EVALUATION OF VARIOUS PEER-TO-PEER PRICING STRATEGIES IN A COMMUNITY MICROGRID

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EVALUATION OF VARIOUS PEER-TO-PEER PRICING STRATEGIES IN COMMUNITY MICROGRID

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

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วิทยานิพนธ์นี้มีวัตถุประสงค์เพื่อประเมินผลกำไรที่พึงได้รับจากการซื้อขายพลังงานที่สถานการณ์แตกต่างกันของผู้ประกอบการด้านพลังงาน โดยพิจารณาจากกราฟภาระงานรายวันและศักยภาพของระบบผลิตพลังงานไฟฟ้าเซลล์แสงอาทิตย์ ในการศึกษานี้ได้ประเมินสภาพแวดล้อมการซื้อขายพลังงาน 4 แบบ ได้แก่ การซื้อขายโดยตรงกับกริด การซื้อขายแบบมีส่วนร่วม การซื้อขายแบบเพียร์ทูเพียร์ขั้นตอนเดียว และการซื้อขายแบบเพียร์ทูเพียร์หลายขั้นตอน นอกจากนี้ยังพิจารณาโหมดการใช้พลังงาน 2 กรณีได้แก่ โหมดปกติและโหมดแลกเปลี่ยน ในโหมดปกติโพรซูเมอร์จะติดตั้งอุปกรณ์เซลล์แสงอาทิตย์ให้ที่มีกำลังการผลิตเท่ากับความต้องการสูงสุด ในทางกลับกันในโหมดแลกเปลี่ยน การผลิตพลังงานทั้งหมดของเซลล์แสงอาทิตย์และความต้องการโหลดของโพรซูเมอร์จะคงที่ เนื่องจากโพรซูเมอร์ได้ใช้พลังงานบางส่วนที่สร้างขึ้น ความสามารถในการสร้างพลังงานของเซลล์แสงอาทิตย์ของโพรซูเมอร์มีการแลกเปลี่ยน แต่ก็ไม่ได้เปลี่ยนแปลงอุปสงค์และอุปทานสะสมทั้งหมดของชุมชน อย่างไรก็ตาม ปริมาณพลังงานที่มีอยู่และความต้องการในตลาดซื้อขายยังคงเปลี่ยนแปลงตามช่วงเวลา ซึ่งส่งผลทันทีต่ออัตราพลังงานและผลกำไรในที่สุด การประหยัดต่อกิโลวัตต์ของการฉีดพลังงานที่ผลิตจากเซลล์แสงอาทิตย์ถูกนำมาใช้เป็นดัชนีเพื่อกำหนดความสามารถในการทำกำไรของตลาดซื้อขาย จากผลการวิจัยพบว่า ดัชนีการประหยัดต่อกิโลวัตต์ของการฉีดพลังงานที่ผลิตจากเซลล์แสงอาทิตย์ในโหมดการแลกเปลี่ยนมีค่ามากกว่าในโหมดปกติของทุกแพล็ตฟอร์มการซื้อขายสำหรับนาโนกริดและไมโครกริดทั้งหมดในทุกระดับการฉีดพลังงานที่ผลิตจากเซลล์แสงอาทิตย์ ผลการจำลองที่ได้รับชี้ให้เห็นว่า ตลาดการซื้อขายแบบมีส่วนร่วมมีพิสัยอัตราพลังงานมากที่สุด หากการมีส่วนร่วมของทุกเพียร์ไม่อยู่ในพิสัยที่เทียบเคียงกันได้ เพียร์ที่มีส่วนแบ่งพลังงานจำนวนมากจะสูญเสียผลกำไร และเพียร์ที่มีความต้องการสูงจะได้รับผลประโยชน์สูงสุด ในทางตรงกันข้าม หากใช้การซื้อขายแบบเพียร์ทูเพียร์หลายขั้นตอน ทั้งผู้ขายและผู้ซื้อจะได้รับส่วนแบ่งของกำไรที่เป็นธรรม และการซื้อขายแบบเพียร์ทูเพียร์หลายขั้นตอนยังสร้างความมั่นใจให้ว่า ค่าพลังงานไฟฟ้าจะไม่สูงไปกว่าบิลเรียกเก็บเงินจากการซื้อขายตารางโดยตรงกับกริด ซึ่งไม่ได้เกิดขึ้นประจำสำหรับการซื้อขายแบบมีส่วนร่วม

ผลการวิจัยชี้ให้เห็นว่า การซื้อขายแบบเพียร์ทูเพียร์หลายขั้นตอนเป็นตลาดซื้อขายที่ทำกำไรได้มากที่สุด เมื่อเทียบกับการซื้อขายแบบมีส่วนร่วมตามที่กล่าวไว้ในโหมดการแลกเปลี่ยน การใช้บริโภคพลังงานที่สร้างขึ้นด้วยตนเองนั้นไม่สมเหตุสมผลจากมุมมองทางเศรษฐกิจ จากเหตุผลนี้

อาจเปิดตลาดการซื้อขายพลังงานชุมชนที่ใช้การแบ่งปันผลกำไรรูปแบบใหม่ที่โพรซูเมอร์รายใหญ่ลงทุนเพื่อติดตั้งการผลิตพลังงานในโพรซูเมอร์ที่มีความต้องการน้อยด้วยข้อตกลงการแบ่งปันผลกำไร นอกจากนี้ อีกวิธีหนึ่งที่เป็นไปได้ในการเพิ่มผลกำไรสูงสุด คือ การใช้แหล่งกักเก็บพลังงานและใช้อัลกอริทึมการประมูล ซึ่งอาจขยายการวิจัยต่อไปในอนาคต

สาขาวิชาวิศวกรรมไฟฟ้า ลายมือชื่อนักศึกษา____________

ปีการศึกษา 2562 ลายมือชื่ออาจารย์ที่ปรึกษา____________

ASHOK PAUDEL: EVALUATION OF VARIOUS PEER-TO-PEER PRICING STRATEGIES IN COMMUNITY MICROGRID. THESIS ADVISOR: ASST. PROF. BOONRUANG MARUNGSRI, D. Eng., 143 PP.

PRICING STRATEGY/ PEER-TO-PEER ENERGY TRADING/ PARTICIPATORY METHOD/ MULTILEVEL TRANSACTION/ COMMUNITY MICROGRID

This thesis aims to evaluate the profit that a prosumer would get from the different energy trading scenarios considering their daily load curve and the potential of the Photovoltaic energy generation system. Four of the energy trading environments, i.e., Direct Grid Trading (DGT), Participatory Trading (PPT), Single Stage Peer-to-Peer Trading (SSP2P), and Multi-Stage Peer-to-Peer Trading (MSP2P), are evaluated in this study. Two cases of the energy consumption mode, namely normal, and interchanged modes, are considered here. In the normal mode, a prosumer will install a PV facility with generation capacity equal to its maximum demand. On the other hand, in the interchanged mode, the total energy generation of PV and the load demand of prosumers are constant since the prosumers consume some power they have generated. The generation capacity of the PV of prosumers is interchanged, which does not change the cumulative supply and demand of a whole community. Still, the amount of power available and the demand in the trading market will change at a particular time instant, which consequently affects the energy rate and, finally, the profit. An index called saving per kilowatt PV injection is used to define the profitability of the trading market. By the results, it is found that the saving per kilowatt PV injection in the interchanged mode is always greater than that in the normal mode in all trading platforms for all

nanogrids and microgrids in all PV injection levels. Results obtained after simulation suggest that the PPT market has the largest range in the energy rate. If the contribution of all peers is not in a comparable range, a peer contributing a larger share of energy will lose its profit, and the peer in high demand receives maximum benefit. On the contrary, if the MSP2P is used, both the sellers and buyers will get their fair share of profit, and the MSP2P ensures that the cost of electricity will not be greater than the bill obtained from direct grid trading, which is not always the case in the participatory method. As a final note, the results suggested that MSP2P is the most profitable trading market compared to the PPT method. As discussed in interchanged mode, the self-consumption of generated energy is not justifiable from the economic viewpoint. This reason may open a new type of profit-sharing based community energy trading market in which a larger prosumer invests in a generation facility to be installed in a low demand consumer with the profit-sharing agreement. Also, another possible way of maximizing profit is by using a storage facility and using the auction algorithm, and it may be the future extension of the research.

School of Electrical Engineering Student's Signature__________________

Academic Year 2019 Advisor's Signature__________________

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Ashok Paudel

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CHAPTER I

INTRODUCTION

1.1 Background

Electricity is considered as one of the fundamental infrastructures of development. All countries are trying to develop a more sustainable and efficient power system. A power system is an interconnected mesh of generation plants, transmission systems, and well-planned distribution systems to supply to the end-user. This requires a huge investment, and since it is directly related to the prosperity and security of the nation. Previously, all rights related to the electricity markets were vested to the government and there was a monopoly market structure where a single electric utility own by the government manages the transactions of electricity all over the system. After the economic crisis of the 1970s, economists started to criticize the worthiness of governmental capability and efficiency, which led towards a great paradigm shift in the subsequent decade known as deregulation. Deregulation is the concept of restricting direct intervention of the government into any kind of business. This concept limited the role of the state as the regulator of the business or market rather than the active player. The concept of deregulation opened a wide variety of opportunities in various sectors, and the electric market is not an exception. After that, electricity become a commodity, and a competitive market for electricity comprising many service providers was established.

Deregulation also provides an opportunity for the development of a concept known as unbundling, meaning dividing the electricity market in mainly three functional groups: generation, transmission, and distribution. Both policies enabled private partnerships or contribution to the electric market. As the private participation was well welcomed and tremendous development in technology enables the utility to incorporate bidirectional energy trading, even a small domestic consumer is considered as the generator as he can generate some power utilizing renewable resources available in his locality and can sell such power to the main grid. This feature is now normally referred to as a prosumer based decentralized market paradigm (Van der Schoor and Scholtens, 2015). The most advanced scenario in such prosumer based energy trading is a peer to peer energy trading (P2P) (Giotitsas et al, 2015).

P2P concept is introduced in the second half of the first decade of this century and is still in the research phase (Beitollahi and Deconinck, 2007), the Brooklyn microgrid project is considered as the first milestone in this field (Mengelkamp et al, 2017). A major feature of this concept is managing locally produced power within the locality. A distribution network is divided into numbers of smaller functional units serving a small area or locality. That unit may behave exactly similar to the main grid. Such units are commonly referred to as a microgrid. However, in P2P, an even smaller unit known as Nano grids may be considered. Each unit consists of its generation facilities, mainly renewable resources and load. It is expected that its total generation is capable of serving its load, and if it fails to do so, power from the main distribution network will help to stabilize the system (Zhanga et al, 2016).

P2P trading concept is an under developing technology and requires a very safe and efficient communication facility, a fully automatic distribution network, bilateral energy meter, and efficient clearing agent and also socio-economic factors (Morstyn, 2018). Initially, this concept was introduced with a contract based clearing mechanism. In this method, two parties agree to buy and sell electricity for a specific time on a specific rate, which utilizes the facility of decentralization and distributed generation, however, lack the flexibility of trading with free market as the rate will not change until the period expires. P2P being a multi bilateral trading concept, overcome the shortcoming of the previous technique. As the number of players (peers) is large in the P2P market, a buyer can buy electricity from the cheapest supplier at any time, as it is mainly available for a short period mainly a day or hour ahead.

1.2 P2P schemes

P2P market models mainly classified based on the degree of freedom and technology used (Sousa et al, 2019). Some of the current schemes available in the literature are explained here:

1.2.1 Full P2P scheme

The full P2P model is commonly referred to as the blockchain model. In this model, two peers can trade directly without the involvement of any centralized control and clearing entity. Each peer announce their capacity to supply and consumption specifying acceptable rate of electricity (buying and selling price) based on the multi-bilateral economic dispatch and transaction occurs based on the agreement between two peers according to the rate specified

Figure 1.1 is the simplified demonstration of the blockchain model. Different kinds of prosumers having various generation facilities like solar and wind are shown. They can transact energy without any direct involvement of the central controller. The blue line represents the transaction among peers, and the red line denotes the transaction through the existing market or maybe grid transaction. If the transaction is solely done by peers (blue lines) without the involvement of the existing market then such mode of transaction is known as a full P2P scheme.

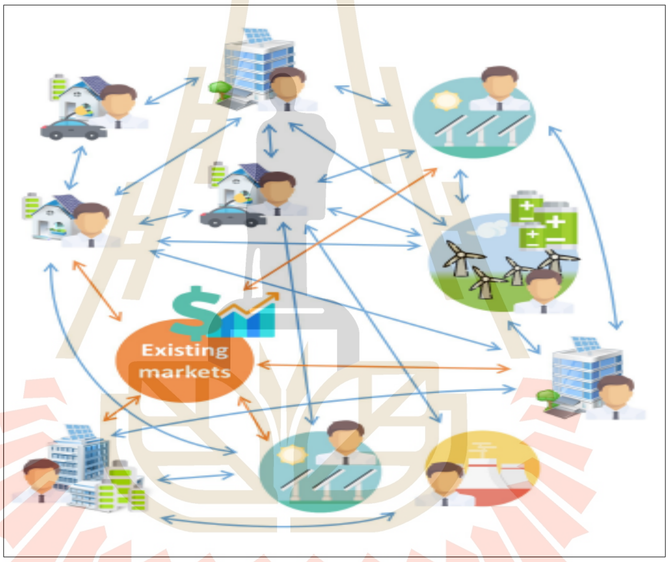

Figure 1.1 Blockchain model (Sousa et al, 2019)

1.2.2 Community P2P

It is clear from the name that it is mainly a community-based market. This model has a community manager (CM) that controls the power trading within the community. Such a manager may act as an agent for external trading, which may be either another community or grid supply. The community manager determines the rate of electricity based on supply and demand economics.

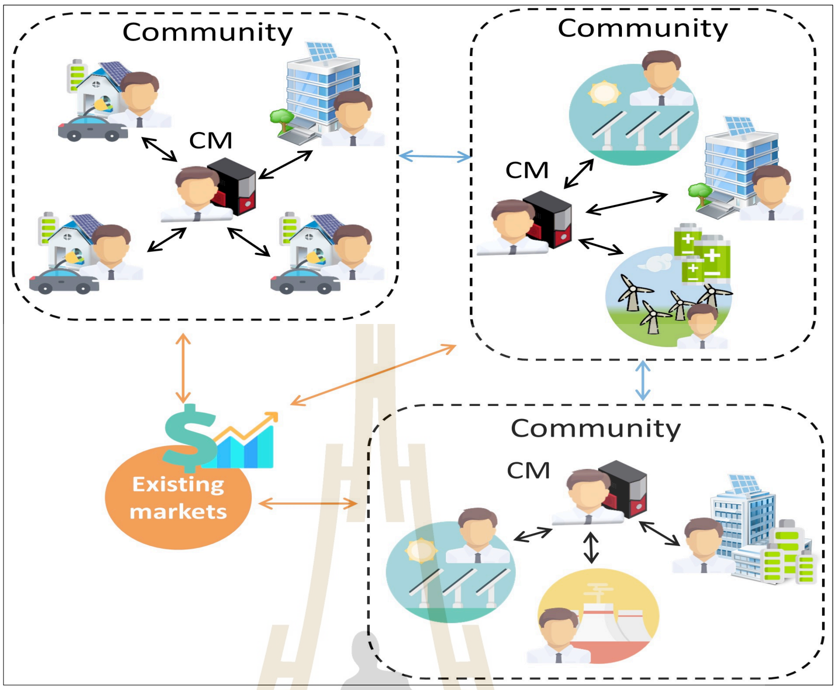

Figure 1.2 Community P2P market structure (Sousa et al, 2019)

Figure 1.2 shows the structure of the community P2P market. Each community has its central controller CM, which is responsible for the management of transactions among the prosumers of that community. It also acts as the sole treading entity among various microgrids or even the grid operator. In Figure 1.2, the transactions among the peers of a microgrid are done through the CM, and such transaction is represented by solid black lines. The blue lines represent the trading among microgrids without the involvement of the existing market or grid, which is interactions between community managers of various communities. If the trading involves the grid then such transaction is represented by a solid red line. To summarize, in a community P2P scheme the peers of a particular community are not able to transact energy to any other member of the same community or of the neighboring community and even the grid rather the transaction must be through the community manager.

1.2.3 Hybrid model

This is the combination of the blockchain model and community model. In this mode, energy trading may be either in any two models depending on energy availability and, therefore, the rate of energy. Figure 1.3 presents a schematic diagram of the hybrid P2P trading market. Energy trading can be done either individually or by forming a community and through a central energy manager. This model has the benefit of full P2P and community P2P. This thesis tries to investigate the models of cost allocation in the community microgrid based P2P market.

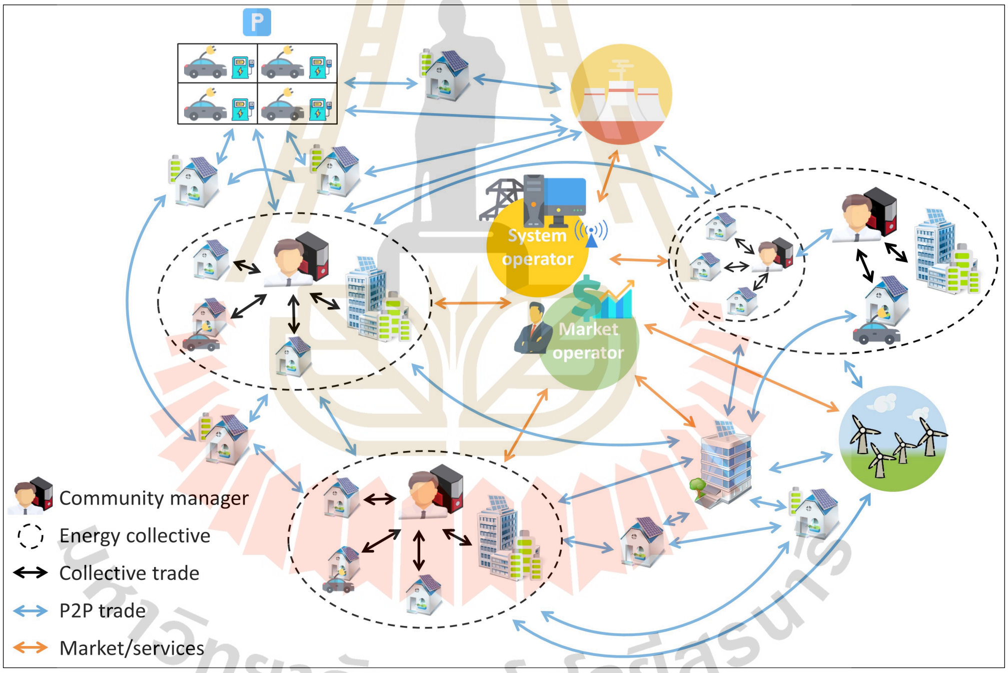

Figure 1.3 Hybrid P2P market (Sousa et al, 2019)

1.3 Common market paradigms or model

Three different market paradigms are formulated in literature, namely, collaborative model, multilevel transaction, and auction-based trading, which are explained below in detail.

1.3.1 Collaborative model

This model is targeted to increase the energy trading collaboration between every household located in the community. It is considered that the power requirement of every entity is different, and their maximum demand occurs at different times. So the power generated by prosumer is utilized within that community to fulfill the demand. The trading is done on the whole community level, meaning the rate of electricity is calculated at the community level irrespective of individual household's supply and demand (Long et al, 2017). The major aim of this model is minimizing the total cost of electricity within the community by utilizing locally available resources rather than minimizing individual bills.

1.3.2 Multilevel transaction

As community P2P can communicate with other peers through community controller or manager, it provides a possibility of multilevel energy transaction, meaning that trading between smaller size community to the progressively larger community and finally to the grid. This approach helps to minimize the cost of the individual prosumer (Paudel, 2018).

1.3.3 Auction based clearing (ABC)

In the ABC market, each prosumer offers their bids for selling and buying price according to their previous experience and (mainly an hour or day cost), then the market declares the actual rate according to the predefined rules. The major objective of this approach is to maximize the profit of both sellers and buyers within the community. The game-theoretic method (Leong et al, 2018) and double side auction (Nazif-faqiry and Das, 2016) method are the two most common auction algorithms applied in the analysis of the P2P market.

1.4 Problem statement

Community P2P is a highly researched topic for the past few years. Many models of cost allocation are proposed based on many factors (Long et al, 2017), (Zhang et al, 2016). However, every model utilizes a different mode of calculating cost based on different parameters. Not a single method is well accepted, and not a full-fledge commercial operating market is established to date. Though some pilot projects were implemented in many countries like Australia, England, Netherlands, and the United States in this scenario, two different pricing methods are considered assuming distinct features. The first method, as described earlier, is a collaborative model that mainly emphasizes collective energy management in a particular community. In other words, it helps community partnerships in the energy sector. The second method is a multilevel transaction, which is a compromised version of the previous method. It first manages its energy within its community, and then if any surplus energy is available, exports it to the other communities or grid (Paudel and Beng, 2018). Similarly, it can import power from the grid. As discussed earlier, the pricing strategy of each market model is different, and hence the outcome will be different. Participatory methods lack competitiveness, and also the fairness of use may be low because there will be no controlling mechanism to restrict the volume and time of power flow. However, it requires the minimum infrastructure than the other methods. Which makes it more appropriate for a small residential microgrid. The multilevel transaction is a relatively complex market structure than the participatory model. It is highly competitive because the fluctuation of supply and demand immediately affects the price of electricity. It requires a proper and secure communication channel between various levels and also among the prosumers.

The comprehensive study of the characteristics of the pricing method, the load profile of the prosumers, power availability in the microgrid, and the effect of the self-consumption of generated solar power is not done yet. To establish the P2P market, a detailed study of the pros and cons of the potential market models is a critical aspect. Effect of particular pricing strategy in the bill of particular prosumers must be thoroughly analyzed to assure community benefit and fairness of community partnership, and this is also very essential to build up the willingness among prosumers to participate in the trading market. This thesis is aiming to address these shortcomings.

Some countries like the US, Australia, UK, and Netherland are making some workable prototypes to implement the P2P market. On the other hand government of Thailand has issued a policy called power development plan 2015 (PDP2015), which emphasizes domestic solar PV production, bidirectional trading, and also microgrid based distribution to increase the share of renewable resources in the total power system. In this scenario, it will be a reasonable attempt to assess the various market model in local scenarios. This thesis is about to evaluate the effectiveness of the above-mentioned market model in terms of per day saving in electricity bills compared to the present grid transaction in Thailand.

1.5 Research objective

The major objective of the research is to determine the selling price and buying price of electricity in a community under various P2P scenario. Two different models are proposed to solve the problem, and each method represents a different trading mechanism and has a different focus. It simultaneously analyzes the effectiveness of each method concerning personal benefit, collective resource distribution rather than simply monetary value.

Some expected benefits of the research are listed below:

A. Determines the actual transaction rate of electricity under P2P various P2P scenario

B. Comparative study of different methods in terms of saving and size and type of prosumer

C. Provides a guide to select the best mode of a transaction according to the community requirement.

1.6 Scope and limitation

The scope and limitation of this study are listed below:

I. This work is solely concern with the calculation of the transaction rate of electricity. P2P market is an energy trading platform, so the first work is to determine the cost of the product (energy rate). In reality, the possibility of trading and other technical aspect related to the power system must be analyzed. However, this thesis work is more concerned about the profit of a particular prosumer from a particular pricing method.

II. It accounts for per day electricity bill as the deciding factor. The P2P markets are generally small-scale energy trading platforms and behave as an hour ahead or day-ahead market. Hence the billing is done daily, and the daily electricity bill is used for comparison.

III. Solar photovoltaic is considered as the generation source. Solar photovoltaic technology, the most common and convenient generation technology for the small-scale prosumers, is considered in this thesis.

IV. The size of PV is assumed as per the load demand of a particular prosumer, and the space availability is neglected. It is presumed that a prosumer can do that. Only the investment cost is considered.

V. It does not consider uncertainty in the generation and the subsequent load variation. To realize an hourly solar generation, a standard solar curve of the city of Korat is considered, and the contingencies and uncertainties are neglected.

VI. It assumes the presence of all infrastructures like power electronics, control, and communication channels. Since the work is solely concerned about the profitability of a particular pricing strategy, technical requirements are neglected or assumed as they are present.

VII. It does not account for the grid utilization fee and any other such fees. The utility may demand compensation for using their distribution network for the trading done by other entities. Such grid utilization fees are not included in this thesis. This assumption is made to ensure that each pricing method will result in maximum profit to the prosumer and is only resulted by the characteristics of the pricing strategy. In reality, this will not be the case, and the fees must be included. This is the possible extension of this thesis. Power flow analysis must be carried out in a real test system to demonstrate the effect of these extra expenses.

VIII. Only economics is the matter of concern so all technical aspect as network power flow, reliability, line congestion, etc. are neglected. i.e. uninterrupted power transmission in the network or community is assumed. Since the study focus on the characteristics of pricing method and how the bill of a prosumer varies in a community, based on supply and demand at a particular time, other technical aspects of actual power exchange are of little concern.

1.7 Research concept

This work intends to formulate varieties of pricing Methods in the community P2P market. As the technological development and policy reforms enable a consumer to not only consume electricity but can be a small generator, combined referred to as prosumer. To encourage the utilization of renewable resources and also reduce the stress in the grid researches are trying to develop a secure and efficient power market, mainly serving a small locality. Apart from communication and controlling and power electronics issues, reliable and economic pricing mechanism is also in a huge concern. To solve that problem some pricing Methods are analyzed here. Each prosumer generates and consumes power, and they are free to trade their power according to their necessity. If the available power in the community is less than the total demand, the grid service is available to serve the load. Similarly, surplus power can be sold to the grid. To ensure the economics of the system grid selling price must be lower than selling to the community and buying price from the grid must be higher than the community buying price.

1.8 Research procedure

The basic outline of the research procedure is presented below:

1. Formulation of microgrid data (solar generation profile and load profile)
2. Calculation of per unit electricity bill using various methods (explained in the methodology section in detail)
3. Calculate daily electricity bill using rate calculated in step 2 and make the comparison
4. Change the number of PV generators (it is quite reasonable to assume that all household is not equipped with PV facility), and also the type of prosumers (commercial dominant or residential dominant)
5. Repeat step 2 and step 3
6. Conclude the result with proper explanation

1.9 Thesis organization

This thesis consists of 5 chapters and presents the detailed description of the research project. Chapter I discuss about the basic introduction of P2P and problems and the research objectives. Chapter II presents the detail of P2P energy trading scenario, history, previous research and future perspectives. Chapter III presents the detailed mathematical analysis of pricing in different trading models. Chapter IV presents detailed analysis of results and finally Chapter V consists of conclusion and future work.

1.10 Chapter summary

Chapter I presents the general introduction of the development of the P2P concept, features, models, and related research. It also describes the existing pricing Methods with its fundamental characteristics and assumption on which it is based.

CHAPTER II

LITERATURE REVIEW

2.1 Background

The electric power system is a gigantic interconnected network of electricity generating stations, transmission facility, distributing and controlling mechanism, and a load. This may be of any size and mainly divided into three parts generations, transmission, distribution, or load side. The major objective of the power system is to provide an adequate supply of electricity to the load maintaining acceptable power quality. Figure 2.1 shows a simplified overview of the power system.

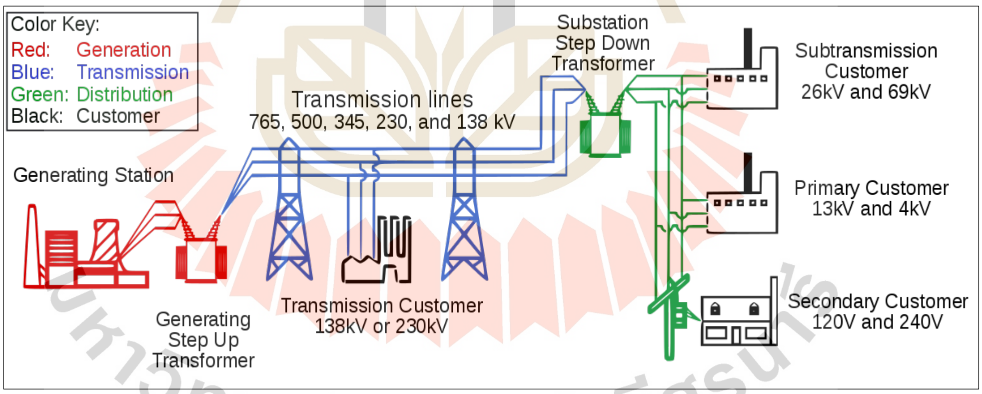

Figure 2.1 Overview of the power system (U.S.-Canada Power System Outage Task Force, 2004)

Generation functional unit generates electrical power from varieties of natural resources like fossil fuel, wind, water, radioactive materials, etc. All generation plants can be divided into two fundamental groups based on the resources they are utilizing to generate electricity. If the energy is generated from resources that are continuously replenished by nature, then such energy is known as renewable energy. Sun, ocean tides or currents, plants, and animal products, etc. are some examples of renewable resources. Apart from those, all generated energy is referred to as non-renewable energy. Coal, petroleum, uranium, etc. are the most common exam of non-renewable resources (National Renewble Energy Laboratory (NREL), 2001).

The main purpose of the transmission functional unit is to transmit the power generated in the generating unit or powerhouse. In most cases, natural resources are available in remote places (hydropower). Hence, power generation must take place in that area, but the major load center may be far away from the generation place; hence such generated power must be transported to the consumer. Transmission lines serve that purpose. It transports bulk power generated by powerhouse to a long-distance minimizing power loss. Transmission lines are mainly categorized into three groups according to their voltage range. Transmission lines up to 220 kV are known as high voltage lines. Similarly, lines in the range of 220 to 765 kV are referred to as extra high voltage lines, and that of the above 765 kV is commonly called an ultra-high voltage line.

Transmission lines are required to interconnect all generating units available within a certain territory (country); such a system is known as interconnected system or grid system. This enables a nationwide transmission of power generated in a specific part of the territory.

Distribution is the third major function unit of the electrical power system. It is the most complicated unit among all three units. The main purpose of distribution is to provide electrical energy to each consumer according to their demand. The supply voltage depends upon the requirement of the consumer. Generally, a distribution voltage may be as high as 132 kV three-phase and also as low as 110 V single phase.

The final destination of a transmission line is a step-down substation where the voltage level is reduced significantly to suit the consumer demand and is the origin of the distribution system. The distribution system feeds that energy to all consumers. Many distribution configurations are available with varying degrees of merits and demerits. The most common distribution methods are radial, loop, and mesh distribution system. The radial distribution system is the simplest and cheapest model of distribution and is common in almost all over the world. In this mode, energy is feed from one end of the line and distributes that to another end (load). Since it emphasizes one-way power transfer, it has the lowest degree of reliability. The loop distribution system is a simple modification of radial system with some interconnections between two or more individual lines, enabling rerouting of energy during any contingencies, which consequently improves the reliability on the contrary cost and difficulty in fault location increases. The mesh distribution system is the most advanced distribution model and is costliest though the reliability of supply is highest in this model comparing to other counterparts. In this distribution system, there are many routes available to supply energy from substation to the load.

Power losses, the voltage drop in the line, reliability of supply, fault detection and clearance, stability, quality of supply, safety, and metering are the basic parameters of a power system. All necessary components and techniques required to maintain these variables within acceptable limits in conjunction with generation, transmission, and distribution functional unit produces a sophisticated electrical power system.

2.2 Thailand power system

Thailand has a very long history of electricity. Electricity was first introduced in the country by field marshal Chao Phraya Surasakdi Montri on 20 September 1884 just a couple year later of installation of first electrical infrastructure in new jersey USA on 31 December 1879 (Electricity generating authority of thailand (EGAT), n.d.). Thailand has witnessed a mammoth revolution in the energy sector since then. As per the data of 2014, the total installed capacity of the country reached 37612 MW. Electricity generation authority of Thailand (EGAT) is the largest energy producer of the state accounting 41.2% of total generation. Remaining is contributed by private energy produces or independent energy producers (IPP), small power producers, very small power produces and import from neighboring nations the share of abovementioned stakeholders in total capacity is 35%, 12%, 5.4%, 6.4% respectively. The major technology used in the country is combined cycle, thermal, and renewable energy technology. Only 8476 MW energy is produced from renewable resources indicating heavy dependency on fossil fuel. Thailand has a very high potential for solar power generation, and it should be a possible option to minimize such a huge dependency. According to the power development plan 2015 (PDP2015) (Energy policy and planning office, 2015) it is expected that the installed capacity in 2036 will reach 70335MW, i.e., the addition of another 57459MW in the next 20 plus year. But the expected power addition from renewable resources is 21648MW only, just above 37%, indicating the nation is still lacking commitments to reducing non-renewable energy dependency. However, one-fifth of total power will be generated from renewable resources in 2036, which is more than double of the current 8%.

The most interesting insight of PDP2015 is it has officially advocated small scale solar generation in individual household level. Solar rooftop like programs is expected to shore in the coming years. Domestic renewable energy generation is forecasted to reach about 12105 MW from 2015 to 2036, which is about 57% of expected renewable generation. This clearly indicates the nation's willingness to incorporate a distributed generation based energy system. P2P technology is one of the most advanced technologies in the sector of small scale energy trading and management and hence is very logical to ascertain its viability at this time.

EGAT is not only the power producer; it is responsible for bulk energy buying from IPP and manage the national grid. Managing transmission line and power dispatch also falls within its jurisdiction. EGAT operates the transmission line of various voltage levels. 115kV, 132kV, 230kV and 500 kV is the currently existing transmission voltage level in Thailand. The total length of all types of transmission lines is just above 33 thousand circuit kilometers and is dominated by 115 kV lines, constituting 56.95% of total length. The cumulative power transfer capacity is 106889 MVA.

Provincial electricity authority (PEA) and metropolitan electricity authority (MEA) are two government-owned utility responsible for the distribution of energy throughout the country. MEA distributes power in Bangkok, Nonthaburi, and Samut Prakhan provinces, and the rest of the places is the responsibility of PEA. Both utilities buy electricity from EGAT and distribute it to the consumers according to their demand. The primary distribution voltage level used by PEA is 22kV. Some private companies are also allowed to sell energy directly to the consumer. Energy regulatory commission is the regulatory body in the power trading sector and responsible for nationwide electricity tariff (Provincial electricity authority (PEA), 2018).

The radial distribution system is the most commonly used distribution model in Thailand. Utilization of local resources to produce energy will benefit the community and nation as a whole considering these facts PEA has started research and investment in microgrid technology. As the policy is to enhance a distributed generation based distribution system, PEA has developed an exemplary microgrid network consisting of solar PV, micro-hydro, and battery storage at Khun Pai village of Chiang Mai province (Kasirawat et al., 2017).

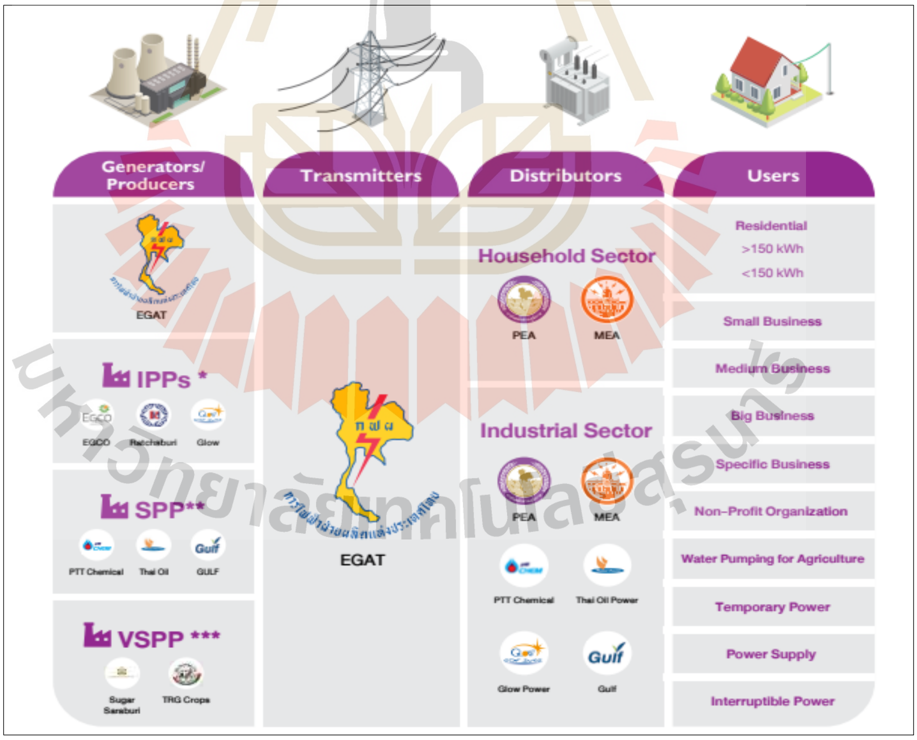

Figure 2.2 Thailand Power System and related organizations (PEA report, 2018)

2.3 Power distribution and microgrids

The power distribution network is part of a power system that serves the load. In other words, the distribution mechanism is the pool between bulk power supplies to the individual load equipment. Radial, mesh, and interconnected models are the commonly used models of distribution networks. However, in recent days due to the technological development distribution system, it is on the verge of reform and the concept of a microgrid is emerging now. A microgrid is almost a replica of the main national grid consisting of its generation and load, which may function either independently or as a subsidiary of the main grid. According to (Microgrid at Berkeley Lab, n.d.) microgrid can be defined as "a group of interconnected loads and distributed resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected and islanded mode". Development of a microgrid based system with its generation facilities gives birth to a new concept of the prosumer based energy system. A prosumer is a consumer also equipped with the production facility. Such a huge paradigm shift in the energy trading sector gives an entirely new aspect of small scale energy trading among prosumers. A bidirectional energy transfer among prosumer with a net metering facility would be the simplest form of trading in a decentralized market. However, it cannot provides maximum benefit to the prosumer as it is unable to account for many aspects like supply-demand, energy storage, etc. An improvement in the operation of microgrid incorporating bidirectional energy transfer between either prosumer to prosumer or prosumer to microgrid operator with the help of information communication technology is known as the P2P market (Liu et al., 2015).

2.4 Prerequisites of P2P market

The primary objective of the P2P market is to distribute power to the consumer ensuring economics, quality of supply and self-governing. Numerous information channels is to be utilized to share information for the proper functioning of the market. A P2P network must be capable of automatically handling contingencies, restoration and must accommodate distributed resources by executing the distributed algorithms. The fundamentals aspects of a P2P market are sharing of resources either physical or informational (logical), decentralization of the energy market and self-organization (since decentralization is already considered the system must be self-sustainable) (Beitollahi and Deconinck, 2007). There are certain elemental necessities to realize the above mentioned aspect of the P2P market and are described hereafter.

2.4.1 Power electronics equipment

The primary characteristic of the P2P market is to manage bidirectional power transactions among the prosumers. The prosumer must be equipped with all appropriate power electronics required to facilitate such transactions. Generally, small scale prosumer generates from solar photovoltaic cells, so the proper power converts and control system is necessary to ensure the quality of supply, safety, and security of the power transfer activities.

2.4.2 Smart metering

Smart metering is the fundamental component of any smart grid technology. It is far more advanced than the traditional energy meters. These are capable of sensing, recording, and transmitting the data of various electrical parameters like voltage, power factor, frequency, etc. with great accuracy. Hence it can be utilized for numerous purposes like automatic meter reading, remote connect disconnect, etc. different information technologies are used to manufacture different kinds of smart meters according to their application. Home area network (HAN) technology-based meters are used in a smart home. It monitors the performance of all equipment and acts as a central commander of the domestic power management system. Neighborhood area Network (NAN) architecture based energy meters are capable of transmitting data to the comparatively larger network and is more suitable for the power exchange application (Ekanayake et al., 2012.). The selection of smart meter technology must be made according to the application.

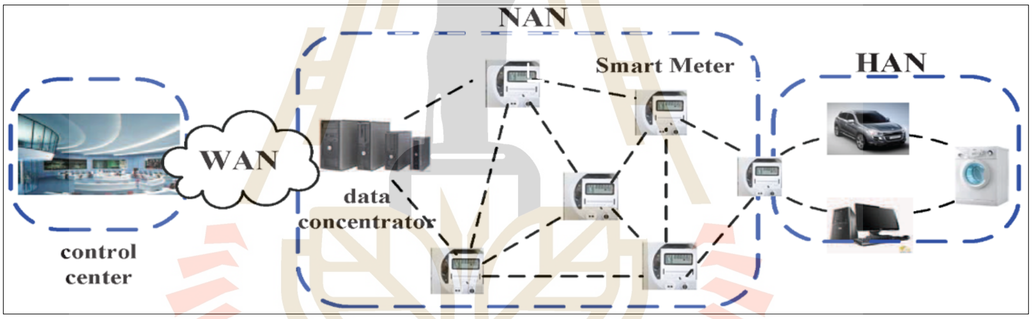

Figure 2.3 Smart meter technologies (Yang et al., 2015)

2.4.3 Communication technologies

Proper synchronization among various peers and entities is the backbone of the P2P market. To ensure such precise synchronism, an advanced, efficient, and secure communication technology or protocol is the must. Many techniques are developed to support the P2P power transaction, and some are in the standardization process. International organization for standardization developed a standard model known as open system interconnection (OSI) model (Oodan et al., 2003). Another standardized communication protocol used in the P2P trading market is TCP/IP protocol (Dunlop and Smith, 1994).

2.4.4 Standards and policies

P2P is a relatively new concept and is not fully commercially available all over the world. Hence, there is very little information about its weaker section. Data security is the most challenging issue in the current time. As the P2P trading technology is still in research phase there is lack of proper standards, guidelines, and framework for many issues related to the technology like power quality, communication technology, data security, personnel privacy, etc. it is expected that as the time passes and such problems will eradicate.

The foundation of the P2P market is the concept of the prosumer. To perform bidirectional power transfer a prosumer must use existing distribution network infrastructure, which listens pleasant to ears but is one of the toughest work to accomplish at low voltages level. Voltage fluctuations, line congestion, overloading of switchgear and protective equipment, the safety of the personnel, wheeling charge, etc. must be taken into account before the establishment of the P2P market. Proper government policies must be there to account for all the above-mentioned factors together with unbundling policies of the power system.

2.5 Impact of P2P on microgrid

P2P market in distribution level prosumers is fundamentally dependent upon the small amount of power produced by the consumer by utilizing locally available distributed energy resources (DER) like solar and wind. Traditionally a distribution line is considered as the passive system as it does not contain any active generators and simply delivers power to the load from the substation. With the integration of distributed generators (DG), it will become an active network and consequently will have many impacts on the distribution system which was first constructed considering passive power networks (Jenkins et al., 2010). To mitigate those problems and ensure the quality of supply utility may restrict the amount of power to be inserted into the system.

The most significant effect of DG will be voltage fluctuation in the system. Voltage deviation is the function of active and reactive power transfer as well as line constants. Since the line parameters will not change, voltage fluctuations can be controlled by either varying active or reactive power transfer. Since the solar PV, which generates active power only, is a common DG type in small domestic consumer groups such deviation may be high so the compensation facility might be needed. The fault level of the system will also increase after DG integration, harmonic distortion may occur due to improper synchronization and flow of harmonic current. All these factors affect both the steady-state and transient stability of the distribution system. Consequently, a serious problem in the quality of supply will occur.

2.6 Four layer architecture of P2P

European standardization organization has proposed a standard model to enhance technological development related to the smart grid and is popularly known as the smart grid architecture model (SGAM) (smart grid coordination group, 2012). It is a three-dimensional chart as shown in Figure 2.4. The first axis is named as a domain which is simply energy production infrastructure and deals with supply chain and economics related to energy production. All physical power system infrastructures like generation, transmission, distribution, and consumer case, and its economics are accounted for in this dimension.

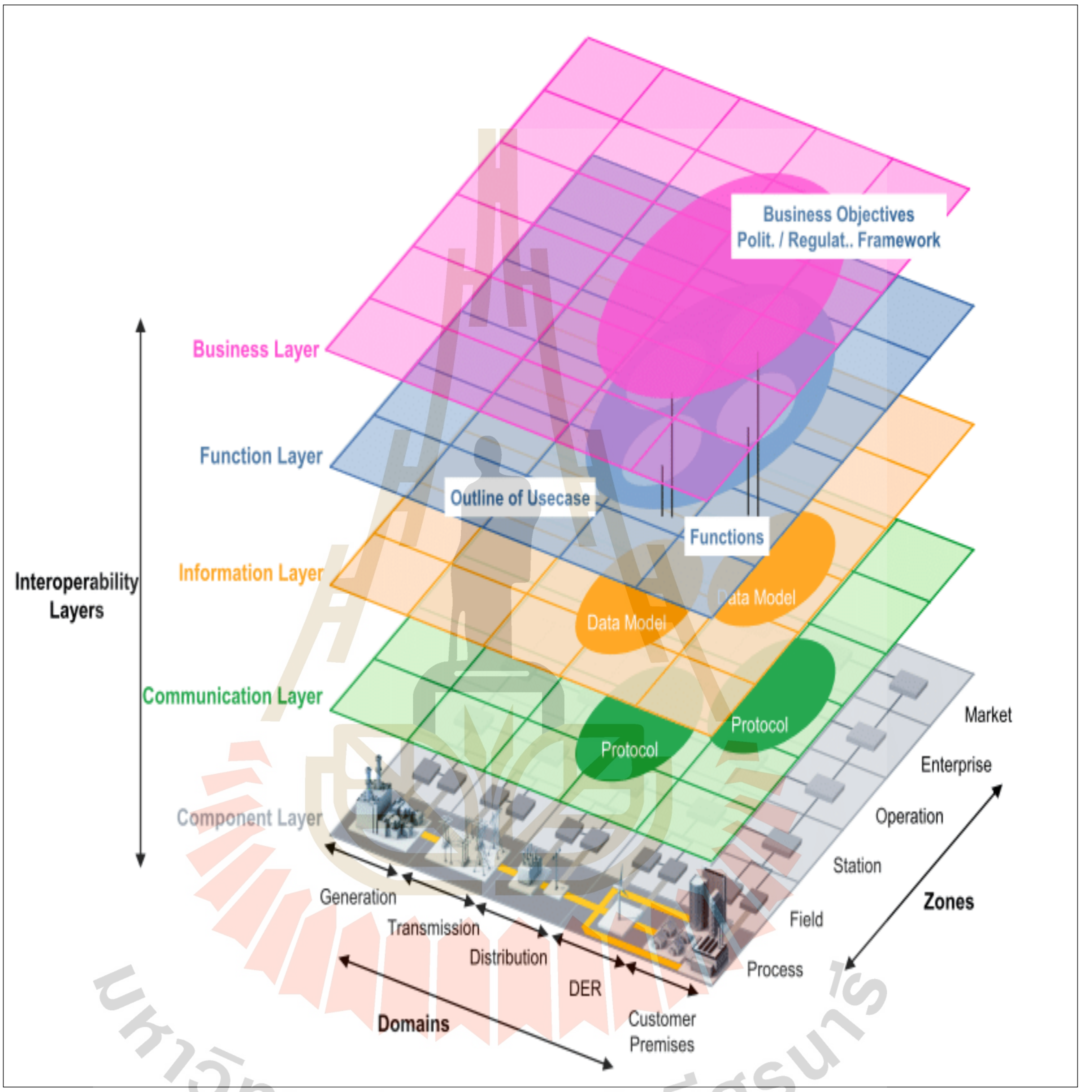

Figure 2.4 SGAM model (smart grid coordination group, 2012)

The second dimension of the model as shown in the figure is named as zones. Zones deal with controlling and managing activities related to the power generation or transfer. It is an ICT based technology and is focused on the effective operation of the power system with the highest standards. It has many functional units as in Figure 2.4.

The market is mainly responsible for large scale trading of energy like. Enterprise's role is to finance the system and includes commercial or organizational structures. The third zone is an operation that is responsible for the operation of a certain department like generation management, communication management, etc. The station represents the data aggregator in the system. It collects data from various fields. The field is an actual working ground like switchgear equipment and its state. It sends data to the station. The final zone, process describes the process of energy conversion and the immediate equipment involved in that process.

The third dimension is named as interoperability layers. Five layers are identified in the figure namely business layer, functional layer, information layer, communication layer, and component layer. Business layer deals with the business plan, the functional layer is responsible for the operation and management of functional unit or services, information layers monitors the data flow and its security whereas communication layer defines technology to facilitate data transfer. Last but not the least component layer deals with both the power and communication physical component involved in the system.

Based upon the SGAM model, Zhang et al. (2016) has developed a four-layer architecture of the P2P trading platform as shown in Figure 2.5. It is also a three-dimensional representation. The information and communication layers of the SGAM model are combined to form a single layer hence called four-layer model.

The second dimension of SGAM is zones and is related to control and monitoring but in the four-layer model describing P2P trading, it is replaced by trading methods and market requirements.

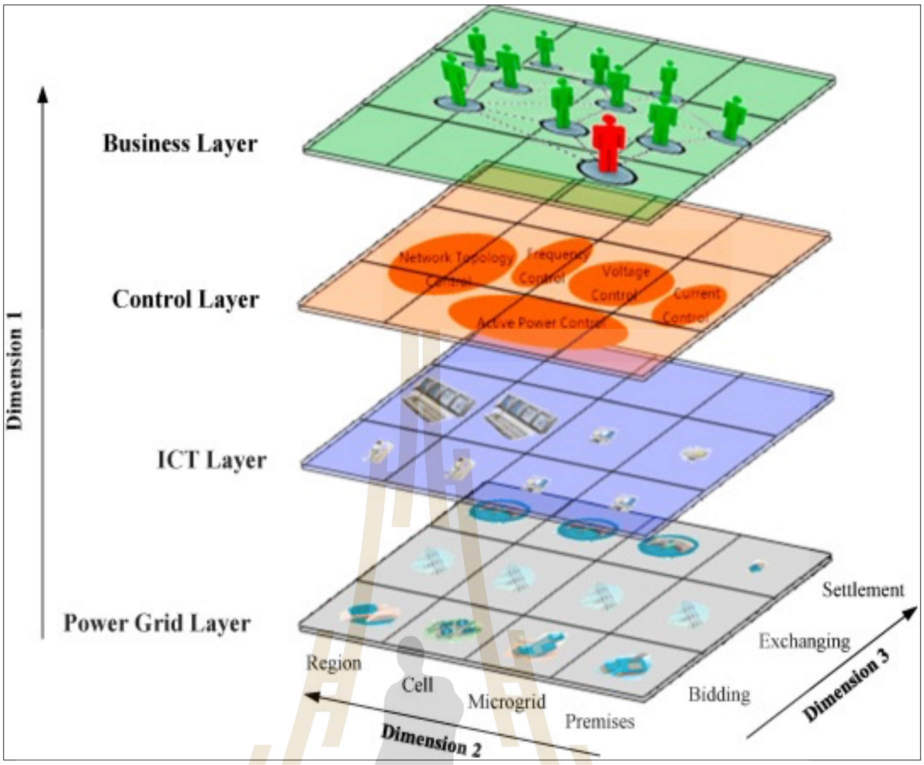

Figure 2.5 Four layers architecture of P2P market (Zhang et al., 2016)

Four inter-operability layers are defined as dimension 1 which are the power grid layer, ICT layer, control layer, and business layer. The power level grid is the primary layer and consists of all power generation and consumption devices and processes involved in those activities. ICT level deals with all information and data transfer devices and technologies required to perform a secure and reliable information-sharing network. The Control layer mainly deals with power system control and load dispatch in the system. The business layer is responsible for all business decisions policy formulations and organizational operations. This layer determines possible buyers and suppliers whether they are peers or grid.

The second dimension mainly deals with the size and character of peers involved in the trading market. Which ranges from a single house as indicated by premises to a region. The smallest possible peer or player in the trading market is a single house. Collection of houses or a community can be served by constructing a microgrid and the whole microgrid can act as a single peer in the market. Similarly, a further larger unit would be multi microgrid and is denoted by name cell in Figure 2.5. The collection of many multi microgrid systems would result in the largest unit region. Clearly from its name, it refers to a large region or area and may consist of many power substations. P2P trading market can be established by considering even a whole region as a peer.

The third dimension mainly deals with the method of electricity price determination and clearance. Which involves bidding, exchanging, and clearance. First of all peers bids the amount based on previous data or trends then such bids are processed to determine supplier and consumer and also amount of power to be exchanged among them. Finally, payments of the power exchange will be made and hence the cycle of power trading completes.

2.7 Current pilot projects in operation

2.7.1 Power Ledger

It is a Perth based startup company working on the implementation of the P2P market (Canstar Blue, n.d.). This company uses the blockchain model as the trading mechanism. This company digitally reads the solar power generated by each player and load demand of potential buyers, then it converts such power in terms of virtual money and offers transactions among the buyers. Buyers then pay the amount in actual money to the offeror.

2.7.2 Lo3 energy

This is another startup company working in southern Australia, which involves auction-based market model. This is the extension of the Brooklyn experiment, and power transaction is possible using a mobile app (Canstar Blue, n.d.).

2.7.3 Sonnenflat

This is an example of a load-sharing type P2P market. It requires an entity to install solar PV of more than 5kw and then subscription of 30$ to 50$ per month. All entities must share a part of their solar generation according to the subscription plan. This mainly focuses on storing and sharing the power to improve the line congestion and utilization of distributed energy resources (Canstar Blue, n.d.).

2.7.4 Transactive grid

The transactive grid is a community electricity network located in Brooklyn. With the help of suitable software and hardware equipment, a single entity can buy or sell power to another entity automatically based on the blockchain method. This is the most appropriate work carried out at the community microgrid level (Zhanga et al., 2016).

2.7.5 Vandebron

It is a market operating in Netherland where consumers can buy electricity directly from wind turbines operated by farmers on their farm. The consumer can prioritize the generator from which they want to buy power and is mainly based on locality and type of supply (Vandebron, n.d.).

2.8 Future of P2P

It is expected that the P2P market will go to a higher level than is in the present. Implementation of a highly secure and reliable blockchain model may virtually eliminate a central controlling agency or distribution system operator using real money. Almost all transactions may occur using virtual money within the community, and if the net income is calculated only then real money is introduced multilevel or hierarchical trading is also expected to become a reality soon. In this scenario, energy trading is done in a level by level manner. Firstly, P2P within the blocks of microgrid then within the microgrid and finally between microgrid.

2.9 Previous research in a community microgrid

Community microgrid trading aspect was originated after reviewing the problem related to the pool market as the pool market usually trades a large amount of power and thus a larger business dependent entity; it cannot address the concept of distributed generation or distributed energy resource utilization. To enhance such utilization, a concept of bilateral contract is introduced; it is the agreement between two parties to trade power, generation facility, or any infrastructure or resources for a specified time frame. Bilateral contracts increase market competition, stabilize the market price, and also enhance renewable energy consumption (Hausman et al., 2008). A study carried out in England concludes that by implementing a bilateral contract between buyer and seller rather than the existing pool market, the whole shale electricity price reduced up to by 10% of current pool price (Bunn and Bower, 1999). Research article (Wu and Varaiya, 1995) and (Wu and Varaiya, 1999) proposed a multi-bilateral treading model as an alternative to the pool market structure it is mainly derived for a large power trading rather than in a microgrid level, however, the concept of P2P develop afterward is almost following it, so virtually we can say this model as one of the origins of P2P trading market structure.

Moret and Pinson (2018) proposed a shared community market based on the fairness of use. When prosumer of a community shares their part of generation among each other, the electricity bill of the whole community decreases. The results show that the quality of experience, which is the measure of consumer satisfaction increased from 0.15 to 0.95 as he shifted from individual grid trading to community trading. It also proved that if a central governor is introduced in the system, its performance and fairness degree will increase as the maximum importer will get penalized an auction-based sharing market model using energy storage mechanism is analyzed in (Tushar et al., 2016). The main contribution of this work is to define a way to calculate the amount of energy that an individual household may share according to the price and supply-demand economics. An agent-centric model is described by Ilic et al. (2012), agent bids the price within the specified range depending upon the basic law of economics. An article by Akter et al. (2016) is not directly involved in the energy trading scenario rather than optimize the cost of energy storage in a community using battery energy storage (BESS). P2P framework is used in much other application apart from the residential community (Alvaro-Hermanam et al., 2016) presents a naval approach to minimize the EV charging load on the grid during peak time using P2P energy sharing between EVs. It shows that the cost of charging drastically reduced up to 71% in a specific are considering grid price and mobility of the owner.

P2P trading consists of four layers, namely power grid level, ICT layer, control layer, and business layer. A game-theoretic approach based on Nash equilibrium Methodology considering the probabilistic cost of generation and convenience of the consumer proposed in Zhang et al. (2016), shows that load balancing strategy can be achieved by using P2P trading market. An auction-based clearing mechanism proposed in Khorasany et al. (2017) accounts for the cost of using existing infrastructure like the distribution line. If a community microgrid is constructed by sectionalizing the existing network and P2P trading is done among the peers in the community, they must pay an amount to the network owner as of the charge of using his property, which seems more practical than others. Some prosumer may shift their peak load of morning and evening to the off-peak period or cheaper period mainly day time as PV generation is only possible at that time. However, it may impact the convenience of consumers. A strategy is developed in Wu et al., (2018) to formulate a pricing strategy that accounts for such inconvenience. Prosumer having higher generation capacity will get maximum profit and consumers having no DER will pay more than any other member of the community. In a competitive market, some players may buy more energy than their demand and store remaining energy to sell such energy at another peak time. This strategy mainly depends upon the revenue and storage possibility. Auction based market is highly investigated in many areas including community microgrid, and the main strategy of market-clearing is the equivalent rate of buying and selling calculated based on the price obtained from bidders which will maintain equilibrium in the system. Another strategy is volume-based clearing, in this concept market clearing is in terms of the number of goods to be traded (Niu and Parson, 2013). A similar trading mechanism in the multi-microgrid system is described in Lee et al., (2015). The authors derived a method to allocate a specific amount of energy rather than per unit energy price. Buyer will be allocated an amount based on the proportion of their price and sellers will get their revenue equal to the proportion of their sharing in the trading. However, it is not quite convincing in terms of community microgrid as the trading volume is significantly small, and also the storage facility will surpass the revenue it could generate. Table 2.1 presents the comparative study of previous researches conducted in this field.

Table 2.1 Literature review

Year	Author	Description
1999	Bower and Bunn	Implementation of the bilateral contract reduced the price of electricity by 10% and is because of the increased competition among retailers
2015	Lee, Guo, Choi and Zukerman	A buyer can buy a higher amount of energy than its demand and store excess energy to sell during a high price period. It optimizes the volume of power that a particular buyer could buy, considering the expected revenue such stored energy would generate and storage facility it has.
2016	Alvaro-Hermana, Ardanuy, Zufiria, Knapen and Janssens	Implementation of the P2P mechanism in electric vehicles to minimize the EV charging load at peak load time. It optimizes the mobility and grid electricity price. It is found that the cost of charging reduces by 70% in some areas.

Table 2.1 Literature review (Continued)

Year	Author	Description
2016	Tushar, Chai, Yuen, Huang, Smith, Poor and Yang	A game-theoretic approach to share the capacity of individual storage capacity for monetary benefit in a community microgrid is proposed in this paper.
2017	Khorasany, Mishra, and Ledwich	A double auction-based hour ahead transactive market is proposed. The clearing price is the mean of reservation price offered by buyers and the buying price offered by buyers. The major feature of this article is that it accounts for the cost of utilizing network infrastructure to transfer power and is imposed on the electricity rate.
2017	Long, Wu, Zang, Thomas, Cheng and Jenkins	Three different pricing strategies are analyzed here, bill sharing, mid-market model, and auction-based transaction. The first method is the simplest market model and focuses on community benefit. The second and third method is similar in terms of declaring the transaction rate only difference is the method of assigning bid.
2018	Zhang, Wu, Zhou, Cheng, and Long	Describes the supply-demand balancing in the P2P scenario. It is found that the peak demand reduced by as high as 17.6%.

Table 2.1 Literature review (Continued)

Year	Author	Description
2018	Wu, Zhang, and Li	It describes two pricing strategies; unified and identified. Unified pricing accounts cost of inconvenience that may occur due to indirect demand response and other methods use the auction algorithm to distribute power. The saving of the peer will be higher in case of identified pricing however the seller having larger capacity will earn more and peer having no generation will pay higher so, community welfare may be questionable.
2018	Moret and Pinson	Community sharing is the basis of community P2P structure and in some cases, such sharing may not result in an equal benefit to the participants. This article analyzes such a scenario by introducing additional cost for higher import. It is found that the presence of an independent controller will result in higher fairness among the members.

Table 2.1 Literature review (Continued)

Year	Author	Description
2018	Paudel and Beng	Authors have presented a novel approach to analyze the possibility of the P2P market in community microgrid taking the existing vertical system as the reference network. They combined the conventional and distributed generation approach and introduced a free market structure at different levels. Pricing strategy is governed by the supply and demand principle of economics.

2.10 Chapter Summary

Chapter II describes about the basic outline of power system and the overview of Thailand power system. It also includes the explanations about the concept, structure, prerequisites and development of P2P with some pros and cons with some previous research conducted in the field of P2P trading.

CHAPTER III

METHODOLOGY

3.1 Introduction

This section describes the different P2P market structures mathematically. Participatory and multilevel P2P market structures are described with their characteristics. The participatory market structure is mainly concerned with community benefit rather than a competitive market based commercial profit, so a time-invariant pricing Method is presented here, which is based on the cumulative power import and export of a day. Multilevel P2P paradigm is a highly competitive, commercially sustainable future distribution model. As supply and demand vary throughout the day, so rate must vary accordingly. To account for such fluctuation in supply and demand a deciding factor named as demand to supply ratio (SDR) is used to calculate the rate of electricity at various levels. Each level has its price within its jurisdiction calculated based on SDR and price defined by immediate upstream power trader.

3.2 Overview of solar power potential of Nakhon Ratchasima

Nakhon Ratchasima is located on the northeastern side of Thailand. Nakhon Ratchasima, commonly known as Korat, is the largest province of Thailand by land area and has an approximate population of 2.7 million. It contributes about 250 billion baht to the national GDP. It is the highest among northeastern provinces, which indicates Nakhon Ratchasima is the major business center of the northeastern region and is one of the rapidly growing cities in Thailand. Expanding the city means rapid growth in energy demand. Korat city currently hosts various shopping centers, business enterprises, universities, and a number of manufacturing industries, clearing indicating the prosperity of the city and the huge power demand. Such demand is curranty supplied by the power generated from many nonrenewable resources. Even so, Nakhon Ratchasima has many renewable power generation stations. Lam Takhong pumped storage plant (500MW) is the largest hydropower plant located in this province. Some wind farms like Wayu wind farms are also operating in this province. However, Korat has a gem in its hand, the sun. This province is in the list of highest solar potential provinces. The average annual solar potential of Nakhon Ratchasima is estimated as 5.2 to 5.4 kWh/m^2/day, whereas average cumulative annual energy production potential is projected in the range of 1899 to 1972 kWh/m^2 as shown in Figure 3.1 (Global solar atlas, n.d.). Considering these facts this region is an ideal place for the solar generation facility. Many small to medium scale solar farms have already been built in this area to harness that power.

According to PDP2015 Thailand, the government is encouraging people to generate electricity from solar photovoltaic and even allowed them to trade with the utility. As the technology advanced and the solar installation cost began to fall drastically, the concept of bidirectional energy trading emerged. One of the recent technologies in the field of the bidirectional transaction is P2P trading. Thailand currently does not has any firms or company which is running any kind of P2P trading business. However, the government is encouraging such activities. In this context, it is logical to study the economic viability in this region by considering the daily load profile and probable solar generation in various P2P trading scenarios.

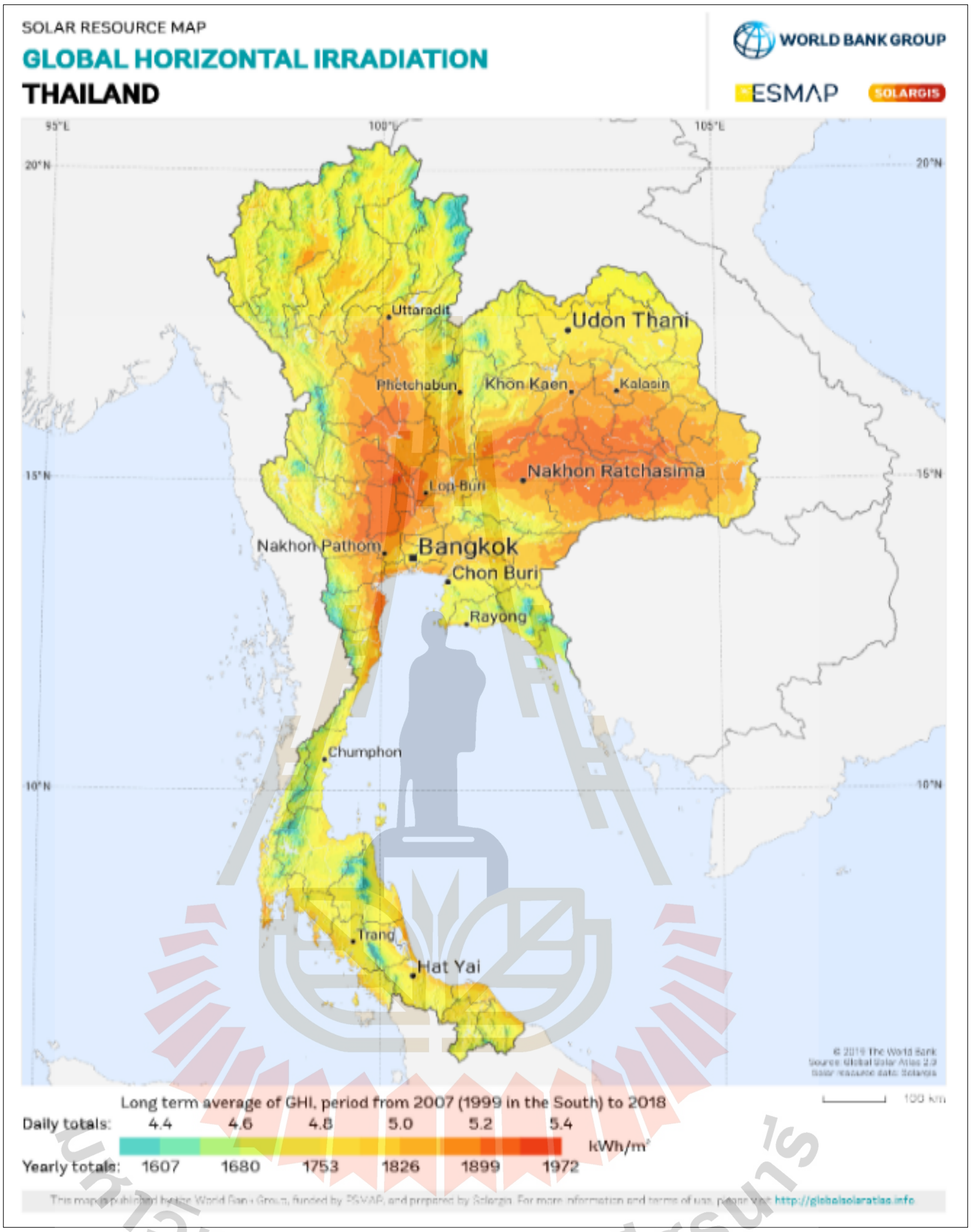

Figure 3.1 Solar power potential map of Thailand (Global solar atlas, n.d.)

3.3 Load curves

The load curve is the graphical representation of the variation of load with respect to time. According to IEC 60050 load curve is the graphical representation of the observed or expected variation of the load as a function of time (International

Electro-technical Commission, n.d.). According to the considered duration of time, load curves are divided into various types. If a load variation of one day (24 hrs.) is drawn, then such a graph is referred to as a daily load graph or curve of a particular consumer. Similarly, the monthly and annual load curve of a specific consumer or area can be obtained. It is observed that a group of the consumer has similar load characteristics and are classified in various groups or types for an easy understanding. Domestic consumers, commercial consumers, and industrial consumers are the three primary consumer groups adopted all over the world. The load pattern of a respective group of the consumer will approximately be similar throughout the nation.

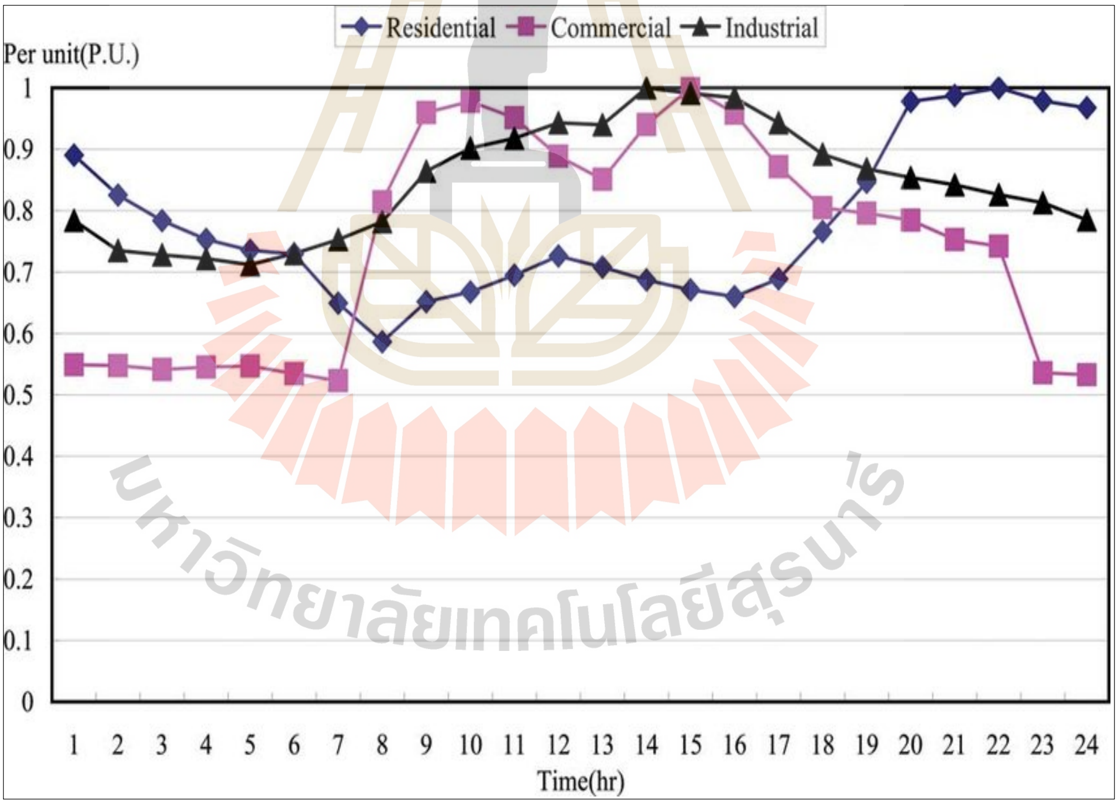

Figure 3.2 Typical load profile (Lin et al., 2008)

Domestic consumers generally have high power demand mostly during evening time and morning time and have minimum load demand during day time. It is because people stay at home and consume energy mainly in the evening and morning hours, but during day hours they go to work and hence the demand will decrease. On the contrary commercial consumers has maximum demand during day times or office hours and low demand at other times as offices and business complexes mostly operate in day times. On the other hand, industrial consumers may have uniform load demand throughout the day if they operate on a shift basis, maintaining almost constant demand.

3.4 Basic solar terminologies

Solar irradiance: it is the sun's radiant power measured in W/m^2 or kW/m^2.

Solar constant: it is the average value of the solar irradiance outside the earth's atmosphere. It is conceded as a constant term having a magnitude of 1366 W/m^2. Whereas it is standardized that any surface of the area one square meter located at sea level, will receive a maximum amount of 1000 W power in a clear day and the time when it occurs is called solar noon. The peak value of 1000 W/m^2 is called the solar peak. In other words, solar irradiance measured outside the atmosphere is known as solar constant, and that measured on the earth surface at sea level is known as peak value having a magnitude of 1366 W/m^2 and 1000 W/m^2 respectively.

Solar irradiation: it is the measure of the sun's radiant energy incident on a surface of unit area. It is measured in kWh/m^2. Solar irradiation is equal to the solar irradiance multiplied by the time.

Peak sun hours: it is the average daily amount of solar energy received on a surface and is equal to the number of hours that the solar irradiance would be at a peak level of 1000W/m^2.

All aforementioned terminologies can be explained by taking the reference of Figure 3.3 its x-axis is the time of day, and the y-axis represents solar irradiance W/m^2. The blue curve is the plot of solar irradiance throughout the day. It starts peaking after sunrise and achieves maximum value at some instant of time, which is known as solar noon, and the maximum value is called the solar peak, which equals 1000W/m^2 if it is located at sea level considering the most favorable condition. After that, it starts declining and becomes zero at the time of sunset. The area under the curve represents solar irradiation or solar energy. If the whole area is squeezed to form a rectangle having the height (Y-dimension value) of 1000W/m^2, then the breadth (x-coordinate) will give the value of peak solar hour.

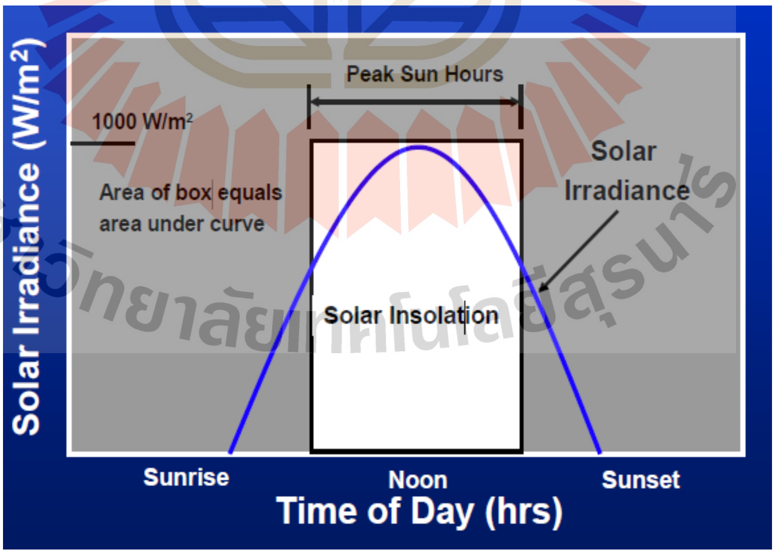

Figure 3.3 Solar terminologies (Dunlop, 2011)

3.5 Participatory method

This is the simplest method for pricing electricity. A whole community appears as a bulk consumer for the utility and bills accordingly. In contrast, individual entity inside the community serves as a contributor for that bill issued by the utility. All member of the community share their generation among the member, and if the demand is still higher than the community generation, then grid support is necessary; similarly, if they have surplus power, it is sold to the grid on the rate prescribed by the utility. This is the community welfare based pricing structure rather than the profit-based market model. As a member of the community shares the power generation, the cost of electricity will reduce, and hence the cost of the individual member will also reduce. Inside the community, it looks like a model of the independent conventional grid having its buying and selling price.

The method of calculating such a price is explained with the flowchart, as shown in Figure 3.4, and the mathematical model is described thereafter. The primary data for the analysis is the daily load profile and the PV generation. The values of these two variables at any particular time t identifies the potential buyer and seller peer. The price calculation in the participatory method is based on the possibility of generation sharing. Energy sold or bought by a particular consumer throughout the day is calculated first. Then the total amount of energy bought or sold by all the members of the microgrid is calculated. On the other hand, a similar calculation can be made considering the whole the microgrid as a single prosumer. In this case, the daily amount of both sold or bought energy will be lower than the sum of the power exchange of all individuals. The ratio of the amount of microgrid transaction to the sum of individual transactions is used to calculate the actual trading price applicable in the microgrid.

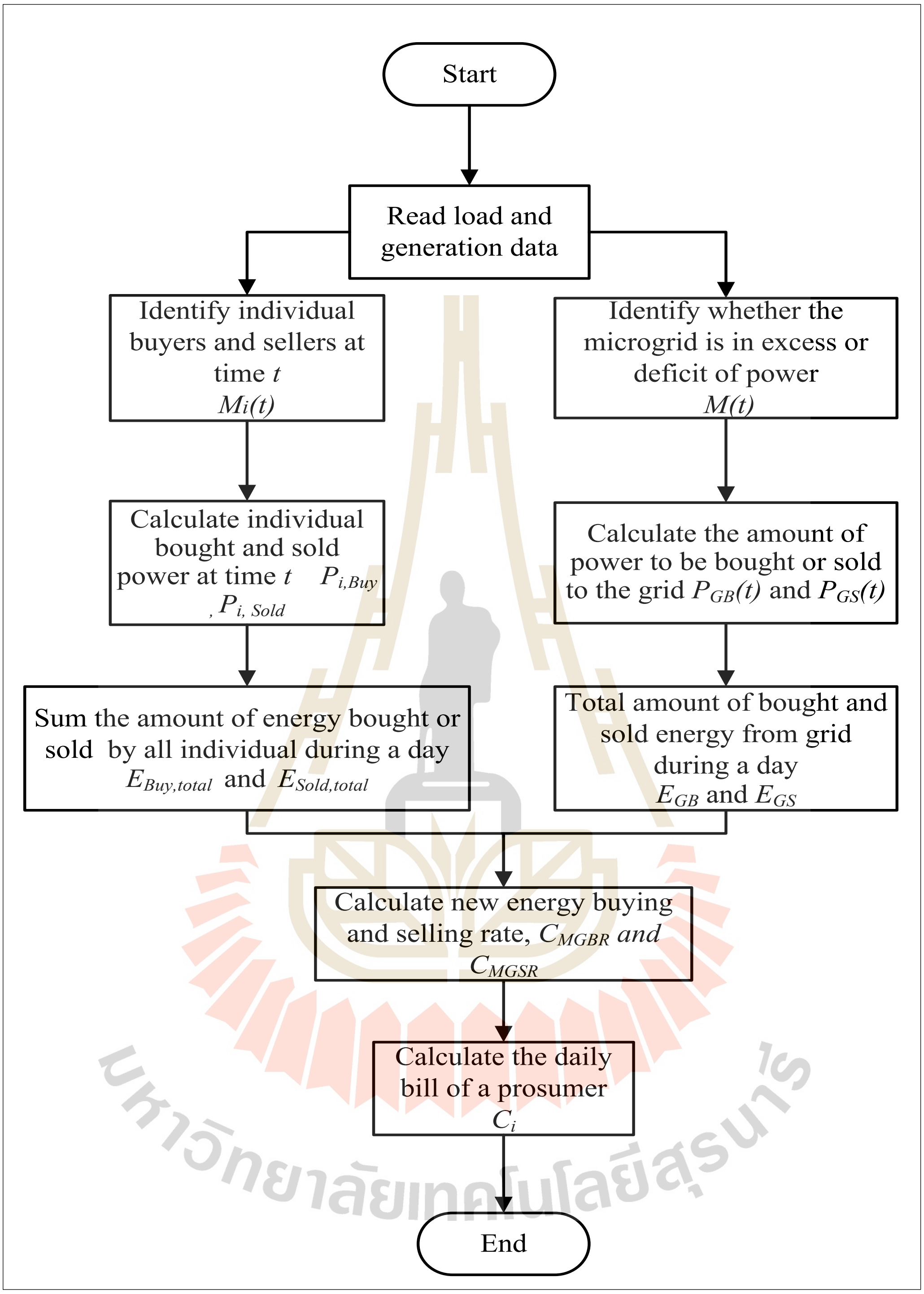

Figure 3.4 Flowchart of pricing in participatory method

Let us consider there are n households in the community, and they are equipped with solar PV facilities. Instantaneous demand of the entity at time t is $D_i(t)$, and generation is $G_i(t)$. Then, the daily demand of individual member is

$$D_i(t) = \left[D_i^1, D_i^2, D_i^3, ..., D_i^T\right] \; i \in [1,2,3,...,n] \tag{3.1}$$

Where,

$D_i(t)$ = demand of prosumer i time t

T = total period, 24 for one day

Similarly,

Hourly generation of a prosumer is

$$G_i(t) = \left[G^1{}_i, G^2{}_i, G^3{}_i, ..., G^T{}_i\right], \; i \in [1,2,3,...,n] \tag{3.2}$$

To identify the potential buyer and seller at the time t, $M_i(t)$ is considered, which is a minimum between demand and generation values at time t. This is used to generate the values of $P_{i,Buy}$, and $P_{i,Sold}$, which will contain either zeros or a positive number.

$$M_i(t) = \min(D_i(t), G_i(t)) \tag{3.3}$$

Now, the amount of power to be bought by a prosumer due to generation deficit is denoted by $P_{i,Buy}$ is calculated as

$$P_{i,Buy}(t) = D_i(t) - M_i(t) \tag{3.4}$$

The excess power available should be sold to the main grid which is given by the equation

$$P_{i,Sold}(t) = G_i(t) - M_i(t) \tag{3.5}$$

Combined energy that a community brought from the grid and sold to the grid represented by $E_{Buy,total}$ and $E_{Sold,total}$ respectively can be calculated as

$$\begin{aligned} E_{Buy,total} &= \sum_{i=1}^{n} \sum_{t=1}^{24} P_{i,Buy}(t) \\ E_{Sold,total} &= \sum_{i=1}^{n} \sum_{t=1}^{24} P_{i,Sold}(t) \end{aligned} \tag{3.6}$$

The buying and selling price of electricity issued by the utility company is represented by C_{GBR} and C_{GSR}, respectively.

The cost of electricity of an individual prosumer in the case of direct grid trading is given by the equation

$$C_i^{DG} = \left(\sum_{t=1}^{24} P_{i,Buy}(t).\Delta t\right).C_{GBR} - \left(\sum_{t=1}^{24} P_{i,Sold}(t).\Delta t\right).C_{GSR} \tag{3.7}$$

Now, as the sharing is considered within microgrid, instantaneous power balance should be calculated in a whole community rather than on an individual basis. This is the representation of the self-consumption of their generation (they share PV generation). It is calculated as,

$$M(t) = \min\left(\sum_{i=1}^{n} D_i(t), \sum_{i=1}^{n} G_i(t)\right) \tag{3.8}$$

Now, the combined power to be brought from the grid (after sharing), represented by $P_{GB}(t)$ and total community sell denoted as $P_{GS}(t)$ is calculated as follows,

$$P_{GB}(t) = \sum_{i=1}^{n} D_i(t) - M(t) \tag{3.9}$$

$$P_{GS}(t) = \sum_{i=1}^{n} G_i(t) - M(t) \tag{3.10}$$

In terms of energy

$$E_{GB} = \sum_{t=1}^{24} P_{GB}(t).\Delta t \tag{3.11}$$

$$E_{GS} = \sum_{t=1}^{24} P_{GS}(t).\Delta t \qquad 3.12)$$

In the P2P scenario, member of the community shares their generation among themselves. The sum of individual imported and exported energy will always remain greater than the community energy import and export.

Now, the community energy manager will calculate the buying and selling rates of electricity. Let say C_{MGBR} be buying price and C_{MGSR} be selling rate (Long et al., 2017).

$$C_{MGBR} = C_{GBR} \cdot \frac{E_{GB}}{E_{Buy,total}} \tag{3.13}$$

$$C_{MGSR} = C_{GSR} \cdot \frac{E_{GS}}{E_{Sold,total}} \tag{3.14}$$

At last the new energy cost of a prosumer based on the modified rate or P2P rate is given by

$$C_i = \left(\sum_{t=1}^{24} P_{i,Buy}(t).\Delta t\right).C_{MGBR} - \left(\sum_{t=1}^{24} P_{i,Sold}(t).\Delta t\right).C_{MGSR} \quad (3.15)$$

3.6 Multilevel P2P energy trading

As technological development and innovation have no limit, a future microgrid may operate in a level by level structure, and at each level, they may introduce a sustainable P2P scheme.

1. The first and the basic level is referred to as nano grid, which is the combination of a small number of household or a community of a particular tiny area. The energy management within the nanogrid is the responsibility of the nanogrid operator (NGO). NGO serves as the single prosumer to the higher-level network.
2. The second level is the P2P among multi-nanogrid within a microgrid. A community energy manager (CEM) will be responsible for the good operation of the network. A basic block diagram of such operation is presented in Figure 3.5.
3. The third level will be energy trading among multi-microgrids as shown in Figure 3.6.
4. The highest level is the trading among various multi microgrid. It can be generalized as the current grid.

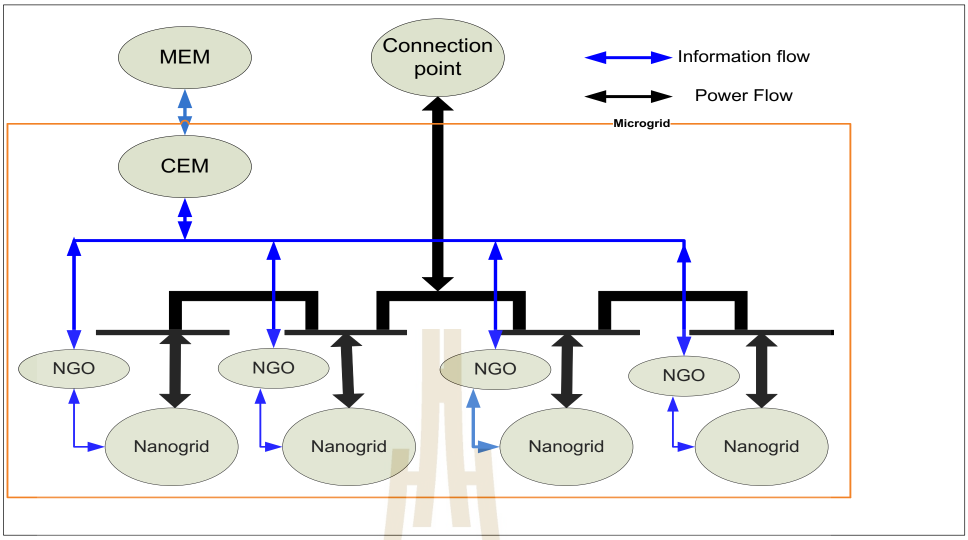

Figure 3.5 Community microgrid operating with various nanogrid

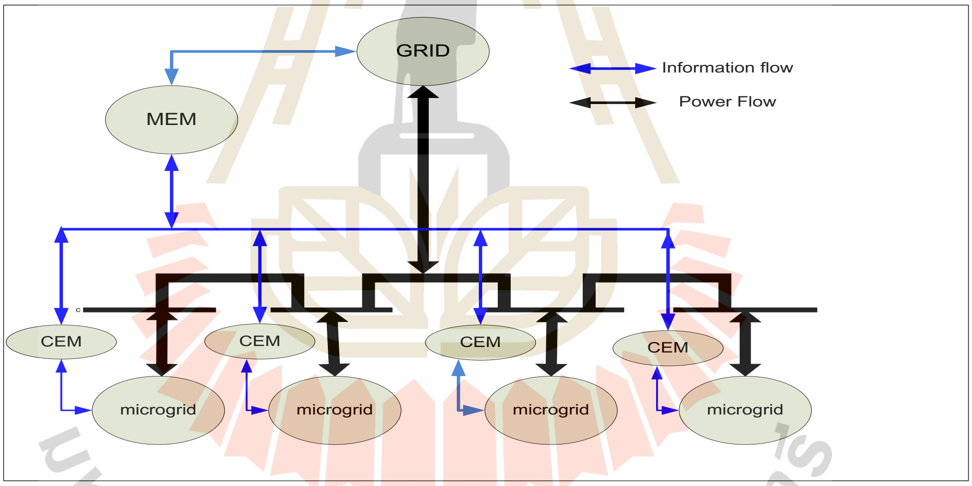

Figure 3.6 Multi microgrid P2P structure

In this study, a simplified multilevel trading scenario, as shown in Figure 3.7, is considered**.** A nanogrid is assumed as a fundamental entity, and each nanogrid is equipped with its own energy manager NGO. So the energy trading will occur among the nanogrid within a microgrid. CEM is responsible for the wellbeing of trading. On the next level, the energy exchange between microgrids is considered. The main controller in this level is named as microgrid energy manager (MEM)

A nanogrid is considered as the functional unit or a prosumer, so the internal pricing and other activities conducted by NGO is not considered here. NGO will give information about the total generation and demand of the nanogrid for a specific time or time instance. The information send by NGO is received by CEM, then it manages the energy among the nanogrid and informs higher-level controller MEM for the trading, i.e., buying or selling. Finally, MEM tries to balance the power demand between the multi microgrid, and in this case, it acts as the medium of grid contact.

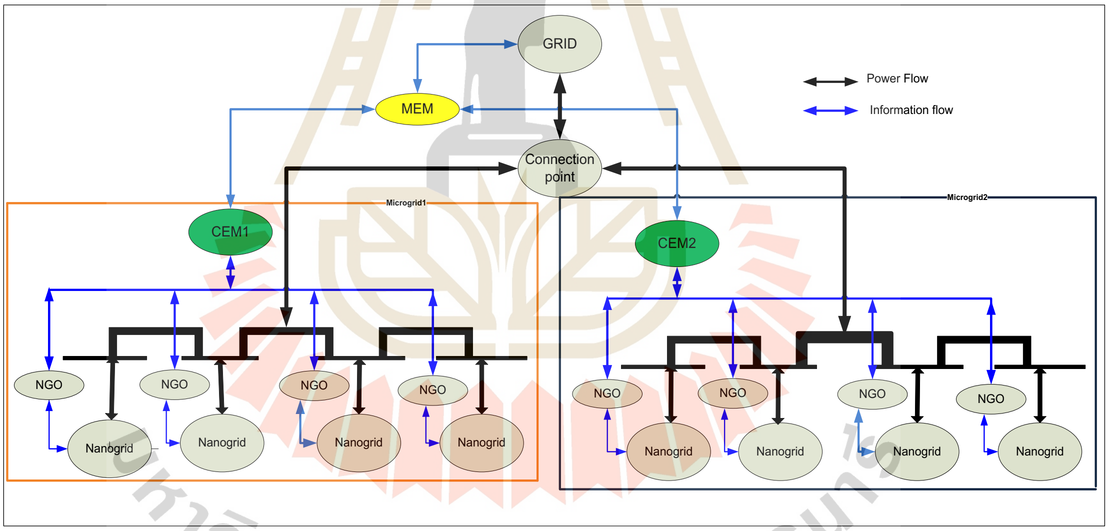

Figure 3.7 Basic block-diagram of multilevel P2P market

3.6.1 Cost calculation

The idea behind the multilevel transaction is the mutual co-coordination among various levels. Such interdependency and the process of actual pricing in various levels is presented in Figure 3.8.

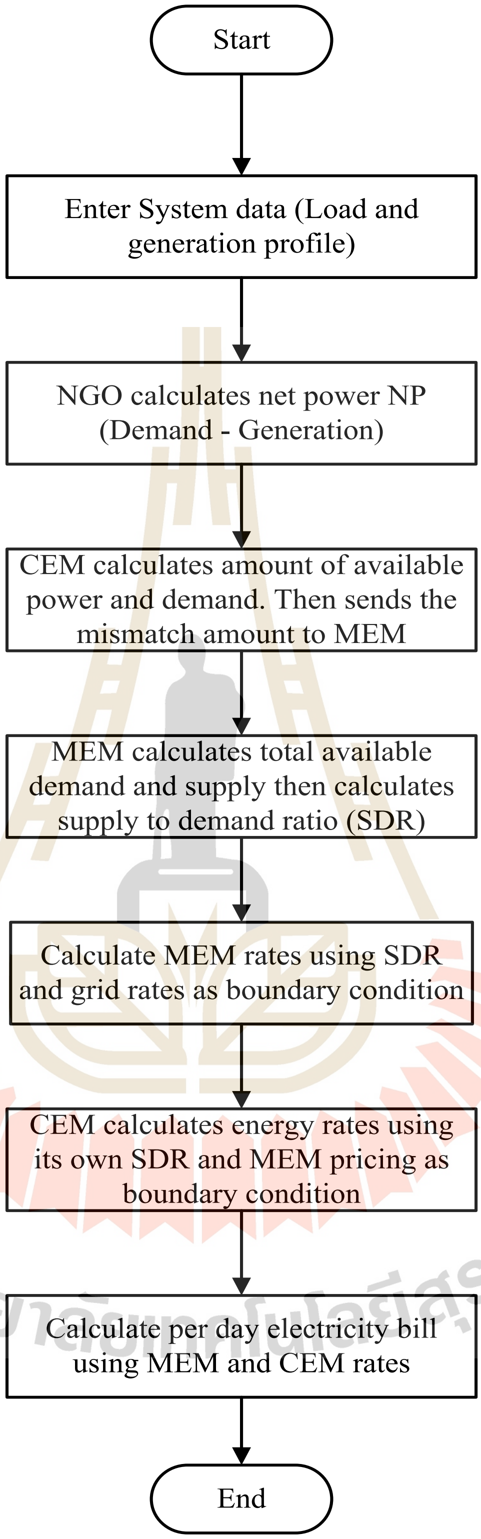

Figure 3.8 Flowchart of pricing in multilevel transactions

As the nanogrid is considered as the basic unit, it may have varieties of load, and it is considered that each nanogrid has its PV generation. The demand profile of the nanogrid at time frame T denoted by D^t and PV generation profile represented by G^t is as follows

$$D_i = [D_i^1, D_i^2, D_i^3, \ldots, D_i^T] \; i \in [1,2,3,\ldots,n] \tag{3.16}$$

Where,

D_i =demand of nanogrid i

T = total time, 24 for one day

$$G_i = [G^1{}_i, G^2{}_i, G^3{}_i, \ldots, G^T{}_i] \;, \; i \in [1,2,3,\ldots,n] \tag{3.17}$$

Self-consumption of nanogrid i is given by

$$S_i^t = \min(D_i^t, G_i^t) \tag{3.18}$$

Power to be imported and exported by a nanogrid can be calculated as

$$P_{i,im}^t = D_i^t - S_i^t \tag{3.19}$$

$$P_{i,ex}^t = G_i^t - S_i^t \tag{3.20}$$

For the sustainable operation of market pricing Method must obey the basic economic principle of demand and supply. So the rate of electricity mainly depends upon supply to demand ratio (SDR) and is given by

$$SDR^t = \frac{TPG^t}{TPD^t} \quad (3.21)$$

Solar power generation and load demand fluctuate from time to time, so SDR also varies accordingly. Consequently, the rate varies throughout time.

3.6.2 Pricing strategy among various level

First of all, NGO determines whether there is an excess of power or deficit of power by subtracting available generation from required demand at a time *t*. i.e., Net power *(NP)* calculated by NGO is

$$NP_i^t = D_i^t - G_i^t \quad (3.21)$$

Ideally, NGO can calculate its energy rate applicable within its territory, but it is a very tiny power network and has very limited members, pricing in this level may not be significantly different than the rate calculated by the higher controller (CEM in this case). This is the main reason for considering nanogrid as the fundamental entity.

Since proper coordination among various levels is the backbone of the multilevel P2P paradigm, NGO sends its information to the immediate upstream controller CEM. Then CEM calculates total available power and total demand by combining data send by each NGO at time *t*. Total power excess *TPE* is the available power for selling, and total power demand *TPD* is the amount of power to be brought from the next level market. Mathematically *TPE* and *TPD* can be written as,

$$TPE^t = -\sum_{i=1}^{n} NP_i^t \quad NP_i^t < 0$$

$$TPD^{t} = \sum_{i=1}^{n} NP_i^t \quad NP_i^t > 0 \tag{3.22}$$

Since a higher-level market is present in the system, it cannot independently define its cost as its cost must agree with the cost calculated by its trading partner. So, the CEM again calculates net residual power in each microgrid in the same manner as the NGO. To avoid confusion, let say it as a power mismatch *(PM)*.

$$PM^{t} = TPD^{t} - TPE^{t} \tag{3.23}$$

Finally, MEM, the topmost controller through which grid interaction is possible, receives information from CET. MEM then calculates total excess power to be sold and power to be borrowed from the grid. TPE and TPD at a time t is now given by;

$$TPE^{t} = -\sum_{j=1}^{m} NP_j^t \tag{3.24}$$

$$TPD^{t} = \sum_{j=1}^{m} NP_j^t \tag{3.25}$$

Now the *SDR* of whole the system for a time *t* is calculated as,

$$SDR^{t} = \frac{TPE^{t}}{TPD^{t}} \tag{3.26}$$

Internal price inside the system varies as SDR varies, but the rate of grid exchange is a time-invariant quantity. α_{buy} and α_{sell} are the rates of grid buying and grid selling price, respectively.

Internal energy rate (β) defined by MEM can be represented as,

$$\beta = \left\{\beta^{1}{}_{\text{Buy}}, \beta^{2}{}_{\text{Buy}}, \beta^{3}{}_{\text{Buy}} \ldots \beta^{24}{}_{\text{Buy}}; \beta^{1}{}_{\text{Sell}}, \beta^{2}{}_{\text{Sell}}, \beta^{3}{}_{\text{Sell}} \ldots \beta^{24}{}_{\text{Sell}}\right\}$$

To get a sustainable economic benefit of the P2P market, the grid price and MEM price must always satisfy the following condition.

$$\alpha_{Sell} \leq \beta_{Sell} \leq \beta_{Buy} \leq \alpha_{Buy} \tag{3.27}$$

Basis of rate determination by MEM is the basic law of supply and demand (Paudel and Beng, 2018) that is *SDR* and the above relation. Then

$$\beta^{t}{}_{Sell} = \begin{cases} \dfrac{\alpha_{Sell} . \alpha_{Buy}}{(\alpha_{Buy} - \alpha_{Sell}).SDR^{t} + \alpha_{Sell}} & 0 \leq SDR^{t} \leq 1 \\ \alpha_{Sell} & SDR^{t} > 1 \end{cases} \tag{2.28}$$

$$\beta^{t}{}_{Buy} = \begin{cases} \beta^{t}{}_{Sell} . SDR^{t} + \alpha_{Buy} (1 - SDR^{t}) & 0 \leq SDR^{t} \leq 1 \\ \alpha_{Sell} & SDR^{t} > 1 \end{cases} \tag{2.29}$$

The price rate calculated by MEM is the boundary limit for individual microgrid or more precisely CEM. CEM determines the internal pricing rate based on its own SDR and price rate received from MEM. SDR of m^{th} microgrid is given by,

$$SDR_{m}^{t} = \frac{TPE_{m}^{t}}{TPD_{m}^{t}} \tag{3.30}$$

Similar to the previous case of MEM, CEM price must satisfy the following relation to maintain the profitable microgrid operation

$$\beta_{Sell} \leq \gamma_{Sell} \leq \gamma_{Buy} \leq \beta_{Buy} \tag{3.31}$$

CEM determines a new price sequence based on the rate obtained from MEM, satisfying the above relation (equation 3.31). So the internal pricing sequence of CEM is given by,

$$\gamma^{t}_{m,Sell} = \begin{cases} \dfrac{\beta^{t}{}_{Sell} \cdot \beta^{t}{}_{Buy}}{(\beta^{t}{}_{Buy} - \beta^{t}{}_{Sell}).SDR^{t}_{m} + \beta^{t}{}_{Sell}} & 0 \le SDR^{t}_{m} \le \\ \beta^{t}{}_{Sell} & SDR^{t}_{m} > 1 \end{cases} \quad . \tag{3.32}$$

$$\gamma^{t}_{m,Buy} = \begin{cases} \gamma^{t}_{m,Sell}.SDR^{t}_{m} + \beta^{t}{}_{Buy}(1 - SDR^{t}_{m}) & 0 \le SDR^{t}_{m} \le 1 \\ \beta^{t}{}_{Sell} & SDR^{t} > 1 \end{cases} \tag{3.33}$$

Finally, the electricity bill of individual nanogrid in various treading scenario is determined as follows,

i. Peer to grid trading

In this case, a peer directly transacts with the grid and hence, the grid exchange rate is applicable.

$$C^{i}_{P2G} = \left(\sum_{t=1}^{24} P^{t}_{i,im}(t).\Delta t\right).\alpha_{Buy} - \left(\sum_{t=1}^{24} P^{t}_{i,ex}(t).\Delta t\right).\alpha_{Sell} \tag{3.34}$$

ii. Single stage P2P trading

$$C^{i}_{SP2P} = \left(\sum_{t=1}^{24} P^{t}_{i,im}(t).\Delta t\right).\beta^{t}_{Buy} - \left(\sum_{t=1}^{24} P^{t}_{i,ex}(t).\Delta t\right).\beta^{t}_{Sell} \tag{3.35}$$

iii. Multilevel P2P trading

$$C^{i}_{HP2P} = \left(\sum_{t=1}^{24} P^{t}_{i,im}(t).\Delta t\right).\gamma^{t}_{m,Buy} - \left(\sum_{t=1}^{24} P^{t}_{i,ex}(t).\Delta t\right).\gamma^{t}_{m,Sell} \tag{3.36}$$

3.7 Chapter summary

Chapter III describes the detailed process of the pricing of electricity in participatory and multilevel trading method with necessary flowcharts and mathematical equations. Additional to that it also discusses about the load curves and the definition of basic solar photovoltaic terminologies. A brief overview of the solar power potential of Nakhon Ratchasima is also presented as the local power generation is a fundamental necessity of any P2P market.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Introduction

This chapter contains the detail explanation of the results obtained from the simulation. Per day electricity bill in different trading platforms is calculated based on actual load curve and PV generation is realized assuming peak power generation equals maximum demand of prosumer. In the first case different combination of PV injection is assumed and daily bill, savings compared to direct grid trading and saving per kW PV installation is calculated. This case is referred as normal case hereafter. The second case is interchanged mode. The PV capacity of prosumers is interchanged among them keeping total capacity unchanged and again the similar calculations were done. It is found that prosumer get more profit in interchanged mode compared to normal mode.

4.2 Data collection and simulation arrangement

Data collection is the fundamental stage of any research project. The primary focus of this thesis work is to determine the possible saving in the daily electricity bill of any prosumer in the different trading platforms. To evaluate such savings, we need to analyze the daily load profile of the prosumer and the daily solar curve (irradiance curve). The daily load profile of some commercial consumers is obtained from provincial electricity authority (PEA), which includes school, university, business complex, hospital, convenient store, etc.

Similarly, the solar generation profile is obtained from an operational solar farm in Korat. Then that graph is normalized and used as the basis for all consumers. The generation facility of each consumer is assumed to be equal to its maximum demand. In other words, peak PV generation equals peak load irrespective of the time of occurrence of maximum demand. If the peak load demand of a particular consumer is 20 kW at 5 PM, then it is assumed that it is equipped with the solar PV generation facility of 20 kW. Obviously, that amount of power will only be generated at solar noon. A total of eight data of the commercial consumer load profile is considered for this thesis work. It is because of the lack of a sufficiently large amount of data. Since the data is comparatively large (in the range of tens of kW), each consumer is considered as a nanogrid or a basic level player (entity) in the trading market. These eight nanogrids are divided into two microgrids comprising five and three nanogrids in microgrid one and two, respectively. The basic block diagram of the trading market is shown in Figure 4.1.

Figure 4.1 presents the case of a multilevel transaction. NGO is simply a smart energy meter capable of handling both power and data transfer. Two microgrids are shown by two boxes having red and black outlines, and it is evident from the Figure that each contains five and three nanogrids. CEM is responsible for power and data management in a respective microgrid, and MEM is responsible for a multi microgrid. The detail of the system is explained in Chapter III.

In the case of the participatory method, no such levels are available. Each microgrid act as a single prosumer, and the total bill is shared among the member nanogrid.

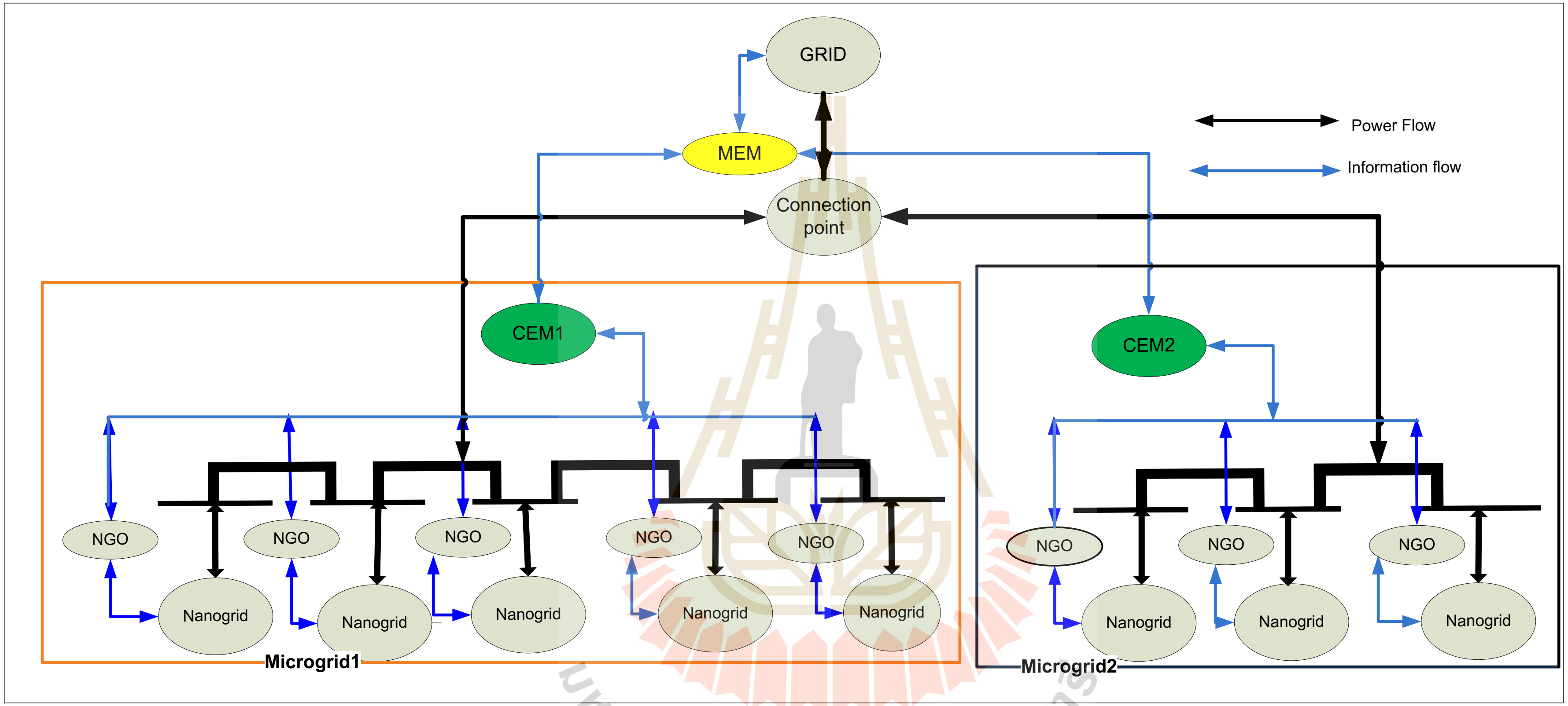

Figure 4.1 Block diagram of the study module

4.3 Data analysis and decision variables

The actual load data obtained from the utility and the assumed solar PV generation data is used for the simulation purpose. MATLAB program is used as the simulation environment. The simulation process and the necessary mathematical calculations are described in chapter III in detail.

The main objective of this study is to specify the most profitable trading method for consumers (prosumers). Hence the primary decision variable is the per day electricity bill of that particular prosumer. The per-day electricity bill of a particular prosumer is calculated according to the various trading mechanisms, and finally, all these values are compared to select the best trading option. Obviously, the trading platform generating the lowest amount of bill will be the best option for the prosumer. The tested trading options considered in this study are direct grid trading, participatory trading method, and multilevel transaction method. The characteristics of these trading options are elaborated in Chapter III.

The analysis is done in two parts; in the first part, trading among commercial consumers is considered. The daily electricity bill is calculated in all three trading options assuming the PV generation equals the maximum demand. Then the same is repeated with different levels of PV generation to analyze the effect of power availability in the system. In the second part, the PV generation capacity of the particular prosumer is exchanged to one another, keeping the capacity constant, which is helpful to study the effect of self-power consumption.

4.4 Analysis of commercial consumers in normal mode (Case I)

4.4.1 Data used

As mentioned earlier, in total, eight nanogrids are divided into two microgrids. Microgrid 1 (MG1) consists of five nanogrid, and the actual load curve of a particular day of October 2019 is presented in Figure 4.2. The data are of the hospital, convenience store, bank, school, and a commercial complex; however, it is not clearly stated in this graph and anywhere else in this thesis due to the privacy issue and represented simply as load.

Similarly, Figure 4.3 presents the load profile of three commercial consumers, which is used as the data for the second microgrid (MG2). It contains the data of the university and business complex.

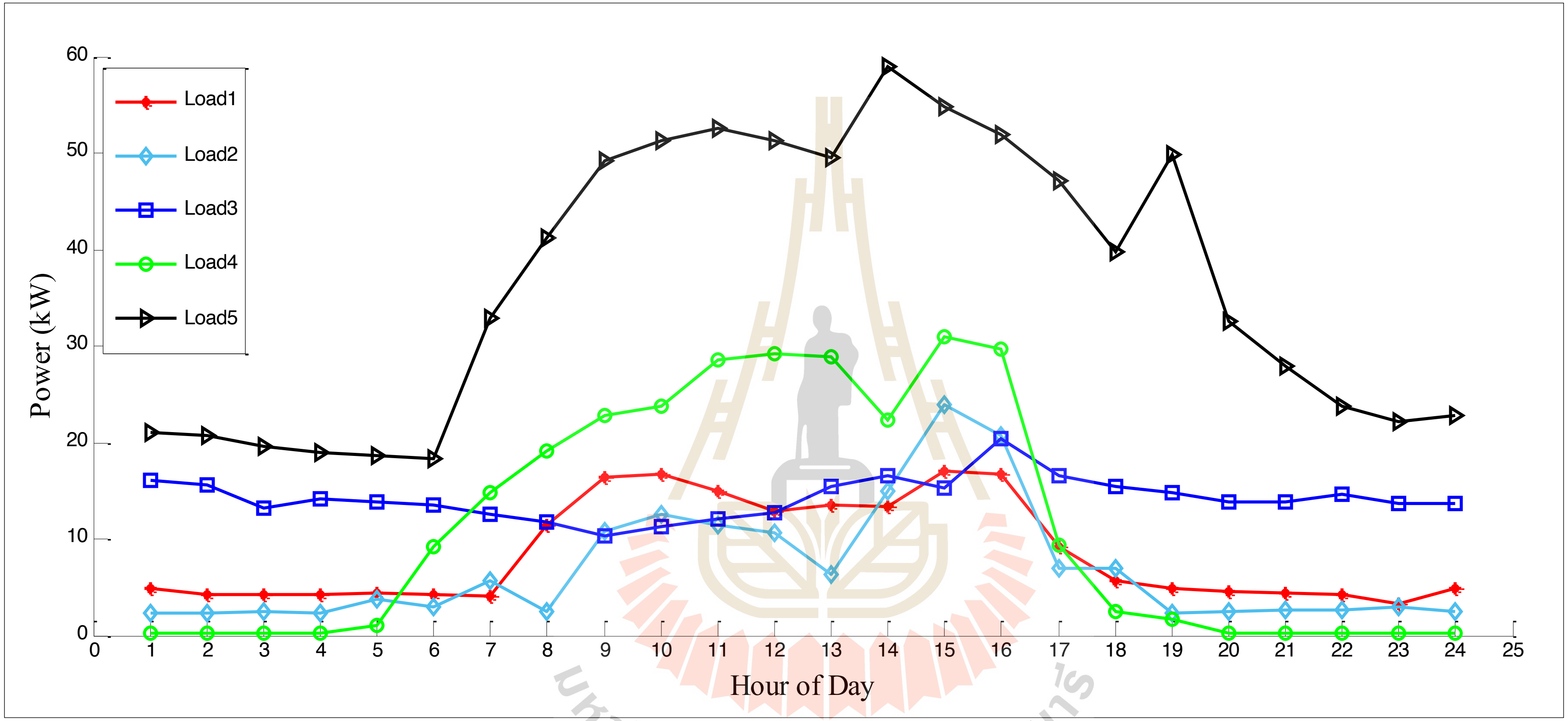

Figure 4.2 Load data of microgrid 1

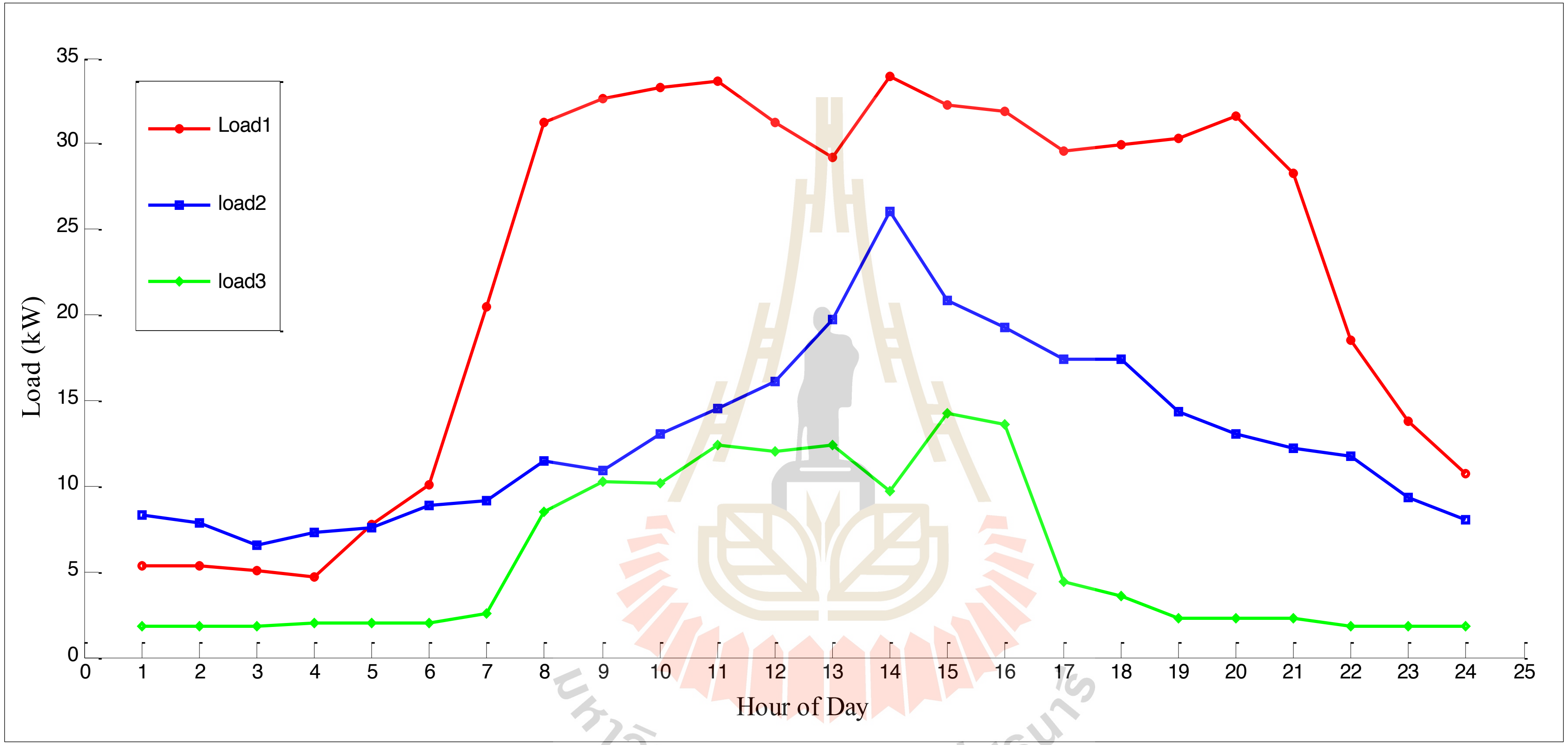

Figure 4.3 Load data of microgrid 2

Since the nanogrids are not equipped with a PV generation facility, it is generalized by normalizing the average monthly generation capacity of a solar farm in korat. Figure 4.4 shows a normalized solar generation curve utilized in this study. It is evident from the Figure 4.4 that the PV installation is capable of generating 80% of peak power or more for a duration of 6 hours. To realize the PV generation at a particular time of a particular consumer data shown in this graph is multiplied by any appropriate magnitude (peak load = peak power generation).

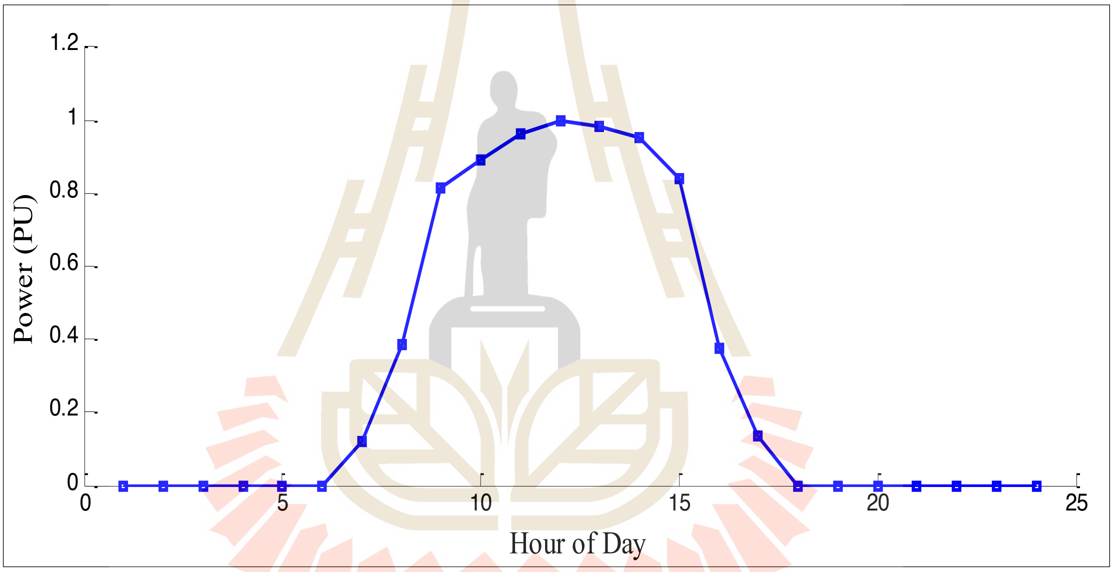

Figure 4.4 Normalized solar PV generation curve

4.4.2 Detail explanation of trading at 100% PV injection

In the first case, the calculations are carried out considering the PV output equal to the maximum demand or 100% PV injection. The detail explanation of trading in various platforms is presented below:

4.4.2.1 Direct grid trading

It is simply the bidirectional energy trading mode using net metering technology. It is not the P2P technology but is included here because the basis of P2P itself lies in bidirectional energy transfer. After the simulation, it is found that the per day electricity bill of prosumers of MG1 is 598 THB, 228 THB, 1645 THB, 391 THB, and 3357, respectively. Similarly, the electricity bill of prosumers of MG2 is 2141 THB, 1023 THB, and 274 THB, respectively. These values are regarded as the base cost values, and other methods are compared to it.

4.4.2.2 Participatory method

The simulation model is run with the above experimental data, and the per-day cost of electricity of prosumers of MG1 and MG2 is presented in Figures 4.5 and Figure 4.6, respectively.

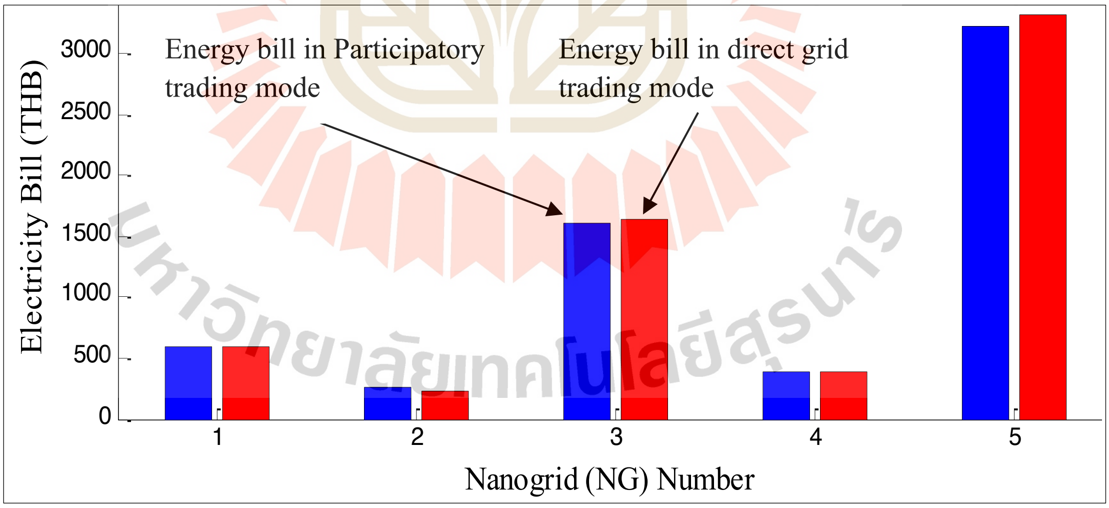

Figure 4.5 Per day electricity bill of NGs of MG1 in PPT and DGT with 100% PV

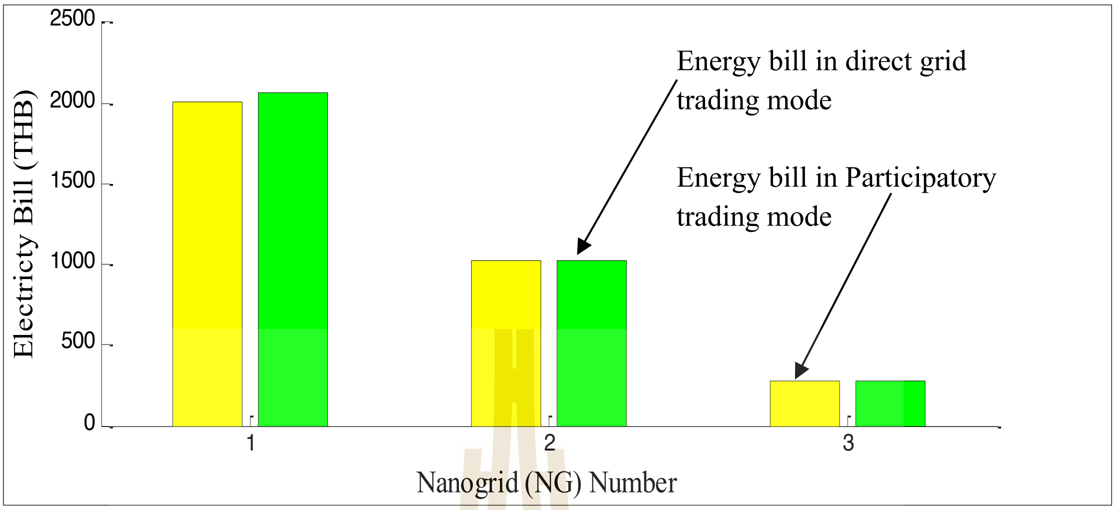

Figure 4.6 Per day electricity bill of NGs of MG2 in PPT and DGT with 100% PV

The bill amount of five NGs of MG1 is 585, 268, 1593, 389, and 3246 THB respectively; similarly, that of three NGs of MG2 is 2084, 1018, and 123 THB respectively. From Figure 4.5 and Figure 4.6, the daily electricity cost of prosumers in the participatory transaction method obtained after the simulation is less or equal to the cost resulted from direct grid trading in almost all nanogrids. However, NG2 of MG1 has a higher bill in the participatory method compared to direct grid transactions. It might have occurred as if the prosumer has not much energy to contribute to the community, and the higher demand of other large consumers came under his bill as he does not has sufficient power he must pay in terms of money. This suggests that the participatory method is more beneficial for large consumes and is clearly seen in the Figures 4.5 and 4.6.

4.4.2.3 Multilevel transaction

The second trading platform discussed here is the multilevel transaction model. A three-stage trading market consisting of nanogrid as the basic unit, multinanogrid, or microgrid as the second level and multi-microgrid as the third level is considered and is represented in Figure 4.1. The fundamental characteristics of this method are the functioning of several markets in each level or layers with synchronism with other layers. The topmost layer defines the rate of electricity considering the supply and demand of the whole system, and then subsequently lower-level market defines the rate applicable in its territory based on the cost obtained from its predecessor level and its own supply to demand ratio.

Since the hourly data is used for the simulation energy price for each hour will be different as the supply and demand vary accordingly. The daily electricity bill is the accumulation of cost of every hour. Referring to Figure 4.1, MEM is the highest level controller or power manager (trader), and grid transaction is possible through this controller only. So it determines the buying and selling price according to the hourly supply to demand ratio, taking the grid exchange rate as a boundary condition. Then the lower-level controllers CEM1 and CEM2 again define their rates based on supply to demand ratio of their respective microgrid considering MEM rates as their boundary condition. Figures 4.7 - 4.9 shows the internal pricing of MEM, CEM1, and CEM2, respectively.

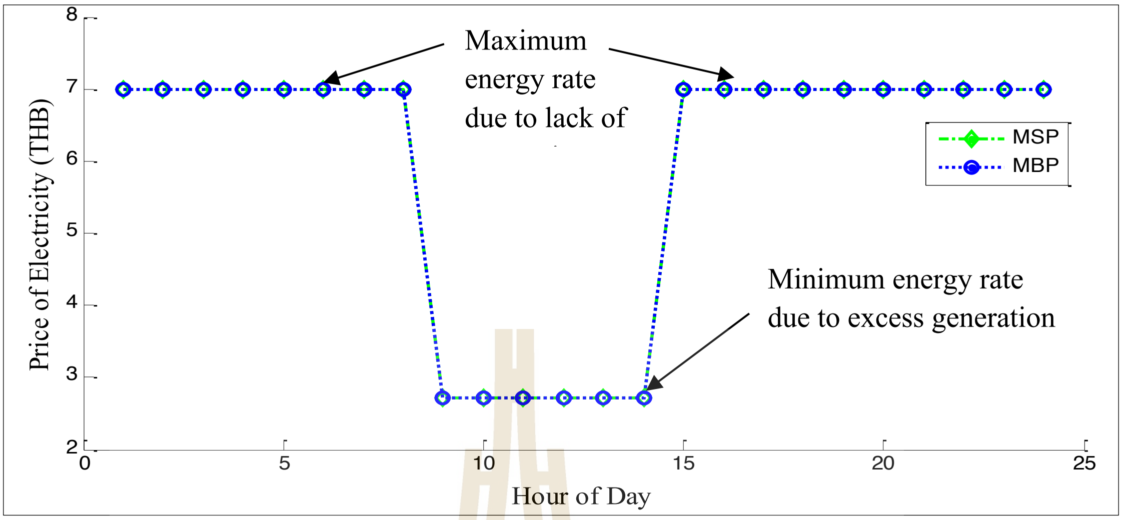

Figure 4.7 MEM Pricing 100% - 100% PV injection case

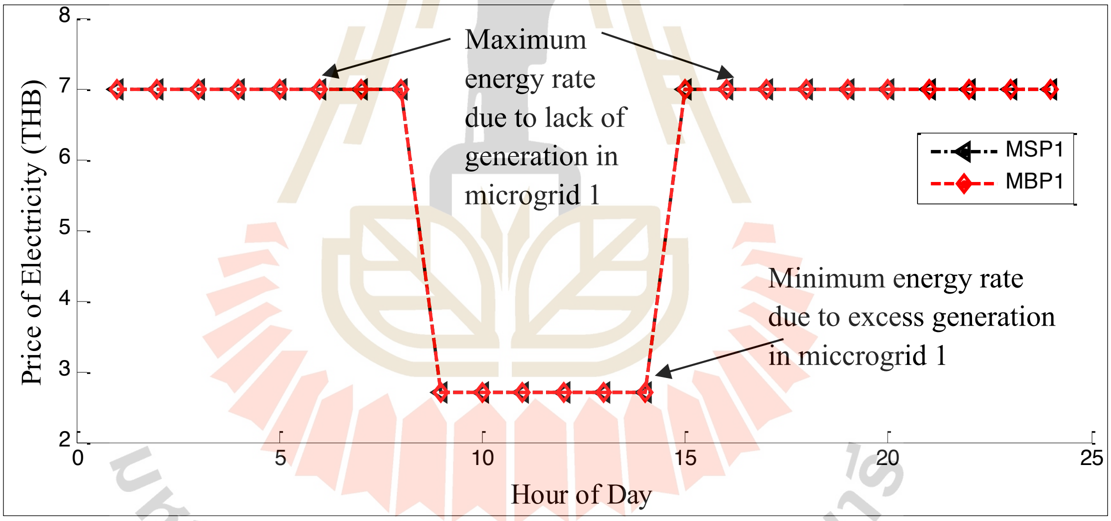

Figure 4.8 CEM1 Pricing 100% - 100% PV injection case

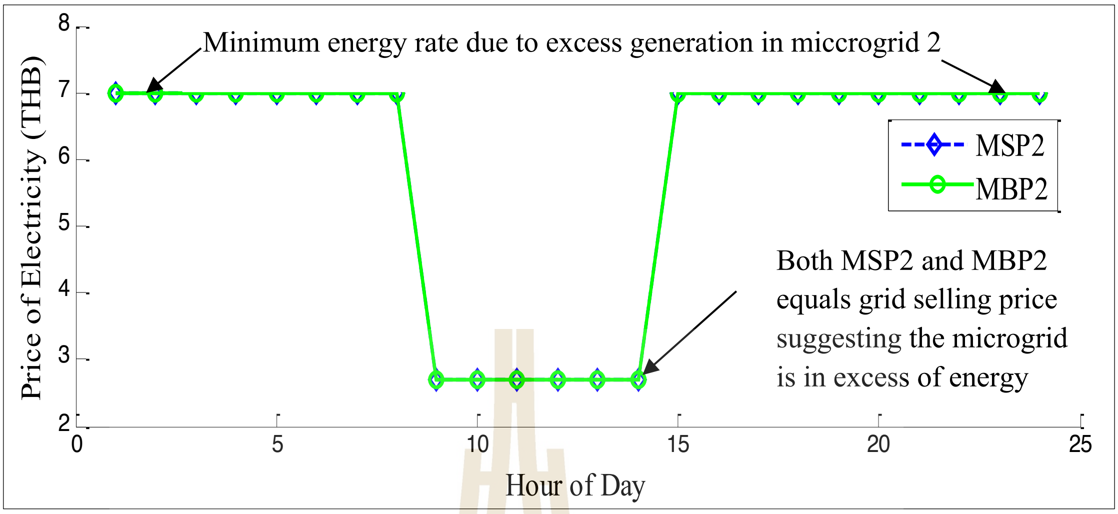

Figure 4.9 CEM2 pricing 100% - 100% PV injection case

It is seen from the Figures 4.7 – 4.9 that the actual market operates for the day time only because the solar generation is only available during day time. If there is no excess energy in the system, then both selling and buying price is maximum and is equal to the grid buying price (7 THB), Which has occurred during morning and evening time. At those time frames, MEM does not have any power in itself, so it wants to buy power from its constituent prosumers by offering the highest possible rate, so the main selling price (MSP) reached 7 THB. However, it is well known that the prosumers do not have any power and in reality, are demanding power so to fulfill that demand MEM buy the power from utility at utility selling price (7 THB) and sell that power to its prosumer at the same price and that price is denoted by main buying price (MBP). It should be noted that the rates described throughout this thesis are from the prosumer perspective; hence the "buying price" is actually the rate on which utility sells power to us, and "selling price" is the rate of electricity offered by the utility to buy prosumers excess power.

On the contrary, if the system has an excessive amount of power in the system and is to be exported to the utility, then both MBP and MSP will be equal to the lowest possible value, which is the rate offered by a utility to buy power.

Main Buying price (MBP) and main selling price (MSP) of the MEM is presented in Figure 4.7. It shows that MSP and MBP are exactly similar, which can be explained by equation (23) and equation (24). If the supply to demand ratio is greater than unity, i.e., if the system has to export power to the utility than the MSP and MBP will be equal to the minimum rate, i.e., grid selling rate. Figure 4.8 and Figure 4.9 represent internal energy rates applicable in microgrid 1 and microgrid 2 offered by CEM1 and CEM2, respectively, as shown in Figure 4.1. These two Figures 4.8 and 4.9 are also identical, which means both microgrids have sufficient powers within their microgrids, and no further trading is required. Since the solar generation, in this case, is assumed to equal the maximum demand of the respective microgrid, such results are quite obvious.

4.4.2.4 Overall cost comparison and discussion

The per-day electricity bill of each prosumer (nanogrid) in various trading models is presented in Table 4.1. It is found that the bidirectional trading with the grid will result in a maximum bill to the prosumer. All eight prosumers except nanogrid 2 of microgrid 1 have the highest bill amount compared to other alternatives. The second trading mechanism is a participatory trading method. The whole microgrid acts as a single prosumer to the utility but shares the resources and cost among participating entities. Hence this method is called participatory method. It is seen that this method is more profitable to prosumer as it results in a significantly lower electricity bill. However, this method does not account for the supply-demand economics and does not adjust the price accordingly. Hence it may be more beneficial to prosumer having higher load demand. Since this load and subsequently, the cost will be shared among the participants equally. Single-stage P2P and multistage P2P accounts such as real-time demand and supply fluctuations and generates a time-varying selling and buying rates applicable within the market. Hence the load and demand of a particular instance of time affect the rate of that instance only resulting in higher fairness among the traders (Prosumers). The electricity bill in a single stage and multistage P2P market is exactly similar, as shown in Table 4.1. It is because all prosumers have sufficient power in their respective microgrid, and the power exchange between microgrids has not taken place or is very minimum.

Table 4.1 Daily electricity cost of NGs in various platform (100–100 % PV injection)

	Electricity bill in microgrid 1 (THB)					Electricity bill in microgrid 2 (THB)		
	NG1	NG2	NG3	NG4	NG5	NG6	NG7	NG8
Direct grid trading	598	228	1645	391	3357	2147	1023	274
Participatory	585	268	1593	389	3246	2084	1018	123
Single stage P2P	579	200	1632	391	3280	2084	1014	227
Multi stage P2P	579	200	1632	391	3280	2084	1014	227

4.4.3 Effect of variation in PV injection in each nanogrid

To study the effect of power availability in the system and consequently to the possible saving in various trading platforms, the same module is run multiple times with various combinations of solar integration in two microgrids. Sixteen possible combinations of PV penetration starting from 50% of maximum demand to 125% of total demand on both microgrid, with an incremental step of 25%. The possible combinations are 50%-50%, 50%-75%, 50%-100% and 50%-125% and repeat the sequence with 75%, 100% and 125% in the place of microgrid 1. The actual electricity bill in all scenarios is first calculated, and the saving compared to the direct grid trading (DGT) of all NGs are presented here. Similarly, the saving per unit PV installation (saving/kW PV installation) is also shown here. Detail data and calculations are listed in appendix A.

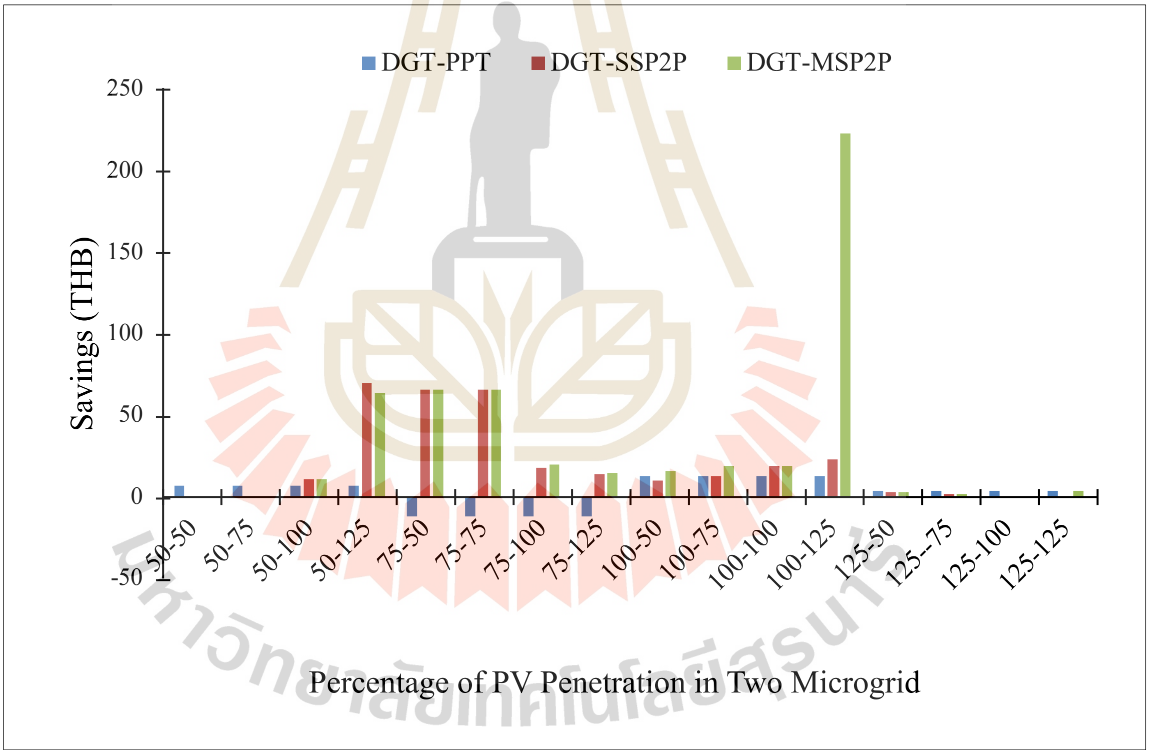

Figure 4.10 Savings in the electricity bill of NG1 in varying PV injection level

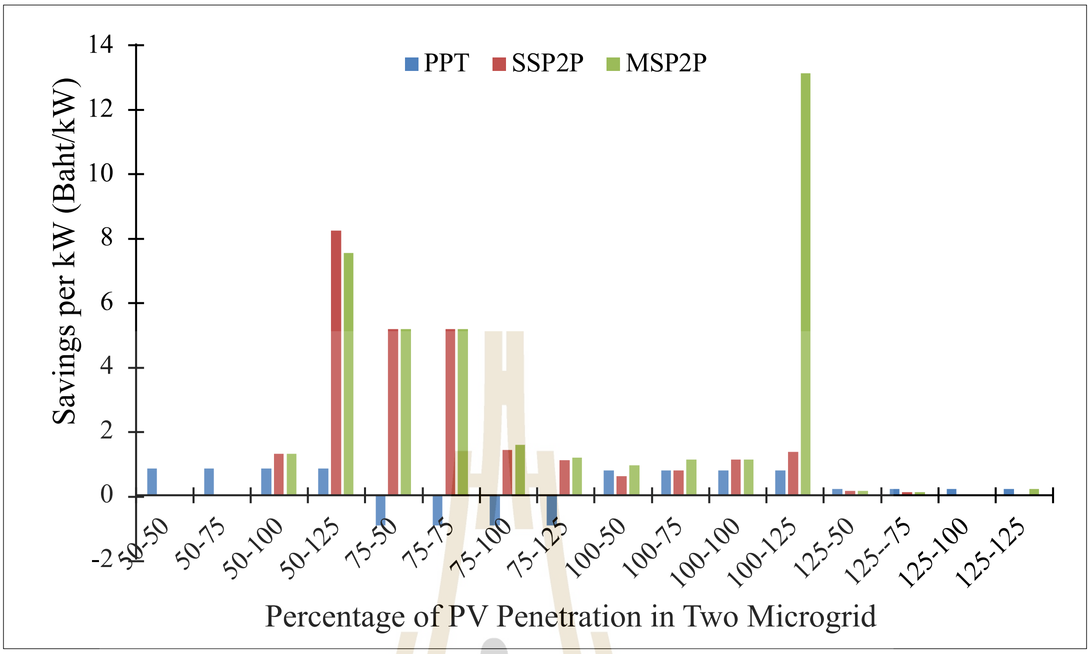

Figure 4.11 Saving per kW PV installation of NG1

Figure 4.10 presents the savings and loss if negative of NG1, in different trading platforms compared to the cost of DGT as the DGT is the basis of P2P trading. On the other hand, Figure 4.11 describes the saving per unit solar generation. This index is considered as the deciding factor to analyze the profitability of the trading conFigureuration.

From the above Figures (4.10 and 4.11), the participatory method (PPT) has a wide range of fluctuations from negative to positive. That means this method may become costlier than the DGT according to power availability. It is seen that when the overall PV penetration of MG 1 is at 50% of its maximum demand, PPT is more profitable than DGT. On the contrary, as the PV penetration of MG1 of which this NG1 is one constituent member, is 75% of its maximum demand PPT became costlier than the DGT through the single-stage P2P (SSP2P), and multistage P2P (MSP2P) has delivered considerable profit to the prosumer at that moment. Such an unusual case may have to be occurred due to its comparatively lower load demand and hence the low generation.

To explain that irregularities, we have to take reference of load curves. NG1 is a small prosumer, and has its demand mainly occurs in the day time. Peak demand for NG has occurred around 10:00 AM. It decreases and again increases and almost equals maximum demand around 3:00 PM, which suggests that the maximum PV generation will not coincide with the maximum demand. At peak generation time, NG1 becomes a seller. When PV injection is 50%, PPT resulted in profit as it is smaller NG, and all NGs are in power deficit mode. A small amount of power will be available in the community considering all the load curves of all NGs. Since NG1 is a small one and does not contribute power to the community (referring to the load curve) so it is in profit because it gets energy from others. As the PV injection is 75%, PPT becomes costlier than the DGT; this may be due to the increased power availability in the system. At that instant, NG1 can contribute some power to the community, and the community is still in the power-hungry mode; it resulted in a loss to the prosumer. On the contrary, when PV injection is 100%, all NG1 has a relatively large amount of power to sell, so again, PPT becomes profitable.

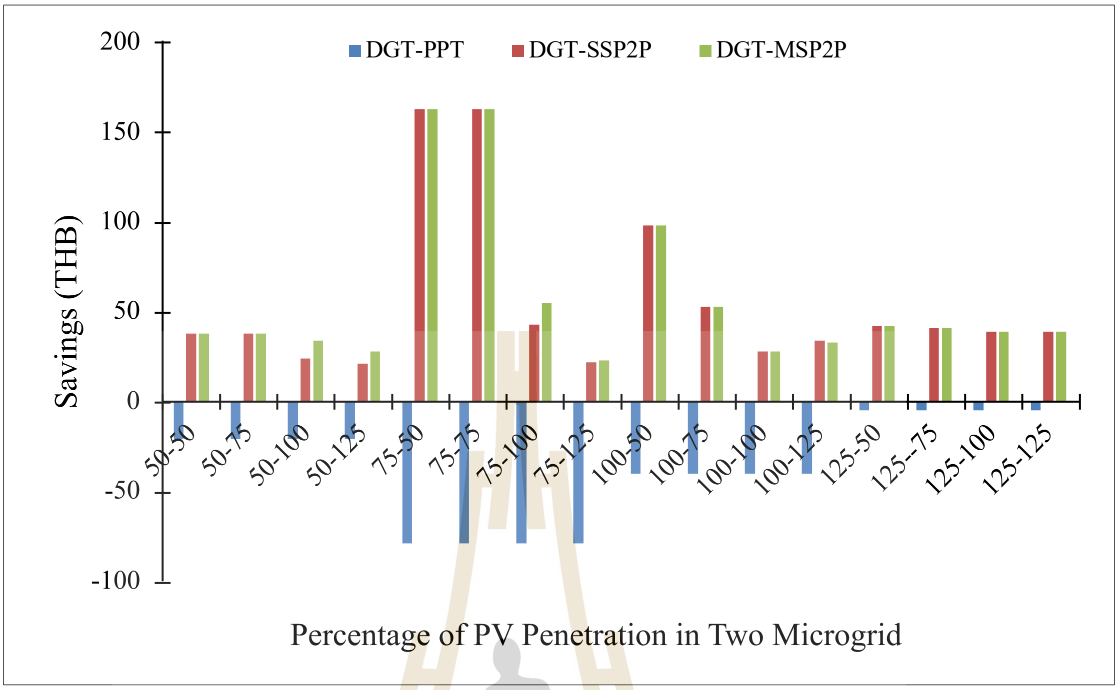

Figure 4.12 Savings in the electricity bill of NG2 in varying PV injection level

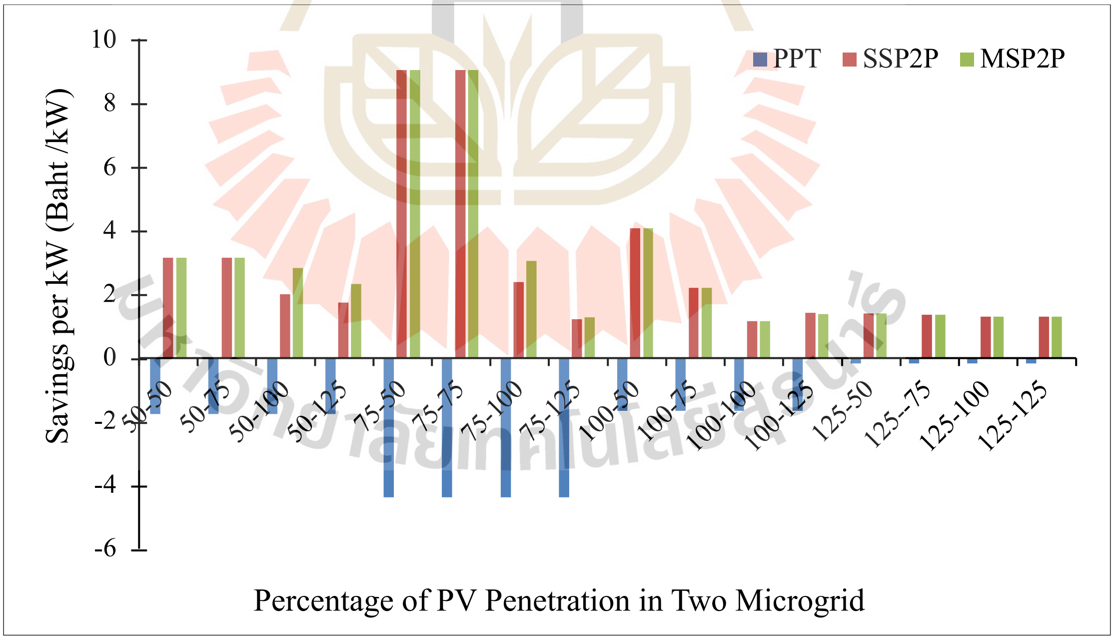

Figure 4.13 Saving per kW PV installation of NG2

Figure 4.12 presents the savings achieved by NG2 in various trading platforms with varying levels of PV injection. Thee subsequent Figure 4.13 describes the saving per kilowatt PV installation. It is evident that the PPT platform always resulted in a loss to the NG2 it is because of its loading characteristics. Referring to Figure 4.2, it is clear that NG2 has a peak load of 24kW, and that occurs at 3:00 PM. In other times its load is less than 12 kW and even less than 5kW in night and morning time. So its PV generation is in excess almost all the time. Since PPT accounts energy requirements and supply on a daily basis, it is quite possible that NG2 has net excess energy supply making net sellers. If the excess power is significantly higher than the other contributors, it will lose substantially. Hence the PPT resulted in a loss in almost all scenarios. On the contrary, SSP2P and MSP2P resulted in considerable profit as its energy rates only depend on hourly supply demand.

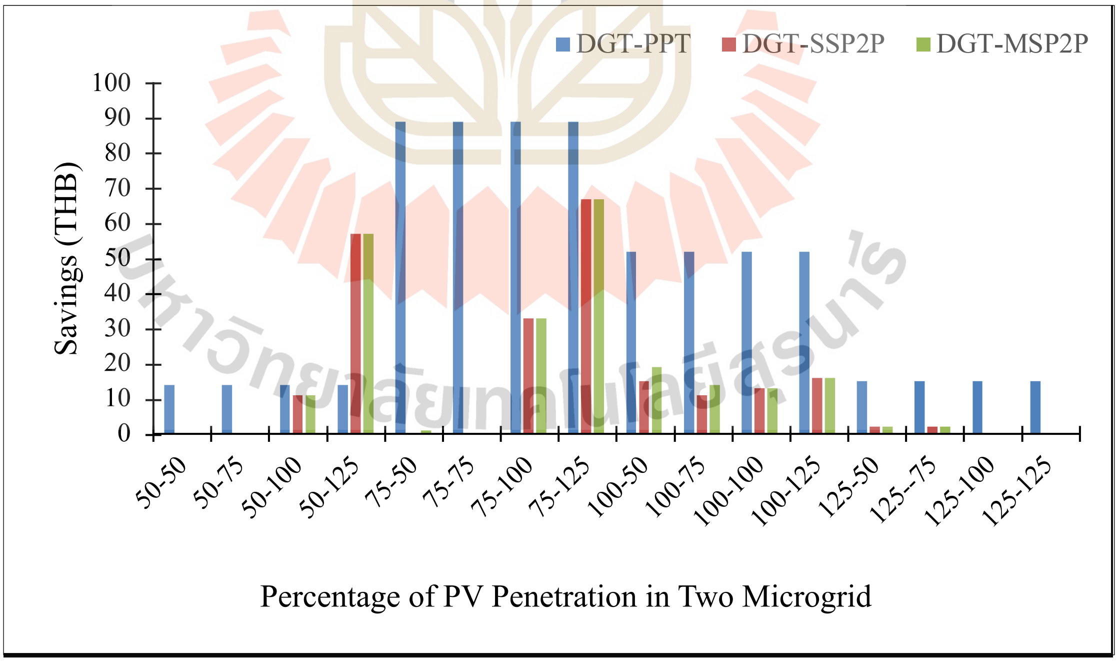

Figure 4.14 Savings in the electricity bill of NG3 in varying PV injection level

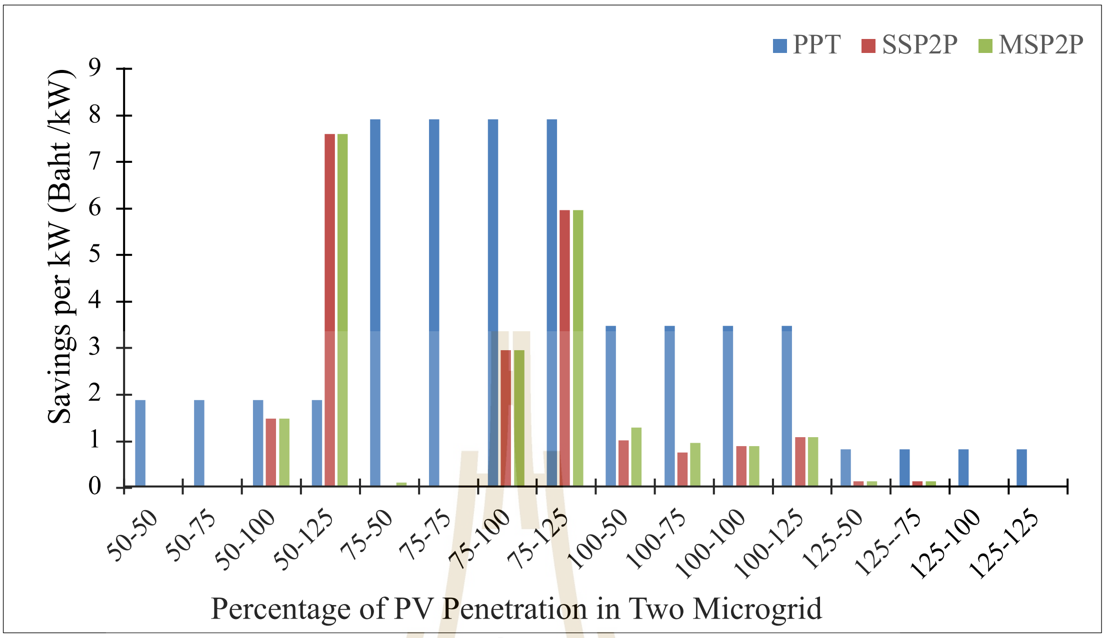

Figure 4.15 Saving per kW PV installation of NG3

Per day savings in the electricity bill of NG3 in various trading options compared to DGT is presented in Figure 4.14. Figure 4.15 presents the saving per kilowatt PV installation. It is evident that the PPT trading method is most profitable than other options. It can be defined by its load curve. Referring to Figure 4.2, NG3 has almost constant demand throughout the day. Its PV generation will be low and is almost sufficient for self-consumption. Hence the energy contribution of NG3 to the community is negligible, but its share in load demand is considerably high. PPT only calculates cost on a daily basis, so NG3 is able to make other NGs pay its bill resulting in a very high profit, as shown in Figure 4.14. it can be explained that the NG3 is in power-hungry mode, taking the reference of SSP2P and MSP2P cost, as shown in Figure 4.14. It is evident that the NG3 earned more significant profit from SSP2P and MSP2P when the PV injection is 50% -125% and 75%-125%, suggesting it is buying cheap power from power reach microgrid 2.

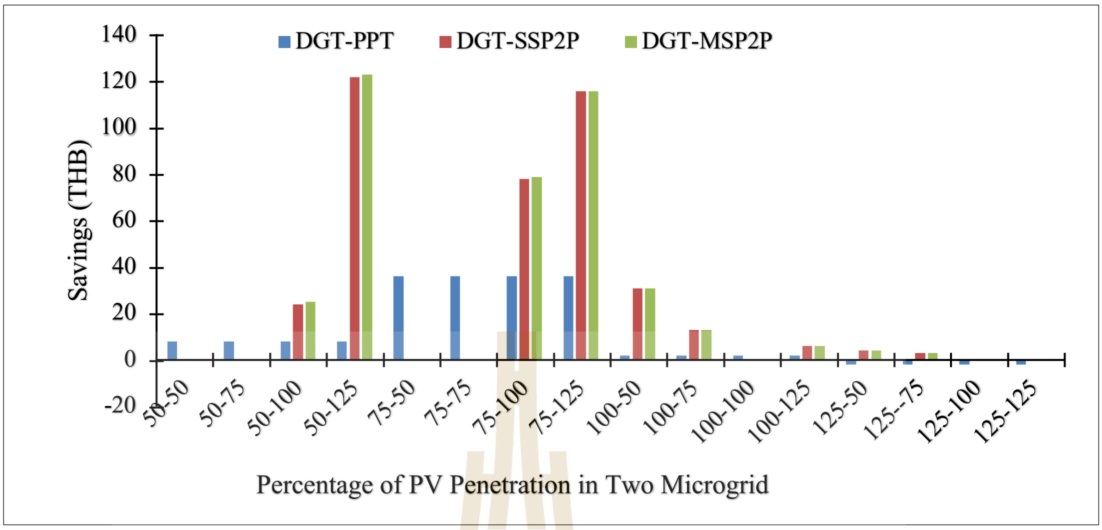

Figure 4.16 Savings in the electricity bill of NG4 in varying PV injection level

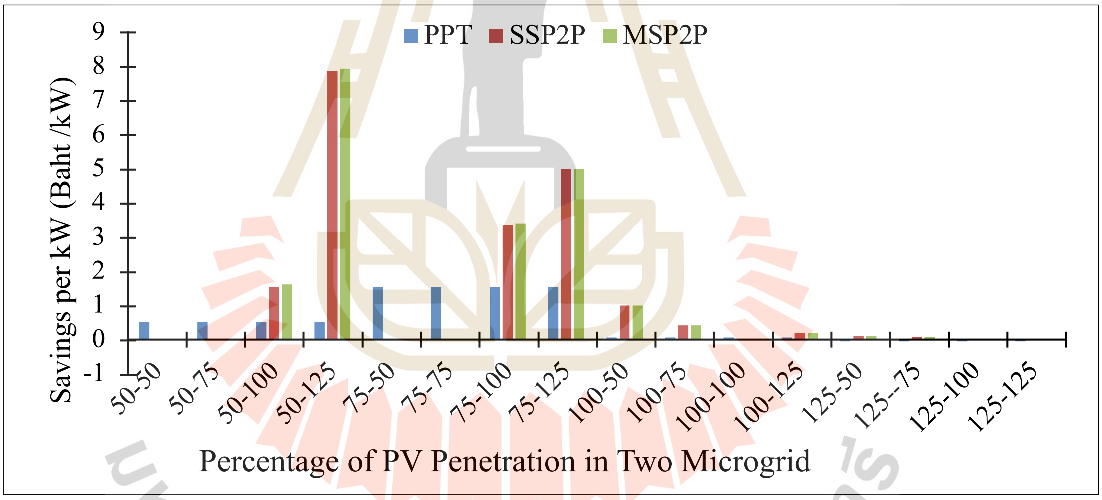

Figure 4.17 Saving per kW PV installation of NG4

Similar to the explanation of NG3, NG4 also is in power deficit mode. As shown in Figure 4.16, SSP2P and MSP2P trading seem more profitable to this NG4 if the next microgrid has excess energy. PPT trading is also profitable if NG4 has a relatively lower PV injection. Per kilowatt, saving is also presented in Figure 4.17. It shows that if the PV injection is excessively high, then the saving per kilowatt is negligibly low, but the return in investment will be considerably high if MSP2P is used and the second microgrid has an excess of cheap power.

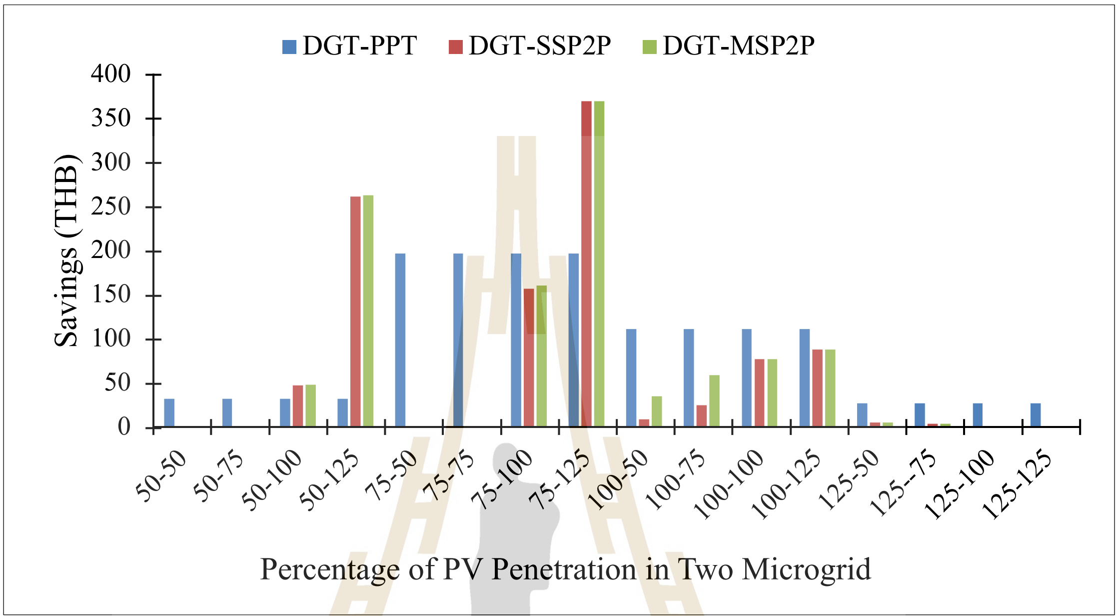

Figure 4.18 Savings in the electricity bill of NG5 in varying PV injection level

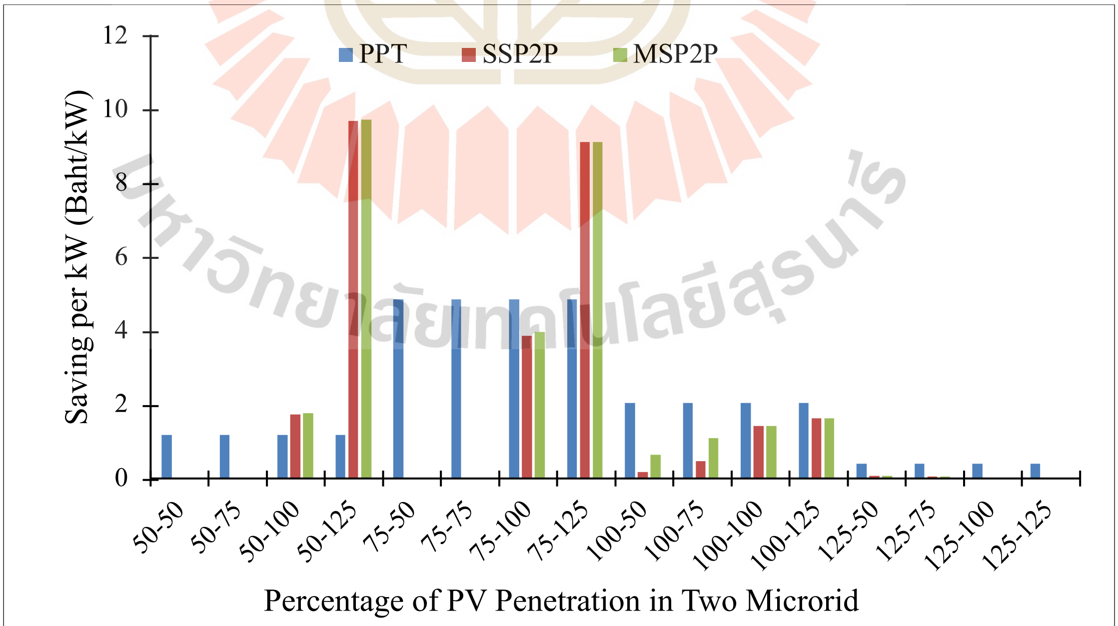

Figure 4.19 Saving per kW PV installation of NG5

NG5 is the final nanogrid of the microgrid. Figure 4.18 describes the per day saving in electricity bill in various trading options compared to DGT, and saving per kilowatt saving is presented in subsequent Figure 4.19, as shown in the Figure 4.18, if the microgrid has very low PV injection (50%) and very high penetration (125%), both SSP2P and MSP2P resulted in almost zero savings, i.e., the billing amount is equal to the DGT bill. It is due to the fact that in both cases, the trading is done with the grid only as there is no necessary supply in one case; on the contrary, no consumption is another case. However, if the power need is supplied by another microgrid as in the case of a 75%-125% PV injection case, a very substantial saving is evident in both SSP2P and MSP2P. PPT resulted in a reasonably fair saving in almost all levels of PV injection. NG5 has the highest load compared to the other members of microgrid 1. Another NGs has shared that load, so the cost reduced, but due to its size, the reduction is minimal; however, that sharing may have caused a substantial increase in the cost of some other NG.

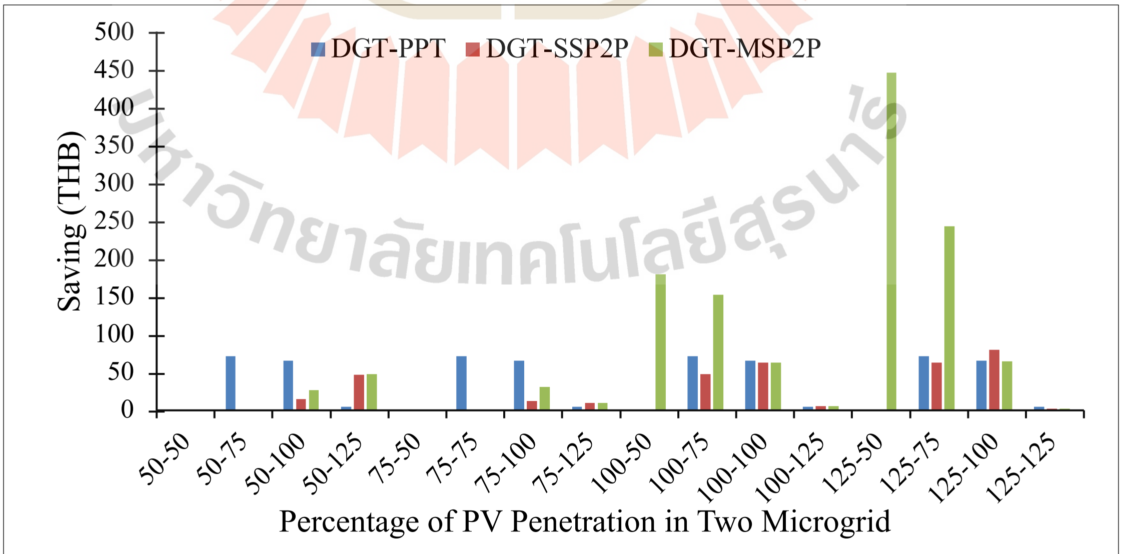

Figure 4.20 Savings in elctricity bill of NG6 in varying PV injection level

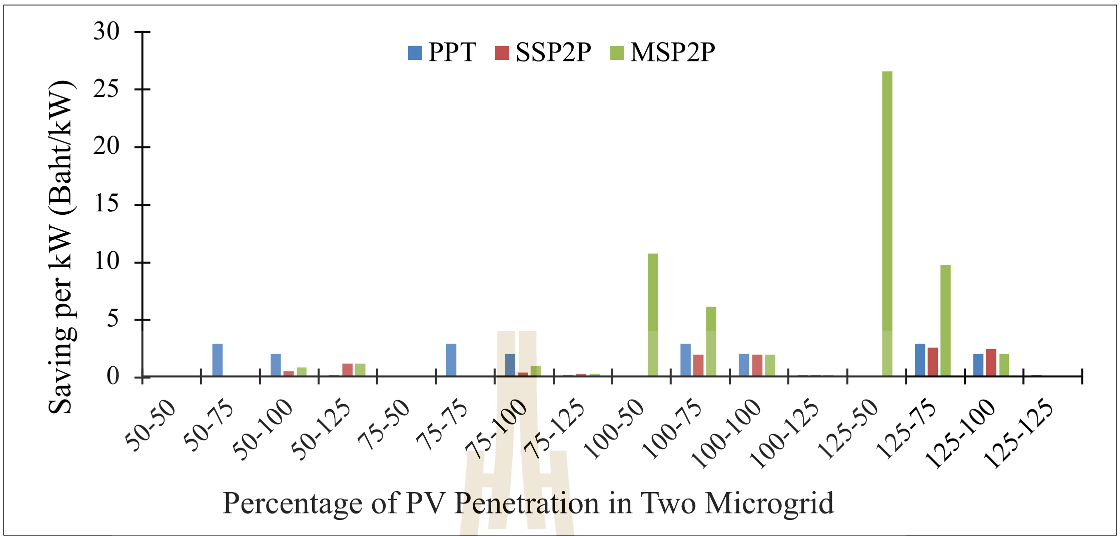

Figure 4.21 Saving per kW PV installation of NG6

NG6 is the first nanogrid of microgrid 2. Figure 4.20 describes the per day savings in electricity bills in various trading platforms with varying levels of solar injection. PPT generated fairly constant saving both in the case of 75% and 100% solar injection but generated zero and negligible savings when PV injection is 50% and 125%. It is due to the fact that in a 50% scenario, the NG6 doesn't have sufficient to generation to support its own load, and the same is true for another member of microgrid, so the grid trading is inevitable and hence zero saving. On the contrary, at 125% PV injection, all NGs have excess power and again sell it to the grid. A small amount in saving suggests that there is a very low degree of power exchange between NGs. SSP2P and MSP2P resulted in a considerable amount of saving when the MG1 is in power reach mode. Referring to the graph (Figure 4.20), it is evident that the saving achieved in 100% - 50% is significantly higher than that during 50%-100%, suggesting that this NG is buying power. The same can also be defined by taking reference to the PV injection level of MG1. The saving of NG6 is significantly higher in the case of

125% injection in MG1than that of 100% injection, suggesting NG6 is always in power-hungry mode. Figure 4.21 represents saving per kilowatt PV installation. This index is utilized to make an investment decision and its significanceand meaning for all nonogrids and microgris is explained in detail in section 4.7.

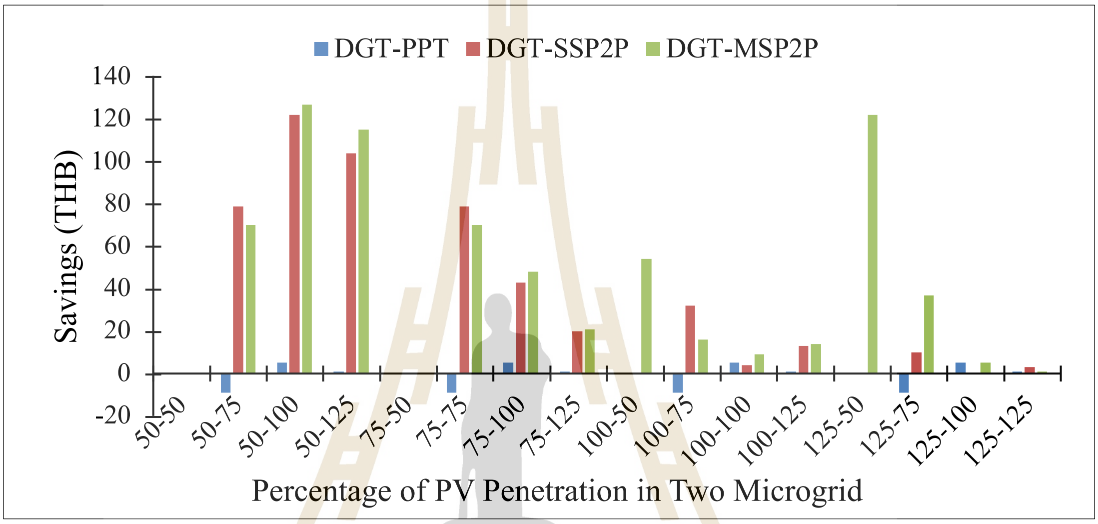

Figure 4.22 Savings in the electricity bill of NG7 in varying PV injection level

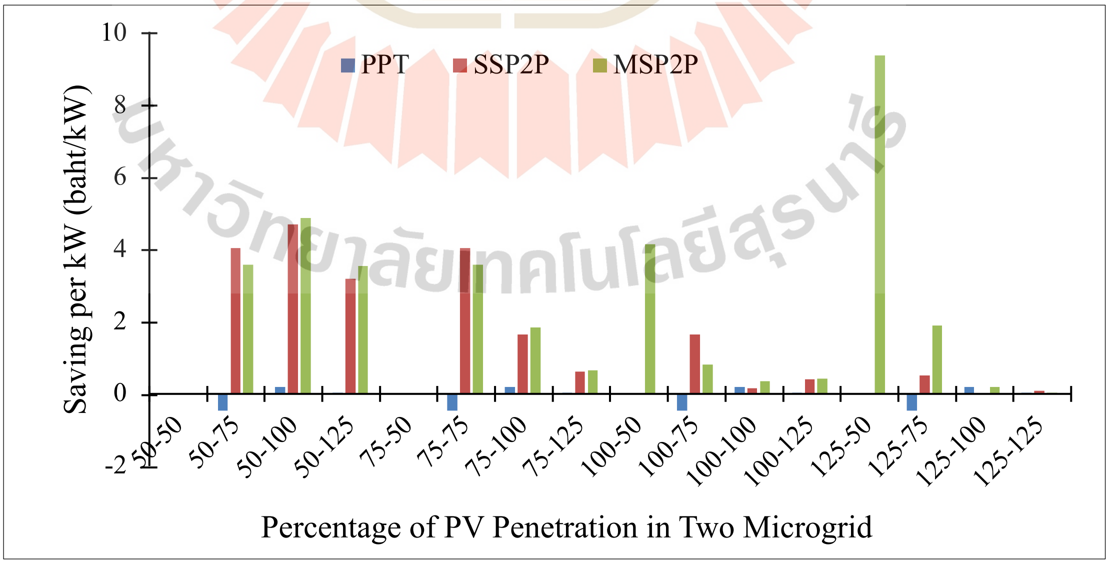

Figure 4.23 Saving per kW PV installation of NG7

Figure 4.22 presents the possible savings in per day electricity bill in various trading models compared to DGT. Taking reference to the load curve of NG7, it is seen that its peak demand occurs at 14 hours and is significantly higher than the normal load. Consequently, it can generate a large amount of power during solar noon and is more than its demand. As a result, it becomes a seller even at 75% PV injection case, and as shown in Figure 4.22 PPT method resulted in some loss in that instant even the SSP2P and MSP2P is providing a decent profit. Interestingly SSP2P is more beneficial in that case than MSP2P it is because NG7 has dominated the excess power availability in the particular case of 50%-75% PV injection. So the supply to demand ratio is in favor of it and get more profit. On the contrary, when calculating supply to demand ratio in MSP2P whole system must be considered, and the amount of power it holds becomes less significant to fluctuate the pricing rate resulting in less profit. However, when the solar injection is increased to 100% and more, other NGs will also have excess power, so the possibility of altering pricing in a larger system is greater than within the community. This NG7 also greatly benefitted by buying power from another microgrid if it is in power shortage condition. It is not quite practical to consider a huge margin between PV injections of two microgrids. Considering Figure 4.23 per kilowatt saving of almost 4 THB is possible in both SSP2P and MSP2P at 75% PV installation in each microgrid, suggesting potential investment options.

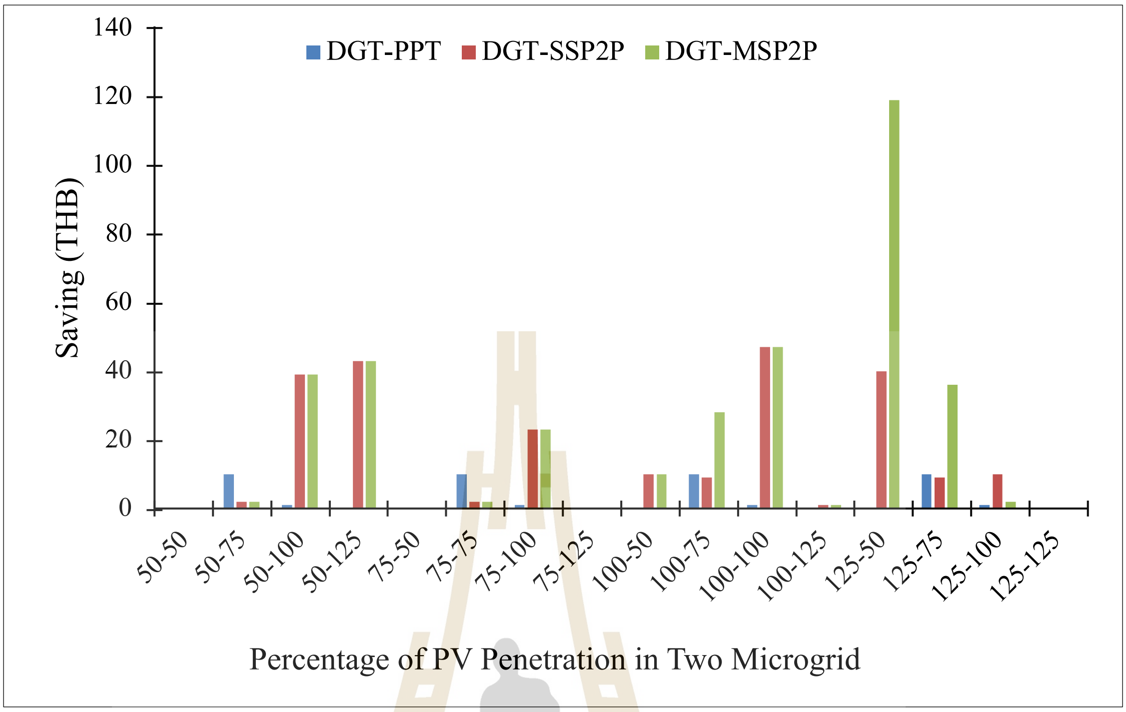

Figure 4.24 Savings in the electricity bill of NG8 in varying PV injection level

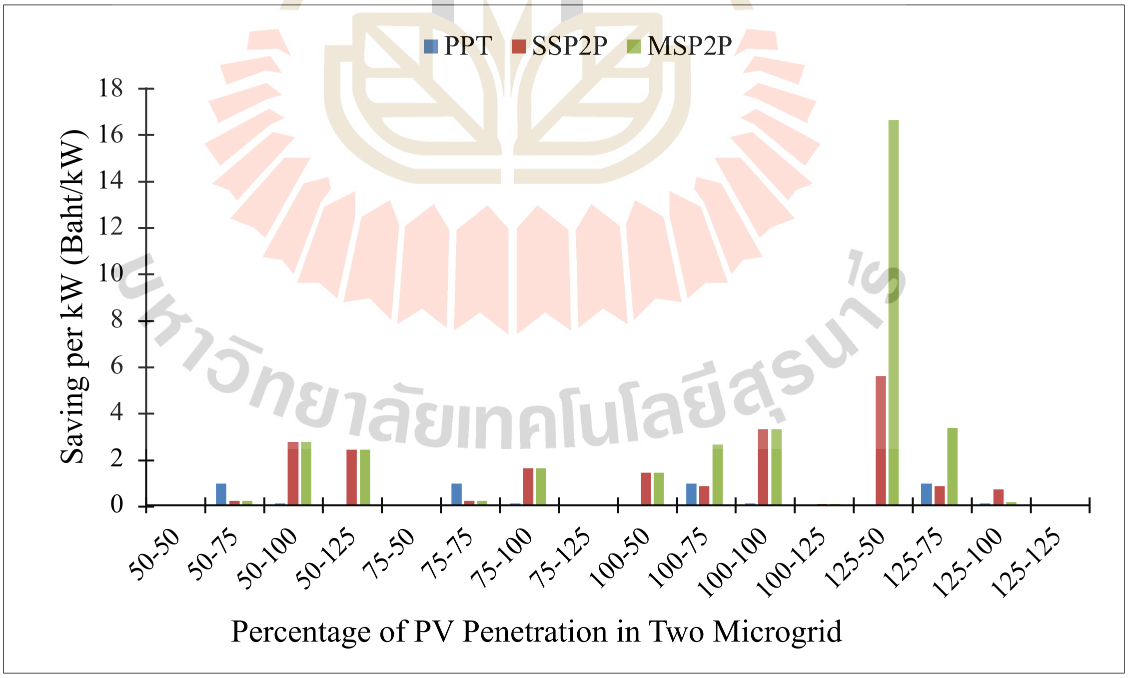

Figure 4. 25 Saving per kW PV installation of NG8

Figure 4.24 describes the per day saving of NG8 achieved in different trading platforms. It is evident that the PPT method resulted in almost no savings in all PV injection level except 75%. A considerable amount of saving was gained by selling power in SSP2P and MSP2P when the NG8 has excess power, and another microgrid is in a serious power crisis, like in 50% - 100% and 50% -125%. But the most significant profit was obtained by buying excess power from microgrid in the MSP2P trading method like in the case of 125%-50%. Referring to the Figure 4.25, such saving is almost 17 THB per kilowatt solar installation. however, in the practical sense, such a huge gap may not always be available in the trading market.

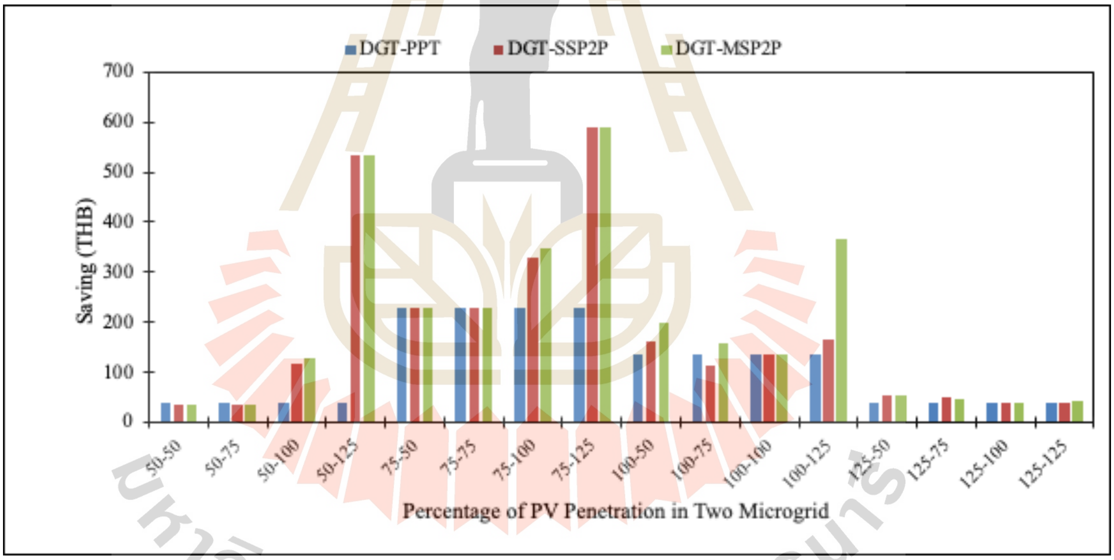

Figure 26 Savings in the electricity bill of MG1 in varying PV injection level

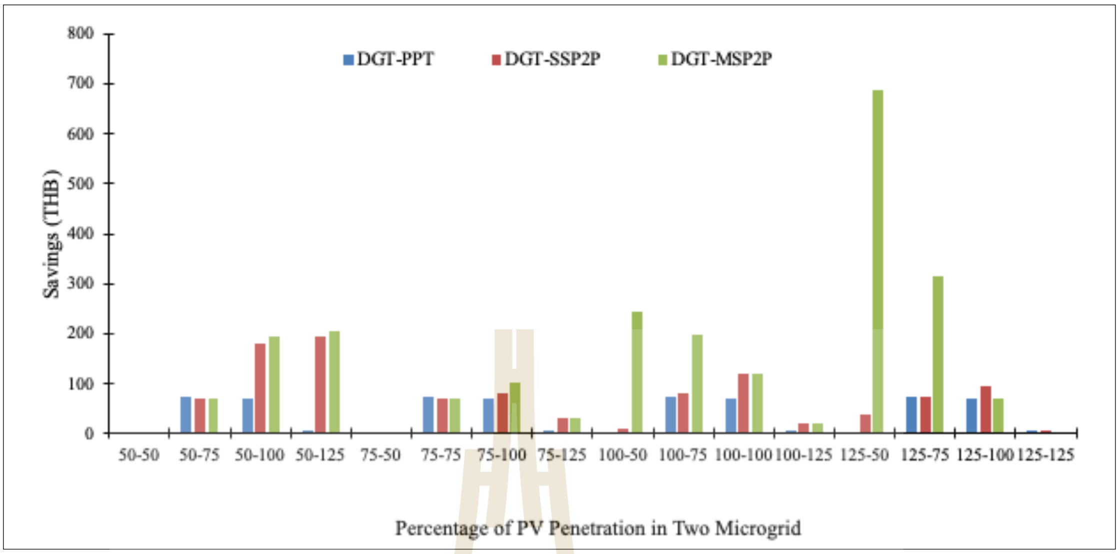

Figure 27 Savings in the electricity bill of MG2 in varying PV injection level

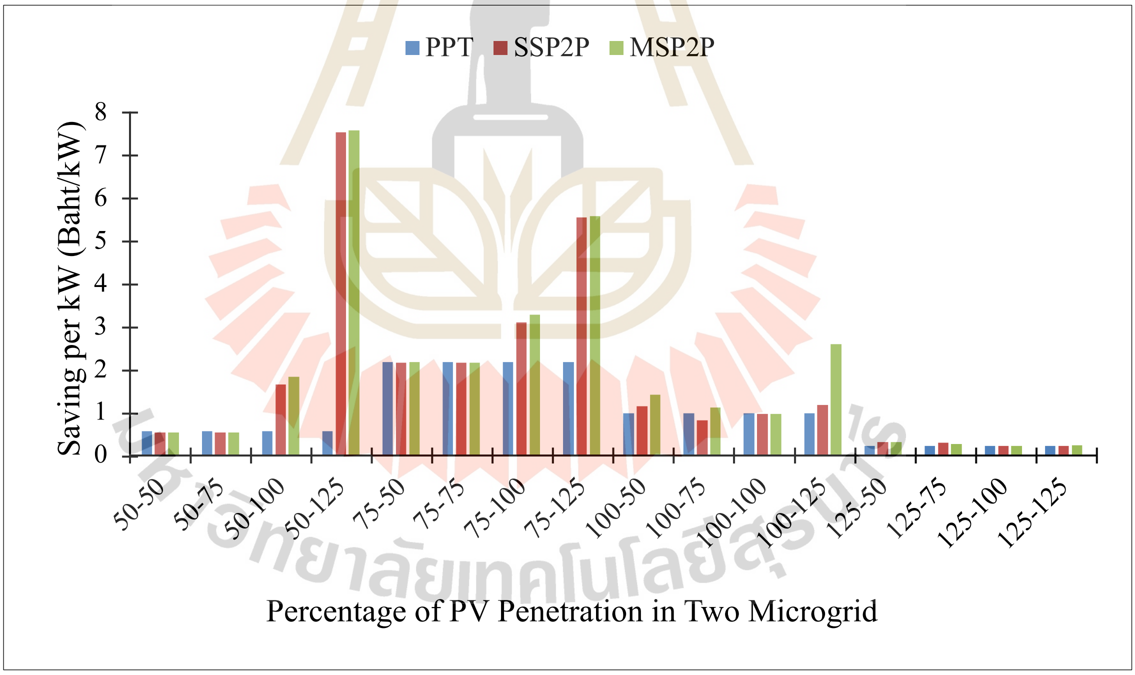

Figure 4.28 Saving per kW PV installation of MG1

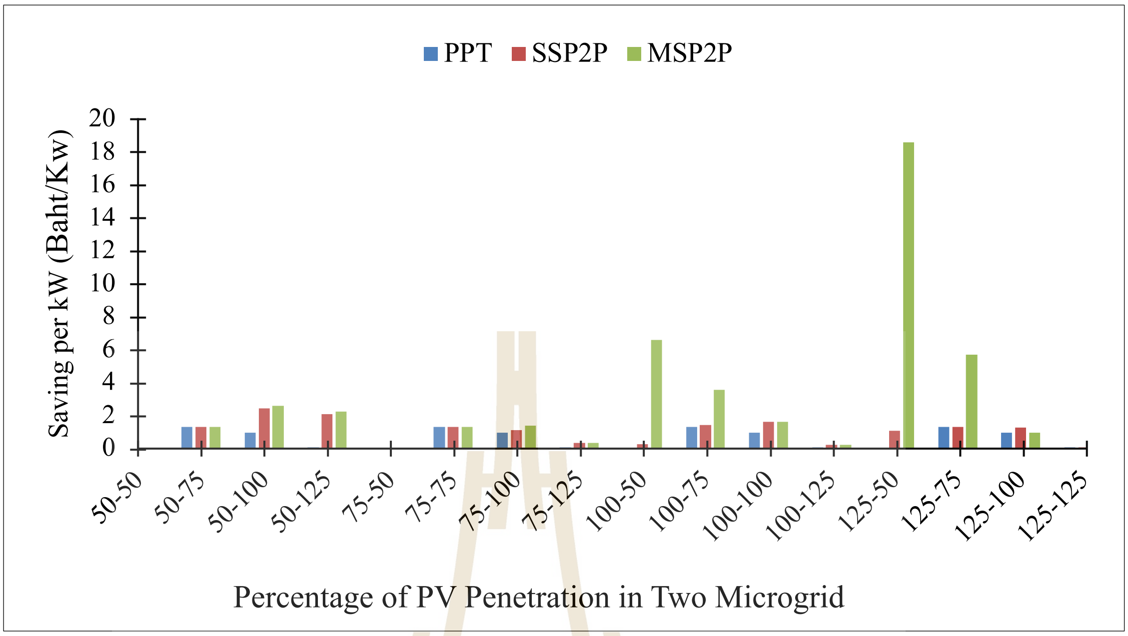

Figure 4.29 Saving per kW PV installation of MG2

Figure 4.26 and Figure 4.27 presents the data of possible saving in per day electricity bill in three trading models compared to DGT with varying PV injection levels. Similarly, Figure 4.28 and Figure 4.29, respectively describes saving per kilowatt solar installation in microgrid 1 and microgrid 2. After analysing the Figures 4.26 - 4.29 following observations were made;

1. MSP2P is the most profitable trading platform

As shown in the Figure above, it is clear that MSP2P resulted in the highest saving than other trading options. However, SSP2P has also produced the same profit in many PV injection levels; it is due to the supply-demand in that particular case. If energy export beyond the microgrid is possible, MSP2P always resulted in higher profit.

2. Saving is mostly dependent on the amount of imported energy rather than export.

The primary consideration of P2P trading is that the rate of energy buying from the grid is higher than the rate on which a prosumer sells back to the grid. On this note, the energy available in the trading market becomes very cheaper than the energy imported from the grid. As the grid buying rate is very higher, a small percentage change in that rate will result in a considerable reduction in the nominal cost of electricity. But the same percentage change in the grid selling rate will not significantly different than the original rate. So the nominal saving in the bill is mainly dominated by the amount of power imported from the trading platform rather than sold energy to the market. However, both sellers and buyers will get benefitted, but the degree of profit is in favor of the buyer. Due to this reason, a high spike in saving has observed when each microgrid has a very low PV penetration level, like 50% and others in 125%. When MG1 has a PV injection of 50% and MG2 at 125%, MG1 gets saving of around 7.5 THB per kW PV installation at the same time MG2 has the maximum saving of the only 2.23THB per kW.

3. Even at around 75% of PV penetration, both the microgrid has saving per kilowatt PV installation greater than zero (around 2), suggesting the worth of the P2P market.

If a consumer has the capacity to generate power, then it is more profitable to establish a P2P market rather than direct power exchanges between prosumer and the utility. From the above results, we can conclude that PPT is more profitable to prosumers if all prosumers have a comparable contribution to the demand and supply; otherwise, a larger power supplier will be in loss, and a higher demand prosumer receives the largest profit which is unfair to the supplier. SSP2P and MSP2P overcome this shortcoming.

When both microgrids are at the PV availability of around 75%, both microgrid achieved per kilowatt saving of around 2 THB in SSP2P and MSP2P model. Which seems worthy investment, however, does that amount surpass the break-even point is the topic of further research.

4.5 Analysis of commercial consumers in interchange mode (Case II)

In the previous scenario, it is considered that each nanogrid has solar generation capacity with the various proportion of their maximum demand. In that particular scenario, the large proportion of power generated by one nanogrid is mainly utilized by itself (self-consumption). So the power available for trading is minimum. It is a good idea to analyze how self-consumption affects the overall profitability of trading mechanisms. The idea is to interchange solar generation capacities to each other, maintaining the total investment and capacity of the system uninterrupted. For the simulation purpose, PV generation capacity of load 1 and 3 and load 2 and 5 were interchanged in microgrid 1. Similarly, in microgrid 2, such interchange is carried out between loads 1 and 3.

Similar to the previous case, a particular example of trading when the solar PV injection is 100% and 75% in two microgrids is explained in detail. Figures 4.30 and 4.31 represent the data used in MG1 and MG2 in this particular case.

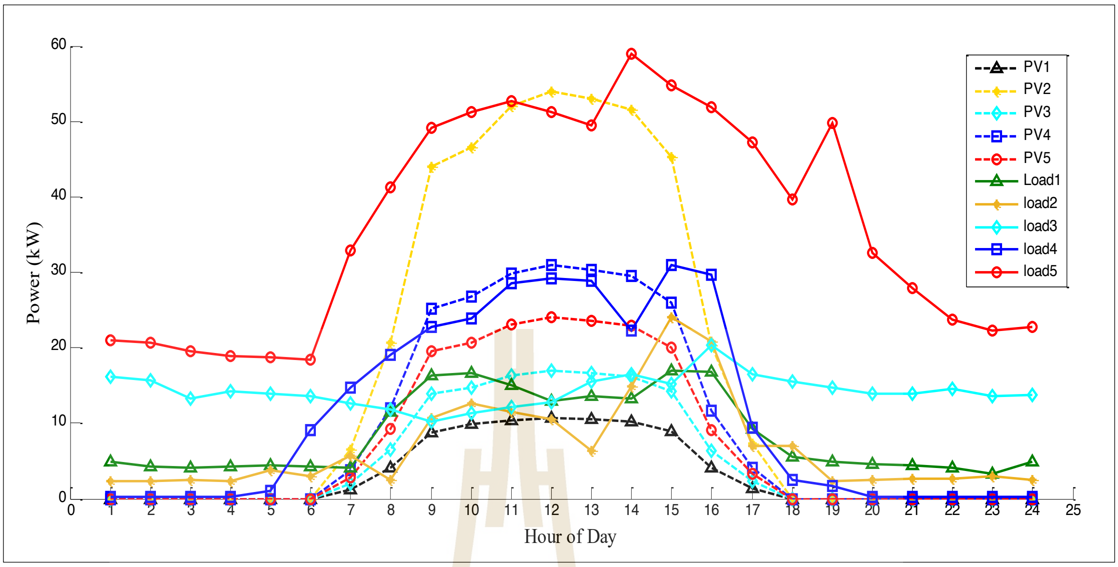

Figure 4.30 Simulation data of MG1 in interchanged mode

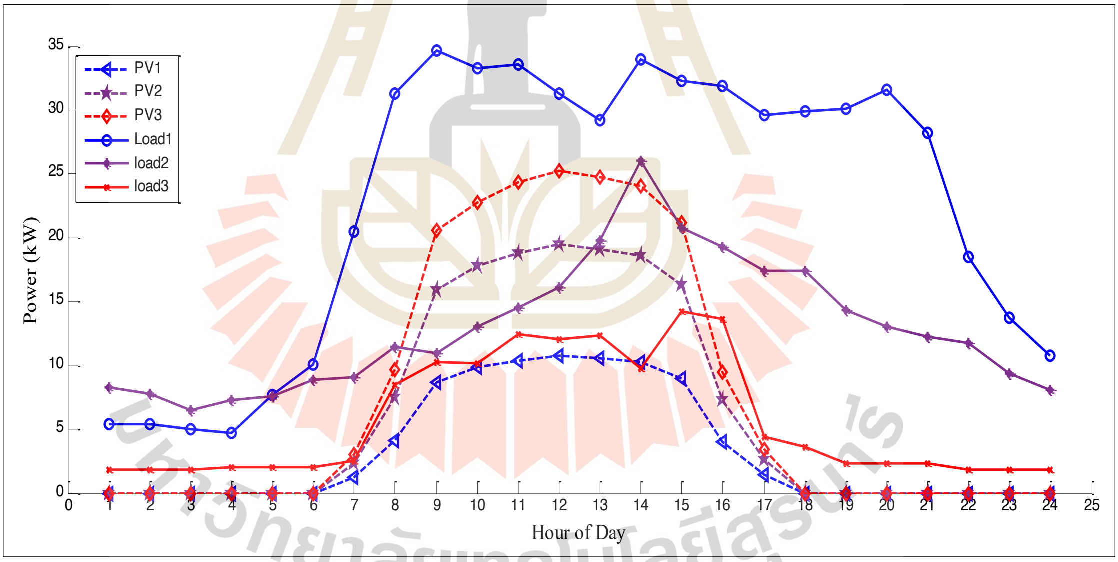

Figure 4.31 Simulation data of MG2 in interchanged mode

The internal Price Rates determined by MEM and CEMs are presented in the Figure below (Figure 32-34).

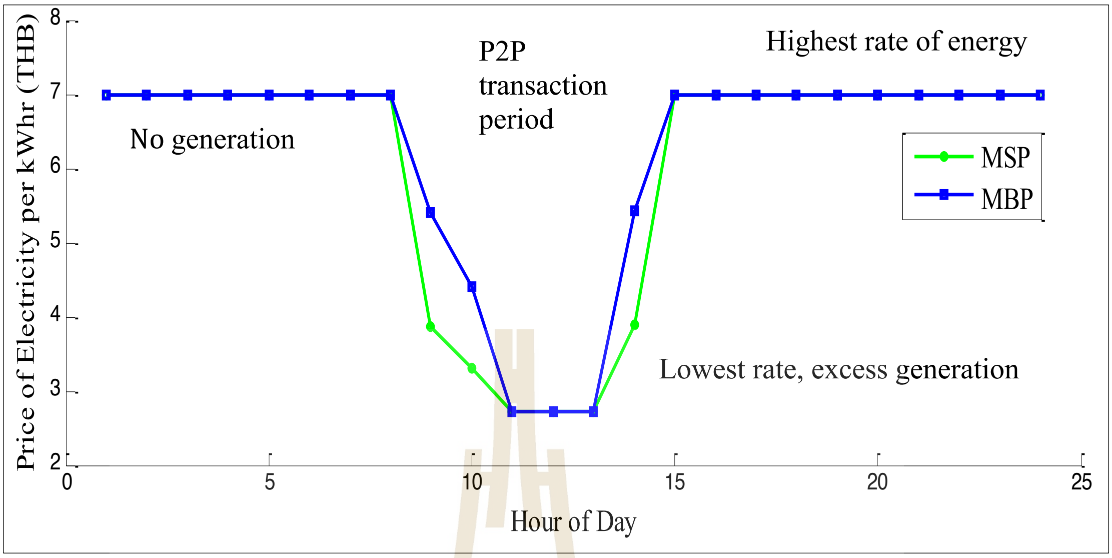

Figure 4.32 MEM pricing (in interchanged mode) at 100%-75% PV injection

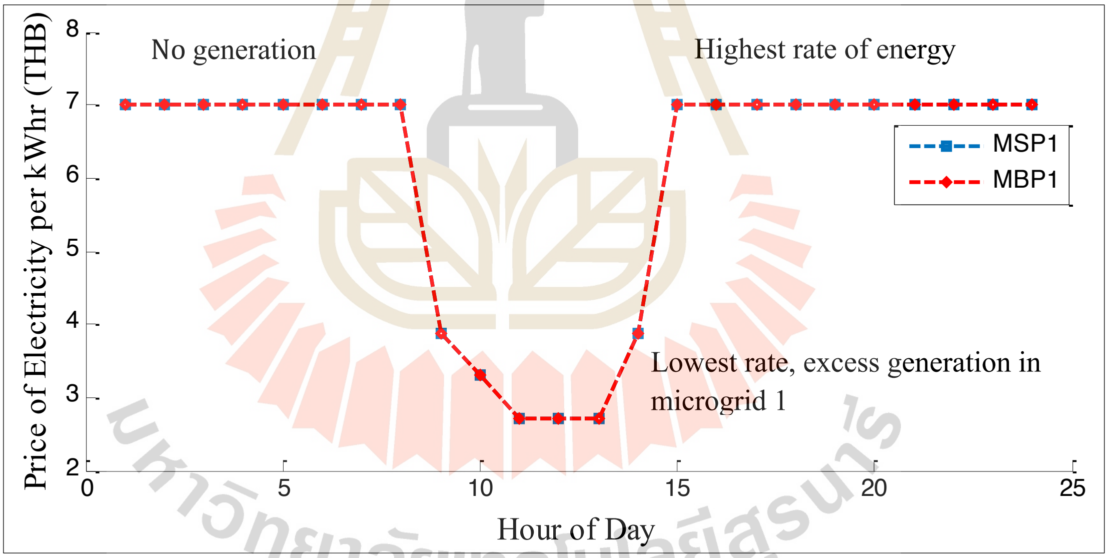

Figure 4.33 CEM1 pricing (in interchanged mode) at 100%-75% PV injection

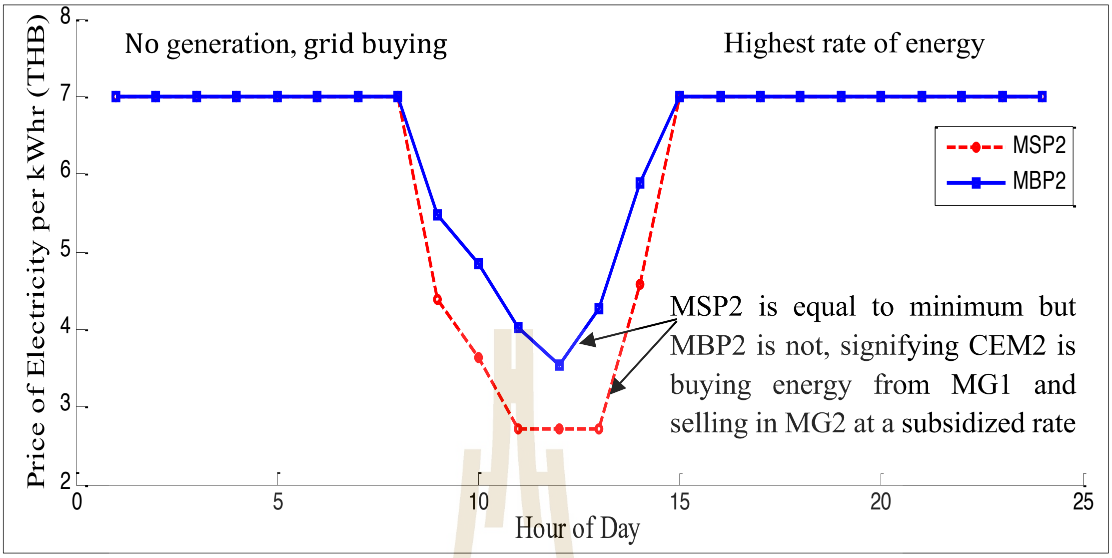

Figure 4.34 CEM2 pricing (in interchanged mode) at 100%-75% PV injection

Figure 4.32 depicts the internal buying and selling rates of electricity defined by MEM. It is quite evident that before 8 hr, and after 14 hr, the rate is maximum and equal to the grid buying price. Similarly, from 11 hr to 14 hr, both MBP and MSP are equal and minimum and equal to grid selling rate signifying that the Mem is exporting power to grid or system has excess power. Figure 4.33 represents the internal energy rate defined by CEM1. In this case, both MSP1and MBP1 are identical and are similar to MSP, which signifies that this microgrid is always in power rich mode or has more generation than demand throughout the day. Similarly, Figure 4.34 indicates the rates in microgrid 2. In this case, MBP2 has not reached the lowest value indicating it is in power deficit throughout the day. The comparison of the actual per day electricity bill in various trading mechanisms in this particular case is presented in Table 2.

Similar to the previous case, direct grid trading is the most expensive model of the transaction from the prosumer perspective. The participatory method not only reduced the cost in almost all nanogrids in some nanogrids. It is a minimum among all trading platforms. It is because that nanogrid has high cumulative demand (total demand of 24 hours). In the case of single-level and multilevel P2P trading, there is no significant difference in the electricity bill they have resulted in this case. However, the lowest bill is obtained in the multilevel transaction method.

Table 4.2 Electricity bill of NGs in interchanged mode at 100%-75% PV injection

	Electricity bill in microgrid 1 (THB)					Electricity bill in microgrid 2 (THB)		
	NG1	NG2	NG3	NG4	NG5	NG6	NG7	NG8
Direct grid trading	598	228	1645	391	3357	2558	1231	407
Participatory	585	268	1593	389	3246	2486	1240	397
Single stage P2P	585	175	1634	378	3332	2510	1215	398
Multi stage P2P	579	175	1631	378	3298	2486	1205	379

4.6 Effect of varying PV injection in the interchanged mode

Again the simulation module is run multiple times with a different combination of PV injection levels similar to the case explained earlier. Since the process and the effect even up to the nanogrid level has explained in detail in the previous case, only the most significant result is explained here, and the daily electricity bill, savings, etc. are placed in the appendix A. Only the most significant phenomena are listed and explained with relevant Figures or data.

The primary findings of the nanogrid level in this study are as follows:

A. The per-day electricity bill of some prosumers is negative, suggesting that they are earning by selling the electricity to the market.

B. The participatory method may become the most expensive trading platform to prosumer if they have a sufficiently large power contribution compared to others.

The per-day electricity bill of some prosumers are negative suggesting that they are earning by selling the electricity to the market

In this case (interchanged mode), the solar PV generation of the particular prosumer is not related to the demand of itself so that it may be very high or low. If the prosumer has a very high amount of excess power, then the cost of energy selling to the market outweigh the expenditure of buying of energy (a prosumer must buy energy to supply its demand in off solar hours as no storage facility is considered). If such a condition occurs in the system, a prosumer may generate net income from the energy trading market. Figure 4.35 is the depiction of per day electricity cost of NG2 with different levels of PV injection. It is clear from the picture that the prosumer is earning from power trading. Except for the participatory method, all trading platforms resulted in net income to the prosumer.

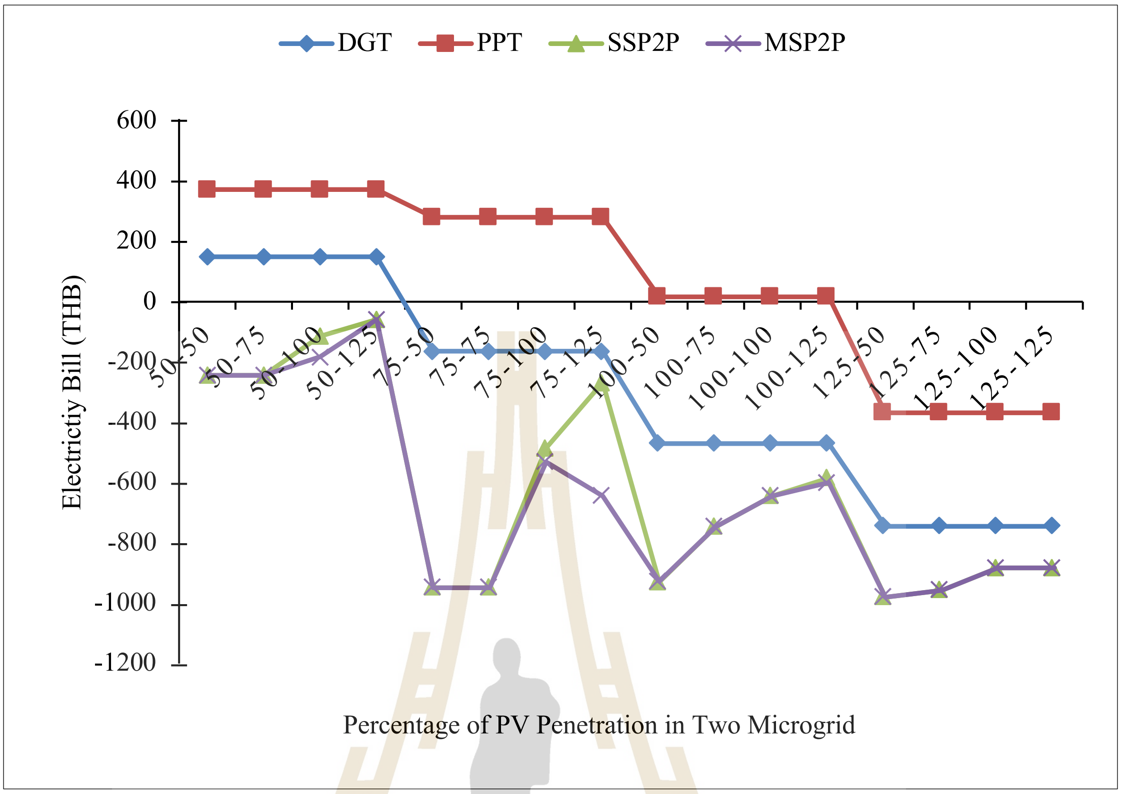

Figure 4.35 Electricity bill of NG2 at varying PV level in interchanged mode

The participatory method may become the most expensive trading platform to prosumer if they have sufficiently large power contribution compared to others

Referring to the above Figure 4.35, it is evident that for some PV injection scenarios, the PPT resulted in the highest energy bill to the prosumers. Such an unusual condition is due to its very high excess power. Taking reference to Figure 4.30, NG2 has very high PV generation capacity and comparatively lower demand; on the other hand, remaining members of the community have a reasonable gap between demand and generation. Consequently, the energy available in the trading market is almost from NG2. It is already explained in equation 3.13 and 3.14 that in the PPT method, the energy rate will always be lower than the grid rates. So the earning of NG2 has reduced greatly due to its largest share in the tradable energy. On the contrary, the other members get the benefit of lower energy buying rates. If they are required to buy energy similarly if a prosumer is selling to the market, it will not get affected badly as they have a considerably small fraction of tradable energy.

4.7 Comparison of two modes in terms of saving per kW PV installation

The primary objective of this study is to find the daily electricity bill of a commercial consumer of Korat city in different P2P energy trading platforms considering the standard solar generation potential of the city. In the first case, the solar generation of a prosumer is calculated considering the consumer's maximum demand and is referred to as the normal case in this text. The second case is interchanging of the PV installation of the prosumer, keeping the total generation of microgrid constant. This case is described as interchanged mode in this thesis. The daily electricity bill and savings of prosumer in each case are already explained earlier. This section analyzes the profitability of the above two cases in terms of savings per kilowatt PV generation.

The data of each prosumer and microgrids are placed in Appendix A. Only the significant observations are described in this section. The following phenomenon was observed from the result obtained:

I. The interchanged mode is more profitable in almost all trading platforms

In both of the cases, the power demand at a time is the same, and also the total PV generation of the microgrid is also unchanged, the parameter that varies in these two modes is the available power for trading at a particular time. In other words, the self-consumption of a prosumer at a particular time instant was altered, which resulted in a new value of supply and demand for that particular time. It is found that interchanged mode has resulted in considerably higher saving per kilowatt of PV installation compared to the normal mode to all prosumers in almost all levels of PV injection in SSP2P and MSP2P. As shown in Figure 4.36, MG1 is always in higher profit in interchanged mode compared to the normal mode in all levels of PV injection in all platforms except at 100% injection and if the PPT method is used. Similarly, MG2 received more profit, as shown in Figure 4.37. the per kilowatt saving in interchanged mode is at least 3 units higher than the normal mode in all PV penetration levels in SSP2P and MSP2P trading platforms. This higher profit is the result of the higher imbalance in supply and demand within the market.

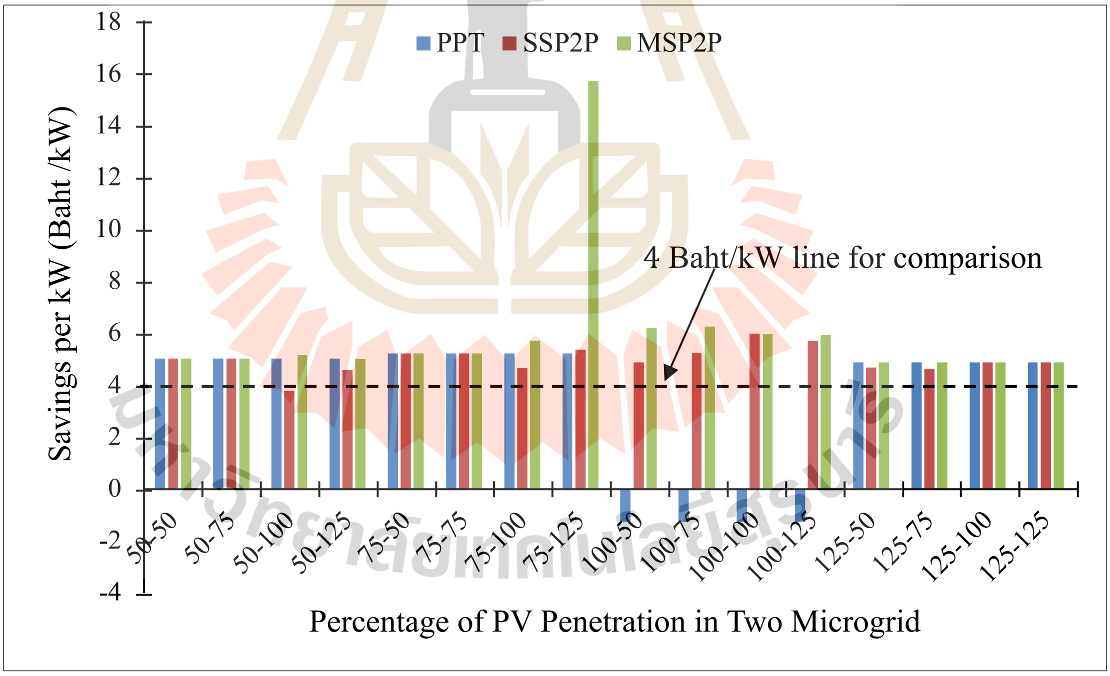

Figure 4.36 Difference in Saving per kW PV installation of MG1 between interchanged and normal mode

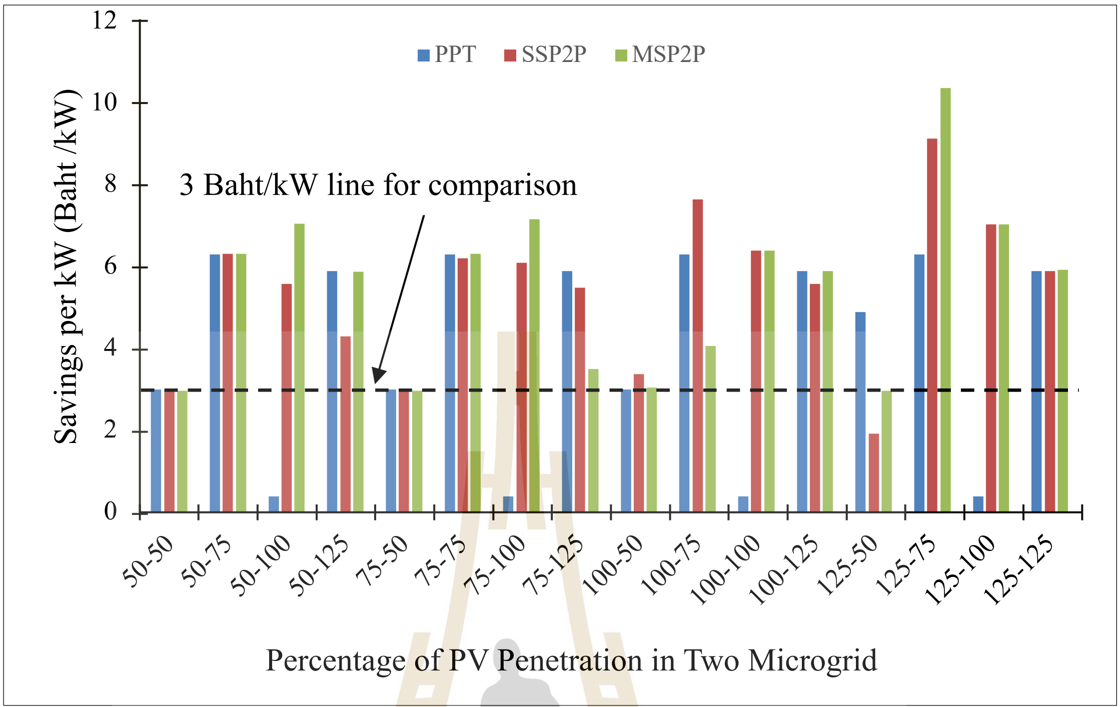

Figure 4.37 Difference in saving per kW PV installation of MG2 between interchanged and normal mode

II. SSP2P and MSP2P is more profitable if a prosumer has large excess power, but PPT method may result in loss

After interchanging the PV facilities, some small prosumers like NG2 get a large generation capacity, which enables such prosumer to sell a large amount of power to the trading market. In that case, the prosumer received a substantial amount of loss in the PPT market, whereas a significant amount of profit is available in the SSP2P and MSP2P trading platforms. PPT distributes power to all prosumers equally. i.e., generation of one particular prosumer is transferred to the prosumer at need without any cost involvement; as a result, a prosumer at a constant load demand may get benefitted, but if a prosumer is in the excess mode for a long time it will lose the profit.

III. If a prosumer has constant generation and load, then it almost remains unaffected of power imbalance in nanogrid if SSP2P and MSP2P platforms are used. However, PPT has a significant effect on it.

In interchanged mode, two nanogrids (NG4 and NG7) were left unchanged, and it was found that the change in the value of saving per kilowatt PV installation is almost zero or negligible for SSP2P and MSP2P trading platforms. Since its generation and load is unchanged in both cases, the amount of power imported and exported and also the time of doing that is unchanged. Due to the change in supply and demand in other NGs, the supply-demand ratio of the system will change; consequently, the energy rates will vary. But the energy to be imported or exported by NG will remain unchanged and is insignificant compared to others. So its cost will also remain comparatively stable in both modes. On the contrary, if the PPT method is used, the only unit of power is considered; hence the cost of electricity will be significantly lower in the interchanged mode as a large amount of power is available in the system.

4.8 Chapter summary

Chapter IV presents the results of the simulations based on the methods explained in Chapter III. The profitability of P2P transactions among some commercial consumers of Nakhon Ratchasima (Korat) was evaluated in terms of per day saving in electricity bills. The analysis was carried out considering the actual load curve and assuming various solar PV penetration scenarios. It is assumed that a prosumer is equipped with a generation facility according to its maximum demand (50%, 75%, 100% and 125% of its maximum demand), this case is referred as normal mode and secondly, the generation facilities are interchanged among them keeping the actual load constant. In both cases, it was found that the multilevel transaction will result in more savings in almost all cases; however, such saving is maximum if the energy demand and supply gap between two microgrids are significantly higher. Participatory method becomes more profitable to those prosumer who have almost constant load demand throughout the day. Finally, the saving per kilowatt of PV installation is also calculated in both cases to evaluate the worth of investment. The result shows the saving per kilowatt PV installation in interchanged mode is higher than that of normal mode by almost 4 units in microgrid 1 and 3 units in microgrid 2 in almost all loading conditions and pricing scenarios. This may lead to the opportunity of resource and profit-sharing based community energy trading market in Korat.

CHAPTER V

CONCLUSION AND FUTURE WORKS

5.1 Conclusion

The primary objective of the study is to analyze the characteristics and profitability of different community P2P trading methods from the prosumer perspective considering local load profile and solar generation potential. As the government of Thailand is promoting solar rooftop based small scale power production, P2P trading may become a reality in the near future. On that note, a qualitative analysis of existing community P2P trading methods based on the actual load profile was carried out. The significant outcome of the research is listed below:

A. MSP2P trading option is most profitable compared to other trading platforms.

B. PPT method is more profitable to a prosumer having almost constant load throughout the day. If a prosumer has significantly higher solar contribution than other prosumers then, PPT may become the most expensive trading option even greater than DGT.

C. The value of saving per kW PV installation of all prosumers is higher for all trading markets in interchanged mode, suggesting the self-consumption of PV generation should be as much avoided as much possible.

Apart from some exceptions, the MSP2P trading platform resulted in maximum profit to the prosumers, followed by SSP2P. So the participation of a prosumer in MSP2P trading is the market is completely risk-free as it won't generate more electricity bills compared to DGT due to its pricing method, which takes grid pricing as two extremes. On the contrary, PPT may result in a huge loss to the prosumer. Still, due to the simplicity of the PPT method, this could be established in a community with certain restrictions about maximum demand to be allowed in the billing calculation.

In interchanged mode, only the generation of prosumers is redistributed among each other's keeping the total generation of a microgrid unaffected. The result obtained is quite impressive in terms of profit generated from the SSP2P and MSP2P trading market, and all except prosumers with very large excess power also benefitted greatly in PPT trading. This shows the disadvantage of self-consumption. This phenomenon may give birth to a new investment plan. If a consumer has a high demand, then he can install a generation facility in the premises of low power consumers signing a profit-sharing agreement. Since an assumption of small prosumer installing large generation facilities is not quite convincing. As per the prosumers considered in this research, the hospital has a huge demand, but a school has very low power demand. It is found that if the hospital installs PV on the school premises, the profit will be higher and that profit could be shared between hospitals and schools.

5.2 Future Work

This work is solely concerned with the economics of trading methods. It does not account for the technical aspects like voltage fluctuation, line congestion, and power loss in the distribution system. Detail technical analysis should be done in advance for the project feasibility. Only the three community P2P methods are considered here, development of blockchain technology-based energy trading has gained a significant pace in recent time, this could be more profitable than community P2P. Only on the grid type PV facility is assumed throughout this thesis, the addition of the storage facility and auction algorithm may present new results. All of these aspects can be integrated with this research to extend its scope.

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APPENDIX A

SYSTEM DATA OF THE TESTED SYSTEM

1 Analysis in normal mode

1.1 Per day electricity bill, savings and saving per kW solar installation of NG1

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SSP 2P	MSP 2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT	SSP2 P	MSP 2P
50-50	991	984	991	991	8.5	7	0	0	0.82	0	0
50-75	991	984	991	991	8.5	7	0	0	0.82	0	0
50-100	991	984	980	980	8.5	7	11	11	0.82	1.29	1.29
50-125	991	984	921	927	8.5	7	70	64	0.82	8.23	7.52
75-50	563	575	497	497	12.7	-12	66	66	-0.94	5.17	5.17
75-75	563	575	497	497	12.7	-12	66	66	-0.94	5.17	5.17
75-100	563	575	545	543	12.7	-12	18	20	-0.94	1.41	1.56
75-125	563	575	549	548	12.7	-12	14	15	-0.94	1.09	1.17
100-50	598	585	588	582	17	13	10	16	0.76	0.58	0.94
100-75	598	585	585	579	17	13	13	19	0.76	0.76	1.11
100-100	598	585	579	579	17	13	19	19	0.76	1.11	1.11
100-125	598	585	575	375	17	13	23	223	0.76	1.35	13.11
125-50	464	460	461	461	21.2	4	3	3	0.18	0.14	0.14
125-75	464	460	462	462	21.2	4	2	2	0.18	0.09	0.09
125-100	464	460	464	464	21.2	4	0	0	0.18	0	0
125-125	464	460	464	460	21.2	4	0	4	0.18	0	0.18

1.2 Per day electricity bill, savings and saving per kW solar installation of NG2

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SSP 2P	MSP 2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT	SSP2 P	MSP 2P
50-50	574	595	536	536	12	-21	38	38	-1.75	3.16	3.16
50-75	574	595	536	536	12	-21	38	38	-1.75	3.16	3.16
50-100	574	595	550	540	12	-21	24	34	-1.75	2	2.83
50-125	574	595	553	546	12	-21	21	28	-1.75	1.75	2.33
75-50	387	466	224	224	18	-79	163	163	-4.38	9.05	9.05
75-75	387	466	224	224	18	-79	163	163	-4.38	9.05	9.05
75-100	387	466	344	332	18	-79	43	55	-4.38	2.38	3.05
75-125	387	466	365	364	18	-79	22	23	-4.38	1.22	1.27
100-50	228	268	130	130	24	-40	98	98	-1.66	4.08	4.08
100-75	228	268	175	175	24	-40	53	53	-1.66	2.2	2.2
100-100	228	268	200	200	24	-40	28	28	-1.66	1.16	1.16
100-125	228	268	194	195	24	-40	34	33	-1.66	1.41	1.37
125-50	75	80	33	33	30	-5	42	42	-0.16	1.4	1.4
125-75	75	80	34	34	30	-5	41	41	-0.16	1.36	1.36
125-100	75	80	36	36	30	-5	39	39	-0.16	1.3	1.3
125-125	75	80	36	36	30	-5	39	39	-0.16	1.3	1.3

1.3 Per day electricity bill, savings and saving per kW solar installation of NG3

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SSP 2P	MSP 2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT	SSP2 P	MSP 2P
50-50	1974	1960	1974	1974	7.5	14	0	0	1.86	0	0
50-75	1974	1960	1974	1974	7.5	14	0	0	1.86	0	0
50-100	1974	1960	1963	1963	7.5	14	11	11	1.86	1.46	1.46
50-125	1974	1960	1917	1917	7.5	14	57	57	1.86	7.6	7.6
75-50	1805	1716	1805	1804	11.2	89	0	1	7.91	0	0.08
75-75	1805	1716	1805	1805	11.2	89	0	0	7.91	0	0
75-100	1805	1716	1772	1772	11.2	89	33	33	7.91	2.93	2.93
75-125	1805	1716	1738	1738	11.2	89	67	67	7.91	5.95	5.95
100-50	1645	1593	1630	1626	15	52	15	19	3.46	1	1.26
100-75	1645	1593	1634	1631	15	52	11	14	3.46	0.73	0.93
100-100	1645	1593	1632	1632	15	52	13	13	3.46	0.86	0.86
100-125	1645	1593	1629	1629	15	52	16	16	3.46	1.06	1.06
125-50	1529	1514	1527	1527	18.7	15	2	2	0.8	0.1	0.1
125-75	1529	1514	1527	1527	18.7	15	2	2	0.8	0.1	0.1
125-100	1529	1514	1529	1529	18.7	15	0	0	0.8	0	0
125-125	1529	1514	1529	1529	18.7	15	0	0	0.8	0	0

1.4 Per day electricity bill, savings and saving per kW solar installation of NG4

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SSP 2P	MSP 2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT 2	SSP2 P3	MSP 2P4
50-50	1097	1089	1097	1097	15.5	8	0	0	0.51	0	0
50-75	1097	1089	1097	1097	15.5	8	0	0	0.51	0	0
50-100	1097	1089	1073	1072	15.5	8	24	25	0.51	1.54	1.61
50-125	1097	1089	975	974	15.5	8	122	123	0.51	7.87	7.93
75-50	720	684	720	720	23.2	36	0	0	1.54	0	0
75-75	720	684	720	720	23.2	36	0	0	1.54	0	0
75-100	720	684	642	641	23.2	36	78	79	1.54	3.35	3.39
75-125	720	684	604	604	23.2	36	116	116	1.54	4.98	4.98
100-50	391	389	360	360	31	2	31	31	0.06	1	1
100-75	391	389	378	378	31	2	13	13	0.06	0.41	0.41
100-100	391	389	391	391	31	2	0	0	0.06	0	0
100-125	391	389	385	385	31	2	6	6	0.06	0.19	0.19
125-50	179	181	175	175	38.7	-2	4	4	-0.05	0.1	0.1
125-75	179	181	176	176	38.7	-2	3	3	-0.05	0.07	0.07
125-100	179	181	179	179	38.7	-2	0	0	-0.05	0	0
125-125	179	181	179	179	38.7	-2	0	0	-0.05	0	0

1.5 Per day electricity bill, savings and saving per kW solar installation of NG5

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SS P2P	MS P2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT	SSP2 P	MSP 2P
50-50	4735	4703	4735	4735	27	32	0	0	1.18	0	0
50-75	4735	4703	4735	4735	27	32	0	0	1.18	0	0
50-100	4735	4703	4688	4687	27	32	47	48	1.18	1.74	1.77
50-125	4735	4703	4473	4472	27	32	262	263	1.18	9.7	9.74
75-50	4033	3836	4033	4033	40.5	197	0	0	4.86	0	0
75-75	4033	3836	4033	4033	40.5	197	0	0	4.86	0	0
75-100	4033	3836	3876	3872	40.5	197	157	161	4.86	3.87	3.97
75-125	4033	3836	3663	3663	40.5	197	370	370	4.86	9.13	9.13
100-50	3357	3246	3348	3322	54	111	9	35	2.05	0.16	0.64
100-75	3357	3246	3332	3298	54	111	25	59	2.05	0.46	1.09
100-100	3357	3246	3280	3280	54	111	77	77	2.05	1.42	1.42
100-125	3357	3246	3269	3269	54	111	88	88	2.05	1.62	1.62
125-50	2908	2881	2903	2903	67.5	27	5	5	0.4	0.07	0.07
125-75	2908	2881	2904	2904	67.5	27	4	4	0.4	0.05	0.05
125-100	2908	2881	2908	2908	67.5	27	0	0	0.4	0	0
125-125	2908	2881	2908	2908	67.5	27	0	0	0.4	0	0

1.6 Per day electricity bill, savings and saving per kW solar installation of NG6

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SSP 2P	MSP 2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT 2	SSP2 P3	MSP 2P4
50-50	3006	3006	3006	3006	16.8	0	0	0	0	0	0
50-75	2558	2486	2558	2558	25.2	72	0	0	2.85	0	0
50-100	2147	2081	2132	2120	33.6	66	15	27	1.96	0.44	0.8
50-125	1863	1858	1816	1815	42.0	5	47	48	0.11	1.11	1.14
75-50	3006	3006	3006	3006	16.8	0	0	0	0	0	0
75-75	2558	2486	2558	2558	25.2	72	0	0	2.85	0	0
75-100	2147	2081	2135	2116	33.6	66	12	31	1.96	0.35	0.92
75-125	1863	1858	1853	1853	42.0	5	10	10	0.11	0.23	0.23
100-50	3006	3006	3006	2826	16.8	0	0	180	0	0	10.7
100-75	2558	2486	2510	2405	25.2	72	48	153	2.85	1.9	6.06
100-100	2147	2081	2084	2084	33.6	66	63	63	1.96	1.87	1.87
100-125	1863	1858	1857	1857	42.0	5	6	6	0.11	0.14	0.14
125-50	3006	3006	3006	2559	16.8	0	0	447	0	0	26.58
125-75	2558	2486	2495	2314	25.2	72	63	244	2.85	2.49	9.67
125-100	2147	2081	2067	2082	33.6	66	80	65	1.96	2.37	1.93
125-125	1863	1858	1861	1861	42.0	5	2	2	0.11	0.04	0.04

1.7 Per day electricity bill, savings and saving per kW solar installation of NG7

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SSP 2P	MSP 2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT 2	SSP2 P3	MSP 2P4
50-50	1499	1499	1499	1499	13	0	0	0	0	0	0
50-75	1231	1240	1161	1161	19.5	-9	79	70	-0.46	4.05	3.58
50-100	1023	1018	896	896	26	5	122	127	0.19	4.69	4.88
50-125	863	862	758	748	32.5	1	104	115	0.03	3.2	3.53
75-50	1499	1499	1499	1499	13	0	0	0	0	0	0
75-75	1231	1240	1161	1161	19.5	-9	79	70	-0.46	4.05	3.58
75-100	1023	1018	975	975	26	5	43	48	0.19	1.65	1.84
75-125	863	862	842	842	32.5	1	20	21	0.03	0.61	0.64
100-50	1499	1499	1499	1445	13	0	0	54	0	0	4.15
100-75	1231	1240	1208	1215	19.5	-9	32	16	-0.46	1.64	0.82
100-100	1023	1018	1014	1014	26	5	4	9	0.19	0.15	0.34
100-125	863	862	849	849	32.5	1	13	14	0.03	0.4	0.43
125-50	1499	1499	1499	1377	13	0	0	122	0	0	9.38
125-75	1231	1240	1230	1194	19.5	-9	10	37	-0.46	0.51	1.89
125-100	1023	1018	1018	1018	26	5	0	5	0.19	0	0.19
125-125	863	862	859	862	32.5	1	3	1	0.03	0.09	0.03

1.8 Per day electricity bill, savings and saving per kW solar installation of NG8

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SSP 2P	MSP 2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT 2	SSP2 P3	MSP 2P4
50-50	593	593	593	593	7.1	0	0	0	0	0	0
50-75	407	397	405	405	10.7	10	2	2	0.93	0.18	0.18
50-100	274	273	235	235	14.3	1	39	39	0.06	2.72	2.72
50-125	177	177	134	134	17.8	0	43	43	0	2.4	2.4
75-50	593	593	593	593	7.1	0	0	0	0	0	0
75-75	407	397	405	405	10.7	10	2	2	0.93	0.18	0.18
75-100	274	273	251	251	14.3	1	23	23	0.06	1.6	1.6
75-125	177	177	177	177	17.8	0	0	0	0	0	0
100-50	593	593	583	583	7.1	0	10	10	0	1.39	1.39
100-75	407	397	398	379	10.7	10	9	28	0.93	0.83	2.61
100-100	274	273	227	227	14.3	1	47	47	0.06	3.28	3.28
100-125	177	177	176	176	17.8	0	1	1	0	0.05	0.05
125-50	593	593	553	474	7.15	0	40	119	0	5.59	16.64
125-75	407	397	398	371	10.7	10	9	36	0.93	0.83	3.35
125-100	274	273	264	272	14.3	1	10	2	0.06	0.69	0.13
125-125	177	177	177	177	17.8	0	0	0	0	0	0

1.9 Per day electricity bill, savings and saving per kW solar installation of MG1

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SS P2P	MS P2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT	SS P2P	MS P2P
50-50	9371	9331	9333	9333	70	40	38	38	0.56	0.53	0.53
50-75	9371	9331	9333	9333	70	40	38	38	0.56	0.53	0.53
50-100	9371	9331	9254	9242	70	40	117	129	0.56	1.65	1.82
50-125	9371	9331	8839	8836	70	40	532	535	0.56	7.54	7.58
75-50	7508	7277	7279	7278	105	231	229	230	2.18	2.16	2.17
75-75	7508	7277	7279	7279	105	231	229	229	2.18	2.16	2.16
75-100	7508	7277	7179	7160	105	231	329	348	2.18	3.11	3.29
75-125	7508	7277	6920	6918	105	231	588	590	2.18	5.56	5.57
100-50	6219	6081	6056	6020	141	138	163	199	0.97	1.15	1.41
100-75	6219	6081	6104	6061	141	138	115	158	0.97	0.81	1.12
100-100	6219	6081	6082	6082	141	138	137	137	0.97	0.97	0.97
100-125	6219	6081	6052	5853	141	138	167	366	0.97	1.18	2.59
125-50	5155	5116	5099	5099	176	39	56	56	0.22	0.31	0.31
125-75	5155	5116	5103	5109	176	39	52	46	0.22	0.29	0.26
125-100	5155	5116	5116	5116	176	39	39	39	0.22	0.22	0.22
125-125	5155	5116	5116	5112	176	39	39	43	0.22	0.22	0.24

1.10 Per day electricity bill, savings and saving per kW solar installation of MG2

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SS P2P	MS P2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT	SS P2P	MS P2P
50-50	5098	5098	5098	5098	36.9	0	0	0	0	0	0
50-75	4196	4123	4124	4124	55.4	73	72	72	1.31	1.29	1.29
50-100	3444	3372	3263	3251	73.9	72	181	193	0.97	2.44	2.61
50-125	2903	2897	2708	2697	92.4	6	195	206	0.06	2.11	2.22
75-50	5098	5098	5098	5098	36.9	0	0	0	0	0	0
75-75	4196	4123	4124	4124	55.4	73	72	72	1.31	1.29	1.29
75-100	3444	3372	3361	3342	73.9	72	83	102	0.97	1.12	1.37
75-125	2903	2897	2872	2872	92.4	6	31	31	0.06	0.33	0.33
100-50	5098	5098	5088	4854	36.9	0	10	244	0	0.27	6.6
100-75	4196	4123	4116	3999	55.4	73	80	197	1.31	1.44	3.55
100-100	3444	3372	3325	3325	73.9	72	119	119	0.97	1.6	1.6
100-125	2903	2897	2882	2882	92.4	6	21	21	0.06	0.22	0.22
125-50	5098	5098	5058	4410	36.9	0	40	688	0	1.08	18.61
125-75	4196	4123	4123	3879	55.4	73	73	317	1.31	1.31	5.71
125-100	3444	3372	3349	3372	73.9	72	95	72	0.97	1.28	0.97
125-125	2903	2897	2897	2900	92.4	6	6	3	0.06	0.06	0.03

2 Analysis in the interchanged mode

2.1 Per day electricity bill, savings and saving per kW solar installation of NG1

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SS P2P	MS P2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT	SS P2P	MS P2P
50-50	1017	951	1017	1017	7.5	66	0	0	8.8	0	0
50-75	1017	951	1017	1017	7.5	66	0	0	8.8	0	0
50-100	1017	951	1005	1002	7.5	66	12	15	8.8	1.6	2
50-125	1017	951	949	945	7.5	66	68	72	8.8	9	9.6
75-50	848	725	848	848	11.2	123	0	0	10.9	0	0
75-75	848	725	848	848	11.2	123	0	0	10.9	0	0
75-100	848	725	814	806	11.2	123	34	42	10.9	3	3.7
75-125	848	725	750	635	11.2	123	98	213	10.9	8.7	18.9
100-50	671	541	664	652	15	130	7	19	8.6	0.4	1.2
100-75	671	541	651	641	15	130	20	30	8.6	1.3	2
100-100	671	541	635	635	15	130	36	36	8.6	2.4	2.4
100-125	671	541	630	628	15	130	41	43	8.6	2.7	2.8
125-50	536	440	529	528	18.7	96	7	8	5.1	0.3	0.4
125-75	536	440	527	527	18.7	96	9	9	5.1	0.4	0.4
125-100	536	440	524	524	18.7	96	12	12	5.1	0.6	0.6
125-125	536	440	524	524	18.7	96	12	12	5.1	0.6	0.6

2.2 Per day electricity bill, savings and saving per kW solar installation of NG2

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SS P2P	MS P2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT	SS P2P	MS P2P
50-50	149	372	-243	-243	27	-223	392	392	-8.2	14.5	14.5
50-75	149	372	-243	-243	27	-223	392	392	-8.2	14.5	14.5
50-100	149	372	-114	-183	27	-223	263	332	-8.2	9.7	12.2
50-125	149	372	-59	-59	27	-223	208	208	-8.2	7.7	7.7
75-50	-164	281	-945	-945	40.5	-445	781	781	-10.9	19.2	19.2
75-75	-164	281	-945	-945	40.5	-445	781	781	-10.9	19.2	19.2
75-100	-164	281	-484	-530	40.5	-445	320	366	-10.9	7.9	9
75-125	-164	281	-267	-642	40.5	-445	103	478	-10.9	2.5	11.8
100-50	-468	18	-927	-925	54	-486	459	457	-9	8.5	8.4
100-75	-468	18	-744	-744	54	-486	276	276	-9	5.1	5.1
100-100	-468	18	-642	-642	54	-486	174	174	-9	3.2	3.2
100-125	-468	18	-583	-598	54	-486	115	130	-9	2.1	2.4
125-50	-742	-366	-977	-977	67.5	-376	235	235	-5.5	3.4	3.4
125-75	-742	-366	-954	-954	67.5	-376	212	212	-5.5	3.1	3.1
125-100	-742	-366	-881	-881	67.5	-376	139	139	-5.5	2	2
125-125	-742	-366	-881	-881	67.5	-376	139	139	-5.5	2	2

2.3 Per day electricity bill, savings and saving per kW solar installation of NG3

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SS P2P	MS P2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT	SS P2P	MS P2P
50-50	1948	1822	1948	1948	8.5	126	0	0	14.8	0	0
50-75	1948	1822	1948	1948	8.5	126	0	0	14.8	0	0
50-100	1948	1822	1938	1936	8.5	126	10	12	14.8	1.1	1.4
50-125	1948	1822	1896	1896	8.5	126	52	52	14.8	6.1	6.1
75-50	1728	1478	1727	1727	12.7	250	1	1	19.6	0	0
75-75	1728	1478	1727	1727	12.7	250	1	1	19.6	0	0
75-100	1728	1478	1714	1714	12.7	250	14	14	19.6	1	1
75-125	1728	1478	1700	1576	12.7	250	28	152	19.6	2.1	11.9
100-50	1577	1478	1556	1556	17	99	21	21	5.8	1.2	1.2
100-75	1577	1478	1570	1570	17	99	7	7	5.8	0.4	0.4
100-100	1577	1478	1574	1576	17	99	3	1	5.8	0.1	0
100-125	1577	1478	1574	1574	17	99	3	3	5.8	0.1	0.1
125-50	1468	1200	1461	1461	21.2	268	7	7	12.6	0.3	0.3
125-75	1468	1200	1463	1463	21.2	268	5	5	12.6	0.2	0.2
125-100	1468	1200	1468	1468	21.2	268	0	0	12.6	0	0
125-125	1468	1200	1468	1468	21.2	268	0	0	12.6	0	0

2.4 Per day electricity bill, savings and saving per kW solar installation of NG4

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SS P2P	MS P2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT	SS P2P	MS P2P
50-50	1097	1026	1097	1097	15.5	71	0	0	4.5	0	0
50-75	1097	1026	1097	1097	15.5	71	0	0	4.5	0	0
50-100	1097	1026	1073	1067	15.5	71	24	30	4.5	1.5	1.9
50-125	1097	1026	975	969	15.5	71	122	128	4.5	7.8	8.2
75-50	720	615	720	720	23.2	105	0	0	4.5	0	0
75-75	720	615	720	720	23.2	105	0	0	4.5	0	0
75-100	720	615	652	645	23.2	105	68	75	4.5	2.9	3.2
75-125	720	615	610	391	23.2	105	110	329	4.5	4.7	14.1
100-50	391	615	360	360	31	-224	31	31	-7.2	1	1
100-75	391	615	378	378	31	-224	13	13	-7.2	0.4	0.4
100-100	391	615	391	391	31	-224	0	0	-7.2	0	0
100-125	391	615	385	383	31	-224	6	8	-7.2	0.1	0.2
125-50	179	181	175	175	38.7	-2	4	4	0	0.1	0.1
125-75	179	181	176	176	38.7	-2	3	3	0	0	0
125-100	179	181	179	179	38.7	-2	0	0	0	0	0
125-125	179	181	179	179	38.7	-2	0	0	0	0	0

2.5 Per day electricity bill, savings and saving per kW solar installation of NG5

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SS P2P	MS P2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT 2	SS P2P3	MS P2P4
50-50	5515	5160	5515	5515	12	355	0	0	29.5	0	0
50-75	5515	5160	5515	5515	12	355	0	0	29.5	0	0
50-100	5515	5160	5441	5422	12	355	74	93	29.5	6.1	7.7
50-125	5515	5160	5109	5089	12	355	406	426	29.5	33.8	35.5
75-50	5203	4451	5203	5203	18	752	0	0	41.7	0	0
75-75	5203	4451	5203	5203	18	752	0	0	41.7	0	0
75-100	5203	4451	4815	4765	18	752	388	438	41.7	21.5	24.3
75-125	5203	4451	4385	4122	18	752	818	1081	41.7	45.4	60
100-50	4891	4451	4558	4378	24	440	333	513	18.3	13.8	21.3
100-75	4891	4451	4352	4218	24	440	539	673	18.3	22.4	28
100-100	4891	4451	4122	4122	24	440	769	769	18.3	32	32
100-125	4891	4451	4082	4067	24	440	809	824	18.3	33.7	34.3
125-50	4579	3662	3948	3914	30	917	631	665	30.5	21	22.1
125-75	4579	3662	3938	3893	30	917	641	686	30.5	21.3	22.8
125-100	4579	3662	3829	3827	30	917	750	752	30.5	25	25
125-125	4579	3662	3827	3827	30	917	752	752	30.5	25	25

2.6 Per day electricity bill, savings and saving per kW solar installation of NG6

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SS P2P	MS P2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT 2	SS P2P3	MS P2P4
50-50	3429	3310	3429	3429	7.1	119	0	0	16.6	0	0
50-75	3240	2768	3240	3240	10.7	472	0	0	44	0	0
50-100	3054	2383	3021	2900	14.3	671	33	154	46.9	2.3	10.7
50-125	2869	2250	2716	2559	17.8	619	153	310	34.6	8.5	17.3
75-50	3429	3310	3429	3429	7.1	119	0	0	16.6	0	0
75-75	3240	2768	3240	3240	10.7	472	0	0	44	0	0
75-100	3054	2383	2854	2756	14.3	671	200	298	46.9	13.9	20.8
75-125	2869	2250	2500	2556	17.8	619	369	313	34.6	20.6	17.5
100-50	3429	3310	3383	3137	7.1	119	46	292	16.6	6.4	40.8
100-75	3240	2768	2831	2930	10.7	472	409	310	44	38.1	28.9
100-100	3054	2383	2556	2556	14.3	671	498	498	46.9	34.8	34.8
100-125	2869	2250	2435	2407	17.8	619	434	462	34.6	24.2	25.8
125-50	3429	3310	3336	2753	7.1	119	93	676	16.6	13	94.5
125-75	3240	2768	2864	2644	10.7	472	376	596	44	35	55.5
125-100	3054	2383	2469	2492	14.3	671	585	562	46.9	40.9	39.3
125-125	2869	2250	2381	2381	17.8	619	488	488	34.6	27.3	27.3

2.7 Per day electricity bill, savings and saving per kW solar installation of NG7

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SS P2P	MS P2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT 2	SS P2P3	MS P2P4
50-50	1499	1447	1499	1499	13	52	0	0	4	0	0
50-75	1231	1090	1161	1161	19.5	141	70	70	7.2	3.5	3.5
50-100	1023	864	896	896	26	159	127	127	6.1	4.8	4.8
50-125	863	731	748	748	32.5	132	115	115	4	3.5	3.5
75-50	1499	1447	1499	1499	13	52	0	0	4	0	0
75-75	1231	1090	1161	1161	19.5	141	70	70	7.2	3.5	3.5
75-100	1023	864	963	963	26	159	60	60	6.1	2.3	2.3
75-125	863	731	833	833	32.5	132	30	30	4	0.9	0.9
100-50	1499	1447	1445	1490	13	52	54	9	4	4.1	0.6
100-75	1231	1090	1208	1209	19.5	141	23	22	7.2	1.1	1.1
100-100	1023	864	1014	1014	26	159	9	9	6.1	0.3	0.3
100-125	863	731	849	849	32.5	132	14	14	4	0.4	0.4
125-50	1499	1377	1481	1377	13	122	18	122	9.3	1.3	9.3
125-75	1231	1090	1214	1194	19.5	141	17	37	7.2	0.8	1.8
125-100	1023	864	1018	1018	26	159	5	5	6.1	0.1	0.1
125-125	863	731	859	859	32.5	132	4	4	4	0.1	0.1

2.8 Per day electricity bill, savings and saving per kW solar installation of NG8

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SS P2P	MS P2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT 2	SS P2P3	MS P2P4
50-50	209	269	99	99	16.8	-60	110	110	-3.5	6.5	6.5
50-75	4	194	-348	-348	25.2	-190	352	352	-7.5	13.9	13.9
50-100	-183	545	-616	-616	33.6	-728	433	433	-21.6	12.8	12.8
50-125	-356	-155	-681	-681	42.0	-201	325	325	-4.7	7.7	7.7
75-50	209	269	99	99	16.8	-60	110	110	-3.5	6.5	6.5
75-75	4	194	-342	-348	25.2	-190	346	352	-7.5	13.7	13.9
75-100	-183	545	-457	-457	33.6	-728	274	274	-21.6	8.1	8.1
75-125	-356	-155	-495	-368	42.0	-201	139	12	-4.7	3.3	0.2
100-50	209	269	174	153	16.8	-60	35	56	-3.5	2	3.3
100-75	4	194	-68	-87	25.2	-190	72	91	-7.5	2.8	3.6
100-100	-183	545	-268	-268	33.6	-728	85	85	-21.6	2.5	2.5
100-125	-356	-155	-445	-445	42.0	-201	89	89	-4.7	2.1	2.1
125-50	209	269	209	209	16.8	-60	0	0	-3.5	0	0
125-75	4	194	-182	-255	25.2	-190	186	259	-7.5	7.3	10.2
125-100	-183	545	-208	-208	33.6	-728	25	25	-21.6	0.7	0.7
125-125	-356	-155	-414	-414	42.0	-201	58	58	-4.7	1.3	1.3

2.9 Per day electricity bill, savings and saving per kW solar installation of MG1

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SS P2P	MS P2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT 2	SS P2P3	MS P2P4
50-50	9726	9331	9334	9334	70.5	395	392	392	5.6	5.5	5.5
50-75	9726	9331	9334	9334	70.5	395	392	392	5.6	5.5	5.5
50-100	9726	9331	9343	9244	70.5	395	383	482	5.6	5.4	6.8
50-125	9726	9331	8870	8840	70.5	395	856	886	5.6	12.1	12.5
75-50	8335	7550	7553	7553	105.7	785	782	782	7.4	7.3	7.3
75-75	8335	7550	7553	7553	105.7	785	782	782	7.4	7.3	7.3
75-100	8335	7550	7511	7400	105.7	785	824	935	7.4	7.7	8.8
75-125	8335	7550	7178	6082	105.7	785	1157	2253	7.4	10.9	21.3
100-50	7062	7103	6211	6021	141	-41	851	1041	-0.2	6	7.3
100-75	7062	7103	6207	6063	141	-41	855	999	-0.2	6	7
100-100	7062	7103	6080	6082	141	-41	982	980	-0.2	6.9	6.9
100-125	7062	7103	6088	6054	141	-41	974	1008	-0.2	6.9	7.1
125-50	6020	5117	5136	5101	176.2	903	884	919	5.1	5	5.2
125-75	6020	5117	5150	5105	176.2	903	870	915	5.1	4.9	5.1
125-100	6020	5117	5119	5117	176.2	903	901	903	5.1	5.1	5.1
125-125	6020	5117	5117	5117	176.2	903	903	903	5.1	5.1	5.1

2.10 Per day electricity bill, savings and saving per kW solar installation of MG2

PV level in microgrids (%)	Per day electricity bill				PV (kW)	Savings			Saving per kW PV		
	DGT	PPT	SS P2P	MS P2P		DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT	SS P2P	MS P2P
50-50	5137	5026	5027	5027	36.9	111	110	110	3	2.9	2.9
50-75	4475	4052	4053	4053	55.4	423	422	422	7.6	7.6	7.6
50-100	3894	3792	3301	3180	73.9	102	593	714	1.3	8	9.6
50-125	3376	2826	2783	2626	92.4	550	593	750	5.9	6.4	8.1
75-50	5137	5026	5027	5027	36.9	111	110	110	3	2.9	2.9
75-75	4475	4052	4059	4053	55.4	423	416	422	7.6	7.5	7.6
75-100	3894	3792	3360	3262	73.9	102	534	632	1.3	7.2	8.5
75-125	3376	2826	2838	3021	92.4	550	538	355	5.9	5.8	3.8
100-50	5137	5026	5002	4780	36.9	111	135	357	3	3.6	9.6
100-75	4475	4052	3971	4052	55.4	423	504	423	7.6	9	7.6
100-100	3894	3792	3302	3302	73.9	102	592	592	1.3	8	8
100-125	3376	2826	2839	2811	92.4	550	537	565	5.9	5.8	6.1
125-50	5137	4956	5026	4339	36.9	181	111	798	4.8	3	21.5
125-75	4475	4052	3896	3583	55.4	423	579	892	7.6	10.4	16
125-100	3894	3792	3279	3302	73.9	102	615	592	1.3	8.3	8
125-125	3376	2826	2826	2826	92.4	550	550	550	5.9	5.9	5.9

3 Difference in savings per kW PV injection in interchanged and normal condition

3.1 Difference in savings per kW PV injection in interchanged and normal condition of NG1

PV level in microgrids (%)	Normal Mode			Interchanged Mode			Change (interchanged. - normal)		
	PPT	SS P2P	MS P2P	DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT	SS P2P	MS P2P
50-50	0.82	0	0	8.8	0	0	7.98	0	0
50-75	0.82	0	0	8.8	0	0	7.98	0	0
50-100	0.82	1.29	1.29	8.8	1.6	2	7.98	0.31	0.71
50-125	0.82	8.23	7.52	8.8	9.06	9.6	7.98	0.83	2.08
75-50	-0.94	5.17	5.17	10.93	0	0	11.87	-5.17	-5.17
75-75	-0.94	5.17	5.17	10.93	0	0	11.87	-5.17	-5.17
75-100	-0.94	1.41	1.56	10.93	3.02	3.73	11.87	1.61	2.17
75-125	-0.94	1.09	1.17	10.93	8.71	18.93	11.87	7.62	17.76
100-50	0.76	0.58	0.94	8.66	0.46	1.26	7.9	-0.12	0.32
100-75	0.76	0.76	1.11	8.66	1.33	2	7.9	0.57	0.89
100-100	0.76	1.11	1.11	8.66	2.4	2.4	7.9	1.29	1.29
100-125	0.76	1.35	13.11	8.66	2.73	2.86	7.9	1.38	-10.25
125-50	0.18	0.14	0.14	5.12	0.37	0.42	4.94	0.23	0.28
125-75	0.18	0.09	0.09	5.12	0.48	0.48	4.94	0.39	0.39
125-100	0.18	0	0	5.12	0.64	0.64	4.94	0.64	0.64
125-125	0.18	0	0.18	5.12	0.64	0.64	4.94	0.64	0.46

3.2 Difference in savings per kW PV injection in interchanged and normal condition of NG2

PV level in microgrids (%)	Normal Mode			Interchanged Mode			Change (interchanged. - normal)		
	PPT	SS P2P	MS P2P	DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT	SS P2P	MS P2P
50-50	-1.75	3.16	3.16	-8.25	14.51	14.51	-6.5	11.35	11.35
50-75	-1.75	3.16	3.16	-8.25	14.51	14.51	-6.5	11.35	11.35
50-100	-1.75	2	2.83	-8.25	9.74	12.29	-6.5	7.74	9.46
50-125	-1.75	1.75	2.33	-8.25	7.7	7.7	-6.5	5.95	5.37
75-50	-4.38	9.05	9.05	-10.98	19.28	19.28	-6.6	10.23	10.23
75-75	-4.38	9.05	9.05	-10.98	19.28	19.28	-6.6	10.23	10.23
75-100	-4.38	2.38	3.05	-10.98	7.9	9.03	-6.6	5.52	5.98
75-125	-4.38	1.22	1.27	-10.98	2.54	11.8	-6.6	1.32	10.53
100-50	-1.66	4.08	4.08	-9	8.5	8.46	-7.34	4.42	4.38
100-75	-1.66	2.2	2.2	-9	5.11	5.11	-7.34	2.91	2.91
100-100	-1.66	1.16	1.16	-9	3.22	3.22	-7.34	2.06	2.06
100-125	-1.66	1.41	1.37	-9	2.12	2.4	-7.34	0.71	1.03
125-50	-0.16	1.4	1.4	-5.57	3.48	3.48	-5.41	2.08	2.08
125-75	-0.16	1.36	1.36	-5.57	3.14	3.14	-5.41	1.78	1.78
125-100	-0.16	1.3	1.3	-5.57	2.05	2.05	-5.41	0.75	0.75
125-125	-0.16	1.3	1.3	-5.57	2.05	2.05	-5.41	0.75	0.75

3.3 Difference in savings per kW PV injection in interchanged and normal condition of NG3

PV level in microgrids (%)	Normal Mode			Interchanged Mode			Change (interchanged. - normal)		
	PPT	SS P2P	MS P2P	DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT	SS P2P	MS P2P
50-50	1.86	0	0	14.82	0	0	12.96	0	0
50-75	1.86	0	0	14.82	0	0	12.96	0	0
50-100	1.86	1.46	1.46	14.82	1.17	1.41	12.96	-0.29	-0.05
50-125	1.86	7.6	7.6	14.82	6.11	6.11	12.96	-1.49	-1.49
75-50	7.91	0	0.08	19.6	0.07	0.07	11.69	0.07	-0.01
75-75	7.91	0	0	19.6	0.07	0.07	11.69	0.07	0.07
75-100	7.91	2.93	2.93	19.6	1.09	1.09	11.69	-1.84	-1.84
75-125	7.91	5.95	5.95	19.6	2.19	11.92	11.69	-3.76	5.97
100-50	3.46	1	1.26	5.82	1.23	1.23	2.36	0.23	-0.03
100-75	3.46	0.73	0.93	5.82	0.41	0.41	2.36	-0.32	-0.52
100-100	3.46	0.86	0.86	5.82	0.17	0.05	2.36	-0.69	-0.81
100-125	3.46	1.06	1.06	5.82	0.17	0.17	2.36	-0.89	-0.89
125-50	0.8	0.1	0.1	12.61	0.32	0.32	11.81	0.22	0.22
125-75	0.8	0.1	0.1	12.61	0.23	0.23	11.81	0.13	0.13
125-100	0.8	0	0	12.61	0	0	11.81	0	0
125-125	0.8	0	0	12.61	0	0	11.81	0	0

3.4 Difference in savings per kW PV injection in interchanged and normal condition of NG4

PV level in microgrids (%)	Normal Mode			Interchanged Mode			Change (interchanged. - normal)		
	PPT	SS P2P	MS P2P	DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT	SS P2P	MS P2P
50-50	0.51	0	0	4.58	0	0	4.07	0	0
50-75	0.51	0	0	4.58	0	0	4.07	0	0
50-100	0.51	1.54	1.61	4.58	1.54	1.93	4.07	0	0.32
50-125	0.51	7.87	7.93	4.58	7.87	8.25	4.07	0	0.32
75-50	1.54	0	0	4.51	0	0	2.97	0	0
75-75	1.54	0	0	4.51	0	0	2.97	0	0
75-100	1.54	3.35	3.39	4.51	2.92	3.22	2.97	-0.43	-0.17
75-125	1.54	4.98	4.98	4.51	4.73	14.15	2.97	-0.25	9.17
100-50	0.06	1	1	-7.22	1	1	-7.28	0	0
100-75	0.06	0.41	0.41	-7.22	0.41	0.41	-7.28	0	0
100-100	0.06	0	0	-7.22	0	0	-7.28	0	0
100-125	0.06	0.19	0.19	-7.22	0.19	0.25	-7.28	0	0.06
125-50	-0.05	0.1	0.1	-0.05	0.1	0.1	0	0	0
125-75	-0.05	0.07	0.07	-0.05	0.07	0.07	0	0	0
125-100	-0.05	0	0	-0.05	0	0	0	0	0
125-125	-0.05	0	0	-0.05	0	0	0	0	0

3.5 Difference in savings per kW PV injection in interchanged and normal condition of NG5

PV level in microgrids (%)	Normal Mode			Interchanged Mode			Change (interchanged. - normal)		
	PPT	SS P2P	MS P2P	DGT-PPT	DGT-SSP2P	DGT-MSP2P	PPT	SS P2P	MS P2P
50-50	1.18	0	0	29.58	0	0	28.4	0	0
50-75	1.18	0	0	29.58	0	0	28.4	0	0
50-100	1.18	1.74	1.77	29.58	6.16	7.75	28.4	4.42	5.98
50-125	1.18	9.7	9.74	29.58	33.83	35.5	28.4	24.13	25.76
75-50	4.86	0	0	41.77	0	0	36.91	0	0
75-75	4.86	0	0	41.77	0	0	36.91	0	0
75-100	4.86	3.87	3.97	41.77	21.55	24.33	36.91	17.68	20.36
75-125	4.86	9.13	9.13	41.77	45.44	60.05	36.91	36.31	50.92
100-50	2.05	0.16	0.64	18.33	13.87	21.37	16.28	13.71	20.73
100-75	2.05	0.46	1.09	18.33	22.45	28.04	16.28	21.99	26.95
100-100	2.05	1.42	1.42	18.33	32.04	32.04	16.28	30.62	30.62
100-125	2.05	1.62	1.62	18.33	33.7	34.33	16.28	32.08	32.71
125-50	0.4	0.07	0.07	30.56	21.03	22.16	30.16	20.96	22.09
125-75	0.4	0.05	0.05	30.56	21.36	22.86	30.16	21.31	22.81
125-100	0.4	0	0	30.56	25	25.06	30.16	25	25.06
125-125	0.4	0	0	30.56	25.06	25.06	30.16	25.06	25.06

3.6 Difference in savings per kW PV injection in interchanged and normal condition of NG6

PV level in microgrids (%)	Normal Mode			Interchanged Mode			Change (interchanged. - normal)		
	PPT	SS P2P	MS P2P	PPT2	SSP2P	MSP2P	PPT	SS P2P	MS P2P
50-50	0	0	0	16.64	0	0	16.64	0	0
50-75	2.85	0	0	44	0	0	41.14	0	0
50-100	1.96	0.44	0.80	46.92	2.3	10.76	44.95	1.85	9.95
50-125	0.11	1.11	1.14	34.62	8.55	17.34	34.50	7.43	16.19
75-50	0	0	0	16.64	0	0	16.64	0	0
75-75	2.85	0	0	44	0	0	41.14	0	0
75-100	1.96	0.35	0.92	46.92	13.98	20.83	44.95	13.62	19.90
75-125	0.11	0.23	0.23	34.62	20.64	17.51	34.50	20.40	17.27
100-50	0	0	10.70	16.64	6.43	40.83	16.64	6.43	30.12
100-75	2.85	1.90	6.06	44	38.13	28.9	41.14	36.22	22.83
100-100	1.96	1.87	1.87	46.92	34.82	34.82	44.95	32.94	32.94
100-125	0.11	0.14	0.14	34.62	24.27	25.84	34.50	24.12	25.69
125-50	0	0	26.58	16.64	13	94.54	16.64	13	67.95
125-75	2.85	2.49	9.67	44	35.05	55.57	41.14	32.55	45.89
125-100	1.96	2.37	1.93	46.92	40.9	39.3	44.95	38.52	37.36
125-125	0.11	0.04	0.04	34.62	27.3	27.3	34.50	27.25	27.25

3.7 Difference in savings per kW PV injection in interchanged and normal condition of NG7

PV level in microgrids (%)	Normal Mode			Interchanged Mode			Change (interchanged. - normal)		
	PPT	SS P2P	MS P2P	PPT2	SSP2P	MSP2P	PPT	SS P2P	MS P2P
50-50	0	0	0	4	0	0	4	0	0
50-75	-0.46	4.05	3.58	7.23	3.58	3.58	7.691	-0.47	0
50-100	0.19	4.69	4.88	6.11	4.88	4.88	5.91	0.18	0
50-125	0.03	3.2	3.53	4.06	3.53	3.53	4.02	0.33	0
75-50	0	0	0	4	0	0	4	0	0
75-75	-0.46	4.05	3.58	7.23	3.58	3.58	7.69	-0.47	0
75-100	0.19	1.65	1.84	6.11	2.3	2.3	5.91	0.64	0.45
75-125	0.0	0.61	0.64	4.06	0.92	0.92	4.02	0.30	0.27
100-50	0	0	4.15	4	4.15	0.69	4	4.15	-3.46
100-75	-0.46	1.64	0.82	7.23	1.17	1.12	7.69	-0.47	0.29
100-100	0.19	0.15	0.34	6.11	0.34	0.34	5.91	0.18	0
100-125	0.03	0.4	0.43	4.06	0.43	0.43	4.02	0.03	0
125-50	0	0	9.38	9.38	1.38	9.38	9.38	1.38	-0
125-75	-0.46	0.51	1.89	7.23	0.87	1.89	7.69	0.35	0
125-100	0.19	0	0.19	6.11	0.19	0.19	5.91	0.19	0
125-125	0.03	0.09	0.03	4.06	0.12	0.12	4.02	0.02	0.08

3.8 Difference in savings per kW PV injection in interchanged and normal condition of NG8

PV level in microgrids (%)	Normal Mode			Interchanged Mode			Change (interchanged. - normal)		
	PPT	SS P2P	MS P2P	PPT	SSP2P	MSP2P	PPT	SS P2P	MS P2P
50-50	0	0	0	-3.56	6.54	6.54	-3.56	6.54	6.54
50-75	0.93	0.18	0.18	-7.53	13.95	13.95	-8.46	13.76	13.76
50-100	0.06	2.72	2.72	-21.64	12.87	12.87	-21.70	10.14	10.14
50-125	0	2.40	2.40	-4.78	7.73	7.73	-4.78	5.32	5.32
75-50	0	0	0	-3.56	6.54	6.54	-3.56	6.54	6.54
75-75	0.93	0.18	0.18	-7.53	13.71	13.95	-8.46	13.52	13.76
75-100	0.06	1.60	1.60	-21.64	8.14	8.14	-21.70	6.53	6.53
75-125	0	0	0	-4.78	3.3	0.28	-4.78	3.3	0.28
100-50	0	1.39	1.39	-3.56	2.08	3.33	-3.56	0.68	1.93
100-75	0.93	0.83	2.6	-7.53	2.85	3.6	-8.46	2.01	0.98
100-100	0.06	3.28	3.28	-21.64	2.52	2.52	-21.70	-0.76	-0.76
100-125	0	0.05	0.05	-4.78	2.11	2.11	-4.78	2.05	2.05
125-50	0	5.59	16.64	-3.56	0	0	-3.56	-5.59	-16.64
125-75	0.93	0.83	3.35	-7.53	7.37	10.26	-8.46	6.53	6.90
125-100	0.06	0.69	0.13	-21.64	0.74	0.74	-21.70	0.04	0.60
125-125	0	0	0	-4.78	1.37	1.37	-4.78	1.37	1.37

3.9 Difference in savings per kW PV injection in interchanged and normal condition of MG1

PV level in microgrids (%)	Normal Mode			Interchanged Mode			Change (interchanged. - normal)		
	PPT	SS P2P	MS P2P	PPT	SSP2P	MSP2P	PPT	SS P2P	MS P2P
50-50	0.56	0.53	0.53	5.6	5.56	5.56	5.03	5.02	5.02
50-75	0.56	0.53	0.53	5.6	5.56	5.56	5.03	5.02	5.02
50-100	0.56	1.65	1.82	5.6	5.43	6.83	5.032	3.77	5.00
50-125	0.56	7.54	7.58	5.6	12.14	12.56	5.03	4.59	4.97
75-50	2.18	2.16	2.17	7.42	7.39	7.39	5.23	5.22	5.21
75-75	2.18	2.16	2.16	7.42	7.39	7.39	5.23	5.22	5.22
75-100	2.18	3.11	3.29	7.42	7.79	8.84	5.23	4.67	5.54
75-125	2.18	5.56	5.57	7.42	10.94	21.3	5.23	5.37	15.72
100-50	0.97	1.15	1.41	-0.29	6.03	7.38	-1.26	4.87	5.96
100-75	0.97	0.81	1.12	-0.29	6.06	7.08	-1.26	5.24	5.95
100-100	0.97	0.97	0.97	-0.29	6.96	6.95	-1.26	5.98	5.97
100-125	0.97	1.18	2.59	-0.29	6.9	7.14	-1.26	5.71	4.54
125-50	0.22	0.31	0.31	5.12	5.01	5.21	4.89	4.69	4.89
125-75	0.22	0.29	0.26	5.12	4.93	5.19	4.89	4.63	4.92
125-100	0.22	0.22	0.22	5.12	5.11	5.12	4.89	4.88	4.89
125-125	0.22	0.22	0.24	5.12	5.12	5.12	4.89	4.89	4.87

3.10 Difference in savings per kW PV injection in interchanged and normal condition of MG2

PV level in microgrids (%)	Normal Mode			Interchanged Mode			Change (interchanged. - normal)		
	PPT	SS P2P	MS P2P	PPT	SSP2P	MSP2P	PPT	SS P2P	MS P2P
50-50	0	0	0	3	2.97	2.97	3	2.97	2.97
50-75	1.31	1.29	1.29	7.62	7.61	7.61	6.30	6.31	6.3
50-100	0.97	2.44	2.61	1.37	8.02	9.65	0.39	5.57	7.03
50-125	0.06	2.11	2.22	5.95	6.41	8.11	5.88	4.29	5.88
75-50	0	0	0	3	2.97	2.97	3	2.97	2.97
75-75	1.31	1.29	1.29	7.62	7.5	7.61	6.30	6.20	6.31
75-100	0.97	1.12	1.37	1.37	7.22	8.54	0.39	6.09	7.16
75-125	0.06	0.33	0.33	5.95	5.82	3.84	5.88	5.48	3.50
100-50	0	0.27	6.60	3	3.65	9.65	3	3.379	3.04
100-75	1.31	1.44	3.55	7.62	9.08	7.62	6.30	7.63	4.06
100-100	0.97	1.60	1.60	1.37	8	8	0.39	6.39	6.39
100-125	0.06	0.22	0.22	5.95	5.81	6.11	5.88	5.58	5.8
125-50	0	1.08	18.6	4.89	3	21.58	4.89	1.91	2.96
125-75	1.31	1.31	5.71	7.62	10.44	16.08	6.30	9.12	10.36
125-100	0.97	1.28	0.97	1.37	8.31	8	0.39	7.02	7.02
125-125	0.06	0.06	0.032	5.95	5.95	5.95	5.88	5.88	5.91

APPENDIX B

MATLAB CODE OF TWO PRICING METHOD USED FOR THE SIMULATION PURPOSE

1. Source code of participatory method

```
m1data=[];          % microgrid 1 data
m2data=[];          % microgrid 2 data
% ----------------------------------------------------------------------
% self power consumption of each nanogrid of microgrid 1 at time t
s1=zeros(5,24);               % calculating self power consumption
for i=1:5
   for j=1:24
      s1(i,j)=min(m1data(j,i),m1data(j,i+5));
   end
end
%  power import and export by each nanogrid of microgrid 1 at time t
 s1t=s1';                              %transpose of s1 to make same dimensional matrix
 pimport1=zeros(24,5);
 pexport1=zeros(24,5);
 for i=1:24
    for j=1:5
       pimport1(i,j)= m1data(i,j+5)-s1t(i,j);
       pexport1(i,j)=m1data(i,j)-s1t(i,j);
    end
 end
 np1=zeros(24,5);
 for i=1:24
    for j=1:5
       np1(i,j)=m1data(i,j+5)-m1data(i,j);
    end
 end
% total power available to export at time t from entire microgrid
TPAt1= zeros(24,1);
for i=1:24
      TPAt1(i,1)= np1(i,1)+np1(i,2)+np1(i,3)+np1(i,4)+np1(i,5);
end
% first priority is to fullfill demand of each nanogrid by exchanging its
% power ie this calculation is done in microgrid 1.
TPA1=zeros(24,1);         %total power available in the nanogrid to sell
TPB1=zeros(24,1);         %total power required to buy from higher level supply
for i=1:24
   if TPAt1(i,1)>1
      TPB1(i,1)=TPAt1(i,1);
   else
      TPB1(i,1)=0;
   end
   if TPAt1(i,1)<1
      TPA1(i,1)=-TPAt1(i,1);
   else
      TPA1(i,1)= 0;
   end
end
% net power imbalance in the microgrid 1
% DP1 is difference of power in microgrid 1
DP1=zeros(24,1);
for i=1:24
   DP1(i,1)= TPB1(i,1)-TPA1(i,1);
end
% ------------------------------------------------------------------
% ----------------------------------------------------------------
```

```
% calculations for microgrid 2
s2=zeros(3,24);    %calculating self power consumption
for i=1:3
   for j=1:24
      s2(i,j)=min(m2data(j,i),m2data(j,i+3));
   end
end
% power import and export at time t
 s2t=s2';            %transpose of s2 to make same dimensional matrix
 pimport2=zeros(24,3);
 pexport2=zeros(24,3);
 for i=1:24
    for j=1:3
       pimport2(i,j)= m2data(i,j+3)-s2t(i,j);
       pexport2(i,j)=m2data(i,j)-s2t(i,j);
    end
 end
%net power in each nanogrid at time t
 np2=zeros(24,3);
 for i=1:24
    for j=1:3
       np2(i,j)=m2data(i,j+3)-m2data(i,j);
    end
 end
% total power available to export at time t
TPAt2= zeros(24,1);
for i=1:24
      TPAt2(i,1)= np2(i,1)+np2(i,2)+np2(i,3);
end
% this TPA2 and TPB2 are calculated in microgrid 2 to share power within
% their nonogrids.
TPA2=zeros(24,1);          %total power available in the nanogrid to sell
TPB2=zeros(24,1);          %total power required to buy from grid IN NANOGRID LEVEL
for i=1:24
   if TPAt2(i,1)>1
      TPB2(i,1)=TPAt2(i,1);
   else
      TPB2(i,1)=0;
   end
   if TPAt2(i,1)<1
      TPA2(i,1)=-TPAt2(i,1);
   else
      TPA2(i,1)= 0;
   end
end
% net power at microgrid 2
DP2=zeros(24,1);
for i=1:24
   DP2(i,1)= TPB2(i,1)-TPA2(i,1);
end
%-----------------------------------------------------------
% now at the microgrid management level
DP=zeros(24,2);
for i=1:24
   DP(i,1)=DP1(i,1);
   DP(i,2)=DP2(i,1);
end
```

```
TPAm=zeros(24,1);
TPBm=zeros(24,1);
for i=1:24
   if (DP(i,1)+DP(i,2))>0
      TPBm(i,1)=DP(i,1)+DP(i,2);
   else
      TPAm(i,1)=-(DP(i,1)+DP(i,2));
   end
end
% --------------------------------------------------------
% calculating per day cost of electricity of each nanogrid
% -------------------------------------------------------

cost1=zeros(5,1);  %cost of a day of individual nano grid in direct grid trade
bfg=7;             %buying from the grid cost
stg=2.71;          %selling to the grid rate per unit kilowatt hour
for i=1:5
   cost1(i)= sum(pimport1(:,i))*bfg- sum(pexport1(:,i))*stg;
end
cost2=zeros(3,1); %cost of a day of individual nano grid in direct grid trade
for i=1:3
   cost2(i)= sum(pimport2(:,i))*bfg- sum(pexport2(:,i))*stg;
end
totimp1=sum(pimport1(:,1))+sum(pimport1(:,2))+sum(pimport1(:,3))+sum(pimport1(:,4))+sum(pim
port1(:,5));
bb1=sum(pexport1);
totexp1=sum(bb1);                 % totexp1 is sum of individual export in microgrid 1
cim1=bfg*sum(TPB1)/totimp1;       % totimp1 is sum of individual import in microgrid 1
cex1=stg*sum(TPA1)/totexp1;
p2pcost1=zeros(5,1);
for i=1:5
   p2pcost1(i)= sum(pimport1(:,i))*cim1- sum(pexport1(:,i))*cex1;
end
% for microgrid 2
totimp2=sum(pimport2(:,1))+sum(pimport2(:,2))+sum(pimport2(:,3));
bb2=sum(pexport2);
totexp2=sum(bb2);                 % totexp2 is sum of individual export in microgrid 2
cim2=bfg*sum(TPB2)/totimp2;       % totimp2 is sum of individual import in microgrid 2
cex2=stg*sum(TPA2)/totexp2;
p2pcost2=zeros(3,1);
for i=1:3
   p2pcost2(i)= sum(pimport2(:,i))*cim2- sum(pexport2(:,i))*cex2;
end
  bar(cost1,'red');
hold on
  bar(p2pcost1,'b');
  bar(cost2,'g');
  bar(p2pcost2,'y');
disp(cost1);
disp(cost2);
disp(p2pcost1);
disp(p2pcost2);
z1=sum(cost1)
z11=sum(p2pcost1)
z2=sum(cost2)
z22=sum(p2pcost2)
z1-z11
```

```
z2-z22
hleg1 = legend('Direct grid treading 2','P2P cost2','base cost 2','P2Pcost2');
grid on
```

2. multilevel transaction code

```
m1data=[];        % microgrid 1 data
m2data=[];        % microgrid 2 data
% ---------------------------------------------------------------------
  %   self power consumption of each nanogrid of microgrid 1 at time t
s1=zeros(5,24);   %calculating self power consumption
for i=1:5
   for j=1:24
      s1(i,j)=min(m1data(j,i),m1data(j,i+5));
   end
end

% power import and export by each nanogrid of microgrid 1 at time t
 s1t=s1';                    %transpose of s1 to make same dimensional matrix
 pimport1=zeros(24,5);
 pexport1=zeros(24,5);
 for i=1:24
    for j=1:5
       pimport1(i,j)= m1data(i,j+5)-s1t(i,j);
       pexport1(i,j)=m1data(i,j)-s1t(i,j);
    end
 end
%
 np1=zeros(24,5);
 for i=1:24
    for j=1:5
       np1(i,j)=m1data(i,j+5)-m1data(i,j);
    end
 end
% total power available to export at time t from entire microgrid
TPAt1= zeros(24,1);
for i=1:24

      TPAt1(i,1)= np1(i,1)+np1(i,2)+np1(i,3)+np1(i,4)+np1(i,5);
end
```

```
% first priority is to fullfill demand of each nanogrid by exchanging its
% power ie this calculation is done in microgrid 1.
TPA1=zeros(24,1);          %total power available in the nanogrid to sell
TPB1=zeros(24,1);          %total power required to buy from higher level supply
for i=1:24
   for j=1:5
      if np1(i,j)<0
         TPA1(i,1)=TPA1(i,1)-np1(i,j);
      else
         TPB1(i,1)= TPB1(i,1)+np1(i,j);

       end
   end
end
% net power imbalance in the microgrid 1
% DP1 is difference of power in microgrid 1
DP1=zeros(24,1);
for i=1:24
   DP1(i,1)= TPB1(i,1)-TPA1(i,1);
end
% ------------------------------------------------------------------
% -----------------------------------------------------------------
% calculations for microgrid 2
s2=zeros(3,24);                 %calculating self power consumption
for i=1:3
   for j=1:24
      s2(i,j)=min(m2data(j,i),m2data(j,i+3));
   end
end
%  power import and export at time t
 s2t=s2';                       %transpose of s2 to make same dimensional matrix
 pimport2=zeros(24,3);
 pexport2=zeros(24,3);
 for i=1:24
    for j=1:3
       pimport2(i,j)= m2data(i,j+3)-s2t(i,j);
       pexport2(i,j)=m2data(i,j)-s2t(i,j);
    end
```

```
end
%net power in each nanogrid at time t
np2=zeros(24,3);
for i=1:24
   for j=1:3
      np2(i,j)=m2data(i,j+3)-m2data(i,j);
   end
end
%  total power available to export at time t
TPAt2= zeros(24,1);
for i=1:24

     TPAt2(i,1)= np2(i,1)+np2(i,2)+np2(i,3);
end
% this TPA2 and TPB2 are calculated in microgrid 2 to share power within
% their nonogrids.
TPA2=zeros(24,1);          %total power available in the nanogrid to sell
TPB2=zeros(24,1);          %total power required to buy from grid in nanogrid level
for i=1:24
   for j=1:3
     if np2(i,j)<0
        TPA2(i,1)=TPA2(i,1)-np2(i,j);
     else
        TPB2(i,1)= TPB2(i,1)+np2(i,j);
      end
   end
end
% -----------------------------------------
% -----------------------------------------------------
% net power at microgrid 2
DP2=zeros(24,1);
for i=1:24
   DP2(i,1)= TPB2(i,1)-TPA2(i,1);
end
%------------------------------------------------------------
% now at the microgrid management level
DP=zeros(24,2);
for i=1:24
```

```
   DP(i,1)=DP1(i,1);
   DP(i,2)=DP2(i,1);
end
TPAm=zeros(24,1);
TPBm=zeros(24,1);
for i=1:24
   for j=1:2
      if DP(i,j)<0
         TPAm(i,1)=TPAm(i,1)-DP(i,j);
      else
         TPBm(i,1)= TPBm(i,1)+DP(i,j);
       end
   end
end
% --------------calculating cost-------------
% SDR=supply to demand ratio
SDR=zeros(24,1);
for i=1:24
   SDR(i)= TPAm(i)/TPBm(i);
end
bfg=7;                    %per unit buying price from grid
stg=2.71;                 %per unit selling price to grid
MSP=zeros(24,1);          %main selling price by microgrid manager
MBP=zeros(24,1);          % main buying price by microgrid manager
for i=1:24
   k=i;
   if SDR(i)>=0 && SDR(i)<=1
      MSP(k)=((bfg*stg)/((bfg-stg)*SDR(k)+stg));
      MBP(k)=(MSP(k)*SDR(k)+bfg*(1-SDR(k)));
   else
      MSP(i)=stg;
      MBP(i)=stg;
   end
end
% -------------------------------------------------------
MSP1=zeros(24,1);
MBP1=zeros(24,1);
SDR1=zeros(24,1);
```

```
for i=1:24
   SDR1(i)= TPA1(i)/TPB1(i);
end
for i=1:24
   k=i;
   if SDR1(i)>=0 && SDR1(i)<=1
      MSP1(k)=(MBP(k)*MSP(k))/((MBP(k)-MSP(k))*SDR1(k)+MSP(k));
      MBP1(k)=(MSP1(k)*SDR1(k)+MBP(k)*(1-SDR1(k)));
   else
      MSP1(i)=MSP(k);
      MBP1(i)=MSP(k);
   end
end
% -----------------------------------------------------
MSP2=zeros(24,1);
MBP2=zeros(24,1);
SDR2=zeros(24,1);
for i=1:24
   SDR2(i)= TPA2(i)/TPB2(i);
end
for i=1:24
   k=i;
   if SDR2(i)>=0 && SDR2(i)<=1
      MSP2(k)=(MBP(k)*MSP(k))/((MBP(k)-MSP(k))*SDR2(k)+MSP(k));
      MBP2(k)=(MSP2(k)*SDR2(k)+bfg*(1-SDR2(k)));
   else
      MSP2(i)=MSP(k);
      MBP2(i)=MSP(k);
   end
end
     p1=plot(MSP,'g--');
  hold on
     p2=plot(MBP,'b');
   p3= plot(MSP1,'black--')
  p4=plot(MBP1,'black')
p5=plot(MSP2,'b--')
 p6=plot(MBP2,'b')
   hleg1=legend('MSP','MBP');
```

```
  xlabel('Hour of Day')
  ylabel('Price of Electricity per kWhr (THB)')
 grid on
% ------------------------------------------------------
% cost calculation in different schenario
% ---------------------------------------------
% FOR PEER TO GRID TRADING
cp2g1=zeros(24,5);
cp2g2=zeros(24,3);
for i=1:24
   for j=1:5
cp2g1(i,j)= pimport1(i,j)*bfg- pexport1(i,j)*stg;
   end
end
for i=1:24
   for j=1:3
cp2g2(i,j)= pimport2(i,j)*bfg- pexport2(i,j)*stg;
   end
end
cp2g1total=sum(cp2g1)
cp2g2total=sum(cp2g2)
% ------------------------------------------------------
% SINGLE STAGE PEER TO PEER
csp2p1=zeros(24,5);
csp2p2=zeros(24,3);
for i=1:24
   for j=1:5
csp2p1(i,j)= pimport1(i,j)*MBP(i)- pexport1(i,j)*MSP(i);
   end
end
for i=1:24
   for j=1:3
csp2p2(i,j)= pimport2(i,j)*MBP(i)- pexport2(i,j)*MSP(i);
   end
end
csp2p1total=sum(csp2p1)
csp2p2total=sum(csp2p2)
% --------------------------------------------------------
```

```
% MULTILEVEL PEER TO PEER
chp2p1=zeros(24,5);
chp2p2=zeros(24,3);
for i=1:24
   for j=1:5
chp2p1(i,j)= pimport1(i,j)*MBP1(i)- pexport1(i,j)*MSP1(i);
   end
end
for i=1:24
   for j=1:3
chp2p2(i,j)= pimport2(i,j)*MBP2(i)- pexport2(i,j)*MSP2(i);
   end
end
chp2p1total=sum(chp2p1)
chp2p2total=sum(chp2p2)
% --------------------------------
 hold on
% bar(cp2g1total,'g')
% bar(csp2p1total,'y')
% bar(chp2p1total,'b')
%  bar(cp2g2total,'g')
%
%  bar(chp2p2total,'b')
% bar(csp2p2total,'r')
%  hleg1 = legend('P2G','SP2P','HP2P');
  hold on
  %-------------------------------------
 sump2g1= sum(cp2g1total)
 sumcsp2p1= sum(csp2p1total)
 sumchp2p1= sum(chp2p1total)
 profot1= sump2g1-sumchp2p1
  sump2g2= sum(cp2g2total)
 sumcsp2p2= sum(csp2p2total)
 sumchp2p2= sum(chp2p2total)
 profot2= sump2g2-sumchp2p2
```

PUBLICATIONS

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BIOGRAPHY

Ashok Paudel received his B. Eng degree in Electrical Engineering from Tribhuvan University, Nepal, in 2017. Then, he went to Suranaree University of Technology, Nakhon Ratchasima, Thailand, in the year 2018 to pursue a master's degree in Electrical Engineering. His research interests include distributed generation, Peer-Peer energy trading, and smart grid.