VOL. 24, NO. 2, 2025, 157-166
elektrika.utm.my
ISSN 0128-4428

ELEKTRIKA
Journal of Electrical Engineering

Auction-Based Energy Trading with Community Energy Storage in Standalone DC Microgrids

Nor Ashbahani Mohamad Kajaan[1,2*], **Md Pauzi Abdullah**[1,3], **Raja Zahilah Raja Mohd Radzi**[4] and **Aminudin Anuar**[1,2]

[1]Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor.
[2]Faculty of of Electrical Engineering & Technology, Universiti Malaysia Perlis, 02600 Arau, Perlis.
[3]Centre of Electrical Energy Systems, Institute of Future Energy, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor.
[4]Faculty of Computing, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor.

*Corresponding author: norashbahani@graduate.utm.my

Abstract: The transition to renewable energy systems has emphasized the need for efficient and decentralized energy management strategies. This paper presents an energy trading framework for standalone DC microgrids, integrating community energy storage (CES) and different types of single-sided auction mechanisms. In this framework, households equipped with solar photovoltaic (PV) systems and energy storage units interact with CES as the central trading entity, eliminating direct peer-to-peer transactions. The study aims to identify the clearing price and examined the suitability of three single-sided auction types: Uniform Price Auction (UPA), Generalized Second Price Auction (GSPA) and Pay-as-Bid Auction (PABA). A MATLAB/Simulink-based simulation evaluates the performance of the system, using 24 hours energy generation and consumption profiles for 10 house nodes. Results demonstrate that CES effectively balances energy supply and demand, while auction mechanisms enable fair and efficient market operations. Each auction type exhibits distinct pricing and allocation characteristics, offering flexibility in diverse market conditions. This study highlights the potential of energy trading with different auction types to improve energy management, maintain system stability and encourage renewable energy utilization for standalone microgrid systems.

Keywords: Auction Mechanism, Community Energy Storage, DC Microgrids, Energy Trading, Standalone System

Article History: received 2 December 2024; accepted 25 June 2025; published 31 August 2025

1. BACKGROUND

In recent years, global energy sector transformations have emerged more rapidly than ever before, largely due to technological advancements and shifting environmental priorities. For instance, the widespread adoption of distributed energy resources (DERs), such as solar photovoltaic (PV) systems and battery storage, is altering traditional power distribution models, creating both opportunities and challenges. According to the International Renewable Energy Agency (IRENA) [1], the global renewable energy capacity increased by approximately 10% from 2019 to 2022, driven by commitments to reduce greenhouse gas emissions and transition to a low-carbon economy. In line with this trend, the European Union has established ambitious climate and energy objectives, targeting a 32% renewable share, a 40% reduction in greenhouse gas emissions and a 32.5% improvement in energy efficiency by 2030 [2].

This substantial growth in renewables, including rooftop solar panels, energy storage systems (ES), electric vehicles (EV) and small-scale wind turbines, is transforming the traditional unidirectional power grid into a bidirectional, smart grid model [3]. Conventionally, electricity was generated at large power plants, transmitted over extensive networks, and supplied to end-users at a fixed rate. However, a smart grid enables the multidirectional flow of electricity, allowing energy generation at the distribution level, which mitigates the need for long-distance transmission lines and fixed-rate distribution networks. The integration of advanced information and communication technology (ICT) within the smart grid framework plays a crucial role in facilitating efficient electricity distribution [4].

The concept of energy trading offers another viable option for managing surplus energy flows and achieving a balance between supply and demand in the grid. Individual users in the community can trade electricity directly with others in the community, meeting energy demand through locally produced surplus energy [5]. If a community lacks surplus energy, peers can request additional energy from the main grid. The energy trading concept, gaining traction particularly with the increase in rooftop solar adoption, has been actively explored since 2007 to foster decentralized and community-based energy systems [6]. End-users in these decentralized grids can now actively manage their energy consumption, though forecasting user behavior remains challenging due to the variable nature of renewable resources and the intermittent supply from DERs. This evolving model transforms traditional consumers into prosumers, by managing multiple renewable sources or distributed PV [7].

A prosumer is a consumer capable of generating energy using a DER within their premises and trading excess energy with other consumers in a distribution network [8]. Prosumers can either sell surplus energy to nearby consumers or feed it back into the main grid, incentivized by financial rewards from other consumers within the network [9]. The combination of prosumers and traditional consumers forms a local energy community (LEC), creating a more flexible and interactive energy market ecosystem. The rise of prosumers highlights one of the most exciting trends in renewable energy. They can now control and manage their usage and generation. This perspective has brought new opportunities and challenges to the power systems. However, existing distribution networks are not designed to manage the reverse power flows associated with the rise of DERs, which can lead to stability issues such as increasing the bus voltage levels. To mitigate these challenges, various solutions have been explored, including energy storage sharing. Community energy storage (CES) can provide economic advantages by enabling energy trading within the community, where trading prices often become more favorable than standard grid tariffs [10], [11].

Auction-based methods are effective for market clearing in local energy trading, functioning as structured negotiation mechanisms where the process is managed by an intermediary that may be an automated set of rules rather than an actual agent. Various characteristics in auctions and can be classified according to specific features. In electricity markets, the most recognized auctions are single-sided, involving bids solely from buyers. Other models, such as double-sided auctions, enable both buyers and sellers to participate, making them particularly suited to energy markets [12].

A single-sided auction in energy trading involves one party, typically the sellers, submitting bids to sell energy, while the market or a centralized entity determines the clearing price based on these bids. Buyers do not actively participate in setting the price, which simplifies the trading process and helps achieve market equilibrium. This type of auction is often used in power markets and microgrids, where sellers aim to maximize revenue by offering surplus energy. The central entity or grid operator clears the market, ensuring a stable transaction, often improving efficiency in energy distribution while minimizing market complexity and volatility. The auctioneer or market operator then processes these bids to establish a market-clearing price, aligning supply with demand to complete the trading process [13]. The gap between the bid and selling prices, reflecting price sensitivity, is constrained within predefined limits, including a maximum (ceiling) and minimum (floor) price. These thresholds are set based on the minimum feed-in tariff payable by the utility to prosumers and the maximum tariff rate charged by the distribution company to consumers, ensuring price stability and market efficiency.

2. RELATED WORK AND CONTRIBUTION

Existing schemes of energy trading rely on the connection to utility supplier or main electricity grid. This is known as peer-to-grid (P2G) energy trading. With P2G system, prosumers with individual battery storage system or ESS will manage their own generations and consumptions. When there is deficient energy from build-in RES and storage system, purchasing energy from the utility will take place while when there is surplus energy, utility grid will buy from the prosumers. To enable this, every node in the microgrid will share the connection to the main grid. Each node with different energy consumption leads to stochastic power drawn from the bus and causes large fluctuation in the power system. For example, EV charging stations. Despite the fact that this concept been widely used by researcher [14], instantaneous and intermittency in output power presenting a crucial issue in electricity grid system. Bulk and efficient energy storage units are required to cope with the temporary mismatch between generation and electricity usage [15].

One of the interests within the distribution systems is the possible local electricity exchange directly between customers and prosumers. The transactions and power exchange process within the participants in the distributed microgrid system is known as Peer-to-Peer (P2P) energy trading. The main goal of P2P energy trading is to break the centralized system of electricity grid infrastructure by enabling direct communication and energy supply and demand among various prosumers with DER [16]. To establish the P2P, it involves not only electrical connection between prosumers but also sharing information among them [17]. The future grid system envisaged to be distributed consists of local generation with local storage, as well as sophisticated energy trading system. Recent studies [18], [19] have emphasized the importance of integrating structured market mechanisms, such as auction-based models, to enhance the efficiency, fairness and scalability of P2P energy trading in DER-based environments. These mechanisms provide a systematic approach to match supply and demand while incentivizing active participation from prosumers. In particular, single-sided auction models have gained attention due to their suitability for community microgrids and localized energy exchanges. The adoption of such mechanisms has been shown to improve energy allocation, promote transparent pricing and support decentralized market operations [20]. These contributions further validate the significance of auction-based strategies in achieving a more resilient and autonomous energy trading framework.

In energy trading markets, auction mechanisms have become essential tools for establishing efficient and economically viable exchanges between energy buyers and sellers. A widely used structure in these markets is the single-sided auction, where only one side—typically the sellers or buyers participates in bidding, while the other side accepts the price determined by the market. This approach simplifies the trading process by reducing the complexity associated with bid matching and market clearing and is often implemented in regulated power markets or grid-tied microgrids [21]. For example, in a study focused on the single-sided auction model in a microgrid environment, a bidding algorithm was introduced to optimize the seller's bids, showing that single-sided auctions can increase profit margins by establishing a structured bidding framework [22]. Similarly, another study examined single-sided auctions in deregulated power systems, where suppliers seek to maximize profits through optimized bid quantities while operating within a centralized pool, ultimately setting the market clearing price [23].

This paper introduces an energy trading model where energy transactions occur only between individual house (node) and a CES system, rather than through direct P2P exchanges. In this setup, each house has the option to either sell surplus energy to the CES or purchase energy from it to meet demand, with the CES serving as the primary intermediary. This model offers unique advantages by centralizing energy exchanges, which enhances market stability and simplifies management of the microgrid infrastructure. Unlike double-sided auctions commonly used in peer-to-peer trading where both buyers and sellers actively set prices [12], the CES-centric approach consolidates trading into a single-sided structure with CES as the central node. This configuration minimizes market complexity and provides a more resilient platform for balancing supply and demand within a standalone network, effectively utilizing the CES to stabilize the energy flow and facilitate efficient trading dynamics [24].

A single-sided auction-based market clearing approach is presented, uniquely designed to facilitate energy trading by allowing sellers to submit bids through a structured platform, while the market determines a fair clearing price. This approach satisfies both sellers and buyers by simplifying the transaction process and ensuring market stability. A review of the most recognized types of single-sided auctions is conducted to identify critical features, guiding the selection of an effective auction mechanism tailored to this energy market model. Key indices are established to benchmark the proposed mechanism against other auction types. The primary contributions of this paper include the following parts:

- Propose a standalone local market community for energy trading directly with CES.
- Design a single-sided auction approach for market clearing in the proposed framework.
- Compare the performance of the designed auction with different types of single-sided auctions for market clearing in the proposed framework.

The remainder of this paper is organized as follows: Section 3 details the methodology, including the system modelling, energy generation and consumption patterns for the standalone system. Section 4 describes the energy trading framework including auction mechanism. Section 5 presents the simulation results and analysis for the proposed trading system. Finally, Section 5 conclude the findings, implications for energy management in microgrids and potential directions for future research.

3. SYSTEM MODEL

3.1 This research focuses on implementing a distributed
3.1 DC microgrid architecture with multiple
3.1 interconnected nodes in a straightforward,
3.1 decentralized configuration that supports local
3.1 renewable generation and consumption in a fully
3.1 standalone setup. Each node within the microgrid is
3.1 equipped with a solar photovoltaic (PV) system,
3.1 serving as the primary renewable energy source. The
3.1 objective of this design is to construct an efficient
3.1 and resilient network in which solar PV arrays
3.1 operate as distributed generators, capable of
3.1 supplying surplus energy to adjacent nodes as
3.1 needed. For modelling the system, the proposed
3.1 stand-alone residential house model as shown in
3.1 Figure 1 is introduced. It incorporates the house
3.1 nodes, known as peer, comprise of individual solar
3.1 PV, local energy storage and a household. All house
3.1 nodes are connected to one shared community
3.1 battery, CES. This model is intended to represent a
3.1 generalized urban residential community, aligning
3.1 with smart energy trends in cities. The load profiles
3.1 used are independently generated based on typical
3.1 urban households.**House Nodes (Peer)**

A peer refers to either an individual user or a group of users within a community who engage in direct electricity trading with another peer. Within a distribution network, peers can act as consumers or prosumers, where prosumers not only consume energy but also generate it, typically from distributed renewable sources like solar PV. Depending on the balance between local solar PV generation and household energy usage, prosumers prioritize their own energy needs and can offer any surplus to other users within the network. Energy trading within house nodes or peer supports decentralized, flexible energy exchanges that enhance grid resilience and consumer autonomy, while reducing transmission losses and balancing local supply and demand. This research simulates an energy trading system among 10 house nodes as prosumers and each house equipped with a solar panel, energy storage units and household loads. A single residence comprises rooftop solar PV panel arrays, a storage system and household loads. The simulation framework captures hourly variations in energy generation, consumption and storage across all nodes. Energy storage levels are updated hourly based on the amounts of energy generated, consumed and traded. The simulation for this work is conducted by using MATLAB/Simulink software, modelling different patterns of energy consumption and simulated PV profiles over a 24-hour period. The energy generation for each house is

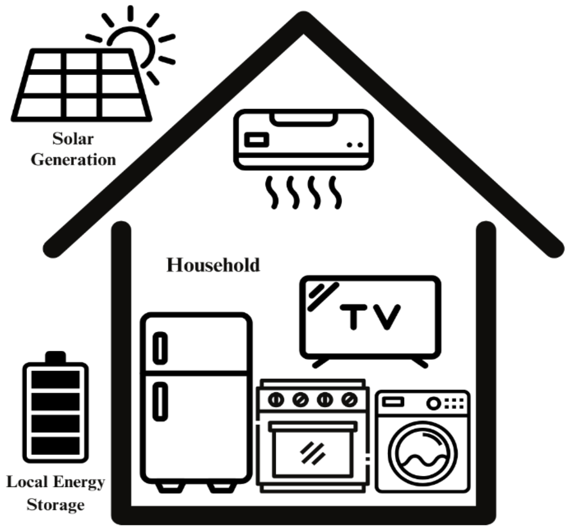


Figure 1. A single residential house for energy trading in

a standalone system

modelled based on a general distribution representing solar output power. The simulation defines two solar generation periods, low generation and high generation period. The energy generation profile has been designed to mimic real solar energy production around the world, where energy output is highest during midday and tapers off in the early morning and late evening [25]. This approach ensures that the simulation captures the typical daily variation in solar energy availability.

Effective energy storage mechanisms are essential for maintaining equilibrium between supply and demand within a microgrid. House generating surplus energy can store the excess, while those experiencing deficits can utilize their stored reserves. This promotes efficient energy distribution, minimizing waste and optimizing overall usage. The simulation calculates the energy storage, consumptions and availability for each house on an hourly basis. Equation (1) shows for each hour (t), the energy storage $E_s(t)$ is updated based on the previous hour's generation $E_g(t-1)$ and consumption $E_c(t-1)$. The storage levels are kept within the bounds of 0 to the storage capacity, *C*.

$$E_s(t) = \min\left(\max\begin{pmatrix} E_g(t-1) + E_s(t-1) \\ -E_c(t-1), 0 \end{pmatrix}, C\right) \quad (1)$$

The energy balance $E_b(t)$ for each house is calculated as the sum of energy generation and storage minus energy consumption as in (2).

$$E_b(t) = E_g(t) + E_s(t) - E_c(t) \quad (2)$$

Different load profiles are defined by assuming the energy consumptions pattern for each house reflect typical household usage, as study case in [26]. These patterns ensure a realistic simulation of varying energy needs throughout the day for all houses. These consumption patterns are designed to reflect diverse household behaviours and ensure that the simulation encompasses a wide range of energy demand scenarios [27]. Energy usage patterns more likely on weekends, where residents have higher and more variable energy demands throughout the day, contrasting with the more predictable and lower consumption patterns typical of weekdays when occupants might be away at work or school. This observation underlines the importance of considering different daily usage patterns in the design and implementation of P2P energy trading systems to ensure they can adapt to varying residential behaviours effectively.

3.2 Community Energy Storage

Community Energy Storage (CES) systems offer a strategic solution for managing surplus energy within the LECs. By allowing prosumers to store excess electricity generated from distributed solar photovoltaic (PV) systems, CES mitigates the challenges associated with exporting (sell) surplus energy to the main grid. As the surplus energy declines during night-time and demand increases, the reliability of energy trading within the LEC using distributed solar PV also decreases. Hence, consumers need to take (buy) electricity from the CES or grid to satisfy their energy demand. As the adoption of distributed solar PV increases, energy exports during peak generation periods can lead to grid imbalances and peak contingencies, incurring additional system costs. Moreover, export tariffs are often lower than the cost of purchasing energy, making self-consumption or P2P trading more economically advantageous for prosumers.

CES enables prosumers to store surplus energy and either use it during periods of low generation or trade it within the community, thereby enhancing energy self-sufficiency and reducing reliance on the main grid. This approach not only optimizes the utilization of locally generated renewable energy but also contributes to grid stability by alleviating the stress caused by large-scale energy exports. Additionally, CES facilitates better trading conditions within the community, as the value of self-consumed or P2P-traded solar electricity often surpasses the benefits of exporting electricity to the grid. By integrating CES into LECs, prosumers can achieve greater economic returns and contribute to a more resilient and efficient energy system.

4. ENERGY TRADING FRAMEWORK

4.1 Peer to CES Architecture

The proposed energy trading framework, depicted in Figure 2, is organized into two distinct layers: the physical layer and the virtual layer. Sellers are prosumers who both produce and consume energy that generate surplus energy and aim to maximize their revenue by trading this excess in the market. Buyers, who are also a prosumer, participate in the market to fulfil their energy demand when their own generation is insufficient. In this framework, energy trading is structured to occur directly between individual households and the CES, establishing CES as the central trading entity. Each house can either sell excess generated energy to the CES or purchase additional energy from it to meet their own consumption needs. This design facilitates a controlled and balanced flow of energy within the network, where CES acts as a stabilizing agent, absorbing surplus energy from prosumers during periods of low household demand and supplying energy back to them during high-demand intervals. By positioning the CES as the primary trading partner, the framework ensures that each household can effectively manage its energy surplus and deficit without requiring direct P2P transactions between individual houses.

This approach enhances the operational stability of the microgrid by centralizing storage and distribution, thereby simplifying energy management, optimizing storage utilization, and supporting a seamless and efficient energy exchange within the standalone network.

4.1.1 Physical Layer

The physical layer represents the tangible elements involved in the trading process, including generation units (solar panels), storage components (batteries and CES), electrical distribution equipment necessary for energy transfer, metering and communication infrastructure. By integrating smart meters at these connection points, the performance of the P2P network can be assessed, particularly in terms of energy efficiency and cost savings [16]. This layer forms the backbone of the energy flow and ensures that physical transactions can be executed efficiently and reliably.

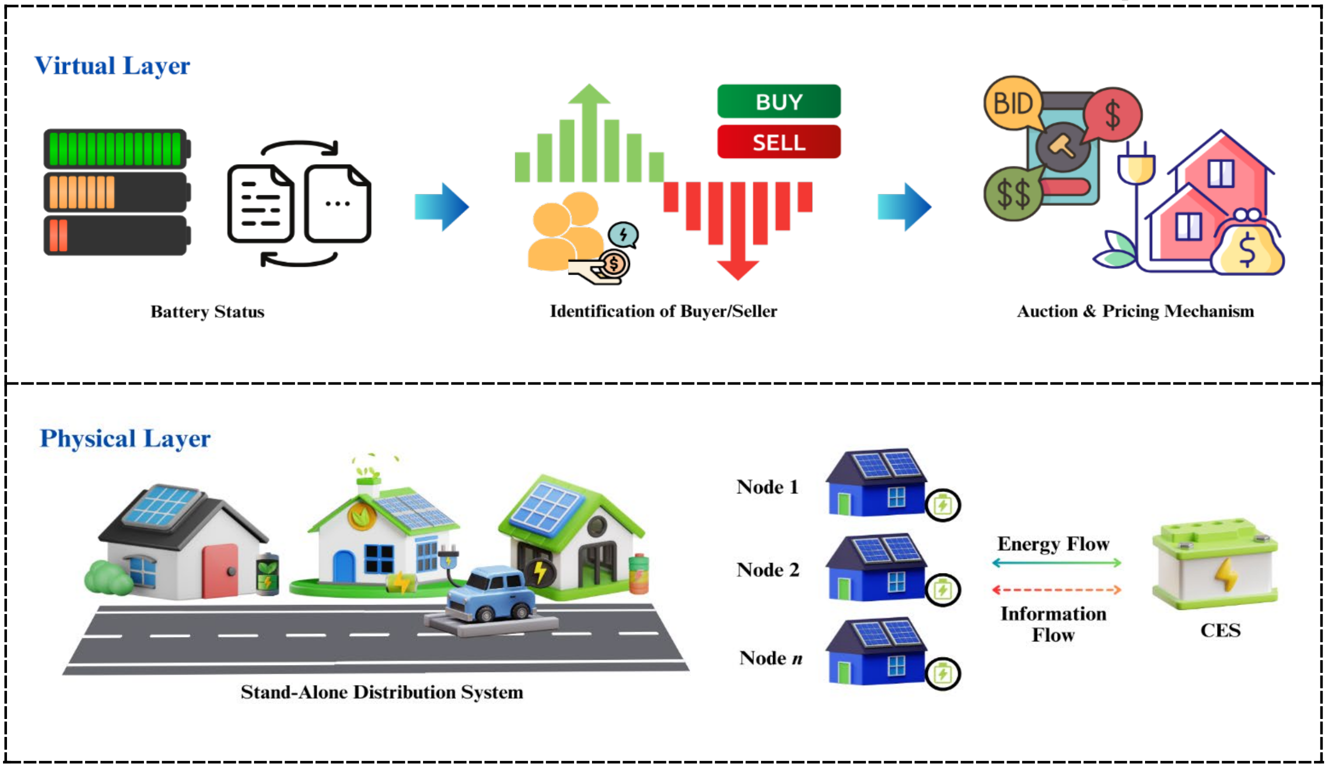


Figure 2. Two main layers in the proposed energy trading framework

4.1.2 Virtual Layer

While the virtual layer facilitates the coordination, communication, and management of energy transactions between participants. This layer operates as the "digital" or "communication" backbone, enabling secure data exchange, real-time monitoring, and the enforcement of trading rules and agreements among buyers, sellers with the CES. It also supports the use of automated trading algorithms and digital platforms, ensuring that each participant's objectives such as maximizing revenue for sellers and minimizing costs for buyers, are optimally managed.

4.2 Auction Mechanism

This study explores the application of auction mechanisms for market clearing and establishes the price and quantity of energy traded between buyers and sellers. A one side or single-sided auction is applied to clear the market. A single side auction is a widely used market clearing strategy where only one side of the market, typically buyers or sellers, submits bids or offers for price and quantity in the energy market [28]. The auction mechanism resolves these bids or offers into a market-clearing price and quantity, ensuring efficient matching between supply and demand, and communicates the results to the participants[29].

This section presents a detailed methodology for implementing single-sided auction types in energy trading systems, that are Uniform Price Auction (UPA), Generalized Second Price Auction (GSPA) and Pay-as-Bid Auction (PABA), has been utilized in previous studies for market clearing [28]-[30]. This approach incorporates the stages of Bidding Process & Market Clearing, Price Determination and Energy Allocation. Each auction mechanism provides a different approach to managing energy market dynamics, ensuring flexibility and adaptability in diverse market conditions.

4.2.1 Different Types of Single-Sided Auction

In the Uniform Price Auction (UPA), all participants are charged the same price for the energy they trade, which is determined based on the aggregate demand and supply in the market. Next is the Generalized Second Price Auction (GSPA) is commonly used in markets where multiple units of energy are being auctioned. This auction format determines the clearing price as the second-highest bid rather than the highest, thereby encouraging truthful bidding and reducing strategic bidding manipulations. In the Pay-as-Bid Auction (PABA), each participant pays exactly the price they bid for the energy, which encourages participants to bid according to their true willingness to pay or accept.

4.2.2 Bidding Process & Market Clearing

In UPA type, both buyers and sellers submit their bids and asks respectively. Buyers indicate the maximum price they are willing to pay, while sellers specify the minimum price at which they are willing to sell energy. The auctioneer collects all bids and asks, then ranks them to identify the demand and supply curves. These curves are combined to determine the point at which the quantity of energy demanded matches the quantity of energy supplied. This clearing point establishes the overall market equilibrium.

Similar to UPA, buyers submit bids and sellers submit asks, but the distinction lies in the ranking process. The auctioneer ranks all the bids and asks in descending order for buyers and ascending order for sellers. The market clearing occurs when the total demand from buyers meets the total supply from sellers, with the aim of matching energy demand with available supply at the best price.

In PABA, buyers submit their bids specifying the price they are willing to pay for energy, and sellers submit their asks specifying the price at which they are willing to sell. The auctioneer collects all bids and asks, ranking them from highest to lowest for buyers and from lowest to highest for sellers. Market clearing occurs when the total quantity demanded by the buyers matches the total quantity supplied by the sellers. The energy transaction is carried out directly between the matched buyer and seller based on their respective bids.

4.2.3 Price Determination

The price for the UPA is determined by the mid-market value of clearing price, which is the price at the arithmetic mean of the bid price from the seller or buyer. This price is uniform for all participants meaning that all buyers pay the same price, and all sellers receive the same price for the energy traded. Mathematically, the clearing price p_c is denoted as Equation (3).

$$D(p_c) = S(p_c) \tag{3}$$

It is the point where $D(p_c)$ is the total energy demanded at price p_c and $S(p_c)$is the total energy supplied at that price during energy trading.

The clearing price in a GSPA is determined as the second-highest price from the submitted bids. Buyers submit bids indicating the maximum price they are willing to pay for energy. These bids are arranged from highest to lowest price. The highest bidder secures the first unit of energy and pays a price equal to the bid of the second-highest bidder; the second-highest bidder obtains the next unit and pays the bid of the third-highest bidder, and this pattern continues accordingly. Sellers receive the prices paid by the buyers, where each seller is compensated based on the price determined by the corresponding buyer's position in the ranking. This mechanism encourages buyers to bid on their true valuations, helps mitigate the potential for overpaying by reducing the incentives for bidders to inflate their offers to influence the clearing price. In this auction, the price p_c is calculated as the second-highest bid from the ranked list of offers:

$$p_c = b_{i+1} \; for \; i = 1,2 \ldots, N-1 \tag{3}$$

The price in a PABA is not determined by a uniform or second-highest price mechanism. Instead, each buyer pays the price they bid, p_b and each seller receives the price they ask, p_s. This results in a direct link between the bidder's price and the amount of energy they are willing to trade. The price determination process ensures that participants will be rewarded according to their true valuation of energy, leading to less price distortion compared to other auction types. If buyer i and seller j are matched, the transaction occurs at the prices as in Equation (4).

$$p_b = p_s \tag{4}$$

Where p_b is the buyer's bid price and p_s is the seller's ask price.

4.2.4 Energy Allocation

Once the clearing price is determined, the auction allocates energy to the buyers and sellers. Energy is allocated such that the total energy demand and supply are balanced and each participant receives the energy they requested. The energy traded in UPA mechanism is then settled at the uniform price p_c, ensuring fairness and efficiency. In GSPA, the allocation of energy is made by matching buyers and sellers based on the bids that are above or below the clearing price. The energy is allocated such that each buyer pays the second-highest price and each seller receives the second-highest price. This ensures that energy is exchanged at a price that reflects the true value of the energy while preventing overpricing and maintaining market efficiency.

The allocation of energy in PABA is straightforward. The energy exchanged between buyers and sellers is based on their matched bids and also depends on the amount each participant is willing to buy or sell at the agreed price. Once the bids and asks are matched, each participant receives the amount of energy they requested, and the transaction is settled at the price they bid. This mechanism is simple but may lead to inefficiencies in cases where the market is highly competitive or where strategic bidding behaviors arise.

4.3 Input Data

In this paper, the framework and auction mechanisms are established with 10 houses as participants (prosumers) in the energy market trading. The energy generation for each house is modelled based on a general distribution representing solar output power. PV generation is simulated for 24 hours where peak generation reaches around 5 kWh at noon. Different load profiles are defined by assuming the energy consumptions pattern for each house reflect typical household usage [25]. These patterns ensure a realistic simulation of varying energy needs throughout the day for 10 houses. These consumption patterns are designed to reflect diverse household behaviors and ensure that the simulation encompasses a wide range of energy demand scenarios. Energy usage patterns more likely on weekends, where residents have higher and more variable energy demands throughout the day, contrasting with the more predictable and lower consumption patterns typical of weekdays when occupants might be away at work or school. This observation underlines the importance of considering different daily usage patterns in the design and implementation of P2P energy trading systems to ensure they can adapt to varying residential behaviors effectively.

Each house will participate in the market as buyers or sellers based on their state of charge (SOC), with buyers identified when SOC is less than 30% and sellers when SOC is more than 80%. A CES is assumed to have infinite capacity, absorbing surplus energy or supplying energy during deficits.

5. RESULTS AND DISCUSSION

5.1 Generations and Consumptions of House Nodes

In this section, the numerical results for the energy trading with auction mechanism between peers and CES are presented. As shown in Figure 3, all houses demonstrate the same solar energy generation profile, peaking around noon and exhibits no generation at night. Different load profiles for 10 houses are illustrated in Figure 4. The dataset used is in one day duration, where generation data is only available during the daytime due to the nature of solar rooftop and the load profiles of all the peers and is over 24 hours. A house will first meet their demand and then sell the surplus energy with CES, depending on the energy difference between distributed solar PV generation and household energy consumption. A house can also act as a buyer at a specific time interval if the energy generated is less than the energy demand and buys energy from the CES.

The tariff at which buyers purchase energy from the CES, as well as the export price at which sellers sell energy to the CES, is assumed to be RM0.40/kWh. This reflects the pricing model applied in prior literature [31] and is consistent with the national pilot project for P2P energy trading by SEDA Malaysia [32]. However, the actual rates may vary depending on region and time.

To complement the visual trends presented in Figure 4, Table 1 summarizes the minimum, maximum and average hourly energy consumption for each house over the 24 hours simulation period. This tabular representation provides a statistical overview of household load variations and highlights the diversity in energy usage across different prosumers. Notably, House 1 and 4 demonstrate the highest average demand, while House 6 shows the lowest, indicating distinct consumption patterns that influence their roles as buyers or sellers in the energy trading system. This comparison supports the trading behaviors observed under different auction mechanisms.

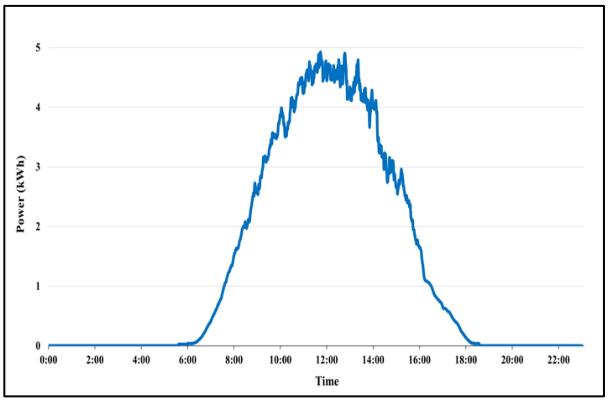


Figure 3. Hourly solar PV generation profile in a sunny day

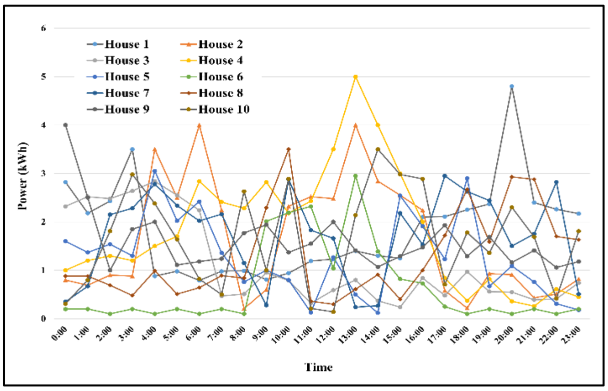


Figure 4. Hourly demand and consumption profile for 10 house nodes in 24 hours

Table 1. Table shows a summary of hourly load patterns across the 10 houses

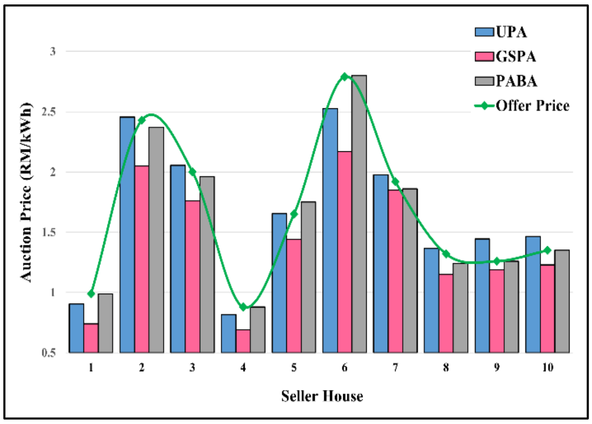
Energy Market Player	Min (kWh)	Max (kWh)	Average (kWh)
House 1	0.79	4.80	1.84
House 2	0.21	4.00	1.65
House 3	0.24	2.84	1.15
House 4	0.26	5.00	1.84
House 5	0.12	3.05	1.28
House 6	0.10	2.95	0.67
House 7	0.24	2.95	1.72
House 8	0.30	3.50	1.30
House 9	1.00	2.50	1.60
House 10	0.14	3.50	1.65

5.2 Pricing for Auction Mechanism

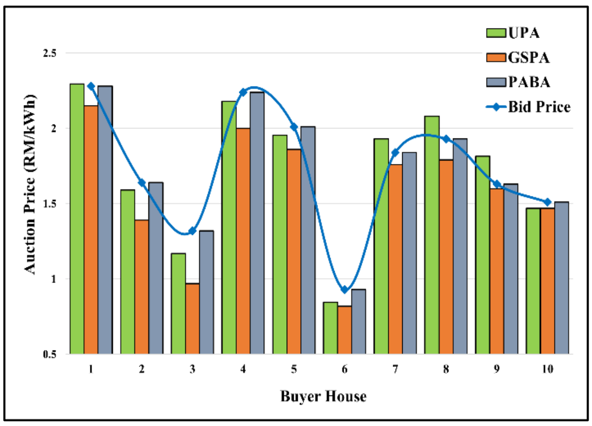
Figure 5(a) and (b) shows the price determination process of sellers and buyers across all three types of auction mechanism in payment schemes. Looking into the performance of specific houses as sellers and buyers reveals interesting trends in energy trading. Certain houses demonstrate a strong preference for selling energy, while others appear more active as buyers. For instance, House 6 consistently participates more as a seller, often paying higher prices when acting as a buyer but make profits due to their engagement in seller market. This may be due to it have better energy storage system and low load profile, allowing it to regularly sell surplus energy into the market while minimizing energy purchases. Meanwhile, houses 1 & 4 show more activity relative to buying, indicating a reliance on external energy supply. Interestingly, houses as 5 & 7 experienced balanced trends, participating equally as sellers and buyers. This could indicate efficient energy management strategies, where energy is sold during periods of surplus and purchased during periods of shortage. This ensures that both cost efficiency and energy reliability are maintained.

UPA mechanism ensure that all sellers and buyers obtain an equal market clearing price, regardless of their respective offers or bids. This regularity advantages of low offer price, who receive payment more than their offer price, but sellers with higher offer price may obtain marginally less than their asking price. This uniformity also benefits buyers with higher bids, as they pay less than their bid price. GSPA implements a tiered pricing model, in which sellers or buyers receive payment determined on the subsequent lower offer or bid. This method promotes competitive bidding and guarantees equity, as sellers with lower offers gain the most by establishing the payment baseline, and sellers with higher offers earn somewhat less than their offer amount. Meanwhile, GSPA mechanism will be more profitable for buyer as the winner will pay the price set by next lower bidder. Hence buyer pay less than their initial bid price. The pricing under PABA demonstrates the actual seller and buyer auction price patterns, as each participants receives precisely their offer amount. This approach encourages truthful bidding but introduces wide price variability among sellers and buyers.

To further understand the results, analysis of individual house trading behaviour is considered. House 6 consistently acts as a seller throughout the day, likely due to a lower load profile combined with higher storage availability, allowing it to accumulate surplus energy. This house benefits from auction mechanisms such as GSPA and UPA where it can gain favourable prices for its energy



(a)



(b)

Figure 5. The total price for different auction mechanisms for (a) seller house and (b) buyer house in a day

contributions. In contrast, House 1 and House 4 show more frequent buying behaviour, reflecting higher energy demand or less efficient storage, leading to greater reliance on CES. Additionally, House 5 and House 7 demonstrate balanced activity, engaging both as buyers and sellers depending on their hourly SOC level and consumption trends. This balanced approach suggests optimized energy use and storage management.

The interaction of different auction mechanisms with this trading behaviour highlights the important of market participation and pricing outcomes for energy trading. UPA offers price fairness but benefits sellers with lower offers and buyers with higher bids; GSPA encourages competitive bidding for both active sellers and conservative buyers; while PABA delivers exact payments based on bids, reflecting true market value but increasing price volatility. This variation of market behaviour highlights how auction type influences active participation, suggesting that mechanism selection should consider both fairness and trading efficiency within standalone microgrid environments.

5.3 Energy Trading Volume of CES

Buyers are identified when SOC is less than 30%, and sellers when SOC exceeds 80%. This hourly condition determines the roles for the participants in the energy market. The amount of energy trade, hourly in the auction for buyers and sellers are as illustrated in Figure 6. The energy trading price are dynamics between house nodes and CES for every hour. The total surplus sold is 88.1 kW while total energy purchased is 90.5kW in 24 hours. The positive region (blue) represents the energy sold to the CES and it generally occurs during the day when solar generation reaches its optimum level. This highlights the efficiency of houses generating surplus energy and contributing to storage.

On the other hand, the negative region (yellow) reflects the energy bought from the CES, commonly observed in the early hours of the morning and late evening to night when there is no solar output. This suggests that prosumers in this system rely on the CES to fulfil energy requirements during low generation period and local energy storage capacity is limited. The role of CES as an effective energy buffer is demonstrated by the balance between energy sold

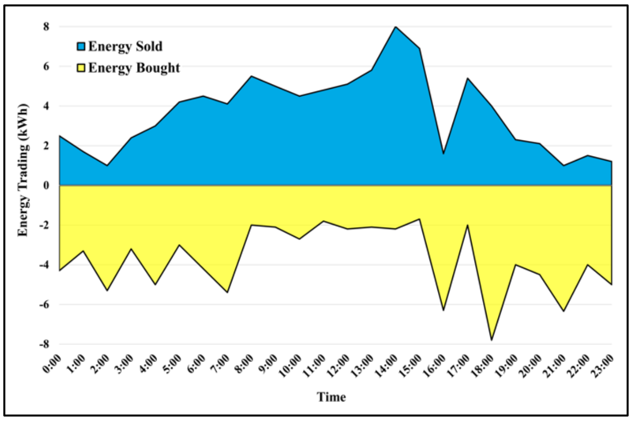


Figure 6. Energy trading volume between peers and CES throughout the day and night

and purchased, which ensures a consistent supply during periods of intermittent solar generation and consumptions by a household.

In overall, UPA mechanism offers the most consistent and uniform auction pricing, fostering simplicity and market stability. Moreover, GSPA provides fairness and efficiency through competitive pricing, whereas PABA prioritizes honest bidding, resulting in increased variability and possible inefficiencies in the energy trading market. The selection of auction mechanism depends on market priorities such as fairness, stability or incentivizing truthful participation. These aspects, however, are not addressed in this paper.

6. CONCLUSION

This paper demonstrates an innovative energy trading framework for standalone DC microgrids, emphasizing the integration of CES with various single-sided auction mechanisms. By positioning CES as the central trading entity, the framework streamlines energy transactions among households equipped with solar PV systems and energy storage units, effectively eliminating the need for direct peer-to-peer interactions. The analysis of three auction mechanisms (UPA, GSPA and PABA) highlights their distinct impacts on market operations. UPA ensures price uniformity, fostering simplicity and predictability; GSPA minimizes overpayment risks, enhancing affordability; and PABA provides participants with full pricing control, adding flexibility. These mechanisms collectively ensure fairness, efficiency and stability in energy trading systems. The results, derived from MATLAB/Simulink-based simulations using 24-hour generation and consumption profiles for 10 house nodes, underscore CES's critical role in balancing energy supply and demand. The centralized storage not only optimizes energy use within the community but also supports greater utilization of renewable energy sources, enhancing system resilience and sustainability.

This study underscores the potential of auction-based energy trading integrated with CES to advance decentralized energy management. By accommodating diverse market conditions and stable operation, the proposed framework contributes to the broader adoption of renewable energy and the realization of sustainable, efficient and resilient standalone microgrid systems.

REFERENCES

[1] IRENA, *Renewable Capacity Statistics 2024*. 2024.
[2] European Commission, "2030 Climate & Energy Framework," 2014.
[3] B. V. Mathiesen *et al.*, "Smart Energy Systems for coherent 100% renewable energy and transport solutions," 2015. doi: 10.1016/j.apenergy.2015.01.075.
[4] V. C. Güngör *et al.*, "Smart grid technologies: Communication technologies and standards," *IEEE Trans Industr Inform*, vol. 7, no. 4, 2011, doi: 10.1109/TII.2011.2166794.
[5] C. Long, J. Wu, C. Zhang, L. Thomas, M. Cheng, and N. Jenkins, "Peer-to-peer energy trading in a community microgrid," in *2017 IEEE Power & Energy Society General Meeting*, IEEE, Jul. 2017, pp. 1–5. doi: 10.1109/PESGM.2017.8274546.
[6] Y. Parag and B. K. Sovacool, "Electricity market design for the prosumer era," *Nat Energy*, vol. 1, no. 4, 2016, doi: 10.1038/NENERGY.2016.32.
[7] Z. Li and T. Ma, "Distributed photovoltaics with peer-to-peer electricity trading," *Energy and Built Environment*, vol. 3, no. 4, pp. 424–432, Oct. 2022, doi: 10.1016/j.enbenv.2021.04.004.
[8] Z. Wang, X. Yu, Y. Mu, and H. Jia, "A distributed Peer-to-Peer energy transaction method for diversified prosumers in Urban Community Microgrid System," *Appl Energy*, vol. 260, 2020, doi: 10.1016/j.apenergy.2019.114327.
[9] S and C, "Peer-to-Peer Energy Trading of a Community Connected with an AC and DC Microgrid," *Energies (Basel)*, vol. 12, no. 19, p. 3709, Sep. 2019, doi: 10.3390/en12193709.
[10] D. Parra, S. A. Norman, G. S. Walker, and M. Gillott, "Optimum community energy storage for renewable energy and demand load management," *Appl Energy*, vol. 200, 2017, doi: 10.1016/j.apenergy.2017.05.048.
[11] N. Vespermann, T. Hamacher, and J. Kazempour, "Access Economy for Storage in Energy Communities," *IEEE Transactions on Power Systems*, vol. 36, no. 3, 2021, doi: 10.1109/TPWRS.2020.3033999.
[12] J. S. Pankiraj, A. Yassine, and S. Choudhury, "Double-Sided Auction Mechanism for Peer-to-Peer Energy Trading Markets," in *Proceedings of the 2021 IEEE International Conference on Progress in Informatics and Computing, PIC 2021*, 2021. doi: 10.1109/PIC53636.2021.9687026.
[13] S. Manukulasuriya, D. W. K. Saw, M. Khorasany, and R. Razzaghi, "Iterative Double Auction for Local Energy Trading in Microgrids: The Monash Microgrid Case Study," in *2021 IEEE PES Innovative Smart Grid Technologies - Asia, ISGT Asia 2021*, 2021. doi: 10.1109/ISGTASIA49270.2021.9715556.
[14] C. T. Ma, "System planning of grid-connected electric vehicle charging stations and key technologies: A review," *Energies (Basel)*, vol. 12, no. 21, 2019, doi: 10.3390/en12214201.
[15] N. Kitamura, A. Werth, and K. Tanaka, "The Open Energy System as an Autonomous DC Microgrid,"

CIRED 23rd International Conference on Electricity Distribution, no. June, pp. 1–6, 2015.

[16] W. Tushar, C. Yuen, H. Mohsenian-Rad, T. Saha, H. V. Poor, and K. L. Wood, "Transforming Energy Networks via Peer-to-Peer Energy Trading: The Potential of Game-Theoretic Approaches," *IEEE Signal Process Mag*, vol. 35, no. 4, pp. 90–111, Jul. 2018, doi: 10.1109/MSP.2018.2818327.

[17] Y. Zhou, J. Wu, and C. Long, "Evaluation of peer-to-peer energy sharing mechanisms based on a multiagent simulation framework," *Appl Energy*, vol. 222, no. May, pp. 993–1022, 2018, doi: 10.1016/j.apenergy.2018.02.089.

[18] F. Muntasir, A. Chapagain, K. Maharjan, M. J. A. Baig, M. Jamil, and A. A. Khan, "Developing an Appropriate Energy Trading Algorithm and Techno-Economic Analysis between Peer-to-Peer within a Partly Independent Microgrid," *Energies (Basel)*, vol. 16, no. 3, 2023, doi: 10.3390/en16031549.

[19] Y. B. Heng, V. K. Ramachandaramurthy, R. Verayiah, and S. L. Walker, "Developing Peer-to-Peer (P2P) Energy Trading Model for Malaysia: A Review and Proposed Implementation," 2022. doi: 10.1109/ACCESS.2022.3161577.

[20] C. Zhang, T. Yang, and Y. Wang, "Peer-to-Peer energy trading in a microgrid based on iterative double auction and blockchain," *Sustainable Energy, Grids and Networks*, vol. 27, 2021, doi: 10.1016/j.segan.2021.100524.

[21] C. Zhang, Y. Yang, Y. Wang, J. Qiu, and J. Zhao, "Auction-based peer-to-peer energy trading considering echelon utilization of retired electric vehicle second-life batteries," *Appl Energy*, vol. 358, 2024, doi: 10.1016/j.apenergy.2023.122592.

[22] H. M. Manjunatha, T. S. Karibasavaraju, L. H. Anjaneya, S. Chandraiah, and P. Arunkumar, "Auction based single buyer energy trading model in grid-tied microgrid with active sellers and buyers," 2023. doi: 10.1016/j.prime.2023.100136.

[23] B. Rampriya, "Optimal Bidding and Generation Scheduling of Utilities Participating in Single Side Auction Markets Including Ancillary Services," *International Journal of Advances in Applied Sciences*, vol. 7, no. 1, 2018, doi: 10.11591/ijaas.v7.i1.pp46-53.

[24] M. N. Faqiry and S. Das, "Double-Sided Energy Auction in Microgrid: Equilibrium under Price Anticipation," *IEEE Access*, vol. 4, 2016, doi: 10.1109/ACCESS.2016.2591912.

[25] J. Dong, C. Song, S. Liu, H. Yin, H. Zheng, and Y. Li, "Decentralized peer-to-peer energy trading strategy in energy blockchain environment: A game-theoretic approach," *Appl Energy*, vol. 325, no. April, p. 119852, 2022, doi: 10.1016/j.apenergy.2022.119852.

[26] B. Mota, P. Faria, and Z. Vale, "Residential load shifting in demand response events for bill reduction using a genetic algorithm," *Energy*, vol. 260, no. July, p. 124978, 2022, doi: 10.1016/j.energy.2022.124978.

[27] H. Liu, J. Li, S. Ge, X. He, F. Li, and C. Gu, "Distributed Day-Ahead Peer-to-Peer Trading for Multi-Microgrid Systems in Active Distribution Networks," *IEEE Access*, vol. 8, pp. 66961–66976, 2020, doi: 10.1109/ACCESS.2020.2983645.

[28] M. Khorasany, Y. Mishra, and G. Ledwich, "Market framework for local energy trading: A review of potential designs and market clearing approaches," 2018. doi: 10.1049/iet-gtd.2018.5309.

[29] M. Khorasany, Y. Mishra, and G. Ledwich, "Design of auction-based approach for market clearing in peer-to-peer market platform," *The Journal of Engineering*, vol. 2019, no. 18, 2019, doi: 10.1049/joe.2018.9313.

[30] S. Malik, S. Thakur, M. Duffy, and J. G. Breslin, "Comparative Double Auction Approach for Peer-to-Peer Energy Trading on Multiple microgrids," *Smart Grids and Sustainable Energy*, vol. 8, no. 4, 2023, doi: 10.1007/s40866-023-00178-x.

[31] Y. H. Yap *et al.*, "A two-stage multi microgrids p2p energy trading with motivational game-theory: A case study in malaysia," *IET Renewable Power Generation*, 2021, doi: 10.1049/rpg2.12205.

[32] International Renewable Energy Agency and Sustainable Energy Development Authority, "Innovations for a decentralised, renewable powered system: Peer to peer electricity trading," *YouTube*, 2020.