^2/day with an average of 5 kWh/m^2/day.x1] for more than 300days per annum. More than 3.9million solar panels have been installed in more than 40,000 villages. According to Momotaz, et al. (2012), 44MW of electricity is being produced daily via solar panels, solar home system (SHS) capacity of 218MW is available from such (Chakma, 2018). As decentralized energy finds prevalence to more spaces, an opportunity is presented by DER owners to earn form their excess energy production.

A net-metering mechanism is currently employed in Bangladesh, where excess power produced by a DER is sold using a long-term contract to the main grid. The DER can conversely buy electricity from the main grid in case of a deficiency. This system incentivizes DERs to produce and trade in more electricity. However, according to Nelson, et al. (2012) this model is not been economically beneficial to the prosumers due to the significant difference between the buying price and selling price of a unit of energy. Information asymmetry between the private and public sector has exasperated this situation, fueled by the political influence of feed-in-tariff (FIT) determination. This situation has prompted prosumers to desire to trade more between themselves directly, without the influence of a central body.

Peer-to-Peer(P2P) energy trading allows prosumers to trade energy directly between themselves, in a decentralized manner, without involving a central body. A P2P energy transaction between two parties is a bilateral contract for exchanging energy at a specific price (Sousa, et al., 2019). As such, a prosumer with excess energy can sell their energy to other peers with an energy deficiency. This system provides the prosumers with an ability to earn more revenue, reduce their electricity cost and lower dependency on the grid. In addition to this, this system facilitates the buying of electricity by consumers at a cheaper price per unit compared to the main grid.

Bangladesh has seen the development of P2P energy trading platforms. Currently, ME SOLshare, founded in 2013 is the most popular form of this system. SOLbazaar, ME SOLshare's IoT driven trading platform is the heart of this operation, and is made of up of three components; SOLbox, SOLapp and SOLweb. The SOLbox, arguably the most critical component, is a bidirectional DC meter, that facilitates the trading of energy and mobile money payments. ME SOLshare currently hosts 48,000 PV capacity (Wp).

Despite the current P2P energy trading systems established in Bangladesh, it is observed that blockchain, as the enabler for the trade, has not yet adopted in the country. Moreover, PV capacity data is scarce in the region. The last available research data detailing the PV potential of Dhaka was conducted in 2014 (Jamal, Ongsakul, Singh, & Sakehin, 2014).

This presents an opportunity to investigate the impact blockchain-enabled P2P energy trading of PV generated power would have in the case study region of Uttara, Dhaka, Bangladesh; in promoting clean energy, and empowering citizens to earn from trading electricity and reducing power demand from the main grid.

1.2 Statement of Problem

There is an increasing interest in the demand for adoption of blockchain-enabled P2P energy trade of PV energy, as a means of promoting green energy. Philipp, et al (2013) discussed swarm electrification featuring Bangladesh in their study. The subject has gained huge traction in the country, and as such projects implemented fostering P2P energy trade. However, little work has been done on the research of the impact of blockchain-enabled P2P PV energy trade in the region and no P2P platform in Bangladesh uses blockchain technology. Moreover, the data available on the PV rooftop potential of the area is half a decade old.

Studying the impact of blockchain-enabled P2P PV energy trade in the region will help gain an understanding of the potential impact of empowering citizens to earn more from P2P trading, as well as demonstrating how central power utilities would be relieved from the peak power demands that are experienced in the region.

This thesis aims to investigate the impact blockchain-enabled P2P trade of solar energy in Uttara, Dhaka, Bangladesh will have on empowering citizens to earn while increasing the power generation capacity of the region and reducing peak loads experienced by central utility companies. This study also proposes models with which future implementations and extended study of the subject in the case area could be achieved.

1.3 Objectives

The objectives of our thesis are the following:

i. To explore the rooftop PV potential for Uttara

ii. To investigate the potential impact of rooftop generated P2P traded solar power to reduce main grid electricity demand in Uttara.

iii. To propose a blockchain-enabled P2P market model of generated PV energy.

iv. To propose a dual power source controller for switching power between the internal SHS battery and external grid connection.

v. To study the financial effect of blockchain enable P2P energy trade to the participant.

1.4 Significance of the Study

The study shall explore the current rooftop potential of Uttara in producing clean solar energy.

The study shall demonstrate how peak power demand faced by central utility companies in the region can be offset via P2P trading of PV energy.

The study shall add to the body of information available on blockchain-enabled P2P PV energy trading models.

The study shall investigate the potential of citizens of Uttara Dhaka to earn from trading of PV energy.

1.5 Scope

The study focuses on Uttara region of Dhaka, Bangladesh. The study takes place between [1-6-2019] to [5-7-2020].

1.6 Limitations

Electricity consumption data for Uttara was unavailable. This was due attributed to the fact that Uttara is a subset region of the greater Dhaka. As such, consumption data of the region was obtained from extrapolation from the electricity consumption data for the Dhaka region. This poses a source of introduction of systematic error into the findings of the study.

The rooftop characteristics of Uttara was had no previous up-to-date research. The last available study on the rooftop potential of PV generation was conducted more than half a decade ago, and based in Dhaka. As such, the Google Earth Pro platform was used to obtain this data. This method opened the study to the possibility of systematic errors from measurements made on the platform.

1.7 Thesis structure

This section broadly highlights the structure of this thesis for a quick glimpse into understanding the thesis.

Chapter 1: Introduction

The energy situation in Bangladesh is introduced in this section. Developments of the energy sector leading up to P2P energy trading in the country is discussed, and objectives and problem statement for this study discussed.

Chapter 2: Literature Review

The theoretical concepts relevant to this study are discussed in this chapter. The evolution of energy distribution systems from traditional to P2P systems are covered. The theory of blockchain technology is covered in this section, and the pricing mechanisms previously employed in determining the exchange mechanisms of energy for money discussed.

Chapter 3: Methodology

This chapter develops models to investigate the research objectives. Models are developed to look into the prospective rooftop PV production capacity of the study region, execute P2P energy trades via blockchain, and investigate the financial implications of establishing blockchain-enabled P2P energy trading systems in the study region. A physical layer design is proposed, designed and simulated. Finally, the criteria used to select a sample region from Uttara as the study region is then discussed.

Chapter 4: Results

The results obtained from implementing the models developed in chapter 3 are presented in this chapter. The rooftop PV generation potential of the study region in Uttara is presented, the commands executing the blockchain functionalities and results from this demonstrated and presented, and the financial implications of P2P energy trading systems on the involved consumers and prosumers presented.

Chapter 5: Discussion

Meaningful information is drawn from the data presented in the results section, typing together the problems discussed in chapter 1 to the findings of the study.

Chapter 6: Conclusion

This chapter summarizes the whole thesis, typing it together neatly and recapping the crucial bits from the study.

Chapter 2

LITERATURE REVIEW

According to Tushar, et al. (2020), P2P networks can be divided into two layers: a virtual layer, and a physical layer. They proposed that the information system is comprised of four main parts: an information system which allows peers to communicate with each other, a market in which energy transactions are carried out, a pricing mechanism for determining the cost of purchasing a unit of energy, and an energy management system for tracking real-time supply and demand of energy in the grid. The physical layer, on the other hand, is comprised of a grid connection, a metering system having bidirectional measurement capacity, and communication infrastructure.

2.1 The Physical Layer

P2P energy trading is the buying and selling of energy between nodes connected in a micro-grid. With P2P energy trading, the consumers of the microgrid may be categorized as either prosumers or consumers. Prosumers are the parties owning energy generation and/ or storage capabilities; while consumers are the parties that only rely on buying prosumer energy to sustain their electricity demand.

2.1.1 Traditional Power Systems

P2P energy trading presents a paradigm shift from the traditional power distribution and Peer-to-Grid(P2G) implementations. The traditional power distribution involves a central utility that receives energy from large-scale power generation facilities and distributes this power to consumers via the main grid. Power flow in this grid is unidirectional. Most electricity consumers worldwide make use of this implementation to meet their electricity needs. Despite its ubiquitous nature, this system faces challenges. First, the system necessitates the installation of extensive infrastructure to reach a large population. This process is extremely costly. The cost-benefit analysis of expanding the grid to rural areas is usually very low for the distributor. As such, huge populations in rural areas are not electrified.

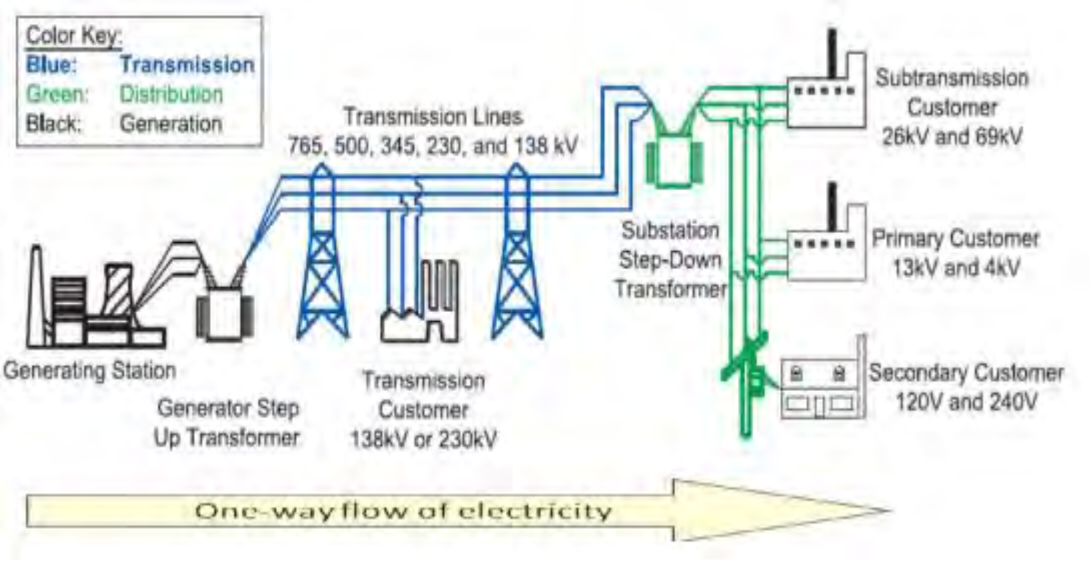


Figure 2.1: Traditional power system [Source: Malik (2013)]

2.1.2 Peer-to-Grid (P2G)

On the other hand, the P2G network is comprised of prosumers, consumers, and the central utility; whereby a prosumer sell their excess energy directly to the central distribution utility. This contrasts the P2P system, where prosumers sell their excess energy to other peers. A FiT provides a framework for this implementation. This mechanism incentivizes the incorporation of distributed energy resources into the main grid. Using the FiT policy, a fixed price is set for different renewable distributed energy resources. This encourages the adoption of particular renewable energy sources over others, ensuring the integration of good quality systems. Moreover, a long-term contract is provided for the distributed energy suppliers, providing security for these parties (Coutre, Cory, Kreycik, & Willams, 2010). This model, however, still faces challenges. There is a big difference between the buying price and selling price of electricity in this system. This demotivates local energy producers (Nelson, Simhauser, & Nelson, 2012). This situation is further exasperated by the information dissonance between the administrative entities setting the prices, and the local community adopting the policy.

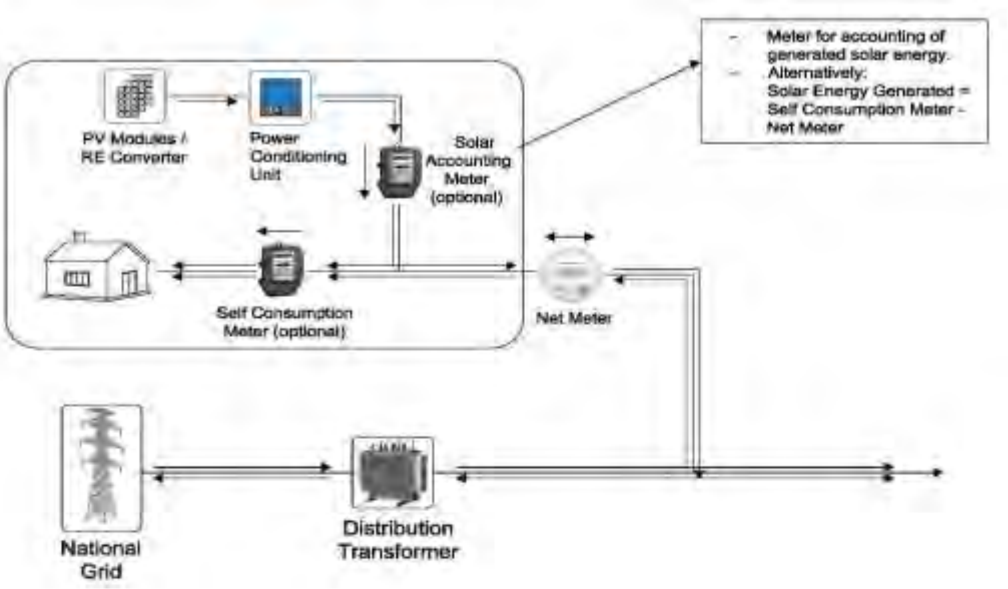


Figure 2.2: Net metering architecture [Source: Chowdhury (2018)]

2.1.3 Introducing Peer-to-Peer (P2P)

P2P is the buying and selling of electricity between consumers and prosumers connected in a grid. Solar power is commonly traded using P2P systems. This model differs from the P2G system, where excess energy is sold directly to a central utility using a feed-in-tariff policy. As such, a P2P platform is more decentralized and utilizes a secure platform such as blockchain.

According to Infinite Energy (2020), P2P energy trading offers several benefits compared to the previous methods:

The necessity of transporting energy over large distances from a central power plant is eliminated. According to AuropaEnergy (2019), 39.4% of a consumer’s electricity bill goes toward managing and maintaining distribution infrastructure.

a) Consumers without generation capacity have access to green energy at a cheaper price compare to from the central distribution utility.

b) Prosumers are enabled to earn more compared to earnings from the feed-in-tariff system.

c) Energy can be bought from a liked source via a secure transparent platform such as blockchain.

In their presentation Philipp, et al. (2013) propose the infrastructural model displayed in (Figure 2.3: Swarm electrification infrastructure). Figure 2.3: Swarm electrification infrastructure in connecting households into a swarm. SHS is typically composed of 20Wp to 85Wp or bigger solar panels, lead-acid batteries and efficient current loads.

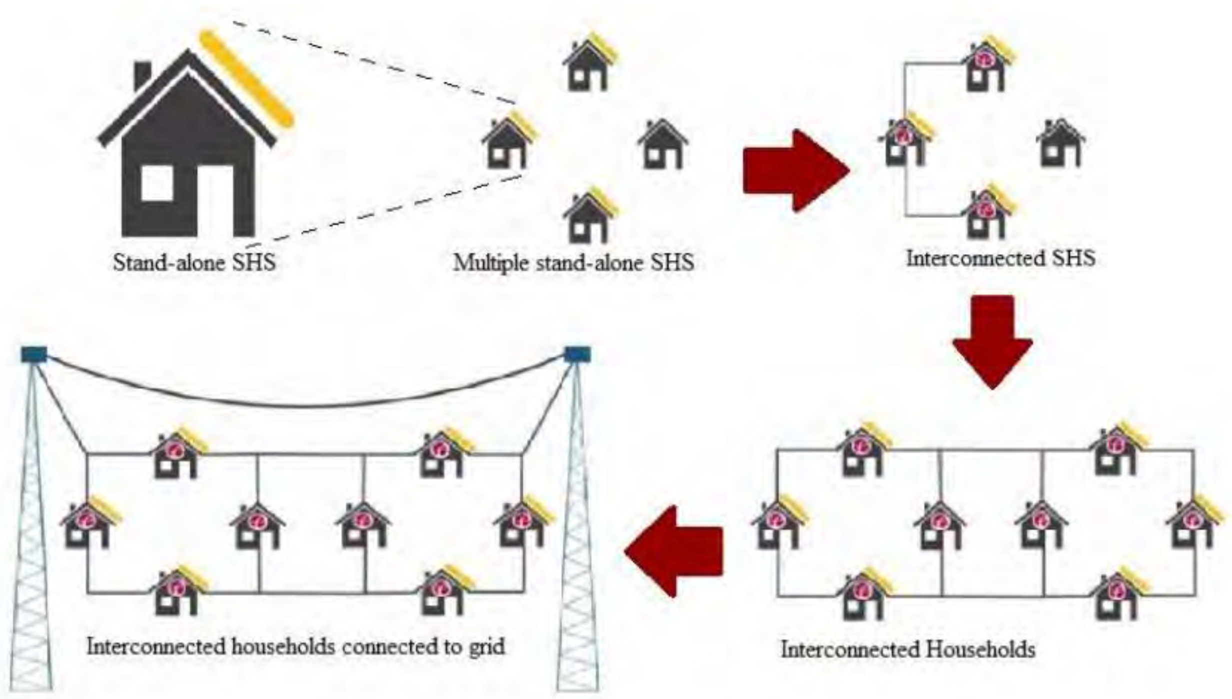


Figure 2.3: Swarm electrification infrastructure [Source: Philipp, et al. (2013)]

Philipp, et al. (2013) found out that four major design parameters have to be considered in implementing a P2P energy trading system. The study contributors proposed the following:

i. The choice of AC or DC for transmitting generating energy has to be considered. Daniel found out that generation using SHS is in the form of DC power. He surmised that transmission using AC is beneficial over long distances, due to the ability to step up electricity to a higher voltage, leading to lower transmission losses. However, transmission over shorter distances, as is the case with micro-grids, is feasible using high-voltage direct current (HVDC). He, therefore, concluded that DC offers more promised for off-grid micro-grids in rural areas.

ii. The topology of the grid also has to be considered. Hannes surmised that a grid has to be designed by optimizing stableness and price. He found out that mesh grids, similar to ring circuits, offered more stability and fault tolerance, due provision of alternative paths of current to reach a load. However, unlike the bus topology, the mesh is more expensive due to the extra cable cost.

iii. Brian analyzed the role of ICT in smart swarms. He deduced that ICT offered a potential in implementing smart meters that could stabilize the network. Remote monitoring and mobile payment were also a huge plus on the role of ICT. However, data privacy remained an issue, raising a question onto the policy by which consumer data would be accessed and used, and by which parties.

iv. Joseph studied the means with which an isolated microgrid could be interlinked. He deduced that connecting the microgrids via the national grid was the most obvious method of achieving this.

2.1.4 Bidirectional meters

A bidirectional meter is an electrical device that measures energy in two directions, from the grid or back into the grid. The bidirectional meter is mandatory for feed-in-tariff implementations and P2P energy trading implementations. Using the bidirectional meter, a prosumer is enabled to receive payment for his/her excess energy exported to the grid and charged for the energy imported from the grid in cases of low production.

Bidirectional meters are also inherently designed to be smart meters. Smart meters record electricity consumption information near real-time. This information enables a consumer to track his or her power consumption, consumed current and power factor while enabling the utility provider to monitor this for ensured quality-of-service (QoS).

2.1.5 Dual Power Source Controllers

Dual power source controllers are necessitated in a P2P energy trading system in the case of prosumers. These devices can switch the power source feeding the loads present in the consuming facility. During high generation periods, the dual power source controller switches power needed by loads to be sourced from the battery present at the prosumer's SHS. During low generation periods, the controller switches the power to be obtained externally from the grid connection.

2.2 The Virtual Layer

2.2.1 Introducing Blockchain

Blockchain is a distributed ledger that allows digital information to be recorded and distributed, but not edited. The basic premise of a blockchain is that the ledger is made up of a chain of blocks, each cryptographically linked to the next via a hash digest. In his paper, Nakamoto (2008) stated that: "Each timestamp includes the previous timestamp in its hash, forming a chain, with each additional timestamp reinforcing the ones behind it".

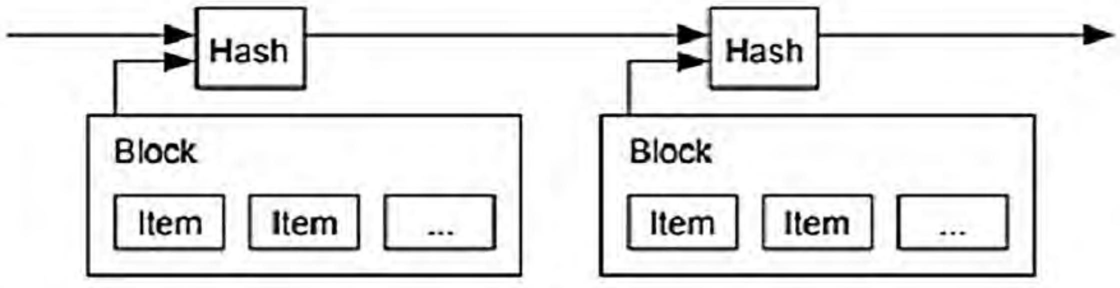


Figure 2.4: Linking blocks on a blockchain [Source:(Nakamoto, (2009)]

A nonce is an abbreviation for “number only used once”. This is the number that miners compute for in a proof-of-work consensus. The process of finding a nonce is a trial-and-error operation and is excessively demanding on computing power. Only when the right nonce specific to a block being mined is found, can the target hash for the block equals the miner’s calculated hash for the block. When a miner finds this nonce, he/she broadcasts discovery of the value, and he/she is awarded a price, for instance, crypto-coin. Mining then proceeds to the next block.

A genesis block is the first block on a new blockchain. All other subsequent blocks mined on the blockchain are linked to this genesis block. Bitcoin’s genesis block was mined by Nakamoto in 2009. (Nakamoto, 2009)

Blockchain technology has given rise to smart contracts (Buterin, 2014)**.** A smart contract is a computer code built into the blockchain that can be used to facilitate, verify, or negotiate a contract agreement. Programming of the contracts is usually done in the blockchains programming language. For instance, Bitcoin users its programming language, Forth, to script a smart contract. Using a smart contract, a buyer and seller can agree to a set of conditions, which when met, the terms of the agreement are automatically executed. Smart contracts can be used in P2P energy trading to create trust between buyer and seller.

Due to the presence of many instances of a blockchain database for each user, trust has to be established to ensure that the blockaded by a user to the blockchain is a valid entry. This situation is a stark contrast to conventional systems where trust is maintained by a central clearing institution. In light of this challenge, several consensus models have been proposed.

The proof-of-work based consensus is the most popular and was proposed by Nakamoto. In this model, miners are challenged to solve a cryptographic puzzle by expending their compute resources. In exchange for this, they are awarded incentives. This is how Bitcoin's miner's cryptocurrency. This model, however, is not ideal, as a lot of resources are expended.

The proof-of-elapsed-time consensus model necessitates that each node on the blockchain network generates a random time. Each node then goes to sleep for the generated time. The first node to wake wins the block. For this model to work, it is necessitated that each node generates a truly random number, to avoid cheating into wining the block. The node must also sleep for the entire duration of the generated time. This model is advantageous over the proof-of-work model as power consumption is heavily minimized during sleep.

The proof-of-burn consensus works by necessitating that miners sent some coins to a verifiably un-spendable address. This model consumes fewer resources than the proof-of-work consensus model.

The proof-of-capacity makes use of a node's memory space rather than the nodes compute power. Nodes with greater memory capacity are at an advantage to finding a blocks nonce value, earning them the right to mine it.

Depending on the openness of a blockchain, the network could be public, private or a consortium. Public blockchains are open to everybody. Anyone can participate in the blockchain and consensus is mandatory to ensure trust. Private blockchains are only open to particular nodes, granted privilege by a specific server. The consensus is not necessitated in this blockchain. Consortiums are only open to a privileged group.

Blockchain offers three main advantages.

- **Decentralized**

Blockchain is distributed across many nodes. Each node has an identical ledger to those contained in other nodes. When a new node adds a new block of data, that piece of information is propagated throughout the network of nodes, ensuring that the whole database converges into a single harmonic ledger. This way, blockchain is seen to be decentralized, no single body is in charge of the entire database.

- **Transparency**

Blockchain fosters transparency. Transparency is especially important for organizations forcing them to be upfront and visible about the transactions they partake. By its virtues of being transparent, however, blockchain does not take away privacy from the users. This is due to the fact that the identity of users using blockchain is hidden, via a digital signal. However, for an organization for which transparency is mandated, the public signature of the organization can be made available. This way interested members could always scrutinize the former’s actions.

- **Immutability**

Once a block has been added to a blockchain, it is ideally unchanging over time. This is a consequence of hashing employed in the blockchain. A hash function is a function that generates a fixed-size unique code for an arbitrarily sized input data. Alongside each block of data, is a hash code generated from the contents of that block. Each block also contains the hash of its previous adjacent block, and so on. If a hacker thus modifies data in a particular block, the block’s hash changes and the hacker has to change data and hash of all previous blocks, an impossible process.

Disadvantages of blockchain

Disadvantages of blockchain are:

- Limited transactional capacity. A standard blockchain with a 1MB block size can only support a maximum of 300,000 transactions per day (Hudson, 2014). This capacity must be shared among all users on the network. Increasing this capacity could result in forking of the blockchain. A fork is a situation whereby the blockchain diverges into two different forward paths. The fork could be only temporary, as is the case in slow consensus, or permanent, as is the case where a protocol changes for the blockchain changes. An example of a parent fork is the split between Ethereum and Ethereum Classic.
- Blockchain is a power-intensive technology. Network miners use a lot of computing power invalidating each transaction. In order for consensus to be achieved by the network, each node is required to carry redundant calculation to ensure tolerance (Song, Shi, Xu, & Gill, 2016). Signature verification further contributes to this problem.
- Proof of work mining presents challenges to implementation of a blockchain in a real-time system. There is a considerable time delay for confirmation of a transaction. This delay is described by a Poisson distribution and could be up to 10 minutes. Proof of work could also expose the network to a 51% attack. This is a type of Denial of Service (DoS) attack where 51% of blockchain users could cooperate to deny transactions on the network (Jake,2019).

2.2.2 Pricing Mechanism

A pricing mechanism is part of a market system, that defines the way that a buyer and seller are to be matched. The price of a commodity plays a key role in determining the actions performed by a buyer, seller and supplier.

The following pricing mechanism has been discussed and found application to the P2P energy market:

- **Stackelberg Game**

The basic premise making up a Stackelberg game is that the prosumer is interested in obtaining maximum profit from sales of his/her excess energy; while a consumer is interested in reducing its cost of energy purchase. In this pricing system, the leader (prosumer), acts first by announcing its available surplus energy and cost at which it is to be traded. Next, the followers (consumers), announce the price at which they are willing to pay. Anoh, et al. (2019) propose a Stackelberg game solution to P2P energy trading in virtual microgrids.

- **Double Auction Market**

Multiple buyers and multiple sellers are involved in a double auction market. In this market, first, the buyers (consumers) submit their bids to the market institution. Next, the sellers (prosumers) submit their bids to the market institution. The market institution then chooses a price p that clears the market. All sellers who asked for less than p sell and all buyers who bid more than p buy at that price p. The challenge to this market is finding a competitive equilibrium; whereby the supply equals the demand. Thakur, et al. (2018) propose a distributed double auction market for P2P energy trading using blockchains.

- **Bill Sharing**

The bill sharing method is a cost-sharing method in which each house pays for their individual electricity use. In this method, the microgrid in which a peer exists is first charged by the central utility distributing via the main grid. The bill charged to the micro-grid is a function of the total power imported into the micro-grid from the main grid. A uniform rate for a kWh unit of electricity consumed and kWh of energy exported is applied to each peer.

2.2.3 Blockchain for Energy Trade

Ernest & Young (2017) stated that “Through the application of blockchain technology there is an opportunity to streamline internal processes and processes shared with external market participants”. They developed a five-point test for accessing whether blockchain is a proper fit for application to particular trading process:

- Are there multiple parties in this ecosystem? Blockchains get more secure with more parties in the network, one participant networks are not especially secure.
- Is establishing trust between all the parties an issue? Blockchains improve trust between participants by having multiple points of verification.
- Is it critical to have a tamper-proof permanent record of transactions? Blockchains create permanent records that cannot be edited or deleted.
- Are we securing the ownership or management of a finite resource? Core logic in the system is designed to prevent double-counting of assets, record ownership and transfers.
- Does this ecosystem benefit from improved transparency? Blockchains are transparent by design — where ownership or control of assets is public and transparent by design.

(Ernest & Young, 2017)

As blockchain application for energy P2P energy trade meets the above criteria, there is increased traction in researching and adopting this technology into the P2P energy trading market. This has seen the development of the local and global project, backed on blockchain.

Power Ledger, an Australian company, founded in May 2016 that has developed a proprietary operating system that makes it easier and cheaper for customers to choose from renewable energy sources. The platform was originally developed to facilitate the trading of solar power and battery stored electricity. The platform has since then incorporated wind power.

The Brooklyn Microgrid is a community-driven blockchain-enabled market place. The project began in April 2016in Brooklyn, New York City. to allow consumers. The project allows participants to buy energy from other prosumers located on the microgrid using a mobile app. Prosumers, on the other hand, are given the flexibility to sell their energy directly to other peers on the microgrid, or net meter.

The NRGcoin project was developed at the Artificial Intelligence Lab of the Vrije Universiteit Brussel. The mechanism provides smart contracts for energy trade, using their local cryptocurrency NRGcoin. This mechanism enforced that 1kWh of green energy equals 1NRGcoin. Their pitch highlighted the potential advantage to peers by using a trustful smart contract and enabling near-real-time payments to prosumers rather than the conventional monthly billing. The project, however, lacks a quantitative analysis on the merits of its implementation.

2.3 Related Studies

Zhang, et al. (2017) propose that blockchain poses a promising technique in simplifying the metering and billing system of P2P energy markets. They also observed that some trial projects only focused on ICT technologies, without considering control systems of the proposed market. They, however, didn’t conduct a study for the outreach of their proposed system.

Ferreira & Martins (2018) proposed an open energy market system, build upon IoT for accounting for energy flows, and blockchain for overcoming the need for a central control entity to allow for the creation of local energy markets to handle distributed energy transactions without needing a central control.

Silvestre, et al. (2018) proposed a blockchain-based model to handle the technical issues in a microgrid.

Kang, et al. (2017) proposed a Consortium blockchain (PETCON) based P2P electricity trading model for plug-in hybrid electric vehicles. They further proposed an iterative double auction mechanism to maximize social welfare in that electricity trading. They found out that their model improves transactional security and privacy protection. Their model, however, was targeted for mobile vehicles and such didn’t focus on the challenges presented by implementing a microgrid.

Jogunola, et al. (2019) demonstrated the application of blockchain to energy P2P trading. They developed a smart contract to establish trust during transactions and expounded challenges faced by implementing blockchain for P2P energy trading.

Kim, et al. (2017) demonstrated a methodology for implementing energy trades via the Multichain platform. They used a python-based module by the name “Savoir” that is based on JSON-Remote Procedure Calls (RPC). In their study, Kim, et al found out that the platform is a potentially operationally feasible solution to the problem. However, they weren’t able to handle partial transactions and discovered that their model predicted that their blockchain network would have a slow consensus in the case of many nodes.

Leberer (2018) conducted a study on the impact of P2P power trading in Alberta. They used the Aspen Gardens in Alberta as their case study region. To calculate PV rooftop potential of the area, they used a Python library called “PV_LIB”. They developed case scenarios to analyze the effects of changing P2P parameters on the economic impact of the system. However, the study didn’t involve blockchain, a promising prospect of the future of P2P trades.

Chapter 3

METHODOLOGY

In this chapter, the model that was developed to test the research question will be introduced and discussed. The model consists of two main parts; the first part modelling Uttara's PV potential against the region's demand, while the second part shall simulate test P2P solar energy trade between peers and the main grid in case of deficiency.

This methodology assumes an Ad-Hoc P2P energy system, where central energy utilities (i.e. the main grid) are connected to the microgrid. This model is advantageous in case the energy demand of the microgrid is not met by its local prosumers, as is the case in urban development where electricity demand is high; the microgrid customers have the flexibility to import electricity from the main grid.

The bill-sharing pricing system was also assumed for this test network. This was influenced by its inherent nature that closely resembles the net-metering system currently employed in Bangladesh's P2G system. This system would impose a narrower paradigm shift from the central utility's current billing system, thus providing a higher incentive for the main grid to be integrated into the microgrid.

3.1 Modelling Uttara's PV Potential against Its Current Electricity Consumption

Step 1: Calculating Uttara's maximum PV potential

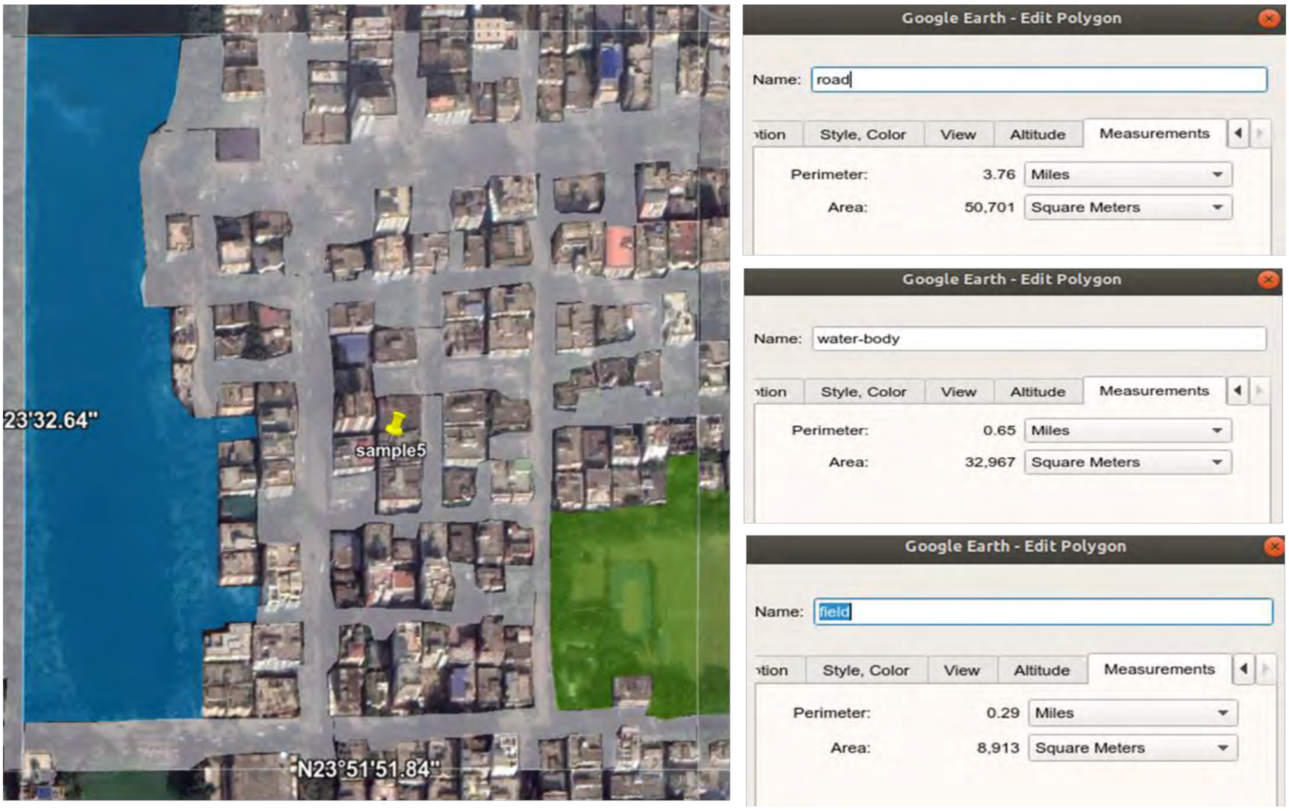
i. The total rooftop area of Uttara's residences, industries and other social buildings was calculated. Google Earth was chosen as the platform upon which this data was to be collected. This platform provided a quick efficient way of obtaining first-hand data about the rooftop area characteristics of the region compared to other techniques, by using satellite imagery of the region to visually inspect the area, and employing the tools provided to perform this analysis.

The following equation (3.1) was used to calculate the total rooftops area of a sample grid:

$$Grid\ rooftops\ Area(m2) = Grid\ Area(m2) - Non-building\ Area(m2) \quad (3.1)$$

The polygon feature was employed in calculating areas of structures and spaces not comprised of buildings, where polygons were drawn on the map, spanning areas not covered by buildings, such as roads, parks, water bodies and unbuilt spaces. The total area of rooftops in that sample grid was then obtained by subtracting this obtained area from the static grid area.

An instance of this procedure in use is demonstrated below for sample 5, where the filled grey regions mark roads and unbuilt spaces, blue filled outline highlights a water body and filled green region highlights a field.



Google Earth - Edit Polygon

Name: road

Perimeter: 3.76 Miles

Area: 50,701 Square Meters

Google Earth - Edit Polygon

Name: water-body

Perimeter: 0.65 Miles

Area: 32,967 Square Meters

Google Earth - Edit Polygon

Name: field

Perimeter: 0.29 Miles

Area: 8,913 Square Meters

Figure 3.1: Calculating rooftop area (Adapted from Google Earth Pro)

ii. Uttara’s insolation data was then obtained via NASA’s Prediction of Worldwide Energy Resources (POWER) platform using the “data access viewer” interface. The latitude and longitude of Uttara (23.8759° N, 90.3795° E) were keyed into the interface and the “All Sky

Insolation Incident on a Horizontal Surface” parameter was used to generate a CSV formatted data set of the insolation parameter from Jan 1, 2019, to Jan 1, 2020. The platform is accurate to a ½ by ½ latitude and longitude.

The potential PV power that could be generated in Uttara was then approximated on a daily basis using the formula:

(daily) generated electricity(kWh) = rooftop area(sqm) x panel efficiency (%) x (day’s)insolation (kWh/sqm) x system performance ratio (%)

The solar panel efficiency is the measure of a solar panel ability to convert sunlight into electricity. The most solar panel have efficiencies between 15% and 20% (AGGARWAL., 2020). This parameter is dependent on factors such as the material of the semiconductor, the organization of wiring and busbars inside the solar panel and reflection of the solar panel.

The system performance ratio describes the overall efficiency of the system. It is dependent on factors such as cable losses, soiling losses, temperature effects, and reflection losses (nsr, 2014).

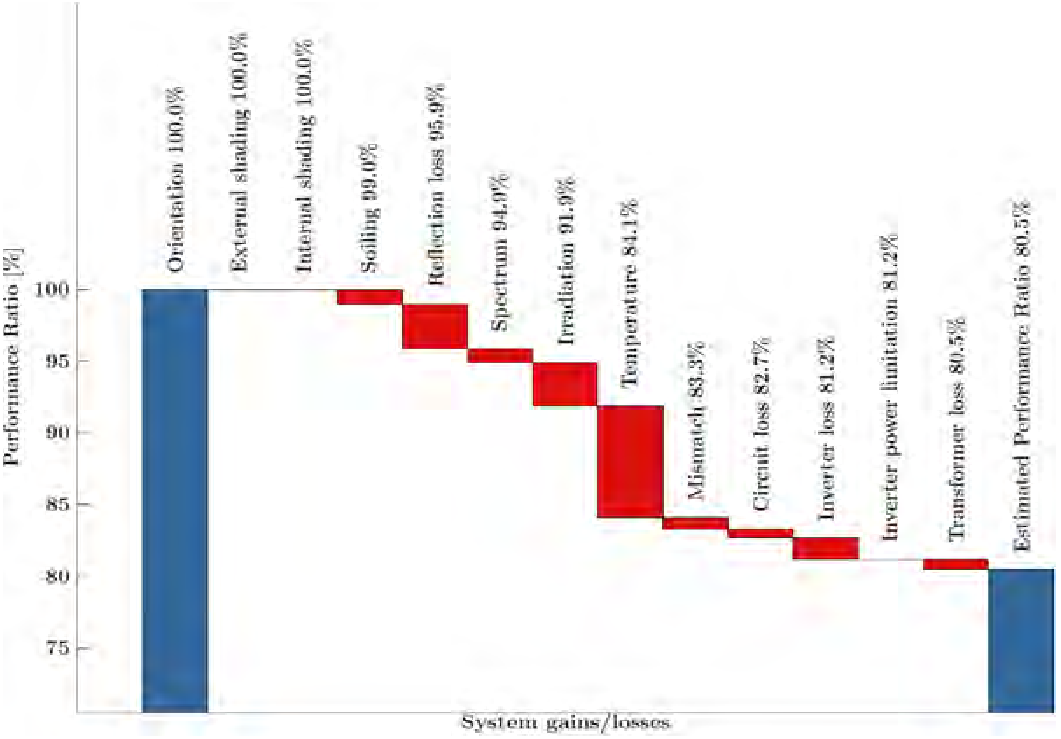


Figure 3.2: System losses [Source: nsr (2014)]

Step 2: Obtaining power consumption of the Region

- Using time series analysis for electricity consumption and regression equation, Istiaque& Khan (2018) forecasted the following electricity demand for the city of Dhaka. They considered temperature, GDP growth, population, increase of cooling appliances and price per unit of electricity as control variables.

Table 3.1: Electricity consumption of Dhaka [Source: Istiaque & Khan (2018]

Electricity consumption (MWh)							
	2014	2015	2016	2017	2018	2019	2020
Jan	1209361	1296571	1451450	1522782	1547219	1578317	1610040
Feb	1173555	1265158	1563573	1519310	1543691	1574718	1630958
Mar	1571965	1721913	1970286	1933514	1964542	2004028	2044307
Apr	2042366	1707700	2130994	2108442	2142277	2185336	2229529
May	2152864	1988717	2055241	2135795	2170069	2213686	2258180
Jun	1984005	1975042	2281348	1947116	1939382	2018125	2058689
Jul	1840256	2812046	1991819	1933514	1964542	2004028	2044307
Aug	1785349	2055334	1991830	1933514	1964542	2004028	2044307
Sep	1796106	1872785	1848934	1871142	1901170	1939381	1978362
Oct	1644389	1958733	2072920	1895417	1925834	1964542	2004028
Nov	1476123	1660048	1608511	1627832	1653955	1687198	1721109
Dec	1351784	1461365	1565803	1584611	1610040	1925834	11675412

- According to the UN (2018), the population of Dhaka in 2018 was projected to be 19,578,000while the region spans 306.4km$^{2.}$ This provides an average population density of 63,897 people/square kilometer. Assuming a uniform population distribution, the population of the study region, which spans 5.68 km^{2}, was estimated to be 362,935.

The monthly electricity consumption data for the year 2019 provided above was scaled for this population size of 362,935. The new consumption profile for the study region is tabulated below:

Table 3.2: Monthly Electricity Consumption of Uttara, 2019

Electricity Consumption (MWh)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2019	29259	29192	37150	40512	41037	37412	37150	37150	35952	36418	31277	35700

This data was used later in the results and discussion sections to analyze the region's PV potential against its electricity demand.

3.2 The Virtual Layer Model

This section proposes a model to be used for setting up a blockchain network and a protocol for negotiating on the assets to be traded leading up to a successful transaction.

The Multichain blockchain platform was selected as the platform upon which the P2P blockchain network proposed in this paper. Multichain is an open-source blockchain platform that enables users to create and deploy private blockchains. The platform was chosen for this study for the following reason:

i. The platform offers private blockchains This allows the generated blockchain to be only visible to the peers trading energy on the microgrid. This is advantageous in that it allows control of the transactions over the network. In addition to this, the costly proof of work mechanism integral to other open blockchains such a Bitcoin can be avoided.

ii. The platform is developer-friendly. An API and command-line interface (CLI) are provided to users to interact with their blockchain. This platform is advantageous in that it reduces development time considerably via its API and CLI interfaces, and also enable a developer to custom-make their blockchain via creating the tradable assets on the network and specifying their native trading currencies.

Three integral parties are involved in this simulation: prosumers have energy-generating capabilities and sell their excess energy to consumers, consumers have no PV generation capacity and buy their energy preferentially from prosumers or a central utility, and the network admin initializes the network, adding peers and issuing cryptocurrency coins for transactions.

The following pseudo-code demonstrates the steps involved in initializing the blockchain for initial use:

- Begin
- Create Blockchain
- Create energy &e-coin assets
- Create Prosumer_Capacities open stream
- Create Consumer_Demands open stream
- Create Peer nodes.

```
•  Grant peers connect, send, and receive permissions
•  For each P2P connection
•      Create a private stream
•  End for
•  End
```

The energy asset represents a unit of electricity in kWh that is to be traded over a blockchain. The e-coin asset is the native currency used to trade assets over a blockchain.

Streams provide a natural abstraction for blockchain use cases which focus on general data retrieval, timestamping and archiving, rather than the transfer of assets between participants (Multichain, 2020). Streams are used to implement a key-value database in this methodology. The “prosumer-capacities” stream is used by prosumers to publish their available excess energy. The “consumer-demands” stream is used by consumers to publish their energy demand. Consumers can view the published capacities of prosumers at a given moment via the “Prosumer_Capacities” stream and prosumers view consumer demands via the “Consumer_Demands” stream. These streams mimic the physical market place better where a buyer and seller can publish their demand and supply.

A key is used to identify each item published on the streams. The JSON object used to publish consumer demands or prosumer’s available excess energy is structured as follows:

{“amount”: *amount*},

Where the amount is the consumer electricity demands in kWh prosumer excess energy for supply in kWh.

Private streams are created for each pair of nodes. Using these streams, a consumer and prosumer can negotiate for a settlement, upon which a transaction is made for the agreed amount. This mechanism solves the problem of partial transaction experienced by Kang, et al. (2017). This is demonstrated later in the Results section.

JSON objects are used in these streams to facilitate information exchange. The following picture demonstrates a simple protocol developed for information exchange, leading up to a successful trade. For this demonstration, a prosumer initiates the negotiation, but the converse also applies.

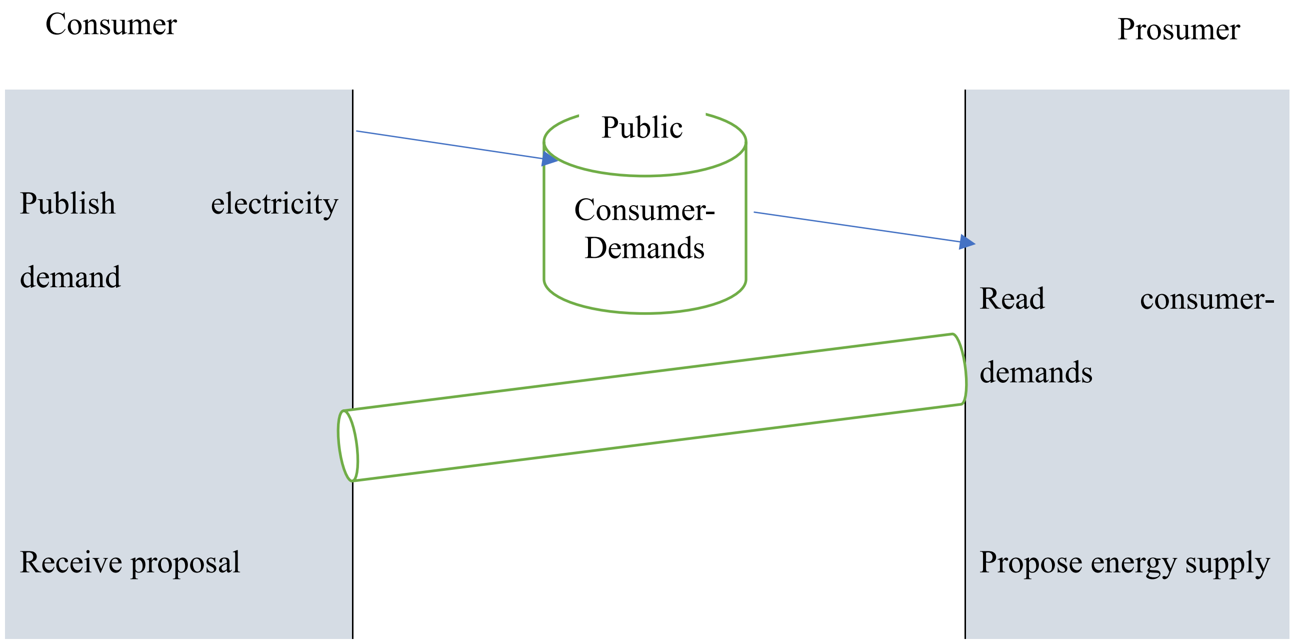


Figure 3.3: Initiating P2P trade proposal on blockchain

The JSON object sent by a prosumer to show interest in supplying energy to a consumer with public demand on the public Consumer-Demands stream is structured as shown:

{“interested”:true, “amount_available”: *amount*}.Using this, the prosumer notifies the consumer if he/she has exactly the amount of energy requested by the consumer, or can only cater for part of the request. If the consumer agrees to the prosumer proposition, the transaction is made complete. This is described by the diagram below:

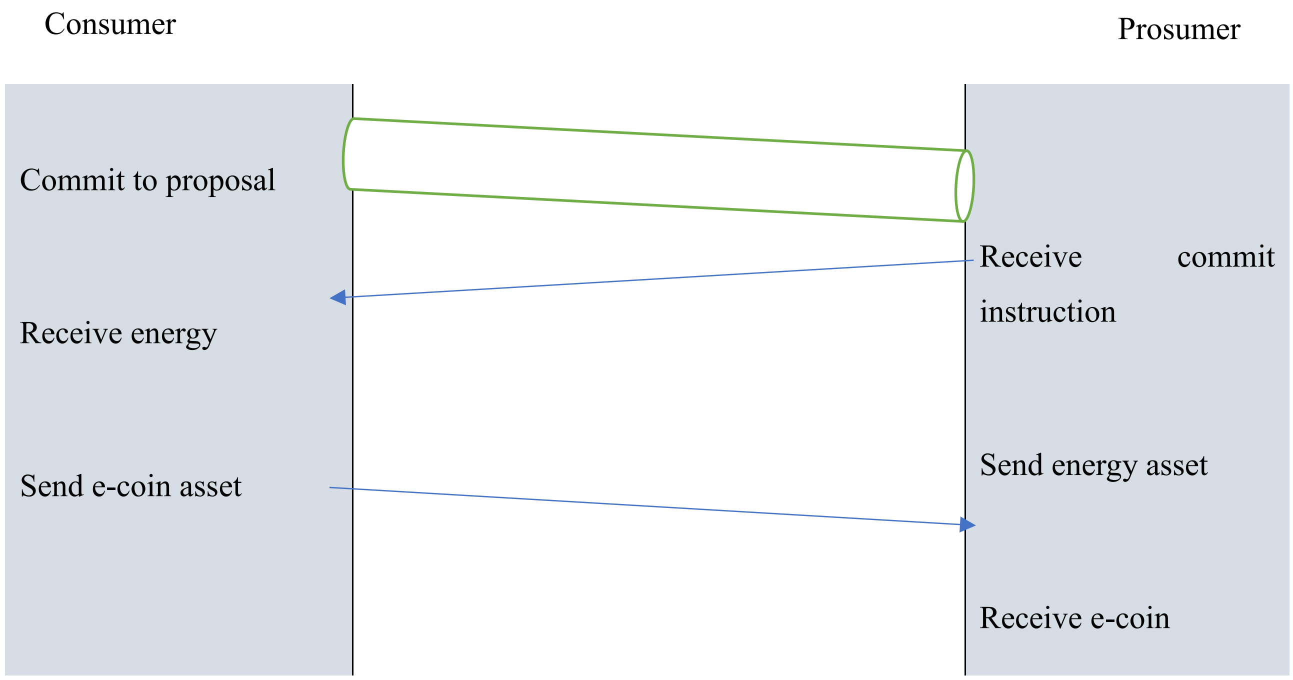


Figure 3.4: Trading P2P assets on a blockchain

An exchange rate of 1 e-coin for 1 kWh of electricity is assumed in this model as used by NRGcoin (NRGcoin, 2020). The P2P energy trade instance is then complete.

3.3 The Physical Layer Model

3.3.1 Prosumer Section

Requirements Analysis

The following requirements dictate the demands the proposed system had to satisfy:

- The system must simulate an SHS setup.
- The system must simulate electricity input from the grid during undercharged periods.
- The system must simulate electricity export during overcharged periods.

Design

The following block diagram below of the proposed system is shown below.

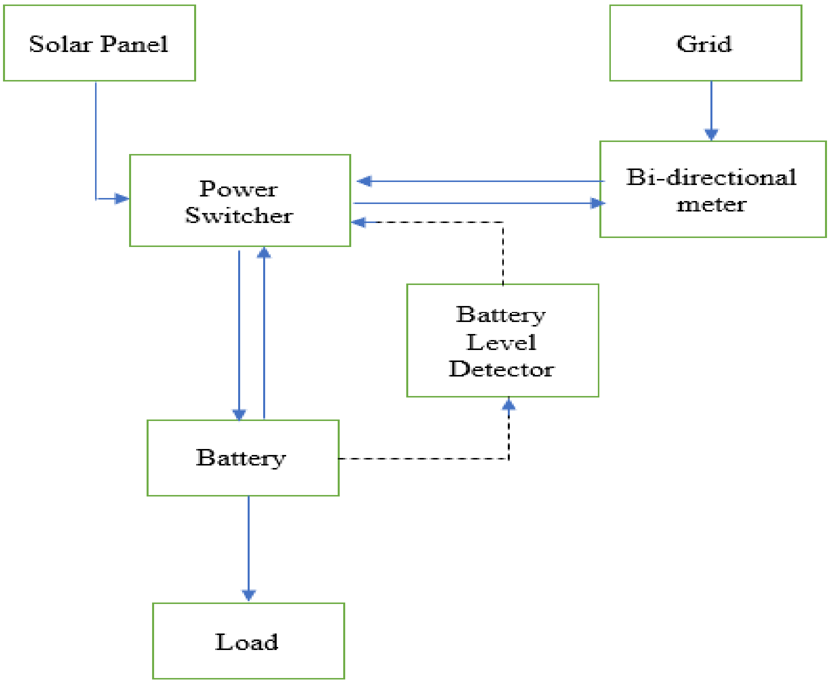


Figure 3.5: Prosumer Control system block diagram

The load is primarily powered by the energy stored in the battery. The system may receive power from the local solar panel, present in the SHS, another prosumer via the grid, or central utility via the grid. A power switcher circuit is at the heart of this design. This circuit determines from where the power feeding the system is to be sourced. The decision from where the power switcher receives power is enabled by the battery level detector.

The following three scenarios dictate the operation of this system:

I. If the battery is undercharged, the power switcher sources power from the grid.

II. If the battery is level is within operating range, power is sourced from the solar panels.

III. If the battery is overcharged, excess power is exported to other peers via the grid.

3.3.2 Consumer Section

Requirements Analysis

The following demands dictate the requirements the consumer system must satisfy:

- The system must simulate electricity input from the grid.

3.4 Economic benefits of P2P Energy Trade

This part develops a model that was used to get the potential economic benefits of a P2P energy trading system in Uttara; to the consumers in saving electricity bill expenditure, and prosumers in earning income.

Projecting the economic benefits of a P2P energy trading system in the region was a challenge due to the monthly nature of electricity consumption data, unlike the daily PV generation data. This is primarily because integral electricity meters are ubiquitous in homes and industries, whereby the electricity bill is computed as a cumulative sum of electricity consumed over the whole month. In addition to this, platforms tracking daily consumption of electricity avoid publishing consumer data due to security concerns, as this information could be used to track the habits of consumers.

In light of this challenge, a kludge solution was designed to generate an expected daily electricity consumption:

- The monthly electricity consumption of a single individual was obtained by dividing the earlier obtained monthly consumption of the study region by the earlier assumed population of the region (362935).

Table 3.3: Individual monthly electricity consumption (kWh)

Month	Electricity consumption (kWh)
Jan	80.6168
Feb	80.433
Mar	102.3612
Apr	111.622
May	113.07007
Jun	103.0812
Jul	102.3612
Aug	102.3612
Sep	99.0591
Oct	100.34436
Nov	86.1782
Dec	98.3672

- A 45-day moving average trend line was applied to this monthly average data, considering the 45 days before January 2019 to generate a smooth dataset extrapolating daily electricity consumption. The graph below visualizes the results of this procedure.

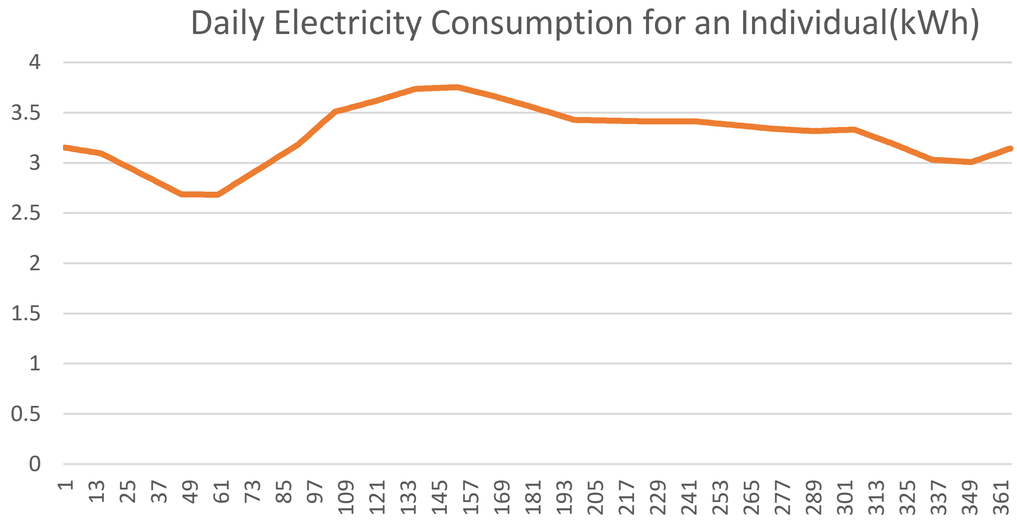


Figure 3.6: Daily electricity consumption for an individual (kWh)

The average cost of an individual in consuming electricity in a month was then calculated as:

$Cost\ Electricity = Cost\ P2P\ sourced + Cost\ Main\ Grid$,

Where $Cost\ P2P\ sourced = Units\ Imported * Cost\ per\ Unit$

And $Cost\ Grid\ Soured = Units\ Imported * Cost\ per\ Unit$

The cost a kWh unit of electricity assumed for a household was 5.335BDT (GlobalPetrolPrices.com, 2019).

A subsidized cost/unit rate of 4BDT for P2P grid was assumed for this study.

The units imported from the P2P microgrid and the main grid was found from analysis of the results obtained from part one.

3.5 Sampling Techniques

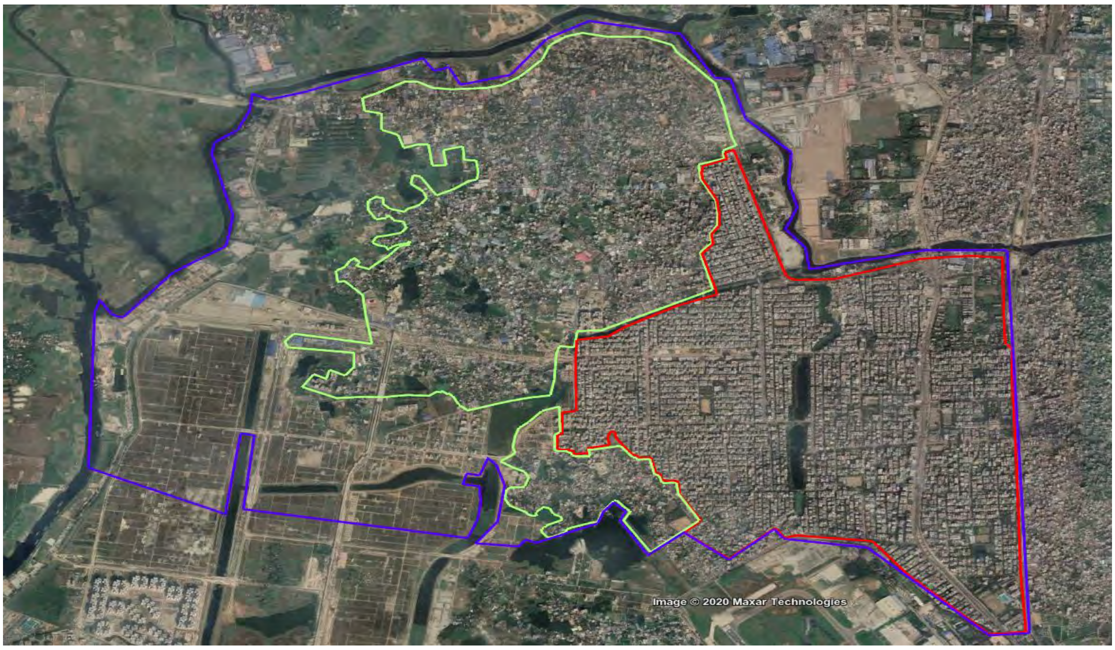
3.5.1 Mapping Study region

The area enclosed by Uttara was first bound by the outermost purple outline. This enclosed region was then divided into three sections, based on their housing densities.

The high-density housing region was bound by the shown red outline. This area encompassed Sector 1, Sector 3, Sector 4, Sector 5, Sector 6, Sector 7, Sector 9, Sector 10, Sector 11, Sector 12, Sector 13, Sector 14 and West Uttara.

The medium density housing region was bound by the green outline and encompassed Bhatuliya, Bhatuliya Mouza, Rasdia Mouza, Kamarpara, Rajabari, Bamnartek, Ranavola, Noa Nagar, Phulbaria, Nalbhog Mouza and Ahalia.

The low housing density region of Uttara was left unbound encompassed Block-A,Block-A1, Block-B, Block-C, Block-C1, Block-D, Block-E, Block-F, Block-G, Sector 15 and Sector 16.



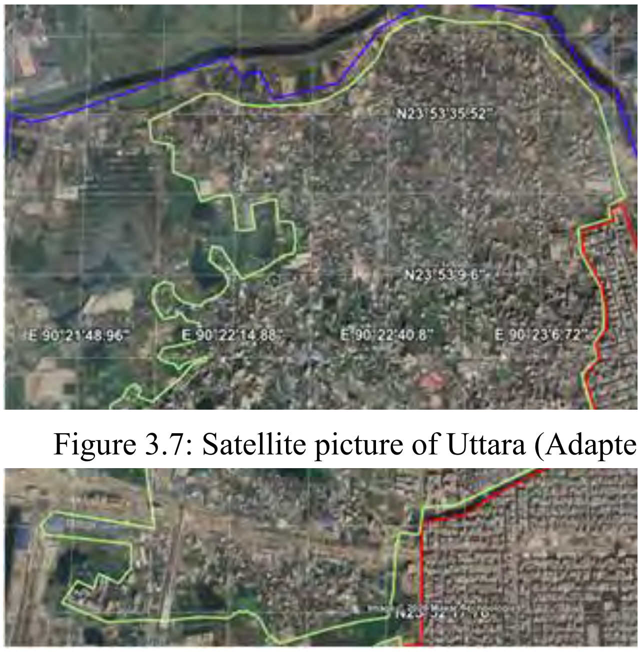


Figure 3.7: Satellite picture of Uttara (Adapted from Google Earth Pro)

Figure 3.8: Medium housing density region

Figure 3.9: High housing density region

Figure 3.10: Medium housing density region1

3.5.2 Choice of Study Region

Of the three regions, the high housing density region was selected for this study. This area was selected as it offered an efficient rooftop area analysis using the Google Earth Pro platform, compared to the other two regions, due to its virtue of nicely clustered building, evenly spaced by roads, parks or water bodies. In addition to this, the area presented a higher financial potential by virtue of its high population.

Grids spanning approximately 375mx375m were then overlaid on the region and grids counted for the region as shown:

Table 3.4: High-density region grid count

Area	Full Squares	Half squares	Total square = Full square + ½ × Half squares
Dense housing	21	34	38

From these grids, the sample size needed to get the rooftop area in the high-density housing region was obtained using the modified Cochran's formula (3.2) defined as:

$$n = \frac{n_0}{1 + \frac{n_0 - 1}{N}}, \qquad (3.2)$$

where N is the available population and no is the Cochran sample size defined as:

$$n_0 = \frac{Z^2 * p * q}{e^2}$$

where Z is the confidence level, p is the probability of finding at least one rooftop in a grid-square, q is defined as (1 – p) and e is the margin of error required.

For this study, a confidence level of 90% was selected that translated to a z-score of 1.65. A probability of 0.9 was chosen, while a margin of error of 10% was defined. The available population considered as the total number of grids in the high-density housing region, 38.

Applying the Cochran's sample size formula:

$$\mathrm{n}_0 = \frac{1.65^2 * 0.9 * (1 - 0.9)}{0.1^2} = 24.5 \cong 25$$

Then taking this into the modified Cochran formula (3.2):

$$\mathrm{n} = \frac{25}{(1 + (25 - 1) / 38)} = 15 \tag{3.2}$$

This was the sample size used for this study.

Simple random sampling was then used to obtain grid samples, for which the total rooftops area in each was to be obtained. A caveat of this sampling methodology was that only full grids were considered for sampling to calculate the rooftop areas of buildings in a sample grid.

Chapter 4

IMPLEMENTATION AND RESULTS

4.1 Uttara’s PV potential against Its Current Electricity Consumption

Rooftops PV potential

15 sample areas were taken, each bound by gridlines of fixed latitude and longitude spans. The areas of places not occupied by buildings were then calculated using Google Earth’s polygon feature. The rooftop area of a grid was then found by subtracting this non-building total area from the grid area. The following results were obtained for the sample grids:

Table 4.1: Sample grids rooftops area

Grid	Span ([Upper Latitude – Lower Latitude], [Westerly Latitude – Easterly Latitude])	Non-buildings Area (m^2)	Rooftops Area (m^2)
Grid1	[23°52’43.68”N - 23°52’30.72”N], [90°23’58.56”E- 90°24’11.52”E]	86603	54022
Grid2	[23°52’43.68”N - 23°52’30.72”N], [90°23’19.65”E – 90°23’32.64”E]	50346	90279
Grid3	[23°52’30.74” N - 23°52’17.76”], [90°23’32.64”E - 90°23’5.59”E]	80895	59730
Grid4	[23°52’4.8”N - 23°51’51.84”N], [90°23’19.65”E – 90°23’32.64”]	55259	85366
Grid5	[23°52’4.8”N - 23°51’51.84”N], [90°23’32.64”E - 90°23’5.59”E]	92581	48044
Grid6	[23°52’30.74” N - 23°52’17.76”N], [90°22’53.74” E - 90°23’6.72”]	60859	79766
Grid7	[90°23’58.56”E- 90°24’11.52”E]	74853	65772
Grid8	[23°52’17.76” N - 23°52’04.81”N], [90°23’45.57”E - 90°23’58.56”E]	72215	68410
Grid9	[23°52’17.76” N - 23°52’04.81”N], [90°23’19.65”E – 90°23’32.64”]	59905	80720
Grid10	[23°52’30.74” N - 23°52’17.76”], [90°23’58.56”E- 90°24’11.52”E]	67755	72870
Grid11	[23°52’17.76” N - 23°52’04.81”N], [90°22’53.74” E - 90°23’32.64”E]	62318	78307
Grid12	[23°52’4.8”N - 23°51’51.84”N], [90°23’58.56”E- 90°24’11.52”E]	80670	59955
Grid13	[23°52’43.68” - 23°52’30.72”N], [90°23’32.64”E - 90°23’5.59”E]	71498	69127

Grid14	[23°52’4.8”N - 23°51’51.84”N], [90°23’45.57”E - 90°23’58.56”E]	84719	55906
Grid15	[23°52’30.74” N - 23°52’17.76”], [90°23’19.65”E – 90°23’32.64”]	66854	73771
Total			1042045

The total rooftop area of the 15 sample grids was calculated to be 1,042,045 m^2. The average rooftop area for one gird in the study region was found to be:

$$\frac{1042045}{15} = 69469.67\ \mathrm{m}^2$$

The total maximum rooftops area in the case study region’s 38 grids was approximated to be:

$$69469.67 * 38 = 2{,}639{,}847.46\ \mathrm{m}^2.$$

Assuming 50% of this total rooftop area was available for solar panel installation, the rooftop area under solar panel was projected to be:

$$2{,}638{,}847 * 0.5 = 1{,}319{,}423\ m^2$$

The all-sky insolation data from NASA’s POWER project for the span Jan 1, 2019, to Dec 31, 2019, was successfully obtained. Using this data and this aforementioned calculated total rooftop area, the formula proposed for calculating the PV rooftop potential of the area was applied. The solar panel efficiency assumed was 0.17 while the system performance ratio was 0.85.

The graph below shows the projected total potential for solar power generation in the region against the estimated daily electricity consumption for a single person Figure 3.6: Daily electricity consumption for an individual (kWh, scaled by the assumed population of 362,935 for the whole region.

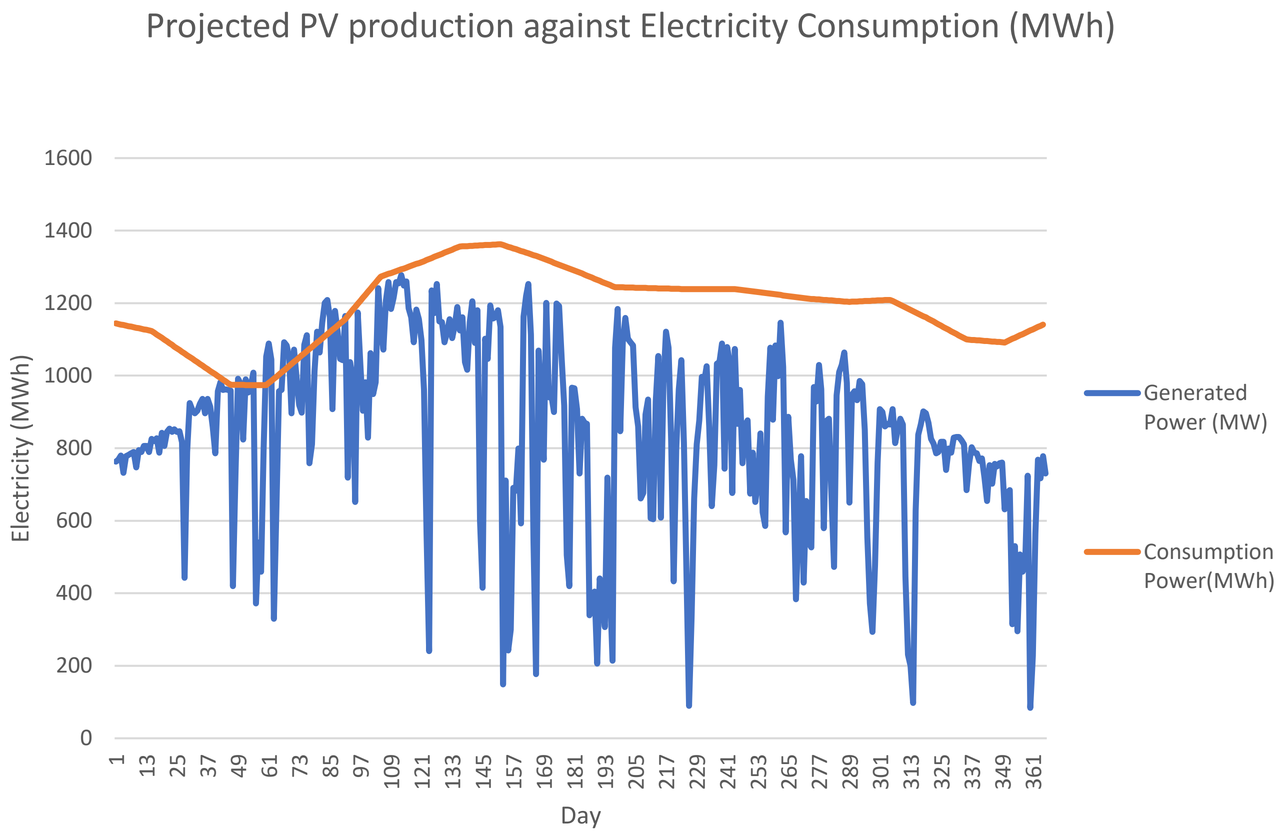


Figure 4.1: Projected PV production vs Electricity Consumption (MWh)

4.2 Simulating P2P trade between peers in Uttara

Initializing blockchain network

This section presents the results obtained from implementing the procedure proposed in section 3.2.

A new blockchain named “uttarap2pblockchain” was created by the admin.

```
Microsoft Windows [Version 10.0.19041.508]
(c) 2020 Microsoft Corporation. All rights reserved.

C:\Users\yamin>cd C:\Users\yamin\AppData\Roaming\MultiChain

C:\Users\yamin\AppData\Roaming\MultiChain>multichain-util create uttarap2pblockchain

MultiChain 2.0.7 Utilities (latest protocol 20011)

Blockchain parameter set was successfully generated.
You can edit it in C:\Users\yamin\AppData\Roaming\MultiChain\uttarap2pblockchain\params.dat before running multichaind for the
 first time.

To generate blockchain please run "multichaind uttarap2pblockchain -daemon".

C:\Users\yamin\AppData\Roaming\MultiChain>
```

Figure 4.2: Creating a new blockchain

The blockchain was then started for the first time. A genesis block was as so created.

```
To generate blockchain please run "multichaind uttarap2pblockchain -daemon".

C:\Users\yamin\AppData\Roaming\MultiChain>multichaind uttarap2pblockchain -daemon

MultiChain 2.0.7 Daemon (Community Edition, latest protocol 20011)

Looking for genesis block...
Genesis block found

Other nodes can connect to this node using:
multichaind uttarap2pblockchain@192.168.56.1:6733

This host has multiple IP addresses, so from some networks:
multichaind uttarap2pblockchain@192.168.0.105:6733

Listening for API requests on port 6732 (local only - see rpcallowip setting)

Node ready.
```

Figure 4.3: Starting new blockchain

The energy asset was created:

```
C:\Users\yamin\AppData\Roaming\MultiChain>set address=19JGMA7h9XqzXDXkBzgHSrtpbnmXXGnuUuGtGw

C:\Users\yamin\AppData\Roaming\MultiChain>multichain-cli uttarap2pblockchain issuefrom %address% %address% "{\"name\":
\"energy\", \"open\":true}" 0 0.001 0
{"method":"issuefrom","params":["19JGMA7h9XqzXDXkBzgHSrtpbnmXXGnuUuGtGw","19JGMA7h9XqzXDXkBzgHSrtpbnmXXGnuUuGtGw",{"na
me":"energy","open":true},0,0.001,0],"id":"14702291-1602704416","chain_name":"uttarap2pblockchain"}

f2d13fefc04ef9ce22384fe611325e1b9a000077513c4a0cc8131347b05ef3f5

C:\Users\yamin\AppData\Roaming\MultiChain>
```

Figure 4.4: Creating energy asset

The e-coin asset was similarly successfully.created

```
C:\Users\yamin\AppData\Roaming\MultiChain>multichain-cli uttarap2pblockchain issuefrom %address% %address% "{\"name\":
\"e-coin\", \"open\":true}" 0 0.001 0
{"method":"issuefrom","params":["19JGMA7h9XqzXDXkBzgHSrtpbnmXXGnuUuGtGw","19JGMA7h9XqzXDXkBzgHSrtpbnmXXGnuUuGtGw",{"na
me":"e-coin","open":true},0,0.001,0],"id":"35055085-1602704557","chain_name":"uttarap2pblockchain"}

54c4988cb2c2dcebfac77f0937aac35404ee26f2c72b267f6e88475f7e7c6489

C:\Users\yamin\AppData\Roaming\MultiChain>
```

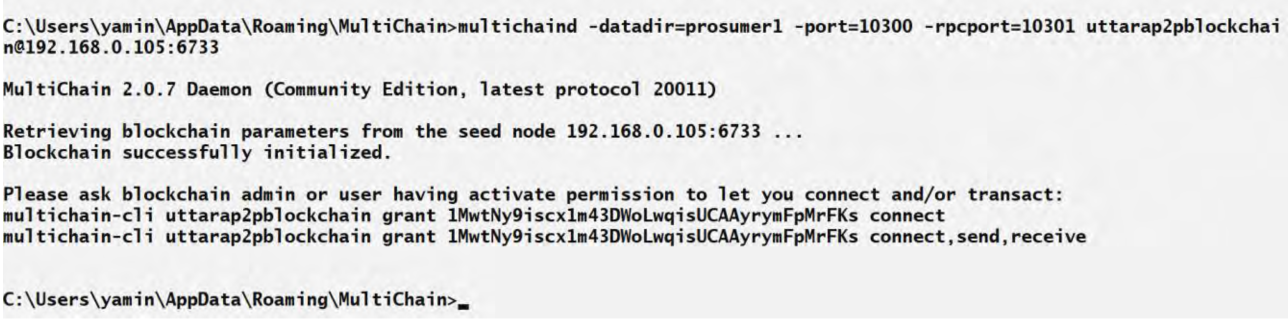
Figure 4.5: Creating e-coin asset

The public “consumer-demands” stream to be used by consumers to publish their energy demands was then created. The “prosumer-capacities” stream was similarly successfully created.

```
C:\Users\yamin\AppData\Roaming\MultiChain>multichain-cli uttarap2pblockchain create stream consumer-demands true
{"method":"create","params":["stream","consumer-demands",true],"id":"48318735-1602704755","chain_name":"uttarap2pblock
chain"}

05305d3dd3c5aeeebb9b00a975372aca31e9267752c4553271ecd02376a2b4d0

C:\Users\yamin\AppData\Roaming\MultiChain>multichain-cli uttarap2pblockchain create stream prosumer-capabilities true
{"method":"create","params":["stream","prosumer-capabilities",true],"id":"15493331-1602704930","chain_name":"uttarap2p
blockchain"}

c2e26f60b9b19b88a07a5c80683a2dd7fdd74f298f59d300f8a140ba5a0a1a47

C:\Users\yamin\AppData\Roaming\MultiChain>
```

Figure 4.6: Creating "consumer-demands and prosumer-capabilities " stream

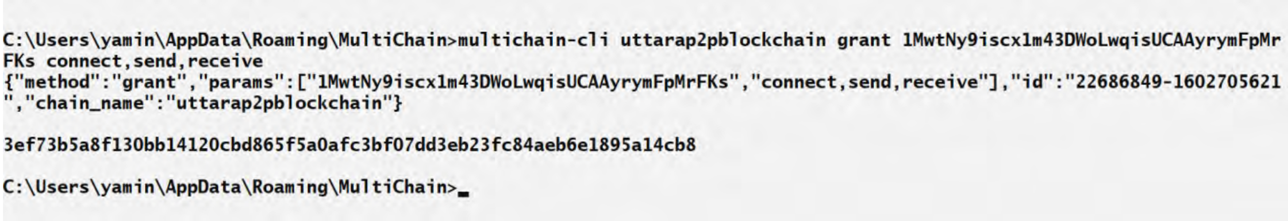
A prosumer node was created on the localhost,



```
C:\Users\yamin\AppData\Roaming\MultiChain>multichaind -datadir=prosumer1 -port=10300 -rpcport=10301 uttarap2pblockchai
n@192.168.0.105:6733

MultiChain 2.0.7 Daemon (Community Edition, latest protocol 20011)

Retrieving blockchain parameters from the seed node 192.168.0.105:6733 ...
Blockchain successfully initialized.

Please ask blockchain admin or user having activate permission to let you connect and/or transact:
multichain-cli uttarap2pblockchain grant 1MwtNy9iscx1m43DWoLwqisUCAAyrymFpMrFKs connect
multichain-cli uttarap2pblockchain grant 1MwtNy9iscx1m43DWoLwqisUCAAyrymFpMrFKs connect,send,receive


C:\Users\yamin\AppData\Roaming\MultiChain>_
```

Figure 4.7: Creating a prosumer node

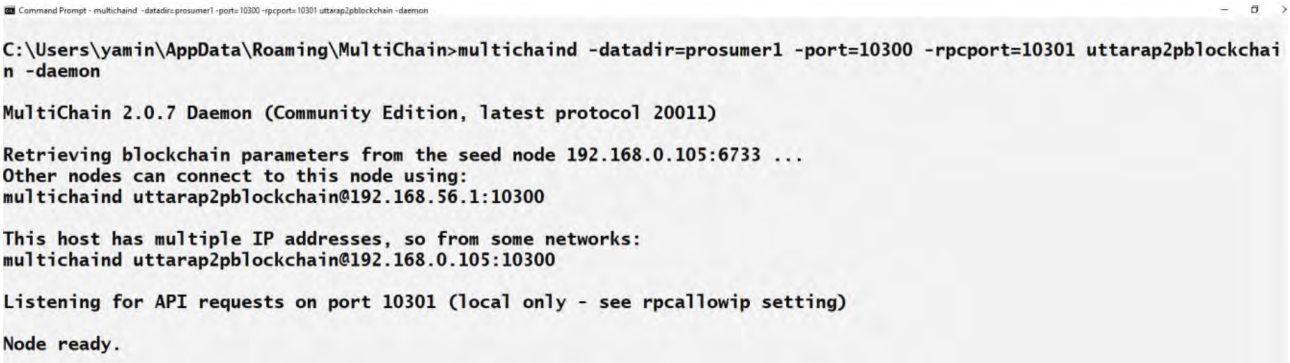
and granted permission by the admin to connect to, send and receive on the blockchain.



```
C:\Users\yamin\AppData\Roaming\MultiChain>multichain-cli uttarap2pblockchain grant 1MwtNy9iscx1m43DWoLwqisUCAAyrymFpMr
FKs connect,send,receive
{"method":"grant","params":["1MwtNy9iscx1m43DWoLwqisUCAAyrymFpMrFKs","connect,send,receive"],"id":"22686849-1602705621
","chain_name":"uttarap2pblockchain"}

3ef73b5a8f130bb14120cbd865f5a0afc3bf07dd3eb23fc84aeb6e1895a14cb8

C:\Users\yamin\AppData\Roaming\MultiChain>_
```

Figure 4.8: Granting prosumer connect, send, receive permissions

This node was then started successfully.

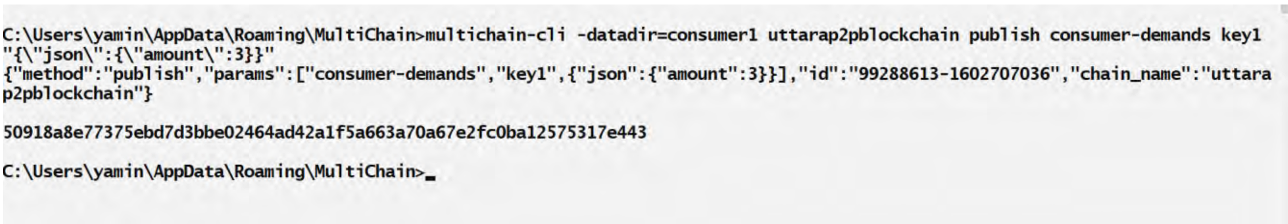


```
C:\Users\yamin\AppData\Roaming\MultiChain>multichaind -datadir=prosumer1 -port=10300 -rpcport=10301 uttarap2pblockchai
n -daemon

MultiChain 2.0.7 Daemon (Community Edition, latest protocol 20011)

Retrieving blockchain parameters from the seed node 192.168.0.105:6733 ...
Other nodes can connect to this node using:
multichaind uttarap2pblockchain@192.168.56.1:10300

This host has multiple IP addresses, so from some networks:
multichaind uttarap2pblockchain@192.168.0.105:10300

Listening for API requests on port 10301 (local only - see rpcallowip setting)

Node ready.
```

Figure 4.9: Starting prosumer node

A consumer node was similarly created, granted permissions by the admin, and started by following the same steps as before for creating the prosumer node. Thus we are not attaching the pictures for consumer node creation.

The consumer then proceeded to publish an open demand for 3kWh of electricity.



```
C:\Users\yamin\AppData\Roaming\MultiChain>multichain-cli -datadir=consumer1 uttarap2pblockchain publish consumer-demands key1
"{\"json\":{\"amount\":3}}"
{"method":"publish","params":["consumer-demands","key1",{"json":{"amount":3}}],"id":"99288613-1602707036","chain_name":"uttara
p2pblockchain"}

50918a8e77375ebd7d3bbe02464ad42a1f5a663a70a67e2fc0ba12575317e443

C:\Users\yamin\AppData\Roaming\MultiChain>_
```

Figure 4.10: Consumer publishing energy demand

The prosumer received the demand,

```
C:\Users\yamin\AppData\Roaming\MultiChain>multichain-cli -datadir=prosumer1 uttarap2pblockchain liststreamitems consumer-deman
ds
{"method":"liststreamitems","params":["consumer-demands"],"id":"63255104-1602707516","chain_name":"uttarap2pblockchain"}

[
    {
        "publishers" : [
            "1TKavnp7qL3dkMzkoEXajZnzqGXoMxhrLP5teB"
        ],
        "keys" : [
            "key1"
        ],
        "offchain" : false,
        "available" : true,
        "data" : {
            "json" : {
                "amount" : 3
            }
        },
        "confirmations" : 11,
        "blocktime" : 1602707058,
        "txid" : "50918a8e77375ebd7d3bbe02464ad42a1f5a663a70a67e2fc0ba12575317e443"
    }
]

C:\Users\yamin\AppData\Roaming\MultiChain>
```

Figure 4.11: Prosumer viewing consumer energy demands

After receiving the demand the prosumer expressed interest in fully supplying to the consumer, using a private stream dedicated for the particular pair only.

```
C:\Users\yamin\AppData\Roaming\MultiChain>multichain-cli -datadir=prosumer1 uttarap2pblockchain publish private-stream1 key1 "
{\"json\":{\"interested\":true,\"amount_available\":3}}"
{"method":"publish","params":["private-stream1","key1",{"json":{"interested":true,"amount_available":3}}],"id":"37038178-16027
09364","chain_name":"uttarap2pblockchain"}

3ce0516352e30ef0359c9760ca710a2da69025359843ecfc0a24bc1f2f550f89

C:\Users\yamin\AppData\Roaming\MultiChain>
```

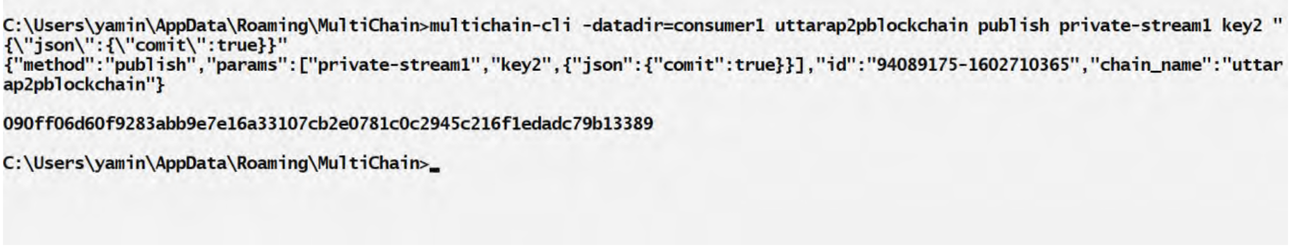
Figure 4.12: Prosumer expressing interest in supplying energy

The consumer then received this proposal via their private stream,

```
C:\Users\yamin\AppData\Roaming\MultiChain>multichain-cli -datadir=consumer1 uttarap2pblockchain liststreamitems private-stream
1
{"method":"liststreamitems","params":["private-stream1"],"id":"47209082-1602709828","chain_name":"uttarap2pblockchain"}

[
    {
        "publishers" : [
            "1MwtNy9iscx1m43DWoLwqisUCAAyrymFpMrFKs"
        ],
        "keys" : [
            "key1"
        ],
        "offchain" : false,
        "available" : true,
        "data" : {
            "json" : {
                "interested" : true,
                "amount_available" : 3
            }
        },
        "confirmations" : 11,
        "blocktime" : 1602709379,
        "txid" : "3ce0516352e30ef0359c9760ca710a2da69025359843ecfc0a24bc1f2f550f89"
    }
]

C:\Users\yamin\AppData\Roaming\MultiChain>
```

Figure 4.13: Consumer receiving a prosumer proposal

When the consumer received the proposal he/she agreed to commit to the proposal.



```
C:\Users\yamin\AppData\Roaming\MultiChain>multichain-cli -datadir=consumer1 uttarap2pblockchain publish private-stream1 key2 "
{\"json\":{\"comit\":true}}"
{"method":"publish","params":["private-stream1","key2",{"json":{"comit":true}}],"id":"94089175-1602710365","chain_name":"uttar
ap2pblockchain"}

090ff06d60f9283abb9e7e16a33107cb2e0781c0c2945c216f1edadc79b13389

C:\Users\yamin\AppData\Roaming\MultiChain>
```

Figure 4.14: Consumer committing to prosumer's proposal

The pair then proceeded to exchange the prosumer’s excess energy for the consumer’s e-coin as follows. The prosumer sent the consumer his/her energy asset.

```
C:\Users\yamin\AppData\Roaming\MultiChain>multichain-cli -datadir=prosumer1 uttarap2pblockchain sendasset 1TKav
np7qL3dkMzkoEXajZnzqGXoMxhrLP5teB energy 3
{"method":"sendasset","params":["1TKavnp7qL3dkMzkoEXajZnzqGXoMxhrLP5teB","energy",3],"id":"24656208-1602711216"
,"chain_name":"uttarap2pblockchain"}

a12132d7e47f70a3ffeb6387a43632401eb6f03434ecdc436391951fec9470a1

C:\Users\yamin\AppData\Roaming\MultiChain>
```

Figure 4.15: Prosumer sending energy asset

The consumer then received the energy asset as he checked his energy balance

```
C:\Users\yamin\AppData\Roaming\MultiChain>multichain-cli -datadir=consumer1 uttarap2pblockchain getmultibalances
{"method":"getmultibalances","params":[],"id":"65825983-1602711341","chain_name":"uttarap2pblockchain"}

{
    "1TKavnp7qL3dkMzkoEXajZnzqGXoMxhrLP5teB" : [
        {
            "name" : "energy",
            "assetref" : "34-265-53746",
            "qty" : 3
        }
    ],
    "total" : [
        {
            "name" : "energy",
            "assetref" : "34-265-53746",
            "qty" : 3
        }
    ]
}

C:\Users\yamin\AppData\Roaming\MultiChain>
```

Figure 4.16: Consumer receiving energy asset

and subsequently sent his/her e-coin asset.

```
C:\Users\yamin\AppData\Roaming\MultiChain>multichain-cli -datadir=consumer1 uttarap2pblockchain sendasset 1MwtNy9iscx1
m43DWoLwqisUCAAyrymFpMrFKs e-coin 3
{"method":"sendasset","params":["1MwtNy9iscx1m43DWoLwqisUCAAyrymFpMrFKs","e-coin",3],"id":"92465895-1602711698","chain
_name":"uttarap2pblockchain"}

03895e02a1f48a48b5a9831dfd4c36a2e80395baa67ed412d5461aae16fa272b

C:\Users\yamin\AppData\Roaming\MultiChain>
```

Figure 4.17: Consumer sending e-coin asset

The prosumer then verified receival of the e-coin asset into his/her wallet by checking e-coin balance

```
C:\Users\yamin\AppData\Roaming\MultiChain>multichain-cli -datadir=prosumer1 uttarap2pblockchain getmultibalance
s
{"method":"getmultibalances","params":[],"id":"89834589-1602711808","chain_name":"uttarap2pblockchain"}

{
    "1MwtNy9iscx1m43DWoLwqisUCAAyrymFpMrFKs" : [
        {
            "name" : "e-coin",
            "assetref" : "43-265-50260",
            "qty" : 3
        }
    ],
    "total" : [
        {
            "name" : "e-coin",
            "assetref" : "43-265-50260",
            "qty" : 3
        }
    ]
}

C:\Users\yamin\AppData\Roaming\MultiChain>_
```

Figure 4.18: Prosumer verify e-coin received balance

The transaction was then complete. At the end of this transaction, the prosumer had exchanged 3KWh of electricity for 3 e-coin, while the consumer exchanged 3 e-coin for 3 KWh of electricity.

4.3 Control Systems

4.3.1 Prosumer

The block diagram designed in Figure 3.5 was synthesized, and the flowing schematic obtained as such.

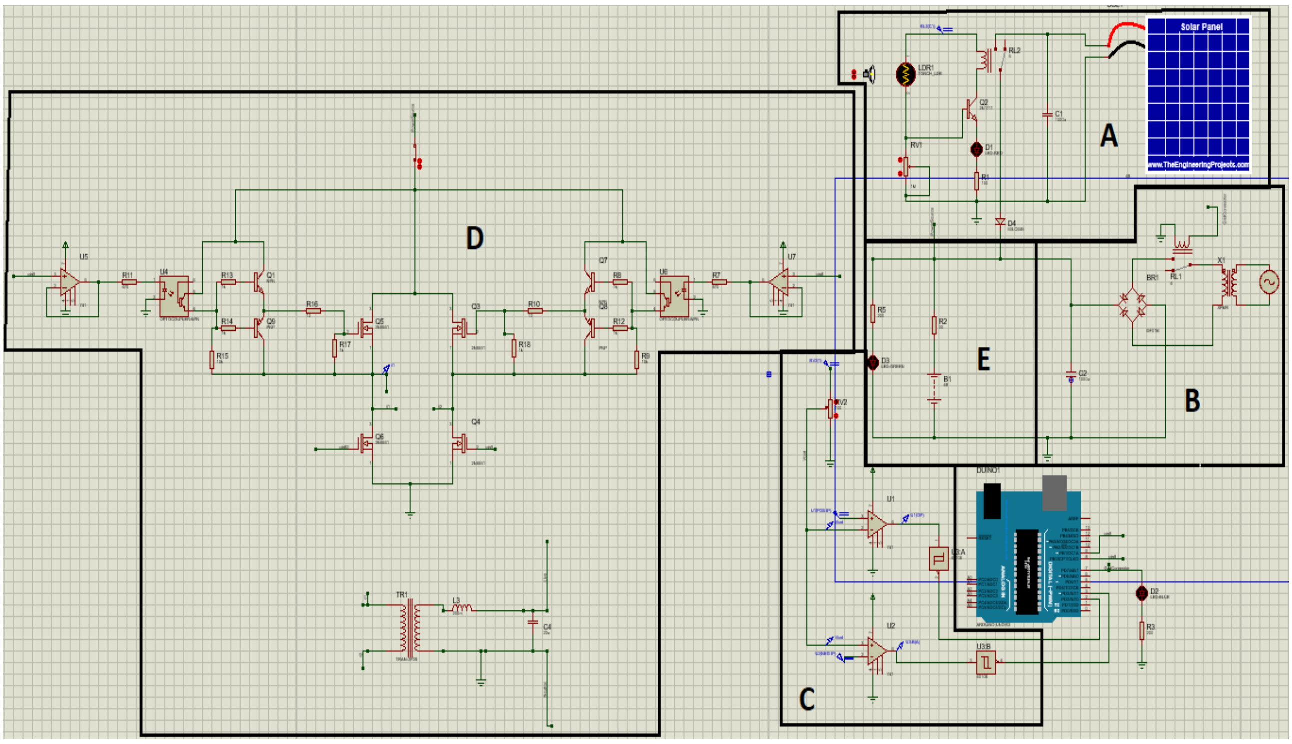


Figure 4.19: Prosumer schematic

The schematic can be divided into five sections:

Section A: This section model the solar production section. The solar panel was modelled in this schematic was adapted fromNasir (2018). A light-dependent resistor (LDR) circuit controls the connection of the solar panel power into the load. During high sunlight hours, the voltage divider network comprised of the light-dependent resistor LDR1 and variable resistor RV1 forward biases the NPN transistor Q2, allowing a current to flow through the collector, drain terminals of the resistor, thus magnetizing the relay RL2. This allowed the solar panel to be connected to the load, charging the battery, and feeding the load. A sample of this in action was captured and displayed in Figure 4.20

below. The sensitivity of the circuit is varied by the variable resistor RV1.

Section B: This is a full-wave bridge rectifier circuit. This section rectifies AC power incoming from the grid via the diode bridge circuit. The capacitor C2 smoothes the rectified power into a constant level. Relay RL1 controls the activation of this section. The relay is triggered by the control logic provided by the Arduino. The bridge connection is normally open. A sample screenshot of the Arduino switching on the bridge circuit in the case scenario of undercharged battery is demonstrated in Figure 4.21.

Section C: This section simulates the battery level detection section. Two operational amplifiers are employed in this section as comparators. The first comparator provided by op-amp U1 detects when the 48V battery is overcharged. When the battery is overcharged, marking surplus energy availability, the prosumer is capable of selling his/her excess energy.

The second comparator provided by op-amp U2 detects when the battery is undercharged. When the battery is undercharged, marking a period of underproduction, the prosumer is necessitated to import power from the grid connection.

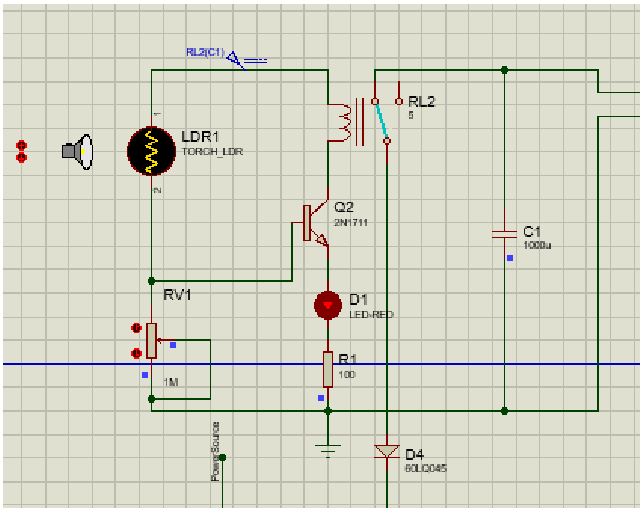


Figure 4.20: Solar Panel Connected

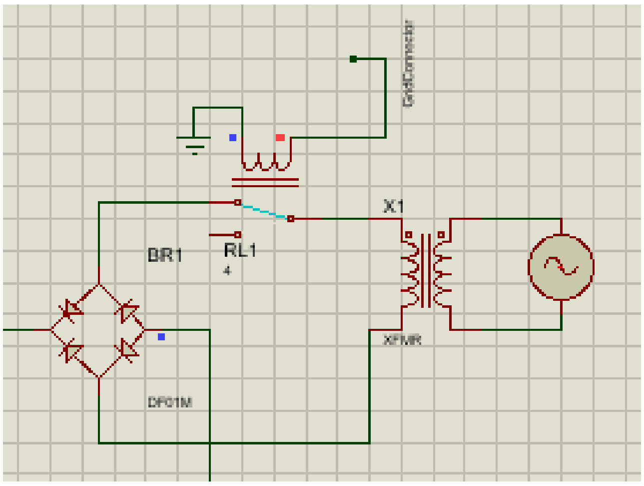


Figure 4.21: Rectifier circuit triggered on by Arduino

This section works in conjunction with the Arduino board, employing the two interrupt pins to detect an overcharged or undercharged scenario. Two Schmitt triggers were used to produce sharp rising or falling edges for the Arduino interrupt pins to detect.

The following diagram shows the transitions imposed by the comparators to the Arduino interrupt pins during different test scenarios.

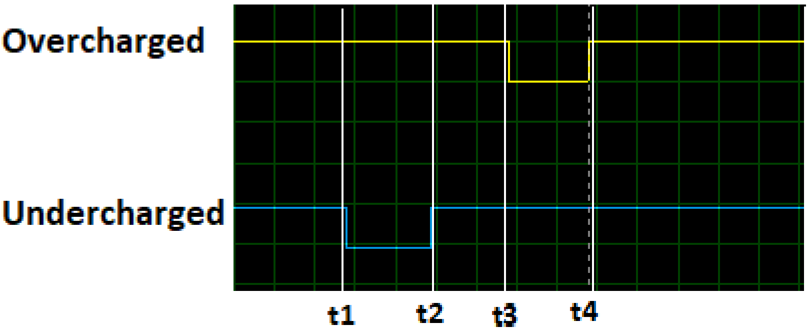


Figure 4.22: Battery level detector operation

It was observed that the comparator U1 tracking the overcharged condition went from high to low when the battery was overcharged (t3), stayed low during this overcharged condition (t3-t4), and went from low to high when the battery was discharged below-overcharged voltage (t4).

On the other hand, the comparator U2 tracking the undercharged condition went from high to low when the battery was undercharged (t1), remained low during this condition (t1-t2), and went highwhen the battery was charged above the undercharged voltage (t2).

Section D: This is the inverter section. An inverter was necessitated to convert battery DC power to AC power, to be exported to the grid and sold to other peers on the microgrid. The basic premise behind the circuit is the H-bridge circuit, composed of n-channel enhancement MOSFETs, as redacted in Figure 4.23. N-channel MOSFETs are turned on by positive gate voltages. For the MOSFET to be completely turned on, it is necessitated that the gate terminal potential be higher than the source terminal potential (Tahmid, 2013).

This condition that the gate terminal potential must be higher than the source terminal voltage presents a challenge for the high-side MOSFETs, Q5 and Q3. As such, the Arduino 5V potential couldn’t directly turn on these high-side MOSFETs, as opposed to the low-side MOSFETs Q6 and Q4. To fix this, a drive circuit was provided for these MOSFETs, as discussed by Tahmid (2013), with operational amplifiers providing isolation of the Arduino pins from the driver circuits.

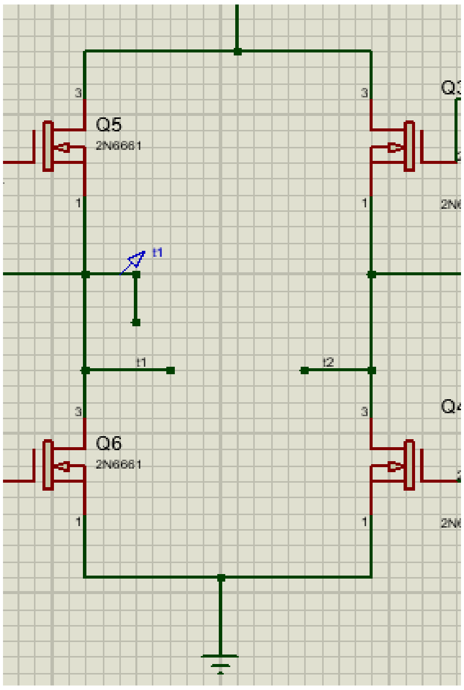


Figure 4.23: H-bridge section

The Arduino board produces positive trigger voltages using pin9 and pin8 to activate the MOSFETs as deemed necessary to produce an AC signal. The H-bridge circuit produces a 50Hz square-shaped AC waveform between point t1 and t2 as captured by the oscilloscope output below.

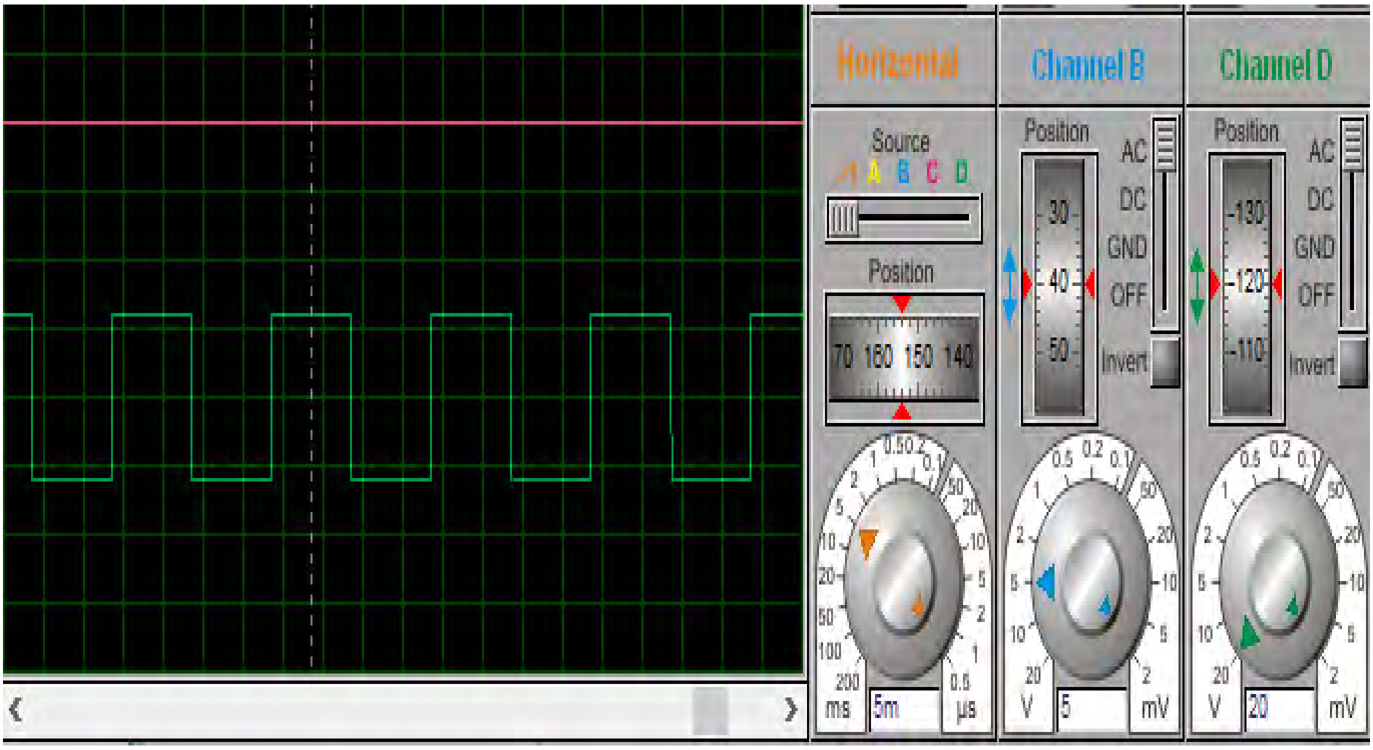


Figure 4.24: Square-wave from H-bridge

This signal was coupled to a resonant LC network to carve the square-wave to a sine wave via the transformer TR1. The transformer was chosen to provide isolation of the square-wave supply from the LC network, and such prevent loading effects presented upon the source by the network. An oscilloscope output of the sine wave produced is shown below.

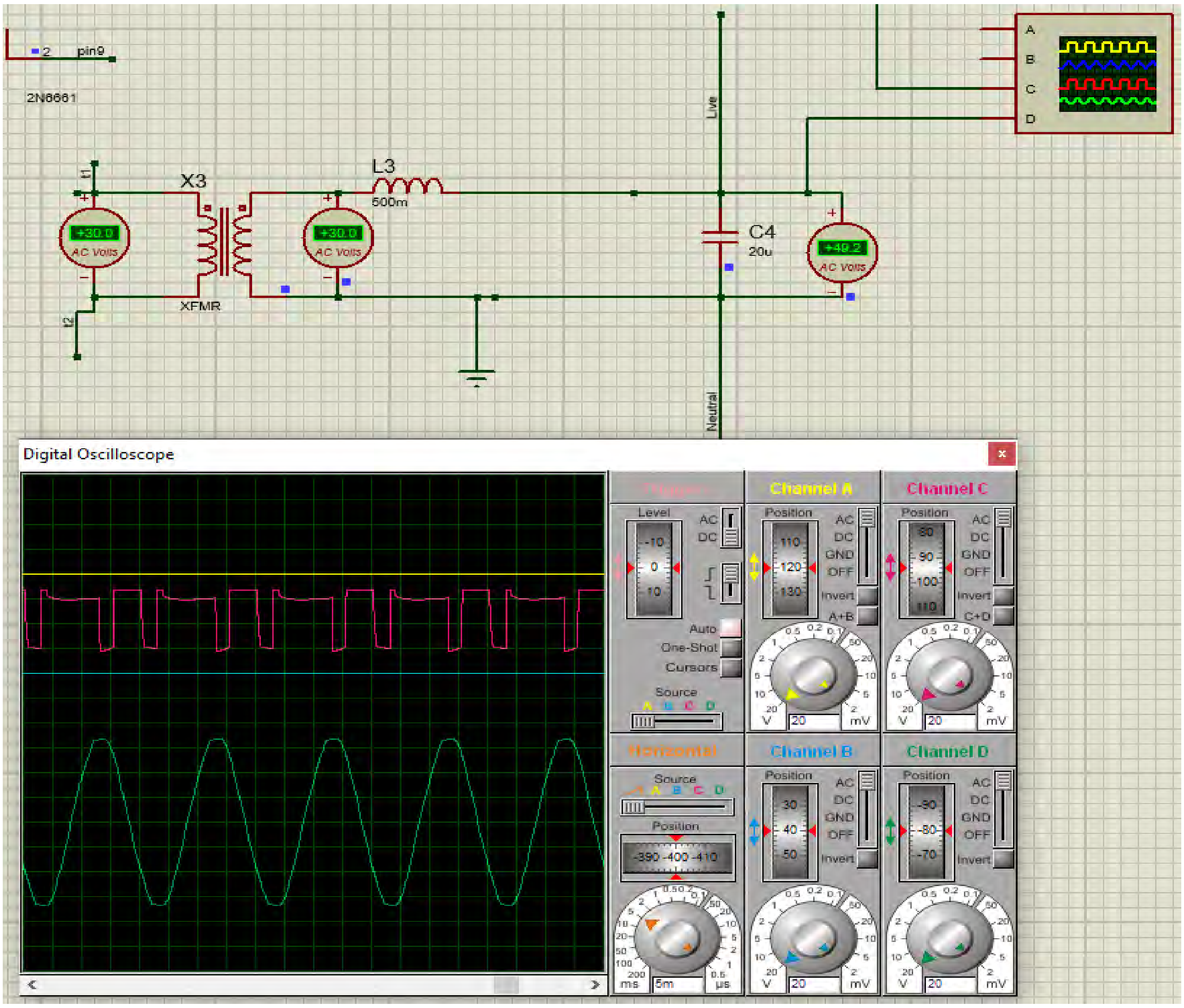


Figure 4.25: Square wave-shaped to sine wave

It was observed that despite the inclusion of the transformer, the original square-wave was distorted. However, the sine wave produced retained the 50Hz frequency of the original ac square-wave.

Section E: This section simulates a simple 200Ω, in series with a green LED.

The Arduino UNO board was the controller for this design. Two interrupt pins, pin2 and pin3 were used to detect an overcharged or undercharged battery condition. Two digital pins, pin9 and pin8 were used to provide triggering signals for the inverter gates. The code executed by the microcontroller is attached in the Appendices section

4.3.2 Consumer

The schematic diagram below displays the results of implementing the consumer system.

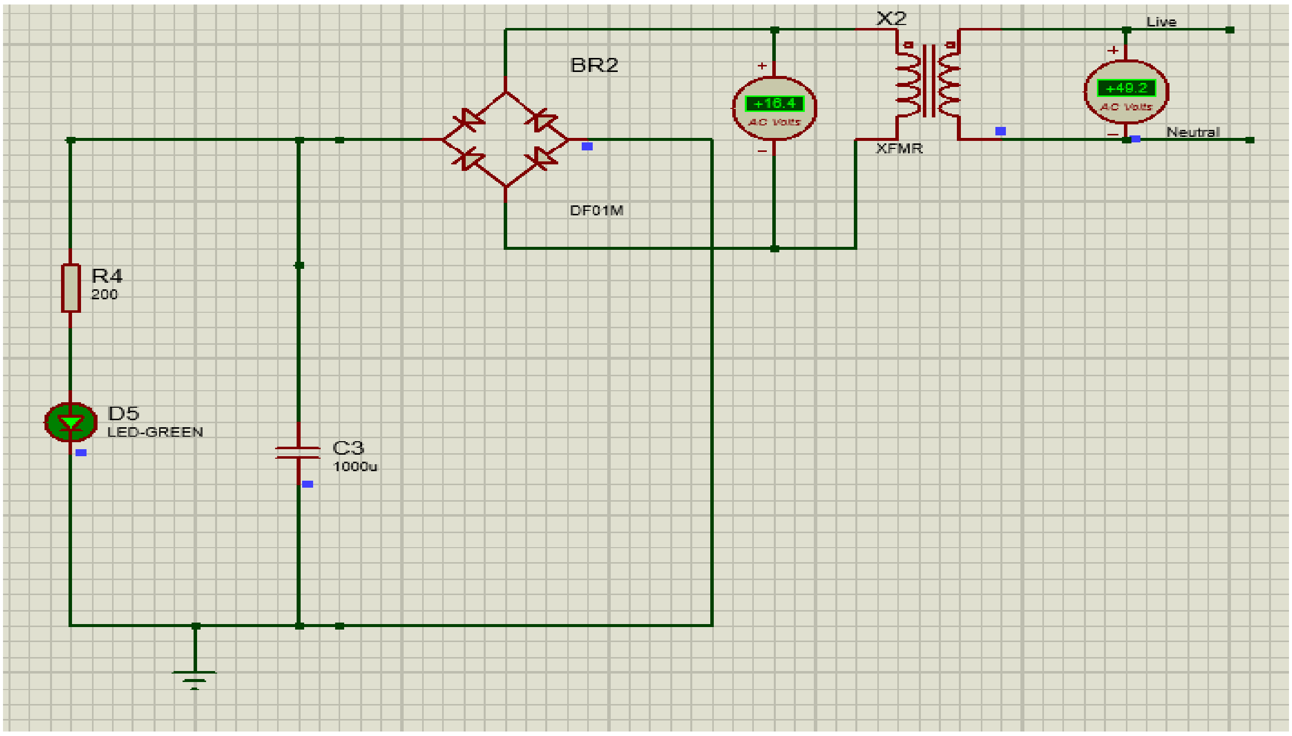


Figure 4.26: Consumer Model

The ac power exported to the grid by the prosumer was imported by the consumer. A transformer with a turns ratio 3 was used in this model. This was value was chosen to reduce the grid 220V down to 73V, which the diodes comprising the rectifier circuit can tolerate. For his simulation, however, the desired 220V was not achieved.

Chapter 5

DISCUSSION

The analysis and interpretation of the results and assumptions used during the Methodology Chapter shall be done in this chapter.

5.1 Validation of Model

This model proposed a model to exchange energy for an e-coin asset after a successful negotiation as described by Figure 3.3: Initiating P2P trade proposal on blockchain and Figure 3.4: Trading P2P assets on a blockchain, on a Multichain platform. This model differed from that proposed by Kim, et al. (2017), whereby atomic exchange was performed without prior negotiation. Despite the differences in methodology, it was found that the model proposed in this study completed an asset transfer.

The application of the developed model in the study region provided some interesting insights into the possible effects of introducing P2P energy market.

5.2 Energy Impact of PV production and P2P Trading

5.2.1 PV Production

The study region experienced a huge fluctuation of PV production throughout the year. It was observed that the highest PV production was during the spring season from March to May. The maximum PV production recorded was 1,277.4MWh from average insolation of 6.7kWh/m^2, during the 112th day of the year. On the other hand, it was observed that the lowest PV production was during the dry season from November to March. The region recorded a minimum PV production of 83.9MWh from average insolation of 0.44kWh/m^2, during the 359th day of the year. This yields a range of 1,193.1MWh, with a standard deviation of 253.55. The average PV production throughout the whole year was 847.5MWh a day.

5.2.2 Energy Supply Before PV

The projected daily electricity demand in the region was observed to be more steady, with fewer variations compared to the PV production. The maximum power consumption for the study region was observed to be 1362.MWh during the 151st day of the year. The minimum projected daily power consumption of the area was found to be 973.9MWh and was during the 59th day of the year.

5.2.3 Grid Power Import after P2P PV Trading

The graph below summarizes the impact of PV production and P2P trades on the main grid input of electricity.

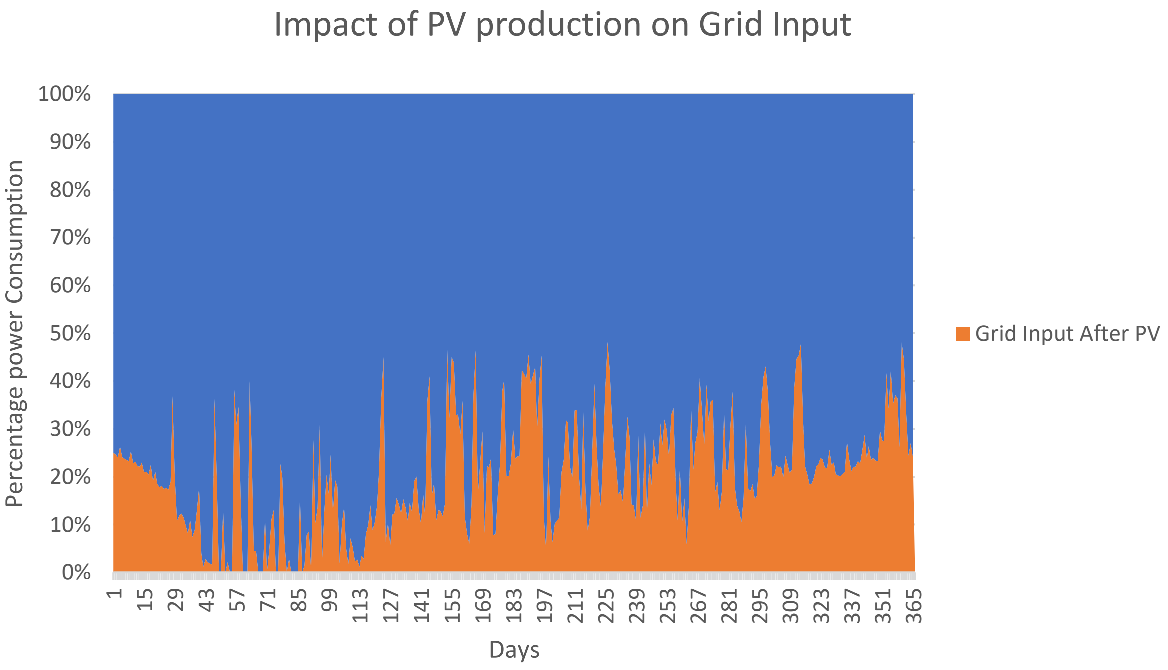


Figure 5.1: Reduction of Grid Input after P2P implementation

The average electricity consumption before PV installation was found to be 1191MWh, while the average electricity imported from the main grid, with 50% of available rooftop area of the study region installed with PV systems, was found to be 344.8MWh. It was therefore deduced that installation of SHS in the area had a potential to reduce electricity importation from the main grid by an average of 71%.

5.3 The Virtual Layer

The virtual layer was simulated using the Multichain platform. The proposed model allowed a prosumer to propose to the consumer the amount of energy he/she was capable of selling to him/her after the consumer published an open request for a specific amount of energy demand. It was inferred that the proposed model was capable of solving the issue of partial transactions faced by Kim, et al. (2017), by allowing smaller exchanges to be conducted after information exchange using private streams.

5.4 The Physical Layer

The following observations were made for the proposed simulation model for the prosumer, synthesized and implemented in Figure 4.19.

- Solar power was able to be simulated. The LDR circuit developed enabled the solar power to be connected and disconnected from charging the battery via a relay.
- Grid power was able to be switched on and off, depending on the battery level. However, the design was not able to authenticate this procedure depending on whether or not the prosumer had paid for this external power.
- An inverter design enabled the prosumer to sell his/her excess energy to a consumer. This design, however, was not able to integrate with the negotiation demonstrated in the virtual layer. A simulation of stepping up output power from the inverter circuit to 220V as necessitated by the national grid was

also not feasibly demonstrated. An output RMS power of 50V was at 50Hz was achieved in this simulation.

- A battery level detection circuit was demonstrated, and integrated with the Arduino UNO control system. The detection of the battery level enabled the prosumer to switch on the circuitry controlling input of the external grid power into the local environment. This process would naturally be a precursor to the prosumer placing a demand to receive external power.

5.5 Economic Impact of P2P Energy Trades

The annual cost of purchasing electricity from the main grid before setup of a PV system for a single consumer at a price of 5.335 BDT/ kWh as described in the methodology was found to be 6390.299 BDT. After setting up SHS utilizing 50% of the total rooftops area of the study, and assuming 71% of the consumer's electricity demand is met by the local P2P grid, the annual expenditure of a single consumer in purchasing electricity was found to be 5254.958 BDT. This is a 17% reduction of the annual consumer bill.

Chapter 6

Conclusion

Bangladesh's energy sector is largely dominated by fossil fuels. The greenhouse effects of this source of power can't be ignored. As such, the nation is heavily advocating for the incorporation of solar power as a clean renewable source of power. With the rise of SHS, the potential of P2P energy trades is gleaming brighter. Moreso, the incorporation of blockchain in this system is of crucial importance in ensuring trust in a system of trustlessness; and enforcing integrity.

This study found out that the incorporation of PV systems onto the rooftops of the study region of Uttara, Dhaka, had a huge potential in generating local electricity. The rooftop areas characteristics of a sample high housing density study region within Uttara, Dhaka, was investigated using the Google Earth Pro platform. With 50% of the rooftops used for Pv installation and standard PV parameters considered, the study found out that this had a potential of offsetting the energy imported from the national grid by an average of 71%.

The study proposed a model for trading energy on a blockchain-based on Multichain. It was discovered that energy and e-coin assets were capable to be created, and traded on the platform. The incorporation of private streams before conducting a trade provided a mechanism for partial trades to be conducted.

The study also proposed a model for the physical layer and synthesized the model on the Proteus platform. A prosumer circuit was synthesized and simulated. The study was able to demonstrate the auto-switching of power source between the local SHS's solar panels and the external grid depending on the battery level, as controlled by an Arduino controller. An inverter design was simulated to demonstrate the exportation of excess energy to other peers. This simulation was, however, unable to simulate the stepping up of power to the 220V voltage employed by the national grid.

The study concluded by investigating the financial impact of the proposed implementation incorporation into the area. Using interpolation and assuming averages, it was estimated that the implementation had a potential of reducing a consumers annual electricity nill by 17%.

This study produced a model that could be used to study the rooftop PV potential of a region. The study was able to propose and demonstrate designs on the virtual and physical layer that could be employed in blockchain-enabled P2P trades. Despite the work done in this study, more effort was still found out to be needed to integrate the physical layer to the virtual layer in a seamless manner.

6.1 Future work

It was observed that this study had provided a provision for more work to be done in validating the models and assumptions used.

The model used Google Earth Pro platform as the avenue with which the rooftop areas of the region was to be approximated. This model, however, was tedious and repetitive, and as such prone to the introduction of human errors for large regions. Jamal, et al. (2014), employed a GIS-based system for their study. The study is, however, half a decade old. An of the rooftop characteristics using advanced GIS platforms could produce higher accuracy results.

The study demonstrated blockchain-enabled P2P trades on the Multichain platform. The sample size used was however limited, and as such the network characteristics not wholly studied. Future studies could look into the impact of the introduction of many nodes on the performance of the model. The physical layer model developed and synthesized provided a foundation on which the systems would operate. The design produced was simulated on Proteus, and basic functionalities tested visually. To gain a deeper understanding of the system, further research into the functional analysis of the model should be done, to fully understand the transient and steady-state characteristics of the system.

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Appendices

Arduino Code

```
const int pin1 = 9;

const int pin2 = 8;

volatile int output = LOW;

volatile bool changed = false;

void setup() {

  // put your setup code here, to run once:

attachInterrupt(digitalPinToInterrupt(2),overcharged, FALLING);

attachInterrupt(digitalPinToInterrupt(3), undercharged, FALLING);

pinMode(pin1, OUTPUT);

pinMode(pin2, OUTPUT);

pinMode(7, OUTPUT);

digitalWrite(7, LOW);

}

void loop() {

digitalWrite(pin1, HIGH);

digitalWrite(pin2, LOW);

  delay(10);

digitalWrite(pin1, LOW);

digitalWrite(pin2, HIGH);
```

```
  delay(10);

digitalWrite(pin2, LOW);

}

void overcharged(){

  output = LOW;

digitalWrite(7,output);

}

void undercharged(){

  output = HIGH;

digitalWrite(7,output);

}
```