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Cooperative Game Theory Approach for Multi-Period Inter-Entity Energy Planning

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The deficiency of natural resources and serious climate change issues have driven the global community's efforts to optimize energy planning using various process integration approaches. One of the keys to optimize energy planning is through horizontal cooperation among the entities that allows internal trading of resources. The inter-entities collaboration presents a great potential to further enhance the energy planning by attaining bill savings. The attainable bill savings are due to the reduction of conventional fuels, which increases the share of renewables that allows the internal sharing among the entities – P2P (Peer-to-peer) energy sharing concept. In this paper, a linear model of P2P energy sharing is presented and used to study the possible bill savings that different entities may achieve for different collaboration scenarios. The presented P2P energy sharing optimization model allows the synergies among different potential players and identify the most favourable collaboration opportunities. The proposed approach is presented using an illustrative case study in which three players with different energy profiles are considered in both non-cooperative and P2P energy trading cooperative scenarios. The results indicated that the most advantageous coalition enables all the players to mitigate their total electricity bills by MYR 1823.43/month (0.69 % reduction as compared to the non-cooperative scheme), without having one of the players compromising and has a total 40 % of carbon emission reduction goal.

1. Introduction

The enormous carbon emission through the burning of fossil fuels has been the main cause of global warming (Beenish et al., 2021). To address the issue, energy-based cooperative game approach is proposed to be utilized in reducing fossil fuels usage in energy production. In recent decades, complex multi-agent power system poses crucial challenges that no longer can be addressed by classical methods of centralized planning or control. The need to simulate the interactions between power systems operators, prosumers, consumers and power manufacturers had urged the community to develop efficient yet realistic simulation models in the context of cooperative or non-cooperative game theories. In non-cooperative games, the agents are assumed to optimize independently without seeking others' benefits and the problems usually solved using equilibrium-based solution concepts. For example, non-cooperative games are commonly utilized for the electricity market equilibria and investment decisions (Zhao et al., 2018). The cooperative games approach assumes mutual benefits agreement among players. It is well acknowledged that the mechanisms of cooperation in power systems have attracted much attention from academia and industry. The majority of prior research indicates that such cooperation mechanism could lead to significant cost savings (Verdonck et al., 2016), carbon emission reduction (Zeng et al., 2021) and power systems flexibility (Kristiansen et al., 2018). For instance, Loureiro et al. (2019) proposed a cooperative investment optimization model for two coupled regions with the objective of cost minimization and the results were positive. Although previous studies have almost exclusively focused on the macro-level (yearly time-basis) for the cooperative model, limited attention has been paid to the micro-level

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(hourly time-basis) of such model (Klemeš et al., 2018). It is believed that the implications of P2P energy sharing model on micro-time basis deserve to be explored since it can help to identify the feasibility of P2P energy sharing concept. In Kong et al. (2022)'s work, micro-level of energy planning optimization has proven that it is capable of integrating the energy efficiency by increasing the renewables share and reducing carbon emissions. The novelty of this work is that the P2P energy sharing model is further incorporated with an actual billing system and cooperative game theory approach. In this work, an illustrative case study in Malaysia that incorporates the local billing system is used to demonstrate the effectiveness of P2P energy sharing cooperation approach and identify the best coalition among the coalitions formed between players that meets total carbon reduction goal.

2. Problem Statement

A hypothetical example is used to illustrate the cooperative game theory on the P2P energy sharing model. The problem definition of P2P energy sharing can be stated as follows: Given the three entities, A, B and C, the set of all possible coalitions for the considered case is {{A}, {B}, {C}, {A, B}, {A, C}, {A, C} and {A, B, C}}. It is assumed that players from one-entity coalitions and non-participating player from two-entity coalitions are not considered in the P2P energy sharing scheme. The time intervals of 30 min in a month are denoted as $T = 1,2 \dots N$. The total energy demand in each interval is indicated as $D_T = \{D_1, D_2 \dots D_N\}$. Each energy source has its emission factor (denoted as CI_F and CI_R for fossil and renewable energy sources). The shared renewables and the energy obtained from the storage system are assumed to have the same emissions factor given that they are coming from the same source of renewable energy. In this work, the objective is to identify the optimum coalition structure that has the highest bill saving opportunities among the players that achieves the total carbon reduction goal.

3. Methodology

In this work, players are firstly modelled with non-cooperative approach where they generate renewables and utilize them without trading to/from other players. The electricity bills for each player with pre-defined carbon reduction goal are determined in this step. In the next step, players are assumed to cooperate with one or more players in cooperative games with the same carbon reduction goal by trading the renewables that would possibly result in lower total electricity bills. Note that even though some players can obtain their maximum benefit in one coalition, it does not mean that the other players can obtain their maximum profits in the same coalition. The inherent conflict of interest among players is the key challenge that needs to be addressed (Tan et al., 2015). It is crucial to decide on the optimum coalition structure based on the profit gained from the coalitions formed in the P2P energy sharing cooperative model. The results generated from different coalition structure are then analysed in the last step. Figure 1 shows the methodology flowchart proposed for the game theory approach for inter-entity energy planning.

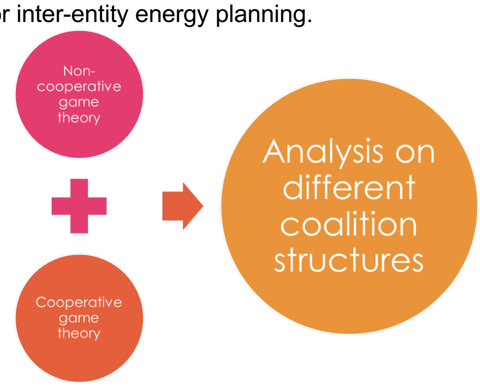

Figure 1: Methodology flowchart for game theory approach for P2P energy trading energy planning

4. Model formulation

The P2P energy sharing cooperative model is an extension of the work conducted by Kong et al. (2021), which incorporates more energy sharing possibilities (the mentioned work only considers energy trading possibility during the off-period of the participating players) between three entities with different energy usage. The possible coalitions for n number of players are equal to = 2^n. It is assumed that players from single-player coalitions and non-participating player from two-player coalitions are not considered in the P2P energy sharing scheme. Note that the model developed in this work can be easily adapted to other costing mechanisms (including government incentives or subsidies) and energy profile, which depends on different utility companies or countries.

4.1 Non-cooperative game theory approach

As for the first step, the minimum amount of renewables of each player is identified in this approach so that the total carbon reduction goal can be met, as shown in Eq(1), where $S_{Total\ Renewables}$ refers the total renewables required for each player across one-month period while the $S_{R,T}$ and $S_{ER,T}$ indicates the amount renewables and stored renewables that are applied to the system at time interval T.

$$Min\ S_{Total\ Renewables} = \sum_{T} (S_{R,T} + S_{ER,T}) \tag{1}$$

The energy demand at each time interval D_T, is represented as Eq(2). It can be fulfilled by either fossil-based energy ($S_{F,T}$), renewables ($S_{R,T}$) or stored renewables ($S_{ER,T}$) during daytime; whereas only fossil-based energies and stored renewables can be utilized during night time. Energy storage system with a capacity of $S_{ER,T}$ is allocated to allow energy to be stored during a given time.

$$D_T = \begin{cases} S_{F,T} + S_{R,T} + S_{ER,T}\big|_{Daytime} \\ S_{F,T} + S_{ER,T}\big|_{Nighttime} \end{cases} \quad \forall T \tag{2}$$

The initial carbon emission, E_{in}can be computed in Eq(3) where it is presumed to be entirely generated from fossil-based energy. As for the carbon emission limit E_L , it is mathematically expressed as Eq(4), where ∂ indicates the carbon emission reduction ratio. The total carbon emission goal, which is also the presumed emission limit, is the product of energy demand and their respective carbon intensities (as shown in Eq(5)).

$$E_{in} = \sum_{T} \left(S_{F,T} \times CI_F\right) \tag{3}$$

$$E_L = E_{in} \times (1 - \partial) \tag{4}$$

$$E_L = S_F CI_F + S_R CI_R + S_{ER} CI_R \quad \forall T \tag{5}$$

The objective of cost minimization can be met by strategically allocating the generated renewables using from Eq(1) to Eq(5). The objective function of cost minimization of each entity can be expressed as Eq(6), where C_T represents the electricity cost at time interval T while C_{MD} is the maximum demand charges.

$$Min\ Cost_{Total} = \sum_{T} C_T + C_{MD} \tag{6}$$

The electricity cost C_T at time interval T can be represented as Eq(7), where the CF_F and CF_R are the cost factor of fossil-based energy and renewables respectively at different time intervals indicated in Table 1.

$$C_T = \left(S_{F,T} \times CF_F\right) + \left(S_{R,T} \times CF_R\right) \quad \forall T \tag{7}$$

As for the maximum demand charges C_{MD} can be determined using Eq(8). Generally, its value is computed by multiplying the highest maximum demand value between mid-peak ($MDV_{mid-peak}$) and peak period (MDV_{peak}) with its respective maximum demand cost factor ($MD_{mid-peak}$ and MD_{peak}).

$$C_{MD} = \max\left(MDV_{mid-Peak}, MDV_{peak}\right) \times \begin{cases} MD_{mid-peak}\big|_{MDV_{mid-peak}=max} \\ MD_{peak}\big|_{MDV_{peak}=max} \end{cases} /0.5h \tag{8}$$

Whereas the maximum demand value of mid-peak periods can be determined by diving the summation of fossil-based energies ($\sum_{T\in mid-peak} S_{F,T}$) in every mid-peak periods to the number of mid-peak time intervals ($\sum_{T\in mid-peak} T$); similar method goes to the maximum demand value of peak periods (expressed as Eq(9) and Eq(10)).

$$MDV_{mid-peak} = \frac{\sum_{T\in mid-peak} S_{F,T}}{\sum_{T\in mid-peak} T} \tag{9}$$

$$MDV_{peak} = \frac{\sum_{T\in peak} S_{F,T}}{\sum_{T\in Peak} T} \tag{10}$$

The above formulations are incorporated into a mixed-integer linear programming model, which is solved using LINGO V18.0.

4.2 Cooperative game theory approach

In cooperative games, the objective is minimize the total electricity bills ($Cost_{Total,P}^{Trading}$) for all players, as expressed in Eq(11). It is certain that different players will obtain different benefits in their coalitions under a cooperative game. In this section, the cooperation between any players in the cooperative game is allowed in the model. There is a slight difference of energy demand expression and total electricity bill calculation in cooperative game model. When one of the players has excess renewables, it can be traded to other players in order for them to reduce their total electricity bills. For the total electricity bill calculation $Cost_{Total,P}^{Trading}$, it is revised as Eq(11), where the cost of renewables traded to other players, $C_{SR,P}$ and renewables traded from other players, $C_{SR,P'}$ are incorporated. The traded renewables cost can be expressed as Eq(12) and Eq(13), in which CF_{TR} indicates the unit cost of traded renewables from/sold to other players.

$$Min \sum_P Cost_{Total,P}^{Trading} = \sum_T C_{T,P} + C_{MD,P} + \sum_P C_{TR,P} - \sum_{P'} C_{TR,P'} \quad (11)$$

$$C_{TR,P} = \sum_T (S_{TR,T,P} \times CF_{TR}) \quad (12)$$

$$C_{TR,P'} = \sum_T (S_{TR,T,P'} \times CF_{TR}) \quad (13)$$

The energy demand expression in cooperative game, it is revised as Eq(14) and Eq(15), where traded renewables from other players, $S_{TR,P'}$ are included. The index P represents the players indicated, while P' refers to the other players. Note that the traded renewables from other players can be directly utilized or stored in the storage system.

$$D_{T,P} = \begin{cases} S_{F,T,P} + S_{R,T,P} + S_{ES,T,P}\big|_{\mathrm{T \in Daytime}} \\ S_{F,T,P} + S_{ES,T,P}\big|_{\mathrm{T \in Nighttime}} \end{cases} \quad \forall T \quad (14)$$

$$S_{ES,T,P} = S_{ES,T,P} + S_{TR,T,P'} \quad (15)$$

The equations formulated in this section for the P2P energy trading cooperative model is solved using LINGO V18.0.

5. Case Study

To illustrate the effectiveness of the proposed methodology, a hypothetical sample of three entities in Malaysia with different energy profiles is adopted as a case study in this work as shown in Figure 2(a). As a note, Global solver in LINGO V18 is used to solve the proposed optimization problem. Figure 2(b) is the one-month daily energy usage profile for three different entities. Given that there are three players considered in this case study, A, B and C, the set of all possible coalitions for the considered case is {{∅}, {A}, {B}, {C}, {A,B}, {A,C}, {B,C} and {A,B,C}}, where ∅ is the empty coalition.The three participating players with vary energy usage pattern (Figure 2(b)) needs to achieve a corresponding carbon reduction goal of 40 %.

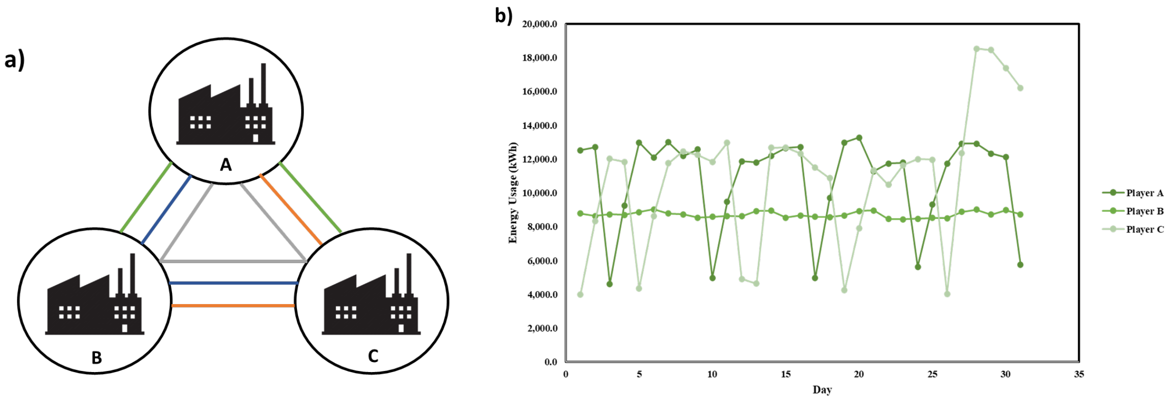

Figure 2: (a) Schematic diagram of cooperative P2P energy trading model between players; (b) Daily energy usage of three players

Table 1: Cost factor for each time interval (Tenaga Nasional Berhad-Enhanced Time of Use (TOU) Tariff Scheme, 2014)

Time (h)	Classification	Cost Factor MYR/kWh)	Maximum Demand Charge (MYR/kW)	Cost Factor of RE (MYR/kWh)
00:00-08:00	Off-Peak	0.202	0.00	0.276
08:00-11:00	Mid-Peak	0.327	35.00	0.276
11:00-12:00	Peak	0.576	38.30	0.276
12:00-14:00	Mid-Peak	0.327	35.00	0.276
14:00-17:00	Peak	0.576	38.30	0.276
17:00-22:00	Mid-Peak	0.327	35.00	0.276
22:00-24:00	Off-Peak	0.202	0.00	0.276

5.1 Results and Discussions

In this study, the electricity bills for each coalition structure are determined via the equations formulated from the former section. Note that the electricity bills indicated in the non-cooperative approach serve as the benchmark of this case study and the total carbon emission is not significantly crucial as the renewables allocated for each player are pre-determined based on preferences of decision-makers and policymakers. In other words, the trading of energy does not affect the total carbon emission as the renewable's utilization amount is still the same to fulfil the total carbon emissions reduction target. The results of non-cooperative and cooperative P2P energy trading scheme for three players with the objective of 40 % carbon emission reduction are tabulated in Table 2.

Table 2: Total electricity bills of entities for different coalitions (∂ =40 %)

	Coalition	Electricity bills for Player (MYR/month)			Total electricity bills (MYR/month)	Rank
		A	B	C		
Non-cooperative	{A}, {B}, {C}	90,962.42	80,692.13	91,318.29	262,972.84	5
Cooperative	{A, B}, {C}	90,585.40	79,245.72	91,318.29	261,149.41	3
	{A}, {B, C}	90,962.42	80,779.84	89,390.43	261,132.69	2
	{B}, {A, C}	90,896.53	80,692.13	89,726.48	261,315.14	4
	{A, B, C}	90,969.24	79,247.01	90,964.98	260,908.23	1

Note that the ranking of each coalition in Table 2 is only based on the total electricity bills, the realistic factor such as compromising behaviour of players needs to be included in determine the optimum coalition structure in P2P energy trading scheme. In the non-cooperative game approach, the electricity bills of player A, B and C are MYR 90,962.42/month, MYR 80,692.13/month and MYR 91,318.29/month. As for the second coalition (where players A and B are involved in the P2P energy trading scheme while player C remains to operate independently), they managed to reduce their electricity bills by MYR 377.02/month (0.41 %) for player A and MYR 1,446.41 (1.79 %) for player B. In the third coalition, where player A is not involved in P2P energy trading scheme while others are, player C can reduce its electricity bill by MYR 1,927.86/month (2.11 %). Player B does not have any significant bill reduction in this particular coalition but increased by MYR 87.71/month (0.11 %). Thus, this makes the second coalition structure to be unfavourable as one of the players (player B) needs to pay more than that of non-cooperative scheme. On the other hand, for the P2P energy trading cooperation among players A and C (fourth coalition), while having player B operating alone, players A and C can mitigate their electricity bills by MYR 65.89/month (0.07 %) and MYR 1,591.81/month (1.74 %). For the last grand coalition, where all the players are assumed to be involved in P2P energy trading cooperation scheme, the total electricity bills can be reduced by MYR 2,034.61/month (0.77 %) compared to the non-cooperative scheme. Player A would have to pay an extra of MYR 6.82/month in the grand coalition scenario, which makes the coalition to be disadvantageous for it even though the total electricity bills have the highest savings among other coalition structures. By looking at the coalition results illustrated in Table 2, the P2P energy trading cooperative scheme has more benefits as compared to the non-cooperative approach (the optimum coalition structure is capable of saving the total electricity bill by MYR 1,823.43/month for this case study and achieve 40 % of carbon reduction goal). Yet, some of the coalitions in cooperative schemes may be less practical given that some of the players would need to sacrifice themselves to pay the additional bill just for the sake of others (e.g., player B in the third coalition and player A in the fifth coalitions). As such, the coalition structures that need players to have additional payment should be eliminated. The key to optimize the P2P energy trading cooperative scheme is the selection of the most advantageous option of “payoff” coalition structure. The numerical calculations showed that the second coalition is the most favourable and advantageous option by far for all the players considered in this case study.

6. Conclusions

This work evaluates the non-cooperative and cooperative game theory approach in P2P energy trading system. Using the case study with three players involved, seven coalitions structure are modelled and analysed. The model of the P2P energy trading systems developed, along with the research and numerical simulations have shown that the cooperative game theory approach can be an effective method for the optimization of energy planning, especially in the context of optimizing the internal trading of renewables among the players involved. The obtained results show that the application of cooperative game theory based on the horizontal trading of energy between players enables receiving the information for different coalition structures. The results indicated that the most advantageous coalition enables all the players to mitigate their total electricity bills by MYR 1823.43/month (0.69 %), without having one of the players compromising. The analysis of the results not only can appeal to those involved in the coalitional theory of games, but also to the decision-makers. Even though the improvement is minimal in this case study, but it is believed that the concept could be a huge positive impact in achieving sustainable energy transition as the number of players increased. The fairness of each coalition structure remains questionable and is worth to be investigated in further research. Factors or uncertainties such as increased infrastructure fee, renewable energy adaption issue for new players and lack of good governance needs to be considered in the future model development.

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