DECENTRALIZED SOLAR PHOTOVOLTAIC DISTRIBUTED GENERATION INTEGRATED WITH BLOCKCHAIN TECHNOLOGY: A CASE STUDY IN LAGOS

Abigail Oyekola

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Supervisors: Professor Tek Tjing Lie and Dr. Adam Taylor

ABSTRACT

The energy industry is moving from the standard distribution energy grid to decentralised renewable energy distributed generation networks. Solar photovoltaic energy is an example of the latter method used to integrate renewable energy sources into the energy industry. However, the impact of this decentralised model as the primary source of energy generation on the centralised grid and the energy industry, is uncertain. Therefore, this research investigates the possibility of renewable energy sources as the primary source of energy generation in the Nigerian energy system; and explores energy trading through the secured blockchain energy-trading platform used by Nigerians. This was achieved by modelling and simulating a decentralised distributed solar photovoltaic generation network in the Lagos State of Nigeria that adopts blockchain technology as the energy-trading platform

MATLAB/Simulink software was used to model and simulate a section of the Nigerian energy network, where solar photovoltaic distributed generation systems were installed in decentralised locations. Subsequently, Python was used to create an algorithm illustrating how the secured blockchain energy-trading platform should function. Then, RETScreen Expert software was used to carry out the financial sensitivity and risk analyses of implementing this project in the Nigerian energy industry.

Research demonstrated that implementing a decentralised distributed solar photovoltaic generation network into the Nigeria energy system could improve the reliability and efficiency of energy generation and supply during different seasons of the year. This was dependent on the appropriate design of the solar photovoltaic generation system and the central storage system. It was also found that the blockchain energy-trading platform could serve as a source of income for some people. This could encourage more Nigerians to efficiently use their generated energy so that enough can be sold to other energy consumers.

Keywords: Solar photovoltaic energy generation; decentralised distributed generation system; blockchain technology energy trading platform; Financial, sensitivity and risk analysis.

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LIST OF ACRONYMS

AC:	Alternating Current
AGC:	Automatic Gain Control
BESS:	Battery Energy Storage System
BCR:	Benefit-Cost Ratio
CBA:	Cost-Benefit Analysis
CEC:	California Energy Commission
COP:	Coefficient of Performance
DG:	Distributed Generation
DISCOs:	Distribution Companies
DER:	Distributed Energy Resources
DPF:	Displacement Power Factor
DNI:	Direct Normal Irradiance
DHI:	Diffuse Horizontal Irradiance
DC:	Direct Current
EPRI:	Electric Power Research Institute
ESS:	Energy Storage System
ECN:	Energy Commission of Nigeria
EM&T:	Energy Market and Trading
FIT:	Feed-In Tariff
GENCOs:	Generation Companies
GHG:	Greenhouse Gas
GDP:	Gross Domestic Product
GPS:	Global Positioning System
GHL:	Global Horizontal Irradiance
IRR:	Internal Rate of Return
LHS:	Left-Hand Side

MTOE: Million Tons of Oil Equivalent

MPPT: Maximum Power Point Tracking

MIRR: Modified Internal Rate of Return

NERC: North American Electric Reliability Council

NPV: Net Present Value

NERC: Nigerian Electricity Regulatory Commission

NEPA: National Electric Power Authority

NASA: National Aeronautics and Space Administration

O&M: Operation and Maintenance

PV: Photovoltaic

P2P: Peer-to-Peer

PCC: Point of Common Coupling

PSO: Particle Swarm Optimization

PP: Payback Period

P&O: Perturbation and Observation

PWM: Pulse Width Modulation

RE: Renewable Energy

P-Q: Real and Reactive

RHS: Right-Hand Side

PLL: Phase-Locked Loop

P: Real Power

PTC: PVUSA Test Conditions

PI: Proportional Integral

PVUSA: Photovoltaics for Utility Systems Applications

PFC: Power Factor Correction

PHCN: Power Holding Company of Nigeria

PPPRA: Petroleum Products Pricing & Regulatory Agency

Q:	Reactive Power
SEMS:	Smart Energy Management System
STC:	Standard Test Conditions
SAM:	System Advisor Model
SMPS:	Switch-Mode Power Supply
SVPWM:	Space Vector Pulse Width Modulation
TCP/IP:	Transmission Control Protocol/Internet Protocol
Tx:	Transactions
THD:	Total Harmonic Distortion
UDP:	User Datagram Protocol
USA or US:	United States of America
VSI:	Voltage Source Inverter
WEG:	Wind Electric Generator
W:	Watt

LIST OF SYMBOLS

A_1:	Producer 1
A_2:	Producer 2
A_n:	Producer n
A_{1s}:	Producer 1 surplus energy
A_{2s}:	Producer 2 surplus energy
A_{1d}:	Producer 1 energy demand
A_{2d}:	Producer 2 energy demand
B_n:	Grid-User n
CO_2:	Carbon dioxide
e:	Denotes times ten raised to power whatever number comes after “e”
GWhr:	Gigawatt hour
Hz:	Frequency
$I_{abc}\_B_1$:	Current of lines a, b, c at bus one
$I_{abc}\_B_2$:	Current of lines a, b, c at bus two
$I_{abc}\_B_3$:	Current of lines a, b, c at bus three
$ILoad_1$:	Current of load one
$ILoad_2$:	Current of load two
$ILoad_3$:	Current of load three
kW:	kilowatts
kWh:	kilowatt hour
$\mathrm{kWh/m^2}$:	kilowatts hour per meter square
$k\mathrm{m}^2$:	kilometer square
L_1:	Load one
L_2:	Load two
L_3:	Load three

MWh:	Megawatt hour
$MTOE$:	Million Tons of Oil Equivalent
pf:	Power factor
µs:	Microseconds
$V_{abc\_}B_1$:	Voltage of lines a, b, c at bus one
$V_{abc\_}B_2$:	Voltage of lines a, b, c at bus two
$V_{abc\_}B_3$:	Voltage of lines a, b, c at bus three
$VLoad_1$:	Voltage of load one
$VLoad_2$:	Voltage of load two
$VLoad_3$:	Voltage of load three
$Vrms\ LL$:	Root mean square line-to-line
$Wh/m^2/d$:	Watt hour per meter square per day

ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

24 March 2020

Signature Date

CHAPTER 1: INTRODUCTION

Rural Nigerians are generally poor when compared to those in wealthy countries. They pay a high cost relative to income for their daily energy needs. Thus, they resort to high emission options like kerosene lamps, which are highly-priced when compared with renewable energy systems like photovoltaics. Distributed renewable energy generation could provide viable and worthwhile alternatives to the national grid, diesel-powered generators, kerosene lamps, and traditional biomass. With renewable energy, the demand for oil and natural gas can be curtailed, reducing stress on the national grid and making it even more accessible to end-users, energy service providers, and utility distribution companies. The trading of energy between distributed small-scale rural providers and energy consumers necessitates a respective trading platform, and blockchain technology could facilitate this trade. This thesis explores the trading of solar photovoltaic renewable energy using the blockchain energy-trading platform.

1.1 RESEARCH BACKGROUND

In the agricultural sector of rural Nigeria, farmers produce energy by either growing corn to make ethanol or by converting the wind to electricity for easy access, rather than relying on an ineffective electricity grid for energy and power [1]. Presently in Nigeria, petroleum and dry natural gas have an estimated energy consumption of 81.9% when compared with renewable energy (RE), which supplies below 18.1% [2] [3]. The energy consumption level has increased from less than 400MWh in 1979 to 1900MWh in 2007, with a projection of approximately 300,000MWh by 2030 [4].

In the global context, a modern market for renewable energy is opening for technological advances as the world is evolving from a standard distribution energy grid to decentralised RE distributed generation systems connected to the national grid, which is a modified exchange of technology [5]. A reliable and effective renewable energy distribution system permits sending the excess of energy generated beyond load demand back to the grid. This presents the national grid with an opportunity to meet global energy demand in Nigeria [4].

1.2 THE ENERGY SYSTEM IN NIGERIA

An energy production level is a determinant and driving force of growth, productivity, and a nation's increased standard of living [6]. Between 2002 and 2007, the highest generation capability of the four primary energy generation sources were 1% coal, 22% hydro, 10% natural gas, and 85% petroleum products [7]. Based on a 10% gross domestic product (GDP) growth rate between 2002 and 2007, industry consumed approximately 16%, transportation consumed 4.7%, households consumed 2.6%, and services consumed 8.7% of the energy generated [1]. By 2030, it is projected that the energy consumption rate of these sectors will increase to about 145.21 million tons of oil equivalent (MTOE) from industry, 33.36MTOE from transportation, 34.27MTOE from households, and 38MTOE from services [7]. This implies that with renewable solar energy generation as the primary source of energy generation, GDP is bound to increase as rural areas and low-income earners have more access to energy. Renewable energy provides one of the cleanest and most beneficial options to procure non-unpolluting and naturally favourable power. When there is no emission release to the atmosphere, carbon dioxide (CO_2) emissions could be reduced across Nigeria [8], [9].

The estimated solar radiation in Nigeria is about 3.5 to 7.0 kWh/m^2 daily [10]. With the solar collectors or modules using 1% of Nigeria's land area of 923,773$k\text{m}^2$, about 1850×103 GWhr of photovoltaic (PV) energy can be generated annually. A daily average solar radiation of 5.5kWh/m^2 can be achieved using efficient and profitable solar-electric generators [11]. This equates to over 100% of national grid energy consumption in the country. The major challenge of multiple influxes of renewable sources into the national grid is ensuring adequate generation capacity for system security without flexible supply-to-demand distribution chain [12]. The issue of trust in trading energy with other parties is another challenge and blockchain can function to fix these trust issues in the energy-trading platform.

PV distributed generation resources bring stability, reliability and are abundant in nature, hence a reduction in possible conflict or vandalisation of the solar energy system, unlike the situation with pipeline vandalism among Niger Delta militant groups [9]. Solar DG system insecurity through vandalisation or theft might have been a cause for concern among investors considering the currently high levels of life and property insecurity in

Nigeria [13]. Another major challenge to accepting PV in Nigeria is the lack of public understanding, making it difficult for the few investors to obtain loans from local banks. Banks fear granting loans to 'new technology' in Nigeria, and a long-term project might appear as a risky investment [9].

1.3 SOLAR PHOTOVOLTAIC IN NIGERIA

Most developed and developing countries are switching from non-renewable energy to solar photovoltaic (PV) renewable energy, not only for electricity generation but also electricity trading between solar PV producers and grid or energy consumers. However, much of the Nigerian community is not informed about the potential and benefits of solar photovoltaic energy generation. The Nigerian government shows little to no interest in diversifying from non-renewable to renewable energy as the nation's primary source of generation [4]. Decision-making about large solar PV generation has caused uncertainty among many stakeholders, such as local and foreign investors [14].

Therefore, this study focuses on how to design and model solar photovoltaic distributed generation systems as a part of the Nigerian energy sector. It considers the impact these systems will have in the energy trading market if solar PV is encouraged and supported by the Nigerian government as the primary source of energy generation.

1.4 BLOCKCHAIN TECHNOLOGY

Blockchain is a medium where goods or services such as energy are sold and bought between geographically diverse places. It is most commonly associated with Bitcoin [15-18]. It also acts as a database shared among people to transact energy in public without relying on an intermediary or central authority [19]. Blockchain is fast, secure, and reliable in logging and transferring information and informs all parties connected to the node about the status of the system [20]. Transactions cannot be altered due to connecting links between the chains of every transaction ever carried out on the node. This makes every transaction permanent, ordered, and available to everyone on the network to prevent the possibility of fraud. Every transaction is tied together using computational logic via the programmed algorithm so that users can automatically trigger transactions between nodes [21]. This fast and accurate platform can add innovation in energy trading to the power sector with a fast demand-side response distributed across the grid to improve balances across the transmission, distribution, and community. It improves regulation by encouraging transparency on all activities carried out on the trading platform [22].

Blockchain works as a peer-to-peer (P2P) energy trading platform where a community lacking enough energy will know if their neighbouring communities have excess energy to sell out without having to go to the national grid directly. It could serve as auxiliary support to the grid to reduce stress, make it more reliable, and prolong the life span of equipment that reduces operating costs and improves the financial earnings of large and small power-generation systems, and operators. It allows consumers to choose their preferred power suppliers and eliminates production and end-user intermediaries which could replace a portion of the utility business in the nearest future. For a blockchain energy trading platform to be more effective in selling solar energy to neighbouring homes and communities, each energy trader must employ a computer as a blockchain node for the solar panels installed in their homes. The essence of the nodes is to reduce data interference or the eventuality of possible downtime by declaring and sharing information via the computer communication network.

Transparency in blockchain functionality has helped resolve the trust issues associated with sharing public domains of economic interactions between people. The accuracy of the programmed codes reveal that blockchain can, to some extent, overcome the issue of trust in economy-sharing platforms, but it is still dependent on the interface of the sharing ecosystem [23]. Creating a trust mechanism where users are given the free will to measure their level of trust in other users helps to resolve trust system functions as a closed ecosystem within the technical boundaries and program accuracy, then trust-based systems are achievable. Blockchain technology prevents fraudulent activities, thereby ensuring the security of energy trading since all parties certify events on the node with the help of a smart meter-monitoring device. Smart meters monitor, record and transmit the generation and consumption rate to the smart grid, connecting the grid and the trading platform using a singular Point of Common Coupling (PCC) for transparency within the blockchain trading platform [20].

1.5 GOALS OF THE THESIS

This thesis aims to study, design, and simulate distributed solar energy generation that incorporates blockchain technology and allows multiple streams of photovoltaic (PV) influx into the Nigerian national grid to improve the reliability and resiliency of the power grid. The main contributions of this thesis come from answering these research questions:

1. How can PV Distributed Generation (DG) be designed and modelled for the Nigerian energy system using blockchain technology?
2. How will blockchain improve the resiliency of the Nigerian electrical energy system?
3. What are the effects of multiple streams of solar PV influx into the Nigeria national grid?

1.6 THESIS ORGANISATION

This thesis is organised into various chapters (like subsystems within a network) as follows:

- Chapter 1: Introduces the basic background, the goals, and overall outline of the thesis.
- Chapter 2: Presents the background and a review of relevant literature.
- Chapter 3: Focuses on the design and modelling of the solar photovoltaic distributed energy network for the thesis study.
- Chapter 4: Analyses the technical simulation, results, and discussion.
- Chapter 5: Details the proposed blockchain energy trading and data analysis.
- Chapter 6: Analyses financial sensitivity and risk analyses for investors involved in the investment decision-making process.
- Chapter 7: Provide conclusions and recommendations for any researcher willing to undertake further studies in a similar subject area.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

This chapter is structured as follows: Section 2.1 introduces the chapter contents; Section 2.2 gives an overview of the Nigerian energy system; Section 2.3 briefs the reader on the state of solar renewable energy in Nigeria; and Section 2.4 is a discussion of greenhouse gas emissions. Sections 2.5 and 2.6 engages with blockchain technology, and energy-trading and marketing platforms, while Section 2.7 tackles the issue of trust and antitrust within blockchain networks. Furthermore, Section 2.8 discusses resiliency issues in the energy system and Section 2.9 reviews the smart energy management system. Then, Section 2.10 reviews the P-Q control system in PV networks, while Section 2.11 reflects on the self-healing of decentralised energy systems. Section 2.12 discusses the use of investment decision tools for potential investors. Finally, Section 2.13 summarises this chapter.

2.2 GENERAL OVERVIEW OF THE NIGERIAN ENERGY SYSTEM

Nigeria has an abundance of non-renewable resources, such as crude oil, and natural gas; and renewable resources, such as sun, wind, biomass, and hydropower, which can generate energy. However, one of the biggest problems in Nigeria is how to balance the energy generated to meet ever-growing energy demand. Because facilities in the grid are poorly managed, the natural renewable energy that would have been used to generate energy in large quantities to meet the energy demand is wasted [4]. The social decline in access to energy has led the country into poverty. Nigeria has seven generation companies, known as GENCOs, responsible for power generation; and eleven distribution companies, known as DISCOs, responsible for the distribution of energy to end-users [24, 25]. However, these DISCOs are still experiencing an inability to meet the constant rise in energy demands from the end-users.

Over half Nigerians reside in rural areas with no easy access to power [26]. The nearest energy connection point to some rural dwellers is far from the intended load with no transmission or distribution lines to bring energy closer to them. Even though they tend to have higher access to capturing photovoltaic energy during sunshine hours, a lack of technology and enlightenment hinders this. Nigeria still generates energy from crude oil in a centralised energy system, leaving natural renewable photovoltaic energy underutilised.

As of 2005, 57% of Nigeria's energy was generated from oil, 36% was generated from natural gas, leaving just 7% of Nigeria's energy to be produced from hydroelectricity [8]. In 2009, Nigeria generated as much as 2000MW while another African country with less than one-third of Nigeria's population density could generate as much as 43,000MW of power [8]. Only about 10% of rural households and 40% of the entire Nigerian population can access power [8]. Hence, one of the purposes of this thesis is to simulate a photovoltaic renewable energy system in a distributed generation operation mode. Thus, energy generation will match energy demand as Nigeria improves her standard of living.

2.3 SOLAR RENEWABLE ENERGY IN NIGERIA

The global energy sector has switched from non-renewable to sustainable renewable energy resources that are secure, clean, environmentally friendly, and reliable to effectively and efficiently match energy generation to meet energy demand. In 2014, about 5% of Brazil's energy came from renewable sources; 4% of India's utility generation came from renewable energy sources, while Egypt generates about 10% of her power from renewable energy while Nigeria is left behind in this global movement [8].

Nigeria's photovoltaic renewable energy source is favourable due to a high intensity of solar radiation estimated to range between $3.8kW/m^2$ to $7.0kW/m^2$ during an average 6.5h/day of sunshine hours. With a land area of $924000km^2$, a radiation average of $5.535\, kWh/m^2/day$, and a daily sunshine hour period of $6.5\, h/day$; as little as 3.7% of this land area is enough to generate photovoltaic renewable energy that meets the needs of the current national storage system [8]. Therefore, photovoltaic renewable energy generation has the potential to bridge the supply-to-demand availability gap, especially when the proposed photovoltaic energy system operates on a decentralised distributed generation platform [26] [27].

The Energy Commission of Nigeria (ECN) and the Nigerian Electricity Regulatory Commission (NERC) are the current regulatory bodies that control energy and electricity-related issues in Nigeria. However, Nigeria is yet to start manufacturing photovoltaic modules, so PV modules are imported from overseas. Therefore, the California Energy

Commission (CEC) ratings for California modules from approved photovoltaic module manufacturers database in the California market in USA is used in this study.

2.4 GREENHOUSE GAS (GHG) EMISSION IN NIGERIA

Nigeria is among the countries with the highest greenhouse gas (GHG) emissions into the atmosphere due to the high carbon dioxide (CO_2) emitted from her oil refineries [8]. Between 1970 and 1986, of the 125.5 million m^3 gas produced from the Niger Delta oil refinery, approximately 17.2 million m^3 was productively utilised, while the rest was discharged into the atmosphere. Thus, Nigeria is currently faced with high greenhouse gas atmospheric pollution from non-renewable energy sources. Solar renewable energy has the potential to reduce this pollution and encourage sustainability. Looking at the current Nigerian energy situation shaped by massive global warming, oil price instability in the global market, unreliable power supply to loads, and poor management of refineries, there is a need to replace non-renewable energy with solar renewable energy generation sources.

2.5 BLOCKCHAIN TECHNOLOGY

Blockchain is often equated to bitcoin, which is a different technology. Blockchain technology is used to arrange and keep whatever data is entered it and acts as a database shared among people to transact in public without relying on an intermediary or central authority [19], [28]. Blockchain is a fast, secure, and reliable means of logging and transferring information. A decentralised, autonomous sensor informs all parties connected to the node about the status of the system, making it a more suitable means of relief and rescue in distressed situations [20]. Some authors see blockchain technology as an unbiased platform that does not change its rules of execution to favour the rich or the poor forcing everyone in the network to transact in a free and fair atmosphere [29]. Every transaction is tied together using computational logic via the programmed algorithm, so users can automatically trigger transactions between nodes [21]. Others see blockchain as a platform that will rearrange the flow of operations in some organisations, cutting out some aspect of an organisation to replace those sections with blockchain technology that operates with smart contracts [29].

Blockchain changes the way businesses operate their transactions by using smart contracts to reduce the need for human intermediaries and guarantees the users an authenticated and permanent system of transactions. It is structured as a trust mechanism for users and players within the network where information shared on the platform cannot be altered once it has been added. Any authorised user with access to the blockchain cannot alter the data already added because all nodes within the network are interconnected. Changing information in one node would amount to doing the same for the rest of the system since the blocks are interconnected, changing one block would change every other block connected to it. The only change that can take place is by adding new blocks of information to already existing blocks.

Blockchain has unique application features that can be used for diverse purposes in public, private or consortium applications [30]. A public blockchain allows anybody to access it, make transactions, and see previous transactions on the network from anywhere across the globe. A private blockchain allows access only to restricted blocks of nodes (also known as ‘users’) programmed with different restrictions than those of public blockchains. These users can view transaction history and confirm their transactions with another node to insulate the blockchain from hacking and unwanted tampering. Consortium blockchain differs from private blockchain as only one administrator has the “write” and “read” permission to add new blocks to the network [30]. However, the “read” permission is accessible by all nodes in the network. In consortium blockchain, a group of nodes have the right to both “write” and “read” in the network to add data, blocks, confirm transactions, and view transaction history. However, they must collectively decide the terms and conditions of validating and adding new blocks to the chains of blocks in the network. Every other node in the network only has “read” permissions that can be used to confirm transactions made with another node and view transaction history in the network.

2.5.1 BLOCKCHAIN TO MODERNISE UTILITY GRIDS

A few countries around the globe are experimenting with blockchain to modernise the grid to enable producing and selling energy in a decentralised manner. For example, Austria and New York are looking at the concept of using blockchain as a platform to trade energy [21], and a utility company in Germany is also researching how validation and billing can be achieved with blockchain technology [21]. There has been debate about blockchain technology removing intermediaries in the utility sector, and the use of remote control to swiftly switch from centralisation to decentralisation of the utility sector. Because blockchain technology is still in its infancy, especially when it comes to decentralisation of energy from the centralised grid, some issues are yet to be resolved. These include: how to incorporate blockchain into the existing landscape of digital services, processes, and infrastructure; or how to adapt decentralised blockchain technology to the existing standard grid.

Blockchain could present flexibility in energy trading using peer-to-peer energy trading among users who have access to a blockchain node on an electronic device, such as a laptop or desktop with smart contracts [19], [21]. Blockchain uses smart contracts to delegate various functions to nodes interacting to create a trust-free setup. One significant advantage of blockchain technology in distributed generation systems is that customers have the upper hand. They can achieve flexibility when connected to a highly reliable network infrastructure that meets their price quotations and trust levels in a digitised global interconnection between buyer and customer, without third parties in-between.

2.5.2 FRAMEWORK OF BLOCKCHAIN-ENABLED TECHNOLOGY

The fundamentals of blockchain technology consist of a distributed database, peer-to-peer transmission, transparency, irreversibility, and computational logic that work together to form a robust blockchain-enabled network. A distributed database enables all nodes to access all transactions on the database without a group of individuals controlling the network data. With the peer-to-peer (P2P) transmission, nodes can trade with other nodes as each transaction is stored and sent to the entire network so that access to information is the same for every node in the network. Moreover, transparency is achieved where each node has access to all data visible to all nodes in the network by using a unique alphanumeric address. Due to the irreversibility of records, which prevents alteration of already inputted data in the database, fraud is minimised. Lastly, computational logic ensures transactions are linked to programmable logic that triggers nodes whenever transactions are added to the network.

Some authors define blockchain as a distributed transactional database that operates using the peer-to-peer (P2P) communication network to links the distributed nodes together as an entire system with its own layer of protocol messages for node communication and peer discovery (see Figure 2.1) [30].

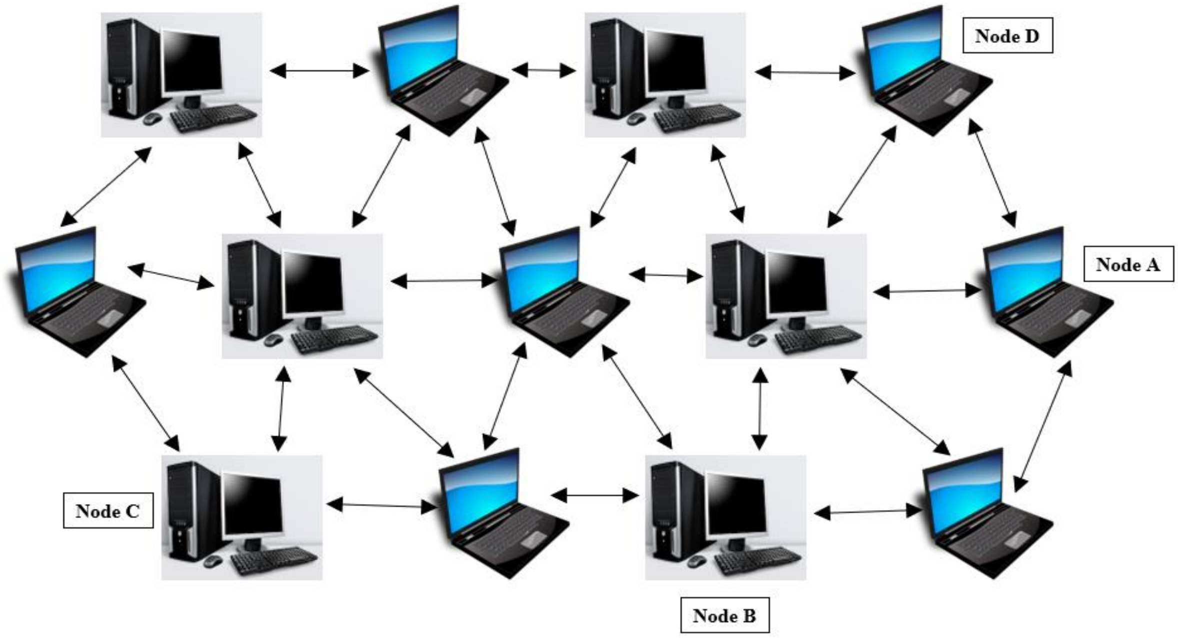


Figure 2.1: Blockchain network showing how information is interconnected between the nodes of a block in the network

A node is that physical/virtual machine, such as a laptop or computer in Figure 2.1 that interacts with other nodes using TCP/IP and UDP. Users are seen on the virtual machine as a public key address within the network. Nodes distinguish each user on the network through their IP address, while users can reference other users using the public key. Users can carry out transactions (Tx) and sign messages cryptographically to guarantee the other party of trustworthy intentions using their private keys within the network. The inherent scripting language at every node (also referred to as smart contracts) is triggered by certain transaction events to store the activities in traditional databases and perform the additional business logic activated by any transaction. Although blocks are interwoven and possess certain similar characteristics, this distributed ledger helps blockchain to function in a decentralised manner, as data is not kept in one central storage system.

Referring to Figure 2.1; if in Block A (community A), Node A (user A) pays Node B 150 for 10 units of energy, this transaction will be T1. All users within the blockchain network can plainly see that Node A (user A) bought 10 units of energy from Node B (user B) for $150 because the information from T1 will be sent to all nodes on the network for transparency purpose. Node C then adds the T1 transaction record, alongside other recent transactions, to those blocks connected to Block A in the blockchain system.

If a computer on the block crashes, data is not lost because nodes on the block are interconnected. Users are assured that other computers within the block still have access to the data secured in the blockchain network, meaning there is no single point of failure on the network [30]. Hash is commonly used in blockchain technology to represent inputs of any length strings entered in the blockchain trading platform to give a fixed-length output by running the hash algorithm using sha256 [31]. The hash from the previous block creates the hash for the next block because all the blocks interconnect to a single system.

Some current technical restrictions faced in the blockchain system include capacity, latency, and query capabilities. However, they are probably caused by the transient nature of blockchain and require future development to address these issues [19]. The blockchain system uses two layers of code: the fabric layer and the application layer (see Figure 2.2).

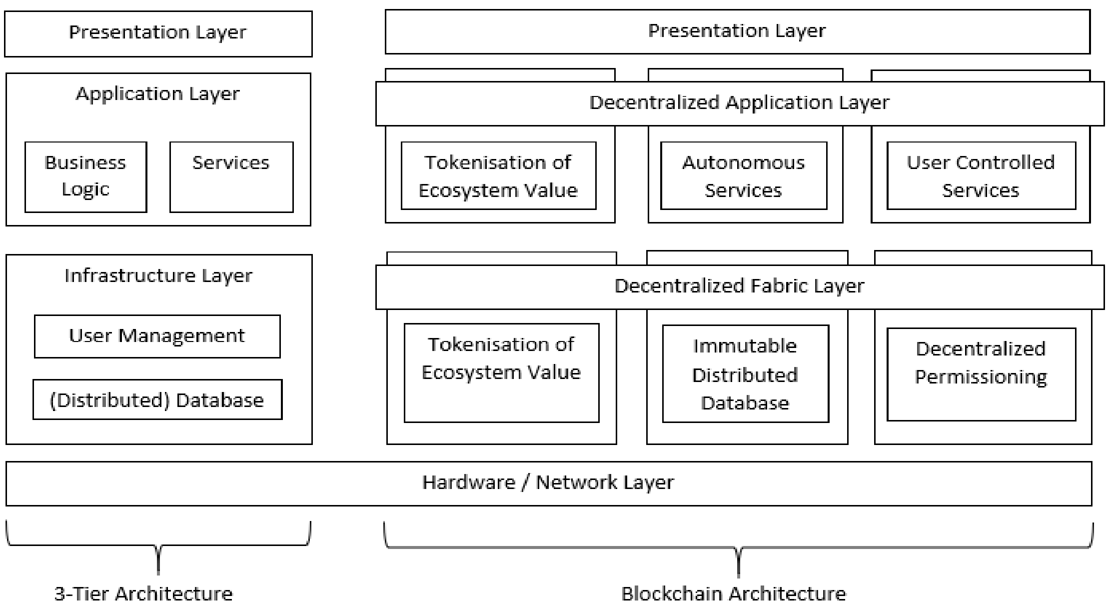


Figure 2.2: Layers of the blockchain network

The fabric layer in Figure 2.2 is the first layer containing the communication layer, public key infrastructure, and data structures required to build and support the blockchain while also allowing the smart contracts codes to operate smoothly. The application layer, which is the second layer is the code behind the logic of application services to keep the system running in the proper way. The code writes and binds users to the system, putting those programmers under the control of the system. Once the application layer is open to the public, fabric layer developers have no control of events in the application layer. Therefore, the entire blockchain network is a decentralised system.

The fabric layer permits diverse kinds of user to have a distinct level of authorisation by working with an integrated module. Distribution companies have their specific permission levels, and users carrying transactions have their ranges of permission on the system. The grid also has permission limits granted to them on the system. However, there is always a super client that has oversight of the full rights control, which makes it easier for that person to distinguish users from the management module. This also empowers full transparency amidst all users identifying with transactions and the smart contract code of other blockchain system users. Any fear of violating privacy only exists if a set of enabled users can see and validate transactions and blocks. That said, only a specific range of permissions will be given to distribution companies that allow them to monitor and track their distribution lines if users intend on using their channels to transact energy between themselves and back to the grid.

2.5.3 MECHANISM OF SMART CONTRACT IN A BLOCKCHAIN-BASED TECHNOLOGY

A smart contract consists of pieces of programming codes that pull the entire blockchain network into a working machine that is accessible to users. Code execution failure in a part of the scripting language will cause the entire transaction to fail, and this hinders the next state from executing. The execution time is restricted by paying for it to prevent system malfunction because an infinite program execution causes the entire blockchain system to stop. As a result, smart contracts need self-execution by external mediation for users to function. Each node representing each user has a unique address and energy storage characteristics peculiar to only that node on the blockchain network. The percentage of profit that each seller gets is directly proportional to the amount of surplus energy that they contribute to the network at any given time [20].

Most literature papers reviewed in this study focus on blockchain technology that employs a bidding system method (see ***Appendix (A.2)***). Here, an unequal playing field exists for several nodes bidding for the same amount of energy from a particular solar PV energy producer willing to trade energy with other nodes. This is because sellers are given a free hand to adjust their demand as they deem fit. Buyers are unaware of their competitors bidding for the same energy available for sale through other energy trading platforms in the blockchain network. Only the highest bidder can win access to the energy that is traded [20]. The smart contract employed for such bidding platforms follows the successive steps described in Figure 2.3 [20].

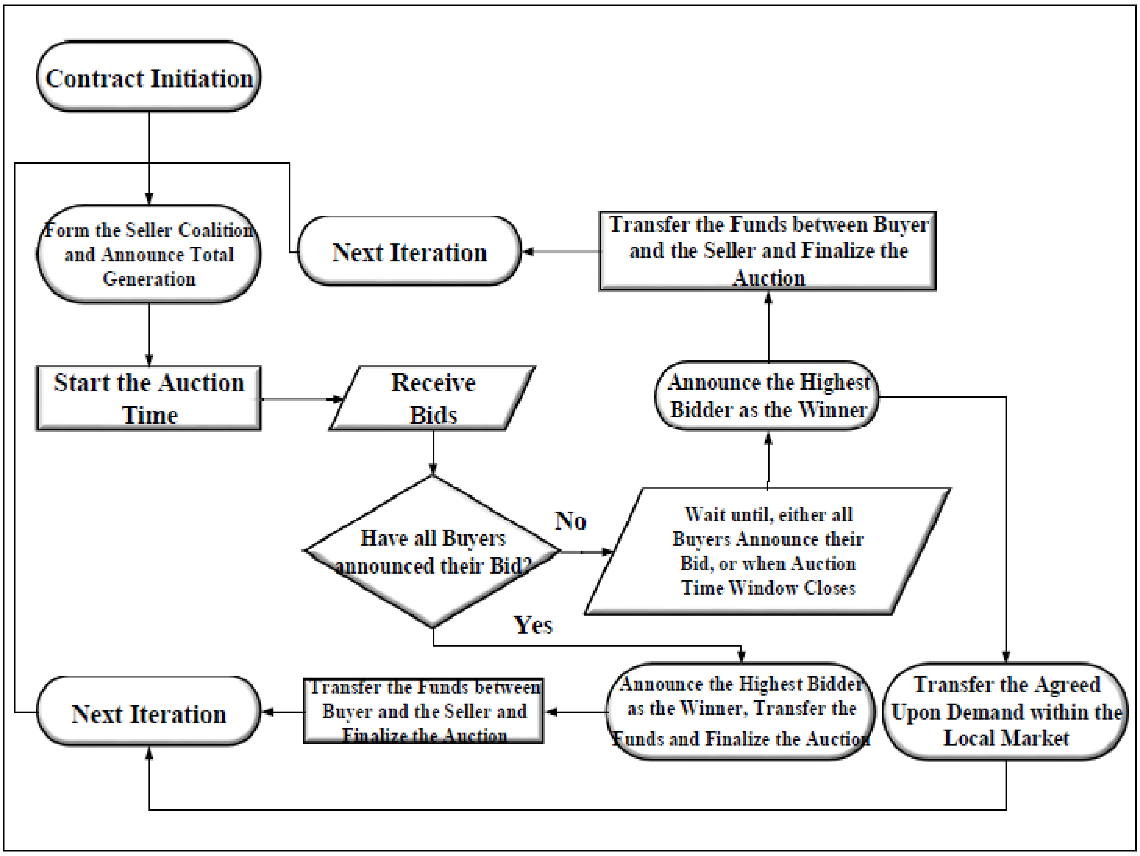


Figure 2.3: Smart contract algorithm

In Figure 2.3, all nodes are informed when each auction iteration is about to commence so that buyers can be informed about the available energy units within the block. This occurs after collating data from sellers who send their information about the amount of surplus energy available for sale. After that, the system announces a time limit for buyers to bid, then waits for that time to elapse, then it assesses the bids before announcing the winner with the highest bid value before the buyer pays the seller the agreed fee for the energy unit. All of this process occurs without the involvement of a third-party to avoid fraudulent activities within the blockchain system.

However, the bidding process might escalate to an outrageously high bidding value, and the competition between buyers becomes intense. This can occur after the downtime from a disaster, which affects the behaviour of the network nodes. Sellers might take advantage of the weakness of the buyers to sell energy for an amount beyond the regular price of that unit of energy. This becomes an issue for less privileged people who may not be capable of surpassing their uninformed competitor's bargaining rate. If these less privileged people cannot beat competitors in the bidding system, they are forced to buy from the standard grid at a higher rate or be without electricity. Thus, the purpose of providing energy to all at an affordable rate is not fulfilled. This indicates that the bidding system tends to favour the wealthy, leaving others stranded of energy when enough is not generated. Therefore, this thesis will focus on utilising a standard rate of energy trade within the blockchain platform, rather than bidding system. With a standard rate regulating the activities of the energy-trading platform, everyone can have access to purchase energy during any season. Besides, more focus is given to energy availability and reliability, rather than the level of competition among energy buyers and sellers. Hence, this study will develop a more suitable approach that accommodates both the wealthy and less privileged.

2.6 BLOCKCHAIN ENERGY-TRADING AND MARKETING PLATFORM

The cost and demand for energy may change at different times in the marketplace based on the frequency of the needs of network nodes [32]. There is the possibility for the price and demand for energy to increase during peak hours, for example, during the Nigerian rainy/winter seasons, where more heating units are utilised; and drop during off-peak hours, for example, during the sunny/summer seasons, where more air conditioning cooling units are in operation.

This study will not focus on the bidding system format. Instead, it will focus on an energy-trading marketplace that adopts centralised energy costing at any given time of the year based on the tariff policy. Without the bidding system, sellers have nothing to worry about regarding other nodes bidding higher than they can afford to buy electricity from the blockchain trading platform. This gives every node an equal opportunity to buy and sell energy among nodes on the energy-trading platform, regardless of their financial capacity. Therefore, the energy trading platform becomes more open and acceptable to low-class and medium-class end-users. They have the same opportunities as high-class end-users to buy and sell energy to each other. More so, with a decentralised solar photovoltaic (PV) distributed generation (DG) system as the primary source of energy generation, it becomes easy to keep the electricity rates low, making energy more accessible to all classes across the nation. A decentralised generation system can generate more energy, leading to more buying and selling activities on the trading platform. This indirectly causes the energy regulatory bodies in Nigeria to establish a generalised rate of selling energy to nodes on the blockchain network.

2.6.1 PEER-TO-PEER MARKETING MODELLING

Smart meters monitor, record and transmit the generation and consumption rate to the smart grid-connected to the grid and the trading platform using a singular Point of Common Coupling (PCC) for transparency within the blockchain trading platform [20]. Smart meters were installed on the distributed generation (DG) units using Photovoltaic Panels to capture renewable energy from the sun [20]. The smart meter is used to monitor, report and dispatch the energy generated and consumed by the node's loads to the smart contract in a synchronous manner. In addition, the singular Point of Common Coupling (PCC) is used to connect the distributed generation to the centralised standard grid.

In this study, a two-dimensional pattern that intertwines the DG grids and standard grids via this blockchain technology is presented to encourage local DG networks to use the natural renewable energy that can be generated within their reach, while reducing stress on the primary grid. However, aside from encouraging this technique of buying and selling, the architecture of this thesis would go further to consider a natural disaster occurring only within a particular zone/community. Depending on when the effects of the disaster are resolved, there is the flexibility of buying from the main grid. Unforeseen circumstances may paralyse local grids and force all nodes to buy from the primary grid. As distribution companies fix disaster damages within the shortest possible time, the price for nodes buying energy from the main grid would be equivalent to the standard of purchasing energy from fellow nodes within/around blockchain networks.

2.7 TRUST AND ANTITRUST IN BLOCKCHAIN NETWORKS

Trust is the foundation of any successful trading platform, hence the need to discuss the impact of trust and antitrust on the blockchain network.

2.7.1 ISSUE OF TRUST IN BLOCKCHAIN SYSTEMS

The issue of trust will occur in every system because an absence of trust will cause the network to fail. Fighting the potential illegitimacy in the system is achievable by featuring the authenticity of the verification tool used to resolve trust or insurance issues between participants in the system [30]. Therefore, as a way of boosting trust levels in the blockchain trading platforms for this study, third parties are limited to grid administrators who maintain a transparent record of transaction activities. This method of supporting trust can work alongside any use made of the hashing algorithm. To an extent, the accuracy of programmed codes enables blockchain to overcome issues of trust in economy sharing platforms. However, it is still dependent on the interface of the sharing ecosystem [23]. There will always be trust issues in some uncontrollable situations where fraudulent users may try to input false information, such as the amount of energy available for sale while charging buyers exorbitant tokens for limited energy levels.

Some researchers pitched the idea of incorporating GPS data into the blockchain system to verify the actual amount of renewable energy the certified seller sells to the certified buyer [30]. After winning the bid for a certain unit of energy, the GPS data is triggered for the buyer to make payment to the seller when the token (blockchain monetary value) gets to the seller's geographical area. However, another big question to be addressed is how the smart contract monitors the actual energy delivered from the seller to the buyer. This study implemented the concept of grid administrators functioning as the intermediary between energy buyers and sellers. In this way, grid administrators only trigger the busbar to release the unit of energy paid to the buyer and deducts the commission and storage fee before releasing the rest of the fee paid by the buyer to the seller.

2.7.2 ISSUE OF ANTITRUST IN BLOCKCHAIN SYSTEM

There is the possible misuse of privilege by a category of nodes with the "write" and "read" permission that has the leverage to do as they wish in the blockchain network. In the US, a specific group of people were worried that the group with "write" and "read" permissions might alarm other nodes, hence limiting transaction [30]. However, government policies can be useful in sanctioning general behaviour within the network.

The nature of the policy set guiding shared information depends on the context of shared user's information. Therefore, when different distribution companies request sensitive data from users when nodes use different distribution to carry out electricity transaction at different period can raise antitrust level likely increase the level of antitrust concerns [30]. However, if a single centralised database is created within the blockchain system with exclusive restricted access different from the general nodes access permit, it can reduce antitrust issues within the network. The exclusive access granted to these distribution companies would limit them to accessing restricted information like statistics for the upgrade of their distribution platforms, information about royalties issues for nodes that use their channels to buy and sell energy from nodes and the grid.

Another medium that addresses mistrust and builds trust levels in the blockchain is the willingness to adopt new nodes into the network. It portrays the view of transparency amidst nodes and puts an end to the notion of secrecy in the minds of users. However, the downside of this is that restrictions to viewing sensitive information by the distribution companies and any other third party that might be in the system will be kept in place [30]. The only information accessible to these third parties will be the information needed to validate each block.

2.8 RESILIENCY IN ENERGY SYSTEMS

An efficient way to deal with the stress imposed on the grid is to create a cluster of smaller DG systems by dividing the distribution system to different zones closer to the load centre, including the "supposed" isolated areas that the central grid cannot supply to [33]. At the end of the power system is the distribution system that carries the electrical power converted from the primary energy (solar PV) to the consumers' end. Hence, the medium of distribution system affects the power supply quality, availability, and reliability received at the consumers' end. Significant faults in the distribution network result in the highest percentage of power outages at the consumers' end [34-36].

Therefore, the resiliency and adaptability of the distribution network are important for satisfying customers and improving the reliability of the Nigerian power supply. Remote control topology makes it easy to achieve optimal operation by isolating the fault. Places without a distributed generation (DG) system can make use of a reconfiguration method by sectionalising switches within feeders or tying switches between feeders in distributed systems to bypass the flow of electrical power from faulted areas to alternative supply sources that meet consumer energy demand [33]. A distributed generation system improves the resiliency of Nigeria's distribution system, and the grid as decentralisation can confine the faulted zone that will need to be resolved in the event of unforeseen situations.

In a centralised energy grid network, when the fault comes from the substation or the distribution system due to the impact of a natural disaster that isolates areas without energy, reconfiguration method may not be appropriate to assure continuity of energy flow. However, decentralisation takes care of the burden when reducing affected areas. In recent times, the global world is shifting from centralisation to decentralisation by integrating the distributed generation (DG) approach to restricting the impacts of natural disaster in a nation to a smaller zone. This makes the reliability/availability of energy from the grid more effective and appreciated by energy consumers.

2.9 SMART ENERGY MANAGEMENT SYSTEM FOR OPTIMAL MICROGRID ECONOMIC OPERATION

There is also the potential instability of moving Nigeria's national energy needs to solar if the energy storage system (ESS) is not included in the network design. The surface area of the solar PV array is a determining factor when calculating how much energy can be generated. This is so because, in mere seconds, any variation in solar irradiance from the sun can change the amount of energy generated [37]. The lack of storage system with already stored energy could be an issue for loads that depend on energy from the PV system. Hence, optimising the complete microgrid operations using the concept of a Smart Energy Management System (SEMS) that includes Energy Storage System (ESS) management is needed to improve power availability [38].

Due to global environmental issues, an exponential increase in energy consumption, and the stress imposed on the centralised grid network, more distributed generation (DG) networks and Energy Storage Systems (ESS) to support these them, are continually installed to tackle these issues [39-42]. The harmonised integration of distributed generation sources and energy storage gadgets such as batteries and controllable loads like water heater and air conditioning units is essential when considering effective, workable microgrids [43, 44].

The recent advancement of Energy Storage Systems (ESS) and power electronics technologies is important in the energy market to provide feasible solutions for the availability and reliability of microgrid energy. Some papers suggested selling stored battery energy at a high cost while also cutting down peak loads from the bigger energy network [45]. To limit the operational cost of the microgrids, linear programming algorithms were adopted to reduce operational costs while also optimising the elements and capacity of the battery charge [46, 47].

On the contrary, a day ahead can be considered in charge of the energy storage device process to meet the energy demands for the next day [48]. This day ahead strategy presents a Smart Energy Management System (SEMS) that can predict energy availability, storage, and trading in the form of power exchange and short-interim schedule to reduce operational costs. Instead of conventional ways of forecasting the weather, the SEMS anticipates the weather forecast and energy generation by the PV system for a 1-day-ahead climate condition. This is achieved by determining the ideal operating roster from the accessible distributed energy resources (DER) equipment available, the capital costs needed for start-ups and the operation and maintenance (O&M) costs needed to run the system throughout its lifespan. The system also forecasts the number of loads that would be running on the networks, energy billing structure, and fuel costs.

2.9.1 SMART ENERGY MANAGEMENT SYSTEM (SEMS)

A Smart Energy Management System (SEMS) is introduced into the energy network to create the best way for renewable energy sources and distributed generation storage systems to optimise energy. It is generated in a cost-effective medium that will meet certain load demand on the distributed energy network. As seen in Figure 2.4, the operational behaviour of the ESS, distributed generation sources, the behavioural pattern of the energy market, and the consumer's load energy consumption pattern contribute to the best optimisation algorithm that will ensure energy availability at all times [38].

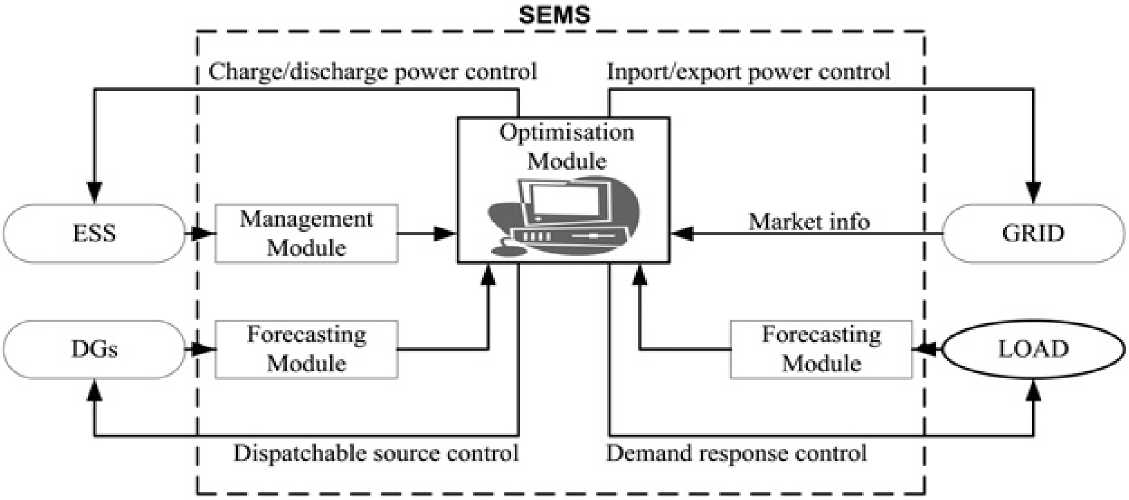


Figure 2.4: Typical illustration of SEMS inputs and outputs

The availability of solar photovoltaic energy is generally affected by many factors such as atmospheric temperature and pressure, photovoltaic (PV) irradiation from the sun at a different time of day, variation in climate change, PV array transfer efficiency, and the positioning and angle of installation [49-53]. The best way to predict energy availability and optimise energy signals to energy consumption units as a load is to use energy generation forecasting. There is a need for proper planning of efficient energy management schemes for either a single day or multiple days ahead before considering which particular Energy Storage System (ESS) to adopt. Also bearing in mind the need to reduce capital, operation, and maintenance costs while running the system.

2.9.2 BATTERY ENERGY STORAGE SYSTEM (BESS)

Battery Energy Storage System (BESS) installation is needed in this study to support energy reliability and availability to energy consumers no matter the climate or seasonal factors [55]. Some authors suggested installing smaller energy storage units at the various distribution generation feeders closer to the loads that are interconnected and remotely controlled at the substation [37, 56, 57]. Some others planted the smaller energy storage units at the different solar PV distributed generation areas closer to the various loads that can only supply load demands in that specific local area [58, 59]. While others preferred a centralized energy storage unit that can meet the total load demands at maximum discharge output level at the distribution substation [60, 61].

It is proposed in this study that readily available substation land areas behind substation fences or unused land areas within the substation land coverage will be a better place to establish a central BESS in one area. With BESS tied to the grid at the same substation, it will be easy to distribute solar photovoltaic renewable energy to loads while also maintaining a high level of power quality at the Point of Common Coupling (PCC) [37].

2.10 REAL AND REACTIVE (P-Q) POWER CONTROL STRATEGIES

Different control strategies have been applied to control power dissipated from DERs into the DG system, such as constant P-Q control, P-V control, adaptive voltage control, and constant current control [62-80]. Some authors used the Newton Raphson load flow method to support the voltage level in the distribution system to supplement for load demand variation in the system [68]. Other authors used the plug-and-play control scheme in a Distributed Generation (DG) system with multiple DERs interconnected to the utility grid, to coordinate the various DERs to regulate voltages in the network [71]. A further group of authors used the P-Q control and P-V control approach for their load-following the Maximum Power Point Tracking (MPPT) modes, respectively [63], [65], [74], [80].

However, the P-Q control technique was adopted in the control section of this study. The reactive power was set to zero such that the network significantly depended on the real power. This was done to avoid complications associated with considering both real and reactive power in the control scheme. Maximum Power Point Tracking (MPPT) was achieved quickly in less than a few seconds at the start irrespective of the variation in solar irradiance. The adaptive perturb & observe algorithm was simulated in Simulink to boost the energy generated from the solar source by the photovoltaic array.

To ensure the PV generated energy meets the energy transmitted across the network of this study, repetitive control is used to represent the Voltage Source Inverter (VSI) that functions as a shunt converter to ensure ancillary services get to the system. However, there is the challenge of the system operating below its optimal operating capacity if the PV real power (P) is less than the inverter maximum power point (MPP). Therefore, the current attached to the P-Q powers in this research is isolated since MPPT control and dc-link voltage control provides a reference to the direct current that controls the real power.

2.11 SELF-HEALING APPROACH TO RESILIENCY IN A DECENTRALISED ENERGY SYSTEM

Rather than the redesigning the energy system to meet evolving energy demand, the grids have remained as initially designed and built for non-renewable generating plants. Because the current energy system is interconnected to a central control source, adjusting the predefined mode of operation will prompt a change in the overall operation of the energy system thereby increasing the impact of that change throughout the energy system [81]. Therefore, the powerhouse has been more sensitive to power outages and costlier to maintain with sometimes incurring yearly financial misfortunes because it has been over-burdened and sometimes stressed beyond its limits [82].

Self-healing has been referenced to centralised power grid systems, only a few have related self-healing with decentralised power systems due to the recent switch in power from a centralised grid system to decentralised distributed generation energy movement [83]. There have been opinions debating the centralised grid as a better self-healing behavioural technique than a decentralised microgrid [84, 85]. However, a collective harmony between the main and locally distributed generation grids smooths out the process of recoiling and healing after undergoing abnormal changes and stress on the grids [84]. Stability is regained, which enhances the strong and resilient behavior of a nation’s power grid system. Self-healing in a centralised system allows choices to be deliberated and agreed upon from a universal viewpoint.

In the event of unforeseen circumstances, the affected area is isolated to contain the impact on the system before making decisions based on predefined models to solve energy restoration in unstable surroundings [34, 86, 87]. Thereafter, loads are dropped from the network lines within the affected area until a stable condition is accomplished. Before any affected area can be isolated, approval must be obtained from the central control system of that energy system control unit. This can be burdensome and more demanding mainly when depending on a large amount of information from data stored in the central database of the energy system network to estimate a central approach to self-healing objectives [88]. In addressing the issue of self-healing, the maximum amount of energy that could be generated, the amount of energy presently generated during running conditions, and the ongoing running loads connected to the generation systems is analysed [84]. The effect of generating more or less energy and its impacts on the grid are assessed before deciding whether to add more loads to the network or reduce the loads already connected to the energy system while still supplying power to critical loads within the network at all times.

With multiple energy generation points, the maximum potential of a decentralised energy system will be assessed using the proposed model in the MATLAB/Simulink platform of this research [89]. With the decentralised distributed energy system in this research, it becomes easy to focus on a smaller geologically affected zone without the impact of such a crisis felt on larger unaffected areas. In addition, the resiliency of the energy system is improved because a fault or unforeseen circumstances in an area do not result in a blackout of the nation's entire energy system. The grid can then step-in to supply energy to affected energy consumers, and unaffected neighbouring zones can sell energy to consumers in affected areas via the blockchain energy-trading platform.

2.12 INVESTMENT DECISION TOOLS

Several investment decision tools exist to assess the viability of a project. However, because of this study's focus, only a few of them, namely: Net Present Value (NPV), Internal Rate of Return (IRR), Cost-Benefit Analysis (CBA), Benefit-Cost Ratio (BCR), and Payback Period (PP) will be discussed.

2.12.1 NET PRESENT VALUE AND INTERNAL RATE OF RETURN

In every decision-making process for any project or investment involving risk, wide ranges of benchmarks are used to estimate economic efficiency (also known as monetary efficiency). One of them is the Net Present Value (NPV) reliability tool which is a pointer in decision-making processes [90-93] to ascertains the profitability and benefits gained by an investor funding a project.

These decision tools will be used later in this study to illustrate the summation of the present benefits of all incoming and outgoing cash flow over time. NPV greater than zero indicates that the investment would be beneficial, which makes the project acceptable as a good investment. An NPV of less than zero implies project loss. With zero NPV, an investor would have to weigh up other options (such as strategy repositioning) and decide whether to forfeit the project or risk chances on the investment.

The Internal Rate of Return (IRR) is used as a performance measurement tool in this study to assess the feasibility of the projected return of capital investments made on a project [94, 95]. This IRR will serve as an indicator to assess the level of investment profitability of a project by projecting the discount rate at which the cumulative net present value of all future cash flow equals the initial investment spent on the project [90, 96].

2.12.2 COST-BENEFIT ANALYSIS, BENEFIT-COST RATIO AND PAYBACK PERIOD

Cost-Benefit Analysis (CBA) is always used to evaluate the value of an investment and plan the most appropriate scenario that favours the investors [97]. The worth of a project involving public expenditure and policy should be assessed by evaluating all potential costs and revenues that might be generated after project completion [98]. This is required to highlight the lowest social cost and highest net social benefits associated with the project. However, a Benefit-Cost Ratio (BCR) is used instead to research the overall monetary value of a project by assessing the relation between incurred costs and projected benefits using equation 2.1.

$$BCR = \frac{Project\ benefits}{Investment\ costs} \qquad \textit{equation 2.1}$$

The Payback Period (PP) is used to assess the economic feasibility of investing in a project and measure the payback period recovering the total capital investment incurred on the project [90], [99-102]. The same technique is applied in this study to figure the time it will take to pay back the capital costs incurred when investing in this project by trading solar photovoltaic (PV) energy with other end-users of energy.

2.13 SUMMARY

This chapter has explained the background theory behind the status and potential of solar renewable energy in Nigeria. Blockchain technology can also be understood in terms of addressing the issues of trust and antitrust that inform the blockchain energy-trading platform. The impact of smart contract in programming a safe energy trading platform for transacting energy among participating nodes in the blockchain trading platform was also stated. Furthermore, the importance of a Smart Energy Management System (SEMS) and how the Battery Energy Storage System (BESS) is adopted in this study was explained. The P-Q control scheme used in this study was addressed, including the impact of self-healing in improving the resiliency of the Nigerian energy system. Finally, the investment decision tools used in this study were addressed for the benefit of decision-makers and investors interested in investing in projects like this.

CHAPTER 3: METHODOLOGY

3.1 INTRODUCTION

Section 3.1 introduces the chapter contents; Section 3.2 highlights the data gathered, and Section 3.3 highlights the choice of software used in this study. Section 3.4 shows how the Matlab/Simulink platform was used to analyse how solar photovoltaic (PV) Distributed Generation (DG) was designed and modelled for the Nigerian energy system using blockchain technology. This section explores the effects of multiple streams of solar PV influx into the Nigerian national grid using a case study for the distribution system of three local areas modelled. Section 3.5 demonstrates how Python and Anaconda programming environments were used to analyse how blockchain could improve the resilience of the Nigerian energy system especially when it comes to energy trading in the Nigerian energy system. Section 3.6 establishes details of the financial analysis, and a summary is given in Section 3.7.

3.2 DATA COLLECTION

The data in ***Appendix (C.5 and C.7)*** was collected from the Power Holding Company of Nigeria (PHCN), formerly known as National Electric Power Authority (NEPA), and RETScreen Expert, which is a NASA-based software. RETScreen Expert is a Canadian clean energy management software system known for energy efficiency and performance analysis for renewable energy. It was used to extract the Nigerian solar irradiance used in the simulations for this study. The data collected (see Appendix) was inputted to form parameters for the design before simulations were carried out for the purposes of observation and discussion.

3.3 CHOICE OF SOFTWARE

Matlab/Simulink, Python programming and RETScreen Expert software were used to carry out research objectives and answer research questions because of their ability to introduce and manipulate real-time data to suit the focus of study. This software was used to design the model of this study as seen in Figure 3.1 to simulate and analyse how solar renewable energy could be implemented and traded in the Nigerian energy system.

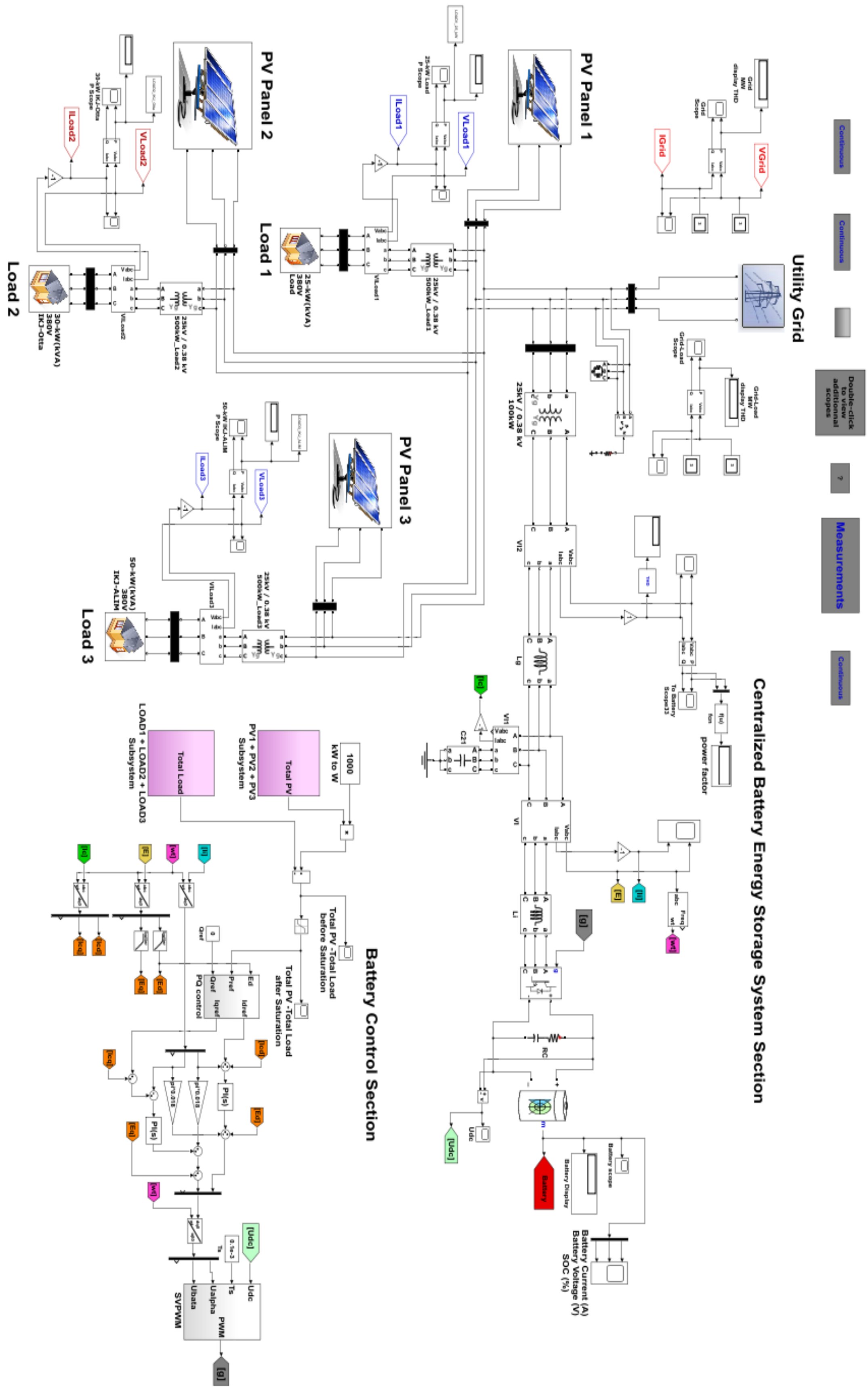


Figure 3.1: Proposed model of this study

Thereafter, the Matlab/Simulink model was interfaced with Python scripts to simulate the operation of the blockchain energy-trading platform. To give clarity to interested investors, RETScreen Expert software was used as a forecasting tool to assess the sensitivity of risk and return benefits for investing in this project. Combining all chosen software ensured the research goals stated in Chapter 1 would be achieved.

3.4 MATLAB/SIMULINK MODEL

The full model designed in ***Appendix (B.1)*** was sectioned into different aspects consisting of solar panels, inverter, smart meter, transformer, storage system, and blockchain technology to effectively apply and simulate the raw data collected. Solar panels were designed to generate energy from the Global Horizontal Irradiance (GHL) obtained from the sun shining on the solar collector. The inverter control system was used to integrate the photovoltaic system to the utility grid, and a smart meter was employed to measure the amount of energy generated by the PV system and the quantity of energy coming and going to the utility grid. Transformers were used to step-up and step-down voltages to avoid voltage loss and the storage system helped to store excess energy generated at any period. Blockchain technology was then used to program energy trading carried out between various nodes (i.e. participants) connected to the proposed blockchain energy-trading platform. Finally, the grid network was modelled using readily available MATLAB manufacturer data sheets in the MATLAB library and relevant data collected before analysing the system behaviour for different operating conditions in this study.

3.4.1 GRID NETWORK DESIGN

Two generation plants with the generating capability of 1500 MVA and 1000 MVA using a power factor of 0.8 were designed inside the utility grid subsystem in ***Appendix (B.1)*** (see Figure 3.2). Schematics of the grid interconnection with the various decentralised solar photovoltaic distribution generations and storage are illustrated in ***Appendix (B.1)***. These two generation plants represent the grid and served as a backup energy source for decentralised locations while also supplying loads to the locations without solar photovoltaic DG system installations.

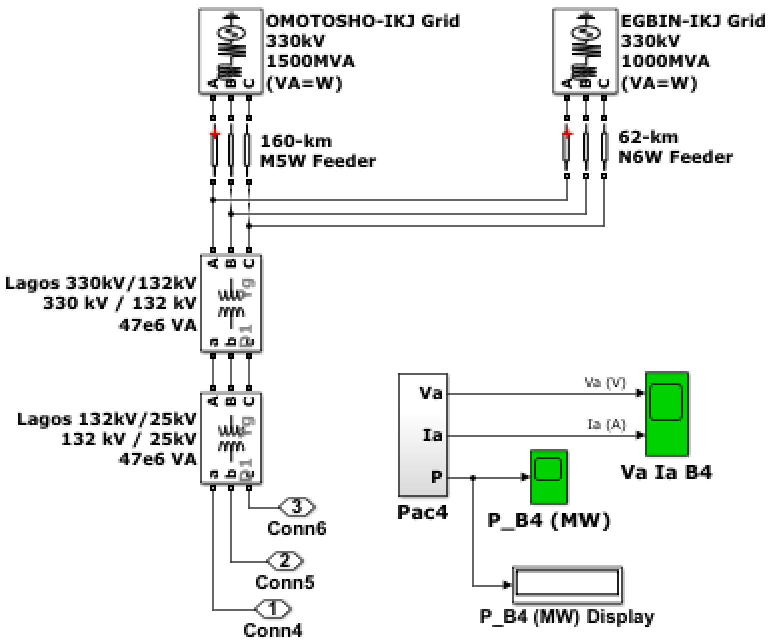


Figure 3.2: Schematics of the two generation plants modelled inside the utility grid subsystem

3.4.2 GRID CONNECTED SOLAR PHOTOVOLTAIC (PV) MODEL

Grid-connected solar photovoltaic models were designed to ensure the bidirectional flow of energy. The grid-connected decentralised solar photovoltaic distributed generation systems were designed to function in a bidirectional way so that energy could be distributed in both directions between the grid and the respective loads with and without PV systems installed in the various locations. The required capacity of PV Array installed at the DC end of the network were determined by assessing the quantity of loads that would demand for energy from PV generation plants. These were then used to run the various simulation scenarios seen in Chapter 4 of this study. Thereafter, from the detailed Excel file list of PV Modules equipment listing available in [104] (last updated May 1, 2019), the SunPower SPR-415E-WHT-D PV Module was selected to design the three decentralised solar photovoltaic model seen in ***Appendix (B.1)***. The SunPower SPR-415E-WHT-D monocrystalline module was chosen because of its 385.2W PTC ratings and 415W CEC ratings.

3.4.3 PV MODELLING

To generate the maximum amount of PV distributed system energy, PV systems were sized under Standard Test Conditions (STC) based on load demands in respective local areas and any potential losses that might occur due to transmission or system errors. Three different decentralised grid-connected PV distributed generators were modelled with Matlab/Simulink software as seen in Figure 3.3 (captured from the full model in ***Appendix (B.1)***).

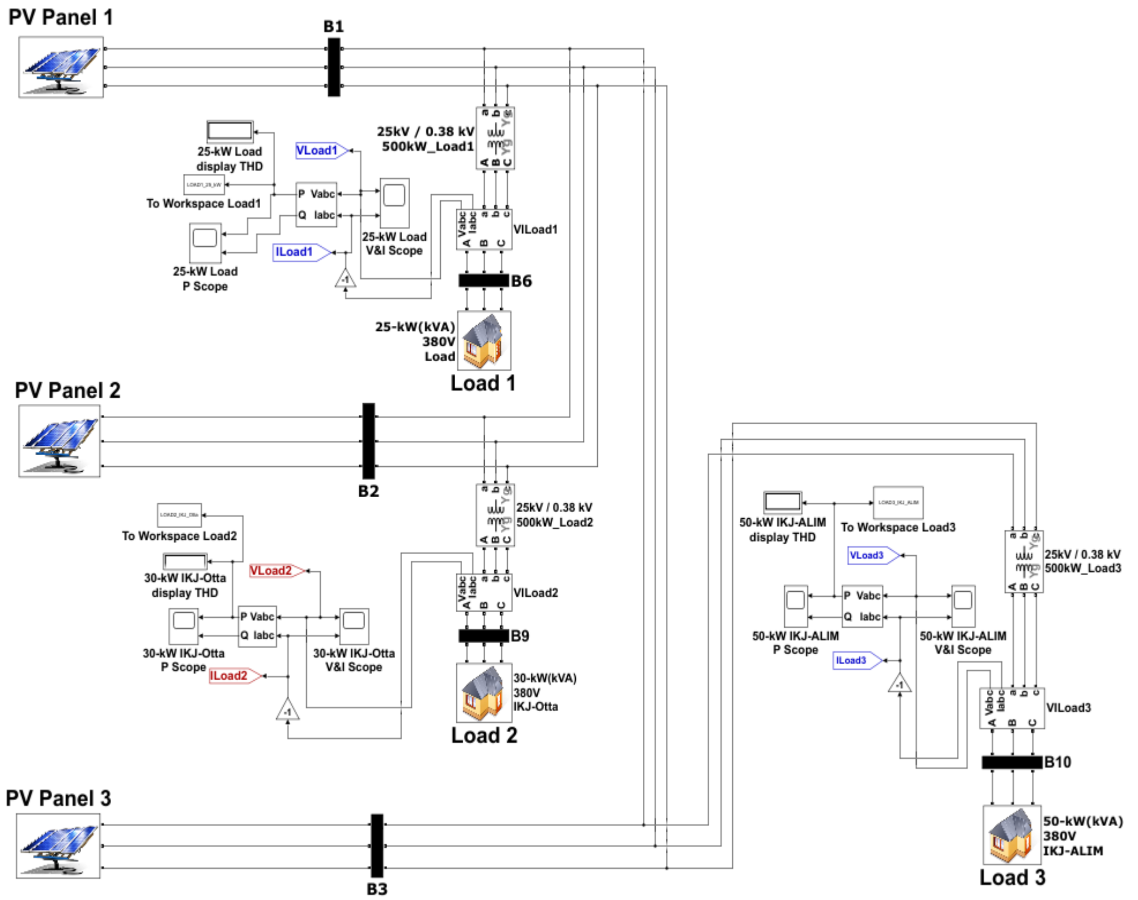


Figure 3.3: Basic concept of how a single photovoltaic system is modelled in Matlab/Simulink platform

3.4.4 PARAMETERS OF THE PV ARRAY IN THIS STUDY

The already predefined PV module parameters from the Matlab/Simulink library seen in ***Appendix (C.1)*** were used for the characteristics of the PV model designed in this study. However, the values of parallel strings and series-connected modules per strings were adjusted based on the different generation outputs that were required by the various PV generation outputs for each scenario simulated in Chapter 4. The parameters from ***Appendix (C.1)*** were then used to plot the I-V and P-V graphs in Figure 3.4 to illustrate the maximum power point tracking that can be achieved using the predefined SunPower SPR-415E-WHT-D model characteristics. The I-V and P-V graphs plotted shows that with 88 parallel strings and 7 series-connected modules installed in the model of this study, the maximum amount of energy generated at $25°C$ and $45°C$ are $255kW$ and $240kW$ respectively.

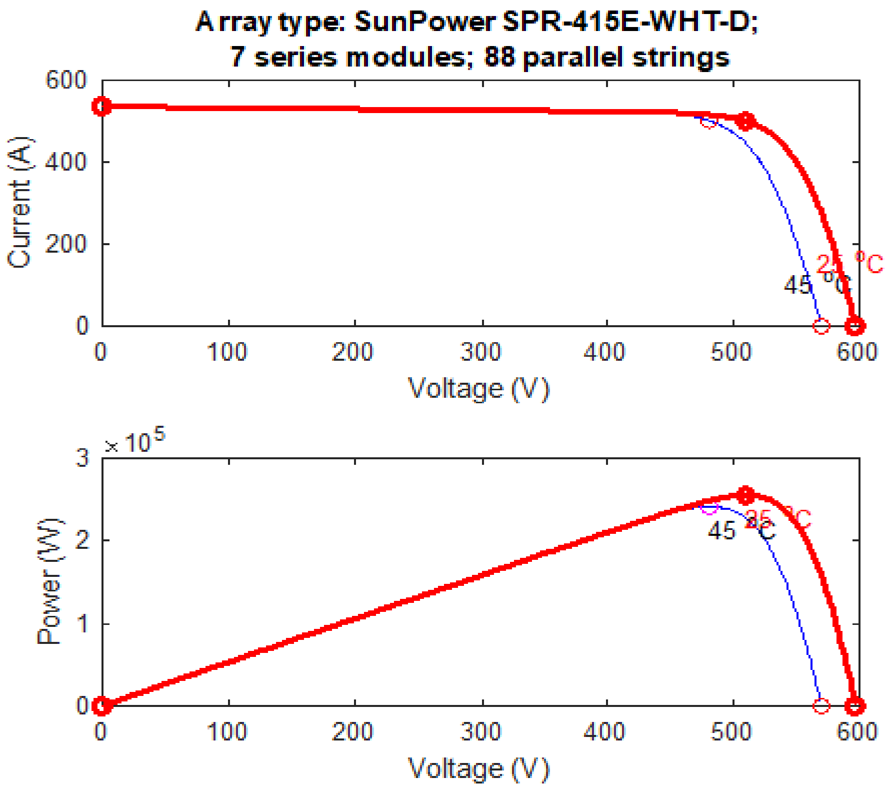


Figure 3.4: I-V and P-V graphs of the SunPower SPR-415E-WHT-D PV array

3.4.5 PV COEFFICIENT OF PERFORMANCE (COP)

In this study, the PV coefficient of performance (COP) was considered during the focus of this study to account for energy inefficiency in generation and distribution. This solar photovoltaic (PV) efficiency was considered to account for the possible energy loss between the installed PV array kilowatts (DC) generation facility and the energy that was successfully transmitted to the PV array kilowatts (AC). The overall DC to AC derate factor was calculated by multiplying the entire derating factors (i.e. system inefficiencies) under the column in Table 3.1 that has input value as the heading, which resulted in 0.795 as seen in Table 3.1. This was then used as the overall DC to AC derate factor when sizing the solar PV models designed in this study.

Table 3.1: Derating factor (i.e. system inefficiencies) calculations

Derating Factors	Input Values	Typical Range
PV module nameplate DC rating	0.950	0.80 – 1.050
Tilt Factor/Orientation Adjustment	1.000	0.50 – 1.000
Inverter	0.950	0.88 – 0.960
Mismatch	0.980	0.97 – 0.995
Diodes and connections	1.000	0.99 – 0.997
DC wiring	0.980	0.97 – 0.990
AC wiring	0.990	0.98 – 0.993
Soiling	0.950	0.30 – 0.995
System availability	0.980	0.995
Shading	1.000	1.000
Sun tracking	1.000	0.95 – 1.000
Age	1.000	0.70 – 1.000
Overall DC to AC derate factor	**0.795**	**0.60 – 0.750**

3.4.6 PV ARRAY SIZING

There will always be energy loss from the installed PV array kilowatts DC facility to the kilowatt's AC facility of the PV array. This made it harder for the maximum installed DC array capacity to reach the PV array AC end of the network. Hence, equation 3.1 was used to determine the DC value for the array in kilowatts (kW), while calculating the needed PV array installed kilowatts (DC) equipment parameters modelled into the design of study in ***Appendix (B.1)***.

$$PV\ Array\ Installed\ Kilowatts\ (DC) = \frac{PV\ System\ Design\ AC\ Capacity\ (kW)}{Derating\ Factor} \quad equation\ 3.1$$

3.4.7 DETERMINING THE NUMBER OF PV MODULES REQUIRED

Once, the PV module and the desired PV Array kilowatts (DC) was calculated, the number of PV Modules required for each scenario testing simulated in this study was determined using equation 3.2. It is also important to know that the number of series connected module per string for this study was set at a constant value of seven (i.e. 7) series connection modules per string.

$$Number\ of\ Modules = \frac{PV\ Array\ Installed\ Watts\ (DC)}{CEC\ Ratings\ (W)} \qquad equation\ 3.2$$

However, the parallel connection modules per string was varied based on the desired PV Array installed watts (DC) calculated per each local area. Hence, equation 3.3 was adopted to determine the desired parallel-connected module per string for each PV distributed generation system.

$$Parallel\ Connected\ Module\ per\ String = PV\ Array\ Installed\ Watts\ (DC) \div (Series\ Connected\ Module\ per\ String \times CEC\ Ratings\ in\ Watts) \qquad equation\ 3.3$$

3.4.8 BATTERY SATURATION

The upper and lower limits were determined by the parameters stated in the Simulink blocks' upper and lower limit with a stated space of 1 as shown in Table 3.2.

Table 3.2: Saturation parameters for scenario one

Parameters	**Units**
Upper limit	300000kW
Lower limit	-300000kW
Treat as gain when linearizing	Enabled
Enable zero-crossing detection	Enabled
Output data type	Inherit: Same as input
Integer rounding mode	Floor

With this upper and lower limit, battery operations could accommodate any amount of energy within the range of 300000kW. However, limits as low as 100000kW could not enable the battery to accommodate all energy transmitted into the battery for storage or discharge.

3.4.9 ENERGY LOSS IN SOLAR PHOTOVOLTAIC SYSTEMS DESIGN

The amount of usable energy that could possibly meet the load demand was calculated using equation 3.4 [105]. Where COP means Coefficient of Performance which sums up all the efficiency of the PV and the inverter efficiency.

$$PV\ Usable\ Energy = PV\ COP \times (EnergyPlus\ cooling\ loads + Cooling\ distribution\ Loss) \qquad equation\ 3.4$$

3.4.10 BOOST CONVERTER DESIGN

The Perturbation and Observation (P&O) method ***(Appendix A.1)*** was used in this thesis to model the operations of the P&O control systems. This was because a lesser amount of sensor was required when compared to other MPPT algorithms, and it beats the constraints associated with system failure due to unforeseen circumstances or oscillatory stability conditions [106-110]. Furthermore, instead of designing a network for discrete power environments (i.e. not changing), the perturbation was designed to vary, based on changes in power continuously adjusted to new system conditions [110, 111]. The boost converter design in Figure 3.5 consisted of Maximum Power Point Tracking (MPPT), Pulse Width Modulation (PWM), inductor and capacitor to monitor the solar PV array's maximum voltage and current i.e. V_{max} and I_{max}.

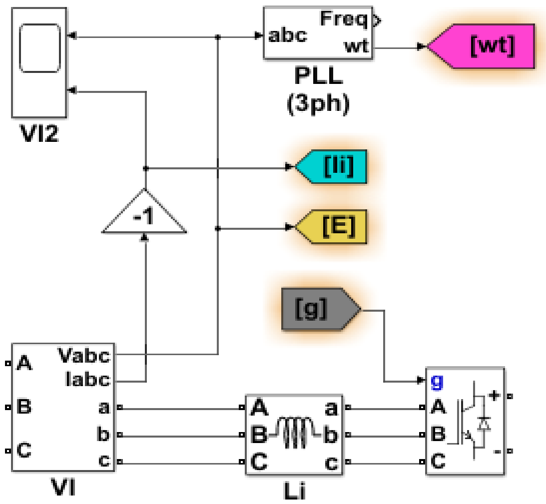


Figure 3.5: Circuit of the boost converter in the system design

From Figure 3.5, the Phase Locked Loop (PLL) system was used to synchronise the frequency and three phase sinusoidal signals by enabling the Automatic Gain Control (AGC) such that the PLL regulator input (phase error) was scaled based on the magnitude of the input signals. To achieve the best possible outcome, the AGC control was enabled by assigning: a minimum frequency of 45Hz, initial inputs of 0° phase and 50Hz, while the regulator gains $[Kp, Ki, Kd]$ was set to $[180, 3200, 1]$. Thereafter, a time constant derivative action of 1×10^{-4} seconds (s) and maximum rate of change of frequency of 12Hz/s was set, while a filter cut-off frequency measurement of 25Hz, with a sample time of zero seconds (s) was set before enabling the automatic gain control icon. The input signal “[g]” fed into the universal bridge in Figure 3.5 is the same as the output signal in the battery control design of ***Appendix (B.2)***.

The inductor in the model was designed to compile and increase the current level with the aid of a frequency switch also effected in the model. The capacitor increased and stored the acquired DC voltage with the help of the electric field flow. Then, the Pulse Width Modulation (PWM) was enabled to stabilise the output voltage of the converter as shown in Figure 3.6 and Figure 3.7. The PWM subsystem block inside Figure 3.7 contains the SVPWM parameters seen in Figure 3.6. The output of the PWM in Figure 3.7 was set as the same output signal in the battery control named as “[g]” as seen in ***Appendix (B.2)***.

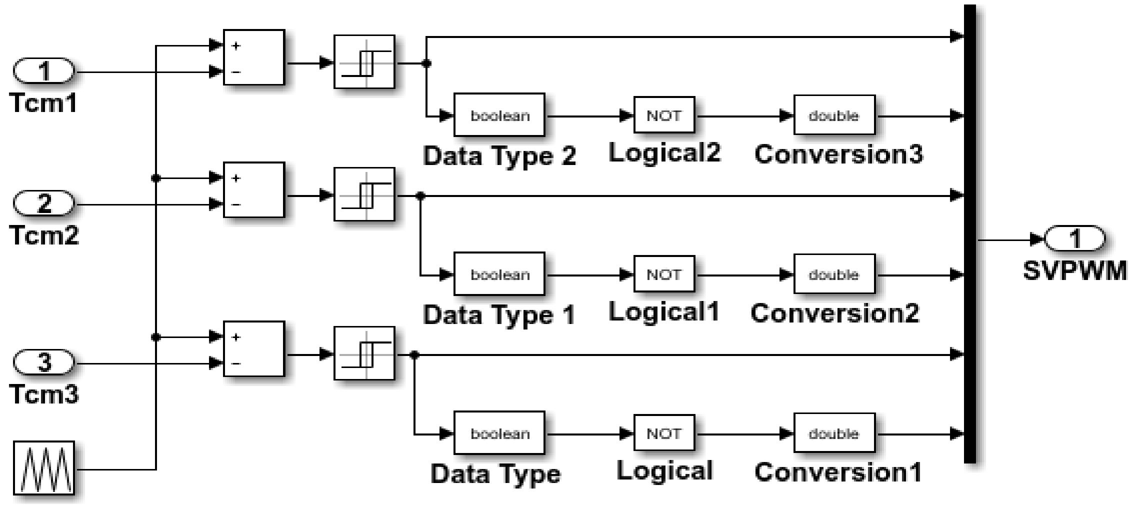


Figure 3.6: Schematics of the Pulse Width Modulation (PWM)

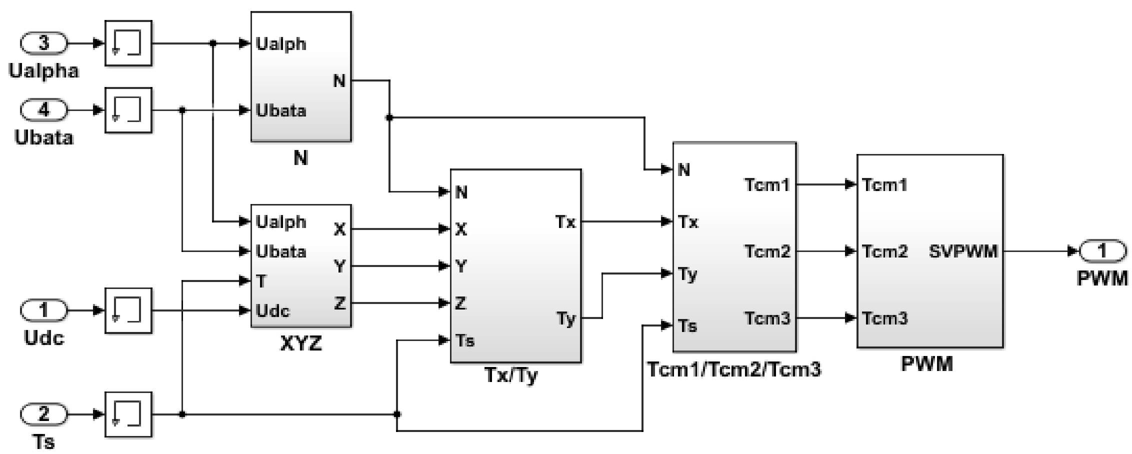


Figure 3.7: Space Vector Pulse Width Modulation (SVPWM) subsystem

3.4.11 REAL AND REACTIVE (P-Q) POWER CONTROL DESIGN

The P-Q control strategy in Figure 3.8 was applied in this study to impose the real (P) and reactive (Q) power. However, to reduce the complexity of this study, the real power (P) was taken from the Maximum Power Point Tracking (MPPT) of the solar photovoltaic (PV) module while the reactive power (Q) was set to zero. The PID parameter seen in ***Appendix (C.2)*** was then used to regulate the real and reactive powers of the Proportional Integral (PI) at their respective reference value as seen in ***Appendix (B.2)***.

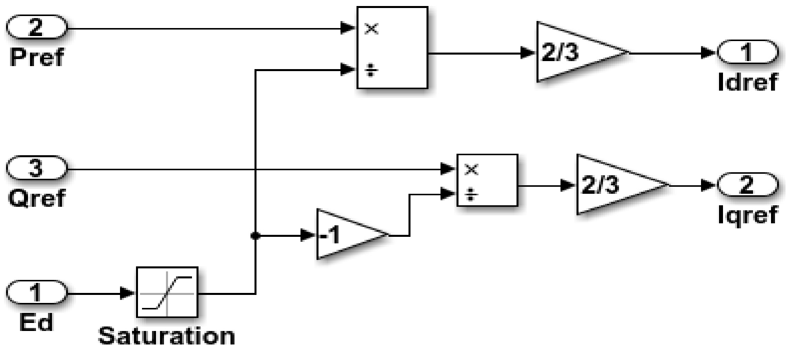


Figure 3.8: Schematics of the P-Q control subsystem

3.4.12 BATTERY DESIGN

A Lithium-Ion battery as seen in Figure 3.9 was considered because of its features such as market popularity, lower energy density, and minimal likelihood of fire or explosion.

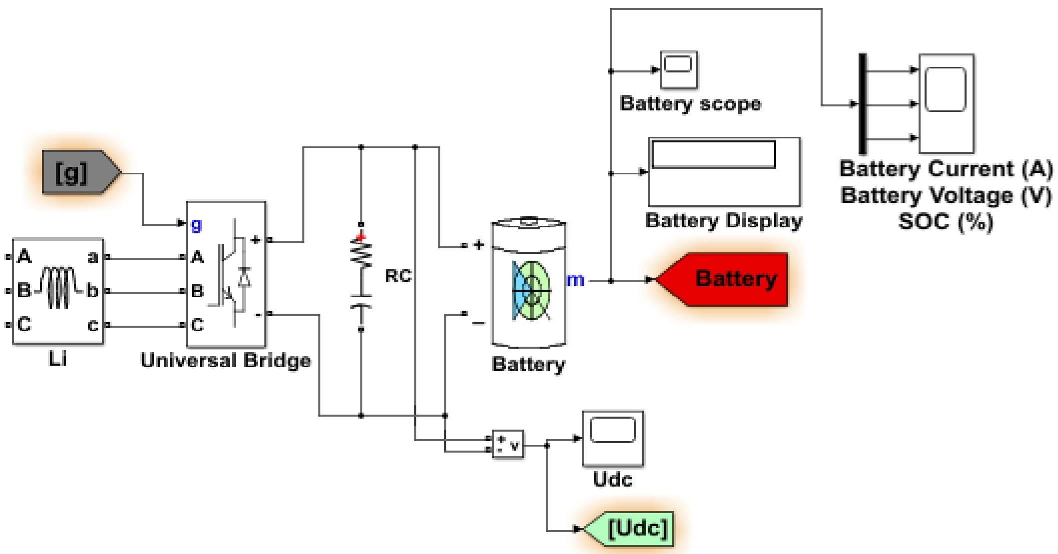


Figure 3.9: Schematics of the BESS considered for this study

The lithium-ion battery was designed to provide a reliable backup energy for the decentralized solar PV distribution generators in this study. A pictorial representation of how the grid-connected battery storage system was modelled in this design is seen in ***Appendix (B.1)***, where the input signal "[g]" going into the universal bridge in Figure 3.9 remains similar to the output signal in the battery control design in ***Appendix (B.2)***. The Battery Energy Storage System (BESS) was modelled to accommodate the overflow (i.e. surplus energy) from the decentralized distributed PV generation systems with an initial state-of-charge (SOC) rate of 50% and a battery response time of 30 seconds (s) (see ***Appendix (C.3)***).

When any of the various modelled decentralised PV systems are unable to generate enough to meet various load demands, generators were given the option of either feeding from their stored energy in the battery or buying energy from other PV generators via the blockchain energy-trading platform. Furthermore, the battery system was designed to discharge the requested energy to consumers with the aid of the grid operator intermediary. With the aid of the limits modelled in the saturation block of the study, the battery was designed to accommodate multiple stream of energy influx from various decentralised photovoltaic systems.

The saturation block was modelled to regulate the output signals of the battery [112, 113]. This saturation block was modelled to bound the input signals entering the battery between a confined upper and lower limit saturation range of $300{,}000$kW and $-300{,}000$kW. Thereafter, the outcome from the saturation block was used as the reference for the real power signal to shape the battery operations control system.

3.4.13 INVERTER CONTROL DESIGN

During the system design, a $250kVA$ inverter was designed by placing each of the inverters as seen in Figure 3.10 inside each of the solar PV panel subsystems in ***Appendix (B.1)***. The inverter control was designed by integrating Phase-Locked Loop (PLL) and measurements; Maximum Power Point Tracker system (MPPT) that uses a Perturbation and Observation (P&O) algorithm approach; Direct Current (DC) voltage regulator; current regulator; and Pulse Width Modulation (PWM), which were functioning together. Furthermore, the inverter was used to convert DC voltage from the PV energy output to

AC voltage that goes into the distribution lines by feeding the measured voltage and current from the PV array as input into the inverter control. The DC voltage, voltage of busbar 1 and current of busbar 1 was also fed into the inverter control as input, and a constant value of one was fed as the MPPT value to show that the MPPT was in operation.

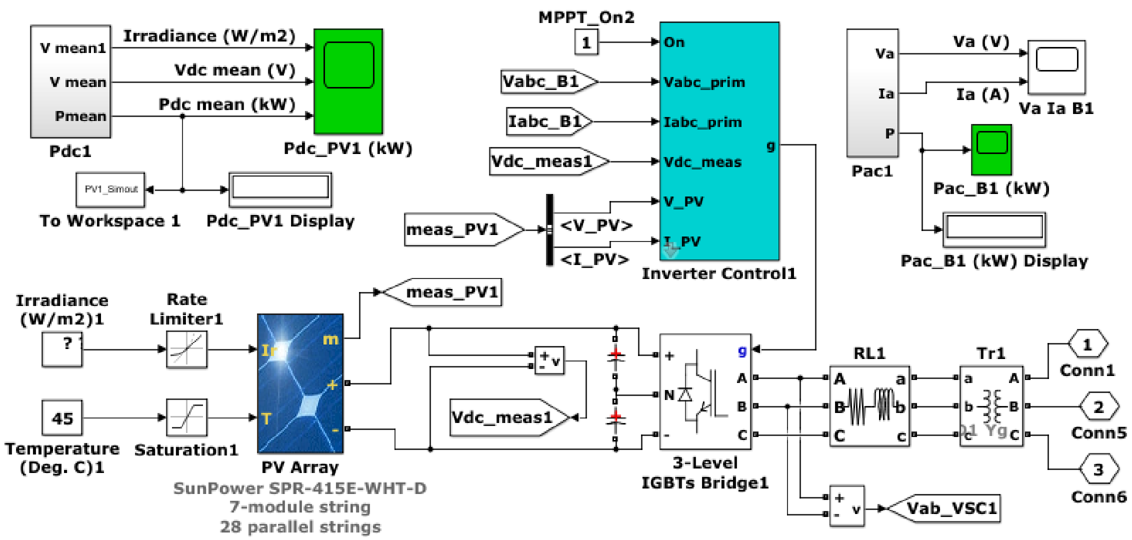


Figure 3.10: Schematics of the inverter control modelled into the design

The nominal values section of the inverter in Figure 3.10 was set to 250kVA; 50Hz frequency; root mean square line-to-line ($Vrms\ LL$) primary voltage of 25k volts (V); root mean square line-to-line ($Vrms\ LL$) secondary voltage of approximately 249.848 volts (V); and 480V DC voltage. The MPPT controller section was set with an output increment of 0.01V; upper and lower output limits of 583 and 357 respectively; and an output initial value of 480V. The DC voltage regulator section was set with a proportional gain of 2 and an integral gain of 400. The current regulator section was set with a proportional gain of 0.3; integral gain of 20; and Rff and Lff feedforward values of 0.0039 and 0.21 respectively. Then, the PWM modulator section was set to 1980Hz carrier frequency, control systems sample time of 5.0505×10^{-5} seconds (s); and a PWM generator of 5.0505μs. All these parameters combined were used to simulate the various scenarios in chapter 4 of this study.

3.4.14 TRANSFORMER DESIGN

The transformer was modelled into the design to function as either a step-up or step down, depending on its position in the model. At the grid's end, two step-down transformers of $330kV/132kV$ and $132kV/25kV$, each with $47MVA$ power were placed to reduce the voltage from $330kV$ to $25kV$. Between the grid generators and the battery, a $25kV/380V$ step-down transformer with $500kVA$ power was placed. In addition, at the solar PV generation end is a $250V/25kV$ step-up transformer with $250kVA$ power was also placed. Closer to the load centers, a $25kV/380V$ step-down transformer with $500kVA$ power was placed.

3.4.15 SMART METER (SCOPE) INTERPRETATION

The smart meter in the model was designed in the form of Matlab/Simulink scope. The voltage and current of the first distributed generation solar photovoltaic (PV) system were represented as $V_{abc}\_B_1$ and $I_{abc}\_B_1$ respectively where abc denotes the lines a, b and c of the three phases. Likewise, $V_{abc}\_B_2$ and $I_{abc}\_B_2$ for the second renewables, and $V_{abc}\_B_3$ and $I_{abc}\_B_3$ for the third renewables.

The smart meter for the grid's voltage and current was denoted as V_{grid} and I_{grid}, and the voltage and current of the smart meter symbol representing the loads connected to the first solar PV generation system were expressed as $VLoad_1$ and $ILoad_1$. The same logic was applied to the loads connected to the second and third PV installed locations. At the battery, another scope was placed for the grid operator to easily monitor battery activities. The battery was designed to accommodate energy when any parts of the solar PV DG system generated far above what was needed for the immediate energy consumption of the loads connected in that local area.

3.4.16 LOAD DESIGN

The loads in the design model in Figure 3.11 were copied from the full design of this model in ***Appendix (B.1)***, and were designed using a three-phase parallel RLC load Simulink block chosen from the Matlab/Simulink library to represent the AC constant Z load-type and connected to the busbar. These loads featured nominal phase-to-phase voltage of $380V$ Vrms operating at the rated frequency of $50Hz$, while the active power varied based on simulation and load location.

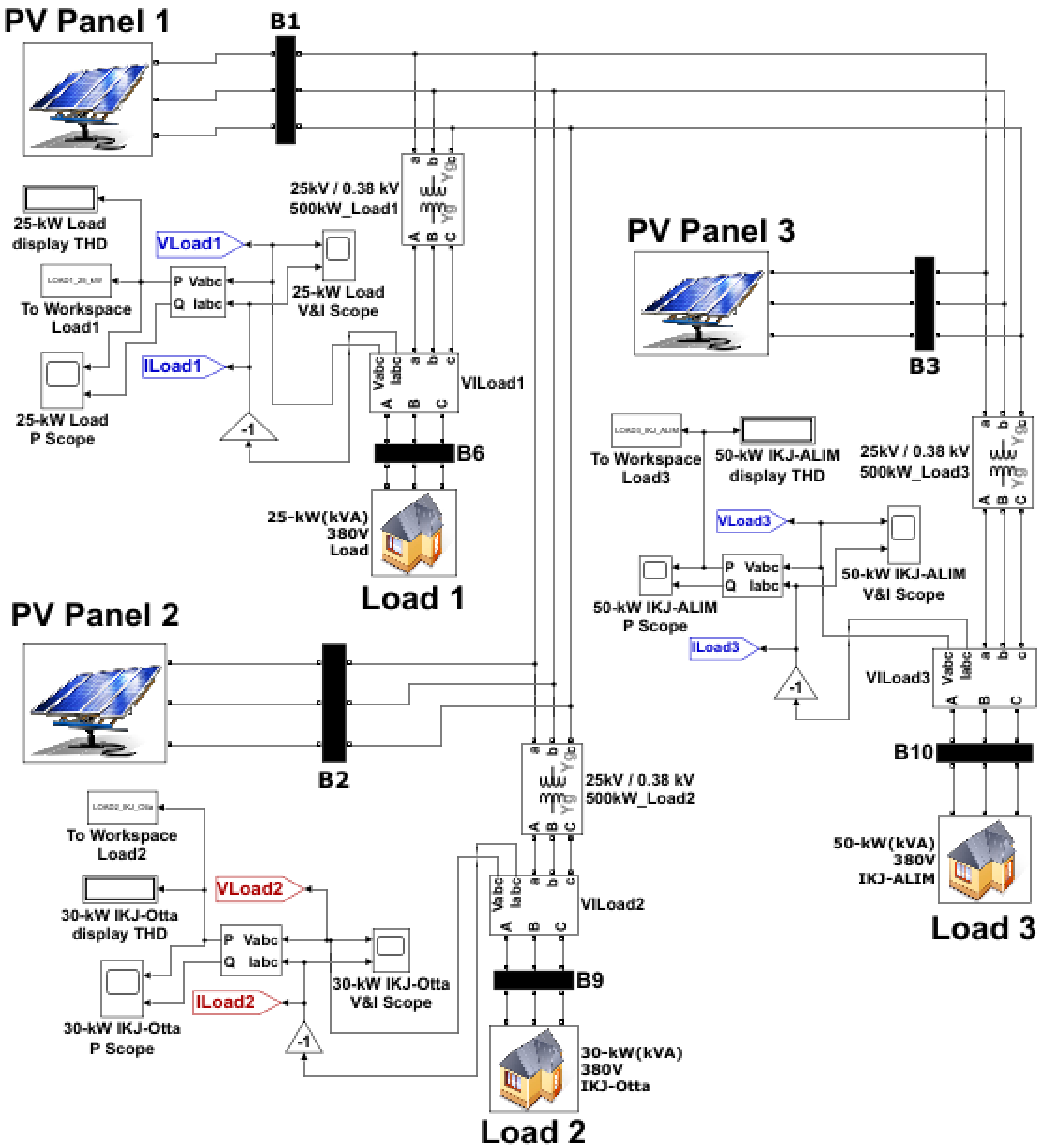


Figure 3.11: Schematics of the three photovoltaic (PV) array systems connected in series to each load centre and connected in parallel to each other

The loads were designed so that the solar PV distributed generation output is their primary source of energy. This was before considering sourcing for energy from either the storage system or the grid generation output to meet deficient energy demands via the grid operator who manages the centralised storage unit and the grid's generation output. The total amount of usable energy consumed by all loads designed in this study was derived using equation 3.5 where COP represents Coefficient of Performance [105].

$$Load\ Usable\ Energy = \frac{(Load \times Distribution\ Loss\ Factor)}{Seasonal\ COP} \qquad equation\ 3.5$$

3.4.17 POWER FACTOR CORRECTION

Since this study was focused on three-phase transmission and distribution power lines, a switch-mode power supply (SMPS) with an active power factor correction (PFC) of 1 was featured (see Figure 3.12) to improve the quality of power factor in the model. The SMPS with active PFC was placed centrally between the national grid and the central storage system, bearing in mind that the national grid and the storage system are both in the same location. This helped to increase the true power factor up to as much as a -0.99 power factor (see Figure 3.12). With an active PFC of 1 in the Simulink simulation environment, the power systems circuit will have a positive power factor and the storage will supply already stored power in the Battery Energy Storage System (BESS) to loads that need power.

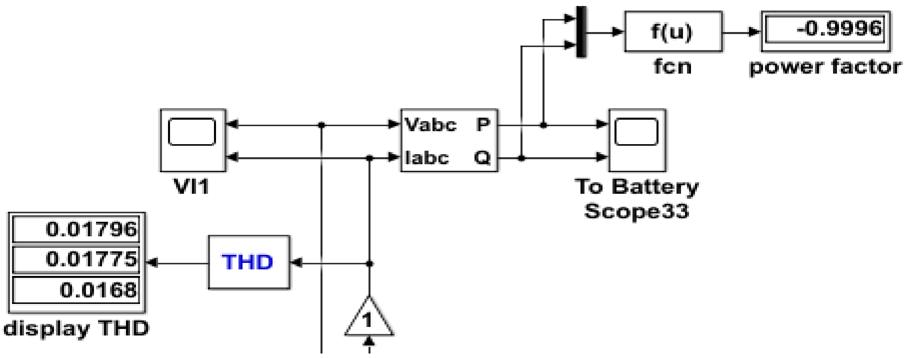


Figure 3.12: Power factor correction of 1 resulting in positive true power factor values

3.4.18 DESIGN OF LOGIC CONTROL FOR ENERGY SYSTEM RESILIENCY

The solar photovoltaic distributed generation systems were designed to be the primary source of energy generation, while the grid’s generation and storage system acts as the secondary source of energy generation either for extreme cases, or because of seasonal variation issues. When any of the three PVs in the model generated more than their loads could immediately consume, surplus energy was transmitted to the grid for storage (see Figure 3.13) until when that producer could decide what to do with the stored energy.

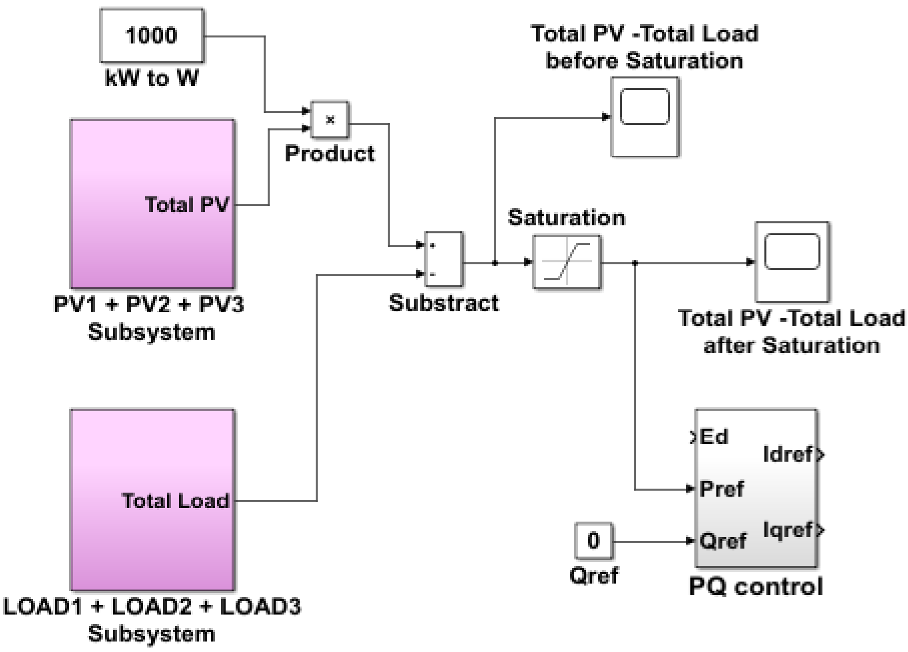


Figure 3.13: Schematics of how the logic control is integrated into the P-Q control system

3.5 PYTHON MODEL

During this research, Python programming language was adopted to programme the pattern of the blockchain energy-trading marketplace for this study. This was because the Python programming language is what most developers and analysts who work in the Energy Market and Trading (EM&T) industries utilise for their trading platforms and data analysis. Among the various Python programming environments, Anaconda, Jupyter Notebook and Visual Studio Code Python environments were used for this research because they of their user friendliness.

Python programming language was used to import the results of the various decentralised solar PV distributed generation networks modelled in the Matlab/Simulink platform into the Python environment. Thereafter, simulation results from the Matlab/Simulink platform were then used to programme a basic energy-trading marketplace in the Anaconda, Jupyter and Python programming environments.

3.5.1 IMPORTING MATLAB/SIMULINK RESULTS INTO PYTHON ENVIRONMENT

The Matlab/Simulink results were first sent into the Matlab workspace before saving onto the research computer hard drive. After this, the Python programming language in

Appendix (D.1) was used to import these results into the Jupyter Notebook environment. The next phase of the program in ***Appendix (D.2)*** was to ensure that available surplus energy could be made known to all nodes in the blockchain-trading platform.

3.5.2 BLOCKCHAIN PLATFORM PROGRAMMING CODES

The first step was to import the hashlib (i.e. the hash library in the Python library) and the datetime as seen in lines (1 – 2) of ***Appendix (D.3)*** before creating the class for the block. This required taking the previous block's hash, data and timestamp into account in lines (4 – 9) of ***Appendix (D.3)***. The timestamp connotes when the block will be created. After this, a function was considered when creating the hash for the new block of transaction that was about to be activated. This hash function was programmed to take all the data in the block header and run it through sha256 two times to make sure that the block was secured and not compromised by theft as seen in line nine of the code.

The next action was achieved by creating the genesis block function that returns the previous block's hash and data in lines (11 – 13) of ***Appendix (D.3)***. The "datetime.datetime.now( )" means the day-time for the timestamp. Then, it became necessary to define the function "get_hash( )" encoded in line (15) which took in only the object within the "( )". At that point, creating the binary representation of the header (strings, in this case) became achievable as this was all the data contained in the header (i.e. "previous_block_hash", "data", and "timestamp") that was encoded in lines (16 – 21) that it could run again in the other hash function. Once the block that took in the previous hash had been created, it became possible to assign data to the block using the timestamps to hash it and avoid alterations.

Subsequently, a simple blockchain code was created using Python programming language which employed the use of a data structure that considered all the parents, so that it was easy to see what had been tampered with (if such a case occurred). If a fraudulent node (known as a scammer) attempted to tamper with the blockchain network, that scammer would have to try more times than can be imagined before breaking through to the system, especially when numerous nodes are continuously transacting energy with each other at a fast pace.

The next phase was to import the function block and assign it to the genesis block before printing the hashed genesis block result in lines (23 – 27) of ***Appendix (D.3)***. However, since every block in the blockchain depends on the previous block (i.e. every parent hash has the little hash value embedded in it), it was ideal to create a little list. This little list was called "block_chain" as seen in line (29). And inside the "[ ]" is where the elements are located in before printing the statement expression "The genesis block has been created" and the hash values in lines (30 – 31), where "Hash: %s" denotes the hash value of the present genesis block. The expression "%s" explains that it is in string format and "-1" shows the value of the last element before this new block's information. In sum, "% block_chain[-1].hash" expresses the string hash value of the last element in the blockchain list.

To add more elements to the block_chain list, line (33) was encoded where the number "10" meant 10 more elements were added to the list. However, during the main energy trading for this study, this value was changed based on the number of additional elements required to successfully complete the Python energy-trading programme codes. Therefore, for every new transaction, lines (35 – 40) was needed to create a new genesis block in "[Block.create_genesis_block( )]", where "i" in line (35) represents the number of the present genesis block which increases as the chain of transaction history also increases. In lines (36 – 38), append connotes adding another block to the block_chain history of blocks. The statement "Block i has been created" with the hash value of this new block was printed to seal the current transaction history until the date preventing it from being tampered with. Finally, the codes in ***Appendix (D.3.1)*** were simulated to test the hashing system of the blockchain codes for ten empty blocks by showing their hash values.

3.5.3 BLOCKCHAIN ENERGY-TRADING FLOWCHART

Since this study is not focusing on the bidding energy trading marketplace but on a centralised standard energy prize rating at any given time of the year, Figure 3.14 was constructed to illustrate the energy trading flowcharts utilised in this study.

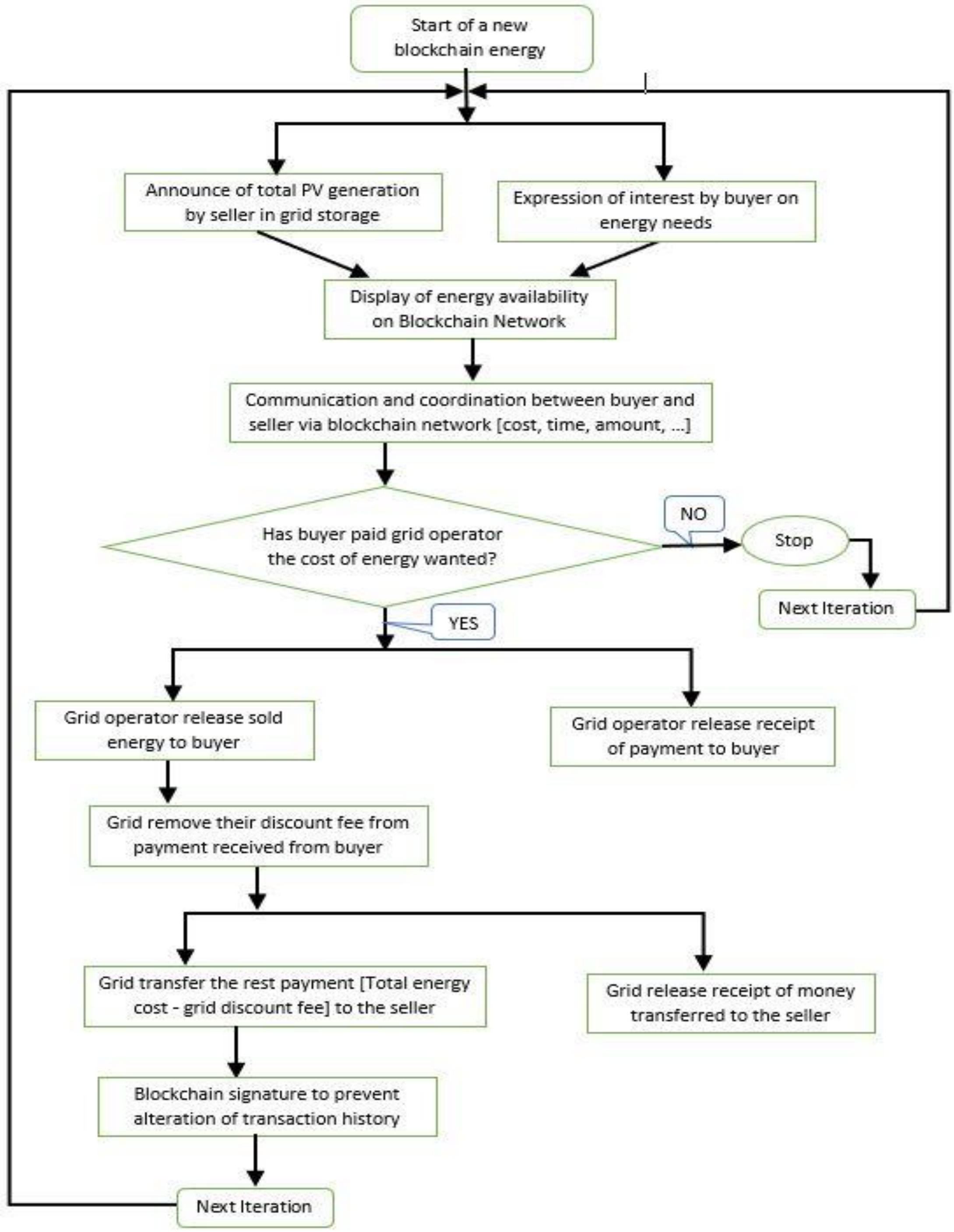


Figure 3.14: Blockchain energy-trading flowchart

Furthermore, the essence of adopting blockchain technology in this study is to ensure the energy-trading security of all nodes participating in the energy trading and marketing platform. The Python programming language was used to develop a simple blockchain energy-trading platform to secure all transaction histories against fraudulent activities that might likely occur. This helps to reduce stealing and faking of energy trading transactions between buyers and seller in the trading platform.

3.5.4 ELECTRICITY FINANCIAL PLAN

Different energy financial plans were tested using the blockchain energy-trading platform programmed in this study to observe the different trading environment that will most likely take place in the real world of an energy-trading platform. The energy financial plans addressed in this study consisted of the grid operator (i.e. utility) acting as a middleman between buyers and sellers to trigger the battery storage system to flow into a consumer's line when the central storage system was located at the grid's location.

3.5.4.1 GRID OPERATOR (UTILITY) ACTS AS AN INTERMEDIARY OR AGENT

A financial plan was simulated for situations when producer A_1 decides to sell energy via the blockchain energy-trading platform to producer A_2 as presented in Figure 3.15.

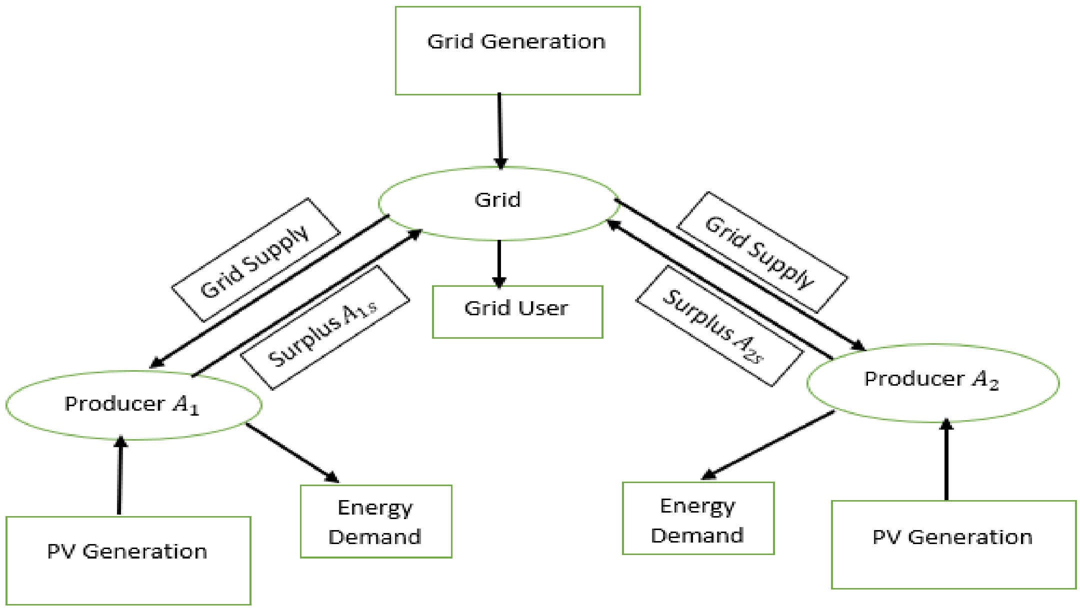


Figure 3.15: Grid operator (utility) acts as an intermediary or agent

When A_1 produces more energy A_{1s} than the load's energy consumption needed, and A_2 cannot produce enough energy to meet the load's energy demand, the grid operator in this study was programmed to act as the middleman to trigger the storage system following the communication channel in Figure 3.14.

When producer A_2 communicates with producer A_1 via the blockchain network, a desire to buy energy from the excess energy that producer A_1 has in surplus (i.e. energy generation minus load energy consumption (i.e., A_{1s})), the grid operator then releases the purchased units of energy to the A_2 distribution line (see the blockchain flow charts in Figure 3.14). However, because the common Energy Storage System (ESS) employed in this thesis is located at the grid's location, the grid operators take a percentage of the transaction as commission fee. This percentage of electricity is charged from the seller for storing producer A_1 excess energy (A_{1s}) at the grid's storage system. Thereafter, the rest of the payment is then released to producer A_1 after deducting this storage fee from the payment made by producer A_2 for buying energy from producer's A_1.

3.5.4.2 GRID SERVING AS A STORAGE SYSTEM FOR ENERGY

Another financial plan was simulated for environments where producers A_1 and A_2 do not incorporate the Battery Energy Storage Systems (BESS) to their PV systems as presented in Figure 3.16.

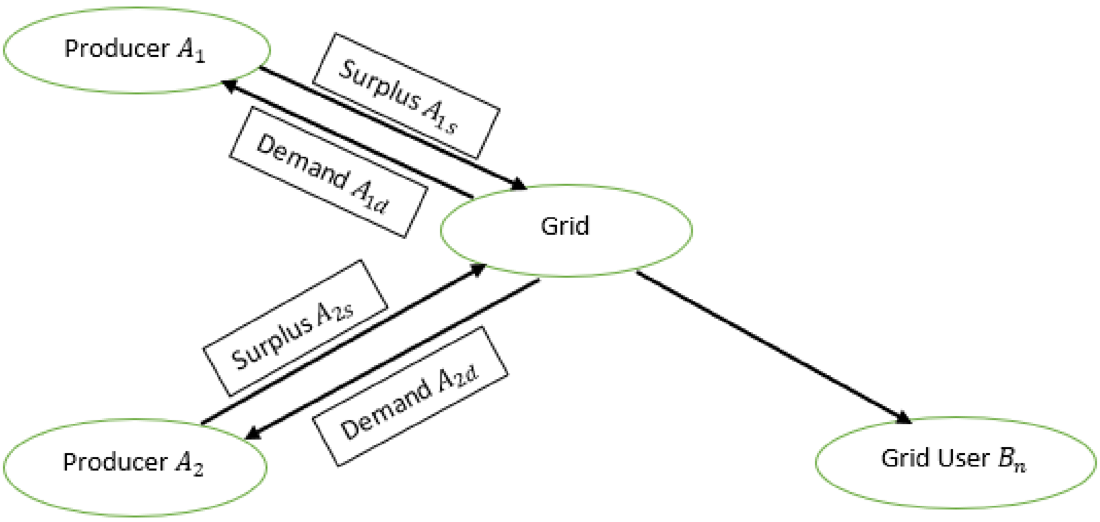


Figure 3.16: Grid serving as a storage system for energy

As these photovoltaic renewable generators generate energy from their PV generating system, they can directly supply energy to their load demands and at the same time feed their surplus energy (A_{1s} and A_{2s}) simultaneously into the grid energy storage system. However, when producer such as A_1 requires a certain amount of energy to meet the load demand, producer A_1 will be able to check if the excess energy A_{1s} stored in the storage system is enough to meet their new load demands. If yes, then producer A_1 will only be charged a storage fee for the electricity that producer A_1 demanded back from the storage system as expressed in equation 3.6.

$$\$A_{1d}\% = A_{1s} - A_{1d} \quad \textit{equation 3.6}$$

Where A_{1d} is the energy demanded back from the grid after initially sending energy to the grid, $\$A_{1d}$ is the price of energy demanded back from the grid, and $\$A_{1d}\%$ is the percentage of the electricity demanded back from the grid.

From Figure 3.16, the grid users B_n represented in this thesis are energy users with no solar photovoltaic (PV) Distributed Generation (DG) system installed. They are implemented in this study to depend on energy generated from PV DG producers in the neighbourhood or energy generated from the grid. They are categorised under the classes of consumers that are large industrial, commercial, or residential energy users that refuse to adopt the idea of PV generation in their neighbourhood.

Therefore, another scenario was designed such that if producer A_1 feeds $30kWh$ of the surplus electricity generated from the solar photovoltaic (PV) Distributed Generation (DG) system into the grid and later (e.g. during night-time) demanded $10kWh$ from the grid, then producer A_1 pays a percentage (e.g. 10%) of the electricity price to the grid operators as a storage fee for the $10kWh$ that producer A_1 demanded back from the grid. With this concept, producer A_1 is bound to receive payment for the $20kWh$ (i.e. $30kWh - 10kWh = 20kWh$ left from the $30kWh$ energy that producer A_1 initially transmitted to the grid) if the final user of the $20kWh$ left was either grid user B_n or any other PV DG producer A_n such as producer A_2 who might be unable to generate enough energy to meet the load's energy demands.

3.5.5 BLOCKCHAIN ENERGY TRADING PLATFORM

After conceptualizing how the blockchain energy trading security will operate in this study, the real energy-trading platform was programmed using the Python programming language on the Jupyter Notebook obtained from the Anaconda navigator environment.

A new block named Block #1 was added to the chain of energy trading transaction history already in the network in ***Appendix (D.4)*** to get the total amount of surplus energy of each producer available in the central storage system at different time of the day. This ensured each decentralised solar photovoltaic (PV) distributed generators was aware of the excess energy stored in the battery via the smart meter designed in the Matlab/Simulink model. This code was programmed to obtain results between the range of 1 to 6 with an energy rise level interval of 2 before finally hashing it for transaction security. These time stamp numbers stand for the different hours of the day.

Another block, named Block #2, was created with the same process for producer A2 with a range of 1 to 20 at an energy rise level of 6 and hashed. However, instead of i=1, in this case, i=2 (i.e. Block 2). Block #3 was created with its own hash key that carries the same process for producer A3, but with a range of 1 to 50 at an energy rise level of 12. Likewise, i=2 (i.e. Block 2). These range numbers represent the hours where 1 is the first hour of the day (12am), 6 for 6am, and so on.

Afterwards, the next code in ***Appendix (D.5)*** was generated to determine the total amount of energy in the centralised battery storage system of Block #4. Remember that this centralised battery storage was sited at the grid's location for all solar PV generators to store their surplus energy. Therefore, it is essential for grid operators to be aware of the level of energy stored in battery storage systems, especially in the event of maintenance or data analysis.

Next, a new block named Block #5 was created to accommodate the next code generated in ***Appendix (D.6)***. This code was designed for situations where energy producers can demand back some portion of their stored energy from the grid operator who manages the centralized battery operations. This might occur during the night-time, or days of rainy season on the basis that the energy producer has sent their surplus energy to the battery for storage. Thereafter, this producer could notify the trading platform about how much energy remained in the battery and could be sold to other energy consumers before the blockchain system hashes this block.

Consequently, a new block named Block #6 was created in ***Appendix (D.7)*** to demonstrate energy trading between the solar PV energy distributed generator and the grid operator before the blockchain system hashes this block. Here, energy trading transactions were carried out at a wholesale price and a storage fee was charged because it was assumed that the generator will have stored all surplus energy before deciding to sell to the grid operator.

Following this, a new block named Block #7 was created in ***Appendix (D.8)*** to demonstrate the energy trading between a solar PV energy distributed generator and the other grid users who are not solar photovoltaic distributed generators of energy. Here, energy trading transactions were carried out at a retail price and a storage fee was charged because it was assumed that the generator would have already stored their surplus energy before deciding to sell to the grid operator. Also, because grid operators serve as intermediaries to coordinate the battery operation, a grid commission fee is involved in this algorithm as seen ***Appendix (D.8)***. This block was then hashed in the blockchain algorithm to secure the transaction history.

Additionally, a new block named Block #8 was created in ***Appendix (D.9)*** to demonstrate the energy trading between two solar PV energy distributed generators. In this algorithm, one generator generates more than the needed energy for load consumption, while the other party had deficiency in generation outputs to meet the load demand for energy. Hence, energy trading transactions were carried out at a wholesale price and a storage fee was charged to the seller because it was assumed that they had stored their surplus energy before deciding to sell to the purchaser. Because the grid operators serve as intermediaries to coordinate the battery operation, a grid commission fee is paid to them by the seller in this algorithm as seen in ***Appendix (D.9)***. After the transaction has been completed, this block is hashed and cannot be tampered with afterwards. Finally, as a way of ending the blockchain energy-trading Python algorithm in this study, a new block named Block #9 was created as conclusion and then hashed (see ***Appendix (D.10)***).

3.6 FINANCIAL ANALYSIS ESTABLISHMENT

With the aid of RETScreen Expert software, a financial plan was created to understand the risk sensitivity and return benefits for the investment decision-making process to justify the development of this project in Nigeria. This RETScreen Expert software, a clean energy management software, was used to carry out energy efficiency, and performance analyses, and scope the feasibility of implementing solar photovoltaic renewable energy in Nigeria. Results from these analyses were then used to identify, assess, and optimise the technical and financial viability of the Nigerian government, private sectors, and general population adopting renewable energy projects to generate and trade renewable energy through blockchain energy-trading platforms.

An analysis of risk sensitivity was carried out to assess the impact of generating solar photovoltaic energy to improve greenhouse gas (GHG) efficiency and reduce carbon dioxide emissions into the Nigerian atmosphere. Risk analysis was also used to explore the probability of successes or failures for stakeholder. The economic state of this project was based on equity payback and 500 forecasting combinations [114]. Lastly, the performance of the simulated analysis was used to measure and verify the energy savings and monetary benefits that this project presents to stakeholders.

3.7 SUMMARY

This chapter has described the methods employed for this study to arrive at a suitable model that could accomplish research goal. The research methodology demonstrated the use of quantitative methods to gather and use relevant data to model a power system simulation environment and outline a proposed blockchain energy-trading platform for the Nigerian energy industry. Finally, this chapter has included methods used to ascertain the financial viability of this project.

CHAPTER 4: SIMULATION RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter is structured into eight parts to present the numerical results and discussions from the simulations presented in Chapter Three. Section 4.2 presents the results of the solar photovoltaic generation outputs, and Section 4.3 presents the results of the first decentralised solar PV distributed generation operation condition simulated when the DGs were oversized. Subsequently, Section 4.4 provides the results of the second decentralised solar PV distributed generation operation condition simulated when the DGs were undersized. In addition, Section 4.5 provides the results of the third decentralised solar PV distributed generation operation condition simulated when the DGs were properly sized, and Section 4.6 – 4.9 gives a detailed discussion of all Matlab simulation results tested in this study. Section 4.10 provides the details of blockchain energy-trading and electricity pricing explored in this study, and Section 4.11 summarises the discussion of the energy trading. Section 4.12 gives the results of the sensitivity analysis carried out in this study, and Section 4.13 gives summarises everything discussed in this chapter.

4.2 SOLAR PHOTOVOLTAIC DISTRIBUTED GENERATION SYSTEMS

After designing the main system of this study in the MATLAB/Simulink environment seen in ***Appendix (B)***, a variety of decentralised grid-connected solar photovoltaic distribution generation operating environments were studied. Table 4.1 indicates that using equation 3.1, equation 3.2 and equation 3.3, a series connection of 7 and parallel strings of 20, 39, and 55 for PV one, two, and three enabled sizing different scenarios for the PV systems simulated throughout the course of this study. With these integrated parameters, a maximum PV array installed watts (DC) outputs of approximately 58.1kW, $113.3kW$, and $160kW$ was generated for local areas one, two and three at a cell temperature of 25℃. In addition, a maximum PV array output of approximately 55kW, $110kW$, and $150kW$ was generated for PV one, two, and three at 45℃ cell temperature.

Table 4.1: PV generation calculations for scenario one

	Local Area 1 PV Panel	**Local Area 2 PV Panel**	**Local Area 3 PV Panel**
PV System Design AC Capacity (kW)	44	88	125
Derating Factor	0.795	0.795	0.795
PV Array Installed kW (DC)	55.4	110.7	157.3
CEC Ratings (W) i.e. $\{P_{max}\}$ (W)	415	415	415
Number of Modules	134	267	380
Series Connected Module per String	7	7	7
Parallel Connected Module per String	20	39	55
PV Array Installed Watts (DC) $\{P_{output\_max}\}$ (W)	58,100	113,295	159,775

4.2.1 INTEGRATED SOLAR IRRADIANCE

From ***Appendix (C.5)***, and the NASA database using RETScreen software, the average monthly solar radiation data for a whole year was inputted into the solar irradiance of this scenario as shown in Table 4.2.

This average annual data was then connected as input to the rate limiter, which goes into the PV arrays for the PV generation. [5.17, 5.28, 5.49, 5.46, 5.21, 4.76, 4.04, 3.95, 3.98, 4.09, 4.55, 4.95, 5.17] × 100. A solar irradiance of [1000, 200, 400, 600, 800, 1000] W/m^2 amplitude and a stair generator sampling time of 5.051µs was also integrated into the PVs in the three different locations.

Table 4.2: Analysis of monthly average radiation data

S/N	Monthly Average	Radiation Data (Wh/m²/d)
1	January	5.17
2	February	5.49
3	March	5.46
4	April	5.21
5	May	4.76
6	June	4.04
7	July	3.95
8	August	3.98
9	September	4.09
10	October	4.55
11	November	4.95
12	December	5.17
Sum		56.82
Average Annual		4.74

4.2.2 POWER SYSTEMS GENERATION OUTPUTS

Figure 4.1 demonstrates the results of the direct current generated from solar PV one, two and three after simulating Nigeria's real-time annual solar irradiance for 12.5seconds.

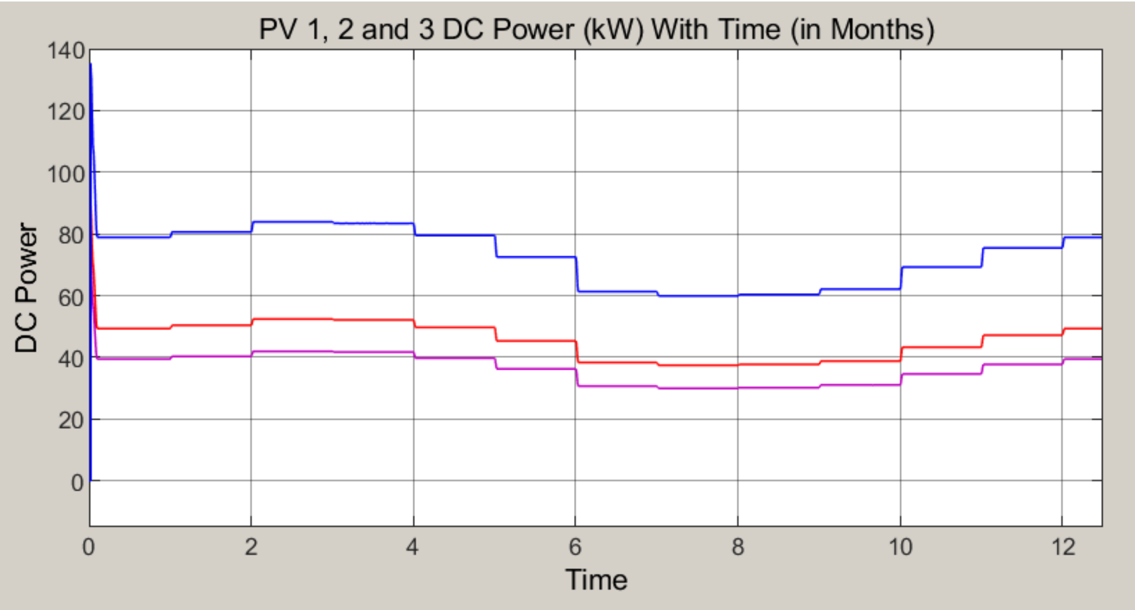


Figure 4.1: PV1, PV2, and PV3 direct current power generation output

From Figure 4.1, the PV/Pdc mean (kW) – purple line, indicated that the photovoltaic direct current generation output from PV1 generated a maximum and minimum output of $42kW$ and $30kW$. The photovoltaic direct current generation output from PV2, represented as PV4/Pdc mean (kW) – red line, generated a maximum and minimum output of $52.4kW$ and $37.4kW$. Likewise, the photovoltaic direct current generation output from PV3, represented as PV5/Pdc mean (kW) – blue line, generated a maximum and minimum output of $83.9kW$ and $59.9kW$.

Figure 4.2 demonstrates the results of the alternate current generated from solar PV one, two and three after simulating Nigeria's real-time annual solar irradiance for 12.5seconds.

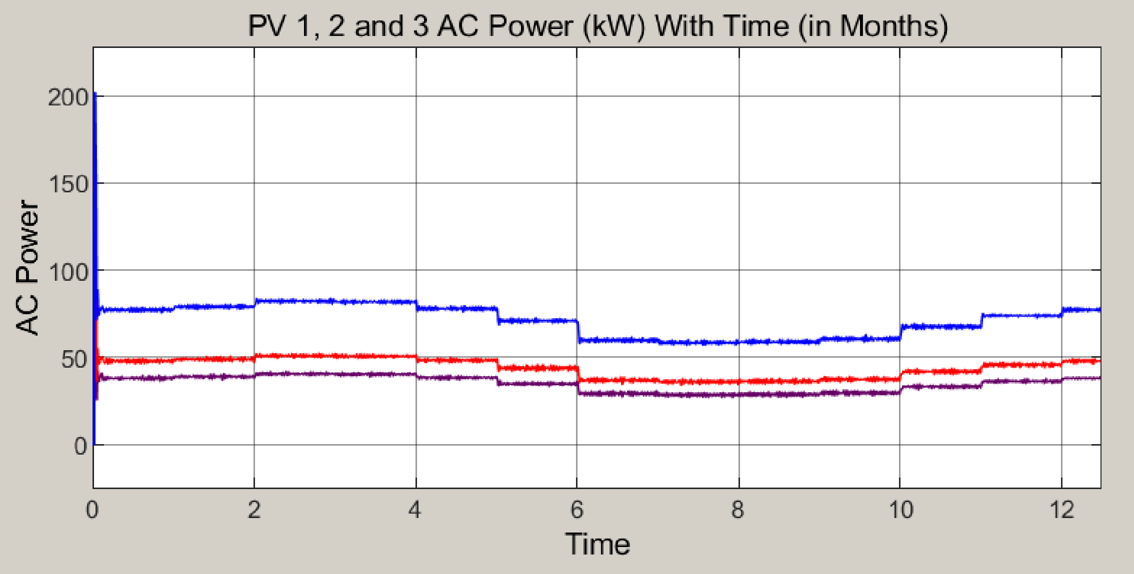


Figure 4.2: PV1, PV2, and PV3 alternating current power generation output

From Figure 4.2, the PV/1 – purple line, indicated that the photovoltaic alternating current generation output from PV1 generated a maximum and minimum output of $41kW$ and $29kW$. The photovoltaic alternating current generation output from PV2, represented as PV4/Pac mean (kW) – red line, generated a maximum and minimum output of $51kW$ and $36kW$. Likewise, the photovoltaic alternating current generation output from PV3, represented as PV5/1 – blue line, generated a maximum and minimum output of $82.5kW$ and $59kW$.

A breakdown analysis of the energy generation output from the decentralised solar PV distributed generators PV1, PV2 and PV3 installed in location one, two and three is given in Table 4.3.

Table 4.3: PV1, PV2, and PV3 location energy generation statistics

PV1 Statistics	$P_{dc\_}PV1$ **mean (kW)**	$P_{ac\_}B1$ **(kW)**	$P_{dc\_}PV2$ **mean (kW)**	$P_{ac\_}B2$ **(kW)**	$P_{dc\_}PV3$ **mean (kW)**	$P_{ac\_}B3$ **(kW)**
Maximum	71.94	111.80	89.51	136.00	134.70	202.80
Minimum	0.00	0.00	0.00	0.00	0.00	0.00
Peak to Peak	71.94	111.80	89.51	136.00	134.70	202.80
Mean	36.30	34.93	45.37	43.97	72.57	71.04
Median	37.74	35.96	47.17	45.26	75.48	73.32
RMS	36.63	35.33	45.78	44.46	73.22	71.79

From Figure 4.1, Figure 4.2 and Table 4.3, it can be seen that the generation output from each solar PV system for each month varied, based on different levels of solar irradiance. At the beginning of the year, generation was high because of high solar irradiance during the sunny season. However, between June and September, the generation output dropped because there was less sun during the rainy season. After September, when solar irradiation increased, the generation output began to increase. The average time difference for stability between the different levels of solar irradiance was estimated at 0.075seconds, after taking the average of the different switching time intervals. This was insignificant compared to the rest of the system outcome.

4.3 SCENARIO ONE: OVERSIZED SOLAR PV DISTRIBUTED GENERATION SIMULATION

The first simulation environment was tested to see the behaviour of the Nigerian energy system when various decentralised solar photovoltaic distributed generation systems were oversized beyond the required load consumption rate. From Figure 4.1 and Figure 4.2, it was observed that at the time of 0.6seconds (s), irradiance dropped due to reduced solar irradiance during the rainy season between June and September and the PV total generation dropped to around $30kW$, $37.45kW$, and $60kW$. However, because the system was oversized, these reductions in PV generation outputs had no effect on the constant supply of power to the loads connected to these PV distributed generation systems across all three local areas that had solar PV installation.

4.3.1 INSTALLED LOAD CONSUMPTION

A group of household energy consumption demands were bracketed according to each local area for each decentralised solar PV distributed generation network installation. In scenario one of this study, 15kW, 20kW, and 35kW capacities were installed in local area one, two and three (see Figure 4.3). In addition, throughout the simulation, the reactive power of the three loads remained at zero as designed in this study.

Figure 4.3: Energy consumption of load 1, 2 and 3 installed in the three local areas

Findings showed that because the solar PV systems were oversized, constant power was supplied to the loads across all three local areas. The solar PV generation plants could to generate enough to meet the necessary load demands and still store surplus energy in the battery storage system. This implied that in these situations, there would be no need for the grid to supply power to the loads with decentralised PV systems installed. Rather, the grid would only focus on other load users like industrial and commercial facilities without PV installation. It is, therefore, likely that the activities of the energy trading platform would be less active if all local areas could generate more than the required energy consumption level throughout the entire year. This could be good for the grid as the grid could buy more energy from decentralised generators to supply energy consumers without generation plants.

Further assessment of the results in Figure 4.3 indicated that instead of the loads consuming the exact amount of energy they were designed to consume, they consumed slightly above or below their rated power usage for several reasons. A possible explanation for this could be the internal heat gain due to transmitted solar heat on the solar PV collector instead of using the solar irradiance to generate power. An alternative explanation could be due to shading effects, computer internal electronics factors, humidity, discomfort hours, the thermal comfort ability of the control strategies environment, lighting, inhabitancy, or even distribution loss factors [105]. The factors may explain why the loads consumed slightly above their designed energy consumption, amounting to approximately a 0.81 distribution loss factor when a 0.795 derate factor was used for the seasonal Coefficient of Performance (COP).

4.3.2 BATTERY ENERGY STORAGE SYSTEM (BESS) BEHAVIOUR

Analysing the results from the battery throughout the entire simulation indicates the battery was charged throughout the year (see Figure 4.4 and Table 4.4) as the battery curve indicated real power was entirely below zero.

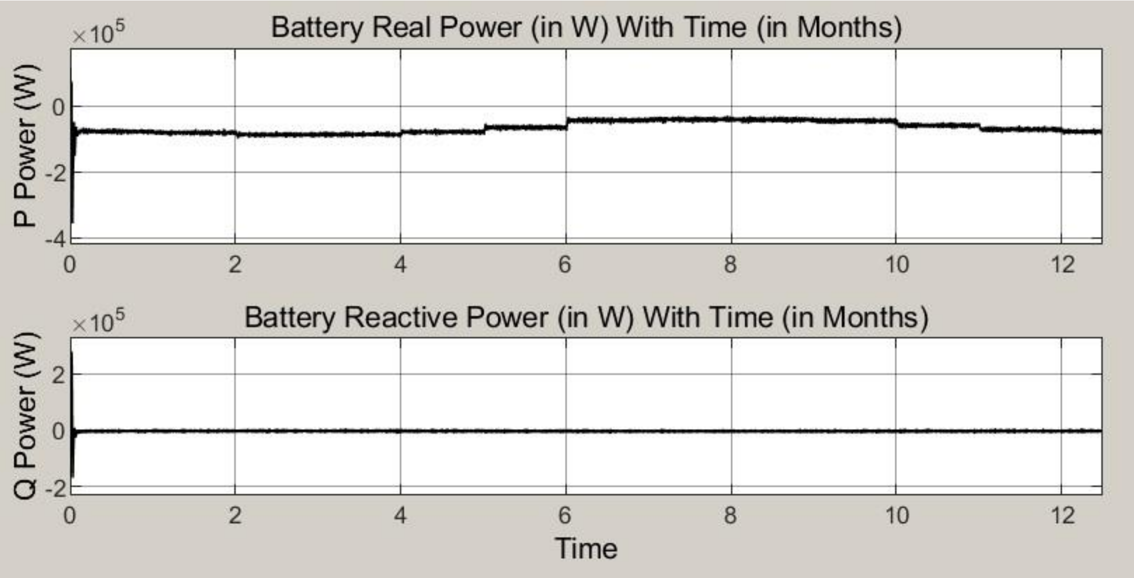


Figure 4.4: Battery operations at upper and lower limits saturation of 300000 and -300000 respectively

Table 4.4: Battery energy supply to loads with limited solar PV generation outputs

Signal Statistics	Battery Energy Distribution to loads (W)
Maximum	1.155×10^5
Minimum	-3.608×10^5
Peak to Peak	4.764×10^5
Mean	-6.529×10^4
Median	-6.913×10^4
RMS	-6.812×10^4

From Table 4.4, the maximum and minimum energy signal statistics of 115.5kW and 360.8kW from the battery distributed to the deficiency load areas occurred because of the initial spike (i.e. state) before the battery achieved equilibrium stability. This could also be consequence of noise, control ripples, and so on especially since control systems were designed for battery operations.

The results showed that there was no need for the grid to supply energy to the three local areas with PV system installations throughout the entire simulation because the PV generation outputs were more than enough to meet load demands. This confirmed the value of sending surplus energy from the PV systems to the Battery Energy Storage System (BESS), where the PV generators could decide to either trade that energy on the blockchain energy-trading platform or use the stored energy later. It is possible to hypothesise a need to enlarge the storage facilities to accommodate more energy from various decentralised solar photovoltaic generation systems. However, if these findings were the case for all local areas throughout the year, it could be difficult to expand the available size of the battery facilities without proper incentives from the Nigerian government. Proper incentives and regulated policies from the Nigerian government could help facilitate storage enlargement and energy sales to Nigeria's neighbouring countries.

4.3.3 EFFECTS OF MULTIPLE STREAM OF SOLAR PV INFLUX INTO THE NIGERIAN NATIONAL GRID

One source of uncertainty is the amount of stress that could be imposed on the transmission lines. The distribution lines in Nigeria were designed to distribute power in a one-way direction from the grid down to the loads. Therefore, it would be necessary to redesign the Nigerian transmission and distribution lines to operate in a bidirectional way that allows the in-flow and out-flow of power from the grids and the decentralised solar PV distributed generation systems across Nigeria. Further interpretation of the findings in Figure 4.1, Figure 4.2 and Figure 4.4 suggest that because more stress could be imposed on the lines. It is recommended to consider stress factors and risk management planning while redesigning the transmission and distribution lines to ensure the successful implementation of this scenario in Nigeria.

4.3.4 GRID SUPPLY BEHAVIOUR

Results from Figure 4.5 showed that power generation from the grid could supply approximately $30MW$ units of energy to the $30MW$ grid load designed during the focus of this study (see Figure 4.6).

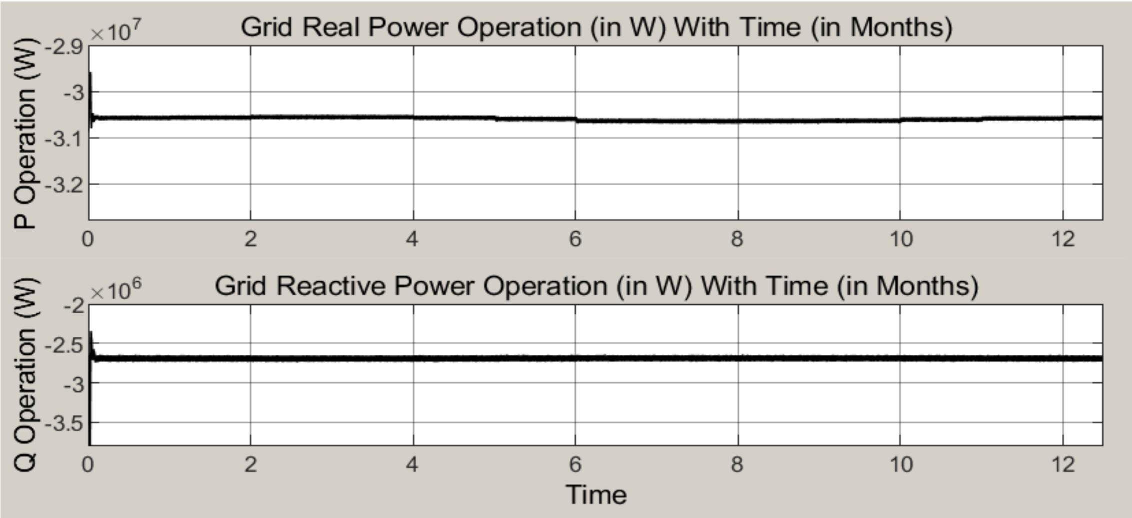


Figure 4.5: Analysis of the national grid operation

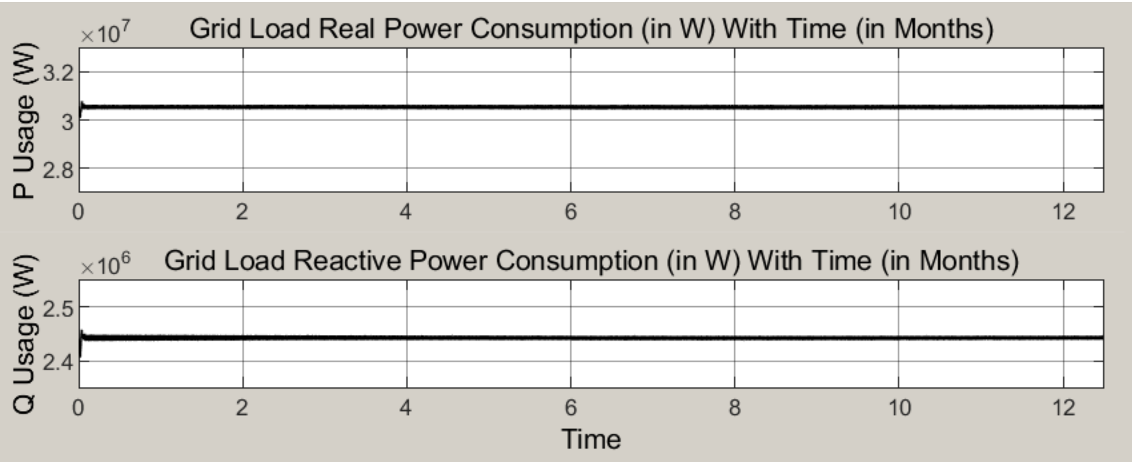


Figure 4.6: Analysis of the 30MW grid load energy consumption

The relationship between the grid generation and the grid load showed that because the $30MW$ grid load was without a PV installation network in that environment it directly consumed energy exclusively from the grid. This explained why the energy consumption rate fed to the grid load matched the exact amount of energy generated from the grid throughout the duration of simulation.

These findings in Figure 4.5 and Figure 4.6 could have important implications for a significant reduction in grid stress levels. Since the grid can focus solely on grid loads without installed solar PV generation plants, pressure on the grid could be reduced to make it more reliable for large industrial or commercial companies who consume energy from the grid. With a reduced stress level, the grid can fully function to its maximum capacity and meet load demands from specific geographical areas during unforeseen circumstances such as blackouts that could hinder certain local areas from generating solar photovoltaic energy from their installed PV systems. Thus, there would be more availability and reliability when transmitting energy from the grid to the general population.

4.4 SCENARIO TWO: UNDERSIZED SOLAR PV DISTRIBUTED GENERATION SIMULATION

The second simulation environment was tested to see the behaviour of the Nigerian energy system when various decentralised solar photovoltaic distributed generation systems were undersized below the required load consumption rate. From Figure 4.1 and Figure 4.2, it was observed that at the time of 0.6seconds (s) when the irradiance dropped due to the rainy season between June and September, the PV total generation dropped to around $30kW$, $37.45kW$, and $60kW$. With these observed reductions, the various undersized decentralised solar photovoltaic generation systems could not supply the necessary power for all load consumption. This explains the correlation between active operations of the battery and the grid supply to maintain a constant power supply to load demands across all three local areas with and without solar PV installation.

4.4.1 INSTALLED LOAD CONSUMPTION

A group of household energy consumption demands were bracketed according to each local area for each decentralised solar PV distributed generation network installation. In scenario two of this study, 43kW, 87kW, and 120kW load capacities were installed in local area one, two and three as seen in Figure 4.7. In addition, throughout the simulation, the reactive power of the three loads remained at zero as was designed in this study.

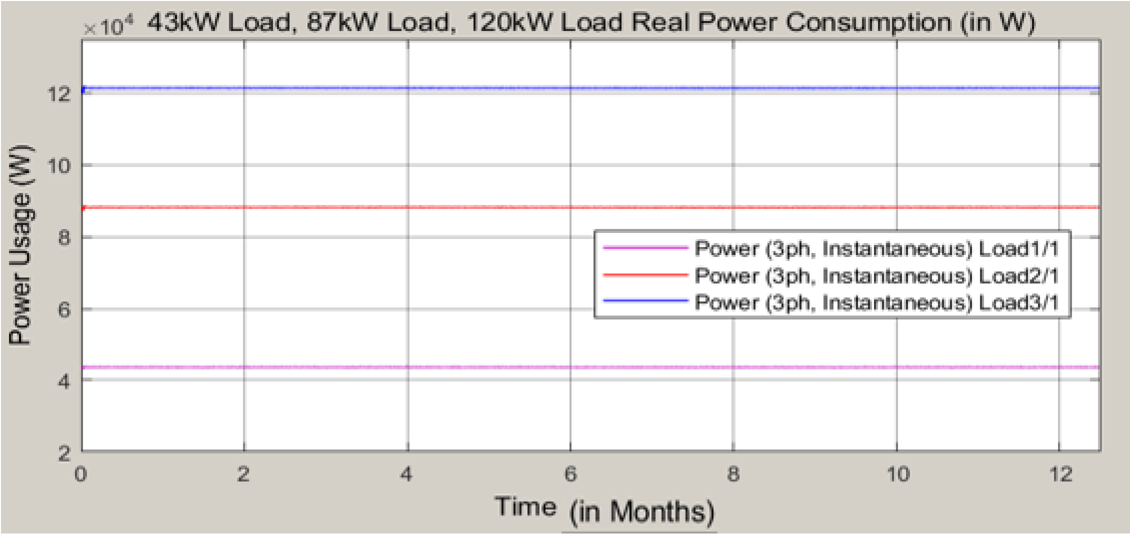


Figure 4.7: Energy consumption of load 1, 2 and 3 installed in the three local areas

Findings showed that the various solar PV generation plants could not generate enough to meet the necessary load demands and therefore had no surplus energy stored in the battery storage system. Despite the undersized solar PV systems, constant power was supplied to the loads across all three local areas and this was always maintained throughout the year because of the involvement of the battery in supplementing the solar PV generation output to meet the loads energy consumption.

4.4.2 BATTERY ENERGY STORAGE SYSTEM (BESS) BEHAVIOUR

Analysing results from the battery throughout the entire simulation, the battery was discharged throughout the year as seen in Figure 4.8 where the battery curve was entirely above zero. Table 4.5 shows the statistical analysis of the battery curve in Figure 4.8.

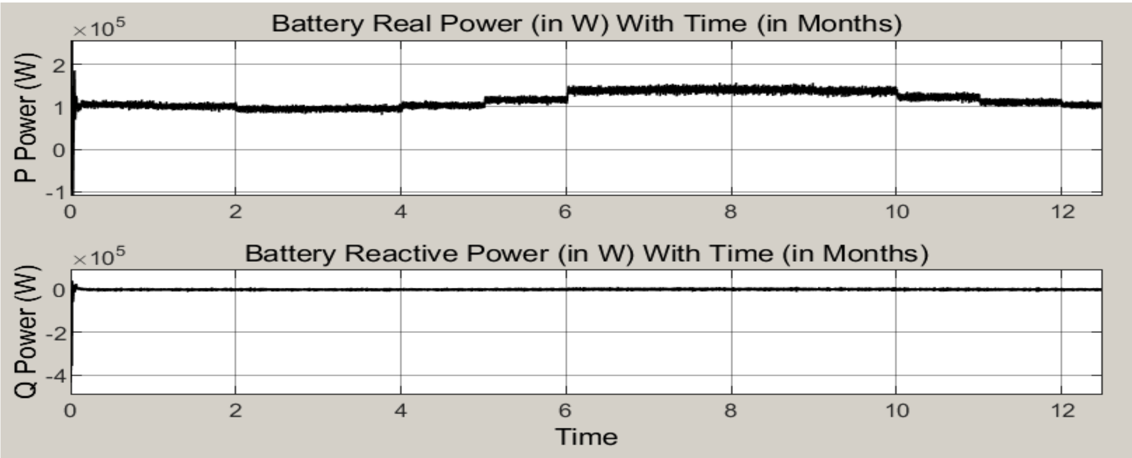


Figure 4.8: Battery operation at saturation's upper and lower limits of 300000 and -300000 respectively

Comparison between the results from the solar PV generation outputs in Figure 4.1 and the battery operations in Figure 4.8 suggest that throughout this simulation, the battery was actively involved in maintaining constant energy availability and reliability to the loads. Findings indicated that all the three decentralised PV systems designed in this study were able to generate a total output of $149.1kW$ in December to meet load demands. Therefore, the battery could supply approximately $104.3kW$ of energy to the loads in all three local areas with solar PV installation during this period.

Table 4.5: Battery energy supply to loads with limited solar PV generation outputs

Signal Statistics	**Battery Energy Distribution to loads (W)**
Maximum	3.113×10^5
Minimum	-1.273×10^5
Peak to Peak	4.386×10^5
Mean	1.163×10^5
Median	1.123×10^5
RMS	1.179×10^5

As seen in Table 4.5, the maximum and minimum energy signal statistics of 311.3kW and −127.3kW from the battery distributed to the deficiency load areas were because of the initial spike (i.e. state) before achieving the equilibrium stability of the battery. However, after stability, the maximum and minimum energy supplied from the battery was 145kW during the rainy season and 0.95kW during the sunny season.

From this simulation result, a possible explanation for the constant battery supply to the loads could be the positive impact of the generation from the grid itself to maintain energy reliability and availability to the general population. Because the central storage system integrated into the design of this study was placed at the grid locations, it seemed possible that the grid shared the same battery storage system with various decentralised solar photovoltaic distributed generators. This observed correlation of shared storage space between the grid and photovoltaic generators led to the explanation that the grid was able to store its own energy in the shared battery storage system. Therefore, despite the shortage of energy generated from solar PV systems, the battery could compensate for the remaining amount of energy to ensure a constant supply of power to the loads.

4.4.3 EFFECTS OF UNDERSIZED SOLAR PV SYSTEMS ON ENERGY TRADING ACTIVITIES

Results from the undersized solar PV generation outputs in Figure 4.1 and the battery activities in Figure 4.8 indicate that the activities of the energy trading platform would be more active in an undersized solar PV installed network when compared with an oversized solar PV installed network scenario. Findings from the undersized solar PV generation capacity and the active involvement of the battery in supplying power generated by the grid or other solar PV generators to the loads suggest constant transactional activities would be actively carried out in the blockchain energy trading platform. This was because all local area solar PV installations couldn't generate enough energy to meet the required energy consumption level throughout the entire year and had to rely on stored energy bought from the trading platform.

These findings raised an intriguing advantage for the grid and surrounding communities with enough PV generation outputs stored in the central battery storage system. More profits from sales would encourage them to generate more energy throughout the year. With this, energy consumers with limited solar PV generation on the blockchain energy-trading platform could buy more energy from either the surrounding decentralised PV generators or the grid.

4.4.4 GRID SUPPLY BEHAVIOUR

Results from Figure 4.9 showed that the power generation from the grid could supply both the $30MW$ grid load and the amount of energy needed to supplement the various decentralised solar PV distributed generation outputs.

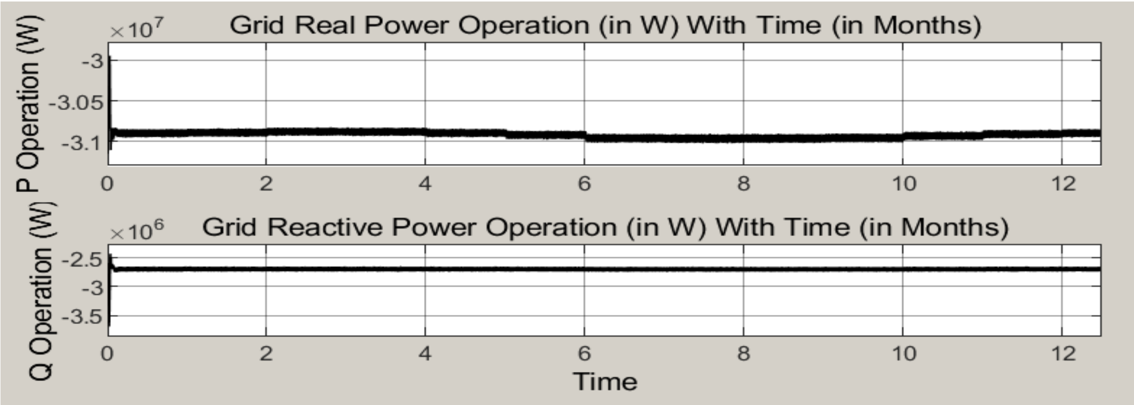


Figure 4.9: Analysis of the national grid operation

The relationship between grid generation and grid load seen in Figure 4.10 showed that because the $30MW$ grid load was without a PV installation network in that environment, the grid load consumed energy exclusively from the grid.

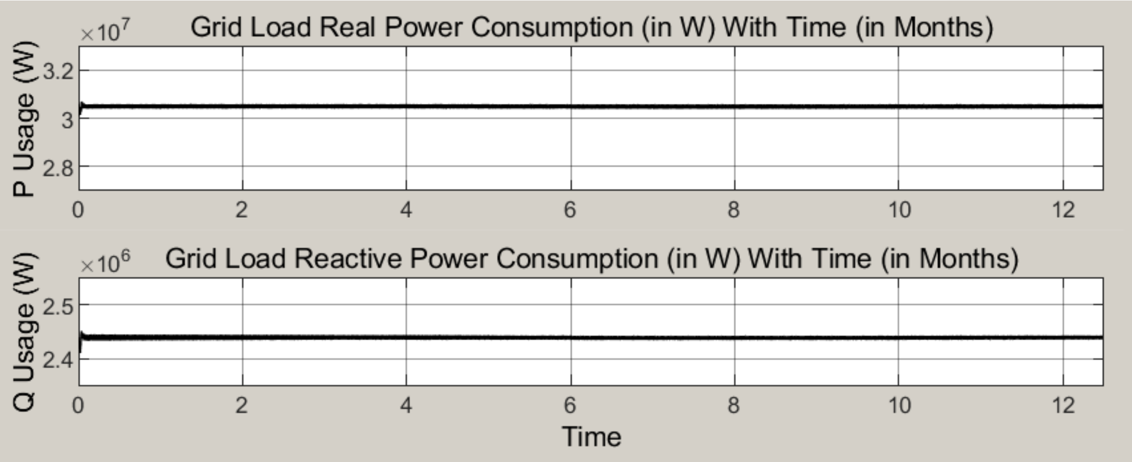


Figure 4.10: Analysis of the 30MW grid load energy consumption

Results from the grid generation in Figure 4.9 also indicated that the grid could store approximately $370kW$ of energy in the battery after supplying about $30.55MW$ of energy to the grid load without PV installation. The implications of the grid's activities suggest that stress on the grid was relatively high when compared with situations where the PV system could selflessly supply power to the loads. However, even though the grid was actively involved in supplying power to the loads, this stress was relatively low when compared with the status of the Nigerian energy system where the grid must entirely supply power to the loads without the assistance of any decentralised solar photovoltaic generation systems installed. It can be deduced that with solar PV functioning as the primary source of energy generation in Nigeria, grid generation outputs could supplement solar PV generation outputs which would lead to more energy availability and reliability from the grid to the masses.

4.5 SCENARIO THREE: PROPERLY SIZED SOLAR PV DISTRIBUTED GENERATION SIMULATION

A third simulation environment was tested to see the behaviour of the Nigerian energy system when the various decentralised solar photovoltaic distributed generation systems were correctly sized to me load energy consumption rate and had energy left over for storage. From Figure 4.1 and Figure 4.2, it was observed that at the time of 0.6seconds

(s) when the irradiance dropped due to reduced solar irradiance during the rainy season, the PV total generation dropped to around $30kW$, $37.45kW$, and $60kW$. However, even with these observed reductions, various decentralised solar photovoltaic generation systems could still supply the necessary power for all load consumption.

4.5.1 INSTALLED LOAD CONSUMPTION

A group of household energy consumption demands were bracketed according to each local area for each decentralised solar PV distributed generation network installation. In scenario three of this study, 25kW, 30kW, and 50kW load capacities were installed in local area one, two and three (see Figure 4.11). In addition, throughout the simulation, the reactive power of the three loads all remained at zero.

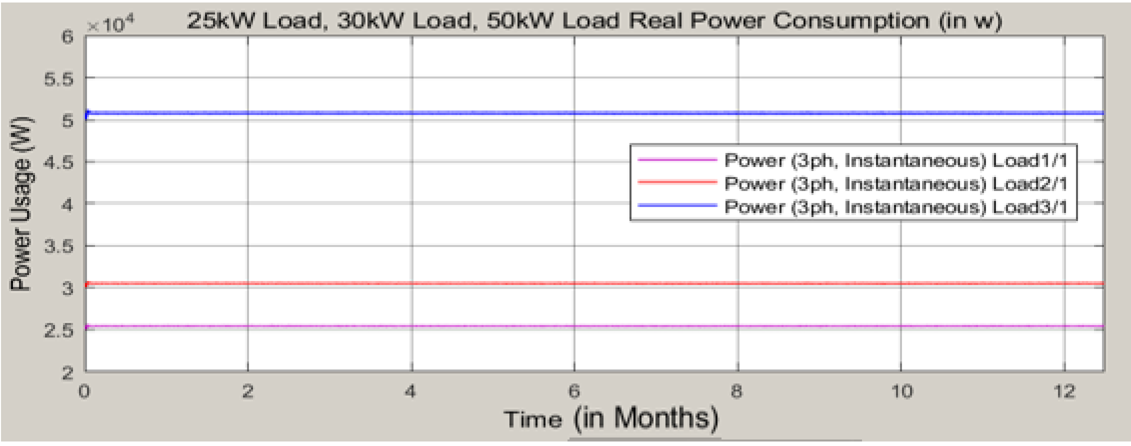


Figure 4.11: Energy consumption of load 1, 2 and 3 installed in the three local areas

Findings showed that the various solar PV generation plants could generate enough energy to meet the necessary load demands and could still store the surplus energy in the battery storage system. Regardless of the season, the PV generation systems were still able to selflessly supply power to the loads across all three PV installed local areas without the help of the grid. This was evident in Figure 4.11, which showed straight lines of power consumption by the loads indicating that there was a constant power supply from the independent solar PV systems to the loads in those locations with solar photovoltaic systems. Further assessment reviewed that the loads consumed slightly above or slightly below their rated power usage for several reasons that were expected because of computer internal electronics and internal heat gain associated with transmission.

These findings suggest that in similar operating environments there would be no need for the grid to supply power to the loads with decentralised PV systems installed. Therefore, the grid can focus solely on other energy consumers without PV generation plants like commercial and industrial facilities purchasing high energy than the smaller decentralised solar PV plants can sell. Furthermore, this observation has important implications for more energy availability and reliability from the grid to the masses in the event of unforeseen circumstances. As the grid does not focus on supplying to the whole nation, more priority would be given to affected locations with unforeseen issues like blackouts or faults in transmission cables.

4.5.2 BATTERY ENERGY STORAGE SYSTEM (BESS) BEHAVIOUR

Results from the battery in Figure 4.12 indicates that the battery was charged throughout the year, where the battery curve was entirely below zero.

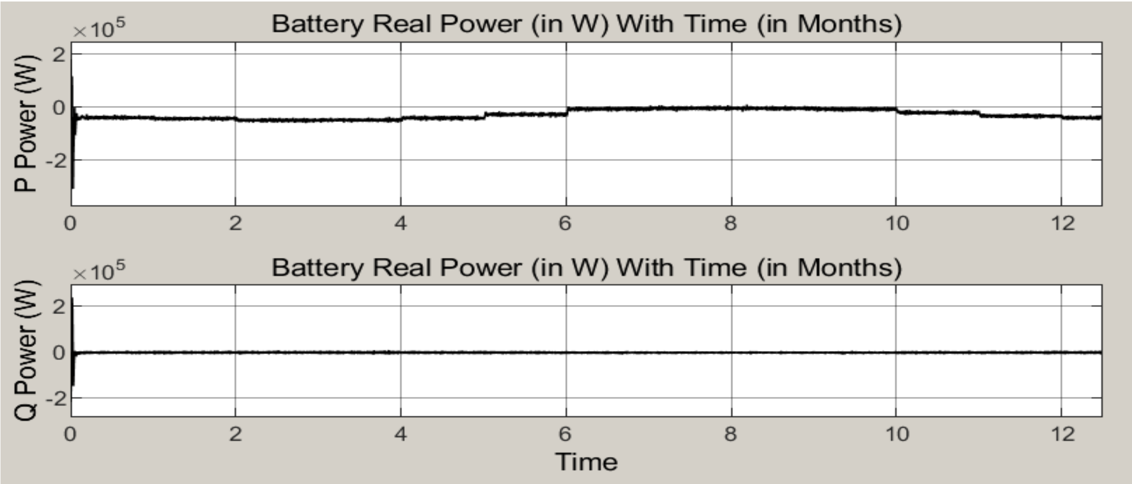


Figure 4.12: Battery operation at saturation's upper and lower limits of 300000 and -300000 respectively

Table 4.6: Battery energy supply to loads with limited solar PV generation outputs

Signal Statistics	Battery Energy Distribution to loads (W)
Maximum	1.826×10^5
Minimum	-3.145×10^5
Peak to Peak	4.970×10^5
Mean	-2.591×10^4
Median	-2.608×10^4
RMS	3.249×10^4

As seen in Table 4.6, the maximum and minimum energy signal statistics of 182.6kW and −314.5kW from the battery distributed to the deficiency load areas was as a result of the initial spike (i.e. state) before the battery achieved equilibrium stability. However, after stability, the maximum and minimum energy stored in the battery by the various solar PV systems was 55kW during the sunny season and 10kW during the rainy season.

The comparison between the results from the solar PV generation outputs in Figure 4.1 and the battery operations in Figure 4.12 suggest that throughout this simulation, the battery was actively charged alongside the PV system continuously maintaining constant energy availability and reliability to the PV connected loads. Findings indicated that from January, the battery curve suggested an active battery charging during the sunny season in Nigeria. However, during the rainy season, the battery was passively charged. This was because generation outputs dropped during the rainy season and were barely enough to meet the load energy consumption rate; therefore, little was available for storage. However, after September, the generation outputs from various decentralised solar PV generators increased, therefore more surplus energy was available to actively charge the battery until the end of the year.

Contrary to the findings in scenario one, where the system was oversized beyond what the load can consume, the findings from this third scenario proposes that there might be no need for expansion of the centralised battery. This is because since the decentralised solar PV distributed generation systems can selflessly supply power to the loads throughout the entire year, this would force the grid to reduce its generation capacity since the grid now acts as a support to solar PV systems. Subsequently, more space would become available for the decentralised solar generators to store their own energy at the centralised battery store in the grid’s location. However, to ensure proper maintenance of the battery storage system, it was proposed in this study that the grid administrators would charge the solar PV generators a storage fee to ensure the battery would be properly maintained. In addition, the Nigerian government could step in to provide more financial support for the annual Operation and Maintenance (O&M) of the storage systems.

4.5.3 EFFECTS OF SOLAR PV SYSTEMS ON THE ENERGY TRADING PLATFORM

The results from the solar PV generation outputs in Figure 4.1 and the battery activities in Figure 4.12 indicate that the activities of the energy trading platform would be more active during the rainy system than during the sunny season in Nigeria. Therefore, there would be more transactional activities carried out in the blockchain energy-trading platform between June and September because of the reduction in the generation outputs from the various decentralised solar photovoltaic distributed generation systems. It is also likely that the activities of the energy-trading platform would be less active if all local areas could generate more than the required energy consumption level throughout the entire year. This could be good for the grid it could buy more energy from the decentralised generators to supply to other energy consumers like large commercial and industrial facilities without generation plants.

Therefore, the findings in this scenario raises an intriguing advantage for the grid and surrounding communities with enough PV generation outputs stored in the central battery storage system, because more sales lead to more profits which would encourage solar energy generators to generate more throughout the year. With this, energy consumers with limited solar PV generations could buy more energy from either the surrounding decentralised PV generators or the grid.

A source of uncertainty is the possibility that solar PV generators might store their surplus energy in the battery during the sunny season while waiting for the rainy season when they can sell at a higher price because of the limited generation outputs. A note of caution is due in terms of Nigerian lawmakers needing to establish favourable energy policies. This study was designed to ensure more energy availability and reliability to the masses through affordable energy prices throughout the energy market. Without favourable policies established to ensure this, certain generators might take advantage of the energy market to demand an exorbitant amount for the purchase of energy on the blockchain energy-trading platform during the rainy season. Therefore, it was proposed in this study that the Nigerian lawmakers needs to establish policies and regulations that ensure a standard energy price rate on the blockchain energy trading platform for the entire year. Further studies on this topic of favourable renewable energy policies are recommended.

4.5.4 GRID SUPPLY BEHAVIOUR

Results from Figure 4.13 showed that the power generation from the grid could supply energy to the $30MW$ grid load.

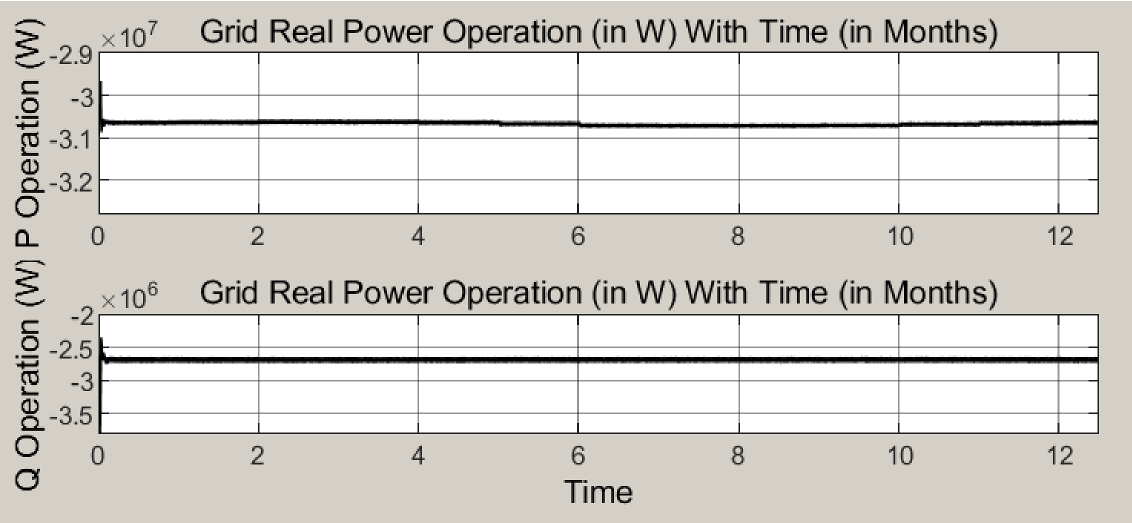


Figure 4.13: Analysis of the national grid operation

The relationship between the grid generation in Figure 4.13 and the grid load in Figure 4.14 showed that because the $30MW$ grid load was without a PV installation network in that environment, the grid load directly consumed energy exclusively from the grid. This explained why the energy consumption rate fed to the grid load matched the exact amount of energy generated from the grid throughout the simulation duration.

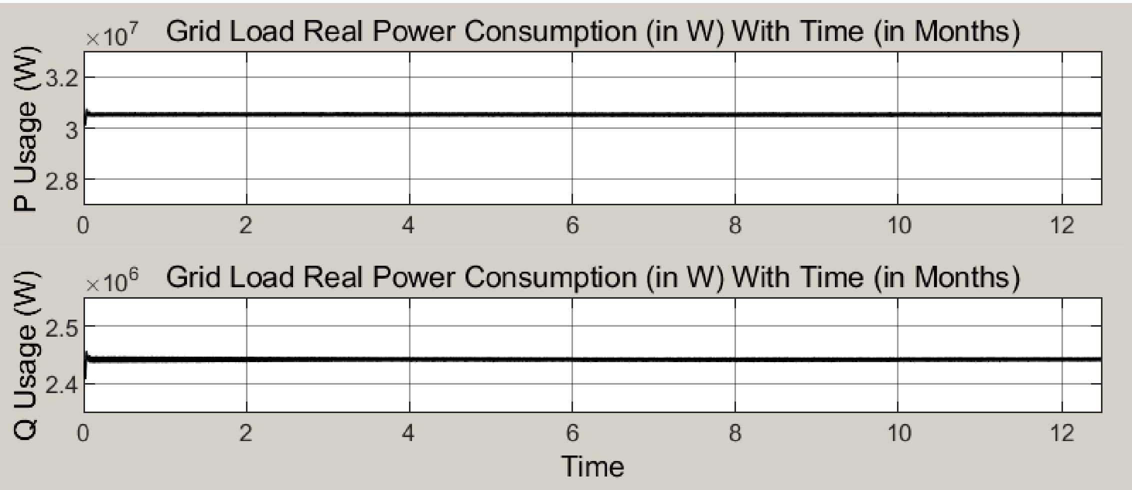


Figure 4.14: Analysis of the 30MW grid load energy consumption

The implications of the findings from this scenario suggest an effective energy availability, reliability, and efficiency of the grid's capability to fully supply power to the

$30MW$ grid load. The pressure and stress on the grid would be relatively low when compared with the status of the Nigerian energy system where the grid must entirely supply power to the loads without the assistance of any decentralised solar photovoltaic generation systems. Therefore, it can be deduced that with solar PV functioning as the primary source of energy generation in Nigeria, the grid generation outputs could focus on supplying power to other grid users like large commercial and industrial organizations depending on power supply directly from the grid. There would be more energy availability and reliability from the grid to the masses in the event of faults or blackouts in certain geographical areas.

4.6 DISCUSSION OF SOLAR PV DISTRIBUTED GENERATION RESULTS

Initially, during the simulation, the grid became most active in supplying all load because the PV system was not yet generating as the first irradiation was set to zero. To solve this, December irradiation data was brought forward to be the start of irradiance fed into the PV array. Instead of running simulation data for January – December, the simulation was set for December – December to have an idea of how an annual network operates. That was why the model maintained a constant energy supply to the load as seen in the scenarios tested in this study.

It was envisioned that throughout the year the solar PV generation outputs coupled with the battery storage would be enough to supply the loads with their required energy needs. This boosts the energy market environment for energy trading between various local area PV generators, energy users and the grid operators, and it implies that the pressure on the centralised grid would be drastically reduced. Therefore, the grid would only have to base their primary focus on local areas without decentralised PV generation networks or local areas with limited generation outputs.

Subsequently, the resiliency of the Nigerian energy system would be improved and more reliable to all parties involved i.e. both customers and stakeholders such as residents and neighbouring countries. Also, with data would become accessible to energy policy makers, solar PV distributed generators, private energy industries, manufacturers, grid, and the transmission and distribution companies who oversee maintaining the distribution lines to properly plan and strategise effective ways to reduce risks and manufacture materials within Nigeria. Finally, the energy trading data analyst and developers can now have access to a stable medium for forecasting the trends of solar PV generation outputs, predicting the energy price and energy trading market, and improving the energy sector.

4.7 DISCUSSION OF BATTERY ENERGY STORAGE SYSTEM (BESS) RESULTS

Previous studies mentioned in the literature review of this study reviewed either centralised or decentralised energy storage systems implemented for storing generated power from solar photovoltaic generation plants. However, demolishing several battery storage systems after the duration of their lifespan was a cause of concern for several researchers especially when air pollution was involved with demolishing several batteries from various decentralised distributed generation locations. With this in mind, the central battery storage system was adopted because they are better and easier to dispose of after their lifespan which indirectly reduces the pollution difficulties arising from decentralised battery storage system networks. Observational studies of the energy-trading algorithm programmed in this study also suggested that even though a central battery system was integrated into the energy system, local populations still had control over sales and generation of power from various decentralised solar photovoltaic distributed generation networks. Therefore, it can be implied that even with a central battery storage system; generators can still have full control over sales and generation outputs from solar photovoltaic systems.

4.8 DISCUSSION ABOUT THE IMPLICATION OF SIMULATION RESULTS ON AN ENERGY MARKET

One of the main aims of this study was to encourage a decentralised solar PV distributed generation system and energy trading amidst local areas. Therefore, local areas with limited generation outputs from solar photovoltaic systems can buy energy from surrounding local areas who were able to generate more than immediate load consumption during the rainy season (i.e. between June – September). It can thus be suggested that the energy market will receive a boost in energy trading between June and September which falls under the rainy season with little solar radiation data if proper planning and management is done. There is a possibility for solar PV producers to engage the habit of managing how they consume power (i.e. by switching off unnecessary loads like air conditioning units, etc. that can be foregone to save power) to increase their storage capabilities so that they can sell more energy to other end-users. In the end, the average Nigerian resident is looking for a way to earn more income.

4.9 DISCUSSION OF EFFECTS OF MULTIPLE STREAM OF SOLAR PV INFLUX INTO THE GRID

The results from all scenario tested showed that with multiple decentralized photovoltaic DG operating as the primary source of energy generation, there would be positive impacts on the national grid such as improvement of grid power reliability and availability to other areas without PV systems installed. This implies that more energy would be made available to other grid users without a heavy reliance on energy from the existing grid, and the stress on the grid could be lessened. With reduced stress on the grid, the existing grid becomes more reliable to end-users without PV networks as opposed to the previous intermittent supply of energy. Since most of the surplus generation outputs from the various local areas with solar PV distributed generation was fed to the central storage system, excess energy would be readily available for other users that do not rely on the solar system.

4.10 BLOCKCHAIN ENERGY TRADING AND ELECTRICITY PRICING

It was proposed in this study that the energy would be traded within the blockchain platform using either the wholesale price rating of $US\ \$0.12/kWh$, retail price ratings of $US\ \$0.15/kWh$, and/or a storage fee of $US\ \$0.12$ depending on the status of the energy buyer whether as a generator, consumer, or grid operator. Producers A_n such as producer A_1 and producer A_2 was designed to sell electricity to the grid operators or between themselves at the wholesale price while the grid users B_n buy energy directly from the grid operators or from the producers at a retail price to meet their load energy demands. This means that the wholesale price is lower than the retail price for electricity trading in the energy marketplace. Therefore, any transaction carried out between the producers A_n or between producers A_n and the grid operators was done at the wholesale price ratings throughout this study. However, any transaction carried out between the grid operators and the grid users B_n or between producers A_n and the grid users B_n was done at the retail price ratings.

4.10.1 ENERGY TRADING TRANSACTION BETWEEN PRODUCER A_1 AND GRID

With the blockchain energy trading algorithm in ***(Appendix D.7)*** in operation, when producer A_1 fed $30kWh$ of surplus electricity A_{1s} generated from the solar photovoltaic (PV) distributed generation (DG) system into the grid, $10kWh$ was later demanded from the battery before producer A_1 sold the remaining $20kWh$ to the grid. Producer A_1 was able to sell the remaining $20kWh$ units of energy to the grid operators at a wholesale price rating of $US\ \$0.12/kWh$ to gain $US\ \$2.4$ from the energy trading transaction. This $US\ \$2.4\ (240\ cents)$ was estimated by multiplying the wholesale pricing ratings of $US\ \$0.12/kWh$ by the units of energy sold to the grid operator.

However, because producer A_1 initially stored the surplus energy A_{1s} of $20kWh$ at the energy storage system (ESS) located at the grid centre and based on the standard storage fee stated above, the grid charged producer A_1 a storage fee of $US\ \$0.12\ (i.e.\ 12\ cents)$ for storing the $20kWh$ at the grid-centred ESS. Therefore, the total amount payable to producer A_1 at the end of the energy transaction by the grid was estimated to be $US\ 240\ cents\ - US\ 12\ cents = US\ 228\ cents$.

If any grid users B_n decided to buy energy directly from the grid, then the grid would sell at a retail price rating of $US\ \$0.15/kWh\ (i.e. US\ 125\ cents/kWh)$ to the grid users B_n without the interference of energy producers A_n because the grid had already bought the energy from the producer before deciding to sell to grid users B_n.

4.10.2 ENERGY TRADING TRANSACTION BETWEEN PRODUCER A_1 AND PRODUCER A_2

Results from the blockchain energy-trading algorithm ***(Appendix D.9)*** showed that producers like producer A_1 could sell energy to each other at a wholesale energy rate. This was seen as an outcome of the energy trading carried out ***(Appendix D.9)*** when producer A_1 sold energy to other producers like producer A_2 who experienced energy deficiency (i.e. an inability to meet load demand for energy consumption). Producer A_2 could buy energy from producer A_1 at the wholesale price of $US\ \$0.12/kWh$ $(i.e.\ 12\ cents/kWh)$ because producer A_2 was also a producer (albeit one who had energy generation deficiency issues at that moment). The implications of producers selling at a wholesale price rating to fellow producers with deficiency of generation outputs are that non-generating energy consumers will be encouraged to generate energy if they want to enjoy the benefits of buying at a lesser rate when they do not have enough energy.

For example, when producer A_2 decided to buy the remaining $20kWh$ of energy that producer A_1 still had stored at the grid centred ESS, producer A_2 was charged $US\ 240\ cents (or\ US\ \$2.4)$ by the grid administrators at a wholesale piece rate of $US\ 12\ cents/kWh$ for the unit of energy bought (see Figure 4.15).

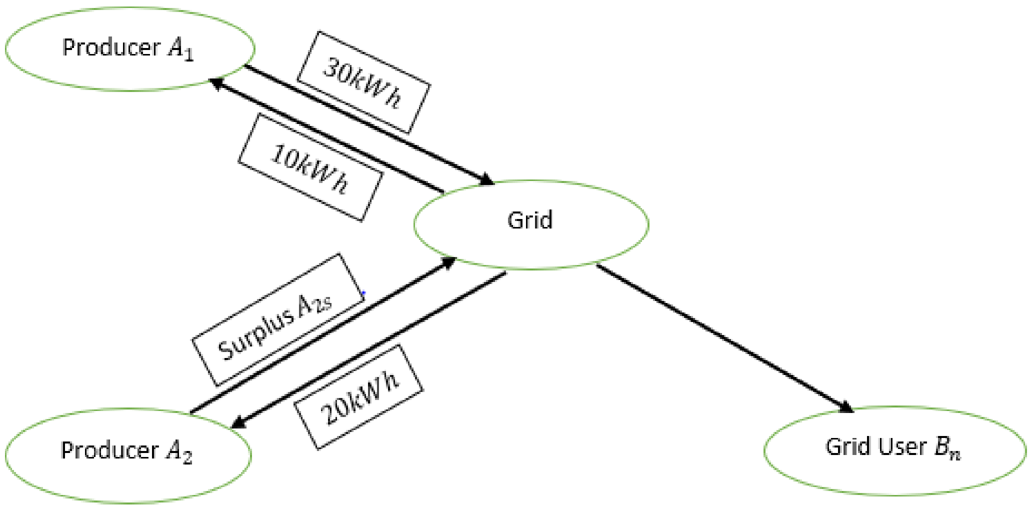


Figure 4.15: Energy trading transaction between producer A_1 and producer A_2

In addition, producer A_1 was charged a storage fee of $US\ \$0.12\ (i.e.\ 12\ cents)$ for storing the $20kWh$ at the grid centred ESS before producer A_2 bought the energy from producer A_1. Because the grid operator functioned as the intermediary (or agent) between producer A_1 and producer A_2, the grid was paid a commission percentage for the energy trading transactions between producer A_1 and producer A_2. Therefore, the grid gets 10% of $US\ \$2.4$ which is $US\ 24\ cents$ from the $US\ 240\ cents$ that producer A_2 paid to the grid. After subtracting $US\ \$0.12$ storage fee and 10% grid commission fee of $US\ 24\ cents$ from producer A_2's payment, $US\ 204\ cents$ was transferred to producer A_1 for selling $20kWh$ of energy to producer A_2.

4.10.3 ENERGY TRADING TRANSACTION BETWEEN PRODUCER A_1 AND GRID-USER B_n

Following the blockchain energy-trading algorithm ***(Appendix D.8)***, any grid user B_n could buy energy from producer A_1. In this instance, a retail price rating of $US\ \$0.15/kWh\ (i.e. US\ 15\ cents/kWh)$ was charged. As illustrated in Figure 4.16, when grid user B_n bought $20kWh$ of energy from producer A_1, the grid user B_n was charged $US\ 300\ cents$ by multiplying the retail price rating with the units of energy bought.

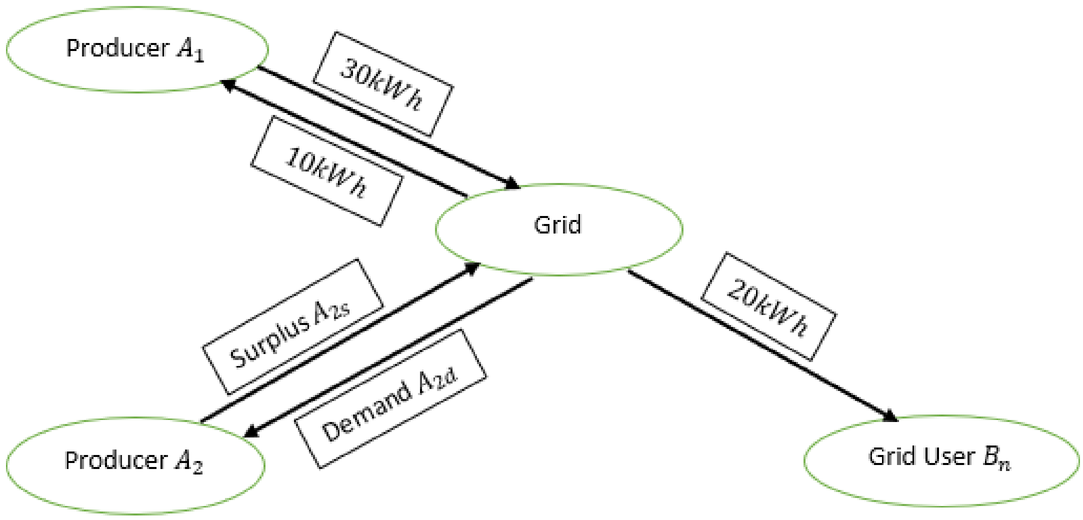


Figure 4.16: Energy trading transaction between producer A_1 and grid-user B_n

Since producer A_1 stored the $20kWh$ at the grid centered battery before trading it to grid user B_n, producer A_1 was charged $US\ 12\ cents$ as a storage fee. With the grid operator acting as the intermediary (or agent) between producer A_1 and grid user B_n, the grid got a 10% commission fee of $US\ 30\ cents$ from the $US\ 300\ cents$ that grid user B_n paid for the energy bought. Hence, producer A_1 profited $US\ 258\ cents$ for trading energy with grid-user B_n via the blockchain energy trading algorithm ***(Appendix D.8)***. This was achieved by subtracting the storage fee and grid commission fee from the amount paid by the grid user B_n to (producer A_1).

4.11 DISCUSSION ON ENERGY TRADING

As mentioned in the literature review, the blockchain algorithm allows energy trading on any platform while ensuring that a high trust level and zero tolerance for fraud. This is not something that all platforms can accomplish. A central blockchain energy-trading platform would allow programmes of the blockchain algorithm to work for their personal gains which might lead to altered transaction histories, as discussed in the literature review. This study set out with the aim of designing the grid administrators to act as the middleman between buyers and sellers of energy on the blockchain energy-trading platform, ensuring that trust is built among all participants of the blockchain trading platform.

It was thus suggested that a 10% commission fee from sales carried out on the trading platform goes to the grid administrators for their role in ensuring a high trust level between energy buyers and sellers, while eliminating scamming from the platform. The implication of this was that once the buyer paid the grid administrator the expected amount for the desired energy units a notification would be sent to the seller who would then give the administrator the authority to release the sold energy units to the buyer since the grid administrators control the centralised battery at the grid. These findings suggest that the trust level within the blockchain energy-trading platform increased as buyers and sellers no longer worried about being scammed over transactions carried out on the blockchain energy-trading platform.

4.12 SENSITIVITY ANALYSIS

A sensitivity analysis was carried out to understand how certain factors like equity payback, operation and maintenance (O&M) cost, debt ratio, and debt term reacts and affect the decision-making process when assessing the feasibility of this project in Nigeria [116, 117].

An analysis was performed based on the equity payback within the sensitivity range of 25% and a threshold value of $7yrs$. The behaviour of the electricity export rate was analysed and forecasted side-by-side the initial costs of the project as seen in Table 4.7 and Figure 4.17.

Table 4.7: Sensitivity analysis of electricity export rate versus initial costs

Electricity export rate		**Initial costs $**				
$\$/MWh$	%	209,734	244,689	279,645	314,601	349,556
		−25.0%	−12.5%	0.0%	12.5%	25.0%
90.00	−25.0%	2.6882	3.4415	4.3448	5.4336	6.7553
105.00	−12.5%	2.6872	3.4402	4.3429	5.4311	6.7519
120.00	0.0%	2.6862	3.4388	4.3411	5.4286	6.7484
135.00	12.5%	2.6853	3.4375	4.3392	5.4261	6.7450
150.00	25.0%	2.6843	3.4361	4.3374	5.4236	6.7416

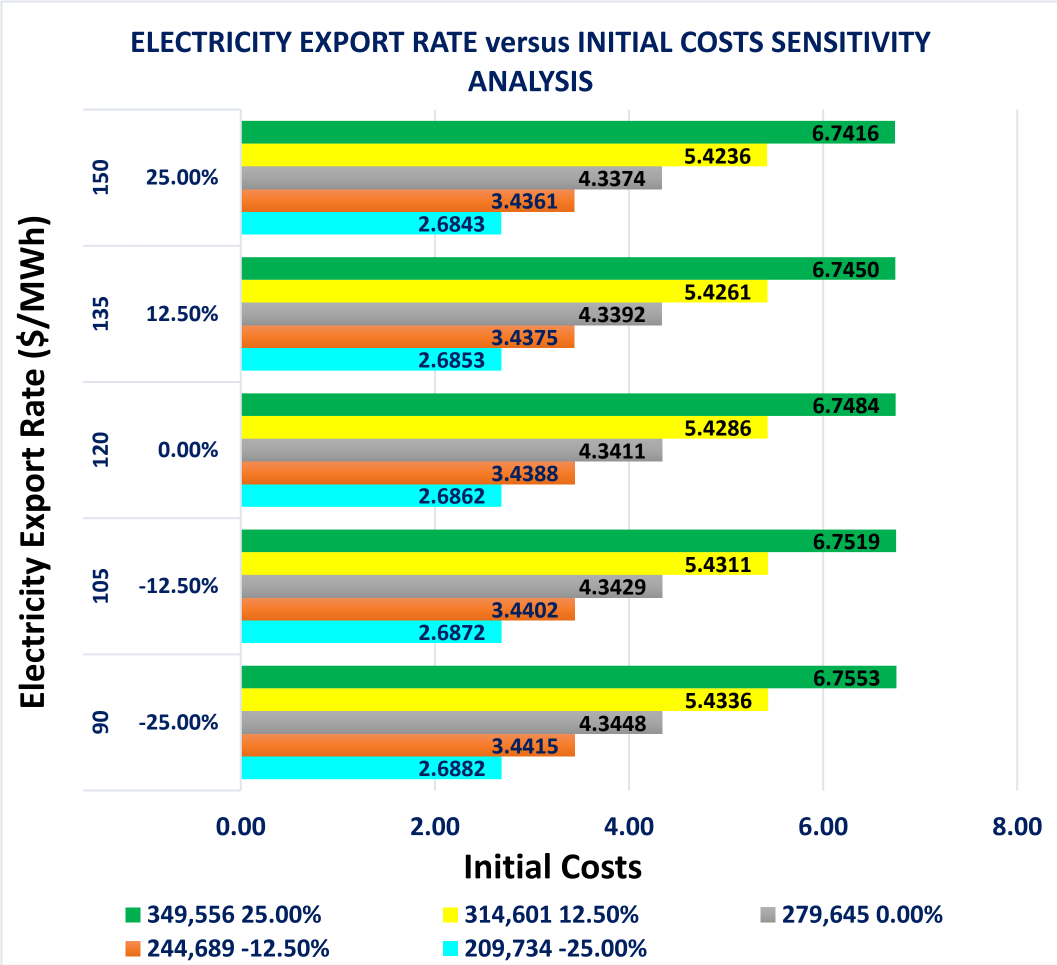


Figure 4.17: Sensitivity analysis of electricity export rate versus initial costs

Findings from the projected outcomes above suggested that within the estimated equity payback periods of seven years, the investment costs were recovered when initial costs between the range of $209,734 – $349,556 were invested into the project. A minimum and maximum payback period of 2.6843 (approximately 2.7) years and 6.7553 (approximately 6.7) years was projected with a minimum and maximum electricity export rate of $\$90/MWh - \$150/MWh$. This analysis implied that investors could make a more informed decision that reduces the level of risk and potential problem to the barest minimum.

Further behavioural analysis of the Operation and Maintenance (O&M) cost assessed alongside the forecasted initial costs of the project revealed the findings expressed in Table 4.8 and Figure 4.18.

Table 4.8: Sensitivity analysis of operation and maintenance cost versus initial costs

O&M costs		**Initial costs $**				
$	%	209,734	244,689	279,645	314,601	349,556
		−25.0%	−12.5%	0.0%	12.5%	25.0%
1875.0	−25.0%	2.6163	3.3425	4.2097	5.2498	6.5048
2187.5	−12.5%	2.6508	3.3900	4.2743	5.3376	6.6242
2500.0	0.0%	2.6862	3.4388	4.3411	5.4286	6.7484
2812.5	12.5%	2.7227	3.4892	4.4101	5.5229	6.8777
3125.0	25.0%	2.7601	3.5410	4.4814	5.6208	7.0117

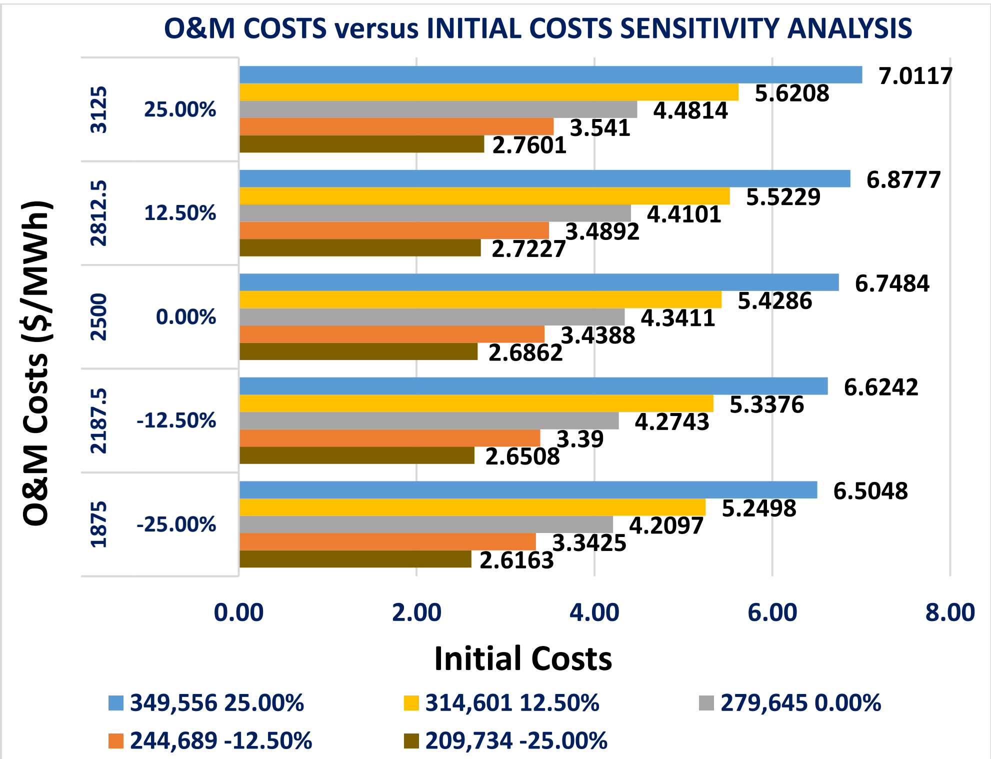


Figure 4.18: Sensitivity analysis of operation and maintenance cost versus initial costs

With a successive increase in initial costs invested into the project within the sensitivity range of $+/-25\%$, the annual O & M costs increased further and the equity payback period increased from approximately $2.6yrs$ to $7.0yrs$. The results in Figure 4.18 suggested that throughout the entire forecasted payback period, the equity Payback Period (PP) still fell within the borderline of seven years, with the exception of one outcome. The only time the duration of equity payback exceeded seven years was at a sensitivity range of 25% and beyond. This implied that investors and generators needed to decide on either an initial investment cost less than \$349,556 or to take the risk of investing beyond the starting cost to construct this project.

Subsequently, the assessment of debt ratio versus debt interest rate was observed to see the impact of the changes on investment decisions as illustrated in Figure 4.19 and Table 4.9.

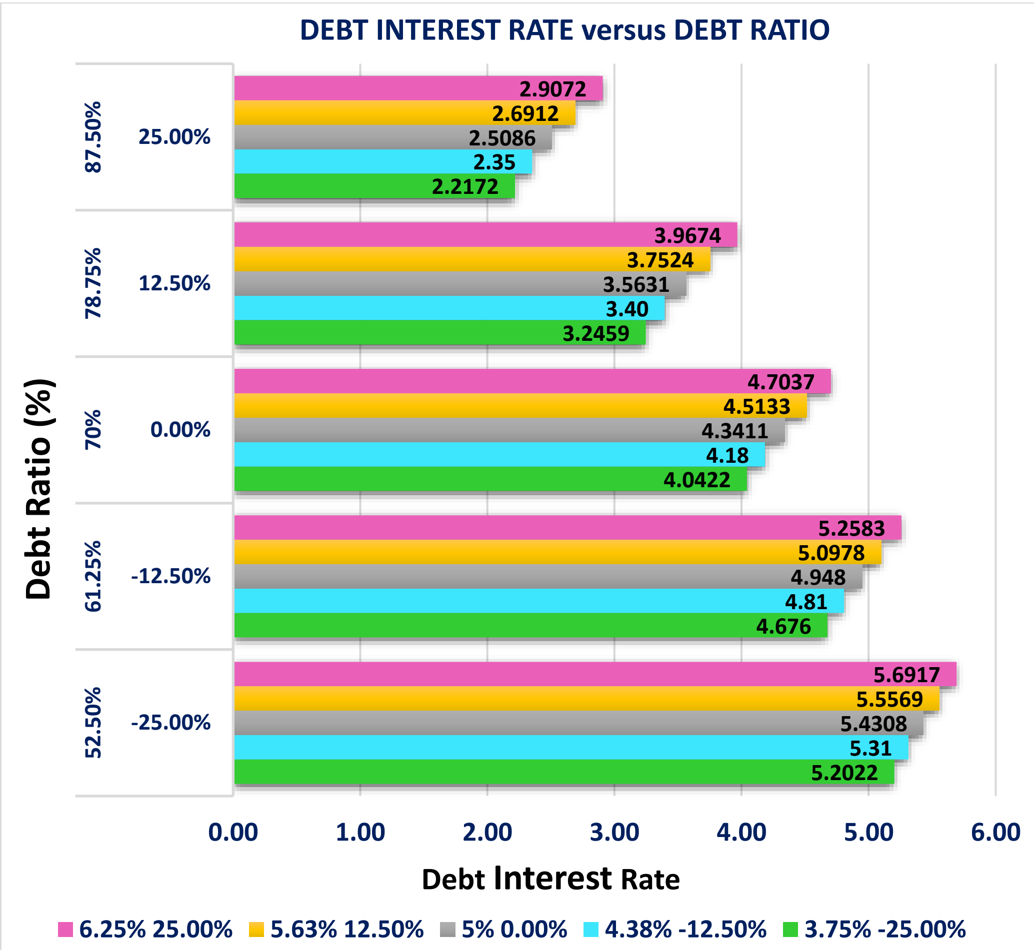


Figure 4.19: Sensitivity analysis of debt ratio versus debt interest rate

Table 4.9: Sensitivity analysis of debt ratio versus debt interest rate

Debt ratio		**Debt interest rate** %				
%	%	3.75%	4.375%	5%	5.625%	6.25%
		−25.0%	−12.5%	0.0%	12.5%	25.0%
52.5%	−25.0%	5.2022	5.3128	5.4308	5.5569	5.6917
61.25%	−12.5%	4.676	4.8067	4.9480	5.0978	5.2583
70%	0.0%	4.0422	4.1847	4.3411	4.5133	4.7037
78.75%	12.5%	3.2459	3.3954	3.5631	3.7524	3.9674
87.5%	25.0%	2.2172	2.3523	2.5086	2.6912	2.9072

From Figure 4.19 and Table 4.9, the highest and lowest debt ratio were estimated to be about 88% at a 25% sensitivity range and 53% at a sensitivity range of −25%. More so, the entire analysis demonstrated that debt interest rates less than 6.25% made the project investable as the payback period remained less than seven years, with the highest duration of $5.7yrs$ to recover costs incurred.

Table 4.10 and Figure 4.20 illustrates the performance of debt term versus debt interest rate that was observed to see the impact of the changes on investment decision when the range of $11yrs - 19yrs$ was considered as the debt term during the analysis.

Table 4.10: Sensitivity analysis of debt term versus debt interest rate

Debt term		**Debt interest rate** %				
$\boldsymbol{yr}$	%	3.75%	4.375%	5%	5.625%	6.25%
		−25.0%	−12.5%	0.0%	12.5%	25.0%
11	−25.0%	5.1083	5.3230	5.5606	5.8249	6.1144
13	−12.5%	4.4338	4.6036	4.7907	4.9976	5.2175
15	0.0%	4.0422	4.1847	4.3411	4.5133	4.7037
17	12.5%	3.7810	3.9118	4.0536	4.2062	4.3746
19	25.0%	3.5979	3.7179	3.8497	3.9950	4.1500

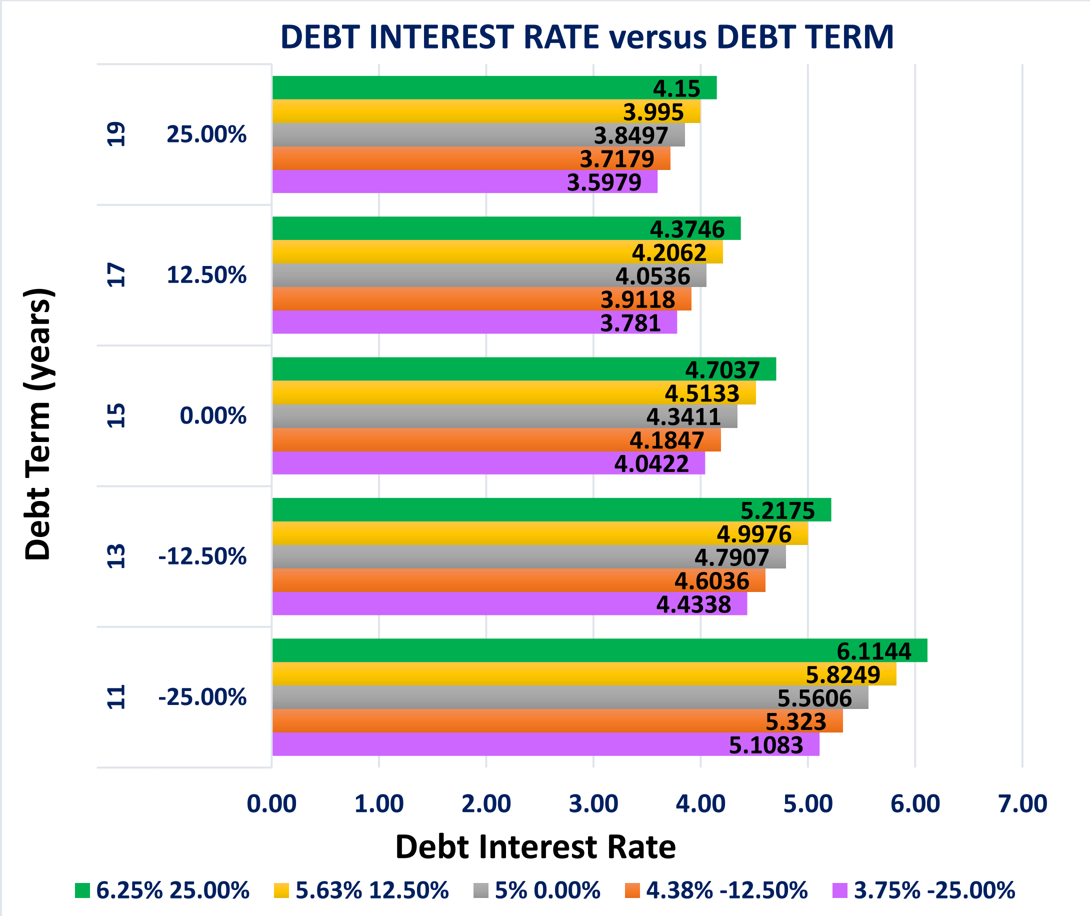


Figure 4.20: Sensitivity analysis of debt term versus debt interest rate

The highest equity payback period was estimated to be approximately $6.1yrs$ when a 25% sensitivity range at debt interest rate of 6.25% and -25% sensitivity range at $11yrs$ was considered for a debt term. The lowest equity payback period was estimated to be approximately $3.6yrs$ when -25% sensitivity range at a debt interest rate of 3.75% and 25% sensitivity range at $19yrs$ was considered for a debt term. Therefore, it implied that within the sensitivity range of $+/-25\%$, the equity paid back fell less than seven years, which is favourable to investors embarking on similar projects as this. Together these results provided important insights for Nigerians who are willing to implement this project in their local areas. Their investment costs can be recovered in time for them to start making profits from trading energy with other energy consumers on the blockchain energy-trading platform.

4.13 SUMMARY

This chapter has outlined the results of the power systems simulations tested in the MATLAB/Simulink environment under three different operating conditions. The first and second operating condition tested model behaviour when the system was undersized and oversized. The third set of operating conditions integrated the Nigerian real time solar irradiance obtained from relevant NASA platforms to assess the impact of decentralised solar photovoltaic distributed generation in the Nigerian energy system. Furthermore, results from the Simulink environment were imported into the Python environment and used to simulate the operations of the programmed blockchain energy-trading platform. The results of these energy trading environments are demonstrated in ***Appendix (D.1 – D.10)*** of this study. Finally, results of the sensitivity analysis were also established to aid a smooth decision process for investors.

CHAPTER 5: FINANCIAL ANALYSIS AND DISCUSSION

5.1 INTRODUCTION

This chapter presents the financial analysis of the simulations carried out and discusses their impact. Section (5.2) presents the financial analysis and viability of carrying out similar projects for one location. Subsequently, section (5.3) provides a risk analysis, and section (5.4) gives a detailed discussion pertaining to this study. Finally, section (5.5) summarises everything highlighted in this chapter.

5.2 FINANCIAL ANALYSIS

Financial analysis was employed in this study to assess the behaviour and impact of adopting decentralised solar renewable energy as the primary source of energy in developing countries like Nigeria [118]. Using a project life span of 20 years, the financial analysis of the project was modelled using RETScreen Expert software. Variables included a fuel cost escalation rate of 2%, an inflation rate of 2%, an equivalent discount rate $r = 9\%$ per year, an reinvestment rate of 9%, no incentives, a debt ratio of 70%, a debt interest rate of 5%, and a debt term of 15yrs. The average monthly horizontal solar radiation data in $(Wh/m^2/d)$ stated in ***Appendix (C.5)*** for the year was used to generate approximately 47kW of power to feed 25kW loads in one location.

5.2.1 COSTS, SAVINGS AND REVENUE

With an approximate of $47kW$ generated from one solar photovoltaic PV distributed generation location every month, approximately $566kW$ was generated annually by multiplying $47kW$ by 12 $months$ in a year. Using an average of 9.6 $hours$ and a $25kW$ load consumption, a total energy of $240kW/year$ was consumed by the load. It implies that a surplus energy of $326kW/year$ was obtained by subtracting the $240kW/year$ annual load consumption from the total $566kW$ generation outputs in a year. Furthermore, when the producer decided to sell to fellow producers at a wholesale rate of US \$$0.12/kWh$, the seller made an annual savings of US \$$39{,}120$. The total initial costs incurred after the installation of this decentralised solar PV distributed generation network was estimated to be US \$$279{,}645$ with an O&M cost of US \$$3{,}000$ as seen in

Figure 5.1. This total initial cost was derived by multiplying the material cost by the labour cost.

Item	Crew	Daily output	Labor Hours (hrs)	Unit	Quantity (Units)	Bare Costs ($)			
						Material	Labor	Total	O&M Cost
PV Module	2	8	1	1	84	1,785	109	159,096	1,500
Inverter	1	2	4	1	1	41,688	219	41,907	1,000
PV component combiner box	1	4	2	1	1	191	109	300	50
Fuse combiner box	1	40	0.2	1	40	18.75	10.95	1,188	100
PV rack system	1	30.5	0.525	1	84	895	23.5	77,154	300
Battery Storage Fee									50
Total Initial Cost								**279,645**	**3,000**

Figure 5.1: Total initial costs of one PV installation

Apart from the total Operation and Maintenance (O&M) costs stated in Figure 5.1, a debt payment fee of $18,859 ensued to be paid annually throughout the 15yrs debt term specified in the analysis. Summing this debt payment fee with the annual O&M cost amounted to a yearly cash flow of $21,859 from year 1. The proposed annual savings and revenue shows that the total annual savings of $39,120 coupled with a yearly electricity export revenue of $68 for the transmission cables summed up to $39,188 total annual savings and revenue. Finally, the net yearly cash flow for year 1 was analysed by subtracting the total annual costs of $21,859 from the total annual savings and revenue of $39,188 which emerged as $17,329 for year 1.

This thesis proposed two options to address the issue of who would pay for the centralized Battery Energy Storage System (BESS) installed at the grid's location. If no battery already exists at the utility land area where the centralised storage system will be placed, then the government could step in to cover the cost of buying and installing the battery while the grid operators used the storage fee they charged various decentralised PV distributed generators to maintain the battery storage system. However, if there was an already existing storage system in the grid location that was used for normal grid operations, then the grid would reduce the amount of energy it generated since people are now generating their own power independently. With this reduced generation on the part of the grid, more storage space would be available for distributed generators to store their energy at the centralised storage system on the grid, while grid operators use the storage fee charges from the PV generators to maintain the storage system.

5.2.2 FINANCIAL VIABILITY

The analysis showed that the equity pre-tax Internal Rate of Return (IRR) and the Modified Internal Rate of Return (MIRR) resulted to 25.3% and 14.8%. While the assets pre-tax IRR and MIRR amounted to 7.1% and 8.1% shows the simple payback period (PP) is 7.7yrs and the equity Payback Period is 4.3yrs in ***Appendix (C.6)***. The graphic representation of pre-tax ($) versus years (yrs) is laid out in Figure 5.2, which shows the decision makers that at the start of the project, they will have a pre-tax cost of $-83893.5 to pay. However, at the end of the first year, investors begin to accumulate profits to cover the capital costs of investing in the project.

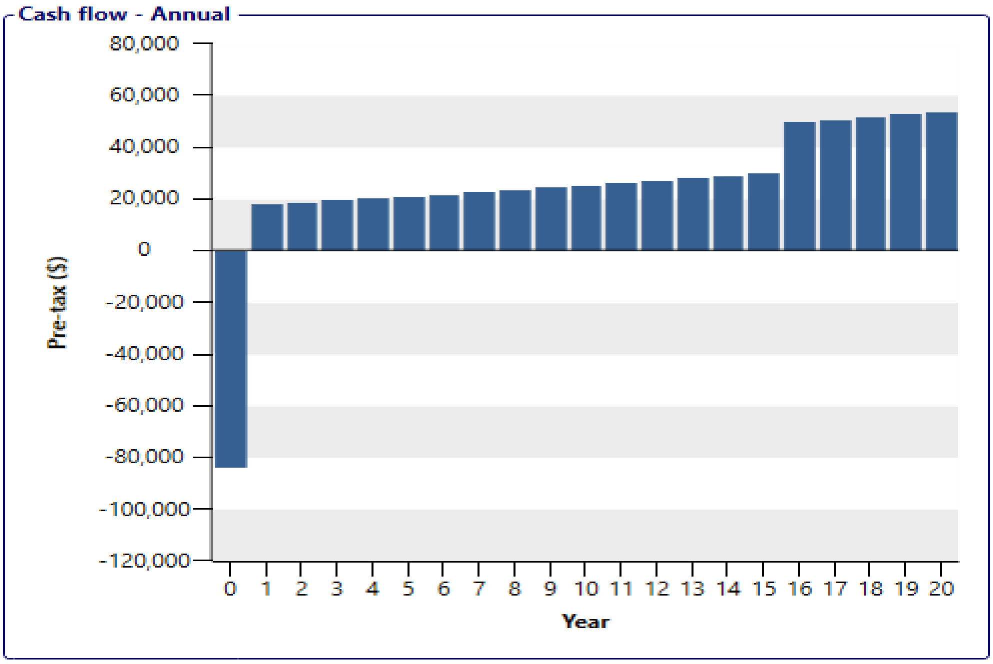


Figure 5.2: Pre-tax ($) versus years (yrs)

Furthermore, Figure 5.3 reflects the blueprint of the pre-tax ($) versus years (yrs) that enlighten the decision makers. As pre-tax increased, the impact of the initial costs reduced gradually. Between year four and five, when the cash flow curve increased above zero on the cumulative cash flow axis, investors would have profits from trading stored surplus energy on the blockchain energy trading platform to energy consumers. This would aid recovery from project investment costs.

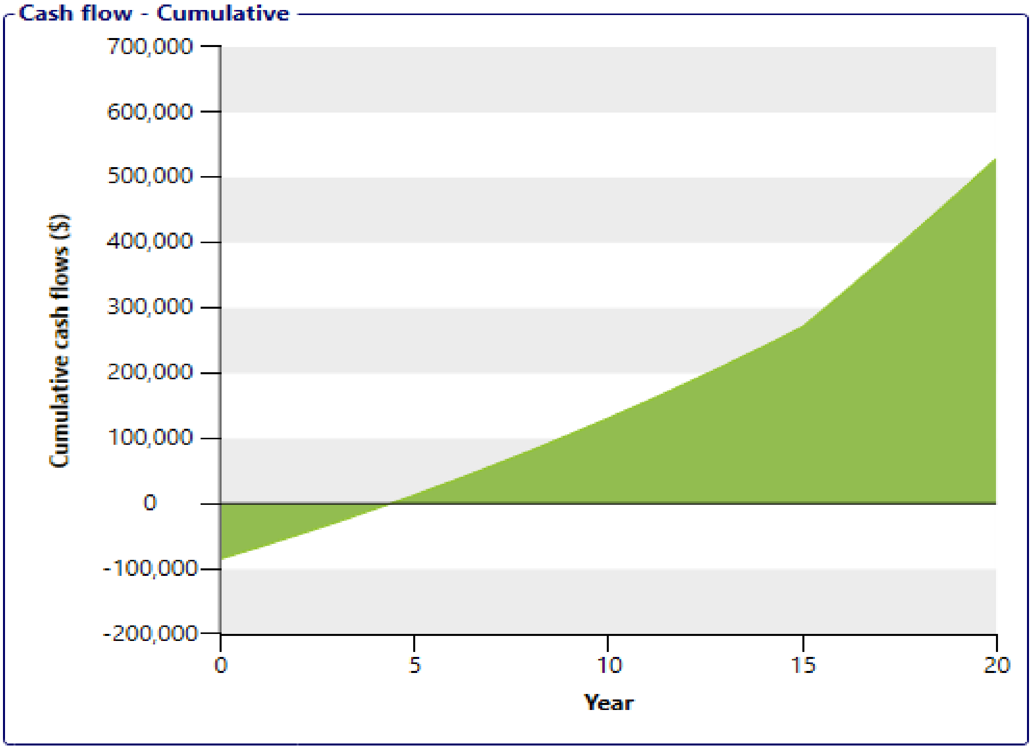


Figure 5.3: Cumulative cash flows ($) *versus years* ($yrs$)

The Net Present Value (NPV) resulted in $151,588 with an annual life cycle savings of $\$16{,}606/yr$ and a benefit-cost (B-C) ratio of 2.8. This advised investors of potential project acceptability as the project benefits surpassed the total costs incurred in project investment. Moreover, the solar photovoltaic generation system helped to improve greenhouse gas (GHG) efficiency by reducing the power industry gross annual greenhouse gas (GHG) emission cost by 93% to $-\$67{,}876/tCO_2$ in 20yrs. Finally, the debt service coverage amounted to 2 while the energy production cost summed up to $\$12{,}000/kWh$.

5.3 RISK ANALYSIS

With a 500 number of forecasting combinations, and a sensitivity range of +/- 25% and using the financial plan of this chapter to invest in solar photovoltaic generation of this size, debts incurred could be paid with 11 – 19 years of project life. The relative impact of this quantitative risk analysis, as seen in Table 5.1, showed that the interest rate ranged between 3.75% – 6.25%.

Table 5.1: Quantitative Risk analysis

Parameter	Unit	Value	Range (+/−)	Minimum	Maximum
Initial costs	$	279,645	25%	209,734	349,556
O&M	$	2,500	25%	1,875	3,125
Electricity export to grid	MWh	0.57	25%	0.42	0.71
Electricity export rate	$\$/MWh$	120.00	25%	90	150
Debt ratio	%	70	25%	52.5	87.5
Debt interest rate	%	5	25%	3.75	6.25
Debt term	yr	15	25%	11	19

Investors and generators will be able to make decisions about the duration and interest rate of paying back all costs incurred in this project using this assessment as a guide. Decision makers can also predict the time needed to fully payback project costs and the flow of profits using this assessment. Furthermore, with a 10% risk level at 25% sensitivity range and an initial cost of $279,645, the impact on the equity payback shows it was distributed across the entire project life of $20yrs$ as seen in Figure 5.4 where the horizontal axis reflects annual risks level of the project from year 1 – 20.

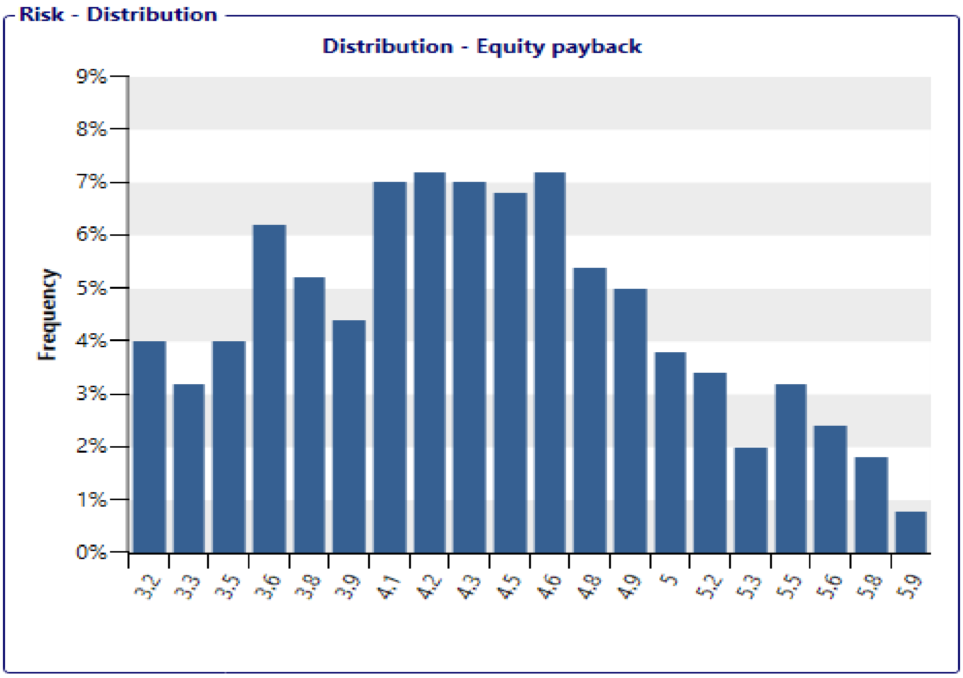


Figure 5.4: Distribution of the equity payback on the project lifespan

There was a steady rise and fall in the risk level of equity payback over the project life of $20yrs$. Between year 7 – 11, the risk frequency between each year was reduced. However, these years had a high frequency of equity payback risks. From Year 12, there was a steady downward reduction of risk associated with equity payback, with the last year of project life having the lowest risk level of approximately 1%. From this observation, it is evident that solar PV generators and investors are guaranteed to experience more risks associated with equity paybacks between year 7 – 11 of project life, and fewer risks in year 20 of project life. If proper energy market risk management and planning were done to reduce this risk level, it would affect the energy market and might lead to a higher market price of energy trading, which would indirectly affect the pattern of energy trading in the blockchain trading platform. Finally, a minimum of $3.2yrs$ confidence level and a maximum of $6.1yrs$ level of confidence was envisaged as the equity payback of project success.

5.4 DISCUSSION

The study has examined the technical and financial implications of integrating renewables such as solar photovoltaics as the primary source of energy generation in the Nigerian energy sector using quantitative assessment. It is established that adopting decentralised solar photovoltaic distributed generation sources and other renewable sources will offer more benefits of availability and an environmentally friendly atmosphere for the Nigerian economy.

5.4.1 BLOCKCHAIN ENERGY TRADING

A limitation to blockchain PV trading is a lack of neighbouring trust. However, this is where the peer-to-peer blockchain energy-trading platform proposed in this study becomes an advantage to the network nodes. The blockchain hashing system ensures sincerity and honesty among all participants in the blockchain energy trading and marketing platform. With this hashing system, there is little to no means for anyone to change the hash codes of the network for any transaction carried out on the platform. Only the blockchain program algorithm can alter transactions, and no developer of the blockchain network can change this. More so, with the proposed energy trading algorithm where fraudulent activities are minimised. Unless the fraudster is smarter and faster than the computer system with figuring out the hash key that the blockchain system will use to seal the next transaction on the transaction history, there is little means available to rig the system. Therefore, this makes the blockchain energy trading platform a secured place for trading.

Since adopting renewable energy generation systems is still new in Nigeria, this study creates awareness of renewables in Nigeria. There is need for the Nigerian government and private sectors to encourage researchers to continue looking for more innovative ways to integrate renewable energy generation and trading to improve the availability and reliability of the Nigerian energy sector. This can be achieved by offering scholarships, research incentives, funds, and training to improve the Nigerian energy industry.

5.4.2 FEED-IN TARIFF (FIT) IN NIGERIA

A feed-in tariff for renewable energy was approved by the Nigerian government in November 2015 for the purpose of boosting renewable energy generation sources and encouraging investments in the Nigerian energy industry. The Nigerian FIT was commissioned by the Nigerian Electricity Regulatory Commission (NERC), which currently only support the costs incurred by large energy generators. However, they are yet to consider the energy traders of smaller decentralised generators [119]. As at 2016, the FIT for solar generation plants was commissioned to be $177/MWh (accounting for $176.85/MWh of capital costs and $0.15/MWh of O&M costs), which is subjected to change every three years [119]. However, this FIT policy was established for solar generation plant within the generation capacity benchmark of 1MW – 5MW with a view of expanding it to 380MW come 2018. The downside of this policy is that it only favours large solar photovoltaic (PV) energy generators, leaving smaller solar generators out of the equation. This could be an issue if decentralised distributed generation systems were embraced in Nigeria. There is need for the Nigerian government to expand favourable policies in terms of incentives such as the Feed-In Tariff (FIT) that encourages Nigerians to embrace decentralised solar photovoltaic renewable energy generation.

The overriding implication of this study encourages the Nigerian government to become more aware of decentralised solar photovoltaic distributed generation at smaller local areas, which could ensure more energy is available to meet consumer demands. With this fresh awareness, current renewable energy policies could be reviewed and more favourable decentralised renewable energy generation, trading policies, and incentives created. Therefore, the focus of this study would encourage the NERC to readjust the FIT to accommodate decentralised solar photovoltaic (PV) distributed generators, which are generating less than the current benchmark capacity of FIT returns. Subsequently, every household will be encouraged to generate more, transport their surplus energy back to the central storage system at the grid, and perform more energy trading. This would indirectly reduce the current rate of poverty in Nigeria. More stakeholders (investors, households, etc.) would be interested to invest in the common goal of NERC i.e. increase renewable energy generations as the primary source of energy generation and create more energy availability to meet demands.

5.4.3 ENERGY POLICIES IN NIGERIA

Presently, favourable energy policies that support renewable energy generation and trading are still lacking as seen in Nigeria's current feed-in tariffs discussed above. This is not to encourage people to generate solar photovoltaic renewable energy in a decentralised manner, especially if they cannot generate as much as 1MW – 5MW. Based on this, it is evident that there is still a lot of work that needs to be done in terms of renewable energy policies. Therefore, focus should be given to establishing renewable energy policies and tariffs in Nigeria that encourage decentralised renewable energy generation such as distributed solar photovoltaic energy. Other aspects of renewable energy need to be addressed, such as rules on the acceptable energy commissioning ratings for photovoltaic modules in the Nigerian energy market. Incentives should be given to energy traders to encourage renewable energy trading between the various decentralised photovoltaic distributed generation outputs and the grid, and vice versa, to reduce stress on the national grid.

5.5 SUMMARY

This chapter addressed the financial viability and risks involved in deploying this study in Nigeria. The results and analysis of this study further prompted discussions on energy losses in solar photovoltaic systems, and the implications of integrating blockchain trading platforms in the Nigerian energy market. Finally, the current feed-in tariffs and energy policies were discussed, and prospects for more favourable feed-in tariffs and regulations for decentralised solar photovoltaic distributed generators were outlined.

CHAPTER 6: CONCLUSION AND FUTURE RESEARCH RECOMMENDATIONS

6.1 INTRODUCTION

This chapter summarises the findings of this research after carrying out simulations testing, analysis, and discussion drawing from the relevant quantitative data collected, before providing a conclusion.

6.2 MATLAB/SIMULINK MODEL

The aim of this thesis was to research how solar photovoltaic (PV) Distributed Generation (DG) can be designed and modelled into the Nigeria energy system using blockchain technology as the energy trading platform. In addition, to investigate how the resilience of the Nigerian energy system can be improved when multiple streams of decentralised solar photovoltaics energy generation are in operation. It also established solar renewable energy sources as the primary source of energy generation creating energy efficiency and availability to all while also adding economic advantage to the energy industry via energy trading as seen in the MATLAB/Simulink simulation results of this study.

By integrating the PV distributed generation as the primary source of energy supply to loads in the model of this study, the stress on the grid was reduced. This gave the grid the capacity to focus only on loads in locations without distributed PV generation systems installations. Furthermore, because decentralised renewable generators ensured more stored energy, the availability of energy improved during low solar radiation seasons. More energy was sold to energy consumers who do not have enough stored energy during the rainy season.

6.3 BLOCKCHAIN ENERGY TRADING PLATFORM

Blockchain energy trading could not only encourage decentralized renewable energy generation among people, but it could also remove third party inside the present energy system. This is one economic advantage of the energy trading platform proposed in this thesis. To implement the blockchain energy trading platform in the Nigerian energy system, awareness could be drawn to its appeal as a secured trading energy system that prevents fraudulent activities. The trust levels of participants on the blockchain energy trading platform would then increase over time.

6.3.1 WHY BLOCKCHAIN TECHNOLOGY INSTEAD OF EXISTING PRICING OR SUBSIDY MECHANISMS FOR THE ENERGY TRADING PLATFORM?

Even though this thesis could have adopted existing retail pricing or existing mechanism of subsidy, blockchain technology here operated in a decentralized manner without the interference of the mandatory control center. Also, the incentive layer embedded in the blockchain technology played a significant role of integrating economic values to the network. Since the incentive and the data layers are the driving force to bring more nodes (energy generators and consumers) into the network, it increases the computing power. Moreover, the more the computing powers, the more the activities on the network increase which indirectly makes it difficult for scammers to bridge into the framework of the network, therefore, trust and transparency become mutual among the connected end-users.

Furthermore, instead of the current regular pricing or subsidy mechanism, blockchain technology was opted for in this thesis because it saves costs, information security, and enables trust in the network. In a centralized energy network currently in place in Nigeria, there exists the issue of high operational costs and imperfect information security due to the number of third parties involved in the network. However, blockchain technology was able to counter these problems by minimizing the level of third parties involved in the network to the barest minimum, now saving additional incurred costs while also ensuring a high level of information security of the participants in the network.

6.4 FINANCIAL AND RISK ANALYSIS

If a similar project was to be developed in Nigeria, the viability and possible percentage of risks involved under a 10% risk level and 25% sensitivity range shows that the Benefit-to-Cost Ratio (BCR) is high and all incurred investment costs can be recovered within 20 years of a typical project life span. This denotes that investing in a decentralised solar photovoltaic distributed generation system in Nigeria is favourable and profitable to all investors and stakeholders. To reduce the risk levels involved in similar projects, this study encourages the use of more risk managers to properly manage the planning, management, and operations of such projects to ensure higher benefits and lower electricity costs.

6.5 SUMMARY: EVALUATION OF RESEARCH TASKS

Nigeria is still at the developing stage of adopting renewable energy and is yet to adopt renewable energy as her main source of energy generation. Rather than depending on non-renewable energy sources as the primary source of energy generation, the objectives of this thesis successfully demonstrated the development of distributed solar renewable energy generation as the primary source of energy generation in the Nigerian energy industry. Not only will the urban residents have access to reliable energy sources, but also rural areas residents will be motivated to generate their own energy without depending on the national grid for electricity. This was assessed using quantitative research methods to arrive at the MATLAB/Simulink simulation results. Furthermore, with the existence of decentralised solar photovoltaic distributed generation systems as the primary source of energy generation in Nigeria, it is possible to see that there will be more blockchain energy trading activities among Nigerian communities. People can use this trading platform as a source of revenue, which will contribute to the eradication of poverty in Nigeria.

6.5.1 ACHIEVEMENT OF THE RESEARCH GOALS:

In order to successfully design the focus of this study, the scope of the Matlab/Simulink software design a system to consider three different local areas. Within these three areas, decentralized solar photovoltaic renewable energy was being generated locally as the primary source of energy generation. The smart meters represented as metering scopes in the Simulink software measured the amount of energy generated on a real-time basis. Moreover, the decentralized solar systems connected to the centralized battery energy storage system (placed at the central grid’s location) operated in a two-way transmission channel. So, the energy generated and not utilized used on a real-time basis was sent directly to the battery storage system till the generator of the energy decided on the consumption behaviour of the energy generated (either personally or via trading to other energy users).

Furthermore, because one of the emphases of this project was the adoption of blockchain technology in energy trading among energy users, Python programming language. The energy trading platform designed using Python language under the group of Anaconda, Jupyter Notebook and Visual Studio Code Python environments, was written to consider various scenarios under which energy could either be bought or sold by the nodes. Moreover, these nodes represented the various solar renewable energy consuming houses connected to the blockchain network. Afterwards, the results of the decentralized solar renewable generations were export from the Matlab/Simulink environment and imported into the Visual Studio Code Python environments using the Jupyter Notebook as the interface to call functions from Simulink to Python environment. Therefore, it was only on the blockchain technology, which represented the energy trading platform, that energy users could check the status of their energy generations and carry out the buying and selling of energy among peers.

More so, considering the current centralized non-renewable energy systems in Nigeria and investors fear of venturing into an innovation that, “to them”, may and may not yield significant profits for them, this research developed financial and risk analysis to address investment issues. The financial and risk analysis evaluated the possible factors that investors assess before venturing into decentralized solar renewable energy generations that adopt blockchain technology for energy trading in the Nigerian economy. It also addressed the financial viability and the number of years it would take investors to fully recover the total initial costs of the system and distribution of the equity payback on the project lifespan.

Besides, the model of this thesis tested how the Nigerian energy system could quickly spring back into operations after a significant blackout or maintenance servicing affecting specific geological location from having lights. Based on the decentralized nature of the network built, the percentage of blackouts caused by one factor is restricted. For instance, a fault occurring in a location did not prevent other locations from generating energy and selling to the places unable to generate energy due to the fault. Since the network was no longer centralized (like what exist currently in the Nigerian energy sector), an affected zone unable to generate power could easily buy energy from other unaffected local zones with enough energy could quickly sell. Furthermore, this ensured that the percentage of no electricity ratings drop down from what is currently happening in Nigeria. The only time a local zone was without energy was during the event of severe faults in the major transmission cables that connected local areas. Nevertheless, outside this fact, the system worked great in improving the ability of the Nigerian energy system to quickly after any unsatisfactory situation.

Finally, the generation outputs of the multiple influxes of solar photovoltaic renewable energy into the national grid much helped in relieving the current stress level of the Nigerian national grid. Based on the simulations tested, because of the decentralized model built in this thesis, local areas did not have to generate as much energy as what a whole nation would consume, which means that only a small amount of solar photovoltaic energy generation is required and stored in the centralized energy storage system. Since the centralized battery is in the grid's location, there was no need to generate as much energy as is currently generated in the Nigerian energy sector. So, when the grid could not generate enough, they could buy energy from the decentralized solar photovoltaic energy generators and distribute to other energy consumers without generations systems within their locality, thereby improving the stability of the Nigerian energy network.

6.6 LIMITATIONS OF THESIS CONTRIBUTION:

One of the significant limitations of this thesis is the unavailability of real-time household energy consumption and insufficient availability of existing retail models due to the privacy issues and protection of trade secrets by the relevant energy institutions contacted at the commencement of this thesis. Scale-up implementation of this thesis results requires readily available real-date data for researchers. Easy access to Nigeria's energy research data would encourage more researchers to dive into the world of developing globally acceptable long-lasting solutions to Nigeria energy security. Therefore, relevant institutions such as the NERC, PPPRA, and ECN should encourage relevant energy institutions to make their data readily available to researchers for research purposes.

Another limitation is that Nigeria government policies on renewable energy generations have a way of affecting the impacts of this thesis in the Nigeria energy system either positively or negatively. Hence, this thesis highlights some of the international contracts and policies not yet in existence in Nigeria, but if established would promote decentralized renewable energy generation in Nigeria and make it possible for the goal of this thesis to be achievable. There has being a huge communication gap between the ECN and the government energy representatives which establishment of united front restores the confidence of the masses on her government. Therefore, the Nigerian energy sector and regulators should develop joint strategic energy plans, which when presented to the government treasury committee would be closely monitored to the completion stage of such projects to avoid embezzlement of public funds. There should be an establishment of a unified body to promote specific targets of sustainable renewable energy generation in Nigeria rather than changing the Nigerian energy sector leadership based on operating political party's choice election year. This unified body should then lead the energy sector so that strategizing, and implementation follows a stable direction rather than back-and-forth practice that disrupts the flow of operations and promotion of renewable energy practices in Nigeria.

More so, the government should create favourable contracts and policies that show committed drive towards supporting investors and masses to generate low cost decentralized renewable energy generation networks such as solar photovoltaic energy generations systems. If the Nigerian government is keen about achieving 30% of renewable energy addition as part of the aggregate energy availability in 2030, with government incentives, this goal is achievable. However, it requires purposeful commitments by the government to reduce importation cost of raw materials, encouraging factories to produce Nigerian made raw materials with minimal impacts on the global ecosystem while still conforming to the international standards across the globe. Necessary regulations that provide energy security is required to encourage masses with smaller generation capabilities to venture into decentralized renewable energy generations, rather than focusing only on the larger generation capability generators. Policies should be created and enforced to encourage individuals to sell excess energy generated via the blockchain network to both grid operators and other consumers at a regulated standard electricity rate. Such policies would make it possible for the realization of steady and uninterrupted power availability in Nigeria, which seems unachievable as at the present frequent power outages in Nigeria. The Nigerian energy sector also needs to train and empower the communities on proper installations and maintenance of renewable energy equipment and facilities.

Another drawback of this thesis is the absence of Energy Internet in this research. Energy Internet has so many features that if coupled with the blockchain energy trading platform programmed in this research would make the trading platform more appealing to participants in the energy trading platform. Energy Internet has the capability of ensuring more accurate energy measurements, a more extensive range of decentralized photovoltaic energy generations, intelligent control, and its open trading abilities which all work together to change the interactive mode of energy trading information. However, because Energy Internet is still in its theoretical and architectural design stage across the globe, further research can be done to investigate how Energy Internet and Blockchain Technology can work together to improve the decentralized renewable energy supply system currently in existence.

6.7 FUTURE RESEARCH RECOMMENDATIONS

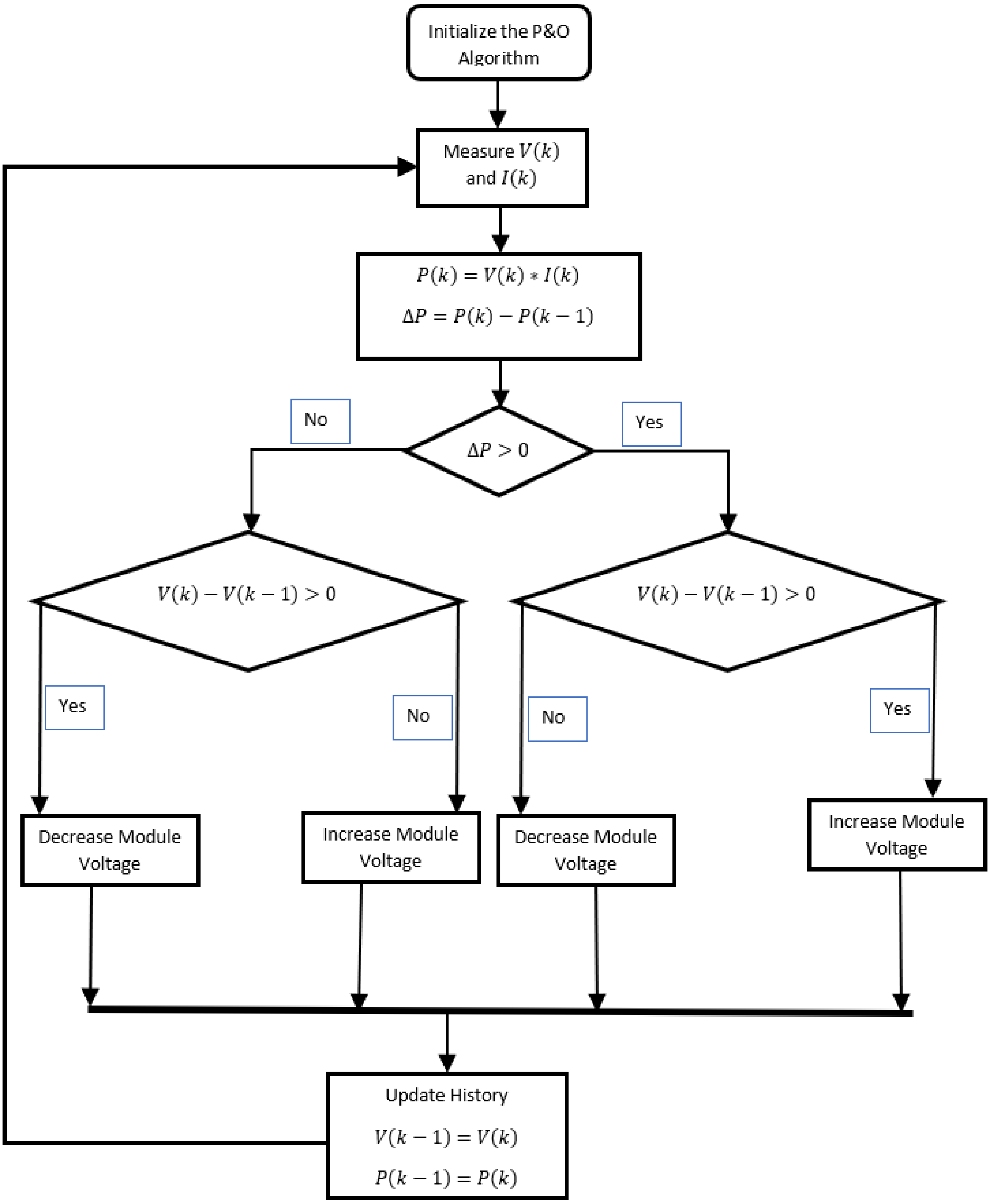
One of the biggest limitations of this research is the proper sizing of distribution lines. The present distribution lines are not made to accommodate multiple influxes of bidirectional energy flow on the distribution lines. When decentralised renewable energy generation becomes the norm in Nigeria, the population size means that there will be a need for distribution line resizing.

Finally, there is a need for research into renewable energy market risk management and planning alongside the blockchain energy trading platform, and stochastic algorithms to forecast the availability of renewable energy to the energy market over time. Finally, more research needs to be carried out on engineering finance and lower energy market prices that favour all stakeholders in the energy industry, while also reducing levels of risk.

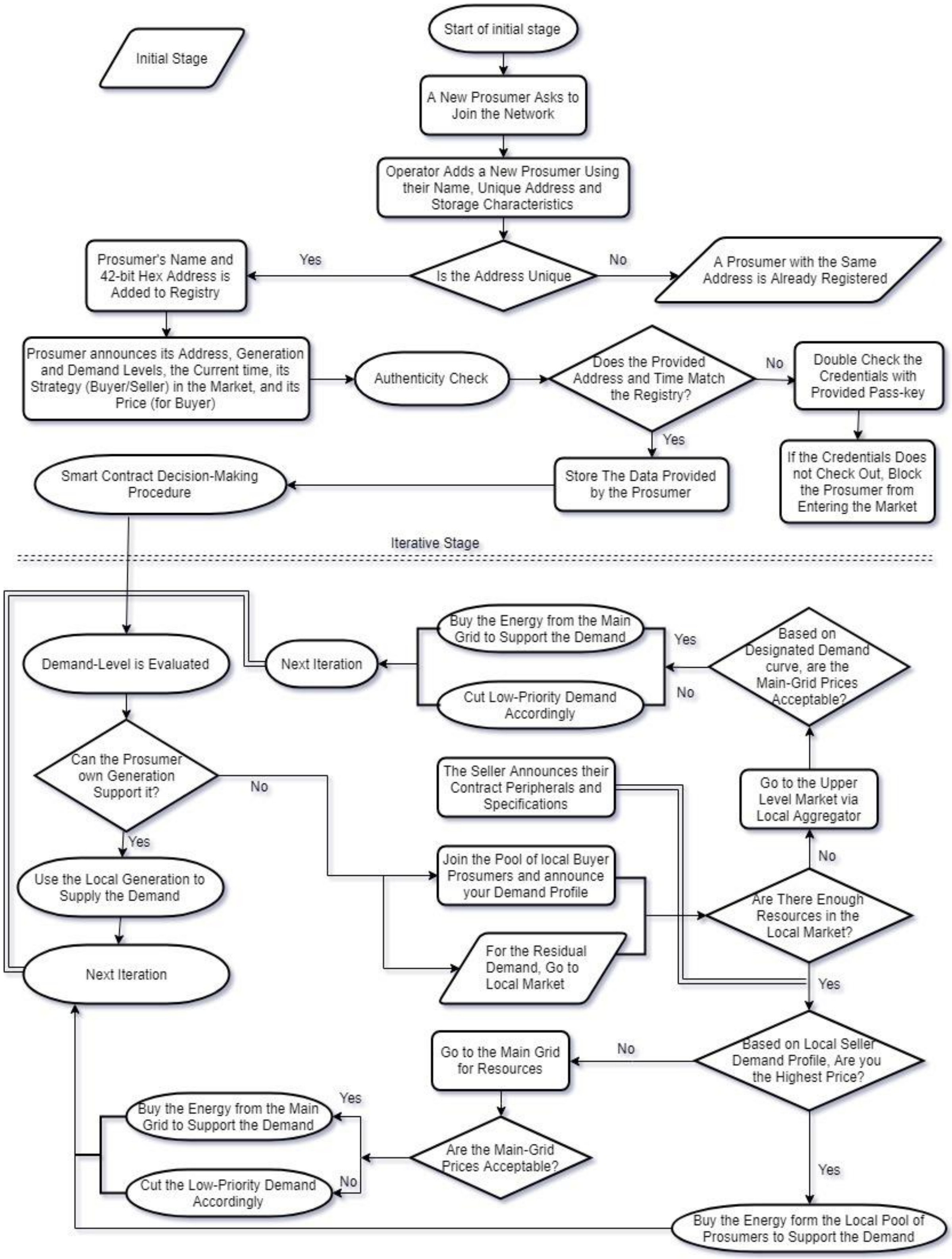
APPENDICES

APPENDIX A: LARGE DIAGRAMS AND FLOWCHARTS

Appendix A.1: Flow Chart of The Perturbation and Observation (P&O) Control Technique

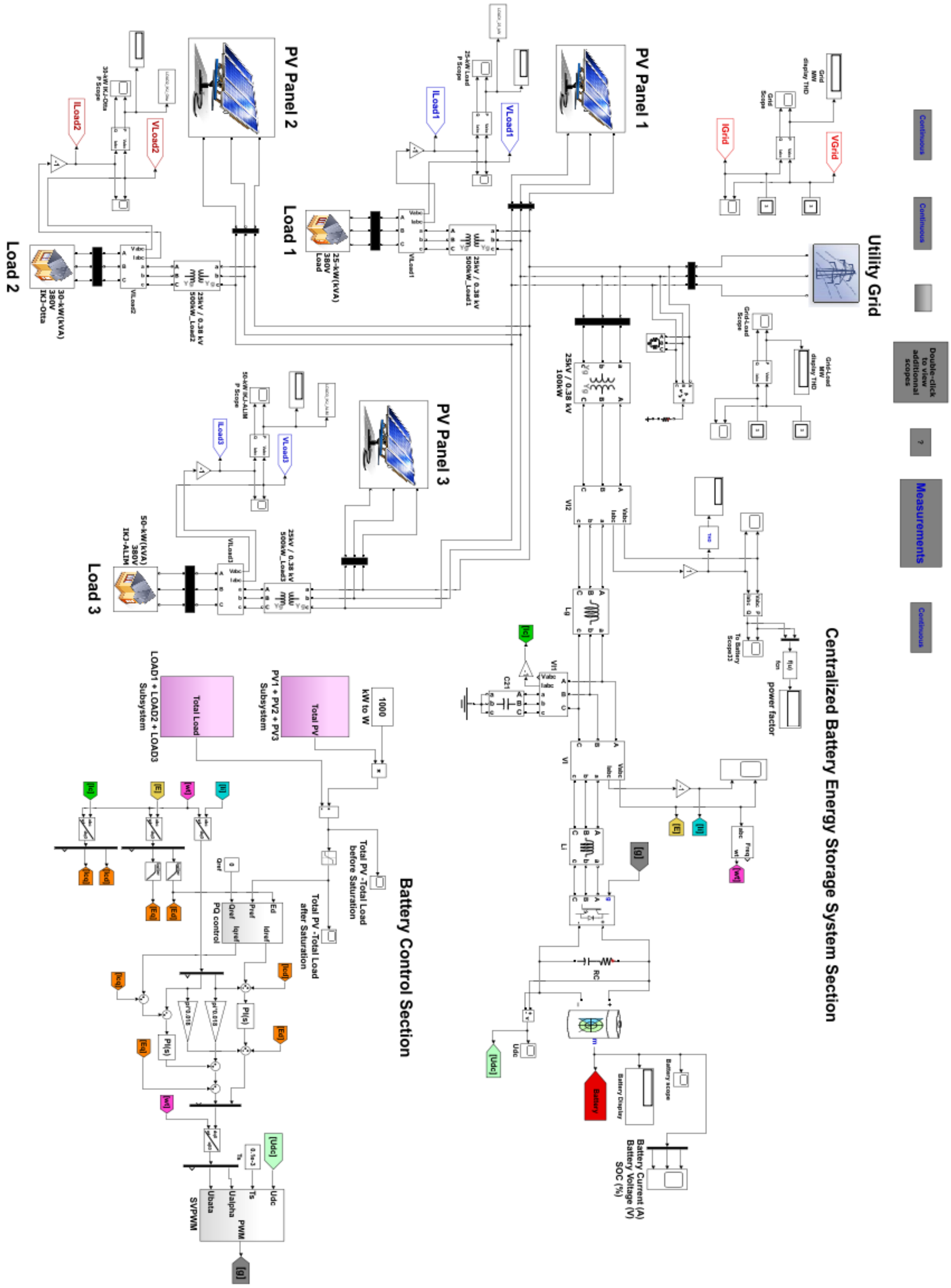


Appendix A.2: Peer-To-Peer (P2P) Bidding Market Structure

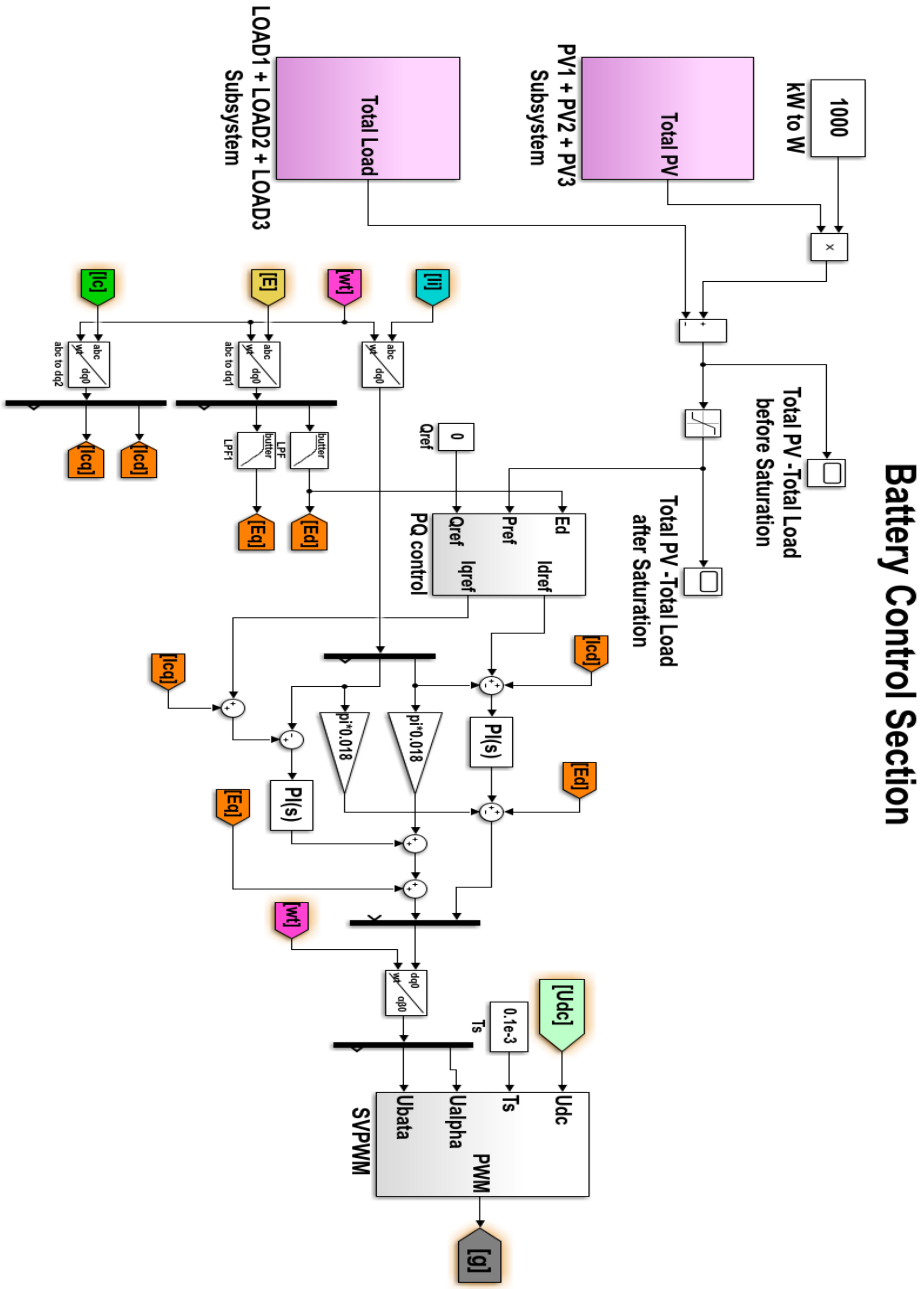


APPENDIX B: FULL DESIGN VIEW OF MATLAB MODEL

Appendix B.1: Portrait Layout of The Full Matlab Model Design



Appendix B.2: Battery Control Section Schematics



APPENDIX C: MODEL DATA

Appendix C.1: Simulink Pre-Defined Parameters of The PV Array Adopted in This Study

S/N	Parameters	
	Array Data	**Array value**
1	Parallel Strings	88
2	Series-connected modules per string	7
3	T_cell (deg. C)	[45 25]
	SunPower SPR-415E-WHT-D Module Data	**Module value**
1	Maximum power (W)	414.801
2	Open circuit voltage V_{oc} (V)	85.3
3	Voltage at maximum power point V_{mp} (V)	72.9
4	Temperature coefficient of V_{oc} (%/deg.C)	-0.229
5	Cells per module (Ncell)	128
6	Short-circuit current I_{sc} (A)	6.09
7	Current at maximum power point I_{mp} (A)	5.69
8	Temperature coefficient of I_{sc} (%/deg.C)	0.030706
	Model parameters	**Model value**
1	Light-generated current I_L (A)	6.0978
2	Diode saturation current I_O (A)	7.1712e-13
3	Diode ideality factor	0.87223
4	Shunt resistance R_{sh} (ohms)	419.7813
5	Series resistance R_s (ohms)	0.5371
6	Time constant (s)	$1\mu s$

Appendix C.2: Simulink Pre-Defined Parameters of The PID Controller Adopted in This Study

S/N	PID Controller Parameters	
1	Controller	PI
2	Form	Parallel
3	Time domain	Continuous time
	Main: Controller parameters	**Selection**
1	Source	Internal
2	Proportional (P)	20
3	Integral (I)	50
4	Tuning method	Transfer function based (PID Tuner App)
5	Compensator formula	$P + I\frac{1}{s}$
	Initial conditions	**Selection**
1	Source	Internal
2	Integrator	0
3	External reset	None
4	Zero-crossing detection	Enabled
	Data types	**Selection**
1	Integer rounding mode	Floor

Appendix C.3: Simulink Pre-Defined Lithium-Ion Battery Parameters

S/N	Lithium-Ion Battery Parameters	
1	Nominal voltage (V)	720
2	Rated capacity (Ah)	1000
3	Initial state-of-charge (SOC) (%)	50
4	Battery response time (s)	30
	Discharge	**Selection**
1	Determined from the nominal parameters of the battery	Enabled
	Display characteristics	**Selection**
1	Discharge current [i1, i2, i3, …] (A)	[6.5 13 32.5]
2	Units	Time

Appendix C.4: Simulink Pre-Defined Parameters of The Three-Phase Transformer

S/N	Three-Phase Transformer (Two Windings) Parameters	
	Configuration	**Selection**
1	Winding 1 connection (ABC terminals)	Yg
2	Winding 2 connection (abc terminals)	Delta (D1)
	Core	**Selection**
1	Type	Three single-phase transformers
	Measurements	
1	All measurements (V I Fluxes)	
	Parameters	**Selection**
1	Units	Pu
2	Nominal power and frequency [Pn (VA), fn (Hz)]	[5000e6 Fnom] where Fnom is 50
3	Winding 1 parameters [R1(pu), L1(pu)]	[0.08/30 0.08] [0.08/30 0.08]
4	Winding 2 parameters [R2(pu), L2(pu)]	[0.08/30 0.08] [0.08/30 0.08]
5	Magnetization resistance Rm (pu)	500 except PV with 200
6	Magnetization inductance Lm (pu)	500 except PV with 200

Appendix C.5: RETSCREEN Expert - Magodo, Lagos, Nigeria Weather Data

	Unit	Climate data location	Facility location	Source
Latitude		6.4	6.6	
Longitude		3.5	3.4	
Climate zone		OA - Extremely hot - Humid		NASA
Elevation	m	12	33	NASA - Map
Heating design temperature	°C	22.4		NASA
Cooling design temperature	°C	29		NASA
Earth temperature amplitude	°C	5.2		NASA

Month	Air temperature	Relative humidity	Precipitation	Daily solar radiation horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days 18 °C	Cooling degree-days 10 °C
	°C	%	mm	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January	26.7	77%	16.43	5.28	100.9	2.8	27.1	0	518
February	27.4	80%	27.44	5.49	100.8	3.4	27.9	0	487
March	27.8	83%	75.33	5.46	100.8	3.8	28.2	0	552
April	27.7	84.50%	142.5	5.21	100.8	3.9	28.2	0	531
May	27.3	85%	186.62	4.76	100.9	3.6	28	0	536
June	26.3	86.40%	248.4	4.04	101.1	4.2	26.9	0	489
July	25.1	87.10%	196.54	3.95	101.2	4.8	25.5	0	468
August	24.7	87.40%	118.11	3.98	101.2	4.8	25	0	456
September	25.2	88.20%	202.5	4.09	101.1	4.4	25.6	0	456
October	26	87%	177.01	4.55	101	3.6	26.7	0	496
November	27	82.80%	48.6	4.95	100.9	2.8	27.8	0	510
December	27	77.70%	20.77	5.17	100.9	2.5	27.5	0	527
Annual	**26.5**	**83.90%**	**1,460.25**	**4.74**	**101**	**3.7**	**27**	**0**	**6,026**
Source	**NASA**	**NASA**	**NASA**	**NASA**	**NASA**	**NASA**	**NASA**		**NASA**
Measures at					m	10	0		

Appendix C.6: Yearly Cash Flow Results from Financial Viability

Year #	Pre-tax $	Cumulative $
0	-83893.50	-83893.50
1	18052.48	-65841.02
2	18790.71	-47050.31
3	19543.71	-27506.61
4	20311.76	-7194.84
5	21095.18	13900.34
6	21894.27	35794.61
7	22709.34	58503.94
8	23540.71	82044.65
9	24388.70	106433.35
10	25253.66	131687.01
11	26135.92	157822.93
12	27035.82	184858.75
13	27953.72	212812.46
14	28889.97	241702.44
15	29844.96	271547.40
16	49678.19	321225.58
17	50671.75	371897.33
18	51685.19	423582.52
19	52718.89	476301.41
20	53773.27	530074.67

Appendix C.7: Line Performance Database

Where the key words are:

SHR: Shiroro Region
SRN: Serial Number
PCD: PACPLAN Code
NOM: Nomenclature
REG: Region
BAU: Bauchi
BEN: Benin Region
ENG: Enugu Region
KAD: Kaduna Region
LAG: Lagos Region
OSH: Osogbo Region
PHC: PortHarcourt Region

SRN	PCD	CIRCUIT	NOM	REG	No. of Circuit	Transmission line capacity (KW)	length of line (KM)	Conductor Size (mm2)	Conductor Type	Fro. Terminal	To. Terminal	Line Impedance (% on 100MVA)						Year of Installation
		330KV TRANSMISSION LINE DATABASE										**R1**	**X1**	**B1**	**R0**	**X0**	**B0**	
1	A5197512	Olorunsogo - Ikeja West	RIW	LAG	1	750000	46	$2x350mm^2$	BISON	T522	T459	0.005384	0.0404801	0.042209	0.12188	0.45	0.38	1975
2	A51A4513	Oshogbo Ikeja West	HIW	LAG	1	750000	250	$2x350mm^2$	BISON	T522	T465	0.011633	0.0874953	0.091327	0.28292	0.45	0.37	1975
3	A5198513	Omotosho Ikeja West	B5W	LAG	2	750000	168	$2x350mm^2$	BISON	T748	T500	0.011005	0.0827658	0.088391	0.24811	1.09	0.48	1981
4	A5144511	Ikeja West Sakete	NWIBS	LAG	1	750000	71	$2x350mm^2$	BISON	T121	T1							2007
5	A5133515	Oke-Aro/Ikeja West 1	N6W	LAG	1	760000	17.8	$2x350mm^2$	BISON	T1	T124	2.653566	19.957776	-0.049235	20.831481	59.971	-0.014879356	1984
6	A5133516	Oke-Aro/Ikeja West 2	N7W	LAG	1	760000	17.8	$2x350mm^2$	BISON	T1	T124	2.653566	19.957776	-0.049235394	20.831481	59.971	-0.014879356	1984
7	A5133517	Egbin/Ikeja West 3	N8W	LAG	1	760000	71	$2x350mm^2$	BISON	T1	T748	1.490166	11.473639	-0.085910533				2005
		132KV TRANSMISSION LINE DATABASE																
8	A514441C A514441D	Ikeja West / Otta	W25Q W26Q	LAG	2		12.24	250mm2	BEAR OR WORF	T1	T34	0.007042	0.0225738	0.018883	0.07755	0.18	0.1	1989
9	A5144417 A5144418	Ikeja West / Ejigbo	W31E W32E	LAG	2		13.68	250mm2	BEAR	T1	T38	0.00669	0.021499	0.22469	0.017938	0.0739	0.06	1988
10	A5144413 A5144414	Ikeja West / Agbara	W27Z W28Z	LAG	2		32.04	250mm2	BEAR	T1	T90	0.015493	0.049661	0.052022	0.041542	0.1706	0.22	1988
11	A5144415 A5144416	Ikeja West / Alimosho	W21L W22L	LAG	2		5.8	250mm2	BEAR	T1	T51	0.002465	0.0079007	0.006609	0.02714	0.05	0.03	1976
12	A5193411 A5193412	Ogba - Alausa		LAG	2		5.76	250mm2	BEAR	T51	T67	0.001108	0.0045147	0.003770	0.01551	0.03	0.03	1998
13	A514441E A514441F	Ikeja West / Oworoshoki		LAG	2			150mm2	BEAR	T1	T105							
14	A5144419 A514441A	Ikeja West / Ilupeju		LAG	2			150mm2	BEAR	T1	T97							1982
15	A5119411 A5119412	Alimosho / Ogba	WT18 W22B	LAG	2		16.25	250mm2	BEAR	T1	T31	0.060669	0.021444	0.017938	0.017938	0.0737	0.18	1976
16		Ikeja West/Ayobo	WOHL1 WOHL2	LAG	2		1	250mm2	BEAR	T1	T51	0.000702	0.00225	0.002365	0.007755	0.018	0.01	2014
17		Ogba/Otta					16.25											

APPENDIX D: PYTHON CODES FOR THE BLOCKCHAIN ENERGY TRADING PLATFORM PROGRAMS IN THIS STUDY

Appendix D.1: Python Code to Import Matlab/Simulink Results into Python Programming Environment

```
cd "C:\Program Files\MATLAB\R2017b"

cd extern\engines\python

import scipy.io as sio

###########################

#       Location 1       #

###########################

## Importing the output from solar PV1 distributed generation from Matlab/Simulink platform.

mat_contents1 = sio.loadmat('pv1.mat')

mat_contents1

# Displaying JUST the PV1 results excluding the other information that comes with it.

oct_PV1_Simout = mat_contents1['PV1_Simout']

oct_PV1_Simout

# Importing the output from load1 connected to PV1 local area in the Matlab/Simulink platform.

mat_contents4 = sio.loadmat('load1.mat')

mat_contents4

# Displaying JUST the load1 results excluding the other information that comes with it.

oct_LOAD1_250_kW = mat_contents4['LOAD1_250_kW']

oct_LOAD1_250_kW

import numpy as np

# Checking the array length of PV1 output

pv1=oct_PV1_Simout
```

```
len(pv1)

# Checking the array length of load1 output

load1=oct_LOAD1_250_kW

len(load1)

# The original array of pv1 is 19801 while the array of load1 is 361015

# Because the arrays of both PV1 and load1 are different,

# PV1-load1 subtraction cannot be done to analyse if there is surplus or deficient energy.

##temp_pv1 is a matrix of the size of load1 with zeros values

#To make PV1 the same size and shape as load1

temp_pv1=np.zeros(load1.shape)

#The new length of pv1 (i.e temp_pv1) is changed from 19801 array size to 361015 array size

#PV1 is now the same size and shape as load1

len(temp_pv1)

temp_pv1

#To the zero matrix, adding or appending the initial value of pv1

#The new value of temp_pv1 is with the size of load2 with values pv1

temp_pv1[:pv1.shape[0],:pv1.shape[1]]=pv1

#The new length of pv1 (i.e temp_pv1) is changed from 19801 array size to 361015 array size

len(temp_pv1)

temp_pv1

#The new size of pv1 is now temp_pv1

print(temp_pv1)

np.set_printoptions(edgeitems=3610)

#We can now subtract load1 from temp_pv1 (our resized pv1)
```

```
temp_pv1-load1

###########################

#       Location 2       #

###########################

## Importing the output from solar PV2 distributed generation from Matlab/Simulink platform.

mat_contents2 = sio.loadmat('pv2.mat')

mat_contents2

# Displaying JUST the PV2 results excluding the other information that comes with it.

oct_PV2_Simout = mat_contents2['PV2_Simout']

oct_PV2_Simout

# Importing the output from load2 connected to PV2 local area in the Matlab/Simulink platform.

mat_contents5 = sio.loadmat('load2.mat')

mat_contents5

# Displaying JUST the load2 results excluding the other information that comes with it.

oct_LOAD2_IKJ_Otta = mat_contents5['LOAD2_IKJ_Otta']

oct_LOAD2_IKJ_Otta

# Checking the array length of PV2 output

pv2=oct_PV2_Simout

len(pv2)

# Checking the array length of load2 output

load2=oct_LOAD2_IKJ_Otta

len(load2)

#The original array of PV2 is 19801 while the array of load2 is 361015

#Because the arrays of both PV2 and load2 are different,
```

```
# PV2-load2 subtraction cannot be done to analyse if there is surplus or deficient energy.

##temp_pv2 is a matrix of the size of load2 with zeros values

#To make PV2 the same size and shape as load2

temp_pv2=np.zeros(load2.shape)

#The new length of pv2 (i.e temp_pv2) is changed from 19801 array size to 361015 array size

#pv2 is now the same size and shape as load2

len(temp_pv2)

sorted(temp_pv2)

temp_pv2

#The new size of pv2 is now temp_pv2

print(temp_pv2)

np.set_printoptions(edgeitems=3610)

#We can now subtract load2 from temp_pv2 (our resized pv2)

temp_pv2-load2

###########################

#       Location 3       #

###########################

## Importing the output from solar PV3 distributed generation from Matlab/Simulink platform.

mat_contents3 = sio.loadmat('pv3.mat')

mat_contents3

# Displaying JUST the PV3 results excluding the other information that comes with it.

oct_PV3_Simout = mat_contents3['PV3_Simout']

oct_PV3_Simout

# Importing the output from load3 connected to PV3 local area in the Matlab/Simulink platform.
```

```
mat_contents6 = sio.loadmat('load3.mat')

mat_contents6

# Displaying JUST the load3 results excluding the other information that comes with it.

oct_LOAD3_IKJ_ALIM = mat_contents6['LOAD3_IKJ_ALIM']

oct_LOAD3_IKJ_ALIM

# Checking the array length of PV2 output

pv3=oct_PV3_Simout

len(pv3)

# Checking the array length of load2 output

load3=oct_LOAD3_IKJ_ALIM

len(load3)

#The original array of PV3 is 19801 while the array of load3 is 361015

#Because the arrays of both PV3 and load3 are different,

# PV3-load3 subtraction cannot be done to analyse if there is surplus or deficient
energy.

##temp_pv3 is a matrix of the size of load3 with zeros values

#To make PV3 the same size and shape as load3

temp_pv3=np.zeros(load3.shape)

#The new length of PV3 (i.e temp_pv3) is changed from 19801 array size to 361015
array size

#pv3 is now the same size and shape as load3

len(temp_pv3)

sorted(temp_pv3)

temp_pv3

#The new size of pv3 is now temp_pv3

print(temp_pv3)

np.set_printoptions(edgeitems=3610)
```

```
#We can now subtract load2 from temp_pv3 (our resized pv3)

temp_pv3-load3
```

Appendix D.2: Python Code to Establish Available Energy in The Trading Platform

```
#Change dimensions using shapes.

#functions can take less matrix. Array can be converted into matrix and then passed into functions

pv1=np.matrix(temp_pv1) #temp1 is solar pv panel 1

pn1=np.matrix(load1) #b1 is load1

pv2=np.matrix(temp_pv2) #temp2 is solar pv panel 2

pn2=np.matrix(load2) #b2 is load2

pv3=np.matrix(temp_pv3) #temp3 is solar pv panel 3

pn3=np.matrix(load3) #b3 is load3

## Where v1 = pv

## Where v2 = load

def any():

   return any()

def n():

   return n

def calcproducerA_Balance(v1, v2):  # Declaration of Producer energy storage level after meeting demand.

   ProducerA_Balance = v1 - v2

   print('Producer_A has __kWh of Energy available for sale (in kWh):')

   print(ProducerA_Balance)

   return ProducerA_Balance

def main4():

# Calculating the available energy producer has to sell.

# the n==1, etc is the menu where we can choose which panel

      n = int(input('Enter Panel number: '))
```

```
    #  b2 = float(input('Enter producer_A demand for stored energy (in kWh): '))

     if n==1:

        ProducerA_Balance = calcproducerA_Balance(pv1[:], pn1[:])

        print('producer_A currently has {ProducerA_Balance:.2f} kWh energy level left
in the storage system.'

     .format(**locals()))

     elif n==2:

           ProducerA_Balance = calcproducerA_Balance(pv2[:], pn2[:])

           print('producer_A currently has {ProducerA_Balance:.2f} kWh energy level
left in the storage system.'

     .format(**locals()))

     elif n==3:

           ProducerA_Balance = calcproducerA_Balance(pv3[:], pn3[:])

           print('producer_A currently has {ProducerA_Balance:.2f} kWh energy level
left in the storage system.'

     .format(**locals()))

     else:

           print('Choose panel 1 to 3')

main4()
```

Appendix D.3: Blockchain Platform Python Programming Codes

```
import hashlib

import datetime

class Block:

    def __init__(self, previous_block_hash, data, timestamp):

        self.previous_block_hash = previous_block_hash

        self.data = data

        self.timestamp = timestamp

        self.hash = self.get_hash()

@staticmethod

def create_genesis_block():

    return Block("0", "0", datetime.datetime.now())

def get_hash(self):

    header_bin = (str(self.previous_block_hash) +

                str(self.data) +

                str(self.timestamp)).encode()

    inner_hash = hashlib.sha256(header_bin).hexdigest().encode()

    outer_hash = hashlib.sha256(inner_hash).hexdigest()

    return outer_hash

from block import Block

import datetime

b1 = Block.create_genesis_block()

print(b1.hash)

block_chain = [Block.create_genesis_block()]

print("The genesis block has been created!")

print("Hash: %s" % block_chain[-1].hash)
```

```
num_blocks_to_add = 10

for i in range (1, num_blocks_to_add+1):
    block_chain.append(Block(block_chain[-1].hash,
                        "DATA!",
                        datetime.datetime.now()))
    print("Block #%d has been created." % i)
    print("Block #%d hash: %s" % (i, block_chain[i].hash))
```

Appendix D.3.1: Blockchain Hash Values for Ten Empty Blockchain Transaction Block

```
from block import Block
import datetime
num_blocks_to_add = 10
block_chain = [Block.create_genesis_block()]
print("The genesis block has been created.")
print("Hash: %s" % block_chain[0].hash)
for i in range(1, num_blocks_to_add):
    block_chain.append(Block(block_chain[i-1].hash,
                        "Block number %d" % i,
                        datetime.datetime.now()))
    print("Block #%d created." % i)
    print("Hash: %s" % block_chain[-1].hash)
```

The output of the above code is seen below:

The genesis block has been created.

Hash: 2f67d33ce9e0f875d57e7e8eed66abec7ae74535811a095294743ea3d3f81778

Block #1 created.

Hash: a8133f501818b93c0a9d3d0c7b16e83f50cd77ccb381cc61ec63289cbb24dfb8

Block #2 created.

Hash: 8ed69aa5f3712b843a5b8e31d86a4e9d15e7550d1f302986f02716de14f899a6

Block #3 created.

Hash: 93b5dec8a7d352faa1f66169c34ebfd2ccc0aeb73503bf1444dfcb755cfd624f

Block #4 created.

Hash: 766e93198e2c941490476ec912c382d14fcc9e36387755a3963502417eac6c22

Block #5 created.

Hash: 2fc998f3ca0748a5fc133ee303d7d3b11fe076d2156ab0ac9294af4b85efdcf4

Block #6 created.

Hash: 2fb0a8ce448712dd357d789454b12c3c4cad23871d39f6e818c3d67a925a0b73

Block #7 created.

Hash: 0794bec21fc4a45a00c6fae32fafdd1a330bfe78237e58a0c8739298e8daf667

Block #8 created.

Hash: c869d5cb132007ccdddba1713f1490f176fad2dc4ff2f81a25bc6327cb88ef73

Block #9 created.

Hash: 19a6e8171b8d3b4973f91d8e693d5dfeae15fa80a0af6933988e15b1561c27d2

Appendix D.4: Blockchain Python Program to Get the Total Energy Each Producer Has Available in The Central Battery Energy Storage System (Bess) At Different Time of The Day

```
num_blocks_to_add = 1 # To add more elements to our block_chain (e.g 10 elements)

for i in range (1, num_blocks_to_add+1): # We create all our blocks here

   i = 1

   # where1 is the genesis block in our list (i.e. in "[Block.create_genesis_block()]")

# append means to add (i.e. create) another block in our block_chain

   block_chain.append(Block(block_chain[-1].hash,  # (block_chain[-1].hash) means
the previous block

                        "DATA!",

                        datetime.datetime.now()))

   print("Block #%d has been created." % i)

## producer 1 surplus energy in the storage at different time of the generation period.

print('NEXT ALGORITHM: PRODUCER A1 - TOTAL STORAGE LEVEL:
Calculating Producer A1 total energy stored in the battery storage system.'

      .format(**locals()))

def calcStorage_Fee_1(sum, StorageFee_Rate):  # Producer Storage Fee for storing __
energy in ESS till it is sold.

      return StorageFee_Rate

def AddProducerA1SurplusinStorageGrid(A1):

   return A1

def main1():

   for A1 in range(1, 6, 2): # Where 1 => start level, 6 => final level for period t, and 2
=> energy rise level

      sum = AddProducerA1SurplusinStorageGrid(A1)

      print('Producer 1 total surplus energy in the Storage (kW):')

      print(sum)
```

```
        # Storage fee cost for the grid operator to keep the surplus energy for the producer
till when needed.

            # Calculating the producer storage fee bill.

        StorageFee_Rate = float(input('Enter storage fee for the grid operator management
till when producer_A decide to sell (in cents_USD): '))

        Storage_Quote = calcStorage_Fee_1(sum, StorageFee_Rate)

        print('Producer_A1 storage bill for ESS total energy of {sum:.2f} is
{Storage_Quote:.2f}_cents USD at a storage fee rate of {StorageFee_Rate:.2f}_cents
USD.'

        .format(**locals()))

main1()

print("Block #%d hash: %s" % (i, block_chain[i].hash))
```

The output of the above code is seen below:

Block #1 has been created.

NEXT ALGORITHM: PRODUCER A1 - TOTAL STORAGE LEVEL: Calculating Producer A1 total energy stored in the battery storage system.

Producer 1 total surplus energy in the Storage (kW):

1

Enter storage fee for the grid operator management till when producer_A decide to sell (in cents_USD): 12

Producer_A1 storage bill for ESS total energy of 1.00 is 12.00_cents USD at a storage fee rate of 12.00_cents USD.

Producer 1 total surplus energy in the Storage (kW):

3

Enter storage fee for the grid operator management till when producer_A decide to sell (in cents_USD): 12

Producer_A1 storage bill for ESS total energy of 3.00 is 12.00_cents USD at a storage fee rate of 12.00_cents USD.

Producer 1 total surplus energy in the Storage (kW):

5

Enter storage fee for the grid operator management till when producer_A decide to sell (in cents_USD): 12

Producer_A1 storage bill for ESS total energy of 5.00 is 12.00_cents USD at a storage fee rate of 12.00_cents USD.

Block #1 hash:

aa1f0766830760fb0ff22fe40070dff19a823d64b791f3ae2e061d22544f9829

Appendix D.5: Blockchain Python Program to Get the Total Energy in The Central Battery Storage

```
num_blocks_to_add = 1 # To add more elements to our block_chain (e.g 10 elements)

for i in range (1, num_blocks_to_add+1): # We create all our blocks here

   i = 4

   # where1 is the genesis block in our list (i.e. in "[Block.create_genesis_block()]")

# append means to add (i.e. create) another block in our block_chain

   block_chain.append(Block(block_chain[-1].hash,  # (block_chain[-1].hash) means
the previous block

                        "DATA!",

                        datetime.datetime.now()))

   print("Block #%d has been created." % i)

## Total storage level.

print('NEXT ALGORITHM: TOTAL STORAGE LEVEL: Calculating the total energy
storage system level.'

      .format(**locals()))

def AddTotal_ESS_Level(A1_Storage_Quantity, A2_Storage_Quantity,
A3_Storage_Quantity):

   return A1_Storage_Quantity + A2_Storage_Quantity + A3_Storage_Quantity

def main():

      A1_Storage_Quantity = float(input('Enter Producer A1 energy level in ESS for
period t (in kWh): '))

      A2_Storage_Quantity = float(input('Enter Producer A2 energy level in ESS for
period t (in kWh): '))

      A3_Storage_Quantity = float(input('Enter Producer A3 energy level in ESS for
period t (in kWh): '))

      Total_Storage_Level = AddTotal_ESS_Level(A1_Storage_Quantity,
A2_Storage_Quantity, A3_Storage_Quantity)

      print('Total energy in the ESS is {Total_Storage_Level:.2f}_kWh for period t.'

      .format(**locals()))
```

```
main()

print("Block #%d hash: %s" % (i, block_chain[i].hash))
```

The output of the above code is seen below:

```
Block #4 has been created.

NEXT ALGORITHM: TOTAL STORAGE LEVEL: Calculating the total energy
storage system level.

Enter Producer A1 energy level in ESS for period t (in kWh): 12

Enter Producer A2 energy level in ESS for period t (in kWh): 17

Enter Producer A3 energy level in ESS for period t (in kWh): 15

Total energy in the ESS is 44.00_kWh for period t.

Block #4 hash:
11ed42f7c86456aef016512c2b502009d62c3072fbb59dd344f2c4533e8b4995
```

Appendix D.6: Algorithm for Generators to Request for Part of Stored Energy from Storage System and Declare the Leftover Available for Sale on The Blockchain Trading Platform

```
num_blocks_to_add = 1 # To add more elements to our block_chain (e.g 10 elements)

for i in range (1, num_blocks_to_add+1): # We create all our blocks here

   i = 5

   # where1 is the genesis block in our list (i.e. in "[Block.create_genesis_block()]")

# append means to add (i.e. create) another block in our block_chain

   block_chain.append(Block(block_chain[-1].hash,  # (block_chain[-1].hash) means
the previous block

                        "DATA!",

                        datetime.datetime.now()))

   print("Block #%d has been created." % i)

## ProducerA energy balance in the storage after demand back some of the initially
deposited energy to the storage system.

   # A_Surplus => Initial Excess energy in the energy storage system (ESS).

   # A_Demand => Load demand requiring stored energy in the ESS via the grid
operator.

print('NEXT ALGORITHM: PRODUCER A1 - LEFTOVER: Calculating Producer A1
remaining energy stored in the battery storage system after requesting for some from the
grid operator.'

      .format(**locals()))

def calcproducerA_Balance(A_Surplus, A_Demand):  # Declaration of Producer energy
storage level after meeting demand.

      if A_Surplus > A_Demand:

            ProducerA_Balance = A_Surplus - A_Demand

            print('Energy available for sale (in kW):')

            print(ProducerA_Balance)

      else:

            A_Surplus == A_Demand
```

```
            print('Producer_An has no stored energy to sell')

            ProducerA_Balance = A_Surplus - A_Demand

            print(ProducerA_Balance)

        return ProducerA_Balance

def main4():

# Calculating the available energy producer has to sell.

        A_Surplus = float(input('Enter producer_A surplus energy in storage (in kWh): '))

        A_Demand = float(input('Enter producer_A demand for stored energy (in kWh): '))

        ProducerA_Balance = calcproducerA_Balance(A_Surplus, A_Demand)

        print('producer_A currently has {ProducerA_Balance:.2f} kWh energy level left in
the storage system.'

        .format(**locals()))

main4()

print("Block #%d hash: %s" % (i, block_chain[i].hash))
```

The output of the above code is seen below:

```
Block #5 has been created.

NEXT ALGORITHM: PRODUCER A1 - LEFTOVER: Calculating Producer A1
remaining energy stored in the battery storage system after requesting for some from the
grid operator.

Enter producer_A surplus energy in storage (in kWh): 30

Enter producer_A demand for stored energy (in kWh): 10

Energy available for sale (in kW):

20.0

producer_A currently has 20.00 kWh energy level left in the storage system.

Block #5 hash:
ba51964da8609a3d6085b74ae78b633d76dd54ce48d830d2112670a9c917d7b9
```

Appendix D.7: Algorithm to Demonstrate the Energy Trading Between Solar PV Energy Distributed Generator and The Grid Operator

```
num_blocks_to_add = 1 # To add more elements to our block_chain (e.g 10 elements)

for i in range (1, num_blocks_to_add+1): # We create all our blocks here

   i = 6

   # where1 is the genesis block in our list (i.e. in "[Block.create_genesis_block()]")

# append means to add (i.e. create) another block in our block_chain

   block_chain.append(Block(block_chain[-1].hash,  # (block_chain[-1].hash) means
the previous block

                       "DATA!",

                       datetime.datetime.now()))

   print("Block #%d has been created." % i)

## Energy trading transaction between producer An and Grid Operator.

# An_Surplus => Producer_An excess energy stored in the energy storage system
(ESS).

# An_Demand => the amount of energy producer_An request back from his stored
energy in the ESS.

# ProducerAn_LeftOver => amount of energy producer_An has left and available in the
ESS to sell to anyone.

# WholesaleRate => the transactions between producers and grid operators attracts an
wholesale pricing rate of 12 cents USD/kWh.

# StorageFee => storage fee rate of 12 cents USD/kWh for the grid operator managing
producer stored energy in the ESS till when producer decided to sell.

print('NEXT ALGORITHM: Energy trading transaction between producer An and Grid
Operator.'

      .format(**locals()))

def calcproducerAnTransactionProfit(ProducerAn_LeftOver, WholesaleRate,
StorageFee):

      return (ProducerAn_LeftOver * WholesaleRate) - StorageFee

def calcproducerAn_LeftOver(An_Surplus, An_Demand):
```

```
    if An_Surplus > An_Demand:
        ProducerAn_LeftOver = An_Surplus - An_Demand
        print('Energy available for sale (in kWh):')
        print(ProducerAn_LeftOver)
    else:
        An_Surplus == An_Demand
        print('Producer_An has no stored energy to sell')
        ProducerAn_LeftOver = An_Surplus - An_Demand
        print(ProducerAn_LeftOver)
    return ProducerAn_LeftOver
def main5():
    # Calculating the amount of energy producer_An wants to sell.
    An_Surplus = float(input('Enter producer_An surplus energy in storage (in kWh):
'))
    An_Demand = float(input('Enter producer_An demand for stored energy (kWh): '))
    ProducerAn_LeftOver = calcproducerAn_LeftOver(An_Surplus, An_Demand)
    print('producer_An LeftOver energy in storage is {ProducerAn_LeftOver:.2f}
kWh.'
    .format(**locals()))
    # Calculating the final producer profit for trading with grid operators.
    WholesaleRate = float(input('Enter wholesale rate to sell leftover to grid operators
(in cents_USD/kWh): '))
    StorageFee = float(input('Enter storage fee for the grid operator managing producer
stored energy in the ESS till when producer decided to sell (in cents_USD): '))
    total = calcproducerAnTransactionProfit(ProducerAn_LeftOver, WholesaleRate,
StorageFee)
    print('producer profit for selling {ProducerAn_LeftOver:.2f} at
{WholesaleRate:.2f}_cents USD to grid operator after deducting the storage fee of
{StorageFee:.2f}_cents USD is {total:.2f}_cents USD.'
```

```
    .format(**locals()))
main5()
print("Block #%d hash: %s" % (i, block_chain[i].hash))
```

The output of the above code is seen below:

Block #6 has been created.

NEXT ALGORITHM: Energy trading transaction between producer An and Grid Operator.

Enter producer_An surplus energy in storage (in kWh): 30

Enter producer_An demand for stored energy (kWh): 10

Energy available for sale (in kWh):

20.0

producer_An LeftOver energy in storage is 20.00 kWh.

Enter wholesale rate to sell leftover to grid operators (in cents_USD/kWh): 12

Enter storage fee for the grid operator managing producer stored energy in the ESS till when producer decided to sell (in cents_USD): 12

producer profit for selling 20.00 at 12.00_cents USD to grid operator after deducting the storage fee of 12.00_cents USD is 228.00_cents USD.

Block #6 hash:
8ac9ab48cef95238d922aab42cef1504361de51eaf3f29cd5327278e6f483895

Appendix D.8: Algorithm to Demonstrate the Energy Trading Between Solar PV Energy Distributed Generator and The Grid Users

```
num_blocks_to_add = 1 # To add more elements to our block_chain (e.g 10 elements)

for i in range (1, num_blocks_to_add+1): # We create all our blocks here

   i = 7

   # where1 is the genesis block in our list (i.e. in "[Block.create_genesis_block()]")

# append means to add (i.e. create) another block in our block_chain

   block_chain.append(Block(block_chain[-1].hash,  # (block_chain[-1].hash) means the previous block

                         "DATA!",

                         datetime.datetime.now()))

   print("Block #%d has been created." % i)

## Energy trading transaction between producer An and Grid User Bn.

# An_Surplus1 => Producer_An excess energy stored in the energy storage system (ESS).

# An_Demand1 => the amount of energy producer_An request back from his stored energy in the ESS.

# ProducerAn_LeftOver1 => amount of energy producer_An has left and available in the ESS to sell to anyone.

# RetailRate => the transactions between producers and grid operators attracts an wholesale pricing rate of 12 cents USD/kWh.

# StorageFee => storage fee rate of 12 cents USD/kWh for the grid operator managing producer stored energy in the ESS till when producer decided to sell.

# CommissionRate => Grid operator commission for acting as middleman between buyer and seller.

print('NEXT ALGORITHM: Energy trading transaction between producer An and Grid User Bn.'

      .format(**locals()))

def calcproducerAn_BnProfit(User_Quote, Grid_Commission, Storage_Quote):   # Producer Final Profit for selling energy to grid user.

      return User_Quote - Grid_Commission - Storage_Quote
```

```
def calcStorage_Fee(ProducerAn_LeftOver1, StorageFee_Rate):  # Producer Storage Fee for storing __ energy in ESS till it is sold.

    return StorageFee_Rate

def calcproducerAn_GnCommission(User_Quote, CommissionRate):   # Grid Operator Commission Fee as middleman.

    return User_Quote * CommissionRate

def calcproducerAn_BnTransactionProfit(ProducerAn_LeftOver1, RetailRate):   # Grid_User Quote to buy to __ energy from producer via the grid operator.

    return ProducerAn_LeftOver1 * RetailRate

def calcproducerAn_LeftOver1(An_Surplus1, An_Demand1):  # Declaration of Producer available energy for sale.

    if An_Surplus1 > An_Demand1:

        ProducerAn_LeftOver1 = An_Surplus1 - An_Demand1

        print('Energy available for sale (in kW):')

        print(ProducerAn_LeftOver1)

    else:

        An_Surplus1 == An_Demand1

        print('Producer_An has no stored energy to sell')

        ProducerAn_LeftOver1 = An_Surplus1 - An_Demand1

        print(ProducerAn_LeftOver1)

    return ProducerAn_LeftOver1

def calcGridUserBn_Need(Bn_Demand):  # Declaration of Grid user declares amount of energy wanting to buy from producers.

    if Bn_Demand > 0:

        GridUserBn_Need = Bn_Demand - 0

        print('I want to buy ___ amount of energy from producers (in kW):')

        print(GridUserBn_Need)

    return GridUserBn_Need
```

```
def main6a():

    # Calculating the available energy producer has to sell.

    An_Surplus1 = float(input('Enter producer_An surplus energy in storage (in kWh):
'))

    An_Demand1 = float(input('Enter producer_An demand for stored energy (in
kWh): '))

    RetailRate = float(input('Enter retail rate to sell leftover to grid_users_Bn (in
cents_USD/kWh): '))

    ProducerAn_LeftOver1 = calcproducerAn_LeftOver1(An_Surplus1,
An_Demand1)

    print('producer_An has {ProducerAn_LeftOver1:.2f} kWh of energy available to
sell at {RetailRate:.2f}_cents USD to the grid user.'

    .format(**locals()))

    # Calculating the amount of energy grid user wants to buy.

    Bn_Demand = float(input('Enter grid user energy demand to buy (in kWh): '))

    GridUserBn_Need = calcGridUserBn_Need(Bn_Demand)

    print('Grid_User_Bn wants to buy {GridUserBn_Need:.2f}_kWh worth of energy
from producer_An at a retail rate of {RetailRate:.2f}_cents USD.'

    .format(**locals()))

    # Calculating the grid user quote to buy __ energy from seller (producer_An).

    RetailRate = float(input('Enter retail rate to sell leftover to grid users (in
cents_USD/kWh): '))

    User_Quote = calcproducerAn_BnTransactionProfit(Bn_Demand, RetailRate)

    print('Grid operator bills the grid_user_Bn {User_Quote:.2f}_cents USD to get
{Bn_Demand:.2f} that he needs from producer_An at a retail rate of
{RetailRate:.2f}_cents USD.'

    .format(**locals()))

    # Calculating the grid operator commission fee.

    CommissionRate = float(input('Enter grid operator commission fee for acting as
middle man between buyer and seller (in %): '))
```

```
        Grid_Commission = calcproducerAn_GnCommission(User_Quote,
CommissionRate)

        print('Grid operator commission fee is {Grid_Commission:.2f}_cents USD at a
commission rate of {CommissionRate:.2f}_cents USD.'

        .format(**locals()))

        # Calculating the producer storage fee bill.

        StorageFee_Rate = float(input('Enter storage fee for the grid operator managing
producer stored energy in the ESS till when producer decided to sell (in cents_USD): '))

        Storage_Quote = calcStorage_Fee(ProducerAn_LeftOver1, StorageFee_Rate)

        print('Producer storage bill is {Storage_Quote:.2f}_cents USD at a storage fee rate
of {StorageFee_Rate:.2f}_cents USD.'

        .format(**locals()))

        # Calculating the final producer profit for trading with grid_user Bn.

        User_Quote = float(input('Enter bill grid user paid the grid operator to buy __
energy from seller (producer) (in cents_USD): '))

        Grid_Commission = float(input('Enter commission of grid operator as middleman
between buyer and seller (in cents_USD): '))

        Storage_Quote = float(input('Enter cost of storing the __ amount of energy grid
user bought from seller prior to selling (in cents_USD/kWh): '))

        ProducerAn_Profit = calcproducerAn_BnProfit(User_Quote, Grid_Commission,
Storage_Quote)

        print('Final Producer profit for doing business with grid user is
{ProducerAn_Profit:.2f}_cents USD.'

        .format(**locals()))

main6a()

print("Block #%d hash: %s" % (i, block_chain[i].hash))
```

The output of the above code is seen below:

```
Block #7 has been created.

Enter producer_An surplus energy in storage (in kWh): 45
```

Enter producer_An demand for stored energy (in kWh): 15

Enter retail rate to sell leftover to grid_users_Bn (in cents_USD/kWh): 15

Energy available for sale (in kW):

30.0

producer_An has 30.00 kWh of energy available to sell at 15.00_cents USD to the grid user.

Enter grid user energy demand to buy (in kWh): 20

I want to buy ___ amount of energy from producers (in kW):

20.0

Grid_User_Bn wants to buy 20.00_kWh worth of energy from producer_An at a retail rate of 15.00_cents USD.

Enter retail rate to sell leftover to grid users (in cents_USD/kWh): 15

Grid operator bills the grid_user_Bn 300.00_cents USD to get 20.00 that he needs from producer_An at a retail rate of 15.00_cents USD.

Enter grid operator commission fee for acting as middle man between buyer and seller (in %): 0.1

Grid operator commission fee is 30.00_cents USD at a commission rate of 0.10_cents USD.

Enter storage fee for the grid operator managing producer stored energy in the ESS till when producer decided to sell (in cents_USD): 12

Producer storage bill is 12.00_cents USD at a storage fee rate of 12.00_cents USD.

Enter bill grid user paid the grid operator to buy __ energy from seller (producer) (in cents_USD): 300

Enter commission of grid operator as middleman between buyer and seller (in cents_USD): 30

Enter cost of storing the __ amount of energy grid user bought from seller prior to selling (in cents_USD/kWh): 12

Final Producer profit for doing business with grid user is 258.00_cents USD.

Block #7 hash:
e3be3986f612621d6a6aff5005fd223db36ec5644d1d386e47da83fbc5d190dd

Appendix D.9: Algorithm to Demonstrate the Energy Trading Between Two Solar PV Energy Distributed Generators

```
num_blocks_to_add = 1 # To add more elements to our block_chain (e.g 10 elements)

for i in range (1, num_blocks_to_add+1): # We create all our blocks here

   i = 8

   # where1 is the genesis block in our list (i.e. in "[Block.create_genesis_block()]")

# append means to add (i.e. create) another block in our block_chain

   block_chain.append(Block(block_chain[-1].hash,  # (block_chain[-1].hash) means the previous block

                          "DATA!",

                          datetime.datetime.now()))

   print("Block #%d has been created." % i)

## Energy trading transaction between producer_An_2a and producer_An_2b.

# ProducerAn_2a => Producer 1.

# ProducerAn_2b => Producer 2.

# An_2a_Generation => Producer 1 generation

# An_2b_Generation => Producer 2 generation

# An_2a_Demand => Producer 1 demand

# An_2b_Demand => Producer 2 demand

# ProducerAn_2a_Output_Bought => Producer 1 energy bought

# ProducerAn_2b_Output_Bought => Producer 2 energy bought

# WholesaleRate => the transactions between producers attracts a wholesale pricing rate of 12 cents USD/kWh.

# GnCommission => Grid Commission

# StorageFee => storage fee rate of 12 cents USD/kWh for the grid operator managing producer stored energy in the ESS till when producer decided to sell.

# CommissionRate => Grid operator commission for acting as middleman between buyer and seller (10% i.e. 0.1).
```

```
print('NEXT ALGORITHM: Energy trading transaction between producer_An_2a (buyer) and producer_An_2b (seller).'

    .format(**locals()))

def calcproducerAn_2a_Profit(ProducerAn_2a_Quote, Grid_Commission, Storage_Quote):   # ProducerAn_2a Final Profit for selling energy to buyer (producer).

    return ProducerAn_2a_Quote - Grid_Commission - Storage_Quote

def calcStorage_Fee_1a(ProducerAn_2a_Output_Bought, StorageFee_Rate):  # ProducerAn_2a Storage Fee for storing __ energy in ESS till it is sold.

    return StorageFee_Rate

def calcproducerAn_2a_GnCommission(ProducerAn_2a_Quote, CommissionRate):   # Grid Operator Commission Fee as middleman.

    return ProducerAn_2a_Quote * CommissionRate

def calcproducerAn_2a_Bought(ProducerAn_2a_Output_Bought):   # Energy Buyer decide to buy

    return ProducerAn_2a_Output_Bought

def calcproducerAn_2a_Quote(ProducerAn_2a_Output_Bought, WholesaleRate):   # Quote for Buyer

    return ProducerAn_2a_Output_Bought * WholesaleRate

###########

def calcproducerAn_2b_Profit(ProducerAn_2b_Quote, Grid_Commission, Storage_Quote):   # ProducerAn_2b Final Profit for selling energy to buyer (producer).

    return ProducerAn_2b_Quote - Grid_Commission - Storage_Quote

def calcStorage_Fee_1b(ProducerAn_2b_Output_Bought, StorageFee_Rate):  # ProducerAn_2b Storage Fee for storing __ energy in ESS till it is sold.

    return StorageFee_Rate

def calcproducerAn_2b_GnCommission(ProducerAn_2b_Quote, CommissionRate):   # Grid Operator Commission Fee as middleman.

    return ProducerAn_2b_Quote * CommissionRate

def calcproducerAn_2b_Bought(ProducerAn_2b_Output_Bought):   # Energy Buyer decide to buy

    return ProducerAn_2b_Output_Bought
```

```
def calcproducerAn_2b_Quote(ProducerAn_2b_Output_Bought, WholesaleRate):   # Quote for Buyer

    return ProducerAn_2b_Output_Bought * WholesaleRate

###########

def calcproducerAn_2a_Output(An_2a_Generation, An_2a_Demand):  # Producer 1 => ProducerAn_2a

    if An_2a_Generation > An_2a_Demand:     # Excess

      ProducerAn_2a_Output = An_2a_Generation - An_2a_Demand

      print('ProducerAn_2a has energy available for sale (in kW): ')

      print(ProducerAn_2a_Output)

    else:

      An_2a_Generation < An_2a_Demand # Deficiency

      ProducerAn_2a_Output = An_2a_Demand - An_2a_Generation

      print('ProducerAn_2a Generation is less than Demand (in kW): ')

      print(ProducerAn_2a_Output)

    return ProducerAn_2a_Output

def calcproducerAn_2b_Output(An_2b_Generation, An_2b_Demand):  # Producer 2 => ProducerAn_2b

    if An_2b_Generation < An_2b_Demand:     # Deficiency

      ProducerAn_2b_Output = An_2b_Demand - An_2b_Generation

      print('ProducerAn_2b Generation is less than Demand (in kW): ')

      print(ProducerAn_2b_Output)

    else:

      An_2b_Generation > An_2b_Demand # Excess

      ProducerAn_2b_Output = An_2b_Generation - An_2b_Demand

      print('ProducerAn_2b has energy available for sale (in kW): ')

      print(ProducerAn_2b_Output)
```

```
        return ProducerAn_2b_Output

def main7():

    # if (An_2a_Generation < An_2a_Demand) && (An_2b_Generation > An_2b_Demand):

        # Calculating the Amount and Quote of energy ProducerAn_2a wants to buy from ProducerAn_2b.

            # Declaration by producerAn_2a on the need to purchase __ (kWh) energy.

            An_2a_Generation = float(input('Enter producerAn_2a (buyer) generation output stored in the ESS (in kWh): '))   # Deficiency

            An_2a_Demand = float(input('Enter producerAn_2a (buyer) demand for energy (in kWh): '))

            WholesaleRate = float(input('Enter wholesale rate to buy excess energy from other producers (in cents_USD/kWh): '))

            ProducerAn_2a_Output = calcproducerAn_2a_Output(An_2a_Generation, An_2a_Demand)

            print('ProducerAn_2a (buyer): I want to buy {ProducerAn_2a_Output:.2f} kWh of energy from other producers at the wholesale rate of {WholesaleRate:.2f}_cents USD to meet my load demand.'

            .format(**locals()))

            # Declaration by producerAn_2b to sell __ (kWh) energy.

            An_2b_Generation = float(input('Enter producerAn_2b (seller) generation output stored in the ESS (in kWh): '))   # Excess

            An_2b_Demand = float(input('Enter producerAn_2b (seller) demand for energy (in kWh): '))

            WholesaleRate = float(input('Enter wholesale rate to sell excess energy to other producers (in cents_USD/kWh): '))

            ProducerAn_2b_Output = calcproducerAn_2b_Output(An_2b_Generation, An_2b_Demand)

            print('producerAn_2b (seller) has {ProducerAn_2b_Output:.2f} kWh of energy available to sell at the wholesale rate of {WholesaleRate:.2f}_cents USD to other producers (buyers).'

            .format(**locals()))
```

```
# Calculating the Quote of __ (cents_USD/kWh) for the __ (kWh) energy producerAn_2a agrees to buy.

ProducerAn_2b_Output = float(input('Enter producerAn_2b (seller) has __ amount of energy to sell (in kWh): '))

ProducerAn_2a_Output_Bought = float(input('Enter producerAn_2a (buyer) wants to buy __ amount of energy from producerAn_2b (seller) (in kWh): '))

WholesaleRate = float(input('Enter wholesale rate to sell excess energy to producerAn_2a (buyer) (in cents_USD/kWh): '))

ProducerAn_2a_Output_Bought = calcproducerAn_2a_Bought(ProducerAn_2a_Output_Bought)

ProducerAn_2a_Quote = calcproducerAn_2a_Quote(ProducerAn_2a_Output_Bought, WholesaleRate)

print('producerAn_2a (buyer) agrees to buy {ProducerAn_2a_Output_Bought:.2f} kWh of energy for {ProducerAn_2a_Quote:.2f} cents_USD/kWh at the wholesale rate of {WholesaleRate:.2f}_cents USD from producerAn_2b (seller).'

.format(**locals()))

# Calculating the bill of __ (cents_USD/kWh) that producerAn_2a pays to buy __ (kWh) energy .

ProducerAn_2a_Quote = calcproducerAn_2a_Quote(ProducerAn_2a_Output_Bought, WholesaleRate)

print('producerAn_2a (buyer) pays {ProducerAn_2a_Quote:.2f} cents_USD/kWh to buy {ProducerAn_2a_Output_Bought:.2f} kWh of energy at the wholesale rate of {WholesaleRate:.2f}_cents USD from producerAn_2b (seller).'

.format(**locals()))

# Calculating the Grid Operator Commission Fee when ProducerAn_2b sells energy.

CommissionRate = float(input('Enter grid operator commission fee for acting as middle man between buyer and seller (in %): '))

Grid_Commission = calcproducerAn_2b_GnCommission(ProducerAn_2a_Quote, CommissionRate)

print('Grid operator commission fee is {Grid_Commission:.2f}_cents USD at a commission rate of {CommissionRate:.2f}_cents USD.'

.format(**locals()))
```

```
        # Calculating the ProducerAn_2b Storage Fee Bill.

        StorageFee_Rate = float(input('Enter storage fee for the grid operator managing
producer stored energy in the ESS till when ProducerAn_2b (seller) decided to sell (in
cents_USD): '))

        Storage_Quote = calcStorage_Fee_1a(ProducerAn_2a_Output_Bought,
StorageFee_Rate)

        print('ProducerAn_2b (seller) storage bill is {Storage_Quote:.2f}_cents USD at
a storage fee rate of {StorageFee_Rate:.2f}_cents USD.'

        .format(**locals()))

        # Calculating the final ProducerAn_2b profit for trading with buyer(producer).

        ProducerAn_2b_Bought = float(input('Enter bill ProducerAn_2a (buyer) paid
the grid operator __ (cents_USD) to buy __ (kWh) energy from seller (producer) (in
cents_USD): '))

        Grid_Commission = float(input('Enter commission of grid operator as
middleman between buyer and seller (in cents_USD): '))

        Storage_Quote = float(input('Enter cost of storing the __ (kWh) energy till buyer
bought energy from seller prior to selling (in cents_USD/kWh): '))

        ProducerAn_2b_Profit = calcproducerAn_2b_Profit(ProducerAn_2b_Bought,
Grid_Commission, Storage_Quote)

        print('Final ProducerAn_2b (seller) profit for doing business with buyer
(producer) is {ProducerAn_2b_Profit:.2f}_cents USD.'

        .format(**locals()))

###########

main7()

print("Block #%d hash: %s" % (i, block_chain[i].hash))
```

The output of the above code is seen below:

Block #8 has been created.

NEXT ALGORITHM: Energy trading transaction between producer_An_2a (buyer) and producer_An_2b (seller).

Enter producerAn_2a (buyer) generation output stored in the ESS (in kWh): 20

Enter producerAn_2a (buyer) demand for energy (in kWh): 35

Enter wholesale rate to buy excess energy from other producers (in cents_USD/kWh): 12

ProducerAn_2a Generation is less than Demand (in kW):

15.0

ProducerAn_2a (buyer): I want to buy 15.00 kWh of energy from other producers at the wholesale rate of 12.00_cents USD to meet my load demand.

Enter producerAn_2b (seller) generation output stored in the ESS (in kWh): 48

Enter producerAn_2b (seller) demand for energy (in kWh): 10

Enter wholesale rate to sell excess energy to other producers (in cents_USD/kWh): 12

ProducerAn_2b has energy available for sale (in kW):

38.0

producerAn_2b (seller) has 38.00 kWh of energy available to sell at the wholesale rate of 12.00_cents USD to other producers (buyers).

Enter producerAn_2b (seller) has __ amount of energy to sell (in kWh): 38

Enter producerAn_2a (buyer) wants to buy __ amount of energy from producerAn_2b (seller) (in kWh): 15

Enter wholesale rate to sell excess energy to producerAn_2a (buyer) (in cents_USD/kWh): 12

producerAn_2a (buyer) agrees to buy 15.00 kWh of energy for 180.00 cents_USD/kWh at the wholesale rate of 12.00_cents USD from producerAn_2b (seller).

producerAn_2a (buyer) pays 180.00 cents_USD/kWh to buy 15.00 kWh of energy at the wholesale rate of 12.00_cents USD from producerAn_2b (seller).

Enter grid operator commission fee for acting as middleman between buyer and seller (in %): 0.1

Grid operator commission fee is 18.00_cents USD at a commission rate of 0.10_cents USD.

Enter storage fee for the grid operator managing producer stored energy in the ESS till when ProducerAn_2b (seller) decided to sell (in cents_USD): 12

ProducerAn_2b (seller) storage bill is 12.00_cents USD at a storage fee rate of 12.00_cents USD.

Enter bill ProducerAn_2a (buyer) paid the grid operator __ (cents_USD) to buy __ (kWh) energy from seller (producer) (in cents_USD): 180

Enter commission of grid operator as middleman between buyer and seller (in cents_USD): 0.10

Enter cost of storing the __ (kWh) energy till buyer bought energy from seller prior to selling (in cents_USD/kWh): 12

Final ProducerAn_2b (seller) profit for doing business with buyer (producer) is 167.90_cents USD.

Block #8 hash:
802e17ce82a03d7c2da2b6a9fe92a571fde73ed9d39ef93baccdb8aebae04826

Appendix D.10: Algorithm to End the Blockchain Energy Trading Platform in This Study

```
num_blocks_to_add = 1 # To add more elements to our block_chain (e.g 10 elements)

for i in range (1, num_blocks_to_add+1): # We create all our blocks here

    i = 9

    # where1 is the genesis block in our list (i.e. in "[Block.create_genesis_block()]")

# append means to add (i.e. create) another block in our block_chain

    block_chain.append(Block(block_chain[-1].hash,  # (block_chain[-1].hash) means the previous block

                        "DATA!",

                        datetime.datetime.now()))

    print("Block #%d has been created." % i)

    print("End of Blockchain Energy Trading Platform Python Algorithm for this study")

    print("Block #%d hash: %s" % (i, block_chain[i].hash))
```

This output is displayed below:

```
Block #9 has been created.

End of Blockchain Energy Trading Platform Python Algorithm for this study

Block #9 hash:
191665c8c45280f2fd90eaff519bd1699f6070acd43a68a79aa495428d4d9987
```

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