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Priority-based market clearing model for off-grid P2P energy trading

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ABSTRACT

Standalone solar PV power system is being used as an option for electrification in remote areas around the world providing basic electricity needs. However, the approach suffers from power mismatch and energy efficiency issues. This paper proposes market-clearing model peer-to-peer energy trading (P2PET) based on multiple standalone solar power system design specification in rural Sarawak, Malaysia. The proposed system combined multiple standalone solar PV system within the community through P2PET trading concept. P2PET creates the platform for energy transaction between each system and even support business such as a workshop to operate high-power electrical appliances. As energy generation is constrained in an off-grid system, the proposed market-clearing model prioritizes the energy trading between the seller and business buyer who bring more benefit to the community. Subsequently, participants in energy trading have a selection of strategies to maximize personal benefits such as profit earning or energy sufficiency. Simulation studies are applied to verify the performance of the proposed model which increases energy efficiency, improves the local economy, and maximizes the community's welfare from electrification.

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1. INTRODUCTION

Based on the report of the International Energy Agency (IEA), 993 million people around the world are still unable to access electricity which 73% of them are live in rural areas [1]. Financial and geography issues have restricted the potential of rural electrification with grid propagation for these countries [2]. A large investment is essential for grid extension to reach the rural area which is considered an uneconomical option as low energy demand from a particular area [3]. To accomplish full electrification globally, renewable energy sources is the cheapest way to achieve especially in rural area [1], [4]. The renewable energy system is an outstanding solution for remote areas with low power demand areas due to the scalability of input power sources. The maturity of the PV technologies and continuing decrease in the cost of solar PV over the years led to the usage of the grid and off-grid electricity increasing [5], [6].

For rural electrification of a remote area in Sarawak, the diesel generator is the common solution although it is costly and has difficulty with fuel transportation. The utilization of local energy resources such as solar, wind, and hydro bring significant benefits such as energy cost saving and greener energy [7]. In Sarawak, several rural electrification schemes utilizing renewable energy as primary sources have been introduces such as Sarawak Alternative Rural Electrification Scheme (SARES), standalone solar hydro hybrid station, Sarawak Energy's CSR Project [8], [9]. Those electrification schemes is aiming to supply electricity for the daily basis of rural communities with standalone solar PVs or integrated with micro-hydro. Figure 1 shows an example of standalone solar PV system in rural Sarawak.

Figure 1. Installed solar PV systems at longhouse in Sarawak [8]

However, the energy efficiency is still low in rural although implemented with renewable energy resources. Current electrification schemes either use energy limiting meters to distribute energy from the standalone system or implement a mini-scale of solar PV system for each household. The energy allocation mechanism from the existing system would be leaving some surplus energy that has never been used and causes the system cannot be fully utilized [10]. Electrification does grow economic in long term with increasing productivity and income of beneficiaries [11]. The existing schemes cannot support rural communities to run micro-businesses that required higher energy demand.

A community-based distributed generation paradigm should be identified as the future power systems paradigm in rural areas [12]. The concept of community-based distributed generation is sharing energy among partners which brings more advantages than traditional distributed generation systems. One of the decent models for this concept is peer-to-peer energy trading (P2PET) [13], [14].

Due to the advancement of information communication technologies (ICT) and blockchain technologies, decentralized P2PET architecture is the potential for future local energy trading in local markets and communities [15]. The consumer who owns a power generation system such as a solar PV system is considered a prosumer. P2PET is an effective market-driven bi-directional energy transactions system [16]. In P2PET energy trading, the peers (household 1, household 2, household 3, and household 4) are represented as energy traders who sell and buy energy directly without third parties such as electric utility companies shown in Figure 2. For example, Household 1 can directly sell surplus energy to household 4 through an energy network since household 1 has surplus energy and household 4 is willing to buy at an acceptable price. Thus, P2PET does reduce costs for energy consumers and brings profit for energy producers through energy transactions.

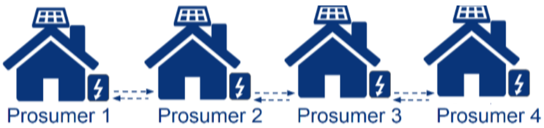

Figure 2. P2P energy trading where prosumers linked together to form a network

The architecture of P2PET energy trading can combine solar PV or microgrid as a peer of the network. Since P2PET energy trading is a community-based distributed power system, the energy generation system is belonging to peers themselves. Besides, P2PET energy trading might be stimulating the growth of the economy in rural areas since P2PET energy trading aggregate the energy resources from peers and improve standards of power for higher energy loads. Thus, socio-economic activities which have high power loads can be carried out by trading the energy with the community members. The involvement of socio-economic activities such as food processing, packaging and storage, school facilities, and agriculture activities in energy trading creates economic value for the community and brings revenues to the community through P2PET and business [17].

Many published studies have been done to apply P2PET system energy trading for the urban, grid-connected microgrid. Aznavi *et al.* [18] proposed industrial P2PET energy trading among charging stations of electric vehicles and business buildings with PV solar generation with a dynamic pricing mechanism. Game theory is frequently used by the researcher for interaction between buyer and seller in energy trading. Yan *et al.* [19] combines multiple microgrids to form a Stackelberg game-based energy trading with power network constraint consideration. In the works of Zhong *et al.* [20] and Jin *et al.* [21], the power network usage fee is considered in game theory-based energy trading. Zhong *et al.* [20] also focuses on social welfare maximization and fairness of profit allocation are in the pricing mechanism. Community-based energy trading is introduced in [13] which focuses on cost-saving and proves the impact of the implementation of energy trading. A game theoretic community based energy trading is proposed in [22]. It has been demonstrated that P2PET offers the community considerable financial and technological advantages. Zhang *et al.* [23] developed community based trading model with demand response mechanism to redact peak load and improve individuals profit. Besides, A P2PET energy exchange model of microgrid for rural electrification is introduced by Harish *et al*. [24].

Although many papers focus on energy trading, however, most of them are focusing on the benefit of individuals in terms of fairness and pricing. In rural electrification, a standalone power system with renewable energy is the typical solution. A major constraint of a standalone power system is the limited amount of energy is generated by the system. Thus, the energy is required to utilize more efficiently to benefit the community instead of individuals' benefits. Moreover, the personal standalone system usually is relatively small. Surplus energy might exist due to low demands and the system cannot even support high demand load for productivity while maintaining daily basic consumption. The maximization of limited energy resources utilization in rural standalone solar PV is the focus of the research by implementing the P2PET concept. P2PET would bring flexibility and increase the utilization of the power system. It connects multiple standalone systems and provides a platform for energy transactions between different participants.

In this paper, a P2PET based on existing rural electrification with a standalone solar power system is introduced. The proposed system framework for standalone multi-combined solar PV is shown in Figure 3. In the proposed market clearing model, the energy sharing provider (ESP) is in charge of collecting data from all participants and based on the strategy of participating priories buyer who brings more benefit to the community such as workshop to trade first with the seller. Besides, power flow analysis is also an operation to reduce the loss in the transaction of energy.

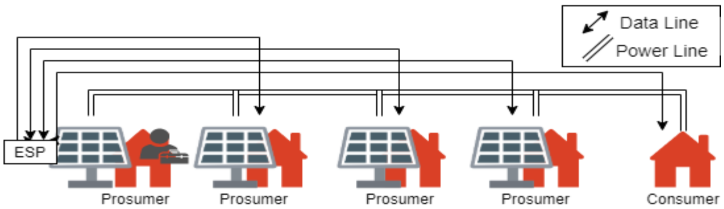

Figure 3. System framework of rural P2PET energy trading

The main contribution of the paper is summarized as follows:

i. An off-grid community-based energy trading framework is developed for rural area conditions.
ii. A priority-based market clearing model is proposed for the energy trading which considers the limitation of energy in off-grid area.
iii. The effectiveness of the proposed framework for P2P energy trading in the rural case is demonstrated and investigated

The structure of the paper is organized as follows. Section 2 discusses the design aspect of system architecture for rural off-grid applications. Section 3 explains the difference between the proposed energy trading system and existing published energy trading. Section 4 explains the simulation setup and experimental data for the performance evaluation of our proposed model. Section 5 discusses the simulated results from the proposed model. Lastly, section 6 concludes the paper.

2. METHOD

2.1. Design aspect of system architecture

The proposed trading system must be kept simple and cost-effective for rural off-grid applications. The main concern in this research is fair energy sharing among the peers without affecting the basic usage of electricity. The solar PV system is selected as the energy source for peers in this research. The trading system is formed by a group of nodes that interconnect with each other. Although REs currently is a good solution to solve rural electrification, implementation of P2PET brings more positive impact toward rural communities compared with using RES alone. The first impact is effective to utilize all the energy resources such as RES, ESS. P2PET links all personal RE systems together so can utilize all the energy effectively and share it with people who demand from people who have surplus energy. It creates a more reliable electricity service provides compare to a standalone RE system.

Secondly, P2PET does improve the quality of living conditions of the trading participants. It increases the source of income as people can sell their surplus energy through the platform. Besides, the inner financial flow formed within the community and make whole communities wealthier. This is because of the cash flow from people who buys energy to the neighbors who sell. Unlike using diesel generators, the cash flow toward outsiders when locals buy fuel from others. The combination of nano grids makes energy that only can support household basic needs becoming supportive to productive uses which refer to productive activities and specifically include the needs coming from agriculture and rural industries. This consequently improves economies in rural areas.

The requirements of the system architecture of P2PET are discussed. The design of the system architecture must consider the conditions of the rural area such as cost-sensitive, poor communication infrastructure, lack of technical capability, and low energy usage. As per the aspect of rural electrification is stated in the previous chapter, the P2PET must capable of the condition mentioned in the following:

i. Operate in islanded modes (isolated) with a reliable electric supply.
ii. Automatic transaction or trade of energy in the network (user friendly).
iii. Energy management to optimize overall power generation and consumption.
iv. Protection from abnormal power system conditions.
v. Fair profit distribution and taking care of the welfare of each participant during trade.
vi. Support load with high energy demand (to support machinery for economic activities).
vii. Power flow protection of each transition node in the power grid.
viii. Low cost but high sustainability and robustness in the overall design.

Based on the requirements above, it can be inferred that P2PET should be able to provide an autonomous, fair energy trade within the network with overflow protection. Below shows the extraction of the functional requirement for the P2P system from the general requirement.

Distributed energy management with abnormal protection: as P2PET can be defined as combining or linking multiple nano-grids to form a bigger grid. Thus, the distributed manner in energy management and control is the best option. From the cost perspective, distributed architecture can only implement with only a microcontroller on each node and peer to form the network while servers and central controllers, and computers are not required which is a cost-saving. The distribution should allow each peer to communicate and share resources to utilize the resources effectively. The system should also be able to maintain the demand response of the overall power system and operate independently.

Distributed structure for coordination and synchronization: control systems in the distributed structure need to synchronize and coordinate all nodes or peers through the communication network to achieve individual and global goals. Information processing and analyzing is not confined to a single machine but multiple independent machines. Energy trading platform for energy transaction: energy exchange platform for utilizing the surplus energy from prosumers. Market algorithm of proposed P2PET formed by three-part which are the market-clearing model, fairness mechanism, and pricing mechanism. The benefits of each participant are taking care and reaching Pareto optimality.

Demand-side management (DSM): DSM aims to reduce and optimize consumer load and electricity usage. DSM is playing a role to calculate the demand for electricity of the consumer based on the consumption pattern from metering. So that, DSM can determine the consumer whether demand more electricity or having surplus electricity. Thus, DSM enables maximum benefits of peers. It also helps the user to get involved in energy trading by making trading decisions autonomously in the energy trading according to the strategy that the user preferred and the willingness of the user to join the trade. It offers significant flexibility to the system through trading decision-making.

Power routing optimization in energy transaction: the energy trading transfers energy from the seller to buy which unlike data transmission can be resent if any failure. Power routing algorithms need to avoid the power distribution network overload when energy transactions. It also needs to optimize the route of the transaction to ensure the stability of the power distribution network and reduce the loss of energy transmission.

2.2. P2PET configuration

In the proposed P2PET system design, there is two major part which is the system framework and the system model. The system framework is the energy management and control architecture that ensures the operation of the energy trading while the system model is the algorithm that operates P2PET. The proposed system framework is developed based on the P2P sharing concept under a decentralized control framework. The market algorithm of the proposed P2PET is formed by three parts which are the market-clearing model, fairness mechanism, and pricing mechanism. Demand-side management is using the data such as energy consumption to analyze and optimize consumers' energy usage patterns to diversify the system and offer significant flexibility to the system through trading decision making.

In the proposed system model, the development of the trading market algorithm is considering the off-grid system in the rural area. The proposed P2PET system model is designed as an hour-ahead energy trading model. Recent work done in community-based P2PET usually only consider grid-connected cases. The objectives of the system are usually peaking shaking and profit maximization of participants. Dynamic pricing mechanism through demand response and auction theory is the common solution that is not suitable for the rural case. Dynamic pricing mechanism only benefits participant who has buying power and sellers. As energy is limited in the off-grid system, generated energy should be utilized properly especially in the rural case which is suffering poverty and resource shortage.

Figure 4 shows the data flow and software architecture of the proposed system model based on the selected framework. Based on Figure 4, the ESP manages the overall trading process with trading model and power routing management. Each peer sends the information for trading and pricing from DSM to ESP before trading begins for each trading timeframe.

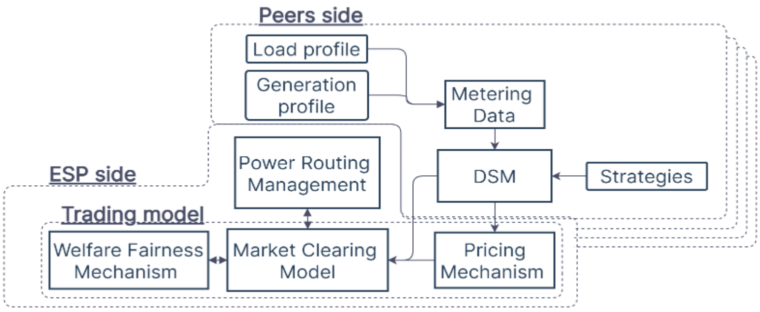

Figure 4. Dataflow and software architecture of the proposed system model based on the selected framework

On the peers' side, the role of DSM is to assist peers in energy trading and energy management. In energy trading, DSM oversees making a trading decision based on the strategy selected by peer and demand response. The assistance of DSM makes the trading autonomously and user-friendly. The demand response is calculated by using metering data and the previous energy profile recorded. The trading model is aiming to maximize the social welfare of the community by prioritizing the buyer who is given more benefit toward the community to match with the seller. To achieve the objective, Welfare fairness mechanism and market clearing model is developed.

The market-clearing model is matching the peers who are willing to involve in energy trading to become sellers or buyers based on the priority mechanism. The priority mechanism will give peers who benefit more toward the community to form the trading pair first. Energy trading in rural, limited energy constraint the amount of energy for trade. Thus, limited energy that available in rural required to maximize the effect on the community but not personal benefit only.

Welfare fairness mechanism is proposed in the trading model to ensure the welfare received through energy trading is fairly distributed to each of the sellers who is willing to contribute. The mechanism extracted the information from the market-clearing model and recorded the trading over the timestamp to obtain the frequency of trading and profit earned by each peer. The welfare fairness mechanism is using an index method for ensuring fairness. Index of peer will be high if the frequency of trade or profit earned is high.

Unlike traditional power systems, the grid of the P2PET is a bi-directional power flow that might face power congestion at a certain point of the power grid during energy transactions. Thus, power flow management is required to take care of the power constraint of the power system. After the market-clearing model formed the trading pairs, the power flow management analysis the capacity of the pathway used by the trading pairs in the grid. If the capacity of the specific node of the grid is overloaded, the management model will respond to the market-clearing model to reform a new trading pair that do not violate power constraint.

In Figure 5, the main flowchart for a trading operation of a typical community-based market is compared with proposed model [14], [22], [23]. The trading model is assumed to have N-prosumers and N-consumers. ESP is in charge to collect information for trading and operate the energy market. First, the demand response of each participant is calculated based on the load and generation profile of each participant. The decision of the participant to sell or buy is based on the demand response and own pre-defined strategy. The participants' decision of involvement in energy trading is then sent to ESP. After receiving all the data which within the receiving period, ESP will make energy trading decisions by running the trading market algorithm based on the trade information from seller and buyer and appointing the trading pair to each trading participant.

The process of the proposed system model in Figure 5 is done by two entities which are ESP and peers. The two first two steps are done by peers. First, the DSM of each peer calculates the demand response from the data given in the metering and monitoring system such as energy generated and consumed. After that, the decision of involved in energy trading in step 2 is made by the DSM of the peer. The decision of DSM is depending on several factors. Initially, the critical factor that affects the decision of trading is a strategy that is pre-selected by the peer. The selection of strategy is shown in Table 1 and there are four types of strategy options. The strategy selected by peers shows the willingness of peers that interest more. Peers who selected DM and SS are a person more concerned about the availability of electricity supply while AM selectors are interested in profit earning from P2PET.

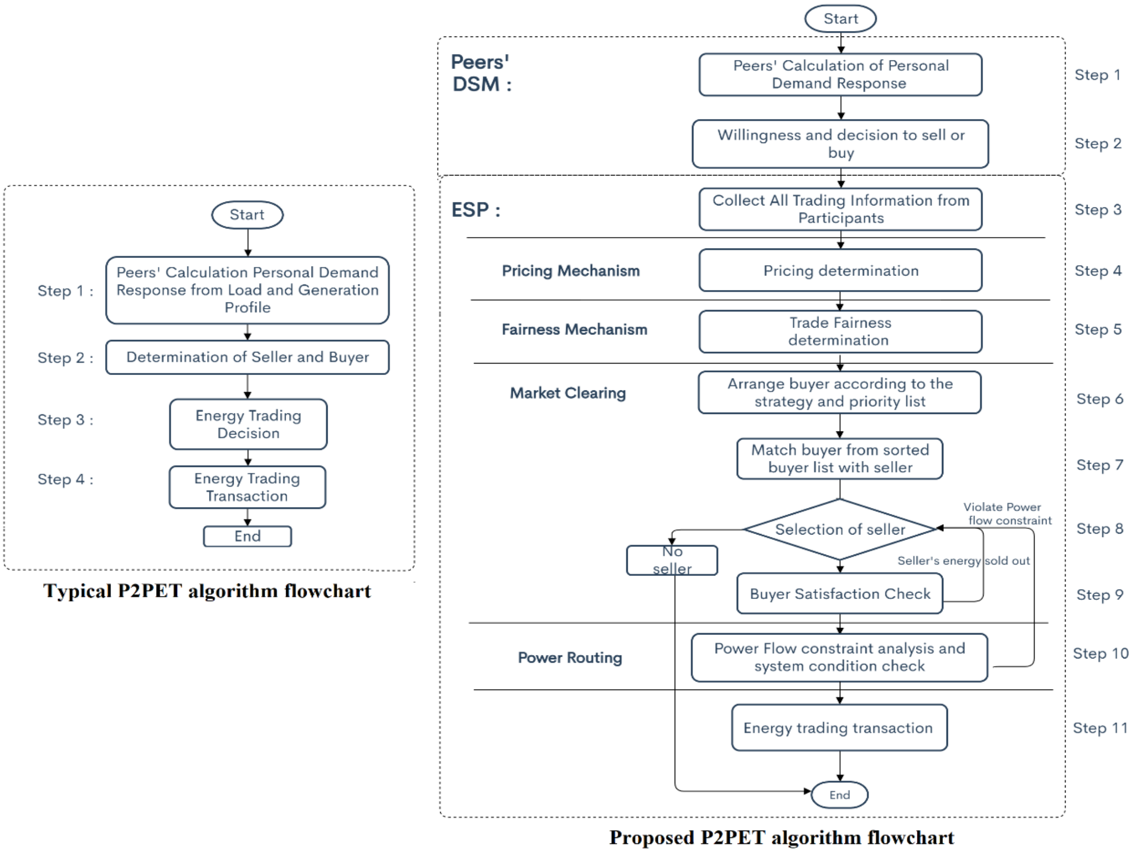

Figure 5. The comparison of the typical P2PET and proposed P2PET algorithm flowchart

Table 1. Types of strategy option of community member with trading decision making setting

Strategy	Description	Battery capacity (%)	
		Buyer	Seller
DM	Member willing to buy energy more and having high load profile	<50%	>80%
AM	Member interested on earn profit and even can scarify the energy consumption to save energy for sell	X	>50%
BC	The member who is the consumer and required to buy energy for high power applications such as machinery	X	>60%
SS	The member who concerns about self-sufficiency but not willing to increase expenses on electric	X	X

The second factor is the battery capacity available. DSM is a rule-based algorithm as shown in Table 1. It will depend on the battery capacity available with the selected strategy and decide to trade or not involve in the market. In the market, participants are can either sell the surplus energy or buy deficient energy with the price at the time slot. DSM might assist the user to secure some energy for consumption or to sell surplus energy in battery storage. In the proposed system, all the energy that is traded is based on the energy stored in the battery which is not considering the energy generated now. This is because solar PV is selected as the primary source of the power system. The power supply from solar PV is intermittent due to the dependency on sunlight. For consumers (BC selectors) who are absent of energy generators, DSM will always buy energy from the market depending on demand response.

Then, the third factor is demand response. Since the developed system model is an hour-ahead energy trading model, demand response is calculated hourly. The proposed P2PET system is assumed all participants are capable of determining the power generation and consumption profile for each time slot. The calculation of demand response is shown as,

$$P^{dr} = P^{Load} - P^{Gen} \tag{1}$$

where P^{Load} is load consumption of prosumer n, P^{Gen} is generated power of prosumer n and P^{dr} is demand response of prosumer n. If the demand response of the peer is positive, battery storage will discharge to cover the demand. If demand response is negative, exceed generated energy is charged into battery storage. DSM is required to check the demand response and energy stored in the battery whether there is surplus energy for trading.

In step 3, participants will send the trading information to ESP via the communication link. The trading information includes willingness for trade (sell, buy or idle), amount of energy for trading, and selected strategy. As the market is hour-ahead, receiving period is given to receive all the trading information from participants before starting trading at a particular time. ESP will ensure all information of the participants is received from each of the participants.

In step 4, the pricing mechanism is proposed to determine the price of the energy. In a free and open energy market, participants are using a bidding method to trade the energy. In the proposed energy trading, the pricing mechanism is depending on the day of autonomy of battery capacity. Day of autonomy is the time a power system will last at a specified load level. In the standalone PV power system, the day of autonomy is the critical factor that affects the stability of energy supply during a long period of a cloudy or rainy day which PV is unable to generate energy effectively. The pricing of the traded energy will remain fixed unless the day of autonomy of overall sellers is less than 1 day. The price will dramatically increase when the day of autonomy of overall sellers is getting lesser. The formulation of the pricing mechanism is shown as,

$$\lambda = \frac{\sum_n P_{N_j}^{dr}}{\sum_n P_{N_i}^{dr}} \times \gamma \tag{2}$$

where λ is the pricing rate of the trading electric, γ is the basic price rate of the trading electric, i and j represent the seller and buyer respectively.

In step 5, welfare fairness mechanism is proposed to take care of the fair distribution of the social welfare or benefit among the sellers in P2PET. Fairness is required to be considered in trading as the trading model might bias to specific peers with given many benefits such as profit earned to specific individual among others. As the market-clearing model is depending the strategy selected by peers, it might face the situation that a group of sellers who chose the same strategy is qualified to trade first. The fairness index from the mechanism is presented to solve the situation. It is used as one of the factors in the priority mechanism.

During the market clearing process, a sorted buyer list is generated first according to the selected strategy of the participants in step 6. In the proposed model, the model generates the buyer list by prioritizing the buyer whose energy usage on activities that create more benefit such as business instead of the buyer who uses for personal energy usage. BC selector will be arranged to match first as the business is assumed as BC selector in the case. Following strategy selector will be DM strategy selector only since another two types of strategy are not willing to buy energy for consumption.

In the following step, the model matches the buyer from the buyer list with the sellers in step 7. The selection of the seller is depending on the strategy selected by the sellers, quantities of energy for sale, and fairness index. The selection of strategy is shown in Table 1 and there are four types of strategy options. Priority of the selection of the seller is first arranged by the desire of the seller to earn the profit according to the selected strategy, and then follows the fairness index of seller and quantities of energy among the sellers who have the same strategy in step 8. The priority order of the strategy in the selection of sellers is AM, SS DM. If the sellers have the same strategy and same fairness index, the model will prefer the seller who has a larger amount of energy for sale.

In step 9, Buyer satisfaction will be checked after a seller is matched with the buyer. If the buyer still demands more energy, the model will match another seller with the buyer again. As this paper is considering a standalone solar PV power system, energy is constrained by the energy generated from solar PV and energy stored in the battery. The market-clearing model will end when there is no seller on the market at the time slot.

In Step 10, the power flow management analysis the capacity of the pathway used by the trading pairs in the grid. Each of the pathways of trading pairs will be generated by using graph theory. The routes that energy transactions by the trading pairs are then recorded with the amount of traded energy. If the capacity of the specific node of the grid is overloaded, the management model will respond to the market-clearing model to reform a new trading pair that do not violate power constraint. The true energy transaction is held during the timeslot according to the settlement of the energy trading that has been created by the trading model before the timeslot in step 11.

2.3. Simulation setup

In this section, the case is reviewed to prove the performance of the proposed market-clearing model. In all case studies, the community consists of 18 members which are 3 consumers, 15 prosumers. The community in the case study as shown in Figure 1 is simulated at Rumah Manggat which is electrified under a rural electrification scheme from the government in 2016. The main source of income of the community members is agriculture, fishing, and forestry [25]. Under the scheme, each of the members has been provided with a small-scale solar PV system. Thus, excess energy cannot be utilized since those systems are standalone.

By applying the P2PET concept, multiple solar PV systems are linked together. We proposed that the energy can support any productive activity from agriculture and rural industries such as post-harvest processing in fruit and vegetable, irrigation, and milling. This feature of P2PET enables the improvement of rural welfare and poverty reduction [17], [26]. A range of micro-businesses such as kiosks, bakeries, halls can also be achievable by setting them as consumers in the energy trading. In the case study, we simulated 2 small workshops and 1 food processing center as the consumer in the community. The load consumption profile of the community members is generated according to the electrical appliances assumed in the design specification as shown in Table 2. The different pattern of load consumption is generated based on the member's nature of job and business and the wealth of the family.

Table 3 explains the assumption of different load profiles used in the simulation. The load consumption pattern from the community members is shown in Figure 6. Energy for the basic needs of the community members is mostly consumed for cooking, lighting, and other electric appliances. In the case study, the load consumption behavior of the community members is based on the "normal" type of load. For the workshop load profile, the consumption pattern is based on the assumption of machinery operation. The power is assumed to supply two machines at once. Besides, a food processing center with freezers is simulated as a consumer in the case. The freezers need to operate the whole day.

Table 2. Assumption of electrical appliances in simulation

No.	Electrical appliances	Unit	Watt
1	Bulbs	5	11
2	Television with video player	1	105
3	Fan	1	38
4	Rice cooker	1	500
5	Freezer	1	100

Table 3. Load profile assumption explanation

Type of load	Period	Energy usage	Description
Normal	Whole day	Cook, lighting, electric appliances	Assume family leaves to work in early morning, rest in afternoon (at home), and go work until evening. Electric mainly used for cooking, TV, and lighting
Workshop	Working hours (8-5)	For machinery tools	Use to operate the machine when working hours but a rest period at (12~13)
Freezer	Whole day	For freezer	Freezer required operate whole day long, increased power is used for cooling after open the freezer

The prosumers in the community are assumed to own an individual 1 kW solar PV generator with two days of autonomy which is a 12 kWh of battery storage with a limit discharge SOC of 10%. The solar PV generation graph is stated in Figure 6. The efficiency of the charging and discharging of the battery is set to 95%. The prosumers are set to have the capability to control the battery charging and discharging and PV generation. Besides, the power capacity of the system is limited to 700 W to prevent system overloading. Since there are 18 families in the community, the simulated power system is an 18-bus radial distribution system which in Figure 7.

In Table 4, each community member's data is displayed. The table depicts the strategy of members, locations in buses, and load profile. The load profile depends on the trading strategy selected by the member.

Table 4 shows that all community members are prosumers who participate in P2PET with a selected strategy based on Table 4. Member 9 and 10 are the light workshop that operates some machinery in the community so the load profile is set as a workshop while member 11 is the central cold storage to store meat for business.

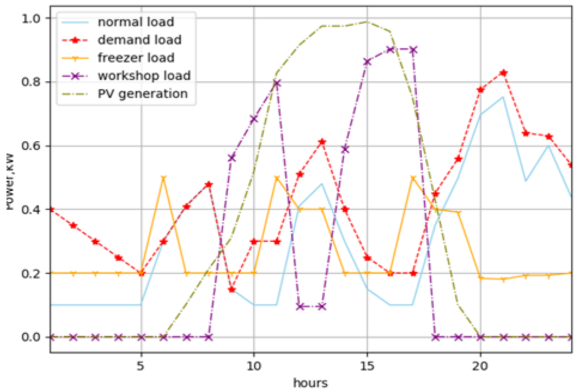

Figure 6. PV generation and different load profile pattern according to the strategy selected

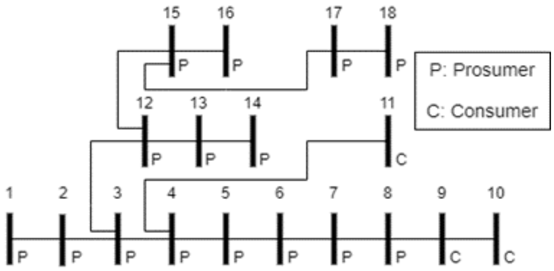

Figure 7. 18-bus radial distribution test system [21]

Table 4. Community member data

Member	Information			Member	Information		
	Strategy	Bus	Load profile		Strategy	Bus	Load profile
1(P)	SS	1	normal	10(C)	BC	10	workshop
2(P)	DM	2	normal	11 (C)	BC	11	freezer
3(P)	SS	3	normal	12(P)	AM	12	normal
4(P)	DM	4	normal	13(P)	SS	13	normal
5(P)	AM	5	normal	14(P)	SS	14	normal
6(P)	DM	6	normal	15(P)	DM	15	normal
7(P)	AM	7	normal	16(P)	AM	16	normal
8(P)	SS	8	normal	17(P)	AM	17	normal
9(C)	BC	9	workshop	18(P)	DM	18	normal

Note: (P): Prosumer; (C): Consumer

3. RESULTS AND DISCUSSION

In the scenario, all the prosumers and consumers are involved in the P2PET trading after the analysis of the personal energy profile. According to their strategy, prosumers who have surplus energy to sell send the trade information to the ESP. Then, ESP forms the trade based on the amount of energy for selling and buying requests from the buyer which the data is collected by participants. The generation of the solar PV system is intermittent due to its fluctuating nature which depends on solar power. Therefore, the proposed P2PET in the paper is depending on the surplus energy stored in the battery of each peer. The community member is required to have a certain amount of battery capacity to become a seller although solar PV generates a certain amount of energy at a particular time slot. This mechanism ensures that trading can be done without violating any power constraint if solar PV does not generate the expected energy for sale. In Figure 8, energy trading in the simulation is based on the proposed system model with 96 hours (4 days) is shown. In Figure 9, The percentage of battery capacity of each community member throughout the day is shown.

3.1. Energy trading over the timestamp

The result shows that consumers 9–11 bought energy throughout the trading based on the energy demand. Consumers 9–11 are the business buyer. Consumer 9 and 10 are the workshop in the community, energy is used to operate the machinery during working hours only so there is no trade during the non-working period. Consumer 11 bought energy to maintain the operation of the freezers all day long. Most of the trade is held during the daytime as demand increase when the workshop is operating.

During the 7th ~11th hour, there is an absence of any trade. The is because no seller exists in the market. At the beginning of the simulation, the percentage of energy stored in battery storage is 50% only. Based on the setting of the proposed system model, battery storage needs to exceed at least 50% to become a seller to sell energy in the market. During the night-time, the prosumers are assumed to consume some energy by discharging the battery since solar PV is still unable to generate electricity. Thus, trading restarts at the 12th hour because of the capacity of the battery up to 50% due to the charging from the solar PV during the daytime. It shows that the sellers in the trading pair might not be the same in each timestamp. This is because the proposed market-clearing model prioritizes the seller to trade in certain factors. The first factor is the strategy selected by the seller. Trade with priority by strategy can fulfill the satisfaction of all entities in P2PET effectively. Each of the entities has its willingness to obtain from P2PET. Prosumer who selected “AM” as the strategy is concerned about the profit earning while prosumer who selected “SS” strategy who willing to sell surplus energy only. “DM” selector willing to pay on excess consumed energy. To ensure a continuous electricity supply to buyers, the system will priories the “AM” selector first who is willing to scarify personal energy consumption for trade and followed by “SS” and “DM”. The second factor and third factors are the fairness index and quantities of energy available to sell respectively. These two factors are used to arrange the sellers who selected the same strategy in the market-clearing model. Therefore, the market-clearing model in the proposed market model will match the seller based on the strategy first then follows by fairness index and quantities of energy stored.

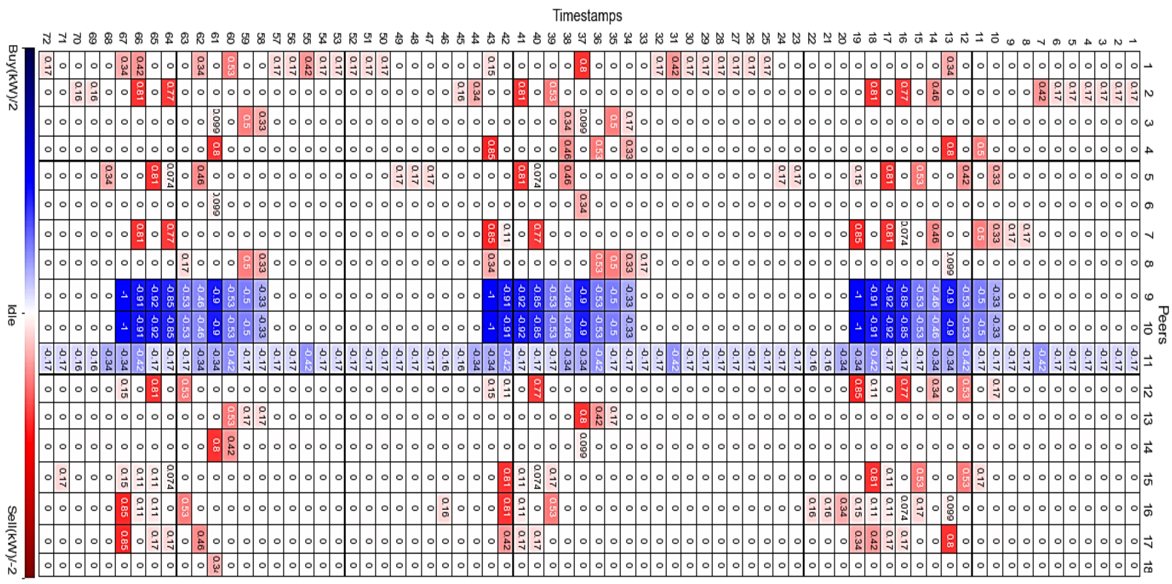

Figure 8. Energy trading over the timestamp

According to the average of total trading frequency among the seller over the timestamp in Table 5, it is shown that the seller matching is based on strategy. Peers who selected “AM” are traded in the highest amount which is 16.4 even though the number of selectors is 8 which is the highest in the community. From Table 6, prosumers who selected “DM” do sell energy in a certain period that “AM” and “SS” selector are not selling at the period to maintain the fulfillment of stable electric supply of buyer from P2PET.

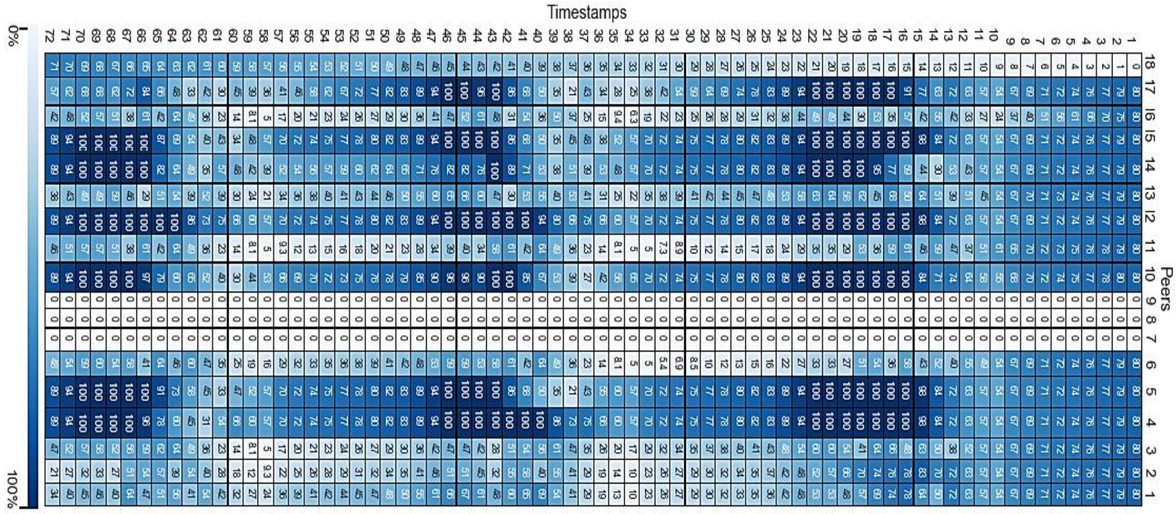

Figure 9. Battery capacity of community members by percentage over the timestamp

Table 5. Trading frequency of the seller in the simulation

Member	Information		Member	Information	
	Strategy	Frequency of trade		Strategy	Frequency of trade
1(P)	SS	10	10(C)	BC	18
2(P)	DM	15	11 (C)	BC	6
3(P)	SS	15	12(P)	AM	9
4(P)	DM	11	13(P)	SS	20
5(P)	AM	18	14(P)	SS	18
6(P)	DM	1	15(P)	DM	16
7(P)	AM	15	16(P)	AM	2
8(P)	SS	25	17(P)	AM	18
9(C)	BC	10	18(P)	DM	6

Note: (P): Prosumer; (C): Consumer

Table 6. Average of trading frequency among strategy selector

Strategy Selected	Average of trading frequency
AM	16.4
SS	13
DM	1.5

3.2. Pricing of the energy trading

The pricing of traded energy during the energy trading over the timestamp is shown in Figure 10. The pricing mechanism is depending on the day of autonomy of all battery capacity of the community member. Thus, the pricing of the trade is directly related to the battery level of the batteries which belongs to the seller. The pricing mechanism is representing the value of the energy that is trading at a specific period. When a thing is scarce, it is precious. Therefore, there are five high peaks and four low peaks over the simulation which shows the autonomy of day of battery capacity is less than 1 day and even 12 hours. In a certain period, it is always at the fixed price because the autonomy of day of battery capacity is not less than 1 day.

At the first and second high peaks, the cause of the high pricing is due to the low battery level issue which is explained in the previous section. Although trade is permitted during the period, the amount of energy stored is still scarce. In the 7^{th} ~11^{th} hour, the price drops to zero since there are no trades during the period. Based on Figure 10, there is the pattern that a small peak occurs after a high peak excepting the first 20 hours. This pattern has occurred during high load demand in the daytime when the workshops operate. The batteries are discharging the energy that is sold to the buyer. However, the power generation of solar PV also occurs during the daytime and generates a high capacity of power during the 12 pm ~ 3 pm every day. Thus, the power generation from solar PV covers the demand and creates a valley between the peaks in the pricing graph

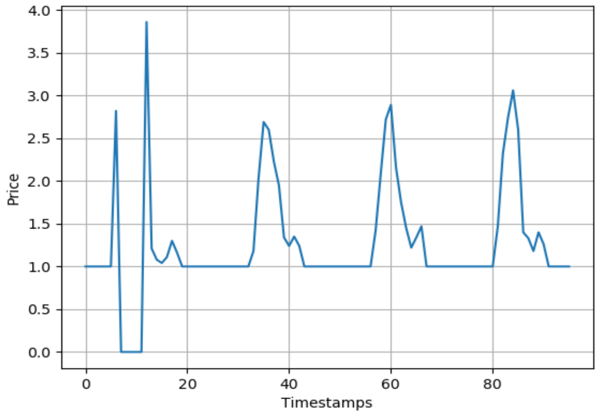

Figure 10. Pricing over the timestamp during an energy trading

3.3. Profit analysis

Figure 11 shows the overall profit and expense of each peer over the day. This refers to the sum of the quantity of power purchased and sold by each peer in the energy trading over the timestamp. The red color bar represents the expense of the peer to buy the energy while bars with blue color represent the profit earned from the energy trading. Among the sellers (Peer 9–11), the expense of peer 11 is the highest because the business requires to buy electricity to maintain the operation of the freezer continuously. The business consumer groups contribute RM 70.29 to the community when the base price for a unit of electricity is set as RM1 in the simulation.

Three groups of prosumers selected “AM”, “SS”, and “DM” earns profit throughout the simulation. Priority of the selection is arranged by the desire on earning money based on the strategy. The arrangement of priority based on strategy is “AM”<“SS”<“DM”. Thus, prosumers who selected “AM” are priories to sell the energy then follow is “SS” in the simulation. Compare with prosumers who selected “SS”, prosumers who selected “AM” earn the most due to the market-clearing mechanism but also encounter the risk of insufficient energy on daily basis. Peer 6 and 18 are selected “DM” as strategy thus little profit earned as they are not concerned with profit but electricity sufficient. Based on the result in Figure 11, the profit earned by the peers who selected the same strategy is distributed nearly even as the fairness mechanism is implemented into the market model to avoid the profit distribution being biased to a specific individual or entity. Therefore, the model has achieved fair profit distribution among the same class.

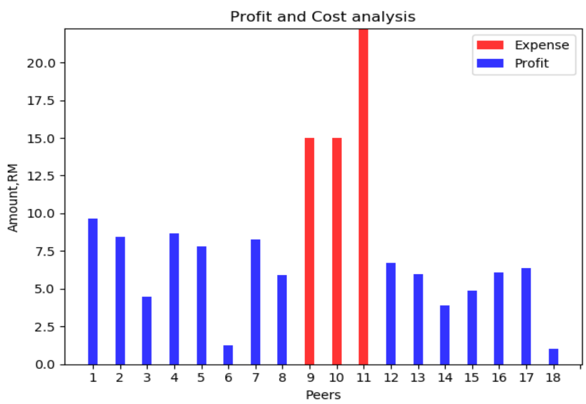

Figure 11. Profit analysis of case

3.4. Power flow management

As the development of P2PET relied on the energy transaction among the peers, power constraints were required to take account into the design aspect of the P2PET platform. Figure 12 shows the power flow of each line throughout the energy trading. The power constraints are been taken care of by the proposed power flow management system. The overload of power capacity in a certain line of the grid during the trading pairing is prevented because the proposed market model will be considering the capacity of the line and eliminate the pairing that violates the power constraints.

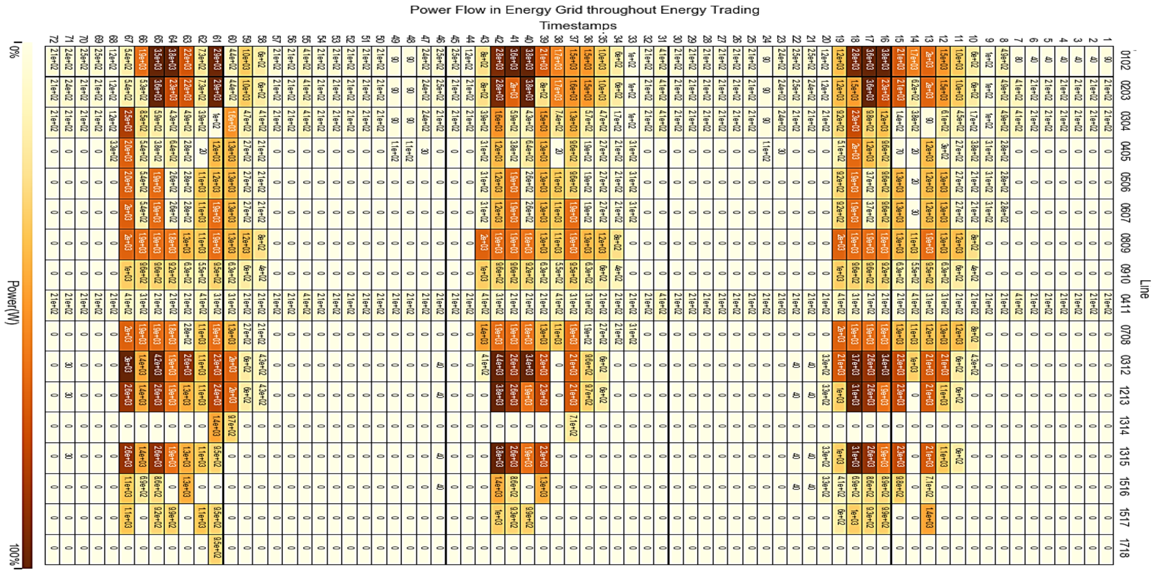

Figure 12. Power flow of each line throughout the energy trading

4. CONCLUSION

In this paper, peer-to-peer energy trading (P2PET) based on existing rural electrification with a standalone solar power system is proposed. The result based on the case studies proves that the proposed algorithm ensures the community has better social welfare and profit from the energy trading when selling energy to the business entity in the community. The proposed market-clearing model that considers limited energy allocation based on ESP operation is proven to maximize the benefits received by the community. For future work, power forecasting of renewable DER and distributed methods of data communication and management in the data layer will be considered in the energy trading solution.

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