Energy Trading Platforms for Isolated and Inter-connected Microgrids Utilizing Adapted Blockchain

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The rapid increase in microgrid technology development has led to a decentralized yet interconnected system that is highly flexible and dynamic. This will change the planning and operational strategies from being grid-connected microgrids (MGs) that switch to islanded mode only during abnormal conditions (i.e., faults) to being sustainable self-adequate MGs that are designed to maintain secure and reliable operation at all times. Moreover, the tremendous increase in the development of energy storage systems, coupled with the continuous decrease in storage costs, makes it much more technically and economically viable for MGs to operate within these new system boundaries. This development entails advancements in the operation, protection, and energy management of MGs.

One of the crucial motivations for this thesis is establishing an energy trading platform that leverages these new trends in microgrid technology. The novel trading platform should be efficient, reliable, swift, scalable, fair, transparent, and executable. Current MGs lack the appropriate energy trading mechanisms to enable all microgrid participants to trade energy securely and swiftly. Fortunately, flourishing blockchain technology represents a feasible and reliable solution to facilitate this market while maintaining the aforementioned market characteristics at no third-party costs.

Recently, energy trading in the active distribution system of Distributed Generation (DG) units that are dispatchable and renewable is gaining significant attention from utilities and regularities. The concept of transactive energy based on blockchain technology has been introduced to the electricity industry to enable more flexibility, including higher penetration of renewable energy. However, in this new decentralized market paradigm for MGs and active distribution systems, some serious challenges need to be further investigated by answering the following fundamental questions: Who will be allowed to participate in the market? Who is responsible for operating the market? Who will be responsible for system reliability and security? Who will be responsible for setting the price and for determining how interconnected markets will interact? In addition to finding robust answers to these questions, another significant challenge in the new market paradigm is developing a business model for utilities that preserves their interests.

This research aims to provide a coherent framework for a novel energy trading paradigm. First, existing blockchain technology is adapted, modified, and integrated with the market model so that during unconfirmed transactions, the credit hold will allow participants with/without historical credibility to join the market. This approach will enable any entity in the MG to participate by offering or requesting energy. Next, a new centralized-based energy trading platform is developed to facilitate energy trading among the interconnected MGs. This platform is formulated for the MGs participating in a restricted centralized distribution system. Finally, a decentralized sequential-based energy trading platform is introduced in this thesis to enable independent energy trading in the distribution system. The proposed energy trading platform is structured in a blockchain-based modular fashion and can be extended to include numerous MGs.

Acknowledgements

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I have discovered that I am a wealthy man, though my banker would probably not agree, to have My father Prof. Rizk Hamouda, mother Einas El-Aidy, brother Ahmed, sister Sherin, sister Nouran, sister Danyah, son Marwan, and son Malek. They have always encouraged me to seek answers to my many questions. I owe the curiosity that made me start this journey to them. Thanks!

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Dedication

This thesis is dedicated to my father Rizk, my mother Einas, my wife Amira, and to the soul of my uncle, Hamdy Hamouda.

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Nomenclature

Acronyms

B-ET-Engine	Blockchain Energy Trading Engine.
CESP	Customer Energy Service Provider.
DER	Distributed Energy Resource.
DG	Distributed Generation.
DISCO	Distribution Company.
DOE	Department of Energy.
DR	Demand Response.
DSA	Double Signing Algorithm.
DSM	Demand Side Management.
DSO	Distribution System Operator.
EMPR	End-user Price Request.
EMS	Energy Management System.
ESS	Energy Storage System.

EuMP	End-user Marginal Price.
EV	Electric Vehicle.
GENCO	Generation Company.
IGC	Intra-Grids Chain.
IMGs	Interconnected microgrids.
IRTB	Intra-Grids Real Time Block.
ISO	Independent System Operator.
LDA	Local Distribution Area.
LMP	Location Marginal Price.
MC	Microgrid Chain.
MCB	Market Commitment Block.
MCP	Market Clearing Price.
MG	Microgrid.
OCM	Offer Cost Minimization.
P2P	Peer to Peer.
P2S2P	Peer to System to Peer.
PCM	Payment Cost Minimization.
PNNL	Pacific Northwest National Laboratory.
POA	Proof of Authority.
POT	Price of the Time.

POW	Proof of Work.
RSA	Rivest Shamir Adleman.
RTB	Real-time Block.
SBD	Self-Benefit Driven.
TE	Transactive Energy.
TLSC	Two Layer Structural Chain.
TOU	Time of Use.
TRANSCO	Transmission Company.
UMP	Uniform Marginal Price.
V2G	Vehicle to Grid.

Parameters

$\gamma D_{s,m}$	Price of block m for demand s.
$\gamma D^{i}_{s,m}$	Price of block m for demand s in microgrid i.
$\gamma E^{i}_{r,t}$	Price of block t for generator r in microgrid i.
$\gamma E^{j}_{r,t}$	Price of block t for generator r in microgrid j.
$\gamma G_{c,k}$	Price of block k for generator c.
$\gamma G^{i}_{c,k}$	Price of block k for generator c in microgrid i.
$\overline{PD}_{s,m}$	Upper energy limit of block k for generator c.
$\overline{PG}_{c,k}$	Upper energy limit of block m for demand s.
$PD^{i}_{s,m}$	Upper energy limit of block m for demand s in microgrid i.

$PE^i_{r,t}$	Upper energy limit of block t for generator r in microgrid i.
$PG^i_{c,k}$	Upper energy limit of block k for generator c in microgrid i.
L	Clustering ratio.
N_{max}	Total number of MGs participating in energy trading.
Q^i	Given number for microgrid i.
SW^i_o	Social welfare for microgrid i without trading.

Sets and Indices

c	Index identifying distributed generators.
i	Index identifying microgrid.
j	Index identifying microgrid.
k	Index identifying generator blocks.
m	Index identifying demand blocks.
r	Index identifying exporter distributed generators.
s	Index identifying demand participants.
t	Index identifying exporter generator blocks.

Variables

η^i_{new}	New internal price for microgrid i after participating in energy trading.
ηD_s	Loss factor for demand s.
ηG_c	Loss factor for generator c.

λ	Internal marginal price.
λ_{real}	Real price after applying penalty factors.
$\lambda^*_{D_s}$	Loss updated price for demand s.
$\lambda^*_{G_c}$	Loss updated price for generator c.
EB^j	Export benefit for microgrid i.
P_{real}	Energy received from smart meters.
$PD_{s,m}$	Energy required from block m for demand s.
$PD^i_{s,m}$	Energy required from block m for demand s in microgrid i.
$PE^i_{c,k}$	Total Energy exported from block k for generator c in microgrid i.
$PE^j_{i_{r,t}}$	Energy exported from block t for generator r in microgrid i to microgrid j.
$PE^i_{j_{r,t}}$	Energy exported from block t for generator r in microgrid j to microgrid i.
$PG_{c,k}$	Energy generated from block k for generator c.
$PG^i_{c,k}$	Energy generated from block k for generator c in microgrid i.
$SW^i_{D_{new}}$	Demand social welfare after trading for microgrid i.
$SW^i_{G_{new}}$	Generation social welfare after trading for microgrid i.
SWE^i	Effective Social welfare for microgrid i.

Chapter 1

Introduction

1.1 Preface

There is currently a thriving customer interest to participate in the electricity market, as witnessed by the flourishing sales of electric vehicles and increased demand for greener energy options. On the industry side, customer interest is being both piqued and stoked by growing deployments of distributed energy resources and emerging storage technologies. The increase in distributed energy resources has led to a more decentralized yet interconnected system, with greater flexibility and dynamics.

The microgrid is defined by the U.S. Department of Energy Microgrid Exchange Group as ***"A group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid"*** [2]. Microgrid planning philosophies are changing from islanding in abnormal conditions to independent sustainability for constant secure and reliable operation. Large independent operators foresee a shift from gigantic-grid bulk generation and transmission to distributed generation (DG) from smaller, interlinked grid clusters. Customers and the community will benefit, but system operators and utilities will face challenges.

Introduced to enhance electricity exchange and the energy market structure in such grids, transactive energy networks favour customers and DG owners, establish a utility business model, and enable power system innovation. Planners are also increasingly interested in blockchains for secure transactions. Blockchain-based transactive energy markets promise flexibility, transparency, security, competition, and superlative low-cost reliability, offering ideal energy-trading solutions in isolated MGs and distribution-level markets.

1.2 Research Motivations

The primary motivation for this thesis is to promote the independent operation of MGs and develop a framework that can manage and enhance energy trading for active MGs at the distribution level. The new trend in MGs is the movement toward self-adequacy, which is subjecting the utilities to heavy financial stress. In response to this situation, the present research offers a new business model for utilities to participate in the emergent microgrid systems and assist in energy management, ultimately increasing the trust in the network and attracting more investors.

In addition, this research is focused on enabling a larger number of participants in the electricity markets, so that it would not be mandatory for participants (e.g., end-user customers) to have a historical record of credibility to participate. This motivation could be achieved by utilizing the blockchain technology as the trading medium to establish a secure monetary fund platform and enable the execution of the smartgrid's market while fitting the existing power system operation philosophy. At the same time, this research aims to change the cash flow cycle in the market to be in the range of minutes rather than months and to encourage customers to get involved in the market programs by offering instantaneous incentives.

One of the main focuses of the present work is enhancing the demand response by changing from the Time of Use (TOU) [3] concept to the Price of the Time (POT) concept. In this latter approach, the market responds in a timely manner to load requests, which means that the demand response is made locally at the end-customer (i.e., enhancing the demand response), while applying penalty factors to those who do not send accurate signals about their demands. This model will benefit all system users and will mitigate problems arising from demand response and peak bouncing.

Furthermore, this research proposes a framework for energy trading among Interconnected Microgrids (IMGs). The proposed framework adapts the centralized existing energy trading philosophy and introduces a new decentralized energy framework that can work independently.

In brief, the transactive energy management system based on blockchain technology could be a viable solution for managing self-adequate microgrids. It eliminates monopolies, initiates trusted competition between and among investors, enables all participants to bid in the market, and enhances the demand response.

1.3 Research Objectives

The main objective of this research is to develop a Distribution Systems Electricity Market (DSEM) and then to ensure market fairness, transparency, security, and efficiency in the application of the novel DSEM. The research objectives can be summarized as follows:

- Develop a new market structure for trading energy in distribution systems. In this part, the new structure ensures that all system players participate in the market.
- Utilize an adapted blockchain technology specially designed for the proposed market model. The new blockchain will ensure system security and will allow a large number of participants to bid safely.
- Allow smart loads (i.e., electric vehicles, storage systems) to participate in the market.
- Design a new energy trading platform for IMGs.

- Ensure that the utility has a new feasible business model in the proposed market model.

These objectives are set to develop a complete and comprehensive framework for energy in the isolated and interconnected MGs.

1.4 Research Challenges

The aforementioned objectives face immense challenges that need solving. These challenges can be categorized as follows:

- Market Challenges.

  In order to achieve the objectives mentioned earlier, the new market should be able to deal with a large number of participants, which is the main feature at the distribution level. These participants have no credit record, and thus advanced money transaction platforms should be introduced. Also, the market platform should be fair, transparent, accurate, and fast. Moreover, it has to maintain a feasible business model for the utility, and the new interconnected energy trading framework should attract the MGs as independent entities, considering their self-benefit-driven (SBD) behaviour.

- Reliability Challenges.

  The new platform should be sufficiently secure to deal with a large number of participants, work in the current market structure, and be easily modified in case of future market changes.

- Blockchain Challenges.

  Existing blockchain technology cannot adopt the physical systems as power systems. Consequently, the blockchain should be adapted to fit the proposed system without losing the blockchain features.

1.5 Thesis Organization

The remainder of this thesis is organized as follows:

- Chapter 2 presents essential background information and a critical survey of previously directed studies for energy trading in isolated and interconnected MGs and the blockchain in the energy sector.
- Chapter 3 proposes an MG energy trading engine to enable trading between prosumers and end-users. This engine allows all participants to bid in the market and utilizes the blockchain as a monetary fund. In this chapter, the conventional blockchain is adapted to fit the characteristics of power systems.
- Chapter 4 introduces a centralized energy trading framework for IMGs. In this chapter, unique utility functions are defined for MGs, and the Nash solution-based algorithm is formulated.
- Chapter 5 presents a decentralized energy trading framework for IMGs to ensure privacy and satisfy the participants' needs. This method settles the market in a novel sequential way and provides a fast and efficient solution.
- Chapter 6 describes the conclusions and contributions of the research presented in this thesis and recommends future work directions.

Chapter 2

Background and Literature Review

2.1 Introduction

Recent developments in microgrid technology have made MGs capable of being self-adequate. This means that MGs are able to provide stable and reliable power during islanding and grid-connected operations. However, the energy management of these resources is still an active research area. By and large, the energy management at the distribution system level remains extremely challenging due to the massive penetration of intermittent green energy units stimulated by climate change and the energy management among many participants [1].

In particular, the energy management of MGs has been underlined by numerous researchers recently. These researchers investigated controlling DERs to manage energy in isolated microgrids and ensure their stability. However, a research gap persists both for energy trading in active MGs and among groups of IMGs.

In view of this work's focus, a general background about the new transactive energy concept is provided. Background information on blockchain is also given, as blockchan will be the primary tool that will enable energy trading for a large number of participants, as will be discussed later. A survey on existing market structure research is presented as well. Moreover, as this work sheds additional light on market operations, a review of conventional market operations is provided to address these operations at the transmission level. Furthermore, a comprehensive survey for energy trading at the distribution level market is addressed. This survey entails the transactive energy research survey and the new concept of peer to peer energy trading. Finally, the applications of blockchain-based energy trading are presented.

2.2 Background

In this section, a brief background on the concept of transactive energy (TE) is given, along with comprehensive information on blockchain.

2.2.1 Trasactive Energy Concept

The concept of transactive energy was introduced recently in order to enhance the demand response and energy trading dynamics at the distribution level. In 2005, the DOE funded the Pacific Northwest National Laboratory (PNNL) in conducting one of the first field studies of what is now called transactive energy [4]. The PNNL defined TE as a "system of economic and control mechanisms that allow the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter" [5].

The broadness of its definition allows for many structures to be a part of TE. According to [6], the system in the definition refers to a network that gathers multiple participants with different objectives (utilities) under the same governing rules. The economic and control mechanisms ensure the coordination and control of all network participants. Moreover, the definition defines that a balance between dynamic load and supply should not violate the system constraints. The value refers to the clearing price for the participants, which should lead to a win-win approach. Finally, all the settlements in the transactive systems should be according to the price signals.

The council has progressed further and highlighted six principles for TE: [5]:

- Should implement highly coordinated entities.
- Responsible for maintaining the system reliability and control, and in the meantime it should guarantee optimal integration of RES and DGs.
- Fair system that guarantees non-discriminatory operation for system participants.
- Observed and supervised.
- Adaptable and extendable for more participants.
- Responsible for the system performance.

The new concept of transactive energy provides a new framework for exchanging energy in a local distribution area (LDA). Specifically, it allows prosumers and end-customers to bid in the market. However, providing a transactive energy mechanism that can securely enable energy trading for many participants is still challenging.

2.2.2 Blockchain Concept

A blockchain is digital, shared and distributed storage (i.e., a database) that maintains a list of ordered transactions, otherwise known as a distributed digital ledger. The transaction data are stored as a block in a sequential chain of blocks forming what is called a blockchain. All blocks are connected using a one-way encryption algorithm, or hash. This hashing process makes the chain immune to manipulation or tampering, as illustrated in Figure 2.1. As indicated in the figure, part of the data in each new block is an encrypted version of the data from the previous block plus the previous hash, which links the current data to all of the data stored in the chain thus far. This strategy makes altering the data within a block almost impossible. According to the literature, the blockchain concept and algorithm were first introduced by Nakamoto for a P2P electronic cash system [7].

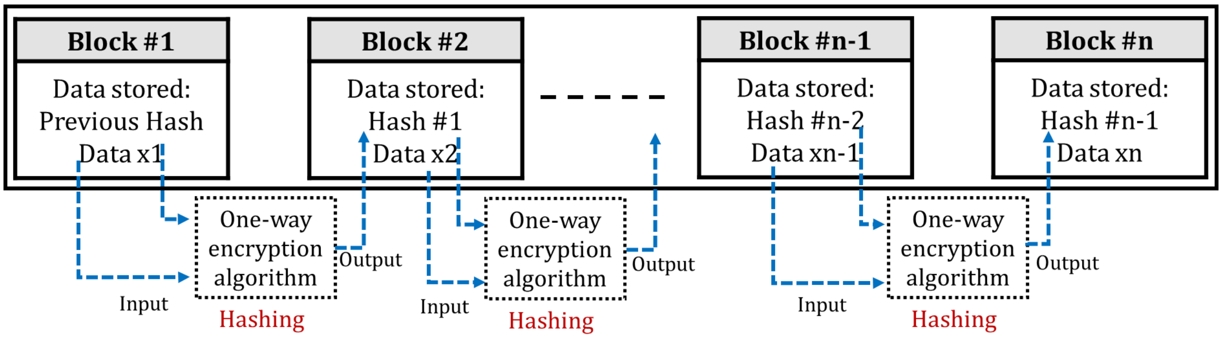


Figure 2.1: Blockchain structure.

The new concept transforms a validation process from centralized, slow, expensive and insecure to decentralized, fast, inexpensive, and secure through the use of a blockchain platform. This novel platform has attracted impressive attention in business markets due to its elimination of the need for a third party while offering secure, fast and reliable operation. A blockchain platform is transparent by nature: its distributed ledger enables participants to recheck the historical record in order to validate their transactions and funds. In fact, blockchains employ a secure and transparent cloud storage approach and use decentralized nodes for validation (i.e., miners). The computational capability of the mining nodes is measured according to their hash-rate in hashes/s.

It is worth mentioning that different types of blockchains rely on different algorithms for block mining and broadcasting. However, all blockchains are executed following the same general steps: 1) creating open transactions; 2) mining and verifying (i.e., creating the block); and 3) broadcasting the block (i.e., attaching it to the chain). Miners are rewarded for their efforts to validate the system using incentives based on game theory [8]. For example, the first node to validate a transaction wins a token as compensation for its validation effort with respect to that transaction [9].

To ensure security, blockchains use both public key and private key cryptography as well as a hash function. A cryptographic hash is similar to a signature for a data file. The SHA-256 Secure Hash Algorithm is usually used for hashing the data and is one of the strongest hash functions available. This algorithm transfers the data into a fixedsize, almost-unique, 256-bit (32-byte) hash. The hash is a one-way function, making it impossible to decrypt the data. The private and public keys also work together so that participants use their private key to sign any transactions digitally. All other participants see only the public key, which anyone can know, and can use it to verify that a specific private key was actually used for signing the transaction.

A Diffie-Hellman (DH) key exchange is one of the best asymmetric cryptography protocols [10] and is based on the Rivest-Shamir-Adleman (RSA) algorithm [11]. The RSA algorithm uses a recipient's public key to encrypt a message while the decryption key is kept secret so that only the recipient can decrypt the message using his/her private key, as illustrated in Figure 2.2.

In the blockchain, the message is encrypted using the signer's private key, and any miner in the network can ensure that the signature is correct by using the following two steps: 1) using the hash function on the data as the sender did to get the data's hash, and 2) using the signer's public key to decrypt the signature and get the data's hash. If the data's hash is matched by using these two steps, the signature is verified by the miners [12]. This sequence is further illustrated in Figure 2.3.

At this stage, the algorithm creates what are called unconfirmed transactions, meaning that they are yet to be approved. As shown in Figure 2.4, these transactions can be

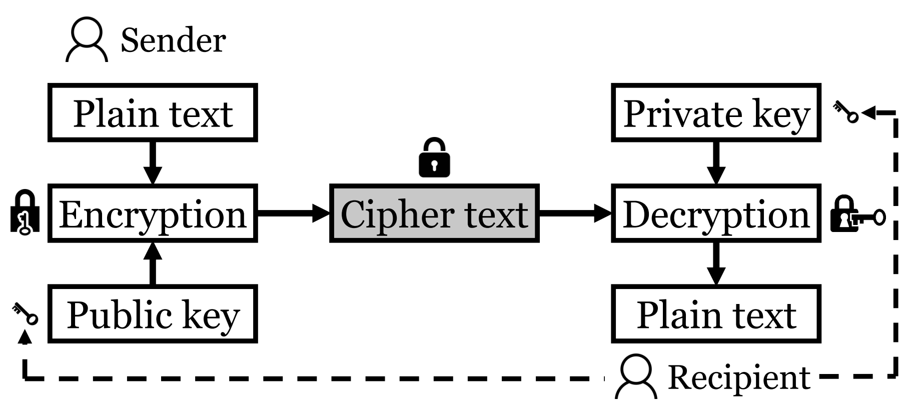


Figure 2.2: Asymmetric cryptography protocol.

approved only by special nodes (i.e., miners). Miners then compete to verify these unconfirmed transactions. After the transactions have been verified, a smart binding contract, also known as a cryptocontract, is issued between the buyer and the seller without the need for a third party. It should be noted that such a third party makes the system centralized, with all of the trust being demanded from a single party, entity, or organization [13].

After these transactions have been completed, all nodes are updated according to these new transactions, and the data are then stored locally. The new block, which contains the transaction data, is added to the blockchain. The primary advantages of this system structure are that the transactions are 1) quickly verified, 2) secure, 3) transparent, and 4) economical. The blockchain platform process is illustrated in Figure 2.4.

Such a blockchain platform is useful for business transactions that require the approval and writing of transactions that have been agreed upon by both the sender and the recipient. Once the parties to the transaction agree on the transaction, it becomes a fact that needs only to be verified and stored in the ledger. The amount of funds transferred equals the amount agreed upon by the sender and the recipient. This concept cannot be adopted and applied to power transactions because the exact amount of power physically

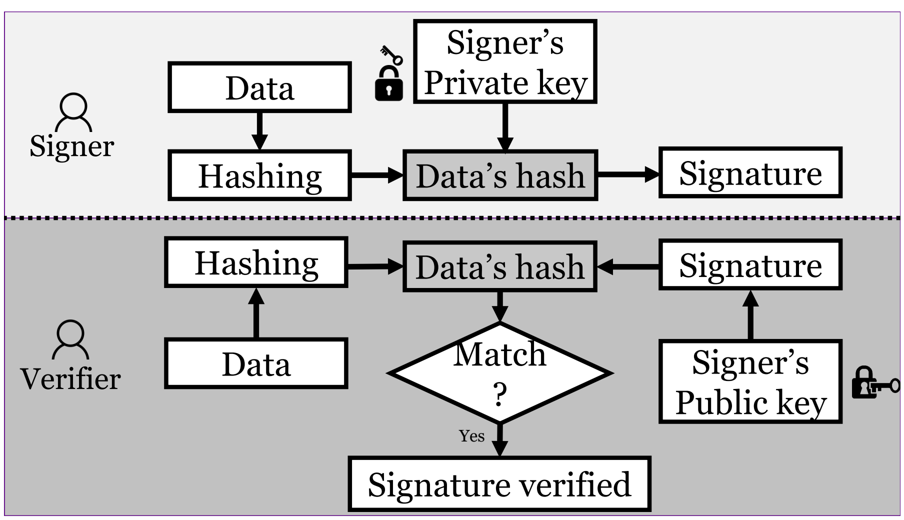


Figure 2.3: Asymmetric cryptography protocol used in blockchain.

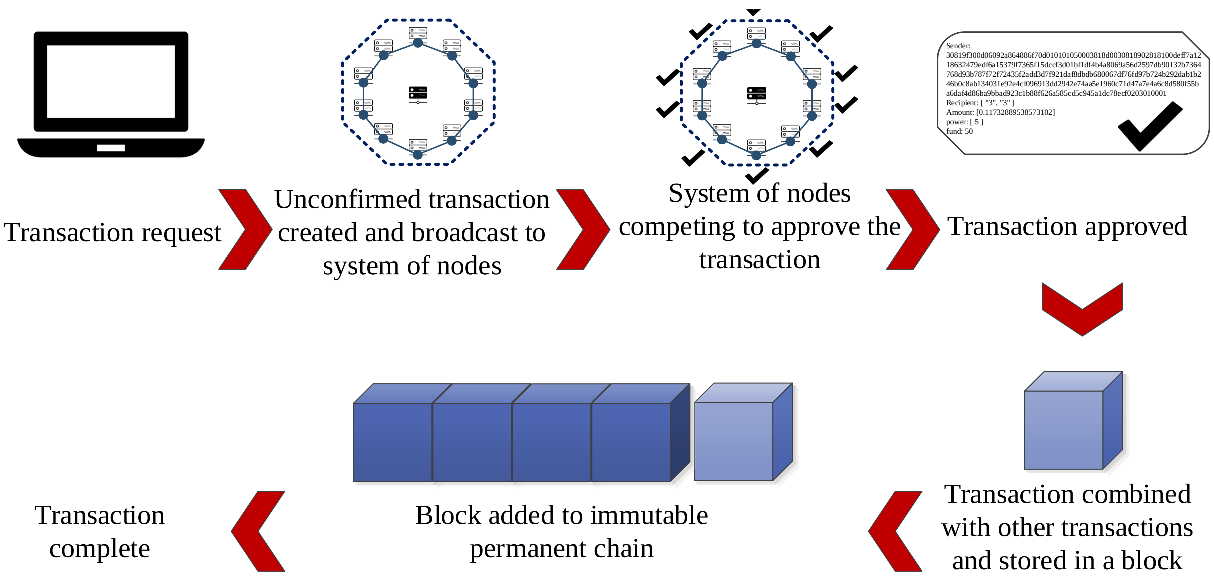


Figure 2.4: Blockchain process.

transferred is not always identical to the amount agreed upon (committed power), since power transfers are controlled by the physical characteristics of the system. For this reason, the blockchain concept must be modified before it can be utilized for electrical energy transactions.

2.3 Literature Review

As mentioned in Chapter 1, the main objective of this work is to develop a framework for energy trading at the distribution level, in particular for active MGs utilizing the blockchain concept and capabilities. Therefore, the literature review in this thesis will start by looking at existing market structures, followed by an overview of comprehensive services for the trending peer-to-peer (P2P) concept. Energy trading among IMGs will also be discussed. Finally, the author will address blockchain technology in the energy sector. It is worth noting that, to the best of the author's knowledge, no research has yet been published in the area of electricity markets of isolated MGs that allow all participants to participate in the market.

2.3.1 Transmission-level Market

This subsection includes a detailed literature review on the transmission level market, starting with the market structure and settlement design, and followed by the market key players. Next, the literature for the market operation analysis is reviewed, after which the market limitations are discussed.

2.3.1.1 Transmission-level market structure

Between 1980 and 1990, state-owned electricity markets faced numerous criticisms over their performance and monopoly of price regulations. In response to the criticisms, several regulatory conditions were introduced to ensure fair market competition and equitable market power [14]. These regulations, which led to the general deregulation of the electricity market's organization and structure, can be summarized as follows:

- Competition should take place everywhere, especially for those who can effectively compete in the market.
- Eliminate government monopoly by ensuring new market structure, and introduce commercial incentives into the enterprises that are owned by the government. However, they can still own assets in the new market.

The degree of competition on the "buyer" side in the deregulated market has three different boards, as follows: [14]:

- The single buyer approach, under which a single entity has the responsibility for purchasing wholesale electricity.
- Wholesale competition, under which entities (such as distribution businesses) have a local monopoly over customers and negotiate on their behalf to procure electricity.

- Retail competition, under which any customer can, in principle, purchase electric power from any supplier.

2.3.1.2 Market design

Electricity markets have different designs in different regions. These differences result in variations in the market settlement and structure. According to [15], there are two main design categories: 1) integrated market and 2) exchanged-based market. In an integrated design, the market has a local optimizer in which the scheduling and dispatch of generators take place, whereas in an exchanged-based design, companies trade based on their own price settlements. North America generally follows an integrated market structure design, according to (FERC,2002) [16].

The electricity market is highly organized with regard not only to price settlements but also to allowing the system to trade only within certain approved performance levels and other constraints (i.e., physical limits). The market is a highly complicated undertaking, as the demand and supply change every instant and customers still do not respond as expected to price changes. Furthermore, the existence of intermittent resources such as wind, solar, etc., makes the task that much more complicated. Given this complexity, a well-designed market is a necessity, as any mistake can be very costly [17].

In general, the main objective of designing any market is to provide reliability at the lowest possible cost. However, there are very important objectives that should be highlighted in designing any market [16]. First is the short-term efficiency, which is about maximizing the usage of all resources. This is a very complicated objective, as it faces physical constraints as a stumbling block. The second objective is long-term efficiency, which includes making sure that the market is attracting investors and is reliable into the future. As well, transparency, fairness and simplicity are also important objectives to achieve.

In order to design a transparent market, the rules for the market should be announced and all real-time data should be posted for the participants. Likewise, the planning process should be transparent [16]. This will yield increased investment and participation by non-traditional players in the market.

2.3.1.3 Changes due to renewable sources penetration

In accordance with the Paris Agreement reached at the UNFCCC COP21 conference [18], major changes are expected to be made to market policies, with the aim of reducing carbon footprints. These changes will undoubtedly be accompanied by increased penetration by renewable resources into the energy market. Europe has already seen significant penetration, as shown in Figure 2.5 [1]. The data for this figure come from the Organization for Economic Co-operation and Development (OECD).

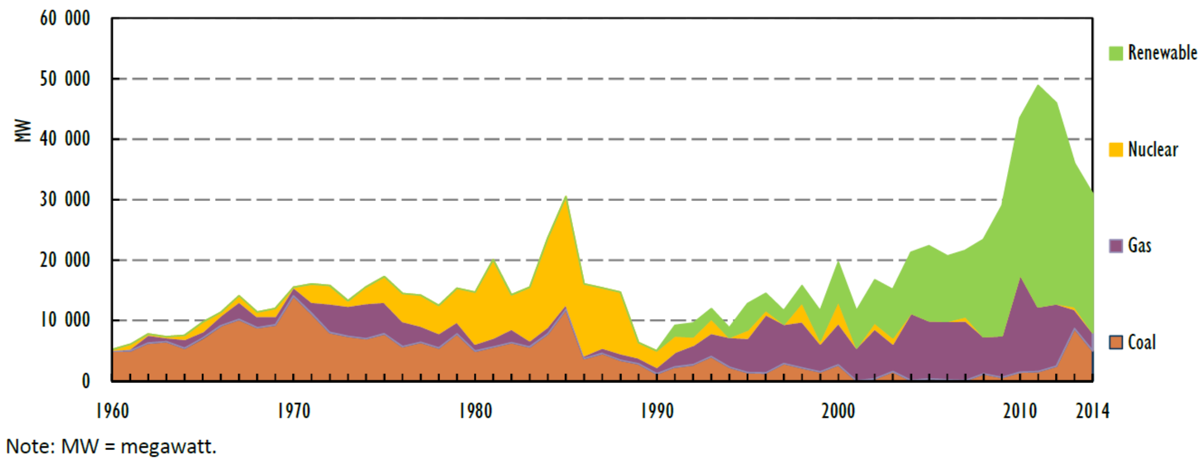


Figure 2.5: Capacity added to Europe (OECD) from 1961 to 2014 [1].

The increased penetration by renewable energy resources will require a new structure and new rules for the market in order to ensure safe and reliable operation. Fortunately, the typical low operating costs of renewable generation units will help to reduce electricity prices.

2.3.1.4 Market key players

In deregulated markets, a number of key players are necessary to produce stable and reliable power:

- Generator companies (GENCOs): These players are responsible for operating the generation resources. They sell energy by bidding in the market through generation curves.
- Transmission companies (TRANSCOs): These players own and operate the transmission lines under the supervision and control of the independent system operator (ISO) to ensure system fairness.
- Distribution companies (DISCOs): These players own and operate the distribution system and are responsible for buying the energy from the market through demand curves.
- Regulator: This player is usually a government agency that sets the market rules to ensure safe, reliable, and fair operation.
- Independent system operator (ISO): This is a very important non-profit player that ensures system security and reliability. This company also provides open access to the transmission system.
- Market Operator: This player is responsible for receiving the bids and settles the price in both day-ahead and real-time markets.

2.3.1.5 Transmission-level market operations

The two core market elements are the day-ahead market and the real-time market. The day-ahead market receives the bids from participants for the next day (hourly) and optimizes the social welfare to schedule the generation/demand for the next day and clear the price. Meanwhile, the real-time market conducts security constraint economic dispatches every 5 minutes at least during the day to set the price at each location (i.e., locational marginal price [LMP]).

Although a lot of research has been conducted to study the market clearing and settlement mechanisms, it remains a challenge to find a mechanism that satisfies all the market objectives [19]. There are two main mechanisms that are widely used for market auctions: 1) Offer cost minimization (OCM), in which the market auction objective is to minimize the generation cost; and 2) payment cost minimization (PCM), in which the auction objective is to minimize the demand payment [20]. Most electricity markets use OCM, which is mathematically very close to the unit commitment problem [21, 20].

The payment minimization cost is the first technique that takes care of customer benefits. As the generation offers are usually inconsistent, this may lead the OCM auction to yield a high payment cost [20]. Many researchers have studied the payment cost minimization mechanisms [22, 19, 23]. Luh et al. [20] was the first author to facilitate the PCM technique, which significantly affects the customer payment. In [24], the author extended his work to include the transmission lines' capacity of the system. Moreover, the author discussed the bi-level model at which the lower level calculates the market clearing price (MCP) and the upper level represents the typical economic dispatch problem to minimize the payment cost. However, the results show that the total system cost is still higher in the PCM over the OCM mechanism. In [22, 23], the bi-level model has been improved to be a single-level model, in which the lower level is expressed as KKT conditions in the upper one.

Customer participation in the market can be boosted through demand-side management (DSM) programs. In order to achieve efficient DSM, FERC order 719 was carried out to allow the DR to bid in the wholesale market [25]. The ISOs then introduced new rules to facilitate the DSM programs to bid in the market [26].

It is worth mentioning that the DSM is very efficient for cost reduction in the isolated system [27]. In [28], the author proposed a day-ahead market in which on-site generation and DSM take place along with ESS. In [29], the author argued that the DSM could play an important role to reduce the payment cost of the customer. Hence, the author proposed an incentive-based market to encourage customers to participate in the demand management programs.

In order to enhance DSM programs and allow the DER to bid in the market, a transactive energy mechanism WAS highlighted by the U.S. Department of Energy (DOE).

2.3.1.6 Transmission-level market limitations

The increase in sales of electric vehicles, along with the emergence of storage technologies and strong customer interest in market participation are all contributing to substantial changes in the market. In the UK, one-quarter of energy consumption is generated from renewable resources [30]. The expansion of distributed energy resources, in particular, is leading to more decentralized yet interconnected systems that feature greater flexibility and are more dynamic, such as self-adequate active distribution systems. This trend, however, is subjecting utilities to growing financial stress. Some researchers have suggested that parallel business models are needed for distribution utilities and/or other market participant. such as distribution system operators (DSOs) and customer energy service providers (CESPs) [31], [32]. The primary consideration is that the operation of active systems might require a distribution-level market structure that can coordinate the settlement of transactions [31].

A recent development is that many energy consumers are becoming prosumers capable of selling their energy back to the distribution system through special programs, such as the FIT and MicroFIT programs in the province of Ontario, Canada [33]. However, the current structure of most energy markets prevents prosumers from participating in the wholesale market or competing in a distribution-level market. This is because the wholesale market usually has a set minimum capacity limit for participation. For example, in Ontario, a participant must have at least 1 MW capacity before being allowed to participate in the wholesale market [34].

The structure of the current market is centralized, with an independent system operator (ISO) collecting all offers and then clearing the price based on the offers received. In practical terms, this arrangement makes it impossible for an ISO to deal with the tremendous number of prosumers. As a result, the market must adopt a cascaded and decentralized structure that allows a greater number of participants to trade energy in a competitive environment. Such a competitive market would help limit the power of monopolies and cut the cost of utilities [35]. Therefore, a secure and reliable monetary fund (e.g., blockchain) is needed to allow smaller energy producers to participate in the market.

2.3.2 Distribution-level Market

Although the distribution level is a conceptual market [36], up to the author's knowledge, there is intensive research to provide reliable and stable energy trading platforms at the distribution level. This area's main research is grouped into two categories: 1) the peer to peer (P2P) energy trading platforms, and 2) studies follow the transactive energy concept as discussed earlier. A literature review for the transactive energy trading and peer to peer energy trading is provided in the following sub subsections.

2.3.2.1 Transactive energy trading platforms

Few studies have yet to be been done in this area [37, 38, 39]. In [37], the author produced a new model to minimize the customer payment and regulate the voltage profile; the author also argued that the TE could cause rebound peaks in the systems and increase system complexity. In [39], the author proposed a framework for the day-ahead transactive market which considers the DSO's role in the ISO's market operations. Based on this framework, a new day-ahead market was proposed under the framework of the transactive energy, with the author formulating the model such that the distribution system operators (DSOs) would operate the transactive market and then communicate with the ISO.

In [40], the authors underlined four different operational models for the microgrid under the transactive energy framework. The study entails energy exchanges between interconnected MGs. Although the main focus of this article was to minimize energy costs, many other requirements for the transactive energy also need to be satisfied.

The dispatch for collective DERs in a transactive energy system was proposed in [41]. However, the author used the time-of-use pricing mechanism in his work, which decreases the dynamics of the market. The problem is then solved in [42], and optimal dispatch of DERs is proposed within a grid-connected market.

The article [43] highlighted the potential of energy storage systems (ESSs) which operate in an economically feasible manner and coherently with various kinds of DR loads. The benefit to the overall multi-microgrid scenario, however, is not given enough focus in the research. In particular, no attempts were made to integrate the DESSs offering energy services in an economically viable manner (compensating the true battery degradation cost) with the various types of adjustable loads (categorized based on their operational preferences) into a unified transactive energy management framework. This integeration could have reinforced the intra- and inter-microgrid energy management in a multi-microgrid scenario.

The author in [43] proposed a transactive energy framework with a comprehensive energy management system (CEMS) for managing auxiliary energy resources such as DERs and ESSs in a group of smart-microgrids connected to a distribution system. This research focused also on reducing dependency on the grid (i.e., minimizing the power mismatch) and looked to non-intermittent energy sources in addition to renewable sources.

2.3.2.2 P2P energy trading platforms

A number of studies have focused on P2P energy trading algorithms. A P2P energy trading mechanism was presented in [44], with the algorithm demonstrating an appropriate response time for P2P negotiations. However, its implementation in the blockchain is ambiguous, and the behavior of the model with respect to real-time mismatches is still questionable, since the settlement of imbalances in a P2P approach is challenging and must be addressed. The authors in [45] developed a decentralized P2P market that includes consideration of the preferences of DSOs, prosumers, and generators. In their method, the grid was assumed to account for all system losses, which might not be the optimal scenario. In [46], the authors proposed a model that includes low voltage constraints in the P2P energy trading model, but all the participants are still questionable.

The literature includes several references to additional P2P platforms that allow energy trading within communities. An efficient and novel P2P methodology for inter- and intra-community energy sharing is presented in [47]. The researchers succeeded in merging the self-interest objectives of community prosumers with the minimization of the global energy cost. Their method features two-phase optimization models for day-ahead and real-time operations. Although this idea is novel, the models fail to account for end-user market participation and do not permit the adoption of large numbers of customers without the integration of a secured monetary fund. Amrit et al. [48] proposed a game-theory approach for P2P trading in which the price settlement is modeled as two separate non-cooperative games: 1) among all sellers, and 2) between sellers and buyers. Their approach achieved stable operation within a small community, but a blockchain integration must be performed in order to enable the adoption of a large number of participants. In other work, a generalized Nash equilibrium method was employed in a P2P energy-sharing framework for community buildings [49].

A common research gap evident from a review of these studies is the lack of a determination of the way financial transactions will be handled and business realized. In the present thesis, this deficiency has been addressed through the integration of blockchain technology to act as the monetary fund.

A series of recent studies indicated that P2P energy trading models can enhance power system operations. In [50]], a secure, efficient, and blockchain-based P2P energy trading framework was proposed as a means of incentivizing the adoption of electric vehicles (EVs). The researchers created an incentive-based model compatible with demand response (DR) programs. The use of this element was expanded upon by the authors of [51], who built a vehicle-to-grid (V2G) energy trading platform, adopted a blockchain technique for securing transactions, and developed an edge computing mechanism to ensure the successful adding of the blocks. A simultaneous clearing model for P2P energy trading coordinated with the ancillary service market was described in [52]. The author uses the grid prices as price signals to incentivize P2P local energy trading to support the grid, thus minimizing the operational cost under contingencies.

At the same time, the study reported in [53] introduced a unique cooperative Stackelberg game in which the grid acts as a leader and the prosumers as followers. While this structure allows prosumers to support the grid during peak demand periods, it fails to satisfy the self-interest needs of the participants. The work presented in [54] involves a method that imposes grid fees onto the P2P market in a decentralized fashion. The author applied an exogenous approach to P2P implementation that entailed minimal contribution owing to the system operator. The author also suggests that, in any consumer-centric system, the security of the participants must be examined.

In short, an energy trading system based on blockchain technology could represent a viable solution for smart grid management because it can handle large numbers of participants, eliminate transaction fees, avoid monopolies, facilitate trusted competition among investors, permit all participants to bid in the market, and enable effective demand response. A summary in the form of a comparison of the related research work is provided in Table 2.1.

2.3.2.3 IMG energy trading platforms

Energy management and trading between interconnected microgrids is gaining noticeable attention. The goal of such a structure is to provide sustainable, clean and economic energy to local participants, including residential, commercial, and industrial costumers. The concept of IMGs has been introduced in [55], where the authors proposed a multi-agent structure with distributed decision-making in order to offer a plug-and-play system. A study showed that adjacent microgrids could provide complementary generation from their renewable resources [56], which can then maintain the sustainable operation of MGs. Another fact that promotes the concept of IMGs is the increased penetration of distributed energy resources.

Under the IMG paradigm, each MG can supply the local load from cheaper energy sources and will thus create competition between and among different sources. DERs will play a major role in this paradigm, as their energy is mostly renewable and unburdened by traffic costS (e.g., transmission line costs). The high penetration of renewable generation units will reduce energy loss and improve MGs' performance [57, 58, 59].

The energy management for IMGs can be categorized into two main structures: 1) centralized management, and 2) decentralized management. The principal drawback of the centralized structure is the existence of one central operator that collects all the data into one pool and then makes a central decision [60, 61, 62]. Nevertheless, the central operator has the ability to make an optimal decision according to the pre-agreed objectives.

Table 2.1: Comparison of related research work for P2P energy trading.

Ref #	P2P trading framework	Blockchain Implementation	Adopting Prosumers	Adopting End-users	New Game Theoretical Approach	UMP based market	Physical system implementation	Fair losses distribution	Utility business model	Smart loads energy participation
43	x	x			x					
44	x	x	x		x					
45	x		x	x			x	x		
46	x		x		x		x	Negligible within MG		
47	x		x		x					x
48	x		x		x					
49		x	x (EV mainly)		x					x
50		x	x		x					x
51	x		x		x		x	x		
52	x		x		x					
53	x		x		x		x	x		

In contrast, the decentralized structure is able to preserve the privacy of the participants and implement a decentralized decision. However, it also requires a complicated technique to reach a global agreement [63, 64, 65, 66, 67].

Several studies have investigated optimal energy management in decentralized-based IMGs by using different algorithms and platforms. Three main approaches have been examined by researches to promote the decentralized energy management structure. These structures can be categorized into two types: 1) optimization-based structures, in which the energy is managed through an optimization problem that can be solved using different optimization techniques [68, 52]; and 2) peer-to-peer (P2P) structures, in which the negotiation is organized between peers directly or through an auctioneer [69, 70, 71].

In [72, 73, 74, 75], the authors utilized limited information to be shared between the energy management systems of the MG and the distribution system operator who is employed to handle the settlement of energy trading. Although the approach succeeded in keeping the privacy, the existence of the DSO as a centralized unit that manages the transaction settlement is still debatable. The author of [76] improved the technique by using the alternating direction method of multipliers (ADMM) to eliminate the central controller (e.g., DSO). Further improvements were proposed in [77] to realize an online management scheme without forecasting the load data. In general, prior work is limited to developing a mathematical method for energy management in IMGs. However, the MGs' goals of the participants are not well-defined, and the internal demand interest is not carefully implemented.

There is an enormous amount of literature on P2P methods to facilitate negotiations between system peers. This technique can be divided into the two categories of auctioneer-based and direct negotiation-based P2P. A bilateral contract auctioneer-based P2P approach is produced in [78], where the auctioneer is designed to be fair between the prosumers and customers. A load aggregator is proposed in [79] to communicate with a virtual intermediate auctioneer that settles the trading. In [80], a non-profit-making-based tool is developed for energy management between energy buildings and consumers.

The other type is using direct negotiations to represent a complete decentralized system.

In [81], the researcher proposes a peer-centric method to handle the transactions between many peers. This strategy is improved to become completely decentralized in [82]. Although the proposed approach is novel, the communication links required to achieve these negotiations are massive, so it needs significant computational overhead. Therefore, one-to-one negotiation is proposed in [83], in which each peer is negotiating and agreed on its contract. Common research gaps are summarized as the lack of end-user needs implementation, achieving a balance between the demand and prosumers' needs, and limiting the communication links to only one level of communication.

Several centralized and decentralized algorithms have been proposed for energy management in IMGs. In [84], the authors proposed an approach utilizing a game-theoretic algorithm to incentivize participants for their fair energy trading. This algorithm is designed for MGs with high renewable energy resources. The proposed model adopted the discomfort cost for each participant as its utility function in the game. In [85, 86], another approach based on fair energy trading using priority factors and aggregators for buyers and sellers was introduced. This algorithm used a utility function for sellers and buyers that inherits their priority factors while the settlement is achieved via solving a Nash bargaining game. The limitation of this algorithm is its use of unified aggregators for sellers and buyers regardless their hosting MGs, and thus no preference can be imposed by the individual MGs. Moreover, the utility function used for buyers does not contain the energy price, which is a main factor for energy trading from buyer's perspective.

None of the aforementioned work considers the uncertainties in renewable sources and load variations. In [87], the authors looked at uncertainties in IMG energy management using a bi-level day-ahead market. Also discussed was a real-time IMG market that took into consideration uncertainties using a modified robust optimization technique [88].

To break the overall optimization problem into distributed problems, the alternating direction method of multipliers (ADMM) is widely used. The ADMM method is well-suited for IMGs in solving sub-problem, as each MG offers better convergence. The authors in [89] presented a closed-form solution for ADMM which significantly improves the computational time of optimizing the energy trading. In [77], the author proposes online energy management without the need of forecast data using ADMM method. Moreover, in order to obtain robust and optimal solution in energy management among IMGs, a distributed adjustable robust optimal scheduling algorithm (DAROSA) is proposed in [90] to strike a compromise between robustness and an optimal solution.

Although several works have studied energy management, a novel collaborative transactive energy algorithm is developed in [91] that includes the physical constraints of the network. However, the problem is solved in a centralized way only.

2.4 Application of Blockchain in the Energy Sector

The new concept of blockchain has recently been applied in a few projects in the energy sector. For example, in 2016, energy was sold directly between the energy prosumers and the customers via blockchain technology in a distribution region in New York. The project was a cooperation between Siemens and a start-up company called "LO3" [9],[69]. This was accomplished without any upper-hand control (third party), indicating the viability of using blockchain for energy management. Establishing a secure decentralized energy management system was the primary motivation for using the blockchain in the transactive energy scheme.

In Australia, the government funded a project with Curtin University to develop a blockchain-based transactive system in which renewable penetration is maximized and customer batteries are integrated [92].

In Canada, IBM and Alectra have co-operated to develop a blockchain interactive system in which the prosumer can maximize their benefit and the utility can manage the charging and discharging of EVs. The project aims to enhance microgrid efficiency [93].

Despite all the aforementioned efforts, however, no-one has yet discussed a transactive energy market in an isolated system based on blockchain technology. This will be proposed in the next chapter. [94].

2.5 Research Gaps

In summary, and to the best of the present author's knowledge of related published research work, the proposed study tackles the following research gaps:

- The provision of a secure, reliable, and fair energy-trading platform for a vast cluster of participants (not only prosumers) in the distribution-level market.

  In this platform, every participant – not just credited prosumers – can submit their preferences (i.e., bidding curves) individually or throw an aggregator to participate in the energy trading platforms. Using the proposed blockchain-based platform requires only a wallet and a smart meter to participate in the energy trading market. If access to the wallet is granted, a credibility check is not needed, as participants can continue to participate in trading as long as their wallet has enough funds.

- Adaptation of the existing blockchain technology to fit with the power system's intrinsic property that is different from other trading and financial transactions.

  Existing blockchain technology is used for P2P trading between two peers. However, this method has the following limitations:

  - Hypothetical transactions between participants.
  - Unfair prices for participants, as it depends on an individual's trading capabilities.
  - Unfair representation for the losses. In most of the cases, they ignore the losses and let the grid take care of it.

- Implementation of system losses in blockchain-based P2S2P energy trading.

  For fair billing, customers should pay for their energy consumption in addition to any losses incurred from delivering this energy to them. Although the current billing system has clear energy prices in Ontario, there is no transparent and clear justification for the delivery fees and adjustments in the bill. As shown in Figure 2.6, for a real electricity bill, the delivery cost is almost 19% of the bill without any clarifications.

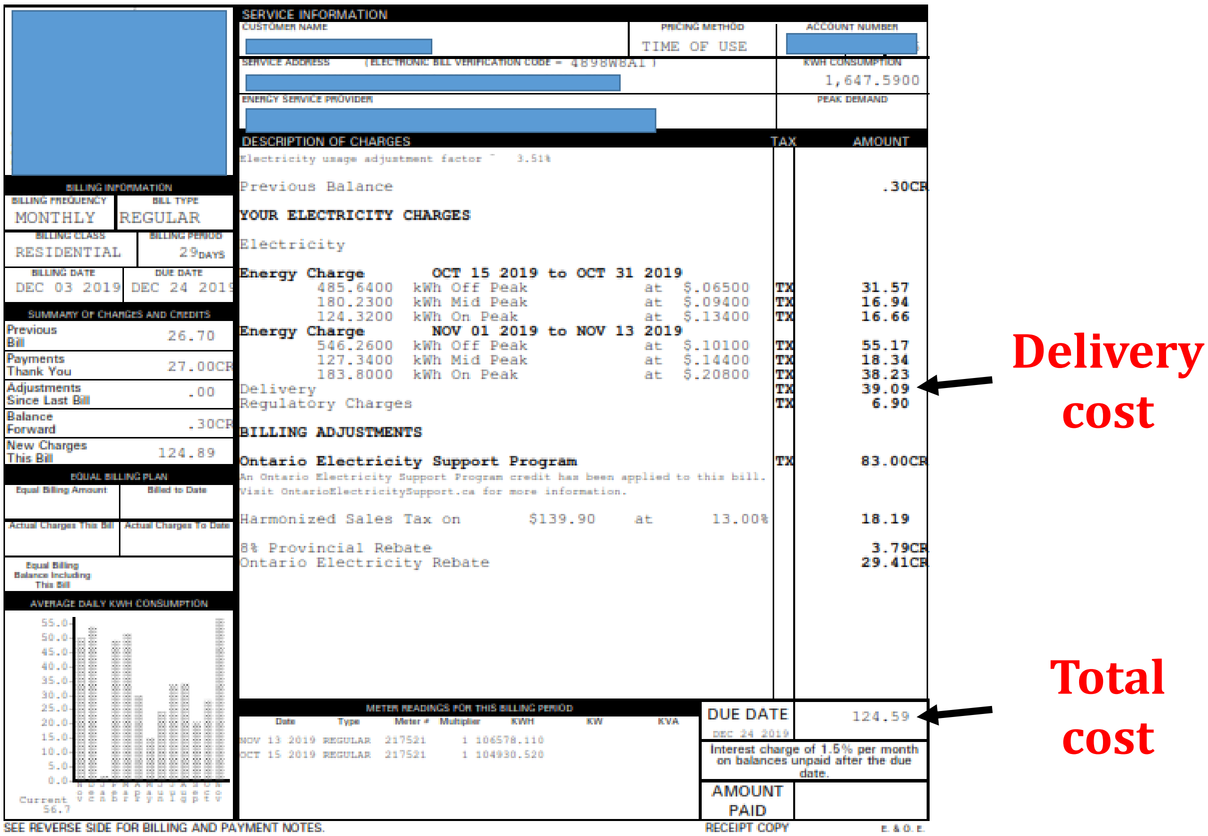


Figure 2.6: Real electricity bill in Ontario.

- Adapting the existing UMP model to be used in a blockchain-based energy trading platform.

  One of the main challenges that face any system operator is restructuring the market model. In Ontario, the market renewal program seeks more participants, market efficiency, and lower energy prices for customers. It is worth noting that IESO is still using the UMP market model for establishing the market-clearing price (MCP). Therefore, the modified market model proposed in this research offers the perfect fit for restructuring such markets.

- Providing a unique and real application for smart meters rather than just storing data for data analysis.

- Developing an energy trading platform for the interconnected MGs that can satisfy each MG's SBD behaviour.

Chapter 3

Blockchain-based Energy Trading Engine

3.1 Introduction

Numerous studies have been conducted over the past several years to investigate transactive energy systems. In these studies, the structure of the energy market was assumed to be peer-to-peer (P2P) transactive, in which conventional and well-known blockchain technology is utilized without adaptation or modifications. This peer-to-peer assumption introduces unnecessary uncertainties and challenges to the market. In addition, these studies ignored the physical power systems and their limitations, which would affect the market significantly. In this chapter, a novel electricity market platform is proposed that takes the limitations of the physical system into account. Furthermore, the blockchain technology is adapted and restructured to achieve the desired operation for transactive energy in distribution systems.

The chapter is organized as follows. Section 3.2 discusses the adaptation of blockchains to fit the intrinsic characteristics of a power system. Section 3.3 explains the methodology for establishing an energy trading engine. Section 3.4 describes a case study that demonstrates the execution of the proposed platform. Section 3.5 discusses a number of points arising from this research, and section 3.6 offers conclusions.

3.2 Blockchain Adaptation

Introducing a comprehensive framework for energy trading based on the use of blockchain capabilities in distribution systems has required the development of an advanced trading engine. The blockchain-energy trading engine (B-ET-engine) entails the adaptation of a conventional blockchain to make it suitable for the energy market. The proposed engine takes into account the physical layer of the power system while establishing transactions such that the financial cash flow and the actual power flow are coupled. Traditional blockchain was invented based on the idea underlying P2P transactions. However, this concept conflicts with the way power flows in a physical system.

In P2P, cash flows from a sender to a receiver while in a physical system the power flows from the recipient of the cash to the power system and then to the sender of the cash. However, there is no guarantee that the power sent will be received, since power flow is governed by the network. In the IEEE 906 bus system example provided in Figure 3.1, generators inject power into the system, and the power then travels through the system to the loads based on the power flow solution. Since determining exactly which generator serves which load is impossible, the blockchain based on P2P transactions shown in Figure 3.1 does not resemble power system transactions.

The work presented in this thesis resulted in a proposed peer-to-system-to-peer concept (P2S2P), whereby the power flow in a power system is exactly mirrored by the blockchain cash flow. The proposed concept is thus consonant with the power flow concept in electric power systems. As shown in Figure 3.1, in the power system layer, power flows from generators to the network to loads, and the cash should thus flow from the loads to the system and then to the generators, as proposed with the P2S2P approach. On the other hand, in a P2P system, the sender and the recipients are assumed to have agreed on the transaction, so the system does not need to be optimized in order to maximize social welfare. The main advantage of using the proposed P2S2P concept is the possibility of incorporating a market model that maximizes the social welfare of market participants as part of the energy trading process.

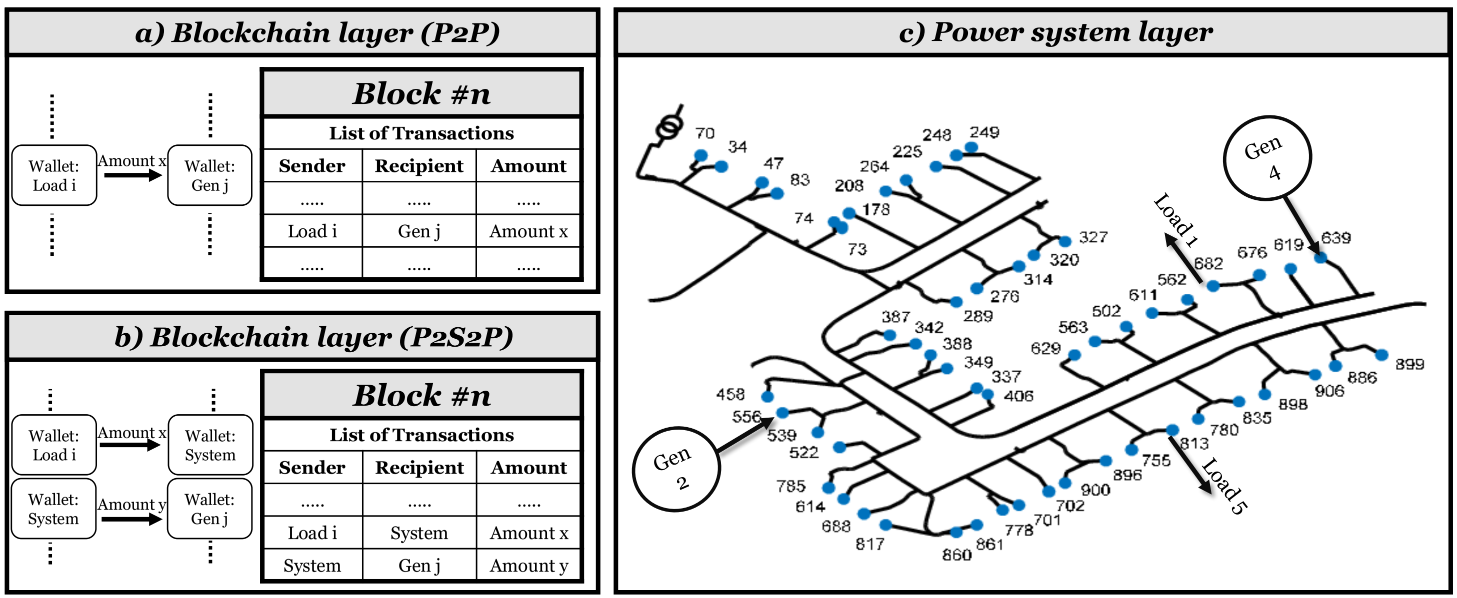


Figure 3.1: (a) Peer-to-peer concept; (b) peer-to-system-to-peer concept; (c) IEEE 906 bus system example of a power system layer.

As well, the chain structure within the blockchain is adapted so that each energy transaction is secured in two bundled blocks rather than one, as in conventional blockchains. The first block stores a list of expected candidate energy transactions obtained from the solution of the market model, while in the second block, the real-time transactions received from the smart meters are stored and secured. The ledger matches participants' energy commitment with their real-time energy transaction (fulfillment). It should be pointed out that the wallets of participants are updated only in the second block. The proposed block structure is presented in Figure 3.2.

Market Commitment Block (MCB)	
List of Transactions Based on Market-Committed Data	
Item	**Details**
Sender	Loads or System
Recipient	Generators or System
Power	Power committed from market module
Price	Price calculated from market module
Wallet Fund	Last updated fund
Time Stamp	Same as traditional blockchain
Proof No.	
Index	

Real Transaction Block (RTB)	
List of Transactions Based on Received Real-Time Data	
Item	**Details**
Sender	Loads or System
Recipient	Generators or System
Power	Real-time power from smart meters
Price	Price adjusted according to penalty factor
Wallet Fund	Updated fund
Time Stamp	Same as traditional blockchain
Proof No.	
Index	

Figure 3.2: Proposed block structure.

3.3 Energy Trading Engine Formulation

This section explains the problem formulation proposed for the distribution system ET-engine, which enables a scalable, transparent, fair, and competitive market for distribution systems. The proposed engine performs the transactions in a P2S2P form rather than the traditional P2P version. With this new approach, all customers have the ability to participate in and benefit from the market or to opt out. The physical flow that occurs in a power system is also included through the integration of smart meter data into the trading process.

The proposed framework starts with the acquisition of participant preferences expressed as bidding curves generated by a bidding management module. Concurrent sensitivity analysis calculates the loss factor at all participant buses. An adapted market model then determines the uniform clearing price and the resultant committed power to/from all participants, based on consideration of the losses. The losses are dispatched accordingly among the participants rather than being assigned solely to the slack. At this stage, the engine communicates these data as unconfirmed transactions to the blockchain module (BC-module). These data contain the committed power and energy prices associated with the participant. The data are then approved (i.e., mined) and stored as a market commitment block (MCB) in the blockchain.

Although these transactions are stored in the chain, the participants' funds are not updated at this stage. After receiving real-time smartmeter data, the engine communicates these data to the BC-module as unconfirmed transactions, which are likewise mined and stored in the blockchain, but this time as a real transaction block (RTB). It is crucial to note that participant accounts are updated at this stage so that the transactions follow the real-time data exactly. The flowchart for the proposed algorithm is provided in Figure 3.3. The major components of the problem formulation relate to the electricity market, the monetary fund (the blockchain), and the power system.

3.3.1 Electricity Market

The electricity market component clears the market and thereby calculates the market clearing price (MCP). Sensitivity analysis is employed for computing the loss factor at each node, which is then incorporated into the market clearing in order to guarantee highly accurate and efficient load dispatch. Using the loss factors from the sensitivity analysis, the market module determines a marginal price at each node. This module was adapted

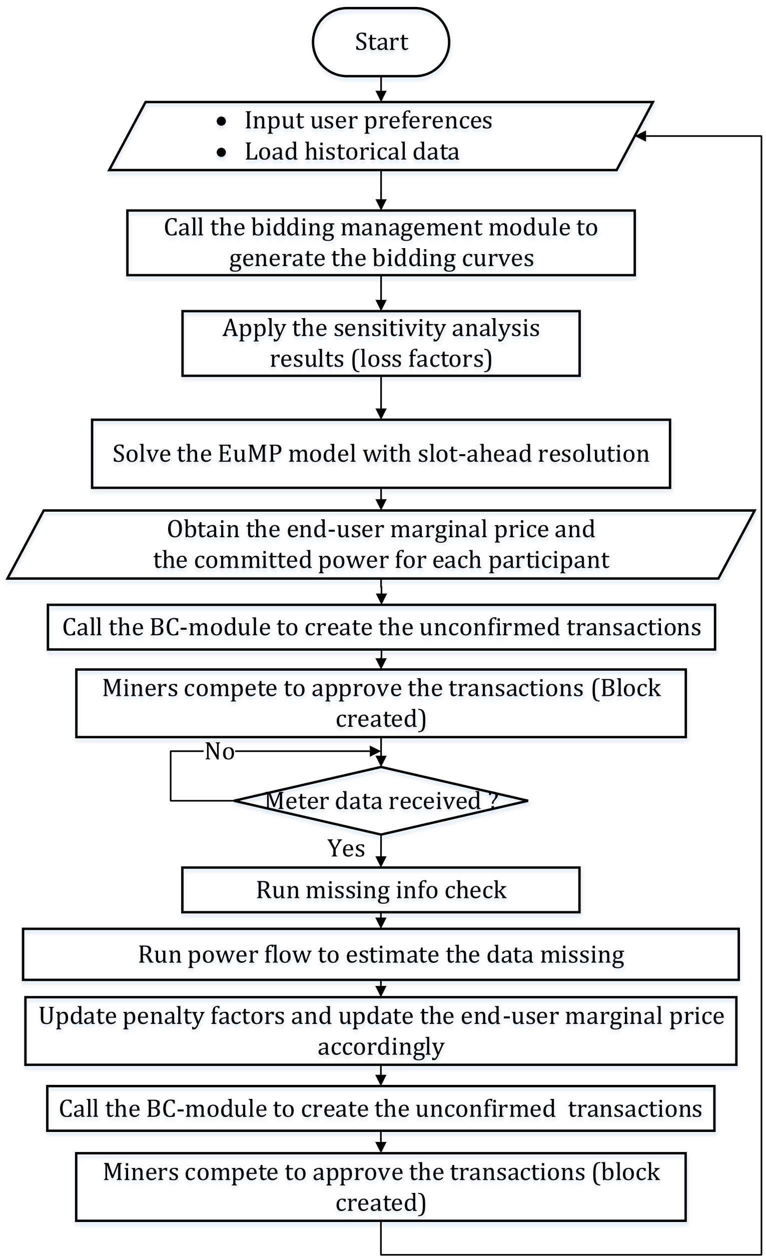


Figure 3.3: Blockchain-ET engine flowchart.

from the current Ontario uniform marginal price (UMP) model and integrated with the calculated loss factors to produce the end-user marginal price (EuMP). The generators' bidding curves, the demand bidding curves, and the calculated loss factors constitute the market module input. Before setting the market price, the algorithm first updates the demand bidding curves, thus making the market fairer and more accurate than the existing UMP model.

The market module can be divided into two submodules: the sensitivity analysis module and the adapted UMP module (EuMP). The sensitivity module calculates and updates the loss factors on a 15-minute basis (time-slot window). The market module considers the loss factor as constant during that slot. The adapted UMP module calculates the UMP from the penalized demand curves and outputs the EuMP. Current Ontario practice is to compute loss penalty factors either yearly or whenever a generation facility larger than 500 MW is added to the system [95].

3.3.1.1 Sensitivity analysis

The following steps are used for calculating the loss factors for each load in the system:

- Step 0: Use the data from the previous slot to forecast the slot-ahead load and generation power.
- Step 1: At each node i, change the power of the node by ΔP (e.g., 1 kW).
- Step 2: Run the power flow.
- Step 3: Calculate the increment in power losses, $\Delta Ploss_i$, resulting from the change at node i, which is computed from the incremental slack bus injections.
- Step 4: Calculate the loss factors as follows:

$$\eta_{D_i} = \frac{\Delta Ploss_i}{\Delta P_i} \tag{3.1}$$

3.3.1.2 End-User Marginal Price (EuMP) model

This module uses modified load bidding curves to solve the UMP problem. The load curves are updated based on the loss factors previously calculated by the sensitivity analysis sub-module. The objective of the UMP model is to maximize social welfare, as follows:

$$\max J = \sum_{s}^{D}\sum_{m}^{D_s}[PD_{s,m}\ \gamma_{D_{s,m}}(1+\eta_{D_s})] - \sum_{c}^{G}\sum_{k}^{G_c}[PG_{c,k}\ \gamma_{G_{c,k}}\ (1-\eta_{G_c})] \tag{3.2}$$

Subject to the following constraints:

- Power balance constraint:

$$\sum_{s}^{D}\sum_{m}^{D_s}[PD_{s,m}\ (1+\eta_{D_s})] = \sum_{c}^{G}\sum_{k}^{G_c}[PG_{c,k}\ (1-\eta_{G_c})] \tag{3.3}$$

- Bidding limits constraints:

$$0 \leq PD_{s,m} \leq \overline{PD}_{s,m} \tag{3.4}$$

$$0 \leq PG_{c,k} \leq \overline{PG}_{c,k} \tag{3.5}$$

The marginal price λ is obtained from the dual variable of Equation (3.3). The market then updates the price at the end-user and generator points according to the calculated loss factor, as follows:

$$\lambda^*_{D_s} = \lambda\ (1+\eta_{D_s}) \tag{3.6}$$

$$\lambda^*_{G_c} = \lambda; \tag{3.7}$$

It should be noted that the market module solves an adequacy problem and is therefore fast regardless of the number of customers. Blockchain technology was selected for the monetary fund because it is a secure, reliable, distributed and transparent technology that can handle a large number of users efficiently without the need for a third party, which means no transaction fees. An adapted and carefully modified blockchain was used for linking the business layer with the physical power system layer and for communicating the correct data between these layers. This re-imagined blockchain layer is used as the monetary fund in the proposed platform.

The time diagram shown in Figure 3.4 represents the operation for one day. The sensitivity analysis is performed on a slot-ahead basis. The market module is activated at the beginning of each 15-minute time slot to create the unconfirmed MCB. Concurrently, the miners are mining the unconfirmed RTB created for the previous time slot since the real-time data are received at the end of the time slot. For example, mining the RTB for T1 occurs in T2 when the data are received. In addition, since the market is assumed to be a slot-ahead market, the MCB for T3 is also mined in the T2 slot after the market module broadcasts the data. Two blocks are thus created in T2: RTB-T1 and MCB-T3.

3.3.2 Monetary Fund (Blockchain)

To secure the data, the mining process is based on a proof of work (POW) consensus algorithm [7]. In this algorithm, the proof number is calculated using a hash puzzle game, as described by the following equation:

$$\begin{aligned} &Hash\ (Unconfirmed\ transaction + previous\ hash + \\ &\qquad proof\ number) = (Hash\ number\ start\ with\ 00) \end{aligned} \tag{3.8}$$

It is worth mentioning that the level of difficulty of the POW can be adjusted to give an estimated time equal to 5 minutes for each block (i.e., one-third of the time required for receiving real-time measurements from smart meters [96]). The general puzzle game is given in Equation (3.9) to Equation (3.11) [97].

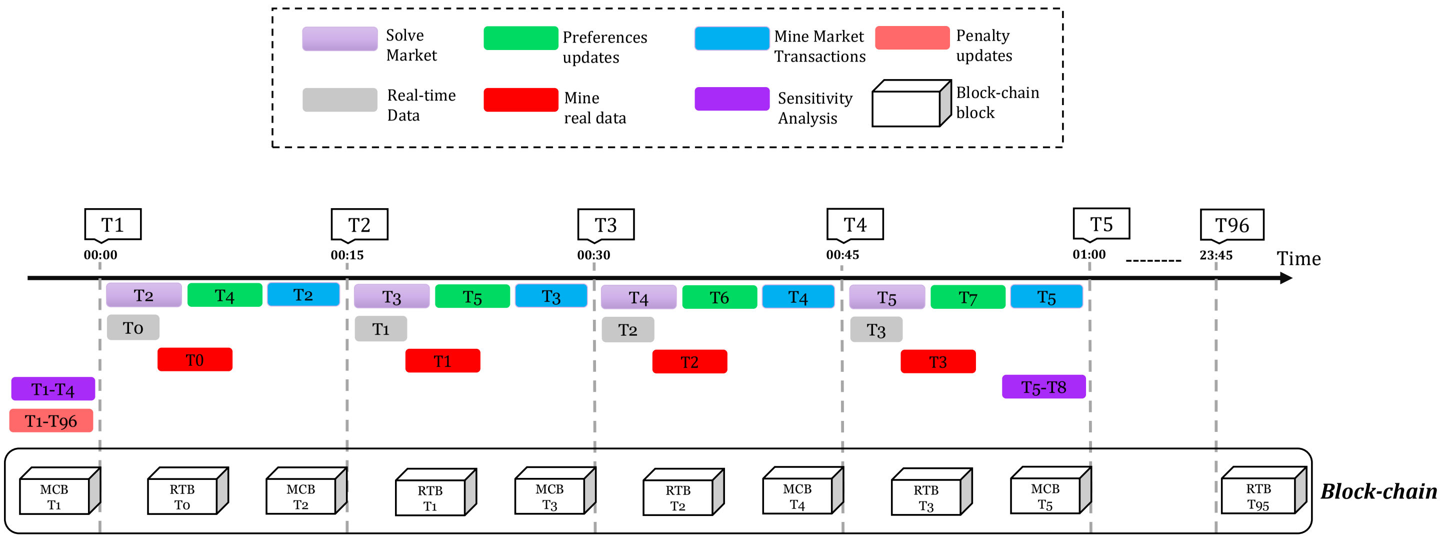


Figure 3.4: Time frame.

$$Hash(Unconfirmed\, transaction + previous\ hash + proof\ number) \leq Target\ value \quad (3.9)$$

while the degree of difficulty is given by

$$Difficulty = \frac{2^{224}}{(Target\ value)} \quad (3.10)$$

The estimated completion time can then be calculated as follows:

$$Estimated\ time = \frac{2^{32}\ (Difficulty)}{(Hash\ rate)} \quad (3.11)$$

3.3.3 Power System

The power system component represents the physical layer where the energy transactions actually occur. The market clears the prices and charges/credits participants based on real transactions happening in the power system. In this context, smart meters are employed for obtaining energy data at the end of each time slot. These data are used for executing transactions and updating funds in real time.

3.4 Platform Execution on IEEE 906 Bus System

The proposed blockchain-based trading platform was developed and tested on the IEEE 906 bus system shown in Figure 3.1. The system has 55 loads located at the end nodes. Four generators are also assumed (at buses 249, 502, 817, and 899) and the bidding for each load and generator are assumed to be given.

As shown in Figure 3.5, MATLAB was employed as the master handler of the platform, with the blockchain developed using Python and the market module implemented on

GAMS. The sensitivity analysis algorithm was developed using MATLAB and is run for each time slot. MATLAB communicates the bidding curves and penalty factors to GAMS and sends an energy market price request (EMPR). GAMS solves the EuMP and responds with an EMP Acknowledge message.

When this occurs, the marginal price is made available to MATLAB and is updated according to the loss factors so that the EuMP can be calculated for each participant. The committed power and the energy price for each participant are communicated to Python for its initiation of the MCB. Upon receiving the real-time data, MATLAB calculates the real prices (λ_{real}), and then communicates the data to Python for an RTB initiation. The miners mine the unconfirmed transaction and create an MCB or RTB whenever they are available. The miners then attach them to the chain and broadcast the confirmed blocks in order to update the ledger.

To emulate the real-time data, a forward-backward-sweep power flow algorithm is run on MATLAB.The same power flow algorithm is employed for the sensitivity analysis and for the calculation of the loss factors. The pseudo-code that details the complete trading process is shown in Figure 3.6.

3.4.1 Sensitivity Analysis Calculations

Sensitivity analysis was performed on the IEEE 906 bus system. As shown in Figure 3.7, the loss factor for absorbing an extra 1 kW at each end user has been calculated. The results reveal that the loss factor could reach as high as 10 % at some locations but zero at others. For this reason, and for a fair and competitive market, individual users should be penalized for their contribution to losses and not be required to share responsibility for losses attributable to others.

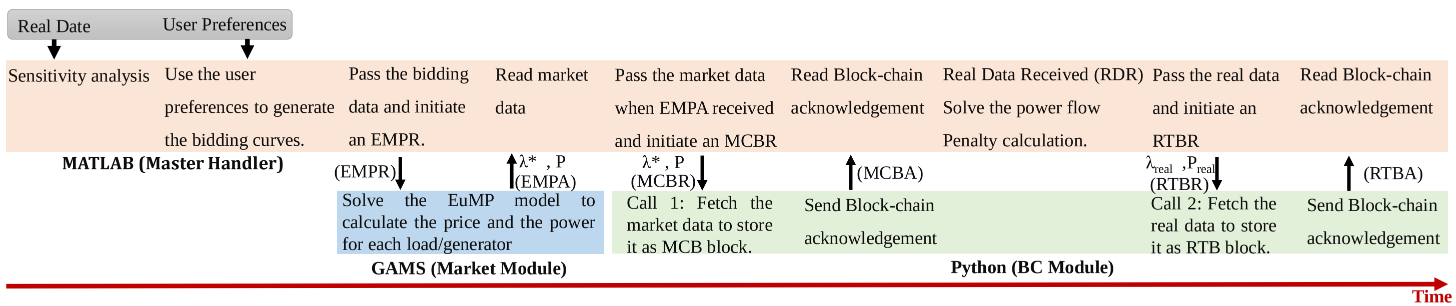


Figure 3.5: Block diagram of the proposed engine.

Pseudo-Code for Engine Algorithm

```
for each time slot     // based on the smart-meter capabilities.
    for i=1 to M       // M denotes the number of users
        η_i = ΔPloss_i / ΔP_i
                // η_i denotes the loss factor for user i
                // ΔPloss_i denotes the change in the system losses
                // ΔP_i denotes the incremental change in the power
        Calculate the bidding data using the market management component
    end for
Send Energy Market Price Request (EMPR)
Solve the EuMP model to calculate the price and the power
Send Energy Market Price Acknowledgement (EMPA)
Send Market Commitment Block Request (MCBR)
Blockchain server stores the data as unconfirmed transactions
Miners compete to approve the transactions (Mining)
Miners approve market data and store them as a block (MCB)
Send Market Commitment Block Acknowledgement (MCBA)
    if real data received
        Solve the power flow
        Update the real data
        Calculate the penalty
        Send Real Transaction Block Request (RTBR)
        blockchain server stores the data as unconfirmed transactions
        Miners compete to approve the transactions (Mining)
        Miners approve real-time data and store them as a block (RTB)
        Send Real Transaction Block Acknowledgement (RTBA)
    end if
end for
```

Figure 3.6: Pseudo code for the blockchain-ET engine.

3.4.2 UMP Model vs EuMP Model

The traditional UMP model was solved, with the uniform price λ found to be 0.085 \$/kWh; system losses are neglected in this model. To include consideration of the effect of loss factors, the EuMP model was developed and solved. Figure 3.8 shows the effect of losses on the updating of the bidding curves. The developed model gives correct pricing and power signals for distribution system end-users. For the same-priced block, the demand

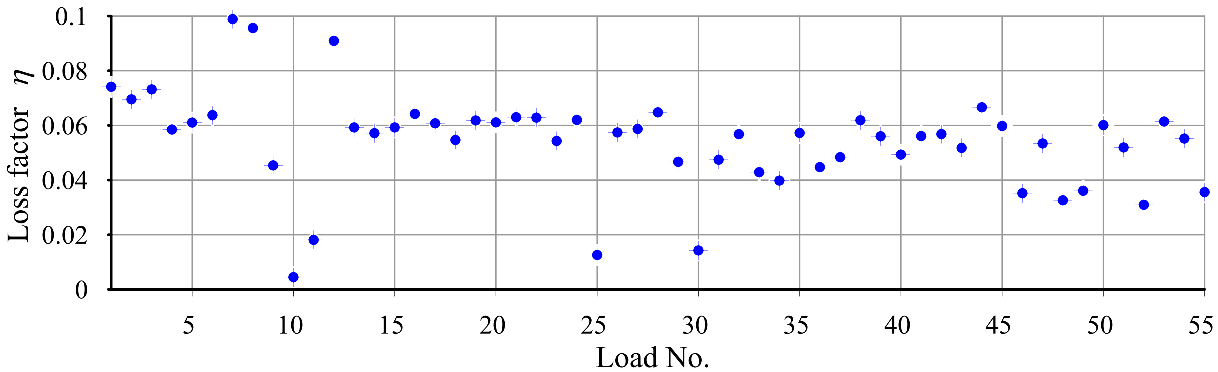


Figure 3.7: Loss factor values at all buses.

bidding is modified using the demand loss factor so that the demand power is increased at the asking price. This feature does not contradict the interests of the demand participant, since more power at the same price is acceptable from a demand perspective. Generators are penalized according to the power they produce but with the offer price kept constant. In this regard, less power is taken from the generator at the offer price, which also aligns with the generator's interest in increasing the price for the power being offered. These modifications of the bidding curves based on the loss factors are presented in Figure 3.8.

As shown in Figure 3.9, the traditional UMP model provides an equal energy price for all participants. In contrast, the proposed EuMP model produces a different price for individual participants based on their contribution to system losses, as indicated in Figure 3.9. For example, load 7 pays more than the average because the calculated sensitivity analysis indicates that it is responsible for greater losses. At the same time, load 10 pays less, reflecting its much lower contribution to the losses.

It should be pointed out that comparing energy pricing according to the existing Ontario market requires the addition of a delivery cost to account for losses. This delivery cost was estimated to be 0.00497 \$/kWh for the case under study and was applied to the UMP obtained. Figure 3.9 indicates the proposed EuMP and the modified UMP. It is clear that EuMP is fairer to users than even the modified UMP. The prices for users with a smaller

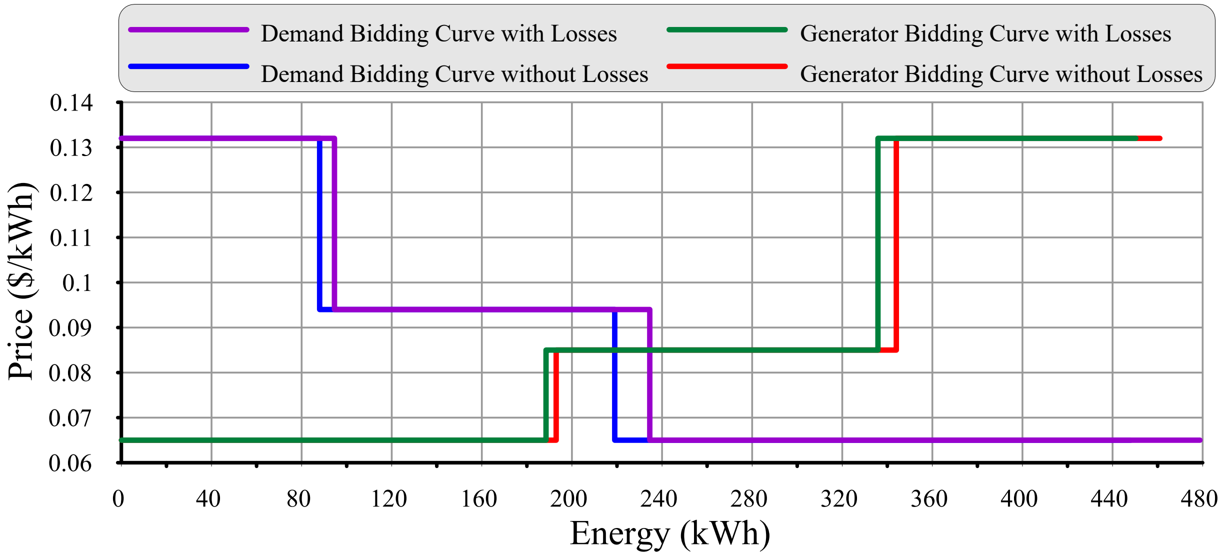


Figure 3.8: Effect of losses on bidding curves.

contribution to losses are lower than the UMP, while users who contribute significantly to losses are charged prices higher than the UMP. The EuMP is also transparent, with no hidden unexplained fees included in electricity bills.

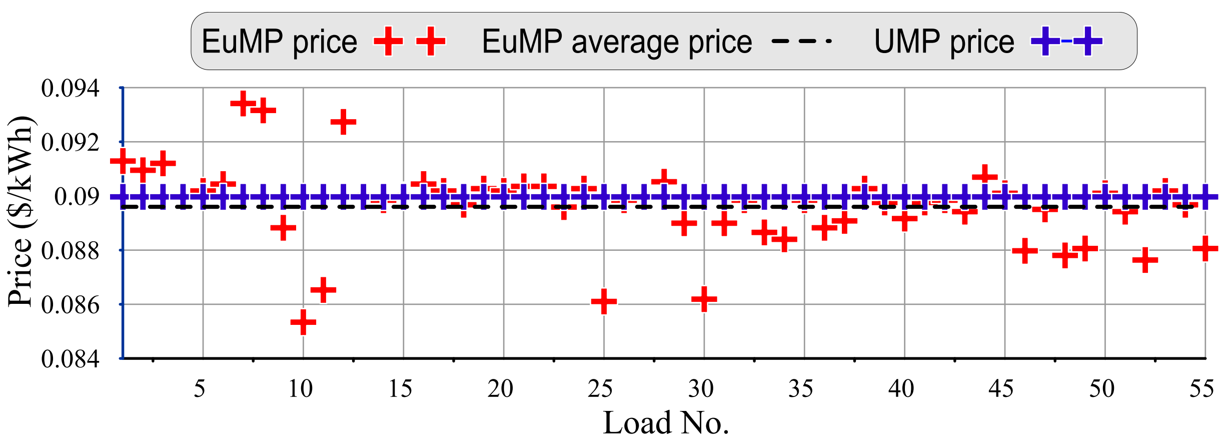


Figure 3.9: EuMP and UMP prices.

3.4.3 Creating an MCB Block

The proposed blockchain was coded using Python. As indicated in Figure 3.5, the coded blockchain successfully received the first call. It accordingly created a block that contains a list of market transactions for all participants. The unconfirmed transaction data are structured as follows: 1) the public key of the sender, i.e., the system, which is considered the sender in our model; 2) the recipient number, i.e., the peers in our model, which are generators or loads; 3) the price calculated from the EuMP model; 4) the committed power; 5) the available wallet fund for each recipient. Samples of the transactions generated in the MCB block are provided in Figure 3.10. In the transactions shown, recipient 33 represents load number 33, which committed to buy 3 kWh of energy at a price of 0.0883 $/kWh. The transaction also shows that the wallet of this recipient has available funds in the amount of $ 50. On the other hand, recipient 58 represents generator number 3, which is committed to generating 40 kWh at a price of 0.085 $/kWh. Note that generators are modeled as recipients with positive transaction amounts, and loads are modeled as recipients with negative transaction amounts, with the system as the sender for all recipients (i.e., P2S2P). At this stage, the funds are not updated, the generator's wallet is not credited, and the load's wallet is not debited.

3.4.4 Creating an RTB Block

The coded blockchain successfully receives the second call to mine the real-time transactions and thus creates an RTB block with the updated funds. Samples of the final transactions created are displayed in Figure 3.11.

3.4.5 Computational Time

The proposed framework was tested on a PC with the following specifications: Intel® Core™ i5-8250U / 8 / 1.60 GHz - Hash rate = 584 h/s. A breakdown of the computational

Sender:
30819f300d06092a864886f70d010101050003818d0030818902818100deff7a1218632479edf6a1537
9f7365f15dccf3d01bf1df4b4a8069a56d2597db90132b7364768d93b787f72f72435f2add3d7f921daf8
dbdb680067df76fd97b724b292dab1b246b0c8ab134031e92e4cf096913dd2942e74aa5e1960c71d47a
7e4a6c8d580f55ba6daf4d86ba9bbad923c1b88f626a585cd5c945a1dc78ecf0203010001
Recipient: ["3", "3"]
Amount: [0.0883]
power: [3]
fund: 50

Sender:
30819f300d06092a864886f70d010101050003818d0030818902818100deff7a1218632479edf6a1537
9f7365f15dccf3d01bf1df4b4a8069a56d2597db90132b7364768d93b787f72f72435f2add3d7f921daf8
dbdb680067df76fd97b724b292dab1b246b0c8ab134031e92e4cf096913dd2942e74aa5e1960c71d47a
7e4a6c8d580f55ba6daf4d86ba9bbad923c1b88f626a585cd5c945a1dc78ecf0203010001
Recipient: ["5", "8"]
Amount: [0.085]
power: [53.011]
fund: 50

Figure 3.10: Sample MCB block transactions.

time is detailed in Table 3.1. Note that the color codes in Table 3.1 follow those shown in Figure 3.4.

3.5 Discussion

This section presents a brief discussion of the proposed blockchain-based engine. The developed algorithm consists of three main modules: 1) The market module, which is responsible for clearing the market and implementing the loss factor based on the sensitivity analysis results; 2) the power system module, which represents the physical layer where the smart meters are employed for obtaining energy data at the end of each time slot; and 3) the blockchain module, which functions as a monetary fund. These modules are located at each miner responsible for mining the transactions. Market module codes are allocated on all miner engines.

Sender:
30819f300d06092a864886f70d010101050003818d0030818902818100deff7a1218632479edf6a1537
9f7365f15dccf3d01bf1df4b4a8069a56d2597db90132b7364768d93b787f72f72435f2add3d7f921daf8
dbdb680067df76fd97b724b292dab1b246b0c8ab134031e92e4cf096913dd2942e74aa5e1960c71d47a
7e4a6c8d580f55ba6daf4d86ba9bbad923c1b88f626a585cd5c945a1dc78ecf0203010001
Recipient: ["3", "3"]
Amount: [0.11732889538573102]
power: [5]
fund: 49.41335

Sender:
30819f300d06092a864886f70d010101050003818d0030818902818100deff7a1218632479edf6a1537
9f7365f15dccf3d01bf1df4b4a8069a56d2597db90132b7364768d93b787f72f72435f2add3d7f921daf8
dbdb680067df76fd97b724b292dab1b246b0c8ab134031e92e4cf096913dd2942e74aa5e1960c71d47a
7e4a6c8d580f55ba6daf4d86ba9bbad923c1b88f626a585cd5c945a1dc78ecf0203010001
Recipient: ["5", "8"]
Amount: [0.085]
power: [53.011]
fund: 54.505935

Figure 3.11: Sample RTB block transactions.

Although the the UMP is a linear problem and can be coded in Python, the present author preferred that the market module be generic and adaptable to any market formulation without the necessity of changing all of the blockchain codes. For example, the market model used here is based on the UMP, which can be replaced in the future with any other proposed market technique while keeping the blockchain code unaltered.

Furthermore, the proposed blockchain is only permissionless for reading the data in order to promote system transparency. Permission is nevertheless required for writing data, in exactly the same way as with consortium and private blockchains. This permission is used for minimizing the energy consumed by the miners and for limiting data interchange. The engine proposed in this work also utilizes a PoW technique because it represents the genesis of the consensus algorithm and offers security against the blockchain rollback problem [98]. Given these points, the proposed blockchain-based engine clearly falls between public and consortium blockchains. To demonstrate the truth of this reasoning, Table 3.2

Table 3.1: Execution Time for Engine Processes

Color code	Process	Computational time
	Solving the EuMP market	1.79 second
	Run sensitivity analysis	20.25 seconds
	Mining the market commitment transactions	4 minutes 37 seconds
	Mining the real-time transactions	4 minutes 37 seconds
	Updating preferences	5 minutes allocated
	Updating penalties	5 minutes allocated
	Longest execution time (Solving the EuMP market + Updating preferences + Mining the market commitment transactions)	9 minutes 38.79 seconds which is less than 15 min time slot.

provides a comparison of public, consortium, and proposed blockchains.

The mining was run on a PC with the above specifications, and the total time required was 9 min 38.79 s. With a PC consumption of 80 W, mining one block will take (5/60 * 80/1000 * 8760 = 58.4 kWh/year). According to the proposed framework, we are mining 8 blocks per hour, so the total consumption would be 467.2 kWh/year. Note that the average household consumption in Canada is 9,600 kWh per year [99].

In the proposed case study, the average energy consumption for the 55 loads would be (9600 * 55 = 52,8000 kWh/year). Assuming five miners are allowed to mine the transactions, the total average energy required would be (467.2 * 5 = 2,336 kWh/year). Mining energy is clearly negligible (2336 / 528000 = 0.00442), less than 0.5 %. In that context, the proposed trading framework entails no conflicts with an energy-efficient smart-grid philosophy.

Table 3.2: Comparison of Public, Consortium, and Proposed Blockchain

	Public	**Consortium**	**Proposed**
Mining authority	Anyone	A set of participants	A set of participants
Consensus algorithm	PoW, PoS, etc	PoA, PBFT, etc	PoW
Reading authority	Anyone	Anyone or selected participants	Anyone
Writing authority	Any one	A set of participants	A set of participants
Transaction throughput	Low	High	Low
Rollback	Almost impossible	Hard but possible	Almost impossible
Infrastructure	Highly decentralized	Decentralized	Decentralized

3.6 Conclusion

This chapter proposed a comprehensive energy trading platform in which the trading is managed through an energy engine that employs a blockchain as the monetary fund. The engine was developed through the integration of several modules mounted on MATLAB, GAMS, and Python software packages. The proposed technique includes a new cash transaction structure that resembles the power transactions in a power system. This P2S2P structure ensures that participants are charged amounts that correspond precisely to their consumption. Energy pricing is based on an EuMP model in which the price calculated at each node includes consideration of the loss factor associated with that node.

Sensitivity analysis conducted on a slot-ahead basis incorporates the losses into the market model, which then offers a fair market with dispatchable losses. The solutions for the slot-ahead market are stored in the blockchain as MCBs. These blocks contain the power committed from/to all generators/loads. Real-time data collected from smart meters on a 15-minute basis are used for finalizing energy transactions in the form of RTBs. These blocks contain the energy consumed/supplied, the EuMP, and the updated funds at all nodes. The cash flow in the proposed energy trading platform was computed on a 15-minute basis, and the results were compared with the current monthly cash flow determined using the existing energy trading system.

As an additional feature, if a recipient or generator fails to fulfill a power commitment and violates a smart binding contract within a specific threshold, a penalty can be applied during the creation of the RTB, since the corresponding MCB is available in the ledger. The threshold for beginning to apply penalties and the amount of the penalty are determined by the trading management entity. The funds collected from the application of these penalties create a surplus fund that already resides in the utility wallet. This offers a new business model for the utility and an incentive for the utility to run the system. A percentage from these surplus funds could be shared with trusted participants who fulfill their obligations for a specified amount of time, as identified by a juridical party.

The work presented in this thesis enhances the demand response by changing the concept from a time-of-use (TOU) basis [3] to a price-of-the-time (POT) concept (i.e., a timely market response to load requests), which means that the demand response occurs locally at the end-customer, and that penalty factors are applied to those who fail to send accurate signals about their demand. This model will benefit all system users and will mitigate demand response and peak rebound problems. The flexibility of the instant application of energy prices, penalties, and incentives at no cost makes the proposed blockchain-based market superior to any currently existing market. Although the developed engine succeeded in handling the transactions in any clustered market (e.g., isolated MG market), energy trading among interconnected MGs while keeping their independent operations is required. Therefore, an energy trading framework is developed in Chapter 4 to handle the transactions among the interconnected MGs.

The main contributions of this chapter can be summarized as follows:

1. A new framework for energy trading that can handle all offers from prosumers and biddings from end-users is proposed. The development of this trading framework, which includes the adoption of existing market models, is discussed in detail in subsequent sections.

2. Existing blockchain technology is adapted to suit the distinct nature of power systems as well as the needs of businesses.
3. An end-user marginal price model has been created in order to ensure fairness and the efficient management of a large number of market participants.
4. An operation cycle framework that ensures harmony among differing market modules has been built.
5. The proposed framework promotes the achievement of a fast billing cycle and efficient cash flow.

Chapter 4

Blockchain-based Centralized IMG Energy Trading Platform

4.1 Introduction

In the previous chapter, an energy trading engine was designed to enable energy trading in MGs. In this chapter, energy trading among IMGs is developed. The proposed framework fits with existing structures in which regulations have a centralized entity that settles the market transactions (i.e., central operator). This chapter's main objective is to develop a fair IMG energy trading framework while preserving the MGs' self-benefit-driven (SBD) character. The blockchain is further adapted to enable transactions between IMGs and connect the internal blockchain developed in the previous chapter. A unique MG utility function is also formulated to ensure that all MGs will have the interest to participate in the framework. Also, the centralized proposed model is solved using the Nash bargaining approach to ensure fairness among all participants.

The rest of the chapter is organized as follows. In section 4.2, the centralized energy trading structure is discussed, while in section 4.3, the proposed centralized platform is investigated in details. In section 4.4, the optimization model used to solve the centralized energy trading model is presented, followed by a discussion of the case studies in section 4.5. Finally, the conclusion is given in section 4.6.

4.2 Centralized Energy Trading Structure

In this work, energy trading between IMGs is enabled by utilizing the centralized IMG structure. Although all of the MGs participating in the energy trading platform seek equilibrium benefits, they are selfish players and will first solve the market internally to maximize their internal social welfare; only afterwards will they trade with others seeking more benefits. Therefore, in this structure, each MG has its own energy management system (EMS) that runs the energy trading engine proposed in Chapter 3 and determines the internal MCP. It then participates in the IMG energy trading platform to gain more benefits either by exporting surplus energy or importing cheap energy.

The DSO is assumed to be the entity handling the energy trading settlement among the IMGs. Therefore, the DSO runs the central market model to provide a fair solution for all participants and determine exporters and importers.

As shown in Figure 4.1, the DSO receives information from the EMS of each MG after executing the energy trading engine proposed in Chapter 3. The information is as follows:

1. Aggregated biddings from MGs for their generators and loads for each MG that decided to participate in the trading after applying the internal loss factor (i.e., the curves in the form of price/energy pairs).

2. Internal social welfare after clearing the internal EuMP model.

3. The excess generation that is available after satisfying internal demands.

The proposed energy trading model is then run to settle the transactions between the MGs. It should be noted that the proposed structure interconnects all MG blockchains to store the IMG transactions, as will be discussed later.

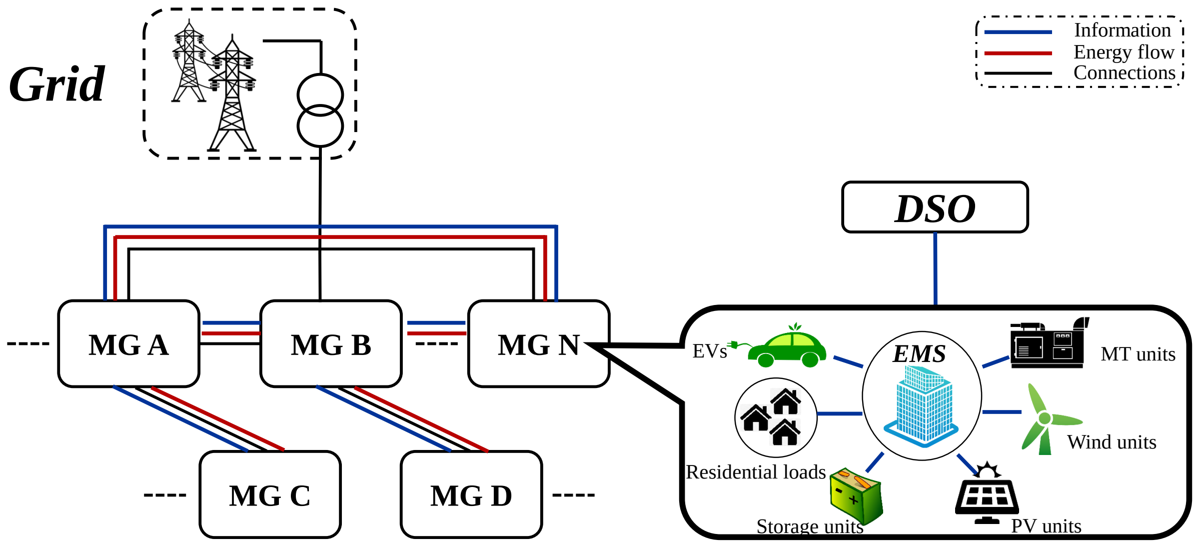


Figure 4.1: IMG structure in centralized Nash framework.

4.3 Nash bargaining-based Centralized Platform

This section describes the Nash solution, algorithms, and assumptions for the proposed energy trading framework for IMGs. As mentioned earlier, a centralized solution will be determined by the DSO. This centralized solution will be developed based on the Nash bargaining formulation between IMGs. This solution aims to find a mutual solution that satisfies all participants. It should be noted that the utility functions are uniquely defined from the basic principle of the UMP model. The developed Nash solution model and the monetary fund for the proposed platform will be discussed in in the next subsections.

4.3.1 Nash Bargaining Solution

This section presents a brief background for the Nash bargaining problem that is widely used in the energy trading algorithms presented in the literature. In this work, a novel model based on Nash bargaining is presented to establish fair settlements for energy trading when considering SBD behaviour from participants.

If two players are negotiating to find a mutual solution that satisfies their interests based on a self-benefit utility function, a Nash bargaining problem can be formulated. Let Q denote the number of feasible solutions and $u_s(q)$ denote the payoff for each player s, should an agreement be reached on a feasible solution $q \in Q$. In the case of a disagreement, the payoffs for each player are donated by d_s. The set of agreements for different solutions for the two players, A , is defined as in Equation (4.1)

$$A := \{u_1(q), u_2(q) \ \mid \ q \in Q\} \tag{4.1}$$

The objective can be stated as finding an agreement such that each player's payoff in case of agreement is greater than the payoff in case of disagreement. Nash [100] developed an axiomatic bargaining solution based on fulfilling the following axioms:

- Individual rationality: Players aim to improve their payoff by participating in the bargaining game, making it impossible to find a solution. Hence, the disagreement solution has a higher payoff than the agreement solution.
- Independence of Linear Transformations: Any linear transformation applied to utility functions will not affect the solution of the game. For example, in the linear transformation $\Omega(x) = Ax + B$, a bargaining problem with a payoff R is independent of the linear transformation, if the payoff considering the utility function that has been transformed using Ω is equal to $\Omega(R)$. This axiom is true if $\forall A, B$.

  Thus, if

  $$P(u, d) = R \tag{4.2}$$

  then

  $$P(\Omega(u), \Omega(d)) = \Omega(R) \tag{4.3}$$

- Symmetry: Symmetric utility functions should have symmetric payoffs. The solution should not discriminate between players but instead depend only on their payoff functions. For a feasible solution region Z defined by Equations (4.4)-(4.5), symmetry implies that the bargaining solution (i.e., (u_1^*, u_2^*)) for the bargaining game is (0.5,0.5) if the disagreements d1,d2=0.

$$region\ Z : u_1 + u_2 \leq 1 \tag{4.4}$$

$$u_1 \geq 0, u_2 \geq 0 \tag{4.5}$$

In other words, if both players have the same utility functions, then symmetry demands that both receive equal payoffs. The solution will be the same for each player that has the same agreement and disagreement payoffs.

- Independence of irrelevant alternatives: Given that $A \subset B$, if a solution is found for a domain A, then the solution will not change for domain B.
- Pareto Optimality: A player cannot find a solution such that any player receives a payoff greater than the one obtained from the Nash bargaining solution.
- Feasibility: For the bargaining problem, at least one feasible solution exists that satisfies all constraints.

Definition: (u_1^*, u_2^*) is a Nash bargaining solution for the two players problem if it satisfies the following optimization problem:

$$\max[(u_1 - d_1)(u_2 - d_2)] \tag{4.6}$$

subject to:

$$(u_1, u_2) \in Q \tag{4.7}$$

$$(u_1, u_2) \geq (d_1, d_2) \tag{4.8}$$

This Nash bargaining solution can be generalized to any number of players, as will be explained in the next section.

4.3.2 MG Utility Definition

In this subsection, the utility function for each participating MG is formulated. Assuming a non-cooperative game, each MG will act to maximize its own benefits defined by its utility function. The utility function used for a single MG aligns with the aforementioned assumption. In this regard, each MG can export/import energy to/from the IMG market in order to increase its social welfare or at least offers energy at cheaper prices (i.e., lower than the internal market clearing price MCP) to its local loads. Given the demand and surplus generation in each MG, the proposed algorithm defines two utility functions – import and export – for each MG to describe its trading mode.

Importing MGs will seek lower energy prices for their own load, and higher demand coverage by buying cheap energy, if any, offered by neighboring MGs. On the other hand, exporting MGs aim to maximize their generators' benefits by exporting surplus energy to neighbours without affecting the energy prices offered to its local loads. These are the logic rules that we considered in our energy trading framework. Importers act to supply more demand at lower prices while exporters try to trade surplus energy and keep their local load prices unchanged.

Figure 5.3 illustrates a general offer/bidding curve for generator/load which is used to find the market clearing price (λ_1: marginal price in case of isolated operation) that maximizes the social welfare (i.e., area between the two curves). When importing cheaper energy from neighbours, an MG will have a modified generator offer curve and thus gain additional social welfare (i.e., import area A_I and price [λ_2: marginal price in case of importing]). As shown in the figure, importing energy will lower the price and/or increase the demand covered within the importing MG.

On the other hand, in case of export, an MG can offer its excess generation (i.e., the energy which remains after clearing the local market) in the IMG market. In this way, an MG can gain additional social welfare for generators (i.e., export area A_E) without changing the local market price (λ_1) after achieving a new export price (λ_3: marginal price in case of exporting). This price (λ_3) is the price for the receiving MG, not the exporting one, and is lower than its MCP, as explained earlier.

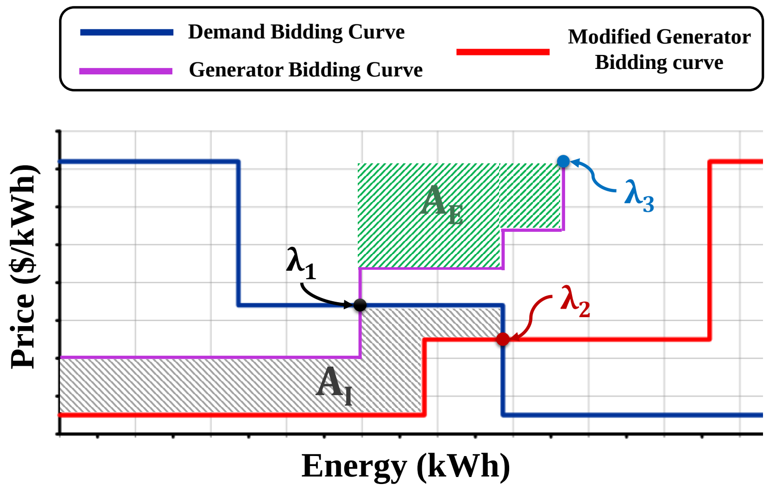


Figure 4.2: Bidding curves.

In this work, the following assumptions are used in the proposed trading framework:

- Each MG is assigned only one mode of operation, either to export or to import through the same link at a given time.
- MGs can be connected in series, parallel, or mesh.
- End-users and prosumers can submit their bidding and participate in the local market.
- For the purpose of calculating social welfare, exporter generators are assumed to be from the importing MG.

4.3.3 Centralized Nash Bargaining Solution

In this work, a centralized Nash equilibrium for non-cooperative strategic energy trading game is proposed. The DSO is assumed to be the entity handling this process, solving the Nash bargaining problem, and identifying the Nash equilibrium for all participants. This technique provides a fair solution for all participants and can easily determine exporters and importers. Although all of the participants are seeking equilibrium, they are selfish players and will first solve the market internally to maximize their internal social welfare, after which they can trade with others seeking additional benefits.

The Nash objective is to maximize the utility difference between agreement (u) and disagreement (d). In our model, the disagreement part is set to zero. As mentioned earlier, MGs participate in order to enhance their gains via trading, so if trading is not improving their gains, no trading is better. Thus, it is logical to assume that the disagreement cost is zero.

$$\max \prod_{i \in \mathbb{S}} (A_I^i + A_E^i) \tag{4.9}$$

subject to:

$$A_I^i + A_E^i \geq 0 \tag{4.10}$$

Equation (4.9) defines the objective of the proposed model as the sum of import and export areas, while Equation (4.10) represents the minimum acceptable trading benefit to participate in the game.

4.3.4 Centralized Platform Monetary Fund

Blockchain technology is used in the proposed framework to promote the independent operation of participating MGs and to utilize the numerous benefits blockchains offer. In the previous chapter, we presented a blockchain structure that can work as a monetary fund for individual grids and handle intra-gird transactions with a single entity running the system. However, this blockchain has to be interconnected with other chains to enable trading in an interconnected market. This entails further adaptations for the blockchain proposed in the previous chapter to make it capable of handling inter-grid transactions.

Figure 4.3 shows a general overview of the proposed structure. As can be seen, the blockchain mimics the physical layer of the power system while establishing transactions, thus mirroring the financial cash flow and the actual power flow. The proposed blockchain structure assumes coupled chains, a microgrid chain (MC) and an inter-grid chain (IGC).

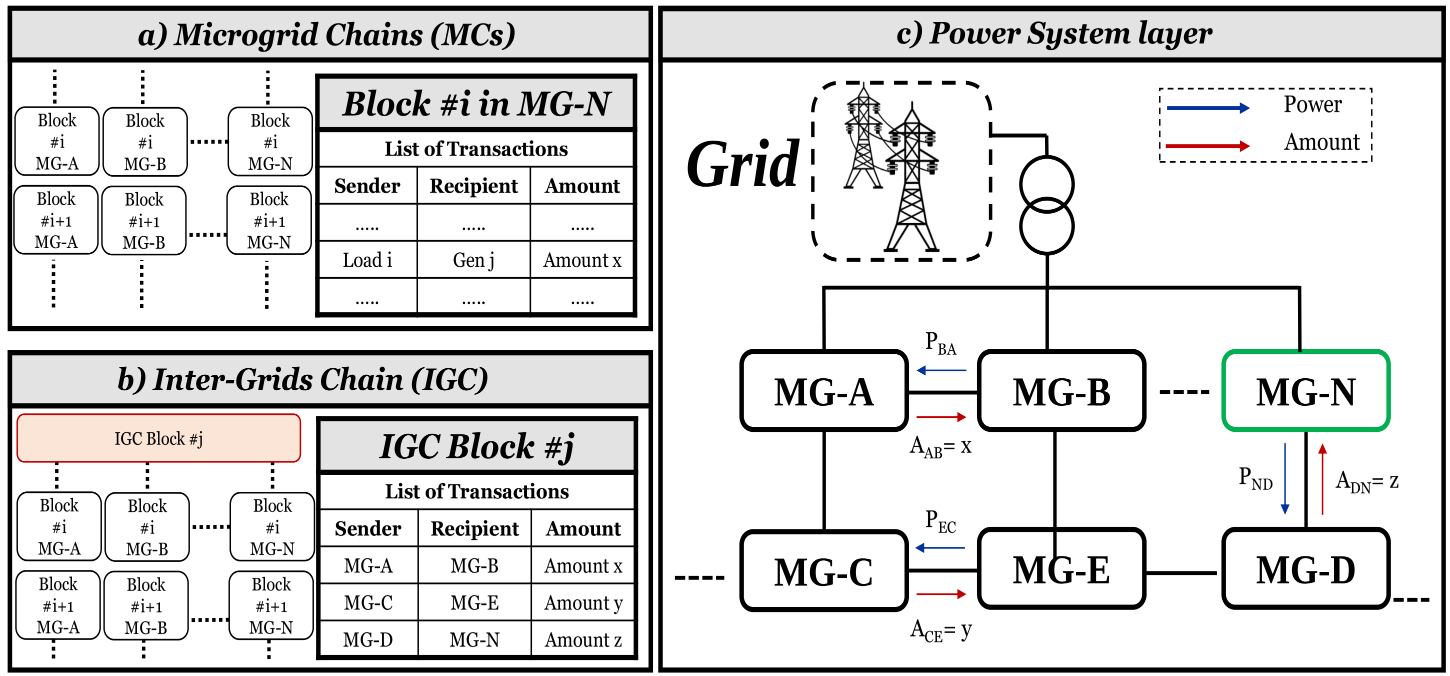


Figure 4.3: a)inter-grid chain (IGC), and c) power system layer.

The MCs are connected to the IGC to handle intergrid transactions while keeping the operation transparent for all MGs. The two-layer structural chains (TLSCs) have the following chains: 1) MCs, which act as a monetary fund for intra-grid trading transactions between loads and generations, as shown in Figure 4.4, and 2) IGCs, which are connected to all MCs with access to the MG's global wallet. Note that IGC blocks store all transactions among participating MGs that have been settled by the centralized market algorithm proposed in section 4.4.

Figure 4.5 demonstrates the hashing algorithm used for the TLSC. Each MG block records the previous hash that inherently contains the data of the previous block as well as the data for the previous IGC block. Furthermore, each IGC block records the hash of the previous one. This provides a very sophisticated security level that stores and encrypts all data (i.e., internal data and interconnected data) in both chains. As a result, the proposed TLSC makes the system immune to any manipulation from participants.

Two consensus algorithms are used in the proposed TLSC structure. The first is the Proof of Work (PoW) algorithm, which is used for mining blocks inside each MG using

MC Block	
List of Transactions based on Market Committed data	
Item	**Details**
Sender	MG's Loads
Recipient	MG's Generators or System
Power	Power received from smart meter
Price	Price calculated from internal market module
Wallet Fund	Updated fund
Consensus	Proof of Work
Time Stamp	Same as traditional block-chain
Proof No.	
Index	

IGC Block	
List of Transactions based on received real-time data	
Item	**Details**
Sender	MG
Recipient	MG
Power	Power received from smart meter
Price	Price calculated from Interconnected market module
Wallet Fund	Updated fund
Consensus	Proof of Authority
Time Stamp	Same as traditional block-chain
Proof No.	
Index	

Figure 4.4: Proposed block structure.

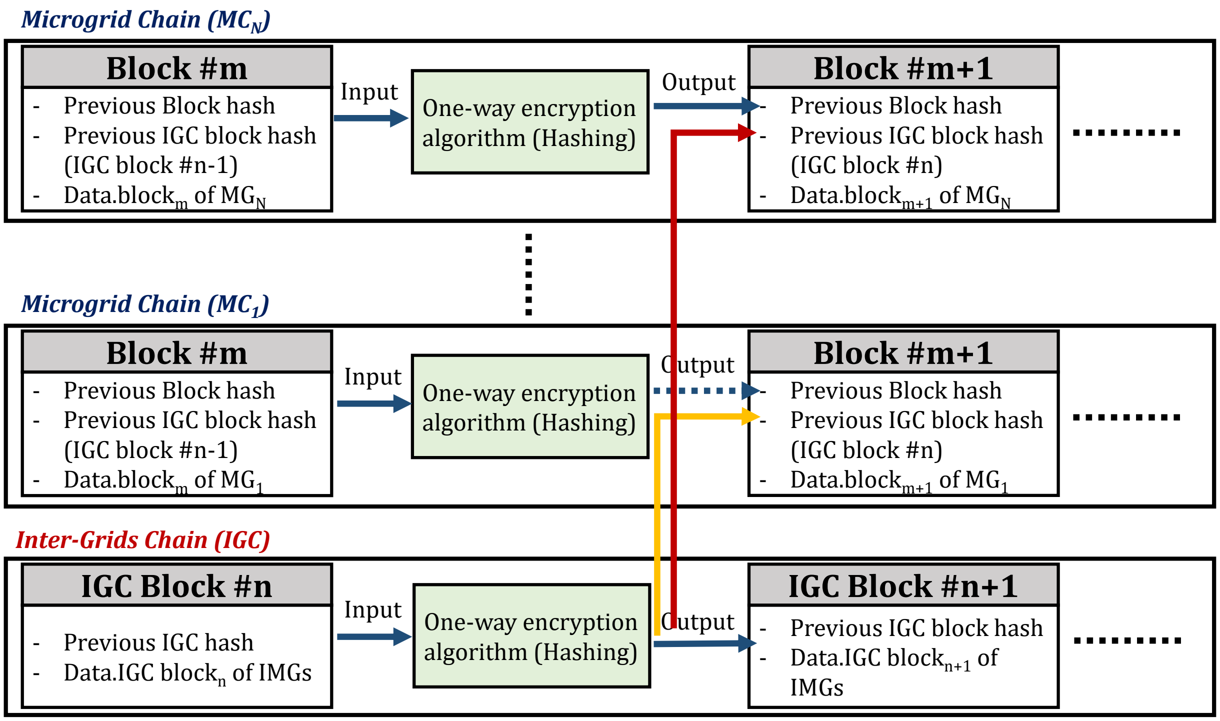


Figure 4.5: TLSC hashing algorithm.

the same concept proposed in the previous chapter. The other is the Proof of Authority (PoA) (i.e., Proof of Identity) algorithm, which is used by DSOs to mine IGS blocks. This separation ensures independent operation for MGs, with each chain's miners only mining their own transactions. It also ensures transparent energy trading within MGs, as the trusted DSO is the only entity that can verify transactions occurring between MGs.

The timing diagram shown in Figure 4.6 represents the operation for one day. The sensitivity analysis is performed on a slot-ahead basis to accommodate for the losses in the MGs. Each MG mining bundled block uses the PoW consensus algorithm. These blocks contain both the internal market data and the real-time data received from the smart meter.

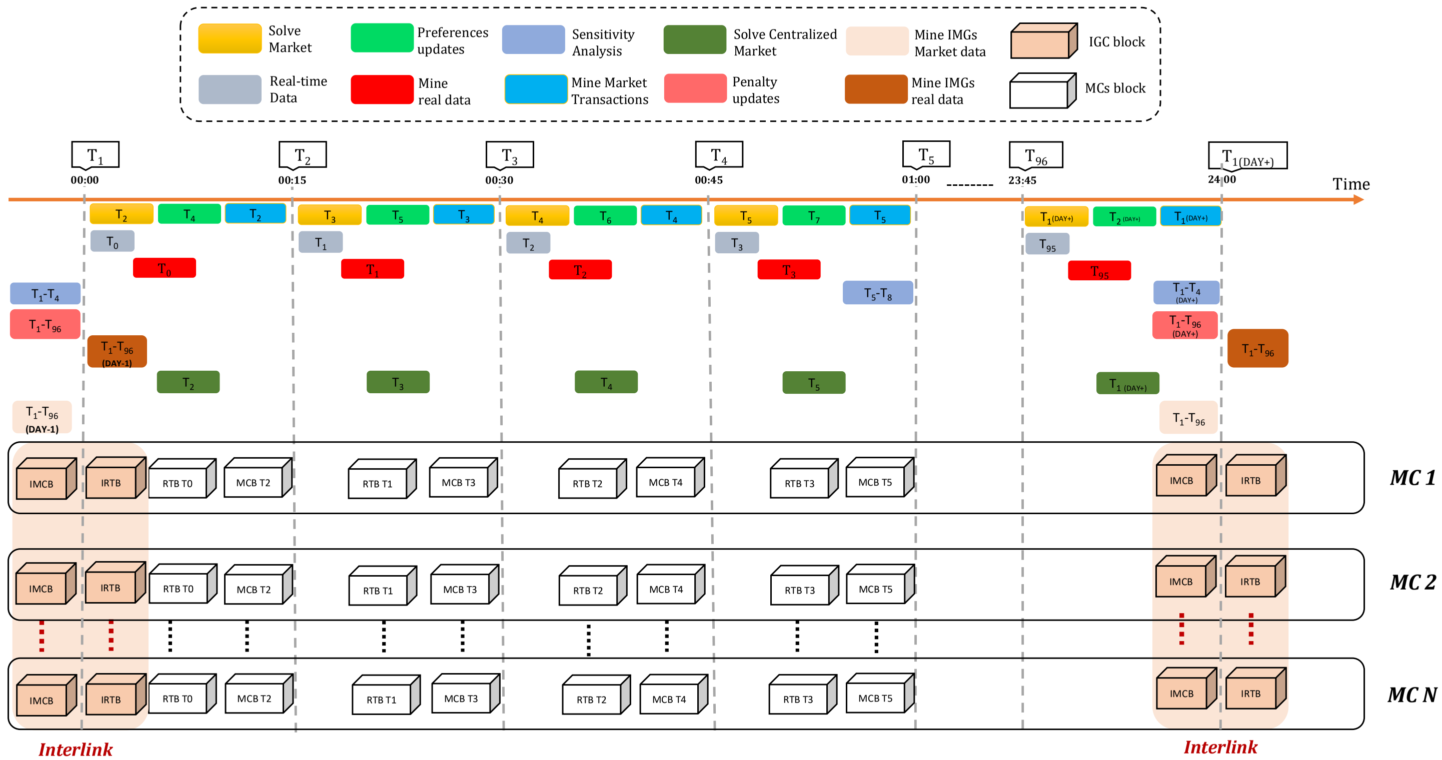


Figure 4.6: Platform time-frame.

Moreover, the DSO receives the data from the MGs after solving their internal market and uses these data to solve the proposed centralized Nash problem in order to settle the transactions between MGs. Afterwards, the internal transactions are updated and mined in each MC as MCB, as shown in Figure 4.6. Thereafter, the market commitment transactions between MGs are mined by the DSO using the POA concept onetime at the last time slot in the day. Also, the real transactions between IMGs are mined and stored at the very first slot of next day, as illustrated in Figure 4.6.

4.4 Centralized Platform Optimization Model

This section explains the mathematical formulation of the proposed energy trading frameworks. As mentioned earlier, two different utility functions are defined for each MG. In the case of importing, the utility function is to maximize the effective social welfare (SWE), as defined by Equation (4.11). In the case of exporting, the utility function to maximizes the export benefit (EB), as defined by Equation (4.12).

$$SWE^i = \sum_{s}^{D}\sum_{m}^{D_i}[PD^i_{s,m}\ \gamma^i_{D_{s,m}}] - \sum_{c}^{G}\sum_{k}^{G_c}[PG^i_{c,k}\ \gamma^i_{G_{c,k}}] - \sum_{j}^{A_i}\sum_{r}^{G_E}\sum_{t}^{G_r}[PE^i_{jr,t}\ \gamma E^j_{r,t}(1-\zeta^i_j)] \quad (4.11)$$

$$EB^i = \sum_{j}^{A_i}\sum_{r}^{G_E}\sum_{t}^{G_r}[PE^j_{ir,t}\ (\lambda^i_{max} - \gamma E^i_{r,t})] \quad (4.12)$$

The first term in Equation (4.11) represents the gross surplus of the customers, while the second term represents the total cost for internal generator units. The no-load cost of the generators is included in the first block submitted by each generator. The third term represents the total cost of exporter generators in the connected MGs that considers the loss factor, has excess energ, and can export. The mathematical model is subjected to the following constraints:

- Power balance constraint: This constraint ensures demand and supply balance at each MG.

$$\sum_{s}^{D}\sum_{m}^{D_s} PD^i_{s,m} = \sum_{c}^{G}\sum_{k}^{G_c} PG^i_{c,k} + \sum_{j}^{A_i}\sum_{r}^{G_E}\sum_{t}^{G_r} PE^i_{j_{r,t}}(1-\zeta^i_j) \tag{4.13}$$

The first term represents the internal demand of MG_i, the second term represents internal generation, and the third term represents imported energy from all neighbours MGs.

- Clearing constraints: These constraints ensure that the cleared demand and generation for each MG do not exceed their upper limits according to the bidding blocks.

$$0 \leq PD^i_{s,m} \leq \overline{PD}^i_{s,m} \tag{4.14}$$

$$0 \leq PG^i_{c,k} \leq \overline{PG}^i_{c,k} \tag{4.15}$$

The cleared exported energy from each MG does not exceed its upper limits assigned by the EMS of each MG.

$$0 \leq PE^i_{r,t} \leq \overline{PE}^i_{r,t} \tag{4.16}$$

The cleared exported energy is defined as the sum of all exported energy to neighbouring MGs,

$$PE^i_{r,t} = \sum_{j}^{A_i} PE^j_{i_{r,t}} \tag{4.17}$$

Exported energy is set to zero if the block's price exceeds the imported MG's internal price

$$\gamma E^i_{r,t} > \lambda^j_o \quad \rightarrow \quad PE^j_{i_{r,t}} = 0 \tag{4.18}$$

- Social welfare improvement constraint: This constraint reflects the greedy participation (SBD) of MGs, as mentioned earlier. Each MG participates in the interconnected market only if this will improve its own benefit irrespective of others. In this regard, the demand of each MG should not get a higher price or receive less energy at the same price after participating in the market. As the demand bidding curve of each MG is known, the price will be reduced or the demand covered will be increased if the social welfare of the MG after trading is greater than that before trading.

$$SWE^i \geq SW_o^i \tag{4.19}$$

- Physical flow constraint: This constraint ensures that each MG can either export or import on the same connection at a given time.

$$\left[\sum_{r}^{G_E^i}\sum_{t}^{G_r^i} PE_{i_{r,t}}^j\right]\left[\sum_{r}^{G_E^j}\sum_{t}^{G_r^j} PE_{j_{r,t}}^i\right] = 0 \tag{4.20}$$

- Trading conditions check:

  Each importer MG is applying this trading check in order to ensure that the MG is obtaining benefits from these offers. In order to pass this condition, the demand covered should increase, as in Equation (4.21), or the internal price should be less, as in Equation (4.22). If the MG fails in these conditions, then the MG should be eliminated from the platform to ensure that the model follows the SBD for each MG.

$$P_{D_{new}}^i > P_{D_o}^i \quad \Longleftrightarrow \quad \eta_{new}^i \leq \lambda_o^i \tag{4.21}$$

$$\eta_{new}^i < \lambda_o^i \quad \Longleftrightarrow \quad P_{D_{new}}^i \geq P_{D_o}^i \tag{4.22}$$

4.5 Case Studies

The proposed energy trading platform was implemented and tested assuming four MGs with different generators and demand bidding. Each MG is assumed to have the typical layout of an IEEE 906 European low voltage test system with 55 loads and four generators. The generator and load bidding for each MG is given as three different blocks of price/power pairs (i.e., B1, B2, and B3). These biddings are illustrated in Table 4.1. A sample of the demands' biddings are shown in Table 4.2. The rest of the biddings are presented in Appendix A.

Table 4.1: Generator Offers in MGs

Generator	MG T1						MG T2					
	Block 1		Block 2		Block 3		Block 1		Block 2		Block 3	
	Quantity $\overline{PG^1_{s,1}}$	Price $\overline{\gamma G^1_{s,1}}$	Quantity $\overline{PG^1_{s,2}}$	Price $\overline{\gamma G^1_{s,2}}$	Quantity $\overline{PG^1_{s,3}}$	Price $\overline{\gamma G^1_{s,3}}$	Quantity $\overline{PG^2_{s,1}}$	Price $\overline{\gamma G^2_{s,1}}$	Quantity $\overline{PG^2_{s,2}}$	Price $\overline{\gamma G^2_{s,2}}$	Quantity $\overline{PG^2_{s,3}}$	Price $\overline{\gamma G^2_{s,3}}$
G1	70	0.071	67	0.077	66	0.087	75	0.020	78	0.036	57	0.108
G2	70	0.035	78	0.081	69	0.088	60	0.023	66	0.028	62	0.105
G3	70	0.010	62	0.076	53	0.085	78	0.026	80	0.036	60	0.102
G4	78	0.004	76	0.067	68	0.092	74	0.012	76	0.024	60	0.107
Generator	MG T3						MG T4					
	Block 1		Block 2		Block 3		Block 1		Block 2		Block 3	
	Quantity $\overline{PG^3_{s,1}}$	Price $\overline{\gamma G^3_{s,1}}$	Quantity $\overline{PG^3_{s,2}}$	Price $\overline{\gamma G^3_{s,2}}$	Quantity $\overline{PG^3_{s,3}}$	Price $\overline{\gamma G^3_{s,3}}$	Quantity $\overline{PG^4_{s,1}}$	Price $\overline{\gamma G^4_{s,1}}$	Quantity $\overline{PG^4_{s,2}}$	Price $\overline{\gamma G^4_{s,2}}$	Quantity $\overline{PG^4_{s,3}}$	Price $\overline{\gamma G^4_{s,3}}$
G1	61	0.114	64	0.138	59	0.142	60	0.107	79	0.134	61	0.144
G2	77	0.105	75	0.124	62	0.152	73	0.113	77	0.134	68	0.148
G3	76	0.107	74	0.123	52	0.151	74	0.102	70	0.122	68	0.145
G4	69	0.110	63	0.136	58	0.155	66	0.119	62	0.138	55	0.150

Note: All quantities data are in kWh, and energy prices are in $/kWh

The proposed framework is assumed to be solved on an hourly basis. Table 4.3 shows the solution of the EuMP model after executing the trading engine, as proposed in Chapter 3, inside each MG. The table presents their internal uniform price and social welfare, along with the total demand covered at this price. An example of the bidding curves of MG-T1 is shown in Figure 4.7. The figure also illustrates the settlement of the internal EuMP model achieving an internal price of 0.065 $/kWh and a total demand cover of 218 kWh.

The sensitivity analysis is executed to calculate the loss factor for the link connecting the microgrids. The line is assumed to be 50 meters in length, with the following specifications [101]:

- line code: 4c_400.
- impedance per meter: 0.0000602 + j 0.00007 ohm.

Table 4.2: Samples of Demand Biddings in MGs

Demand	MG T1						MG T2					
	Block 1		Block 2		Block 3		Block 1		Block 2		Block 3	
	Quantity $\overline{PD}^1_{s,1}$	Price $\gamma D^1_{s,1}$	Quantity $\overline{PD}^1_{s,2}$	Price $\gamma D^1_{s,2}$	Quantity $\overline{PD}^1_{s,3}$	Price $\gamma D^1_{s,3}$	Quantity $\overline{PD}^2_{s,1}$	Price $\gamma D^2_{s,1}$	Quantity $\overline{PD}^2_{s,2}$	Price $\gamma D^2_{s,2}$	Quantity $\overline{PD}^2_{s,3}$	Price $\gamma D^2_{s,3}$
D1	1.494	0.132	2.150	0.094	4.074	0.065	1.012	0.132	2.003	0.094	3.968	0.065
D2	1.470	0.132	2.982	0.094	3.727	0.065	1.176	0.132	2.286	0.094	4.584	0.065
D3	1.420	0.132	2.801	0.094	3.241	0.065	1.172	0.132	2.260	0.094	3.256	0.065
D4	1.425	0.132	2.946	0.094	3.555	0.065	1.158	0.132	2.294	0.094	4.182	0.065

Demand	MG T3						MG T4					
	Block 1		Block 2		Block 3		Block 1		Block 2		Block 3	
	Quantity $\overline{PD}^3_{s,1}$	Price $\gamma D^3_{s,1}$	Quantity $\overline{PD}^3_{s,2}$	Price $\gamma D^3_{s,2}$	Quantity $\overline{PD}^3_{s,3}$	Price $\gamma D^3_{s,3}$	Quantity $\overline{PD}^4_{s,1}$	Price $\gamma D^4_{s,1}$	Quantity $\overline{PD}^4_{s,2}$	Price $\gamma D^4_{s,2}$	Quantity $\overline{PD}^4_{s,3}$	Price $\gamma D^4_{s,3}$
D1	1.175	0.132	2.170	0.094	3.294	0.065	1.255	0.132	2.512	0.094	3.328	0.065
D2	1.468	0.132	2.563	0.094	3.452	0.065	1.459	0.132	2.641	0.094	3.339	0.065
D3	1.029	0.132	2.732	0.094	3.332	0.065	1.435	0.132	2.946	0.094	4.802	0.065
D4	1.461	0.132	2.257	0.094	3.577	0.065	1.202	0.132	2.547	0.094	3.480	0.065

Note: All quantities data are in kWh, and energy prices are in $/kWh

Table 4.3: MG Internal Results After Executing Energy Trading Engine

	MG-T1	MG-T2	MG-T3	MG-T4
Uniform Price ($/kWh)	0.065	0.0285	0.1047	0.1024
Social Welfare ($)	19.3084	26.905	1.903	2.02628
Demand Covered (kWh)	218	428.032	69.734	68.518

For simplicity, assuming identical connection between MGs, the loss factor (ζ^i) is determined to be 0.00289.

4.5.1 IEEE 906 Bus UMP-based Benchmark Case Study

The classic UMP model was employed in this study as a benchmark for energy trading among IMGs. The model is solved for the four IMGs mentioned earlier. Table 4.4 illustrates the output from the UMP model. It should be noted that this model is still in usage by the IESO. Furthermore, it is clear from Table 4.4 that this model offers a unified internal

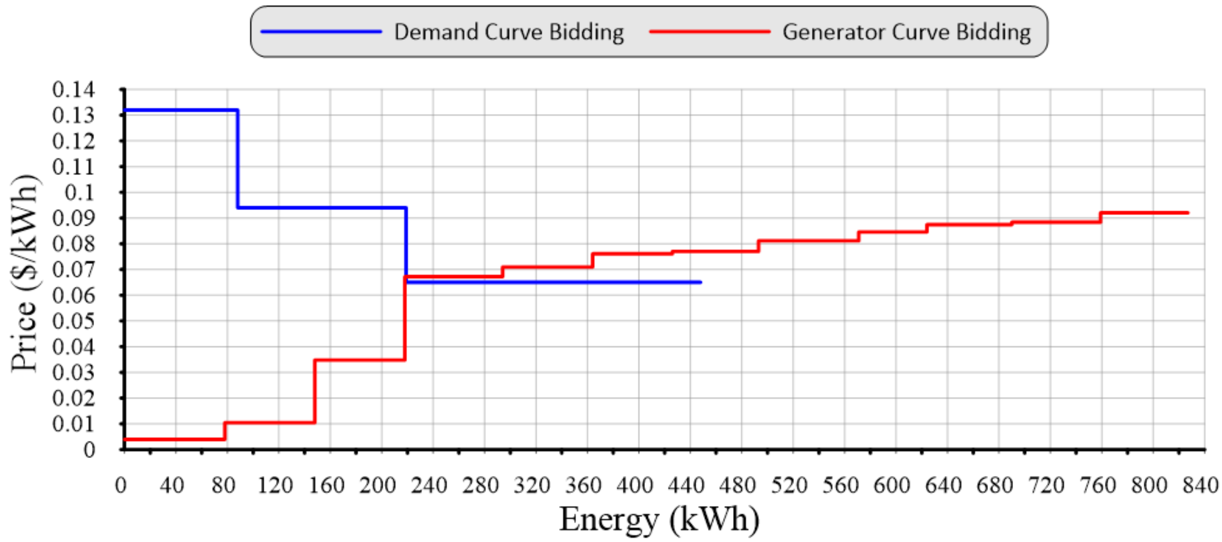


Figure 4.7: Generator and bidding curve of MG-T1.

price for all participating MGs. Also, it can be seen that the power is exported from the low-priced MGs (i.e., MG-T1 and MG-T2) to the high-priced ones. This model is used as a benchmark because it can provide a fast and reliable solution while adopting a large number of participants.

4.5.2 IEEE 906 bus Centralized Nash-based Case Study

The Nash bargaining model was applied to two different scenarios. For the first scenario, all MGs are assumed to be interconnected (Mesh-connection), so each MG can exchange energy with the other three MGs. In the second scenario, the interconnection link between MG-T2 and MG-T1 and the link between MG-T2 and MG-T4 were removed. This assumption is used to show not only that the proposed approach will find the proper solution for any interconnection topology, but also to highlight the effect of inter-connectivity on the market solution and energy trading. The mathematical model used to solve the centralized

Table 4.4: UMP model results

	MG-T1	MG-T2	MG-T3	MG-T4
Exported Energy	31.576 kWh	381.48 kWh	0	0
Imported Energy	0	0	208.178 kWh	205.056 kWh
Total Social Welfare	$68.083			
Export Benefit	0	0	0	0
Internal Price	0.067 $/kWh			
Demand Covered	208.788 kWh	205.520 kWh	208.178 kWh	205.056 kWh
Total Demand Covered	827.542 kWh			

problem is formulated as follows:

$$\max \prod_{i \in \mathbb{N}} S\hat{W}E^i + E\hat{B}^i$$

$$s.t.$$

$$(4.14) - (4.20)$$

In both scenarios, N= 4, but the connections between MGs are different.

4.5.2.1 First scenario: All MGs are interconnected

Figure 4.8 show the results obtained from solving the centralized Nash bargaining algorithm. As seen from the results, MG-T1 and MG-T2 are chosen by the algorithm to export power, as they have a low internal uniform price. For MG-T1, the Nash solution selected generators G1, G3, and G4 to export energy. In order to benefit all participants, the low-price generators exported to MG-T3 and the high-priced energy is exported to MG-T4, which has the highest internal energy price. For MG-T2, generators G1, G2, and G3 are selected to export. As expected, Block#3 for all generators is not selected to export except for Generator #3, as the price of these blocks is higher than the internal prices of importing MGs. The exported energy from MG-T1 is 299.388 kWh and the imported

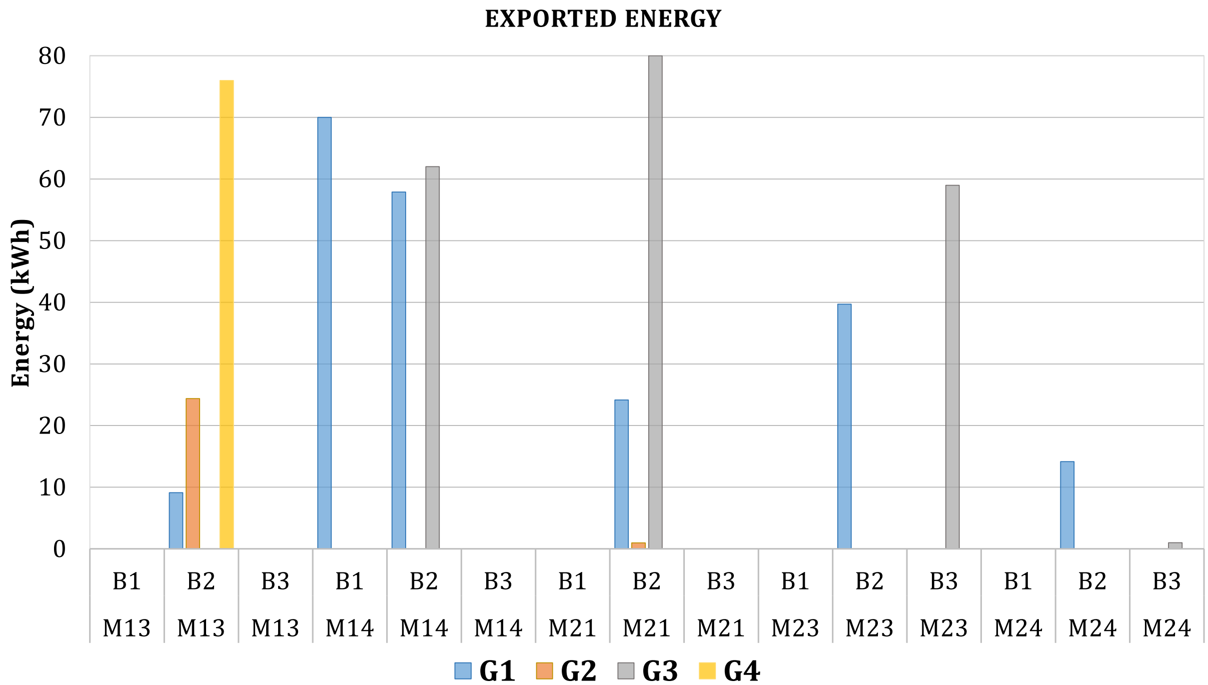


Figure 4.8: Export power from MGs in first scenario.

energy is 105.116 kWh, as shown in Table.4.5. From the table, it is clear that the trading held the internal price of MG-T1 constant while increasing the export benefits and the demand cover. It is worth mentioning that the algorithm determines for each link whether to export or import in a way to maximize MG benefits while being fair to all participating MGs.

On the other hand, the utility function used to represent each MG in the Nash bargaining is selected assuming a SDB from the MG. An MG cannot export and import on the same link at the same time, but it can export and import via different links simultaneously. For MG-T2, the algorithm selected to export 218.962 kWh to neighbours. The export benefits for MG-T2 increased while the SWE remained unchanged. Furthermore, the total exported energy from MG-T1 is higher than that of MG-T2, as is MB-T1's normalized utility. The reason for this can be found in the amount of available energy for export from MG-T2.

The results show that the total demand covered in MG-T3 increased to 208 kWh, and the price dropped to 10.2 ct/kWh. Although the price remains constant for MG-T4, the total demand covered increased by almost 200%, as presented in Table 4.5. The normalized utility values for MGs prove that the Nash solution tried to be fair to all MGs by improving their normalized utility functions correspondingly.

Table 4.5: Centralized Nash Results (Scenario#1)

	MG-T1	**MG-T2**	**MG-T3**	**MG-T4**
Exported Energy	299.388 kWh	218.962 kWh		
Imported Energy	105.116 kWh		208.178 kWh	205.056 kWh
Effective Social Welfare	$23.239	$26.950	$7	$7.127
Export Revenue	$30.539	$18.445	0	0
Normalized utility	0.234	0.185	0.147	0.149
Import/**E**xport	**E & I**	**E**	**I**	**I**
Internal Price	0.065 $/kWh	0.0285 $/kWh	0.102 $/kWh	0.102 $/kWh

4.5.2.2 Second scenario: Connection lost between two MGs

In the second scenario, the link connecting MG-T2 and MG-T4 is removed and thus no energy can be traded between them. The same restriction was applied to MG-T2 and MG-T1. However, the Nash solution maximized MG-T2's benefits by increasing its export to MG-T3 by 120% compared with the first scenario, as shown in Figure 4.8 and Figure 4.9. As presented in Table 4.6, the settlement price of MG-T3 remained the same in both scenarios, even though the total energy imported increased. At the same time, despite no energy being exported from MG-T2 to MG-T4, the normalized utility for MG-T4 is nearly constant compared to the first scenario. This indicates that the centralized Nash method

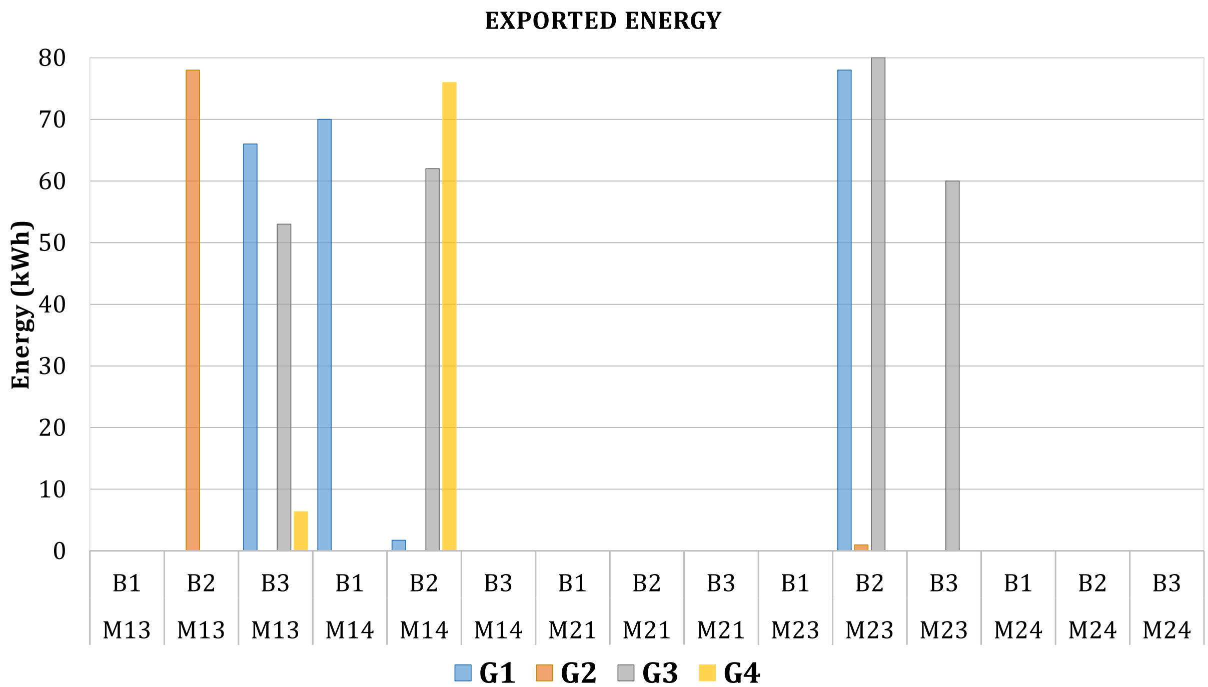


Figure 4.9: Export power from MGs in second scenario.

is adapting the solution to any change in MG connectivity and thus can be used for any topology, not just meshed or parallel connected MGs.

4.5.3 Centralized Nash Solution vs Benchmark Solution

The output from the proposed centralized Nash solution is compared with the UMP benchmark presented earlier in Table 4.7. It is clear that the low-priced MGs received higher internal prices, as highlighted in yellow, giving these MGs no incentive to participate in the UMP model. Also worth noting is that the internal demand covered for the low-priced MGs is less when using the UMP model. On the other hand, the high-priced MGs received better internal prices, which provides an incentive for the participants to participate in this model at this time. This may not, however, be the case in another time slot. Therefore the UMP model is a hypothetical model that is not feasible because it does

Table 4.6: Centralized Nash Results (Scenario#2)

	MG-T1	**MG-T2**	**MG-T3**	**MG-T4**
Exported Energy	413.082 kWh	218.962 kWh		
Imported Energy			421.06 kWh	209.087 kWh
Effective Social Welfare	$19.3084	$26.950	$7.153	$7.276
Export Benefit	$32.486	$22.33		
Normalized utility	0.107	0.186	0.151	0.153
Import/**E**xport	**E**	**E**	**I**	**I**
Internal Price	0.065 $/kWh	0.0285 $/kWh	0.102 $/kWh	0.077 $/kWh

not satisfy the SBD for all participating MGs.

4.6 Monetary Fund Verification

In order to verify the integration of the proposed Nash solution and the adapted blockchain, the proposed blockchain was coded using Python. The coded blockchain succeeded in integrating with the internal blockchain of all MGs and to record the transactions between MGs. As shown in Figure 4.10, MG-T3 solved the internal EuMP market proposed in Chapter 3 and created unconfirmed transactions (a sample of these transactions for generator2 is shown in Figure 4.10). Afterwards, the DSO solved the centralized Nash proposed algorithm, as shown in Figure 4.11. Therefore, the unconfirmed transaction created by MG-T3 was deleted according to the Nash solution, as MG-T3 will import more cheap energy from neighbours. The coded blockchain then succeeded in storing the market commitment block in the MC3, as illustrated in Figure 4.12.

It is worth mentioning that the MCB of MG-T3 contains the previous hash of the internal blocks (i.e., RTB) and the previous intra-grids block (i.e., IRTB), as discussed in section 4.3.4 . The process keeps repeating until the final slot of the day. Finally, the

Table 4.7: Comparison Between Nash and Benchmark Results

	MG-T1		MG-T2		MG-T3		MG-T4	
	C-Nash[1]	**C-UMP[2]**	**C-Nash**	**C-UMP**	**C-Nash**	**C-UMP**	**C-Nash**	**C-UMP**
Exported Energy	299.388 kWh	31.576 kWh	218.962 kWh	381.48 kWh	0	0	0	0
Imported Energy	105.116 kWh	0	0	0	208.178 kWh	208.178 kWh	205.056 kWh	205.056 kWh
Effective Social Welfare	$23.239	N/A	$26.950	N/A	$7	N/A	$7.127	N/A
Export Revenue	$30.539	0	$18.445	0	0	0	0	0
Demand Covered	323.116 kWh	208.788 kWh	428.032 kWh	205.520 kWh	208.178 kWh	208.178 kWh	205.056 kWh	205.056 kWh
Import/**E**xport	**E & I**	**E**	**E**	**E**	**I**	**I**	**I**	**I**
Internal Price	0.065 $/kWh	0.067 $/kWh	0.0285 $/kWh	0.067 $/kWh	0.102 $/kWh	0.067 $/kWh	0.102 $/kWh	0.067 $/kWh

[1] Centralized based on Nash model
[2] Centralized based on UMP model

blockchain creates the IMCB and the IRTB, as shown in Figure 4.13 and Figure 4.14.

A sample of the transactions recorded in the IRTB block is shown in Figure 4.15, with the transaction 70 kWh priced at 0.102 $/kWh between MG-T1 and MG-T4. As illustrated, the coded blockchain recorded both the public key of the sender MG (i.e., MG-T1) and that of the recipient (i.e., MG-T4). Further, the power calculated from the Nash solution is recorded with the corresponding price (i.e., amount) and the new funds of the recipient and sender are calculated assuming that the recipient has consumed all the power in real-time. It is worth noting that only the funds of the recipient are shown in the transaction to match the transaction's size of the internal transactions stored in MCs.

4.7 Conclusion

This chapter proposed a platform for energy trading between IMGs utilizing adapted blockchain technology, using a centralized Nash bargaining algorithm to settle the IMG market. The proposed platform was developed to satisfy MGs' SBD behaviour while allowing them to participate in a fairly settled market. The platform can be used for any MG topology and was tested for two different scenarios. Microgrids were allowed to export and import to maximize their benefit with the Nash bargaining algorithm, ensuring fair social welfare distribution among participating MGs.

The case studies presented in this chapter showed the effectiveness of the proposed platform in handling the IMG market. It can be seen from the presented results that the participating MGs gained benefits from participating in the trading. For normalized utilities, the normalized benefits of all the MGs were improved correspondingly. A novel definition for import and export utility functions was also introduced to reflect the rational behaviour of MGs. Moreover, the platform presented a swift integration of the MGs' transactions and inter-grid transactions through a TLSC.

Also in this chapter, a secure and transparent blockchain structure was proposed by using two consensus algorithms, namely POW for MC and POA for IGC. The platform was developed and tested by integrating several software packages: MATLAB, GAMS, and Python. The IMGs' transactions were stored in the blockchain and verified via sample transactions. Although the proposed algorithm is efficient and can provide a fair solution among the interconnected MGs, their privacy is not kept and they cannot take further actions after the central operator settles the market. These limitations make this algorithm suitable only if there is a regulation to have a central operator. Therefore, a decentralized platform must be developed to ensure privacy and grant MGs the privilege to make greedy decisions while ensuring efficient feasible energy trading platforms. This decentralized platform is developed and discussed in detail in the next chapter.

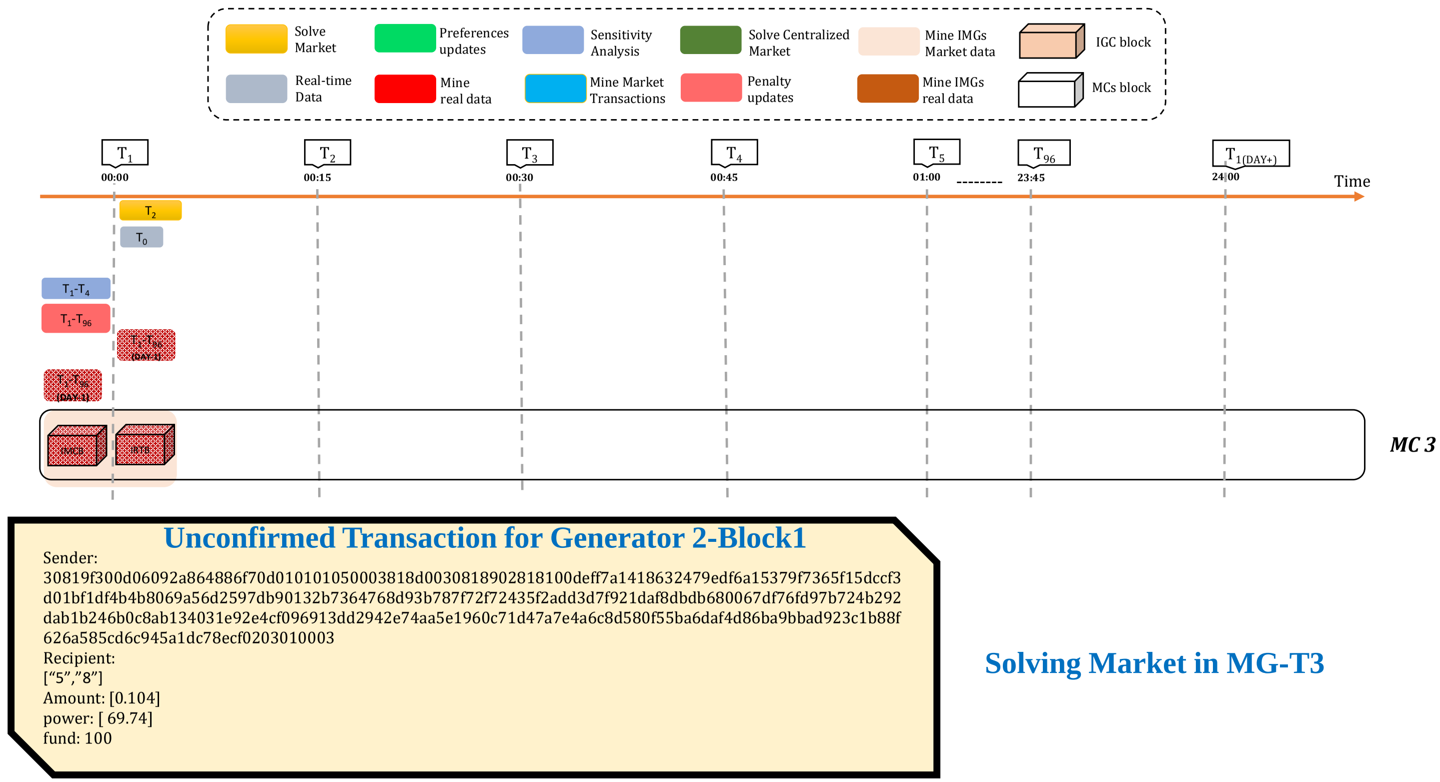


Figure 4.10: Solving internal markets and creating unconfirmed transactions.

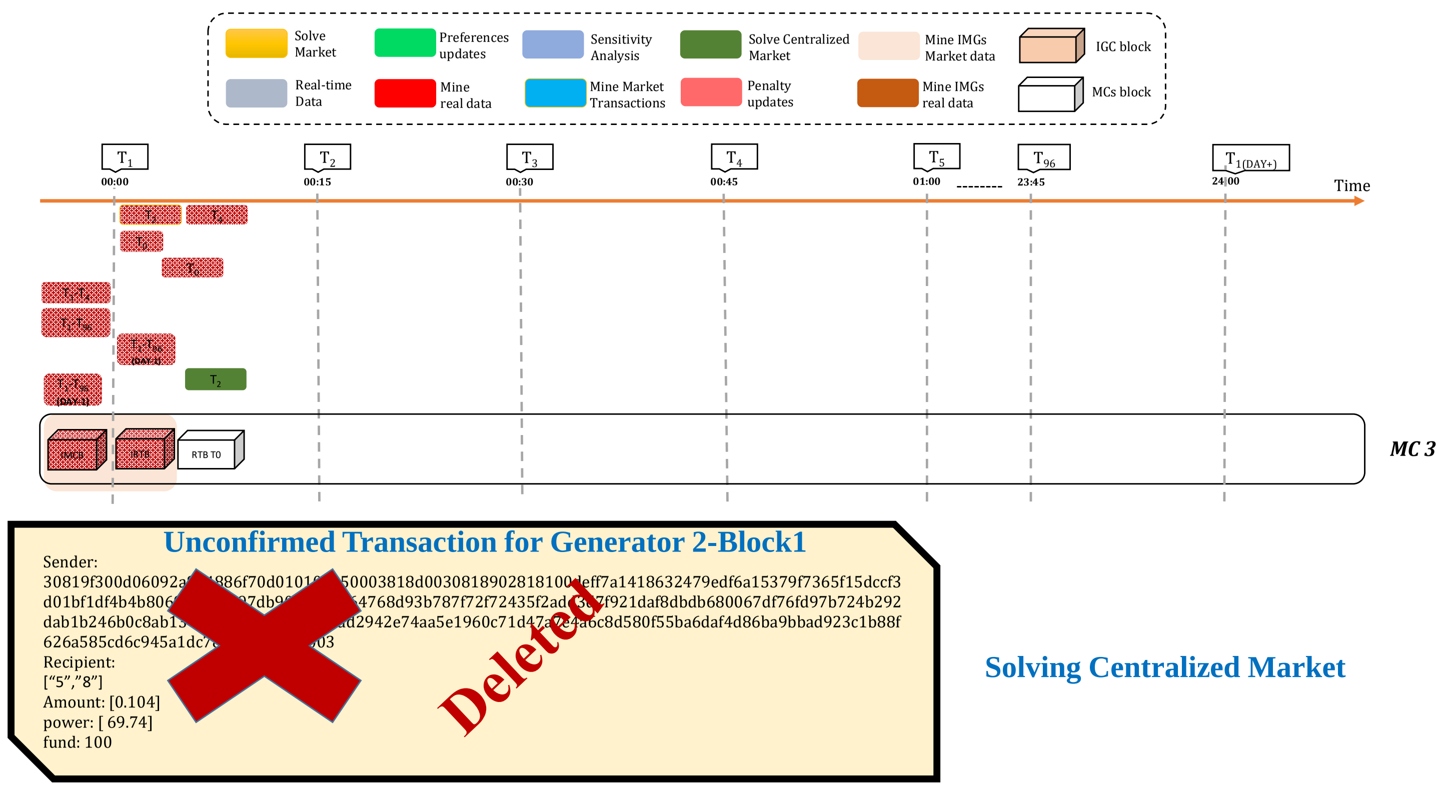


Figure 4.11: Solving centralized Nash algorithms and updating unconfirmed transactions.

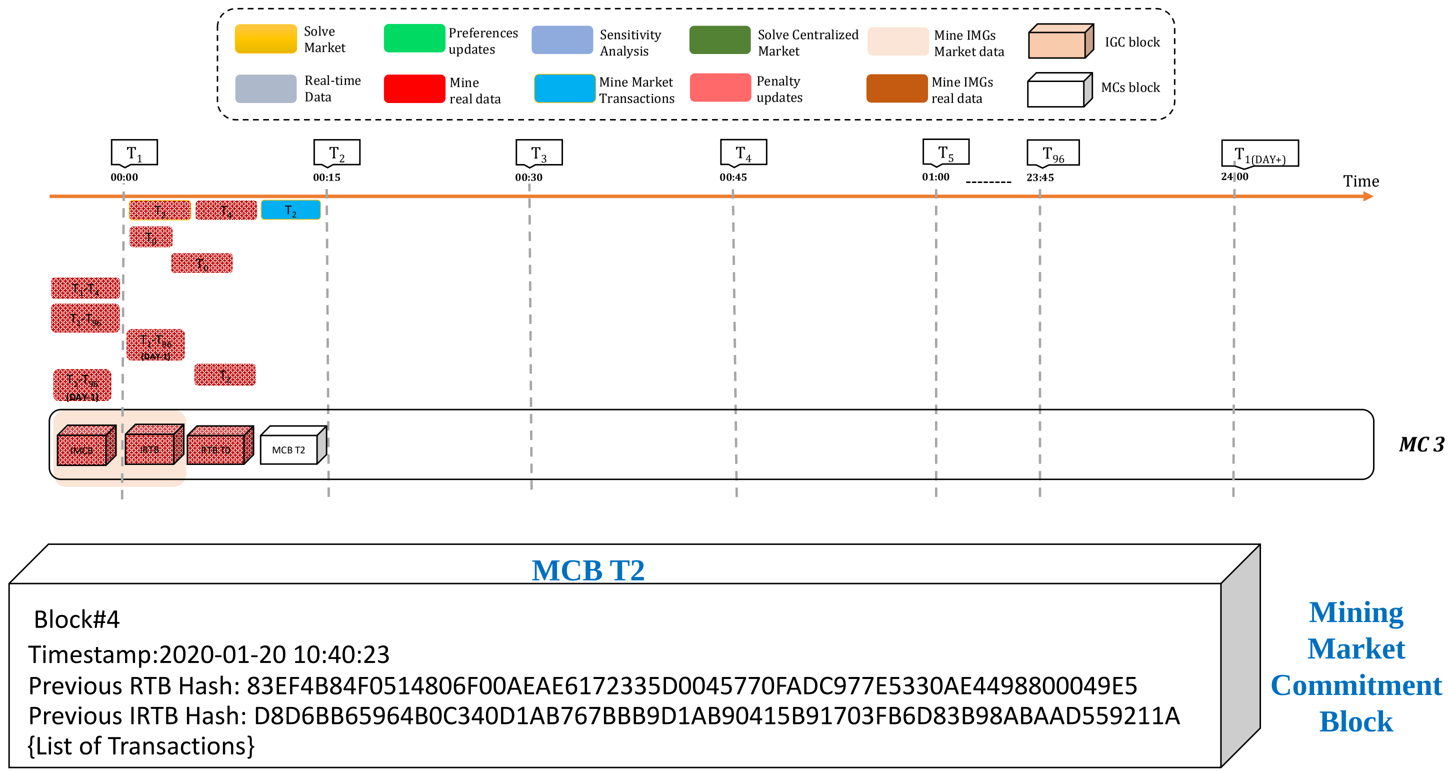


Figure 4.12: Creating MCB in MG-T3.

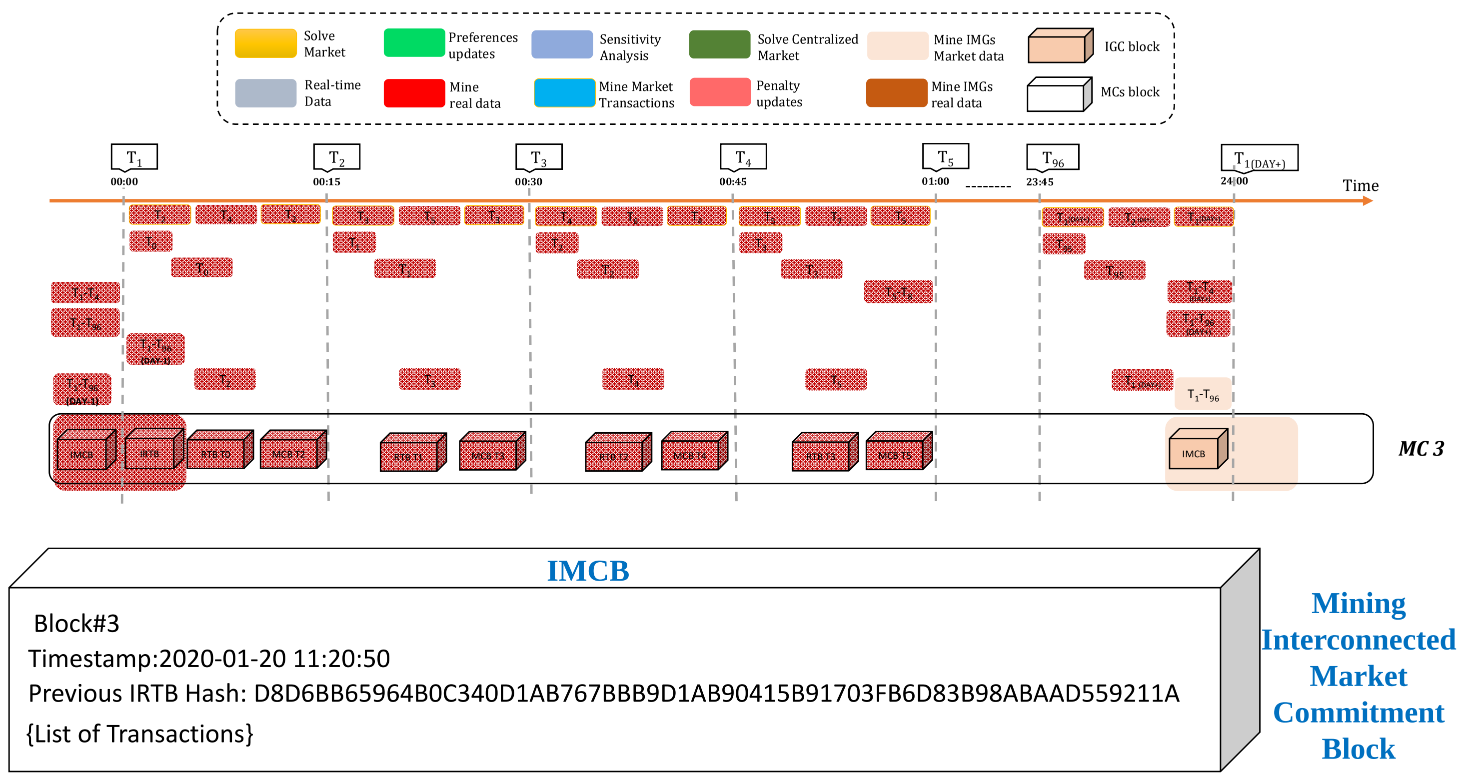


Figure 4.13: Creating IMCB.

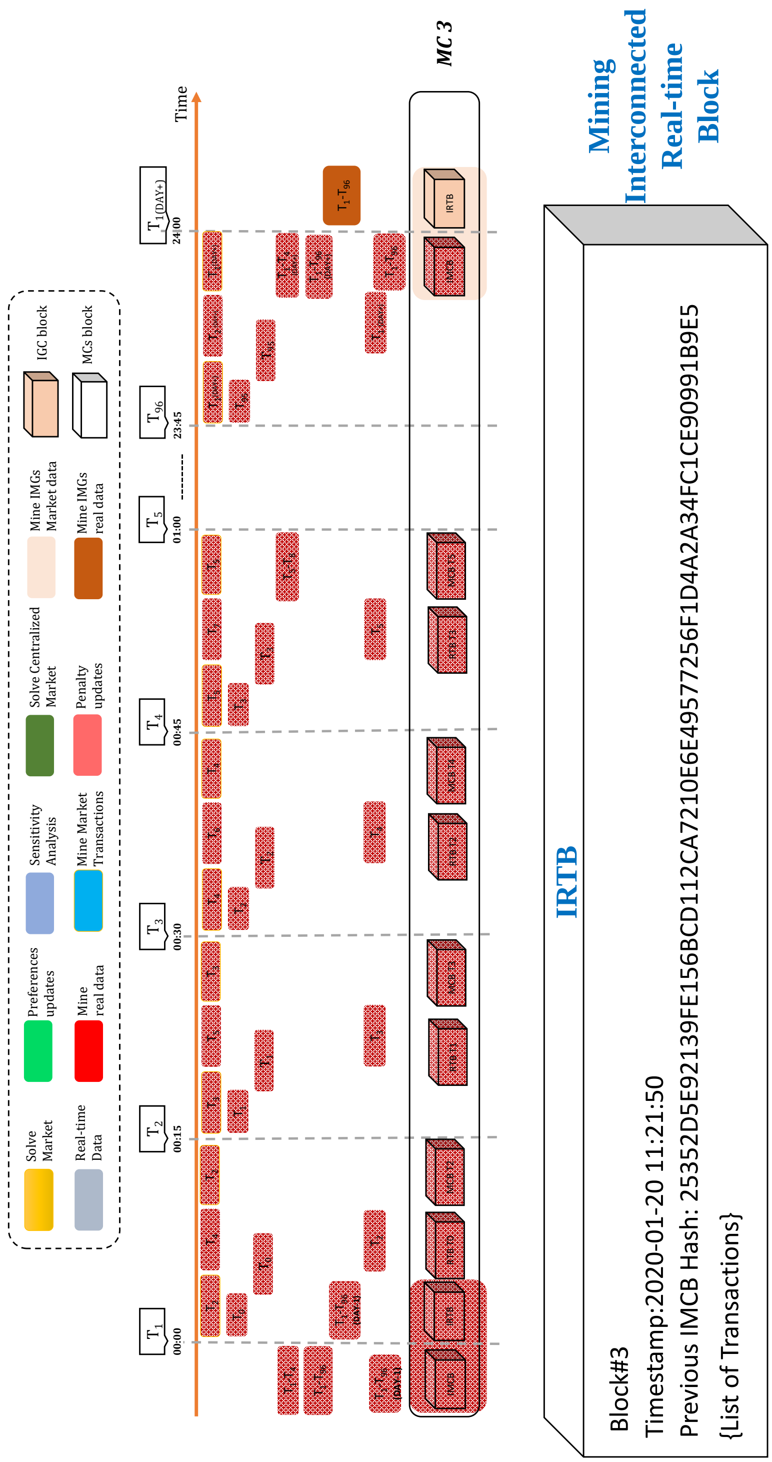


Figure 4.14: Creating IRTB.

Sender:
30819f300d06092a864886f70d010101050003818d0030818902818100deff7a1218632479edf6a1
5379f7365f15dccf3d01bf1df4b4a8069a56d2597db90132b7364768d93b787f72f72435f2add3d7f9
21daf8dbdb680067df76fd97b724b292dab1b246b0c8ab134031e92e4cf096913dd2942e74aa5e196
0c71d47a7e4a6c8d580f55ba6daf4d86ba9bbad923c1b88f626a585cd5c945a1dc78ecf0203010001
Recipient:
30819f300d06092a864886f70d010101050003818d0030818902818100ba99f01daa86ba9e3cc4e0c1a84da
6e413925990a692731b97be99a753d6447b4c5b5707b4ebe6c1400e3b97ea44659ec7dcfee9284db3e6f15c
e141426f0afefaeb519defb7800cc014d722dd227debb1e9113b0b6812fac048ea35b9ed8655f52bd93da5fba
6d9877a3724424cff9fe7852f262d052bb424aa4663c89f07eb0203010001
Amount: [0.102]
power: [70]
fund: 92.86

Figure 4.15: IRTB transaction sample.

Chapter 5

Blockchain-based Decentralized IMG Energy Trading Platform

5.1 Introduction

A centralized energy trading platform was developed in the previous chapter to enable energy trading among IMGs. However, the solution was suitable mainly for IMGs that have a regulation for a central operator, which contradicts data privacy practices and the SBD for the MGs. Therefore, in this chapter, a new decentralized-based energy trading platform is developed to allow each MG to participate and gain from the platform while maintaining self-benefit-driven (SBD) actions. The proposed platform provides a market-clearing approach that uses sequential rounds and allows the MGs with the lowest price to maximize their benefits by exporting surplus energy. A decentralized ranking algorithm is also developed to determine the cheapest MGs in each round while keeping the data private.

The rest of the chapter is organized as follows. In section 5.2, the decentralized energy trading structure is presented, while in section 5.3 the proposed decentralized energy trading platform is discussed. In section 5.4, the developed optimization model used in the proposed platform is examined, and in section 5.5, case studies are provided. Finally, in section 5.6, the conclusion is given.

5.2 Decentralized Energy Trading Structure

In this section, a decentralized framework is proposed assuming SBD action from participants. The presented framework enables energy trading between interconnected MGs while preserving data privacy. The trading framework is designed to give MGs with low energy prices the privilege to offer their energy in the market first. Therefore, the MG with lowest energy price will have the opportunity to export its maximum available energy. Once this occurs, the MG is eliminated from the platform and the next-lowest price MG is selected to export, and so on.

As shown in Figure 5.1(a), centralized bargaining requires all bargaining to take place simultaneously, while in the proposed sequential decentralized algorithm, the bargaining takes place sequentially. Using this algorithm, the benefits gained are as follows: 1) Ensuring and maintaining MG privacy; 2) promoting cheap energy trading; and 3) enabling SBD energy trading between MGs.

In order to solve the aforementioned sequential approach, all MGs have to be ranked in a decentralized manner. Therefore, two sequential ranking algorithms are developed and proposed in this chapter. The first algorithm, called the #1-focused ranking algorithm, finds the MG with lowest price (#1) in a distributed fashion. This algorithm allows only the cheapest MG to export its energy in each round. The second algorithm is the Price Range-focused (PR-focused) ranking approach. In this method, the energy prices in MGs are clustered in a definite number of groups according to price range. MGs in the same group have energy prices within a certain price range and are allowed to export energy at the same time. It is worth mentioning that if the number of MGs in a study is small, the #1-focused algorithm is suitable, but if the number of MGs is large, the #1-focused algorithm will take too long, so the PR-focused algorithm would be more suitable. This is because the latter algorithm uses the cluster concept, and hence the effective number used

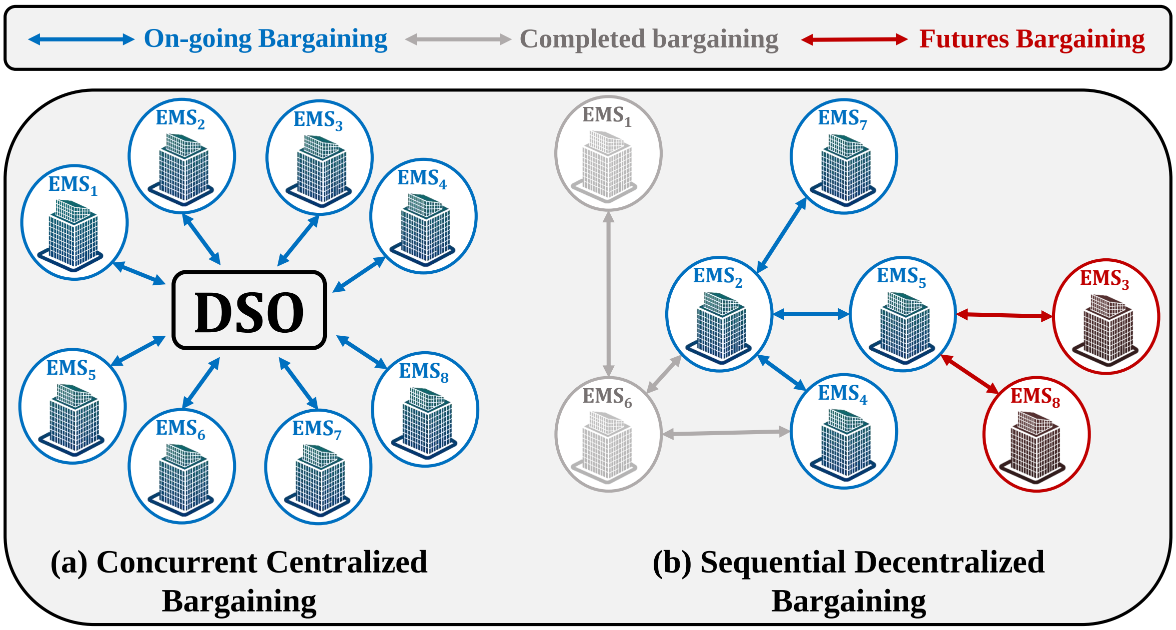


Figure 5.1: Concurrent and sequential bargaining.

in the calculation will be reduced and the solution will again be fast.

As shown in Figure 5.2, the information is exchanged only between directly-connected neighbours. In addition, the proposed decentralized system does not have a DSO to influence market settlements. The trading is based solely on offer and demand, with the privilege given to low-priced sellers.

5.3 Decentralized Energy Trading Platform

This section describes the assumptions, algorithms, and problem formulation for the proposed decentralized energy trading framework among IMGs. The proposed framework is modelled to ensure and maintain privacy while using a greedy algorithm for all participants, as will be explained later. To satisfy each MG's self-interest, a unique objective function is defined from the basic principle of the UMP model. This objective function is defined

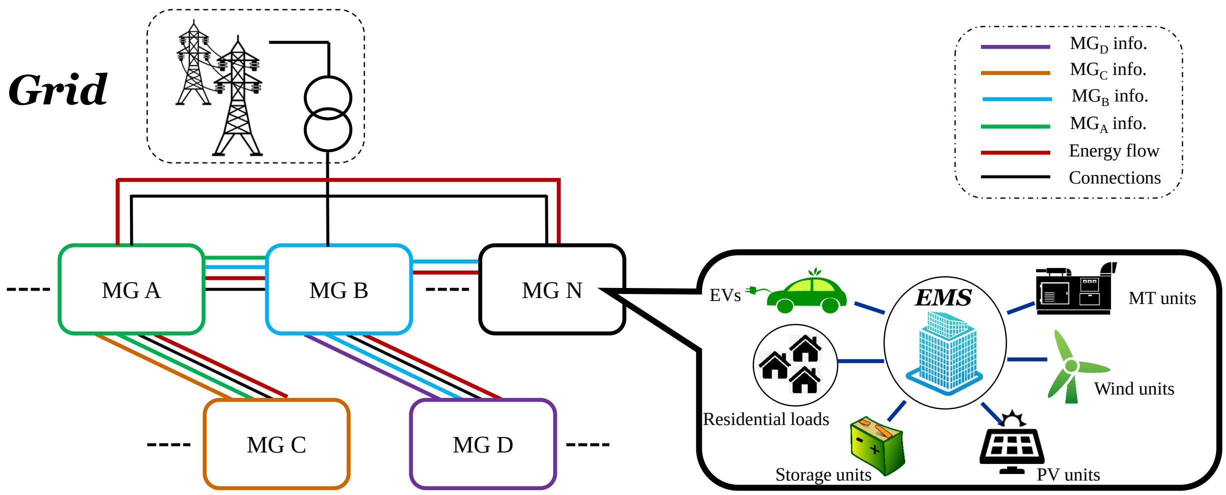


Figure 5.2: IMG structure in decentralized framework.

in the next subsection.

5.3.1 Sequential Market Clearing Methodology

The proposed sequential market starts by ranking the participating MGs according to their internal clearing price (λ_o). The developed ranking is done via the developed decenteralized ranking algorithms, as explained in the next subsections. At any round, after ranking, the MG with rank #1 (or group#1) firms the offers it has (if any) and then sends export offers to all its neighbouring MGs. It should be noted that the MG (or group #1) with the lowest energy prices will not be interested in importing power from the high-priced MGs. The MG that has rank#1 (or group#1) tries to maximize its export benefits by exporting any surplus energy to its directly connected MGs.

The MGs that receive offers solve a UMP model internally to maximize their social welfare after including the offered generator's bidding from exporting MGs. The offer-taker MGs can accept or reject (firm) these offers when they are assigned to be rank#1 (or group#1). Afterwards, rank#1 (or group#1) MG is eliminated from the market and the remaining MGs are re-ranked to find a new rank#1 (or group#1) MG to start over again. This sequence is repeated until all MGs are eliminated (i.e., all are given a chance to send export offers). Note that MGs can withhold offers as long as they are not rank#1 (or group#1). Once an MG is assigned rank#1, it must firm the withhold offers (accept/reject) from previous rounds before sending export offers to others.

5.3.2 Exporter MG Objective Function Definition

In this subsection, the objective function for each participating MG is formulated. Assuming a non-cooperative game, each MG is looking to increase its benefits from exporting energy to its neighbours participating in the IMG market. Exporting MGs aim to maximize their generators' benefits by exporting surplus energy without affecting the energy prices offered to local loads.

Figure 5.3 shows a general offer/bidding curve for generator/load, which is used to find the market clearing price (λ_1: marginal price in case of isolated operation) that maximizes the social welfare (i.e., the area between the demand and generator curves shown in Figure 5.3). In case of export, an MG can offer its excess generation (i.e., after clearing the local market) in the IMG market. In this way, it can gain additional social welfare for its generators (i.e., export area A_E) without changing the local market price (λ_1) after achieving a new export price (λ_2: marginal price in case of exporting). This price (λ_2) is the one in the receiving MG which is higher than the internal MCP in the exporter MG.

The following assumptions are used in the proposed trading framework:

- Each MG is assigned only one mode of operation, either to export or to import through the same link.
- No restrictions on MG connections means that they can be connected in series, parallel, or mesh.
- End-users and prosumers can submit their bidding and participate in the local market. The EMS of each MG can then use these data to bid in the IMG energy trading platform.

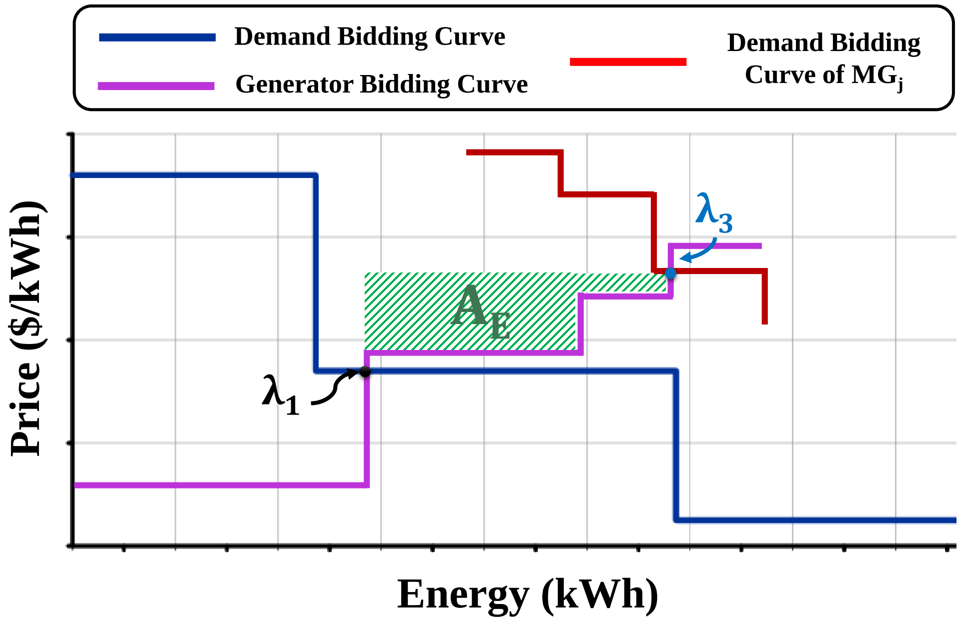


Figure 5.3: Demand and generator with and without export.

- Each MG can exchange data only with directly connected neighbours.
- Greedy action from MGs indicates that the Nash solution is not guaranteed.

5.3.3 Sequential Market Using #1-Focused Ranking Algorithm

As mentioned in the previous subsection, the proposed decentralized energy trading algorithm is based on finding the MG with the lowest internal price (rank#1). Keep in mind that the information cannot be propagated more than one level (i.e., the MGs must be directly connected) for security and privacy concerns. Therefore, a decentralized ranking algorithm is used to find the rank#1 MG.

Considering a system with N microgrids, each microgrid MG_i solves the internal UMP market model to obtain its own uniform price (λ_i) and social welfare (SW_i). These data are broadcast to the directly connected neighbours, along with the aggregated biddings of the demands and generators, after which it calculates and broadcasts the attribute-based rank r_{ij}. Note that r_{ij} indicates the rank of microgrid MG_j as ranked by microgrid MG_i to all microgrids connected with microgrid MG_i. After receiving ranks r_{ij}, each microgrid can check its average rank to see if it is rank#1.

The pseudocode for the active thread at MG_i is shown in Figure 5.4. It is worth mentioning that this thread exchanges the information periodically. If the MG is rank#1, it execute the rank#1 passive thread. Otherwise, the microgrid has to wait for a predefined time T. This predefined time is set to allow exporter MGs to solve the optimization problem and send offers.

The rank#1 passive thread starts by deciding upon adopted and withheld offers. The feasible offers (i.e., those that improve an MG's social welfare) are committed while the others are rejected. Afterwards, the MG runs the market-clearing optimization algorithm designed to maximize its export benefits. Finally, it sends offers to neighbours and activates their offer-received flag, which is a flag that indicates a microgrid has received offers).

An exporter MG can set its price to a very high value after sending offers, as shown in Figure 5.4. This tactic ensures that it will be excluded from the next ranking round. If the offer-received flag is activated, the MG executes rank#2 thread. Microgrids that received offers should adopt the feasible offers and withhold the other offers for further rounds. The adopted offers are used to update the MGs' price, social welfare, and generator biddings before entering subsequent rounds. However, these offers are not firmed yet, as the MGs may receive better offers in the next rounds. The presented procedures run until all the MGs receive rank#1, at which point all deals are firmed and the MGs exchange contracts for these commitments.

5.3.4 Sequential Market Using PR-focused Ranking Algorithm

The #1-focused rank algorithm suffers from time limitations when solving systems with a large number of participating MGs. Therefore, a PR-focused algorithm is proposed to overcome these limitations while promoting a cheap energy exchange. In a PR-focused algorithm, all MGs are divided into a definite number of price range clusters based on their internal prices, and the group with the lower price range is selected to send offers to the neighbours in order to maximize their export benefit. All MGs in the lowest price group will send offers to their neighbours, so the grouping is based on price, not on the topology of the system.

Pseudo-Code for active thread at MG_i

```
1  : Broadcast D_i, G_i, λ_i, SW_i    \\ D_i , G_i denotes self aggregated demands' and generators' biddings
                                      \\ λ_i , SW_i denotes internal uniform price and social welfare

2  : Read D_j, G_j, λ_j, SW_j         \\ j denotes interconnected microgrids

3  : Rank r_ij                        ∀ j∈ A_i  \\ r_ij denotes rank of microgrid j that is ranked by microgrid I

4  : Broadcast ranks r_ij             ∀ j∈ A_i

5  : Receive ranks r_ji               ∀ j∈ A_i  \\ r_ji denotes rank of microgrid i that is ranked by microgrid j

6  : Average rank = Σ_j r_ji / Σj     ∀ j∈ A_i  \\ A_i denotes set of connected microgrids with Microgid I

7  : if  Average rank =1;
8          Execute rank#1 thread
9  : else
10 :       wait (T)                   \\ T denotes predefined waiting time
11 : end if

12 : if offer_received_i =1           \\ offer_received denotes a flag for receiving offers
13 : Excute rank#2 thread
14 : end if
15 : Counter= counter+1
16 : if Counter = N_max               \\ N_max denotes maximum number of MGs
17 :       Reset
18 : end if
```

Pseudo-Code for Rank #1 thread at MG_i

```
1  : for l=1:k
2  :       for s=1:j
3  :               if offer_ls feasible
4  :                       Commit offer_ls
5  :               else
6  :                       Reject offer_ls
7  :               end if
8  :       end for
9  : end for
10 : Run P2
11 : Generate and broadcast offers_mj'
12 : Send offer_received_j' =1
13 : Set price = 1000
14 : Go to line 12 in active thread
```

Pseudo-Code for Rank #2 thread at MG_i

```
1  : read offers_mj                \\ offers_mj denotes block m
                                     offered from microgrid j

2  :       for k=1: m
3  :               if offer_kj feasible
4  :                       Accept offer_kj
5  :               else
6  :                       Withhold offer_kj
7  :               end if
8  :       end for

9  : Update (G_i, λ_i, SW_i)

10 : set offer_received =0
```

Figure 5.4: Pseudo-code for sequential market clearing approach.

The main advantage of this method is that it can handle a large number of MGs efficiently in terms of computational time. However, in this approach, the lowest priced MG is not given the privilege to sell first; rather, the group with the lowest price range will sell simultaneously.

Note that all assumptions proposed earlier are used here.

In this ranking algorithm, each MG has a pre-known Number Q$\subset$ (0,N$_{max}$], enabling it to calculate a sequence for its directly connected MGs (i.e., r_{ij}). After settling the internal market model, each MG_i will calculate the attribute sequence (i.e., price sequence) for each directly connected MG. Each MG has two sequences at this stage: one for the predefined numbers, and the other for the price sequence. Then each MG can choose another MG to exchange its rank with. This exchange is accomplished by using an indicator called *gain*. For each MG, the gain between it and all its neighbours can be calculated using Equation 5.1 [102].

$$Gain_{ij} = a_{ii}\, r_{ij} + a_{ij}\, r_{ii} - a_{ij}\, r_{ij} \qquad \forall j \in A_i \tag{5.1}$$

The exchange MG_j is the MG with the highest $gain_{ij}$. Once this exchange MG is found, MG_i will exchange its number Q_i with Q_j. It should be noted that these $gain_{ij}$ calculations are repeated until Q_i is no longer exchanged for the number of A_i. The clustering ratio (L) is the reciprocal of the number of clusters with selected prices based on the computational power of the trading engine and time limitations. Afterwards, each MG passes the condition given in Equation 5.2 and sets itself to be in group#1; therefore, it executes the group#1 passive thread and sends offers to its neighbours. Otherwise, the MG waits for a predefined time T before repeating the process again. This predefined time is set to allow exporter MGs to solve the exporting optimization problem that maximizes their export benefits, then sends these offers to neighbouring MGs.

$$Q_i \leq L\; N_{max} \tag{5.2}$$

For further illustration, the pseudo-code for the active and passive threads are shown in Figure 5.5.

Pseudo-Code for active thread at MG_i

Initialization at each MG_i

```
1  : Each MG participate has a pre-known Number Q ⊂ (0,N_max]
2  : Calculate sequence rij        \rij donates ordering of all connected microgirds according to their Q
```

Active thread at MG_i

```
1  : Broadcast D_i, G_i, λ_i, SW_i     \\ D_i , G_i denotes self aggregated demands' and generators' biddings
                                        \\ λ_i , SW_i denotes internal uniform price and social welfare
2  : Read D_j, G_j, λ_j, SW_j          \\ j denotes interconnected microgrids
3  : Calculate attribute based sequence aij  \\aij denotes sequence for all connected microgrids
                                                  according to their prices
4  : Broadcast sequences r_ij and a_ij    ∀ j∈ A_i
5  : Receive sequences  r_ji  and a_j     ∀ j∈ A_i   \\ r_ji denotes rank of microgrid i that is ranked by
                                                       microgrid j
6  : Set gain_max to 0.
6  : for j ∈ A_i
7  : calculate gain_j
8  :       if gain_j > gain_max
9  :       gain_max ← gain_j
10 :       MG*_j ← MG_j
11 : end for
12 : Check if (a_i-a_j) (Q_i-Q_j) <0  for MG*_j
13 :            Q_i ← Q_j
14 : else if Q∈(1,2)& price =1000 ∀ j∈ Ai
15 :       Q_i ← Q_j (Guaranteed Swap)
16 : Set Guaranted swap flag_j =1
17 : end if
18 : Send(a_i,Q_i) to MG_j
19 : Execute passive thread Microgrid j
20 : if Q_i < L N_max
21 :        Set MG_i as seller MG.
22 :        Execute group#1 thread
23 : else
24 :        Set MG_i as buyer MG
25 :        if offer_received_i =1
26 :        Execute group#2 thread
27 :        else wait time = predefined_2
28 :        end if
```

Passive thread at MG_i

```
1  : Receive (a_j,Q_j) from MG_j
2  : Check if (a_i-a_j) (Q_i-Q_ij) <0 or
          Guaranteed swap flag_i =1
3  :            Q_i ← Q_j
4  : end if
5  : Go to line 1 in the active thread
```

Pseudo-Code for Group#1 thread at MG_i

```
1  : for l=1:k
2  :       for s=1:j
3  :              if offer_ls feasible
4  :                     Commit offer_ls
5  :              else
6  :                     Reject offer_ls
7  :              end if
8  :       end for
9  : end for
10 : Run Sequential Market Clearing mathematical algorithm
11 : Generate and broadcast offers_mj'
12 : Send offer_received_j' =1
13 : Set price = 1000
14 : Go to line 1 in active thread
```

Pseudo-Code for Group#2 thread at MG_i

```
1  : read offers_mj                 \\ offers_mj denotes block m
                                       offered from microgrid j
2  :       for k=1: m
3  :              if offer_kj feasible
4  :                     Accept offer_kj
5  :              else
6  :                     Withhold offer_kj
7  :              end if
8  :       end for
9  : Update (G_i, λ_i, SW_i)
10 : set offer_received =0
```

Figure 5.5: Pseudo-code for sequential PR-focused ranking algorithm.

5.3.5 Decentralized Energy Trading Monetary Fund

In the previous chapter, an adapted blockchain is used for the centralized energy trading platform. However, a mandatory modification on the blockchain must be developed in order to be able to handle the transactions in the proposed decentralized sequential trading platform. The main differences between the centralized and the decentralized trading are:

- In the centralized platform, the offers sent by the central operator are firm and the Nash solution is obligatory. Thus, the MGs cannot reject any firmed offers.
- In the decentralized platform, as mentioned earlier, the MGs have the ability to accept/reject the withhold offers when it is their turn to export.

Therefore, a double signing algorithm (DSA) is needed to accurately log the transactions of the actual offers into the blockchain. This DSA requests sender MGs and recipient MGs to sign on the transaction to ensure full acceptance of the offer and eliminate any third party. It is worth mentioning that each MG can participate in any other MG's energy trading by opening an MG wallet.

The main modification will be in creating the unconfirmed transactions. So, any MG can send offers, and these offers are listed as offered transactions. The offered transactions are signed by the sender MG only. Eventually, the recipient MG will approve a part or all of these transactions. The approved transaction will be listed as an unconfirmed transaction, which are signed by both the sender and the recipient (i.e., DSA). It is worth repeating that the miners are the only authorized group that can approve these unconfirmed transactions when real-time transactions are received, and the only authorized group that can store them in the blockchain. The process for creating these transactions is further explained using the pseudo-code in Figure 5.6.

Pseudo-Code for Creating unconfirmed transactions

```
Receive request for creating transaction
if    Sender's ID & Recipient's ID ∊ MG wallet's ID
      initiate Check#1
      if check#1 = 0
            break
      else if check#1=1
            create offered transactions
      else if check#1=2
            create unconfirmed transactions
      end if
end if
```

Pseudo-Code for check#1 thread

```
if transactions ⊂ offered transaction
      if transaction double signed
      return 2
      else
      return 0
else if transactions ⊄ offered transaction
      if sender signed
      return 1
      else
      return 0
end if
```

Figure 5.6: Psuedo-code for creating unconfirmed transactions.

5.4 Decentralized Platform Optimization Model

This section explains the mathematical formulation of the proposed energy trading framework. As mentioned earlier, the objective of the exporter MG is to maximize the export benefit (EB). This EB is defined by Equation (5.3).

$$EB^i = \sum_{j}^{A_i} \sum_{r}^{G_E} \sum_{t}^{G_r} [PE^j_{i_{r,t}} \, (\lambda^i_{max} - \gamma E^i_{r,t})] \tag{5.3}$$

The objective function is subjected to the following constraints:

- Power balance constraint:

  This constraint ensures demand and supply balance in each MG.

$$\sum_{s}^{D} \sum_{m}^{D_s} PD^i_{s,m} = \sum_{c}^{G} \sum_{k}^{G_c} PG^i_{c,k} + \sum_{j}^{A_i} \sum_{r}^{G_E} \sum_{t}^{G_r} PE^i_{j_{r,t}} (1 - \zeta^i_j) \tag{5.4}$$

  The first term represents the internal demand of MG_i, the second term represents the internal generation, and the third term represents the imported energy from all neighbouring MGs.

- Clearing constraints:

  These constraints ensure that the cleared demand and generation for each MG do not exceed their upper limits according to the bidding blocks.

$$0 \leq PD^i_{s,m} \leq \overline{PD}^i_{s,m} \tag{5.5}$$

$$0 \leq PG^i_{c,k} \leq \overline{PG}^i_{c,k} \tag{5.6}$$

  The cleared exported energy from each MG does not exceed its upper limits assigned from the EMS of each MG.

$$0 \leq PE^i_{r,t} \leq \overline{PE}^i_{r,t} \tag{5.7}$$

  The cleared exported energy is defined as the sum of all exported energy to the neighbouring MGs,

$$PE^i_{r,t} = \sum_{j}^{A_i} PE^j_{i_{r,t}} \tag{5.8}$$

The exported energy is set to zero if the block's price exceeds the imported MG's internal price

$$\gamma E^{i}_{r,t} > \lambda^{j}_{o} \quad \rightarrow \quad PE^{j}_{i_{r,t}} = 0 \tag{5.9}$$

- Social welfare improvement constraint:

  This constraint reflects the greedy participation of MG, as mentioned earlier. Each MG participates in the interconnected market if this will improve its own benefit, regardless of others. In this regard, the demand of each MG should not receive a higher price or receive less energy at the same price after participating in the market. As the demand bidding curve of each MG is known, the price will be reduced or the demand covered will be increased if the social welfare of the MG after trading is greater than the social welfare calculated before trading.

$$SWE^{i} = \sum_{s}^{D}\sum_{m}^{D_i}[PD^{i}_{s,m}\ \gamma^{i}_{D_{s,m}}] - \sum_{c}^{G}\sum_{k}^{G_c}[PG^{i}_{c,k}\ \gamma^{i}_{G_{c,k}}] - \sum_{j}^{A_i}\sum_{r}^{G_E}\sum_{t}^{G_r}[PE^{i}_{j_{r,t}}\ \gamma E_{j_{r,t}}] \tag{5.10}$$

$$SWE^{i} \geq SW^{i}_{o} \tag{5.11}$$

- Trading conditions check:

  Each importer MG is applying this trading check in order to ensure that the MG is gaining benefits from these offers. In order to pass this condition, the social welfare of the demand in addition to the social welfare of the internal generators should be higher than the social welfare before trading.

$$SW^{i}_{D_{new}} + SW^{i}_{G_{new}} \geq SW^{i}_{o} \tag{5.12}$$

$$SW^{i}_{D_{new}} = \sum_{s}^{D}\sum_{m}^{D_i}[PD^{i}_{s,m}\ (\gamma^{i}_{D_{s,m}} - \gamma^{i}_{new})] \tag{5.13}$$

$$SW^i_{G_{new}} = \sum_{c}^{G} \sum_{k}^{G_c} [PG^i_{c,k}\ (\gamma^i_{new} - \gamma^i_{G_{c,k}})] \tag{5.14}$$

5.5 Case Studies

The proposed energy trading platforms were implemented and tested using the same four MGs presented in Chapter 4. Two case studies are proposed in this section. In the first case, four interconnected MGs are considered for participation in energy trading using the #1-focused sequential clearing approach. In the second case study, eight MGs are admitted for participation in the framework using the PR-focused sequential clearing approach.

5.5.1 #1-focused Sequential Market Clearing

The same MGs presented in Chapter 4 are considered for applying the proposed sequential market clearing. In this model, we define two processes: 1) Ranking, in which the ranking algorithm mentioned above is used to find the rank#1 MG that will be exporting to its neighbours and firming any withhold or adopted offers; and 2) Offers, in which the rank#1 MG solves an optimization problem to maximize its export benefits and send offers to neighbouring MGs. These processes of Ranking and Offers are run in rounds, with the rank1 MG selected as the exporter. After each round, the selected MG is eliminated and the ranking algorithm is run to select the next exporter. In this case study, the first scenario used in the previous chapter is adopted. The objective function for the exporter MG is modelled as maximizing the export benefit according to the following problem:

$$\max(EB^i)$$
$$s.t.$$
$$(5.3) - (5.11)$$

Note that the exporter MG has to run the trading condition check modeled by Equation (5.12) in order to accept or reject the withhold offers.

5.5.1.1 First round

The #1-focused Ranking algorithm is performed to identify rank#1 MG, based on the prices shown in Table 4.3, MG-T2 is selected to export. By executing the optimization problem introduced earlier, the solution shows that each MG will import from MG-T2. Each MG then runs its own EuMP model to adopt or withhold offers; however, no offers are rejected from round 1, as shown in Table 5.1. Although the price of the MG-T1 remains constant after round#1, the total demand covered with the same price increased by 62%.

Meanwhile, for MG-T3 and MG-T4, the price and total demand covered remain constant; however, the effective social welfare increased. This indicates that the exporter generators offered lower prices compared to the importer's internal generators. Therefore, these offers are being withheld. After this stage, MG-T2 is eliminated from the platform, and the Ranking algorithm is re-run. MG-T1 is selected as rank#1 to export in the next round, as presented in Table 5.2.

Table 5.1: First Round of Sequential Market Clearing Results Using #1-Focused

		MG T1	**MG T2**	**MG T3**	**MG T4**
Round #1	Price	0.065 $/kWh	0.0285 $/kWh	0.1047 $/kWh	0.1024 $/kWh
	Social welfare	19.3084	26.90522	1.903386	2.02628
	Total Demand covered	218 kWh	428.032 kWh	69.734 kWh	68.518 kWh
	Rank #1		x		
Offers #1	Available offers from Rank #1	135.816	N/A	61.077	21.102
	MG Eliminated		x		

5.5.1.2 Second round

In round 2, MG-T3 and MG-T4 are found to be importers of energy from MG-T1. However, both MGs rejected unfeasible offers from the offered energy, as shown in Table

5.2. Moreover, the price of energy in both MGs is reduced and the total demand covered is increased, so MG-T1 is eliminated from the platform at this stage. Finally, MG-T3 is selected to be rank#1 after running the ranking algorithm.

Table 5.2: Second Round of Sequential Market Clearing Results Using #1-Focused

		MG T1	MG T2	MG T3	MG T4
Round #2	Price	0.065 $/kWh	Eliminated	0.1047 $/kWh	0.1024 $/kWh
	SWE	23.257		2.145	3.428
	Total Demand Covered	353.408 kWh		69.734 kWh	68.518 kWh
	Trading Condition	Pass		Fail	Fail
	Offers	Accepted		Withhold	Withhold
	Rank #1	x			
Offers #2	Available offers from Rank #1	N/A	N/A	345.163	273.837
	MG Eliminated	x			

5.5.1.3 Third round

In round 3, MG-T4 was found to be importing energy, as indicated in Table 5.3. However, MG-T4 rejected offers received from MG-T3 after running the internal UMP model.

5.5.1.4 Fourth round

In round 4, although MG-T4 is rank 1, no feasible export can be found, as other MGs already have lower prices, as presented in Table 5.4.

The total exported power after trading is settled is illustrated in Figure 5.7. The power is exported from the low-priced MGs to the high-priced ones. As can be seen, MG-T1

Table 5.3: Third Round of Sequential Market Clearing Results Using #1-Focused

		MG T1	MG T2	MG T3	MG T4
Round #3	Price	Eliminated	Eliminated	0.081 $/kWh	0.088 $/kWh
	SWE			7.059	6.577
	Total Demand Covered			207.553 kWh	204.44 kWh
	Trading Condition			Pass	Pass
	Offers			Rejected 138.062 kWh	Rejected 89.888 kWh
	Withhold offers			Rejected 60 kWh	Accepted
	Rank #1			x	
Offers #3	Available offers from Rank #1			N/A	0.025
	MG Eliminated			x	

Table 5.4: Fourth Round of Sequential Market Clearing Results Using #1-Focused

		MG T1	MG T2	MG T3	MG T4
Round #4	Price	Eliminated	Eliminated	Eliminated	0.088 $/kWh
	SWE				6.577
	Total Demand covered				204.44 kWh
	Trading Condition				Fail
	Offers				Rejected
	Rank 1				x

exported 353 kWh more than any other MG. The reason for this is that MG-T1 has a connection to the lowest price MG (i.e., MG-T2), so it imported cheap power for internal use, as shown in Figure 5.7. It then exported power to high-priced MGs (i.e., MG-T3 and MG-T4). MG-T2 exported less power than MG-T1 because the available low-price generation units were limited. Therefore, it could not export to MG-T3 and its export power to MG-T4 is much less than MG-T1, the latter which has a higher internal price.

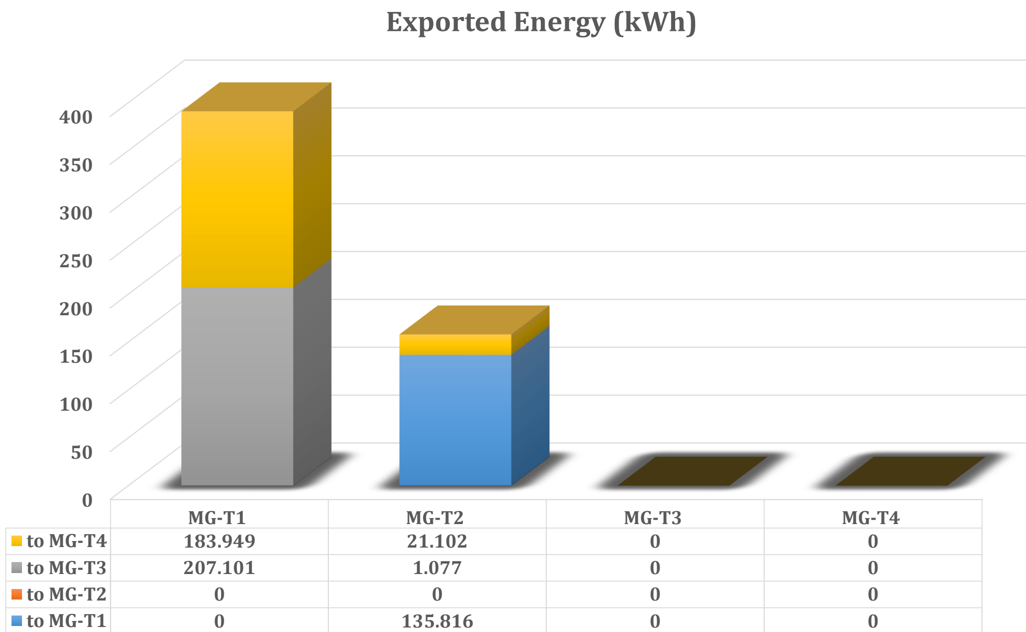


Figure 5.7: Exported power.

For further demonstration, the internal prices before and after the trading are shown in Figure 5.8. As expected, the prices do not change for the exporter MGs. For the importer MGs, however, the internal prices decrease. Specifically, in MG-T3 and MG-T4, internal prices decreased 77% and 86% of their internal prices prior to trading, respectively.

5.5.2 PR-focused Sequential Market Clearing

The energy trading framework has been further tested using the proposed PR-focused clearing approach. The same MG types shown in Table 4.3 have been adopted in this case study. However, the topology of the MGs is different, with eight MGs assumed to be

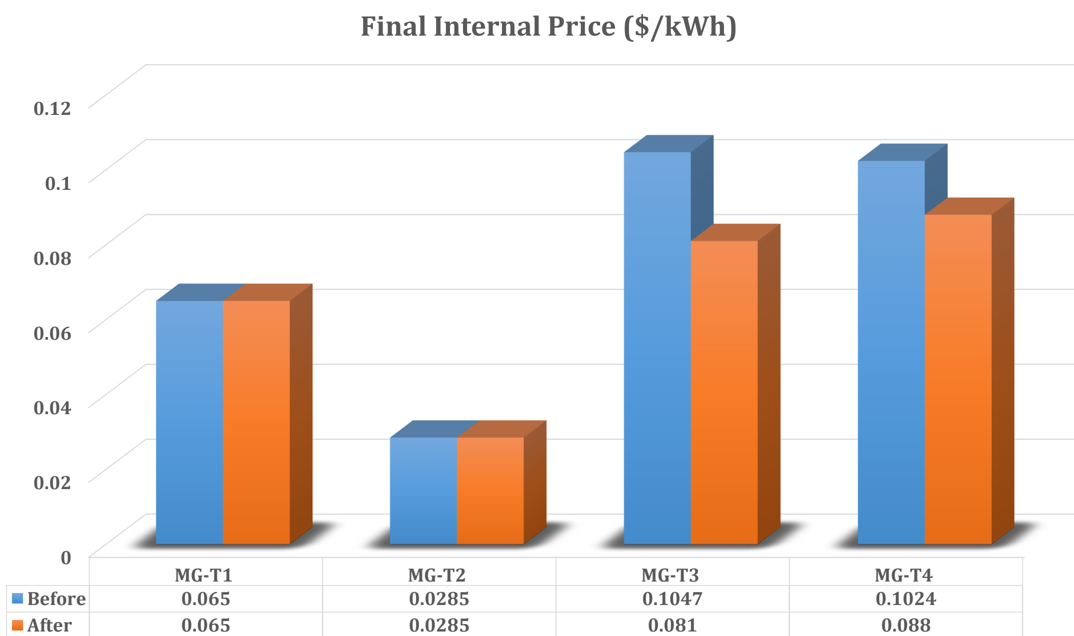


Figure 5.8: Internal price before and after energy trading.

connected, as shown in Figure 5.9. In addition, the same definitions for offers and ranking processes are used in this case study.

The proposed sequential market using a PR-focused algorithm has been executed assuming clustering of the participating MGs into four clusters (i.e., L=0.25).

5.5.2.1 First round

In round#1, both MG-T2_ID1 and MG-T2_ID2 are found to be group#1 based on their internal prices, as shown in Table 5.5. These MGs then send trading offers to their neighbours based on the connectivity of the network. It is worth noting that these offers are generated to maximize the export benefit of exporter MG. Therefore, MG-T2_ID1 sends offers to MG-T1_ID1 and MG-T1_ID2. Given that those MGs are identical, thus, they received the same offers. On the other hand, MG-T2_ID2 has sent more offers as it is connected to three MGs. At this stage, Group#1 MGs are eliminated from the energy

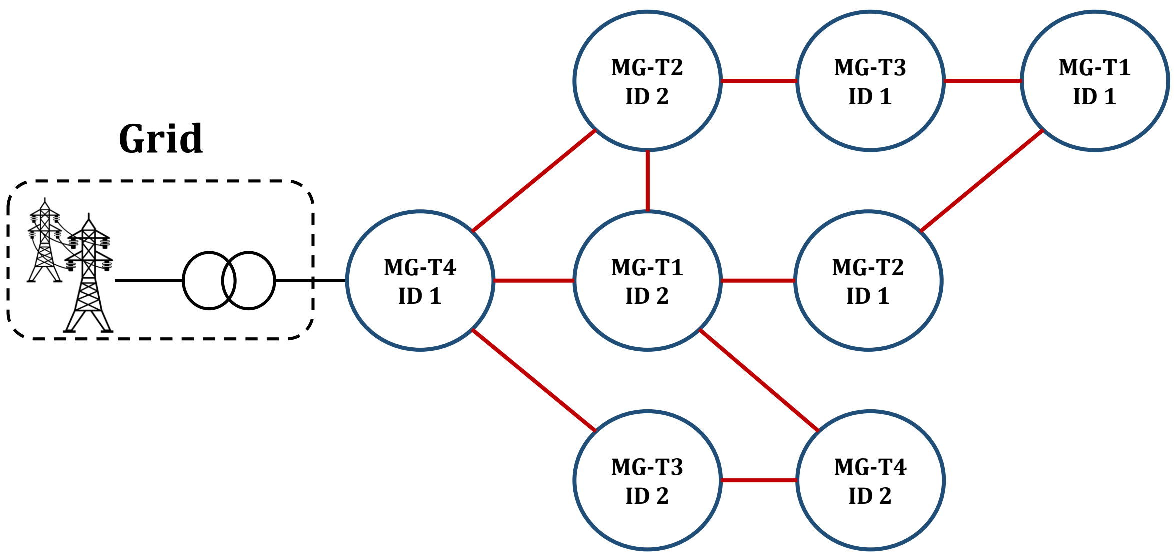


Figure 5.9: Microgrid connectivity.

trading.

Table 5.5: First Round of Market Clearing Results Using PR-Focused (L=0.25)

		MG-T1_ID1	**MG-T1_ID 2**	**MG-T2_ID 1**	**MG-T2_ID 2**	**MG-T3_ID 1**	**MG-T3_ID 2**	**MG-T4_ID 1**	**MG-T4_ID 2**
Round #1	Price	0.065 $/kWh	0.065 $/kWh	0.0285 $/kWh	0.0285 $/kWh	0.1047 $/kWh	0.1047 $/kWh	0.1024 $/kWh	0.1024 $/kWh
	Social welfare	19.3084	19.3084	26.90522	26.90522	1.903386	1.903386	2.02628	2.02628
	Total Demand covered	218 kWh	218 kWh	428.032 kWh	428.032 kWh	69.734 kWh	69.734 kWh	68.518 kWh	68.518 kWh
	Sellers			**x**	**x**				
Offers #1	Available offers from Sellers	79 kWh from MG-T2_ID1	79 kWh from MG-T2_ID1	N/A	N/A	61.077 kWh from MG-T2_ID2	N/A	21.107 kWh from MG-T2_ID2	N/A
			135.816 kWh from MG-T2_ID2						
	MG Eliminated			**x**	**x**				

5.5.2.2 Second round

In the second round, MG-T1_ID1 and MG-T1_ID2 are found to be the exporters, so they cleared all withhold offers and generated offers to their neighbours. As a result, utilizing the offers approved by MG-T1_ID2, the internal price dropped to 0.036 $/kWh, as shown in Table 5.6. However, the price in the ID1 did not change, as it was not involved in round1. MG-T1_ID1 has sent offers to MG-T3_ID1. Also, MG-T1_ID2 has sent offers to MG-T4_ID1 and MG-T4_ID2, as shown in Table 5.6.

Table 5.6: Second Round of Market Clearing Results Using PR-Focused (L=0.25)

		MG-T1_ID1	**MG-T1_ID 2**	**MG-T2_ID 1**	**MG-T2_ID 2**	**MG-T3_ID 1**	**MG-T3_ID 2**	**MG-T4_ID 1**	**MG-T4_ID 2**
Round #2	Price	0.065 $/kWh	0.036 $/kWh			0.1047 $/kWh	0.1047 $/kWh	0.1024 $/kWh	0.1024 $/kWh
	Social welfare	21.614	25.205			1.903386	1.903386	2.02628	2.02628
	Trading Conditions	Pass	Pass			Fail	N/A	Fail	N/A
	Rejected offers	N/A	Rejected 11.988 kWh from MG-T2_ID2	Eliminated	Eliminated	N/A	N/A	N/A	N/A
	Withhold Offers	N/A	N/A			61.077 kWh from MG-T2_ID2	N/A	21.107 kWh from MG-T2_ID2	N/A
	Total Demand covered	297 kWh				69.734 kWh	69.734 kWh	68.518 kWh	68.518 kWh
	Sellers	**x**	**x**						
Offers #2	Available offers from Sellers	N/A	N/A	Eliminated	Eliminated	428.716 kWh from MG-T1_ID1	N/A	213.89 kWh from MG-T1_ID2	213.89 kWh from MG-T1_ID2
	MG Eliminated	**x**	**x**						

5.5.2.3 Third round

Four remaining MGs have participated in the third round, as shown in Table 5.7. As a result of importing low priced power, the MG-T3_ID1 price has dropped by 27.4%. Additionally, the price of MG-T4_ID1 has dropped by 17%. This drop allows both of the MGs to be selected in group#1. It is worth noting that both MGs have accepted some of the offers and rejected the rest, as indicated in Table 5.7. It was not feasible for MG-T3_ID1 to generate any offers, as its neighbours have a lower internal price. However, MG-T4_ID1 has sent offers to MG-T3_ID2.

Table 5.7: Third Round of Market Clearing Results Using PR-Focused (L=0.25)

		MG-T1_ID1	MG-T1_ID 2	MG-T2_ID 1	MG-T2_ID 2	MG-T3_ID 1	MG-T3_ID 2	MG-T4_ID 1	MG-T4_ID 2
Round #3	Price	Eliminated	Eliminated	Eliminated	Eliminated	0.076 $/kWh	0.1047 $/kWh	0.085 $/kWh	0.087 $/kWh
	Social welfare					7.474	1.903386	7.36	6.322
	Trading Conditions					Pass	N/A	Pass	Pass
	Rejected offers					Rejected 221.615 kWh from MG-T1 ID 1	N/A	Rejected 29.941 kWh from MG-T1 ID 2	Rejected 8.834 kWh from MG-T1 ID 2
	Withhold Offers					Rejected 60 kWh from MG-T2 ID 2	N/A	Accepted 21.107 kWh from MG-T2_ID2	N/A
	Total Demand covered					218.178 kWh	69.734 kWh	205.056 kWh	205.056 kWh
	Sellers					x		x	
Offers #3	Available offers from Sellers	Eliminated	Eliminated	Eliminated	Eliminated	N/A	74 kWh from MG-T4_ID1	N/A	0
	MG Eliminated					x		x	

5.5.2.4 Fourth round

The remaining MGs settled their prices, as shown in Table 5.8. MG-T3_ID2 has rejected all the offers because they could not pass the trading condition of the MG. Although the number of MGs in this case study is doubled, the time consumed to settle the market remains the same.

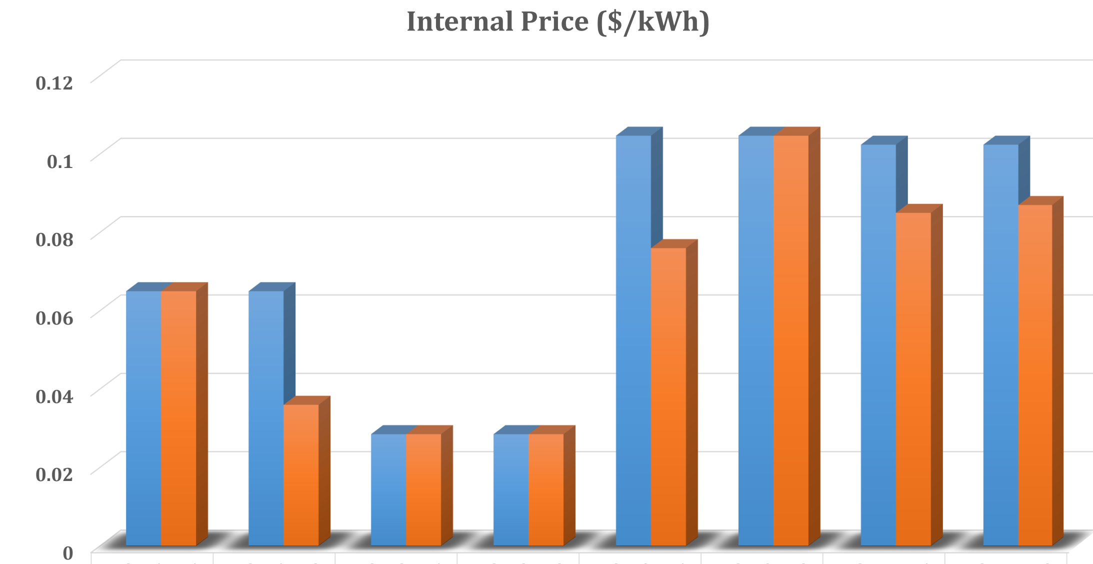
As a further demonstration of the application of the proposed method, the internal prices before and after energy trading are illustrated in Figure 5.10. The prices have remained constant for the MGs with the lowest prices (i.e., MG-T2_ID1 and MG-T2_ID2). Also, the price has not changed for MG-T1_ID1, as it is consuming power at the same price. As a result of not accepting any offers, the price remained constant for MG-T3_ID2. On

Table 5.8: Fourth Round of Market Clearing Results Using PR-Focused (L=0.25)

		MG-T1_ID1	MG-T1_ID 2	MG-T2_ID 1	MG-T2_ID 2	MG-T3_ID 1	MG-T3_ID 2	MG-T4_ID 1	MG-T4_ID 2
Round #4	Price	Eliminated	Eliminated	Eliminated	Eliminated	Eliminated	0.1047 $/kWh	Eliminated	0.087 $/kWh
	Social welfare						1.903386		6.322
	Trading Conditions						Fail		N/A
	Rejected offers						74 kWh from MG-T4_ID1		N/A
	Withhold Offers						N/A		N/A
	Total Demand covered						69.734 kWh		205.056 kWh
	Sellers								x
Offers #4	Available offers from Sellers	Eliminated	Eliminated	Eliminated	Eliminated	Eliminated	0	Eliminated	N/A
	MG Eliminated								x

the other hand, the prices have changed for importer MGs (i.e., MG-T1_ID2, MG-T3_ID1, MG-T4_ID1, and MG-T4_ID2), which proves the efficiency of the proposed energy trading concept. The effect of the proposed energy trading algorithm on the total demand covered in each MG is shown in Figure 5.11. As expected, the demand is constant for the lowest-priced MGs. Also, the demand is constant for MG-T3_ID2, as it did not import any power. It is worth noting that MG-T3_ID2 is connected to two MGs with high prices, as shown in Figure 5.9; thus, it could not import any cheap energy from its neighbours. As a result, MG-T3_ID2 did not benefit from energy trading in this case.

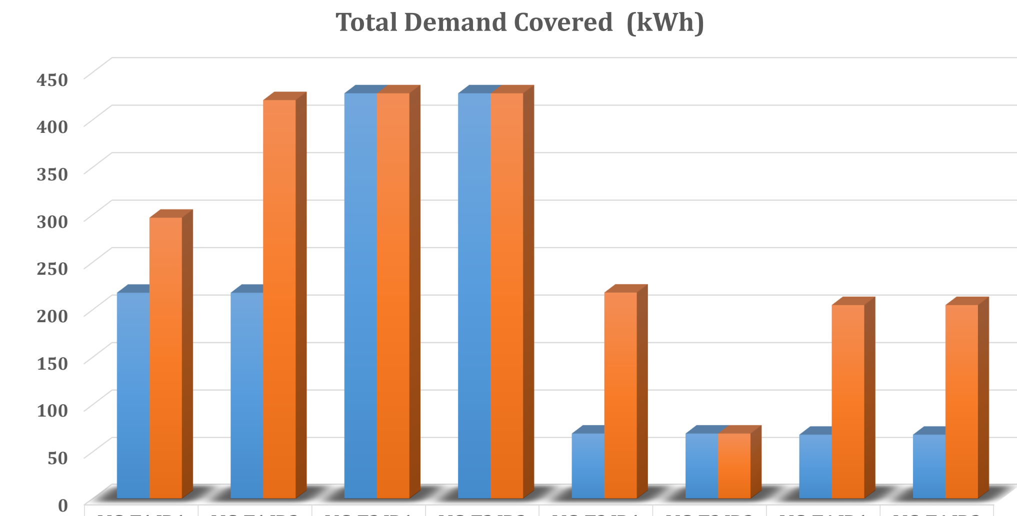
On the contrary, the total demand covered in MG-T1_ID2 is almost double the low price, as it is located between two MGs with very low prices and available sources. Although the internal price of MG-T1_ID1 remained the same, the total demand covered increased by almost 20%. The total demand covered is almost tripled for the high-priced MGs, proving the effectiveness of the proposed method. The effect of the energy trading platform on the internal generation units is shown in Figure 5.12. As expected, the internal generation units in the high-priced MGs are not dispatched after market settlement. Nevertheless, due to applying the trading condition discussed before, that is not guaranteed as in MG-T3_ID2.



	MG-T1 ID1	MG-T1 ID2	MG-T2 ID1	MG-T2 ID2	MG-T3 ID1	MG-T3 ID2	MG-T4 ID1	MG-T4 ID2
Before	0.065	0.065	0.0285	0.0285	0.1047	0.1047	0.1024	0.1024
After	0.065	0.036	0.0285	0.0285	0.076	0.1047	0.085	0.087

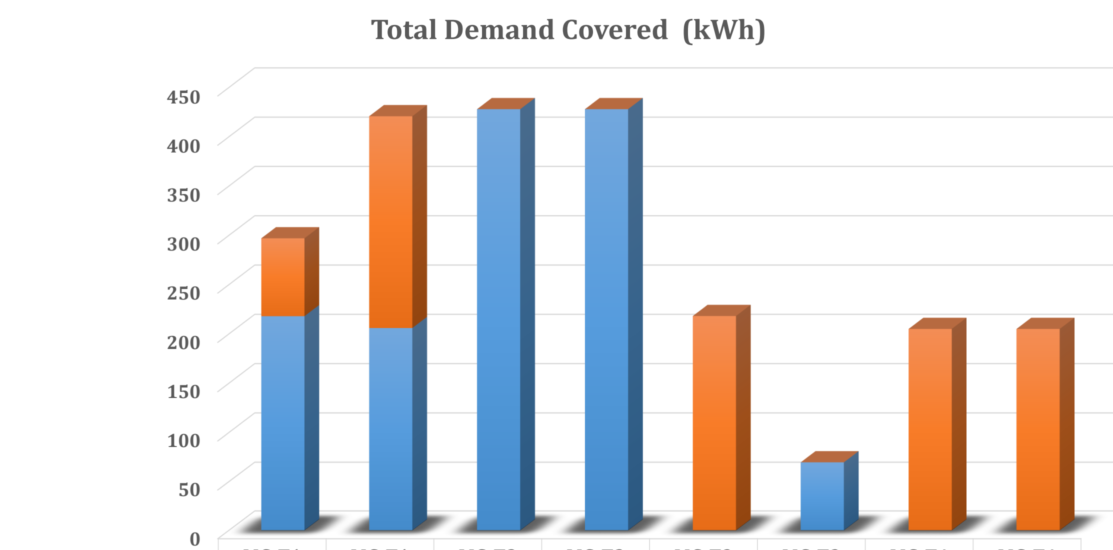
Figure 5.10: Internal prices before and after energy trading.

The total exported power from each MG participating in energy trading is shown in Figure 5.13. MG-T1_ID2 has the most export power among all MGs because it is connected to both low-priced and high-priced MGs. Therefore, it imported low-priced power for internal use and exported its surplus to the high-priced MGs. It can be seen that MG-T2_ID1 has slightly higher export power than MG-T2_ID2; this occurred because MG-T2_ID1 is connected to more MGs, boosting its ability to export. It goes without saying that the ability to export is much less in cases of high prices, as shown in Figure 5.13. The export benefits gained for all MGs are illustrated in Figure 5.14. Although it might be concluded that export benefits follow the same pattern of export power, this is not always the case. The export benefits in this platform depend on the market settlement in the importer MG.



	MG-T1 ID1	MG-T1 ID2	MG-T2 ID1	MG-T2 ID2	MG-T3 ID1	MG-T3 ID2	MG-T4 ID1	MG-T4 ID2
Before	218	218	428	428	69.734	69.734	68.518	68.518
After	297	420.828	428	428	218.178	69.734	205.056	205.056

Figure 5.11: Total demand covered before and after energy trading.



	MG-T1 ID1	MG-T1 ID2	MG-T2 ID1	MG-T2 ID2	MG-T3 ID1	MG-T3 ID2	MG-T4 ID1	MG-T4 ID2
Imported Generation	79	214.816	0	0	218.178	0	205.056	205.056
Internal Generation	218	206.012	428	428	0	69.734	0	0

Figure 5.12: Internal and imported generation after energy trading.

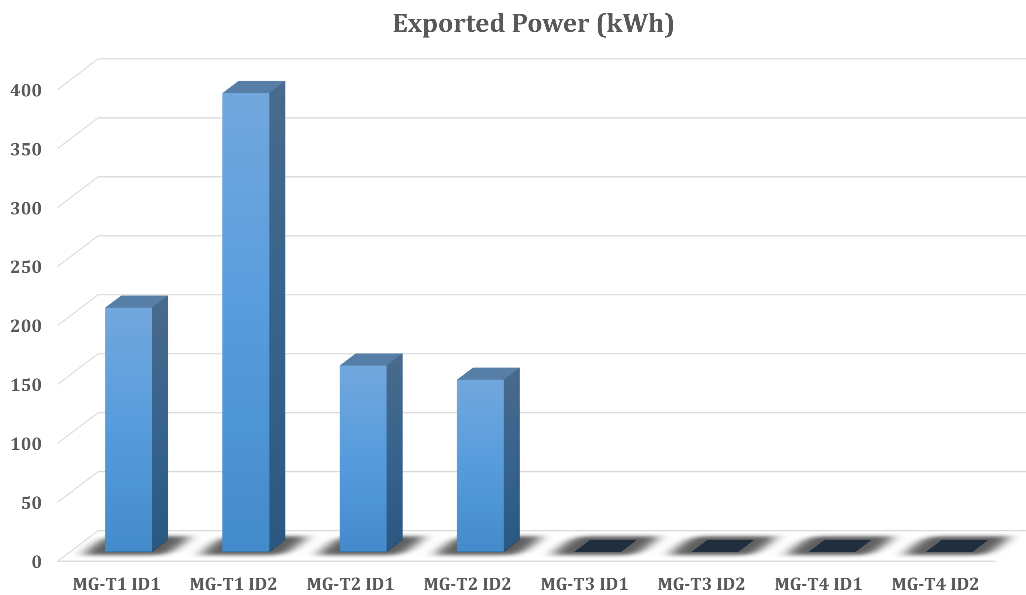


Figure 5.13: Total exported power.

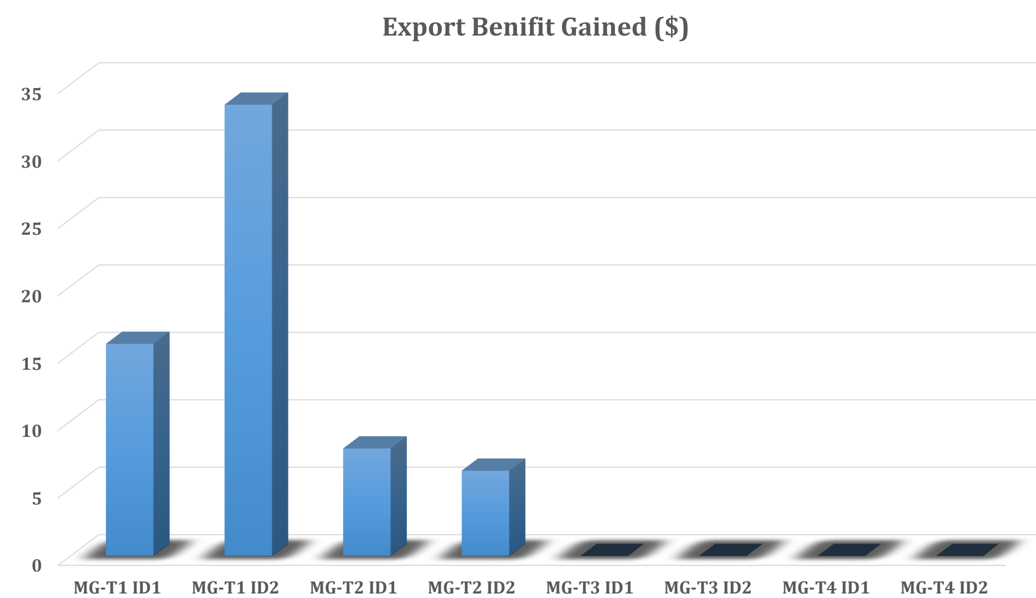


Figure 5.14: Export benefits gained.

5.5.2.5 Ranking execution

The PR-focused ranking algorithm was run throughout the market clearing. The numbers Qi were swapped smoothly and efficiently between MGs, which proves the effectiveness of the proposed ranking algorithm. Table 5.9 illustrates the swapping of the numbers. More detailed calculations are found in Appendix (B).

Table 5.9: PR-Focused Q Swapping

Time →

Microgrid Name	Node code	Qi-Initiation	Qi-gain swab (e-h)	Qi-gain swab (d-f)	Qi-gain swab (b-e)	Offers #1 starts	Qi-gain swab (d-f)	Qi-gain swab (b-a)	Qi-gain swab (a-e)	Offers #2 starts	Qi-gain swab (c-d)	Qi-gain swab (a-e)	Qi-gain swab (h-e)	Offers #3 starts	Qi-Guaranteed swap (c-d)	Qi-Guaranteed swap (d-f)	Qi-Guaranteed swap (f-e)	Qi-gain swab (e-h)	Qi-gain swab (a-g)	Offers #4starts
T4 ID1	a	4	4	4	4		4	1	3		3	1	1		1	1	1	1	6	
T2 ID2	b	3	3	3	1		1	4	4		4	4	4		4	4	4	4	4	
T3 ID1	c	8	8	8	8		8	8	8		2	2	2		8	8	8	8	8	
T1 ID1	d	2	2	7	7		2	2	2		8	8	8		2	7	7	7	7	
T1 ID2	e	5	1	1	3		3	3	1		1	3	5		5	5	2	3	3	
T2 ID1	f	7	7	2	2		7	7	7		7	7	7		7	2	5	5	5	
T3 ID2	g	6	6	6	6		6	6	6		6	6	6		6	6	6	6	1	
T4 ID2	h	1	5	5	5		5	5	5		5	5	3		3	3	3	2	2	

5.5.3 Sequential Market Solution vs Nash Solution

The output from the proposed sequential clearing algorithm using 1-focused is compared with the Nash solution provided in Chapter 4. No comparison with the UMP model is required, as that model is not a feasible solution for IMG energy trading, as discussed earlier. As illustrated in Table 5.10, the total demand in each case is almost the same using both frameworks. Also, MG-T2 has a lower export value in the decentralized approach, because of the greedy decision from MG-T1, which rejected offers from MG-T2. This is not, however, possible using the Nash framework.

On the other hand, the exported power increased in the decentralized technique for MG-T1 because it imported from cheap energy and exported its internally generated power on the next round, as demonstrated earlier. It is worth mentioning that the internal price for MG-T3 and MG-T4 is less in the decentralized case, as it imported more power from MG-T1 with better prices. Nevertheless, it can be concluded that the decentralized technique solution is close to the centralized Nash one in terms of internal prices, effective social welfare, demand covered, and export revenue.

Table 5.10: Comparison Between 1-Focused and Nash Solution

	MG-T1		**MG-T2**		**MG-T3**		**MG-T4**	
	D-#1-focused[1]	**C-Nash[2]**	**D-#1-focused**	**C-Nash**	**D-#1-focused**	**C-Nash**	**D-#1-focused**	**C-Nash**
Exported Energy	391.05 kWh	299.388 kWh	157.995 kWh	218.962 kWh	0	0	0	0
Imported Energy	135.816 kWh	105.116 kWh	0	0	208.178 kWh	208.178 kWh	205.056 kWh	205.056 kWh
Effective Social Welfare	$23.257	$23.239	$26.905	$26.950	$7.059	$7	$6.577	$7.127
Export revenue	$32.96	$30.539	$10.772	$18.445	0	0	0	0
Demand Covered	353.816 kWh	323.116 kWh	428.032 kWh	428.032 kWh	208.178 kWh	208.178 kWh	205.056 kWh	205.056 kWh
Import/**E**xport	**E & I**	**E & I**	**E**	**E**	**I**	**I**	**I**	**I**
Internal Price	0.065 $/kWh	0.065 $/kWh	0.0285 $/kWh	0.0285 $/kWh	0.081 $/kWh	0.102 $/kWh	0.088 $/kWh	0.102 $/kWh

[1] Decentralized based on #1-focused model
[2] Centralized based on Nash model

5.6 Monetary Fund Verification

In order to verify the proposed modification of the blockchain, the proposed blockchain was coded using Python. The coded blockchain succeeded in creating both the offered transactions and the unconfirmed transactions. A sample of the transactions recorded in the blockchain is shown in Figure 5.15, where the total transactions were recorded as 273.837 kWh between MG-T1 and MG-T4. As illustrated, the coded blockchain succeeded in allowing the recipient MG (i.e., MG-T4) to reject 89.888 kWh, as shown in Table 5.3.

5.7 Conclusion

This chapter proposed a novel decentralized-based energy trading platform for IMGs. The proposed platform is based on a sequential market clearing algorithm to give the cheapest MG the privilege to maximize its benefits by exporting its cheap surplus power to directly connected MGs. The selection of the cheapest MG is made in a decentralized fashion using two ranking algorithms. The first one is called 1-focused and is suitable for a low number of MGs. The other is called PR-focused and is suitable for a high number of MGs.

Moreover, a blockchain adaptation has been developed, and a new double sign algorithm (DSA) proposed to allow MGs to accept a few of the offered transactions and reject the rest (if needed). The decision of each MG is made according to its own greedy decision. This platform has been tested using different software packages (MATLAB, GAMS, and Python). The results show that the proposed algorithm can achieve valid results that are close to the Nash solution algorithm while maintaining the MGs' privacy. Furthermore, the proposed algorithm promotes the independent operation of every MG and ensures that each can make its own greedy decision. The blockchain results have been verified and ensure that each MG is able to accept or reject the offered transactions.

Offered Transaction

Sender:
30819f300d06092a864886f70d010101050003818d0030818902818100deff7a1218632479edf6a1
5379f7365f15dccf3d01bf1df4b4a8069a56d2597db90132b7364768d93b787f72f72435f2add3d7f9
21daf8dbdb680067df76fd97b724b292dab1b246b0c8ab134031e92e4cf096913dd2942e74aa5e196
0c71d47a7e4a6c8d580f55ba6daf4d86ba9bbad923c1b88f626a585cd5c945a1dc78ecf0203010001
Recipient:
30819f300d06092a864886f70d010101050003818d0030818902818100ba99f01daa86ba9e3cc4e0c1a84da
6e413925990a692731b97be99a753d6447b4c5b5707b4ebe6c1400e3b97ea44659ec7dcfee9284db3e6f15c
e141426f0afefaeb519defb7800cc014d722dd227debb1e9113b0b6812fac048ea35b9ed8655f52bd93da5fba
6d9877a3724424cff9fe7852f262d052bb424aa4663c89f07eb0203010001
Amount: [different prices]
power: [273.837]
fund: 100

Unconfirmed Transaction

Sender:
30819f300d06092a864886f70d010101050003818d0030818902818100deff7a1218632479edf6a1
5379f7365f15dccf3d01bf1df4b4a8069a56d2597db90132b7364768d93b787f72f72435f2add3d7f9
21daf8dbdb680067df76fd97b724b292dab1b246b0c8ab134031e92e4cf096913dd2942e74aa5e196
0c71d47a7e4a6c8d580f55ba6daf4d86ba9bbad923c1b88f626a585cd5c945a1dc78ecf0203010001
Recipient:
30819f300d06092a864886f70d010101050003818d0030818902818100ba99f01daa86ba9e3cc4e0c1a84da
6e413925990a692731b97be99a753d6447b4c5b5707b4ebe6c1400e3b97ea44659ec7dcfee9284db3e6f15c
e141426f0afefaeb519defb7800cc014d722dd227debb1e9113b0b6812fac048ea35b9ed8655f52bd93da5fba
6d9877a3724424cff9fe7852f262d052bb424aa4663c89f07eb0203010001
Amount: [0.088]
power: [183.949]
fund: 100

Figure 5.15: Offered and unconfirmed transaction sample.

Chapter 6

Summary, Contributions, and Future Work

6.1 Summary and Conclusions

The main objective of this work was to develop a new management and trading system for distribution systems, in which the utility has a new business model to preserve their interests. To achieve this objective, the present research utilized blockchain capabilities in order to manage the large number of participants in the distribution market and facilitate transactive energy while offering security, fairness, and transparency.

The first stage of this work was discussed in detail in Chapter 3. In the chapter, a new blockchain-ET-engine was proposed to facilitate the blockchain concept's energy trading. Adapted blockchain technology was utilized to consider the power system's physical limitations. As well, a new end-user marginal price (EuMP) model was proposed to account for the losses, which are considered using sensitivity analysis for loads participating in the market. The blockchain algorithm is called twice in the same slot cycle. The first call is to write down the market commitment block (i.e., committed power and price for each user along with the user wallet fund). The second call is to mine the real-time block (i.e., real-time power and cost for each user along with the user wallet fund).

The proposed engine consists of three modules: 1) market module, 2) power system module, and 3) monetary fund module (i.e., blockchain). These modules are mounted on each miner to provide a decentralized trading framework. The results show seamless integration between the three modules and offer a transparent, fair, and accurate framework.

The second stage of this work developed a framework of interconnected MGs and was discussed in detail in Chapter 4. The proposed framework was developed to function within the existing paradigm, with an obligation to operate under a centralized supervised entity. Further, the proposed framework was developed to work fairly between participants, utilizing the Nash bargaining theory. The utility functions employed in this research were uniquely designed to model each MG's interest in the case of import or export. A blockchain adaptation was also made to interconnect the MGs' chains using a novel two-layer structure chain (TLSC) concept. The first chain is the self microgrid chain (MC), in which the intra-grid transactions of the MGs are stored. The other chain is the inter-grid chain (IGC), in which inter-grid transactions are stored safely.

Two mining techniques were proposed in this framework. The first one is based on the Proof of Work (PoW) consensus algorithm, which is employed to mine the block transactions of MCs. The other is the Proof of Authority (PoA) consensus algorithm, which is utilized for mining the block transactions of IGCs. The proposed model was tested by integrating different software packages. The results showed a fair and efficient framework, and the transactions on the blockchains were verified.

In Chapter 5, an energy trading method for IMGs in a decentralized manner was developed to maintain the privacy of each MG and follow the self-benefit-driven (SBD) interests of the participating MGs. A sequential market clearing algorithm based on multi-rounds was also proposed to settle the transactions between MGs. In each round, a ranking algorithm was run to determine the lowest-priced MG (rank1 MG) and give it the privilege to send offers to other MGs directly linked with it. Each MG tries to maximize its own export revenue.

Additionally, two decentralized-based ranking algorithms were introduced in this work. The first one, called 1-focused algorithm, was used to find the rank1 MG. The second algorithm, called PR-focused, was used to find a group of MGs with low-prices to export. The blockchain was adapted to enable the transactions in this proposed framework. The framework was tested, with the results showing good support for the proposed idea. It is worth noting that the present author promotes this framework, as it is aligned with the idea of the independent operation of MGs developed in Chapter 3.

That being said, this thesis has provided a platform that enables energy trading in both isolated and interconnected MGs. The decentralized IMG platform is ideal for facilitating energy trading in IMGs while maintaining the SBD of participating MGs. Equally important, it ensures and maintains the MGs' privacy, which is a crucial concern for participants.

6.2 Contributions

The main contributions of this work may be summarized as follows:

1. A new framework was developed for energy trading that can handle all offers from prosumers and biddings from end-users. The development of this trading framework, which includes the adoption of existing market models, has been discussed in detail in the thesis.

2. Existing blockchain technology was adapted to suit the distinct nature of power systems as well as the needs of businesses.

3. An end-user marginal price model was created to ensure fairness and the efficient management of a large number of market participants.

4. A operation cycle framework was built that ensures harmony among differing market modules.

5. A framework that promotes the achievement of a fast billing cycle and efficient cash flow was built.

6. A novel framework for energy trading in IMGs that can handle DER offers and end-user bidding was introduced.
7. A unique self-benefit utility function for each MG to export/import energy to/from an interconnected market was defined.
8. A centralized energy trading platform using Nash bargaining and implementing an UMP market model to ensure market fairness was developed.
9. A blockchain layer to handle trading transactions and deal with the proposed market was integrated in the design.
10. A new framework for energy trading in IMGs that can handle any number of MGs was proposed.
11. An SBD operation of MGs participating in the market that satisfies both demand and prosumers was promoted.
12. A decentralized energy trading platform based on sequential settlements to establish a fair market was developed.
13. Blockchain technology was adapted to enable it to deal with the proposed market and to provide a safe, reliable, and transparent monetary fund.

6.3 Future Work

Based on the previous investigations in this thesis, the following fields are suggested for future research:

1. Developing the penalty metrics to calculate the penalties to be applied to uncommitted participants.
2. Developing the bidding management system to translates preferences set by the end-user to bidding curves.

3. Planning MGs to maximize profits from participating in the proposed energy trading framework for interconnected MGs.

4. Studying the effects of using different consensus algorithms, such as Proof of Stake and Byzantine Fault Tolerance (BFT).

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Appendices

Appendix A

Generator and Load Bidding Data

Table A.1: Generator Offers in MGs

Generator	MG T1						MG T2					
	Block 1		Block 2		Block 3		Block 1		Block 2		Block 3	
	Quantity $\overline{PG^1_{s,1}}$	Price $\gamma G^1_{s,1}$	Quantity $\overline{PG^1_{s,2}}$	Price $\gamma G^1_{s,2}$	Quantity $\overline{PG^1_{s,3}}$	Price $\gamma G^1_{s,3}$	Quantity $\overline{PG^2_{s,1}}$	Price $\gamma G^2_{s,1}$	Quantity $\overline{PG^2_{s,2}}$	Price $\gamma G^2_{s,2}$	Quantity $\overline{PG^2_{s,3}}$	Price $\gamma G^2_{s,3}$
G1	70	0.071	67	0.077	66	0.087	75	0.020	78	0.036	57	0.108
G2	70	0.035	78	0.081	69	0.088	60	0.023	66	0.028	62	0.105
G3	70	0.010	62	0.076	53	0.085	78	0.026	80	0.036	60	0.102
G4	78	0.004	76	0.067	68	0.092	74	0.012	76	0.024	60	0.107

Generator	MG T3						MG T4					
	Block 1		Block 2		Block 3		Block 1		Block 2		Block 3	
	Quantity $\overline{PG^3_{s,1}}$	Price $\gamma G^3_{s,1}$	Quantity $\overline{PG^3_{s,2}}$	Price $\gamma G^3_{s,2}$	Quantity $\overline{PG^3_{s,3}}$	Price $\gamma G^3_{s,3}$	Quantity $\overline{PG^4_{s,1}}$	Price $\gamma G^4_{s,1}$	Quantity $\overline{PG^4_{s,2}}$	Price $\gamma G^4_{s,2}$	Quantity $\overline{PG^4_{s,3}}$	Price $\gamma G^4_{s,3}$
G1	61	0.114	64	0.138	59	0.142	60	0.107	79	0.134	61	0.144
G2	77	0.105	75	0.124	62	0.152	73	0.113	77	0.134	68	0.148
G3	76	0.107	74	0.123	52	0.151	74	0.102	70	0.122	68	0.145
G4	69	0.110	63	0.136	58	0.155	66	0.119	62	0.138	55	0.150

Note: All quantities data are in kWh, and energy prices are in $/kWh

Table A.2: Demand Biddings in MGs

Demand	MG T1						MG T2					
	Block 1		Block 2		Block 3		Block 1		Block 2		Block 3	
	Quantity	Price	Quantity	Price	Quantity	Price	Quantity	Price	Quantity	Price	Quantity	Price
D1	001.494	000.132	002.150	000.094	004.074	000.065	001.012	000.132	002.003	000.094	003.968	000.065
D2	001.470	000.132	002.982	000.094	003.727	000.065	001.176	000.132	002.286	000.094	004.584	000.065
D3	001.420	000.132	002.801	000.094	003.241	000.065	001.172	000.132	002.260	000.094	003.256	000.065
D4	001.425	000.132	002.946	000.094	003.555	000.065	001.158	000.132	002.294	000.094	004.182	000.065
D5	001.300	000.132	002.595	000.094	004.165	000.065	001.375	000.132	002.945	000.094	003.747	000.065
D6	001.305	000.132	002.144	000.094	004.258	000.065	001.488	000.132	002.663	000.094	004.775	000.065
D7	001.192	000.132	002.410	000.094	003.058	000.065	001.495	000.132	002.713	000.094	004.165	000.065
D8	001.103	000.132	002.252	000.094	004.924	000.065	001.407	000.132	002.745	000.094	003.436	000.065
D9	001.434	000.132	002.788	000.094	004.648	000.065	001.270	000.132	002.678	000.094	004.790	000.065
D10	001.394	000.132	002.397	000.094	004.837	000.065	001.163	000.132	002.381	000.094	003.315	000.065
D11	001.359	000.132	002.760	000.094	004.451	000.065	001.424	000.132	002.345	000.094	003.723	000.065
D12	001.187	000.132	002.955	000.094	003.127	000.065	001.192	000.132	002.518	000.094	004.737	000.065
D13	001.002	000.132	002.588	000.094	003.204	000.065	001.281	000.132	002.236	000.094	004.059	000.065
D14	001.227	000.132	002.432	000.094	003.475	000.065	001.098	000.132	002.757	000.094	004.697	000.065
D15	001.178	000.132	002.569	000.094	003.505	000.065	001.187	000.132	002.515	000.094	003.355	000.065
D16	001.394	000.132	002.675	000.094	004.634	000.065	001.257	000.132	002.233	000.094	003.845	000.065
D17	001.482	000.132	002.750	000.094	003.103	000.065	001.177	000.132	002.567	000.094	004.918	000.065
D18	001.082	000.132	002.816	000.094	003.082	000.065	001.206	000.132	002.408	000.094	004.980	000.065
D19	001.431	000.132	002.278	000.094	004.083	000.065	001.190	000.132	002.081	000.094	003.854	000.065
D20	001.369	000.132	002.918	000.094	004.673	000.065	001.248	000.132	002.700	000.094	003.233	000.065
D21	001.179	000.132	002.224	000.094	003.390	000.065	001.054	000.132	002.279	000.094	003.554	000.065
D22	001.035	000.132	002.677	000.094	003.637	000.065	001.347	000.132	002.730	000.094	004.521	000.065
D23	001.337	000.132	002.867	000.094	003.671	000.065	001.445	000.132	002.913	000.094	004.165	000.065
D24	001.208	000.132	002.394	000.094	003.729	000.065	001.124	000.132	002.435	000.094	003.309	000.065

D25	001.331	000.132	002.450	000.094	003.685	000.065	001.025	000.132	002.143	000.094	003.469	000.065
D26	001.059	000.132	002.352	000.094	004.388	000.065	001.499	000.132	002.643	000.094	004.773	000.065
D27	001.349	000.132	002.271	000.094	003.499	000.065	001.393	000.132	002.436	000.094	004.031	000.065
D28	001.201	000.132	002.728	000.094	004.897	000.065	001.373	000.132	002.362	000.094	003.723	000.065
D29	001.407	000.132	002.388	000.094	004.249	000.065	001.389	000.132	002.766	000.094	004.320	000.065
D30	001.134	000.132	002.557	000.094	003.886	000.065	001.088	000.132	002.709	000.094	003.023	000.065
D31	001.093	000.132	002.484	000.094	003.983	000.065	001.022	000.132	002.542	000.094	003.772	000.065
D32	001.098	000.132	002.735	000.094	003.175	000.065	001.041	000.132	002.049	000.094	003.229	000.065
D33	001.237	000.132	002.869	000.094	004.181	000.065	001.085	000.132	002.241	000.094	003.728	000.065
D34	001.117	000.132	002.361	000.094	004.954	000.065	001.421	000.132	002.853	000.094	003.317	000.065
D35	001.271	000.132	002.935	000.094	003.149	000.065	001.473	000.132	002.282	000.094	003.732	000.065
D36	001.106	000.132	002.861	000.094	004.153	000.065	001.090	000.132	002.946	000.094	003.478	000.065
D37	001.153	000.132	002.684	000.094	003.609	000.065	001.179	000.132	002.123	000.094	004.879	000.065
D38	001.149	000.132	002.311	000.094	003.520	000.065	001.178	000.132	002.974	000.094	003.233	000.065
D39	001.028	000.132	002.300	000.094	003.879	000.065	001.476	000.132	002.522	000.094	004.706	000.065
D40	001.016	000.132	002.488	000.094	003.291	000.065	001.198	000.132	002.031	000.094	004.261	000.065
D41	001.067	000.132	002.714	000.094	004.704	000.065	001.399	000.132	002.861	000.094	003.749	000.065
D42	001.013	000.132	002.573	000.094	003.584	000.065	001.236	000.132	002.487	000.094	004.082	000.065
D43	001.158	000.132	002.519	000.094	004.217	000.065	001.214	000.132	002.250	000.094	004.537	000.065
D44	001.052	000.132	002.299	000.094	003.672	000.065	001.297	000.132	002.603	000.094	003.610	000.065
D45	001.132	000.132	002.239	000.094	003.329	000.065	001.047	000.132	002.164	000.094	004.453	000.065
D46	001.313	000.132	002.792	000.094	003.344	000.065	001.170	000.132	002.407	000.094	003.385	000.065
D47	001.411	000.132	002.877	000.094	003.868	000.065	001.192	000.132	002.333	000.094	004.421	000.065
D48	001.339	000.132	002.202	000.094	003.347	000.065	001.323	000.132	002.352	000.094	004.938	000.065
D49	001.135	000.132	002.778	000.094	003.487	000.065	001.217	000.132	002.847	000.094	004.437	000.065
D50	001.054	000.132	002.629	000.094	003.556	000.065	001.484	000.132	002.984	000.094	004.599	000.065
D51	001.081	000.132	002.918	000.094	004.927	000.065	001.321	000.132	002.493	000.094	004.349	000.065

D52	001.248	000.132	002.926	000.094	003.610	000.065	001.272	000.132	002.484	000.094	003.262	000.065
D53	001.149	000.132	002.364	000.094	004.452	000.065	001.284	000.132	002.102	000.094	004.486	000.065
D54	001.220	000.132	002.417	000.094	003.310	000.065	001.023	000.132	002.240	000.094	004.895	000.065
D55	001.245	000.132	002.026	000.094	003.884	000.065	001.288	000.132	002.963	000.094	004.473	000.065

Demand	MG T3						MG T4					
	Block 1		Block 2		Block 3		Block 1		Block 2		Block 3	
	Quantity	Price	Quantity	Price	Quantity	Price	Quantity	Price	Quantity	Price	Quantity	Price
D1	001.175	000.132	002.170	000.094	003.294	000.065	001.255	000.132	002.512	000.094	003.328	000.065
D2	001.468	000.132	002.563	000.094	003.452	000.065	001.459	000.132	002.641	000.094	003.339	000.065
D3	001.029	000.132	002.732	000.094	003.332	000.065	001.435	000.132	002.946	000.094	004.802	000.065
D4	001.461	000.132	002.257	000.094	003.577	000.065	001.202	000.132	002.547	000.094	003.480	000.065
D5	001.034	000.132	002.622	000.094	003.899	000.065	001.119	000.132	002.549	000.094	004.455	000.065
D6	001.320	000.132	002.688	000.094	003.722	000.065	001.015	000.132	002.839	000.094	004.783	000.065
D7	001.019	000.132	002.984	000.094	004.731	000.065	001.113	000.132	002.249	000.094	003.288	000.065
D8	001.005	000.132	002.555	000.094	004.927	000.065	001.276	000.132	002.707	000.094	003.042	000.065
D9	001.328	000.132	002.634	000.094	003.673	000.065	001.227	000.132	002.338	000.094	004.048	000.065
D10	001.155	000.132	002.938	000.094	004.616	000.065	001.124	000.132	002.799	000.094	004.362	000.065
D11	001.491	000.132	002.968	000.094	003.425	000.065	001.002	000.132	002.461	000.094	003.797	000.065
D12	001.352	000.132	002.610	000.094	004.942	000.065	001.110	000.132	002.877	000.094	004.276	000.065
D13	001.184	000.132	002.428	000.094	003.798	000.065	001.089	000.132	002.371	000.094	004.388	000.065
D14	001.204	000.132	002.778	000.094	003.537	000.065	001.481	000.132	002.877	000.094	003.923	000.065
D15	001.353	000.132	002.018	000.094	004.814	000.065	001.335	000.132	002.272	000.094	003.880	000.065
D16	001.337	000.132	002.082	000.094	004.079	000.065	001.180	000.132	002.058	000.094	004.300	000.065
D17	001.468	000.132	002.576	000.094	004.028	000.065	001.183	000.132	002.152	000.094	004.118	000.065
D18	001.499	000.132	002.724	000.094	004.168	000.065	001.391	000.132	002.121	000.094	004.755	000.065
D19	001.047	000.132	002.053	000.094	004.281	000.065	001.447	000.132	002.033	000.094	004.219	000.065
D20	001.280	000.132	002.688	000.094	004.371	000.065	001.395	000.132	002.282	000.094	004.677	000.065

D21	001.052	000.132	002.483	000.094	004.286	000.065	001.129	000.132	002.967	000.094	004.876	000.065
D22	001.188	000.132	002.470	000.094	004.395	000.065	001.373	000.132	002.745	000.094	003.752	000.065
D23	001.443	000.132	002.267	000.094	003.372	000.065	001.448	000.132	002.528	000.094	004.000	000.065
D24	001.429	000.132	002.921	000.094	004.102	000.065	001.058	000.132	002.130	000.094	003.579	000.065
D25	001.160	000.132	002.824	000.094	003.646	000.065	001.238	000.132	002.239	000.094	004.278	000.065
D26	001.011	000.132	002.490	000.094	003.387	000.065	001.214	000.132	002.500	000.094	004.849	000.065
D27	001.443	000.132	002.630	000.094	004.269	000.065	001.049	000.132	002.163	000.094	004.179	000.065
D28	001.394	000.132	002.540	000.094	004.401	000.065	001.253	000.132	002.994	000.094	003.673	000.065
D29	001.133	000.132	002.150	000.094	003.309	000.065	001.128	000.132	002.707	000.094	004.601	000.065
D30	001.351	000.132	002.883	000.094	003.811	000.065	001.190	000.132	002.633	000.094	004.961	000.065
D31	001.486	000.132	002.245	000.094	004.528	000.065	001.464	000.132	002.068	000.094	003.072	000.065
D32	001.452	000.132	002.782	000.094	003.815	000.065	001.222	000.132	002.208	000.094	003.741	000.065
D33	001.377	000.132	002.475	000.094	004.479	000.065	001.407	000.132	002.058	000.094	003.901	000.065
D34	001.484	000.132	002.364	000.094	003.700	000.065	001.137	000.132	002.774	000.094	003.058	000.065
D35	001.243	000.132	002.348	000.094	003.111	000.065	001.320	000.132	002.015	000.094	003.473	000.065
D36	001.110	000.132	002.931	000.094	004.466	000.065	001.385	000.132	002.767	000.094	003.988	000.065
D37	001.429	000.132	002.860	000.094	004.340	000.065	001.181	000.132	002.794	000.094	003.321	000.065
D38	001.255	000.132	002.047	000.094	004.768	000.065	001.144	000.132	002.358	000.094	003.294	000.065
D39	001.408	000.132	002.317	000.094	004.370	000.065	001.038	000.132	002.628	000.094	004.696	000.065
D40	001.251	000.132	002.652	000.094	004.847	000.065	001.071	000.132	002.778	000.094	004.325	000.065
D41	001.490	000.132	002.613	000.094	004.184	000.065	001.368	000.132	002.280	000.094	003.641	000.065
D42	001.060	000.132	002.000	000.094	004.363	000.065	001.486	000.132	002.863	000.094	004.879	000.065
D43	001.046	000.132	002.160	000.094	003.026	000.065	001.299	000.132	002.061	000.094	004.398	000.065
D44	001.301	000.132	002.849	000.094	003.488	000.065	001.264	000.132	002.967	000.094	004.675	000.065
D45	001.201	000.132	002.287	000.094	003.209	000.065	001.181	000.132	002.897	000.094	004.865	000.065
D46	001.324	000.132	002.297	000.094	004.547	000.065	001.380	000.132	002.667	000.094	003.942	000.065
D47	001.456	000.132	002.375	000.094	003.661	000.065	001.395	000.132	002.096	000.094	003.690	000.065

D48	001.461	000.132	002.418	000.094	003.657	000.065	001.034	000.132	002.250	000.094	004.187	000.065
D49	001.026	000.132	002.967	000.094	003.271	000.065	001.353	000.132	002.447	000.094	004.509	000.065
D50	001.111	000.132	002.103	000.094	003.871	000.065	001.215	000.132	002.211	000.094	003.073	000.065
D51	001.153	000.132	002.469	000.094	004.987	000.065	001.097	000.132	002.186	000.094	004.704	000.065
D52	001.263	000.132	002.685	000.094	004.357	000.065	001.277	000.132	002.141	000.094	003.435	000.065
D53	001.432	000.132	002.636	000.094	003.536	000.065	001.171	000.132	002.778	000.094	003.653	000.065
D54	001.064	000.132	002.076	000.094	003.407	000.065	001.399	000.132	002.136	000.094	004.716	000.065
D55	001.037	000.132	002.763	000.094	004.906	000.065	001.311	000.132	002.874	000.094	003.481	000.065

Note: All quantities data are in kWh, and energy prices are in $/kWh

Appendix B

PR-Focused Ranking Detailed Calculations

Calculations for Round1:

- gain at node h

  $r_{ij}= \begin{bmatrix} h & e & g \\ 1 & 2 & 3 \end{bmatrix}$

  $a_{ij}= \begin{bmatrix} h & e & g \\ 2 & 1 & 3 \end{bmatrix}$

  g_{he}=4+1-2=3

  g_{hg}=6+3-9=0

  $\Rightarrow (e-h)\ \ gain\ \ swap$

- gain at node d

$r_{ij}= \begin{bmatrix} f & c & d \\ 2 & 3 & 1 \end{bmatrix}$

$a_{ij}= \begin{bmatrix} f & c & d \\ 1 & 3 & 2 \end{bmatrix}$

g_{df}=4+1-2=3

g_{dc}=6+3-9=0

$\Rightarrow (d-f)\ \ gain\ \ swap$

- gain at node a

  $r_{ij}= \begin{bmatrix} b & e & g & a \\ 2 & 1 & 4 & 3 \end{bmatrix}$

  $a_{ij}= \begin{bmatrix} b & e & g & a \\ 1 & 2 & 4 & 3 \end{bmatrix}$

  g_{ab}=6+3-2=7

  g_{ae}=3+6-2=7

  g_{ag}=12+12-16=8

  ⇒ no change, as a has lower price than g, and a has a lower rank than g

- gain at node b

  $r_{ij}= \begin{bmatrix} a & c & e & b \\ 3 & 4 & 1 & 2 \end{bmatrix}$

  $a_{ij}= \begin{bmatrix} a & c & e & b \\ 3 & 4 & 2 & 1 \end{bmatrix}$

g_{ba}=3+6-9=0

g_{bc}=4+8-16=-4

g_{be}=1+4-2=3
$\Rightarrow (b-e)$ $gain$ $swap$

Calculations for Round2:

- gain at node d

  $r_{ij}= \begin{bmatrix} c & f & d \\ 3 & 1 & 2 \end{bmatrix}$

  $a_{ij}= \begin{bmatrix} c & f & d \\ 2 & 3 & 1 \end{bmatrix}$

  g_{df}=1+6-3=4

  g_{dc}=3+4-6=1

  $\Rightarrow (d-f)$ $gain$ $swap$

- gain at node b

  $r_{ij}= \begin{bmatrix} a & e & c & b \\ 3 & 2 & 4 & 1 \end{bmatrix}$

  $a_{ij}= \begin{bmatrix} a & e & c & b \\ 2 & 1 & 3 & 4 \end{bmatrix}$

  g_{ba}=12+2-6=8

g_{be}=8+1-2=-7

g_{bc}=16+3-12=7

$\Rightarrow (b-a)\ \ gain\ \ swap$

- gain at node a

  $r_{ij}= \begin{bmatrix} b & e & g & a \\ 4 & 2 & 3 & 1 \end{bmatrix}$

  $a_{ij}= \begin{bmatrix} b & e & g & a \\ 4 & 1 & 3 & 2 \end{bmatrix}$

  g_{ab}=8+4-16=-4

  g_{ae}=8+1-2=7

  g_{ag}=6+3-9=0

  $\Rightarrow (a-e)\ \ gain\ \ swap$

Calculations for Round3:

- gain at node c

  $r_{ij}= \begin{bmatrix} b & d & c \\ 2 & 1 & 3 \end{bmatrix}$

  $a_{ij}= \begin{bmatrix} b & d & c \\ 2 & 1 & 3 \end{bmatrix}$

  g_{cb}=2+6-4=1

  g_{cd}=1+9-3=7

$\Rightarrow (c-d)$ *gain swap*

- gain at node a

$r_{ij}= \begin{bmatrix} b & e & g & a \\ 3 & 1 & 4 & 2 \end{bmatrix}$

$a_{ij}= \begin{bmatrix} b & e & g & a \\ 4 & 3 & 2 & 1 \end{bmatrix}$

g_{ab}=3+8-12=-1

g_{ae}=1+6-3=4

g_{ag}=4+4-8=0

$\Rightarrow (a-e)$ *gain swap*

- gain at node h

$r_{ij}= \begin{bmatrix} e & g & h \\ 1 & 2 & 3 \end{bmatrix}$

$a_{ij}= \begin{bmatrix} e & g & h \\ 3 & 2 & 1 \end{bmatrix}$

g_{he}=1+9-3=7

g_{hg}=2+6-2=4

$\Rightarrow (h-e)$ *gain swap*

Calculations for Round4:

- guaranteed swap c-d

- guaranteed swap d-f
- guaranteed swap f-h
- gain at node h

  r_{ij}= $\begin{bmatrix} e & g & h \\ 1 & 3 & 2 \end{bmatrix}$

  a_{ij}= $\begin{bmatrix} e & g & h \\ 3 & 2 & 1 \end{bmatrix}$

  g_{he}=1+6-3=4

  g_{hg}=3+4-6=1

  $\Rightarrow (h - e) \ \ gain \ \ swap$

- gain at node g

  r_{ij}= $\begin{bmatrix} a & h & g \\ 1 & 2 & 3 \end{bmatrix}$

  a_{ij}= $\begin{bmatrix} a & h & g \\ 3 & 1 & 2 \end{bmatrix}$

  g_{ga}=2+9-3=8

  g_{gh}=4+3-2=5

$\Rightarrow (g - a) \ \ gain \ \ swap$

B.0.1 Different Initial Qi

Here, the MGs have been assigned new numbers (Qi) and the PR-focused ranking algorithm has been executed again. Table B.1 and Table B.2 show the Q swapping for two different cases. The results indicate that even if the initial numbers change, the selected MGs (Q=1 and Q=2) remain the same to generate offers. This yields precisely the same energy trading results.

Table B.1: PR-Focused Q Swapping (case1)

Time →

Microgrid Name	Node code	Qi-Initiation	Qi-gain swab (b-c)	Qi-gain swab (e-h)	Qi-gain swab (g-h)	Qi-gain swab (h-e)	Qi-gain swab (e-f)		Qi-gain swab (b-e)	Qi-gain swab (d-f)	Qi-gain swab (b-a)		Qi-gain swab (c-d)	Qi-gain swab (a-e)	Qi-gain swab (h-e)		Qi-gain swab (a-g)	Qi-gain swab (g-h)	Qi-Guaranteed swap (c-b)	Qi-Guaranteed swap (b-a)	Qi-Guaranteed swap (a-g)	
T4 ID1	a	6	6	6	6	6	6	Offers #1 starts	6	6	3	Offers #2 starts	3	1	1	Offers #3 starts	8	8	8	2	3	Offers #4starts
T2 ID2	b	7	1	1	1	1	1		3	3	6		6	6	6		6	6	2	8	8	
T3 ID1	c	1	7	7	7	7	7		7	7	7		2	2	2		2	2	6	6	6	
T1 ID1	d	4	4	4	4	4	4		4	2	2		7	7	7		7	7	7	7	7	
T1 ID2	e	8	8	5	5	2	3		1	1	1		1	3	5		5	5	5	5	5	
T2 ID1	f	3	3	3	3	3	2		2	4	4		4	4	4		4	4	4	4	4	
T3 ID2	g	2	2	2	8	8	8		8	8	8		8	8	8		1	3	3	3	2	
T4 ID2	h	5	5	8	2	5	5		5	5	5		5	5	3		3	1	1	1	1	

Table B.2: PR-Focused Q Swapping (case2)

Time →

Microgrid Name	Node code	Qi-Initiation	Qi-gain swab (b-c)	Qi-gain swab (e-a)	Qi-gain swab (d-c)	Qi-gain swab (f-e)	Qi-gain swab (h-e)	Qi-gain swab (g-h)	Qi-gain swab (e-h)		Qi-gain swab (b-e)	Qi-gain swab (d-f)	Qi-gain swab (b-a)		Qi-gain swab (c-d)	Qi-gain swab (a-e)	Qi-gain swab (h-e)		Qi-gain swab (a-g)	Qi-gain swab (g-h)	Qi-Guaranteed swap (c-b)	Qi-Guaranteed swap (b-a)	Qi-Guaranteed swap (a-g)	
T4 ID1	a	2	2	6	6	6	6	6	6	**Offers #1 starts**	6	6	3	**Offers #2 starts**	3	1	1	**Offers #3 starts**	8	8	8	2	3	**Offers #4starts**
T2 ID2	b	5	1	1	1	1	1	1	1		3	3	6		6	6	6		6	6	2	8	8	
T3 ID1	c	1	5	5	7	7	7	7	7		7	7	7		2	2	2		2	2	6	6	6	
T1 ID1	d	7	7	7	5	5	5	5	5		5	2	2		7	7	7		7	7	7	7	7	
T1 ID2	e	6	6	2	2	8	4	4	3		1	1	1		1	3	4		4	5	5	5	5	
T2 ID1	f	8	8	8	8	2	2	2	2		2	5	5		5	5	5		5	4	4	4	4	
T3 ID2	g	3	3	3	3	3	3	8	8		8	8	8		8	8	8		1	3	3	3	2	
T4 ID2	h	4	4	4	4	4	8	3	4		4	4	4		4	4	3		3	1	1	1	1	