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Optimisation Framework of Multi-Energy Peer-to-Peer Trading with Hybrid Market Models in Eco-industrial Parks

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The research developed a non-linear programming (NLP) model in Python for the Industrial Multi-Energy System (IMES) to implement Peer-to-Peer (P2P) trading for electricity and thermal energy in a hybrid market model. The model proposes that the grand coalition of all peers working together in the scheme is the optimal trading coalition. The distributed single-buyer model with grid integration is proposed for the electricity market, and a fully decentralised market for the thermal energy market. The net-metering scheme is implemented for the P2P trade of electricity. The Alternate Direction Methods of Multipliers (ADMM) algorithm is implemented for the P2P trade of thermal energy to clear the market and optimise trading decisions under constraints such as storage and network load. All peers involved in the P2P trading scheme reduced their overall total annual costs (TAC) by an average of 25.20 %. Peer A achieved an overall cost reduction of 28.91 %. Peer B and C achieved overall cost reductions of 15.34 % and 31.43 %. The average energy cost savings across all peers are 45.80 % for electricity and 92.20 % for thermal energy. The higher cost savings for thermal energy can be attributed to the fully decentralised network, enabling the full implementation of the ADMM algorithm that optimises the trading decision.

1. Introduction

The industrial sector has consistently recorded the highest energy consumption in Malaysia since the turn of the 21st century (IEA, 2023). As a developing nation with a significant portion of its economy relying on the industrial sector, it is expected to continue growing and, consequently, increase its energy needs (O'Neill, 2024). This occurrence is not exclusive to Malaysia, as similar developing countries with economies that rely heavily on the industrial sector are also susceptible to increasing energy demand. Therefore, there lies a need to diversify energy sources and maximise energy efficiency while minimising environmental impact.

Industrial Symbiosis (IS), a subset of industrial ecology, refers to the mutually beneficial exchange of materials, energy, and waste products between industrial companies (Dong et al., 2013). IS is based on a natural paradigm, which claims that an industrial ecosystem should mimic a natural one where resources are shared and recycled (Jensen et al., 2011). The IS concept is easily applied in an eco-industrial park due to factors such as a similar geographical location and suitability in fostering corporate collaboration to exchange resources (Butturi et al., 2019). The industrial multi-utility energy system (IMES) is proposed as an example of a solution to the IS concept, where it allows industrial companies to recycle waste and by-product steam and hot water to reduce energy consumption (Lee and Chen, 2023). The units within an IMES are linked through coupling components such as electric heat pumps, Combined Heat and Power (CHP) and Combined Cooling, Heating, and Power (CCHP), which allows decentralised systems to be integrated into an integrated one (Chao and Zhu, 2021).

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A Peer-to-Peer (P2P) energy trading scheme integrated with energy storage(s) is also proposed to allow companies (peers) to trade excess energy to one another within a decentralised microgrid for thermal energy and a grid-integrated scheme for electricity, which takes advantage of existing electricity transmission infrastructure. The peer-to-peer energy trading scheme is expected to reduce costs and decrease reliance on carbon-based fuels, while also promoting the ownership of Distributed Energy Resources (DER). Cooperative Game Theory (CGT) is studied to find optimal coalitions for the P2P trading scheme. With CGT, the grand coalition of all peers working together is expected to yield the highest overall benefit in terms of cost reduction (Kong et al., 2022). CGT also fosters the stability and confidence of the involved peers, ensuring that no peer is worse off by participating in the scheme and encouraging them to remain within the coalition.

The Alternate Direction Method of Multipliers (ADMM) algorithm is proposed to overcome the lack of a centralised energy market structure in a decentralised P2P energy trading scheme. ADMM allows the global trading problem to be decomposed into local subproblems, which peers can solve independently, thereby maintaining privacy and security as they are not required to disclose sensitive information, such as operational data, to a centralised controller (Liu et al., 2017).

Most studies on the P2P energy trading scheme focus on electrical-based power systems and are primarily limited to the commercial and residential sectors, excluding the potential of industrial-scale DERS. In Malaysia, a pilot test run of the P2P energy trading was conducted by the Sustainable Energy Development Authority (SEDA) using a test bed of commercial and residential entities. In the test run, only electricity DER systems were considered (SEDA, 2020). Therefore, a remaining research gap exists to conduct comprehensive studies for multi-energy, the industrial sector and utilising industrial-level DERS such as the proposed IMES. Multi-energy refers to the generation and trading of both electricity and thermal energy, as the different equipment within an IMES utilises and/or generates one or both forms of energy. The commonly studied and proposed fully decentralised P2P trading solution may not always be feasible due to barriers such as the lack of a physical energy transmission network or in countries with strictly regulated energy market practices and structures. Malaysia lacks a centralised thermal energy transmission and distribution network. Meanwhile, the electricity market structure in Malaysia is that of a single-buyer model where Independent Power Producers (IPP) are permitted to operate but are ring-fenced into selling their energy to the national grid entity, a regulation that may prevent a fully decentralised electricity grid. Thus, the national grid entity maintains a monopoly over electricity transmission and retail (Sibeperegasam et al., 2021).

In this research, a fully decentralised thermal physical network for thermal energy is proposed for implementation within the Eco-industrial Park (EIP), alongside a grid-integrated electricity trading scheme, in a hybrid multi-energy manner that operates simultaneously with each other. The superstructure of the IMES with detailed mathematical constraints is modelled using Python. ADMM is implemented to clear the P2P trading market for the thermal network, optimise peers' trading decisions, and coordinate equitable pricing and information exchange in the absence of a central controller, such as in a centralised network. ADMM also promotes privacy, as only a limited amount of information is required due to its decomposition of a global problem into subproblems, which peers can solve independently (Aminlou et al., 2024). A single-buyer electricity model is proposed to integrate well with CGT and supports the grand coalition as the optimal trading coalition for the highest savings (Tay et al., 2024). P2P trade of electricity is proposed to be implemented through the national grid network net-metering scheme, utilising available physical infrastructure while respecting energy transaction laws. The proposed hybrid P2P trading scheme for both grid-involved electricity and decentralised microgrid thermal networks is expected to benefit not only peers within the EIP by lowering their total annual costs but also improve energy efficiency and reduce environmental impacts by decreasing reliance on carbon-fuel sources for energy generation.

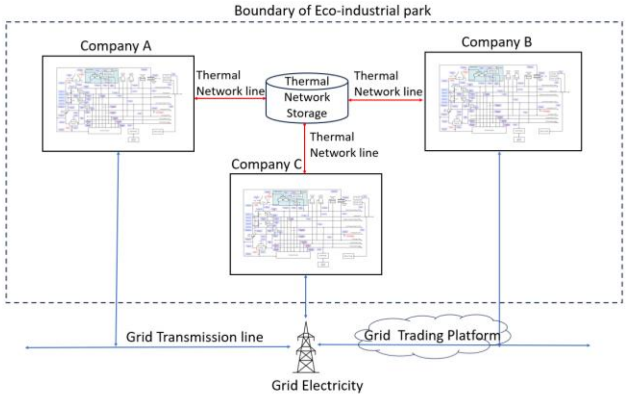


Figure 1: Illustration of the multi-energy networks within the EIP.

2. Methodology

A Non-Linear Programming (NLP) model was developed in Python for the IMES alongside a multi-energy mixed-mode P2P energy trading framework. The IMES comprises fuel-fired boilers, a CCHP system, steam headers, steam turbines, letdown valves, and steam recovery devices. The process is conducted sequentially in layers, the optimisation and operational layers. The optimisation layer adheres to the CGT studies, which state that a grand coalition of all peers within an EIP provides the highest benefits versus other forms of coalition, in terms of lowering costs, as reported in Tan et al. (2023). The total costs of the grand coalition are calculated. Detailed mathematical constraints for each energy generation unit, their interactions within the IMES, and their production and demand profile are provided to the model for better accuracy in an actual scenario. In the operational layer, energy trading takes place. Thermal energy is traded through the decentralised thermal network within the EIP, and electricity is traded through a grid-integrated network. The pricing strategy for the decentralised network attempts to emulate that of a regular centralised network, where energy prices are pricier during peak hours. The ADMM algorithm is implemented as a market-clearing mechanism and optimises energy trading decisions to minimise costs under practical constraints such as network capacity and storage limits.

2.1 Total Annual Costs formulation

The TAC of all the peers cooperating in the grand coalition is formulated in Eq(1). It includes the capital cost of equipment, C_{CC} , operational costs, C_{OP} , cost of energies traded to other players, $\sum_P C_{H,P}$, and cost of energy traded from other players, $\sum_{P'} C_{H,P'}$.

$$TAC = C_{cc} + C_{OP} + \sum_P C_{H,P} + \sum_{P'} C_{H,P'} \tag{1}$$

The operational costs formulated through Eq(2) include the operating and maintenance costs, C_{OM} , cost of natural gas, C_{NG} , cost of purchasing water, C_W , cost of electricity from the grid, C_{PG} , and carbon tax, C_{CT} .

$$C_{OP} = C_{OM} + C_{NG} + C_W + C_{PG} + C_{CT} \tag{2}$$

The P2P trading of electricity through the single-buyer model is conducted over the national grid. Peers generate excess electricity and gain profit by selling it to the national grid. Peers may also purchase energy generated by other peers from the pool, which is then sold to the national grid. The national grid processes and completes the transaction and distribution process through its transmission lines. In the model, each peer is equipped with an electricity energy storage (EES) system. Peers prioritise storing energy during periods of excess production to be consumed during peak hours to avoid high demand costs. Excess electricity produced and not stored in the EES is sold in the P2P trading scheme. The electricity cost, C_{PG}, is calculated within the operational costs, C_{OP}. C_{PG} is formulated in Eq(3). The energy supplied from the EES at time step *t* is represented by $\mathrm{E_{EES}[i]}$. $E_d[t]$ is the energy demand while $E_p[t]$ is the energy generated from the DERs at time step t. The modification of electricity costs according to peak and off-peak charges is represented, respectively, by $\mathrm{C_{peak}}$ and $\mathrm{C_{offpeak}}$. Peak intervals represented by $16 \leq \mathrm{i} \leq 44$. To account for profits of selling excess electricity to the grid, it is subtracted from the costs with $\mathrm{E_s[t]}$ at a selling price per unit determined by the grid at $\mathrm{C_{sell}}$. The maximum demand charge incurred is represented by $\mathrm{D_{max}}$.with 37 being the cost coefficient per unit of kWh peak demand.

$$C_{pg=} \sum_{j=1}^{d} \left[\sum_{t=1}^{48} \left(\max\left(0, E_d[t] - E_p[t] - E_{EES}[t]\right). \left\{ \begin{matrix} C_{peak,}\ if\ 16 \leq i \leq 44 \\ C_{offpeak}, otherwise \end{matrix} - \sum_{t=1}^{48} (E_s[t]. C_{sell}) \right\} \right) + D_{max}. 37 \right] \tag{3}$$

2.2 ADMM trading approach

ADMM enables the decentralised optimisation of the P2P trading scheme without a central controller. ADMM is also highly scalable and can assist with optimisation even in centralised systems by optimising a peers' trading decisions. With ADMM, each peer can independently optimise their trading actions while maintaining coordination with other peers through a shared global consensus variable. The optimal trading solution is determined when the ADMM algorithm terminates at convergence, when the primal residual and dual residual fall below predefined thresholds. In this research, the convergence tolerance is 0.001. The ADMM process begins with each peer, *i*, at time, *t*, independently minimising their local objective function to capture their net trading profit adjusted by a penalty term that enforces consensus in the distributed optimisation framework.

The local objective function for the peers is formulated in Eq(5). $P_{i,t}^{sell}$ and $P_{i,t}^{buy}$ denotes the amount of energy that a peer decides to sell and buy; $C_{sell,t}$ and $C_{buy,t}$ denotes the revenue cost of selling and buying thermal energy to and from the decentralised network; z_t denotes the global consensus variable; $\lambda_{i,t}$ denotes the dual variable; ρ denotes the optimisation penalty term.

$$min_{\substack{P_{i,t}^{sell} \\ P_{i,t}^{buy}}} = \left[C_{sell,t} \,.\, P_{i,t}^{sell} - C_{buy,t} \,.\, P_{i,t}^{buy} + \frac{\rho}{2}\left(P_{i,t}^{sell} - P_{i,t}^{buy} - z_t + \frac{\lambda_{i,t}}{\rho}\right)^2\right] \tag{5}$$

The local objective function as described in Eq(5) is subjected to the constraints as shown in Eq(6) to Eq(7). Eq(6) denotes the storage-energy balance constraint to ensure that the model does not allow peers to sell more than the energy they produce, store and do not require for demand. Where, $E_{i,t}^{avail}$ denotes the amount of energy available from a peer; $S_{i,t-1}$ denotes the energy stored from the previous time period; $D_{i,t}$ is the energy demand of a peer at a time step.

$$P_{i,t}^{sell} - P_{i,t}^{buy} \leq E_{i,t}^{avail} + S_{i,t-1} - D_{i,t} \tag{6}$$

Eq(7) formulates the storage capacity constraints for the personal energy storage (TES or EES) owned by each peer. This constraint ensures that peers do not store energy exceeding their individual limits. The equation dynamically updates over time and is comprehensive, taking account of all energy flows from previous storage levels, production, demand, and P2P trade.

$$S_{i,t-1} = S_{i,t-1} + P_{i,t}^{buy} - P_{i,t}^{sell} + E_{i,t}^{avail} - D_{i,t} \leq S_i^{max} \tag{7}$$

The network capacity constraint is formulated as shown in Eq(8). This ensures peers' trading decisions do not violate the thermal network's capacity limit. p_t^{max} denotes the upper limit of energy flow allowed in the network at time period, *t*.

$$P_{i,t}^{buy} - P_{i,t}^{sell} \leq p_t^{max} \tag{8}$$

After each peer has successfully solved their local optimisation problems independently, the global consensus variable, as shown in Eq(9), ensures coordinate trading decisions across all peers within the system. N represents the total number of peers, a value that is highly scalable based on situations. p_{max}^t is the maximum allowable net energy transfer in the network at a time period. $Proj$ clips the consensus value to respect network's physical constraints within a reasonable range at a given time, ensuring stability of the system.

$$z_t{}^{k+1} = Proj_{[-p_{max}^t,\ p_{max}^t]}\left(\frac{1}{N}\sum_{i=1}^{N}\left(P_{i,t}^{sell} - P_{i,t}^{buy}\right)\right) \tag{9}$$

After computing the updated global consensus, $z_t{}^{k+1}$, each peer updates their associated dual variable $\lambda_{i,t}$, which acts as the coordinating signal. The dual variable updated is shown as in Eq(10). α is the relaxation factor that determines each step size for updating the dual variable. $P_{i,t}^{sell} - P_{i,t}^{buy} - z_t{}^{k+1}$ is a term that reflects the "disagreement" between a peers' individual decision and the global consensus. In this step, peers are gradually pushed through iterations to the global consensus.

$$\lambda_{i,t}{}^{(k+1)} = \lambda_{i,t}{}^{(k)} + \alpha\rho\left(P_{i,t}^{sell} - P_{i,t}^{buy} - z_t{}^{k+1}\right) \tag{10}$$

3. Results and Discussion

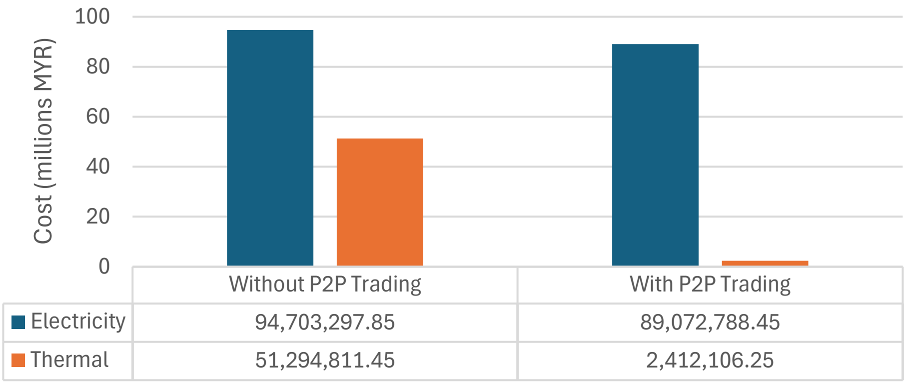
The total annual energy costs with and without P2P trading are shown in Table 1. All peers record a reduction in energy costs with the involvement of P2P trading. The net total energy cost of trading with energy is recorded after accounting for profits from trading energy. Peer A records a more than 100 % reduction in costs, resulting in a total reduction of -103.52 %, indicating that they are a net seller of energy compared to Peer B and Peer C, at -45.23 % and -32.62 %, respectively. In this case, Peer B and Peer C are considered net buyers, although they still manage to reduce their overall energy costs. The total energy cost for the three peers in the EIP without P2P trading is 146.00 x 10^6 MYR; with P2P trading, it is 92.39 x 10^6 MYR. The P2P trading scheme reduces the overall EIP's total energy costs by -36.72 %.

Table 1: Total annual energy costs with and without P2P trading

Peer	Total energy cost without P2P trading (MYR)	Net total energy cost with P2P trading (MYR)	Change in cost (%)
A	6,698,195.30	-236,195.15	-103.52
B	9,904,800.60	5,423,659.10	-45.23
C	129,395,113.40	87,199,431.75	-32.62

The breakdown cost distribution of the energies for the entire system is as shown in Figure 2. Electricity costs comprise the majority of energy costs, both with and without P2P trading, compared to thermal energy. Both thermal and electricity energy costs are reduced when participating in P2P trading. However, thermal energy costs are significantly reduced by 92.2 % compared to electricity costs, resulting in an overall reduction of 45.8 %. This is possibly due to the fully decentralised P2P trading scheme for thermal energy, where peers maintain complete authority over the trading process, subject to physical constraints. Additional information is shown in Figure 3 below, which displays the production and demand of both thermal and electricity energy for all peers in the EIP involved within the P2P trading system.

After the energy cost is calculated, the total TAC of each peer with and without P2P trading can be found and tabulated as shown in Table 3. Reducing both thermal and electricity costs through the P2P trading scheme helps to contribute to the lowered TAC, as the cost of energy is a significant portion of the TAC. Peers benefit from participating in the P2P trading scheme rather than not participating in it. The total TAC of all peers within the EIP without P2P trading is 187.64 x 10^6 MYR, and with P2P trading, it is 134.03 x 10^6 MYR. The average TAC reduction for all peers is 25.20 %, approximately a quarter of the total cost reduction.



	Without P2P Trading	With P2P Trading
🟦 Electricity	94,703,297.85	89,072,788.45
🟧 Thermal	51,294,811.45	2,412,106.25

Figure 2: System-wide Energy cost distribution

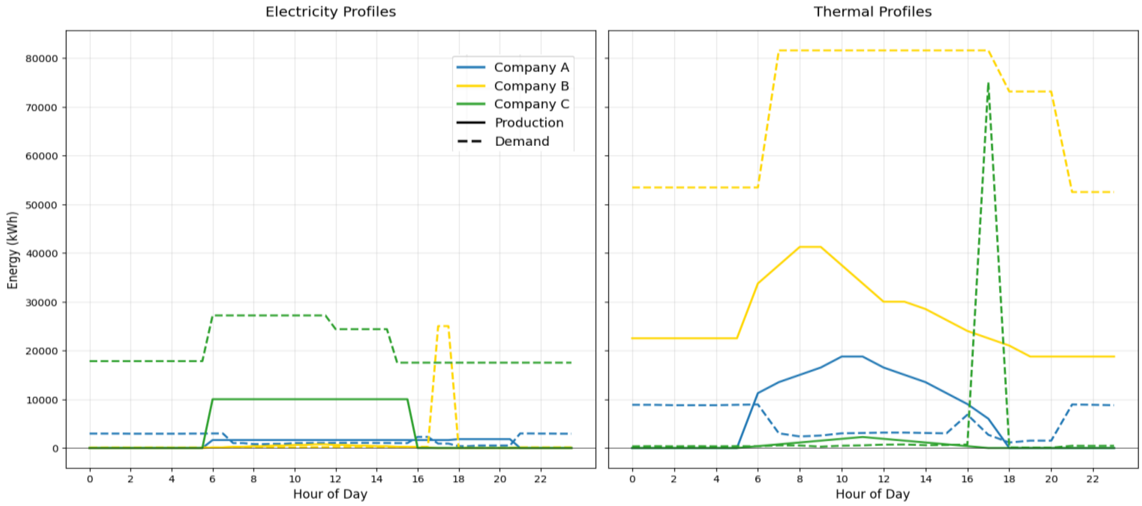


Figure 3: Demand and production profiles for electricity and thermal energy of the companies

Table 2: Total annual cost comparison

Peer	Total annual costs without P2P trading (MYR)	Total annual costs with P2P trading (MYR)	Change in cost (%)
A	24,039,824.25	17,105,433.80	28.91
B	29,100,247.83	24,619,076.33	15.34
C	134,504,492.16	92,308,809.51	31.43

4. Conclusions

The NLP model developed using Python in the research integrated P2P electricity and thermal energy trading for the IMES of an eco-industrial park in a multi-energy hybrid market model —a distributed single-buyer model for electricity and decentralised for thermal energy. All peers involved in the scheme reduced their TAC compared to a non-P2P trading scenario, indicating that overall, it is beneficial to participate in the scheme. The average electricity cost reduction across all peers is 45.8 %, while the average thermal energy cost reduction is 92.2 %. The higher cost reduction for thermal energy is attributed to the ADMM algorithm's ability to optimise the decisions on the quantity and peers involved in the trading. ADMM also prioritises achieving consensus among peers, as shown by the 8.07 % difference between the peer with the highest and lowest cost savings, compared to a 121.52 % difference for electricity. Although savings from the distributed single-buyer market model for the P2P trade of electricity do not produce as much savings, peers who can generate excess electricity can still reduce their overall costs compared to a non-trading model. The research successfully develops a hybrid-market multi-energy optimisation framework for P2P trading involving IMES in eco-industrial parks. The ability of the ADMM algorithm to optimise trading and ensure fairness among peers, even when implemented on only one layer of the trading process, demonstrates its suitability and scalability for adaptation. Further studies can include the optimisation of the electricity P2P trading process by implementing ADMM on the national grid side to offer an electricity sell-and-purchase strategy, or through other suitable algorithms. A proposed fully decentralised P2P electricity scheme without grid integration can also be studied at an industrial level.

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