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Peer-to-Peer Trading for Multi-Utility Energy Systems in Eco-Industrial Park

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The decentralised microgrid energy system is believed to accelerate the energy transition in the energy sector and give flexibility to future energy systems. Integration of renewable energies will be increasing and adapted quickly to the microgrid. One approach that enables prosumers to trade their excess energy is peer-to-peer (P2P) energy trading. Previous works frequently studied the P2P energy trading scheme on electricity distribution systems. The inter-company energy recovery opportunity in an industrial park could be enhanced through the centralised utility network or microgrid system with various energy carriers, such as steam, water and hydrogen. This study aims to develop a P2P approach for the multi-energy utility microgrid systems, which involves thermal, power and cooling energies based on a non-linear programming (NLP) model using Advanced Interactive Multidimensional Modeling System (AIMMS) software. The model is incorporated with the cooperative game strategy of the P2P energy sharing scheme. The Shapley value method is used to describe the profit distributed among cooperating companies. An illustrative case study of three companies exchanging surplus energy with the centralised utility system was demonstrated. The model showed that the grand coalition has the most overall savings of 944.91 MUSD/y (40.96 %), with a total annualised cost of 1,362.12 MUSD/y. The developed structure is crucial to laying the groundwork for P2P multi-energy trading planning in Malaysia.

1. Introduction

The concern about climate change on energy systems has made clear the urgency of establishing the sustainable balance of the energy trilemma in energy system planning regarding energy security, energy equity and environmental sustainability (World Energy Council, 2022). A decentralised microgrid energy system is believed to accelerate the energy transition in the energy sector and give flexibility to future energy systems. The microgrid system localises the energy supply, which makes it closer to the energy demands, allows effective energy management based on demand, ensures smooth energy transmission, and minimises the possibility of inefficiencies (Tao, 2022).

One approach in the decentralised microgrid system that enables producer-consumers (prosumers) to trade their excess energy is peer-to-peer (P2P) energy trading. In the energy market, “peers” refers to two or more grid-connected parties, including generators, consumers and prosumers (Muhsen et al., 2022). The increasing connection of distributed energy resources (DER) has become a viable choice for prosumers to get involved in the energy market in recent years and promote more installation of renewable energy in the community in transitioning to a low-carbon energy system. Bagheri-Sanjareh et al. (2021) presented that thermal and electrical energy storage systems are considered for energy savings in the islanded residential power microgrid. However, the P2P energy trading concept is being explored and implemented within local electricity distribution systems only due to data privacy challenges and conflicts of interest. The P2P energy trading scheme is more frequently

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studied for the power system only (Zhang et al., 2018). According to Kokchang et al. (2020), most reviewed existing P2P energy projects implement an entire P2P market where the peers can directly trade with others without coordination from a third party. However, regulatory barriers include the licensed energy supplier issue, billing and settlement process, and network charging issues. The community-based market is believed to be a potential business model for the future P2P electricity market that can mitigate the issues. Multi-energy or Combined Cooling, Heating and Power (CCHP) microgrid system has been frequently researched for residential area and community level. Considering the economic and control mechanisms, Liu et al. (2019) proposed a transactive energy-based distributed microgrid energy management system with thermal and power requirements at a community level. Pang et al. (2023) proposed a multi-objective optimisation model with heating, cooling, power and hydrogen microgrids for the industrial and community sectors.

Energy conservation in industrial parks through microgrid systems has been established as part of the industrial ecology or industrial symbiosis, in which the opportunity for inter-company energy recovery is explored (Maes et al., 2011). Several centralised utility networks have been investigated to understand the opportunities for inter-company or inter-plant energy recovery. Kong et al. (2022) presented a P2P energy-sharing optimisation model to mitigate the total electricity bills of all players. An integrated solar thermal system involving centralised thermal energy storage (TES) facilities was proposed by Ismail et al. (2022) to reduce the dependency on fossil fuel consumption. The inter-plant or inter-company utility system is commonly structured as a multiple microgrid system with different types of energy carriers, such as steam, water and hydrogen. Unfortunately, all of the above research did not demonstrate a P2P trading of multi-level steam in the microgrid can further maximise the energy exchange capacity that benefits all companies on the site.

This study demonstrates the P2P energy trading scheme in the multi-energy utility microgrid systems, which involves power and heat energies. The multi-level steam utilities are exchanged to recover further waste heat, which helps conserve additional resources such as water, fuel and electricity. The model is further studied with cooperative game theory to verify the feasibility of forming a coalition between the companies. This approach would address the gaps in constructing a centralised multi-energy system in the distributed markets that maximise the economic and energy-saving benefits in the industrial sector, reducing the environmental impact.

2. Problem statement

An illustrative example of industrial multi-utility systems model is used to demonstrate the cooperative game strategy of the P2P energy sharing scheme. Figure 1 shows the comprehensive multi-utility, which consists of electricity, cooling and heating requirements to be met by each company A, B and C. The P2P strategy allows local consumers to convert from consumers to prosumers and share their surplus energy. This allows the companies to form coalitions with a sharing multi-utility system. It should be noted that the P2P energy-sharing framework does not take players from coalitions with only one company or non-participating players from coalitions with two companies into account.

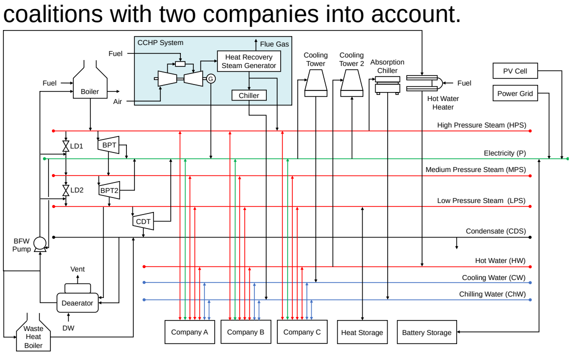

Figure 1: Superstructure of the Multi-Energy Utility Microgrids Optimisation Model

All the companies in the industrial park will be encouraged to participate in P2P multi-utilities networks to exchange their energies by selling excess energies to the centralised system or purchasing from the system. Each company can vary in process demand due to their operation. The prosumer (company) can serve as consumer in purchasing energies from the centralised system, which operates by a centralised system operator. The prosumer can also serve as producer to sell the surplus energies to the centralised multi-utilities facility when generation exceeds demand. The excess energies from a company can be traded to other companies through the system which can help to reduce the consumption of non-renewable energy sources. A photovoltaic (PV) cell transforms renewable solar energy into electricity. Heat storage and battery storage are served to store excess thermal and electricity. The system operator is a third party that takes control of the operations, including the organisation, maintenance and monitoring, and the payment of transaction fees. The main advantage of this model is that it helps the company to reduce the total annual cost of purchasing the devices by sharing the same multi-utility network. Besides, it encourages the efficient use of energy and minimising energy loss. This study aims to determine the optimum coalition structure that offers the players the most potential for total annual cost savings.

3. Methodology

This section outlines the procedure for formulating the model that satisfies the process demand. The players are initially simulated using a non-cooperative strategy in which they own a multi-utility system that generates energy and utilises them without trading to/from other players. In this stage, the total annual costs for each player are determined. The following step involves players cooperating in cooperative games with one or more other players by exchanging energy that might reduce overall total annual costs due to sharing a centralised multi-utility system. All the formulations presented will be solved using CONOPT 4.1 solver to solve the non-linear programming (NLP) problem via Advanced Interactive Multidimensional Modeling System (AIMMS) software. The P2P energy sharing framework is understood to exclude companies from single-player coalitions and non-participating companies from two-player coalitions. Although some companies can obtain the most significant gains in a single coalition, it does not necessarily mean that other companies can do the same in the same coalition. In the P2P energy-sharing cooperative model, choosing the optimum coalition structure is essential based on the overall savings obtained by the coalitions constructed. Shapley value is used in the cooperative game theory approach to describe the profit allocation among cooperating companies. The results produced from both approaches are evaluated in the final stage.

3.1 Non-cooperative game theory approach

The objective function of the one-player model is to minimise the total annual cost of the system TAC, as shown in Eq(1), containing the capital cost of each installed piece of device C_{CC}, the operating and maintenance cost C_{OM} and the energy utility cost C_E.

$$\text{Min TAC} = C_{CC} + C_{OM} + C_E \tag{1}$$

The annualised capital cost C_{CC} for the system can be formulated as shown in Eq(2), where i is the index of the devices, including energy converters, renewable energy generators and energy storage devices. r denotes the discount rate, which is defined as 7 % in this study, n denotes the economic lifetime of device i, which is specified as 20 y, θ_i and C_i stand for the device's capacity and unit capital cost.

$$C_{CC} = r(1+r)^n / \left((1+r)^n - 1\right) \times \sum_i (\theta_i \cdot C_i) \tag{2}$$

The operating and maintenance cost C_{OM} is calculated as shown in Eq(3), where $E_{i,t}$ denoted the energy output of device i at time t, λ_i is the unit maintenance cost of device i.

$$C_{OM} = \sum_i \sum_t (E_{i,t} \cdot \lambda_i) \times d \tag{3}$$

The energy utility cost C_E consists of the fuel cost of natural gas C_{NG}, the water purchase cost C_W and the electricity cost purchased from the power grid C_{PG} as shown in Eq(4).

$$C_E = C_{NG} + C_W + C_{PG} \tag{4}$$

The fuel cost of natural gas, C_{NG} is formulated in Eq(5), where $F_{i,t}$ is the natural gas consumption for device i at time t, c_{NG} is the fuel price, and d is the 365 days in 1 y. The water purchasing cost C_W can be calculated as shown in Eq(6), where $S_{W,t}$ and c_W denotes water supply to the deaerator and water price. The electricity cost C_{PG} at time interval t can be presented from Eq(7) to Eq(8), where $E_{PG,t}$ is the electricity obtained from the grid, CF_{PG} is the cost factor of electricity at different time intervals, while the maximum demand charges, C_{MD} is the multiplication of the highest maximum demand value between off-peak, $MDV_{off\text{-}peak}$ and peak period, MDV_{peak} with its respective maximum demand cost factor $MD_{off\text{-}peak}$ and MD_{peak}. The maximum demand value of off-peak periods, $MDV_{off\text{-}peak}$ can be calculated by dividing the total electricity purchased, $\sum_{t \in off\text{-}peak} E_{PG,t}$ in every off-peak period to the number of off-peak time intervals, $\sum_{t \in off\text{-}peak} t$ as shown in Eq(9). Eq(10) shows a similar method for the maximum demand value of peak periods, MDV_{peak}.

$$C_{NG} = \left(\sum_i \sum_t F_{i,t} \times c_{NG}\right) \times d \tag{5}$$

$$C_W = \left(\sum_t S_{W,t} \times c_W\right) \times d \tag{6}$$

$$C_{PG} = [\sum_t (E_{PG,t} \times CF_{PG}) + C_{MD}] \times d \quad (7)$$

$$C_{MD} = \max(MDV_{off\text{-}peak}, MDV_{peak}) \times \begin{cases} MD_{off\text{-}peak}|_{MDV_{off\text{-}peak}=max} \\ MD_{peak}|_{MDV_{peak}=max} \end{cases} /h \quad (8)$$

$$MDV_{off\text{-}peak} = (\sum_{t\in off\text{-}peak} E_{PG,t}) / (\sum_{t\in off\text{-}peak} t) \quad (9)$$

$$MDV_{peak} = (\sum_{t\in peak} E_{PG,t}) / (\sum_{t\in peak} t) \quad (10)$$

3.2 Cooperative game theory approach

In this section, the objective is to minimise the total annual cost of the system, $TAC_{Total,P}^{Trading}$ for all players, as shown in Eq(11). The model enables any player to cooperate with other players in the cooperative game. Each player can benefit differently in their coalitions with the cooperative game strategy. The players can trade their energies to others through the centralised utility system. In the cooperative game model, the expression of total annual cost, $TAC_{Total,P}^{Trading}$ is revised as Eq(11), where the cost of energies traded to other players, $C_{H,P}$ and energies traded from other players, $C_{H,P'}$ are incorporated. The traded energies cost can be expressed as Eq(12) and Eq(13), in which CF_H indicates the unit cost of traded energies (electricity, high-pressure steam (HPS), medium-pressure steam (MPS), low-pressure steam (LPS), hot water (HW), cold water (CW) and chilling water (ChW)) from/sold to the centralised system.

$$\text{Min } TAC_{Total,P}^{Trading} = C_{CC} + C_{OM} + C_E + \sum_P C_{H,P} + \sum_{P'} C_{H,P'} \quad (11)$$

$$C_{H,P} = \sum_t (E_{H,t,P} \times CF_H) \quad (12)$$

$$C_{H,P'} = \sum_t (E_{H,t,P'} \times CF_H) \quad (13)$$

The cooperative game technique – Shapley value introduced by Shapley (1953) determines the cost allocated to each company based on their marginal contribution to the coalition. The mathematical formula of Shapley value is shown in Eq(14), where $\phi_i(v)$ refers to the expected contribution of player i to the overall cost of any coalition.

$$\phi_i(v) = \sum_{S\subseteq N\text{-}i} \frac{|S|!(n-|S|-1)!}{n!} [v(S\cup\{i\}) - v(s)] \quad (14)$$

The notation N-i above denotes the set $N\setminus\{i\}$ where all the possible coalitions that do not contain player *i*. The term $|S|!(n-|S|-1)!/n!$ can be translated as the probability that in any combination where the members of coalition S are ahead of a distinguished player i. The term $v(S\cup\{i\})-v(s)$ refers to the marginal contribution of player i to the overall cost of coalition S.

4. Case study

An illustrative example of three companies in the industrial park located in Malaysia with various energy profiles is used as a case study to demonstrate the effectiveness of the proposed methodology, as illustrated in Figure 1. Given that three companies, A, B and C, are considered in this case study, the possible coalitions for the considered case include {Ø},{A},{B},{C},{A,B},{A,C},{B,C} and {A,B,C}, where Ø is the empty coalition. The one-day hourly multi-energy usage profiles for the companies are shown in Figure 2. The process demand data were adopted from literature, two process plants data from Jamaluddin et al. (2022) and a process plant data from Liew et al. (2018). The electricity cost factor and maximum demand charges for each time interval are simplified based on Tenaga Nasional Berhad (2014). Table 1 shows the utility cost factor, carbon emission factor and energy trading cost. The carbon emission factor of buying electricity is from coal power plant energy source, which is the main power generation source in the country.

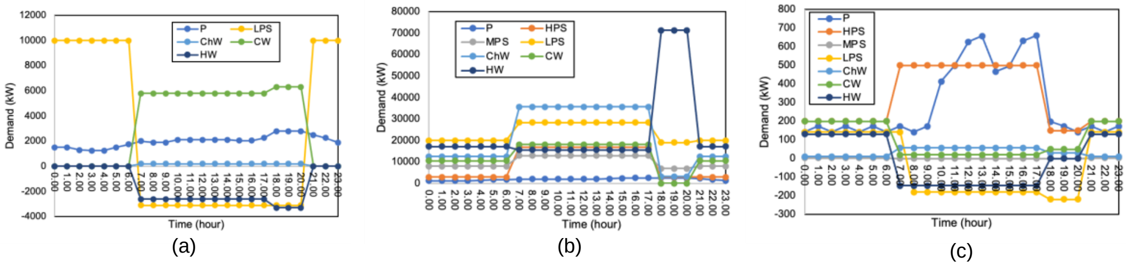

Figure 2: (a) Hourly energy usage of company A; (b) Hourly energy usage of company B; (c) Hourly energy usage of company C

Table 1: Utility cost factor, carbon emission factor and energy trading cost

Utility Cost Factor			Carbon Emission Factor					
Natural Gas	0.22	USD/kg	Natural Gas	0.22	kg/kWh$_{th}$			
Water	0.00043	USD/kg	Power Grid	0.968	kg/kWh$_{e}$			
		Energy Trading Cost, CF$_{H}$						
Electricity	0.0803	USD/kWh$_{e}$	LPS	0.0335	USD/kWh$_{th}$	CW	0.0139	USD/kWh$_{th}$
HPS	0.0410	USD/kWh$_{th}$	ChW	0.0315	USD/kWh$_{th}$	HW	0.0268	USD/kWh$_{th}$
MPS	0.0357	USD/kWh$_{th}$						

5. Results and discussion

This study determines the total annual cost, TAC for all coalitions, for non-cooperative and cooperative P2P energy trading schemes, as shown in Table 2. The TAC presented using the non-cooperative method will serve as the benchmark for this case study.

The ranking of each coalition in Table 2 is based on the capital cost of the device, operating and maintenance cost, fuel cost, water cost and electricity cost of the centralised multi-utility system. In the non-cooperative game approach, the total TAC of companies A, B and C is 2,307.03 MUSD/y. For the cooperative game approach, the first coalition where companies A and B are involved in the P2P energy trading scheme managed to reduce their TAC by 539.64 MUSD/y (23.39 %). In the second coalition, where company B is not involved in the P2P energy trading framework, companies A and C saved a total of 420.32 MUSD/y (18.22 %). Both companies need to pay more, making the second coalition structure less favourable than the first coalition. The third coalition of the P2P energy trading scheme, which involves companies B and C, is more favourable than the second coalition as both companies successfully saved more on their TAC which is 422.85 MUSD/y (18.33 %). In the last grand coalition, the company A, B and C can save the most significant amount by 81.28 % (334.01 MUSD/y), 21.97 % (335.28 MUSD/y) and 74.52 % (275.62 MUSD/y). Although the amount of TAC saved is obtained for the three companies, the fair allocation of saving for all companies in the P2P energy trading scheme remains questionable whether the savings depend on the transaction amount of energy. However, the most optimal "payoff" coalition structure selection must be chosen to maximise the P2P energy trading cooperative framework. The calculations revealed that the grand coalition is the most advantageous and favourable solution that will lead to collaboration in reducing the cost of constructing, operating and maintaining the multi-utility system in the industrial park.

Table 2: Total annual cost of companies for different coalitions

	Coalition	Annual cost for Companies (MUSD/y)			Total annual cost (MUSD/y)	Rank
		A	B	C		
Non-cooperative	{A}, {B}, {C}	410.944	1,526.209	369.877	2,307.030	5
Cooperative	{A, B}, {C}	141.126	1,256.390	369.877	1,767.393	2
	{A, C}, {B}	200.784	1,526.209	159.716	1,886.710	4
	{B, C}, {A}	410.944	1,314.785	158.452	1,884182	3
	{A, B, C}	76.932	1,190.933	94.258	1,362.122	1

6. Conclusions

In this work, the non-cooperative and cooperative game theory approaches are both evaluated. These approaches used an NLP formulation to determine the appropriate shares, given the TAC determined for every possible sub-coalition. The coalition structures are modelled and analysed using a case study that involves three companies with predefined process demands. The P2P multi-energy trading system showed that the cooperative game theory approach is helpful in energy planning in the industrial park. The centralised multi-utility system successfully helped all companies save their TAC by constructing their own utility plant in the local community-based market structure. The coordinator sends pricing signals to the company, influencing their decision to trade energies with the centralised microgrid. This strategy provides a higher level of privacy and autonomy for the companies. The results showed that the most optimal coalition allows all companies to reduce their TAC by 944.91 MUSD/y (40.96 %). The construction of a centralised multi-utility system is believed to impact significantly future energy planning for companies in the industrial park in achieving sustainable energy transition and efficient energy usage. For further studies, the pricing of traded multi-energy should be evaluated to study the company's energy demand response. Factors such as the increment of participating companies in the coalition and the settlement of fees to the coordinator should also be investigated to obtain a fair allocation between companies.

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