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Peer-to-peer Economic Decision Analysis Model for Integrated Thermal Energy Trading

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Solar energy harvesting technologies that are environmentally friendly and sustainable are being utilized worldwide as a viable alternative for lowering energy consumption. Solar thermal is one of the emerging technologies for industrial processes to supply steam and hot water. The technology also has the potential to be installed as an integrated solar thermal network to reduce costs while maximising the use of available surplus heat. The intermittent solar irradiance and temperature variance of process demand complicate the supply chain of heat networks. The collaboration among stakeholders necessitates using a mutual transactive energy distribution approach to coordinate supply and demand to achieve smooth operation at a lower cost. This study aimed to develop a peer-to-peer (P2P) approach for the economic decision analysis model that would assist the industry in determining the cost of an integrated solar thermal system and thermal energy distribution pathways based on a mixed integer programming model using a General Algebraic Modelling System (GAMS). It was applied to an illustrative case study of centralized thermal energy storage (TES) facilities to validate the economic decision analysis. The model showed that the integrated solar thermal system could supply 3.73 % thermal energy from TES for Prosumer 2, Consumer 1 (19.76 %) and Consumer 2 (27.50 %), with a total capital investment cost of 551,744 USD/y.

1. Introduction

Global annual solar thermal energy yields increased from 51 TWh in 2000 to 425 TWh in 2021, resulting in 45.7 Mt of oil and 147.5 Mt of CO_2 savings (Weiss and Spörk-Dür, 2021). The expansion demonstrates solar thermal's significant contribution to lowering global greenhouse gas (GHG) emissions, and they are to be located in regions with high solar availability (Martín 2022). A substantial increase in solar thermal systems is due to the huge potential for various industry applications (Kumar et al., 2021). A solar collector system can store excess thermal energy generated during the day for use at night, during cloudy weather, and periods of high demand. The demand and range of temperature required for each plant may differ depending on the production. Due to the stochastic nature of solar thermal systems and their high reliance on climate, they are regarded as a variable resource and may be installed in an integrated thermal energy system setting. Many similar problems in solar thermal were solved by modelling in the literature.

Most of the recent studies focused on building and district heating models. Winterscheid et al. (2017) proposed a methodology to incorporate large solar heating systems in an existing district heating system, while in an existing district heating system, Rämä and Wahlroos (2018) investigated the effects of new heat pumps and solar collector capacity. A multi-period Mixed-Integer Non-Linear Programming (MINLP) model was developed to integrate solar thermal with a cluster of buildings' space heat and hot water supply networks (Abikoyea et al. (2019), and Abdalla et al. (2021) developed a model for micro-thermal networks for thermal energy sharing by harvesting thermal energy between buildings in integrated energy communities. A model for modelling and

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comparing District Energy Systems (DES) and Low-Temperature Thermal Networks (LTTN) also was developed by Rogers et al. (2022).

Ismail et al. (2021a) developed a decision-making analysis for the industry for solar heat networks and optimal thermal energy storage (TES) for an exemplary industrial case study. This study determined the best configuration and optimal design to meet multiple sources and demand scenarios based on a mathematical decision framework. However, the study only reported for two scenarios based on full and 75 % load of heat demand, which does not reflect the overall integrated system. Some industries may be reluctant to install the system because of the high installation costs and limited space available, preferring to obtain thermal energy from peer and centralized sources. The integrated heat thermal network approach is promising to reduce costs, as seen from the successfully implemented solar photovoltaics (PV). Recently, there have been many developments in the peer-to-peer (P2P) approach to solar generation technologies. These advancements have allowed for lower production costs and increased system efficiency, including consideration of demand response, energy storage services, and a secure and transparent information system. Interoperability is required in an integrated thermal network to communicate and share energy data while maintaining operational and service constraints. Omu et al. (2016) developed a model to improve the accuracy of the solar collector and storage tank models while keeping the optimization problem tractable and applicable.

The P2P market structure for electricity has been studied in the literature, and numerous papers have discussed the topic. A concept of P2P trading was developed by Yebiyo et al. (2020) for a more robust and better electricity grid with the inclusion of distributed energy storage. Alvarez (2022) studied a model that minimised the total operating cost of the large-scale system in a smart grid. Unfortunately, few studies on P2P market structure were carried out for solar thermal. Ismail et al. (2021b) performed a study to assess the economic viability of a P2P approach for solar thermal network configurations. However, the Levelized Cost of Heat (LCoH), which includes the cost of solar collectors and storage facilities, was the only economic factor assessed in this study. Although different programming models have been performed for P2P, an efficient decision model is still lacking to evaluate the optimal cost for the overall integrated solar thermal system. Detailed analysis for the optimization approach is also needed to help users in the decision-making process to determine the ideal energy distribution path for each option in an optimization model. This study aimed to optimise the cost of an integrated thermal network via mathematical modelling while considering the optimal pathway for thermal energy distribution. The outcome of the study is envisioned to facilitate decision-making to determine the optimal cost and logistic operations by considering the trade-off between economic and process performance.

2. Problem identification

An integrated thermal system means that solar thermal energy generation, demand, and supply are enclosed within a specific industry, company or use. The P2P approach enables individual consumers to become prosumers and share their excess energy with their neighbours. An integrated thermal network system is demonstrated in Figure 1, consisting of consumers, prosumers, and TES. A consumer is a user without solar thermal. Consumers can reduce their thermal energy consumption by purchasing thermal energy at a lower cost through P2P heat networks.

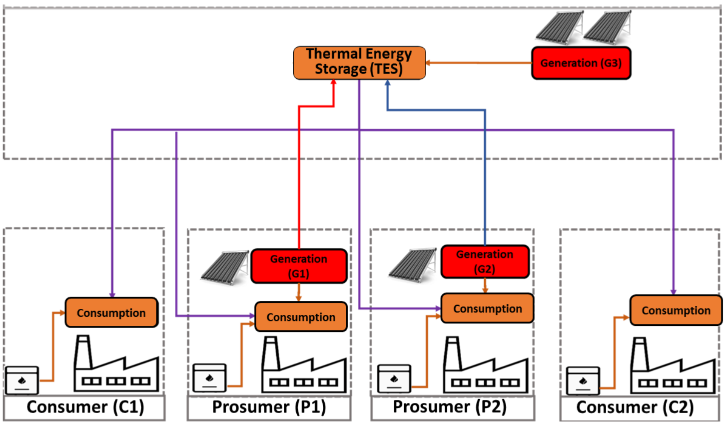

Figure 1: Schematic diagram of an integrated solar thermal network

Prosumers will be encouraged to participate in P2P heat networks if they have solar thermal and benefit from selling surplus thermal energy to nearby users or purchasing from centralized TES. The heat generated by prosumers can be used for self-sufficiency, sending any excess to a centralized thermal energy storage facility. When consumption exceeds generation for prosumers, the plant can purchase heat from the centralized system to compensate for the differences. In this case, the prosumer can also be a customer if additional heat is required. The prosumer can sell the excess thermal to the centralized thermal storage managed by a centralized thermal system operator at TES. The system operator at TES is a third party in charge of the integrated solar thermal system's operations, including maintenance, organization, and supervision of the trading platform and the settlement of transaction fees.Transferring heat networks from and to the centralized system results in many possibilities and uncertainties in practical business operations. Cost constraints and supply-demand imbalances can also be significant challenges. Consequently, optimising integrated solar thermal systems is typically difficult and complex. A simultaneous solution is required to determine the optimal configurations and sizes of heat network systems. Thus, decision-making modelling will be utilized for a more comprehensive analysis based on the P2P methodology and economic analysis. The individual customer and the centralized thermal system operator can achieve a win-win situation by determining the optimal thermal energy distribution path. The main advantage of this method is that it helps reduce the cost of implementing a solar thermal system while promoting the efficient use of energy with minimal loss.

3. Methodology

This section describes the methodology used to determine the optimal number of solar collectors and storage sizes for the solar thermal system. The integrated model was formulated to satisfy the daily demand for heat energy. The model's objective was to minimise the cost of the solar thermal system by utilising external supply from centralized thermal energy storage to reduce the dependence on fossil fuels. In this case study, Prosumers 1 and 2 would install solar collectors while Consumers 1 and 2 bought the heat energy from the centralized TES.

3.1 Determination of demand

In an integrated solar thermal system, heat is supplied from different solar collectors to centralized thermal storage, which caters to multiple industry demands. The daily availability of thermal energy is dependent on the daily solar radiation. For simplification, the daily average solar radiation data has been used, and the daily demand is assumed for each hour. The process demand for Consumer 1 (C1) is assumed to be 475 kWh, Consumer 2 (C2) is 540 kWh, while 425 kWh for Prosumer 1 (P1) and 675 kWh for Prosumer 2 (P2). It is important to note that the heat requirements for the shared industry must be in the same range to ensure practicability. In this case study, several assumptions were made. The solar thermal system was assumed to supply facilities with hot water at 80 °C. Thermal energy generated from the boiler will operate once solar collectors cannot fulfil demand. The distance between each facility is also assumed to be the same length.

3.2 The mathematical formulation for the economic decision analysis model

In this study, the daily supply of integrated thermal systems was limited within the studied area. The general mathematical formula of the total solar thermal cost had to be determined to obtain the optimal economic decision analysis model. A Mixed-integer linear programming (MILP) mathematical model was developed based on the energy balance principle to perform the heat allocation from centralized storage to satisfy the daily heat demand. The objective function, Eq(1) is to minimise of the solar thermal system cost, as shown in Eq(1) which is the sum of the prosumer's solar collector capital cost ($CostPro_i$), the sum of consumer cost ($CostCons_j$) and TES capital cost ($CostTES$). The capital cost for prosumer's solar collector which is the sum of natural gas price (C_i^{gas}), solar thermal collector (C_i^{coll}) and boiler (C_i^{boiler}) as shown in Eq(2)- Eq(5). α and β are the annualize capital cost factor for the investment cost of solar thermal collectors and boilers. The calculation of the consumer cost was determined by Eq(6) – Eq(9). The TES capital cost was calculated using Eq(10), where γ is the annualized capital cost factor for the investment cost of thermal energy storage.

$$f_{obj} \min TotalCost = \sum CostPro_i + \sum CostCons_j + CostTES \tag{1}$$

$$CostPro_i = C_i^{gas} + C_i^{coll} + C_i^{boiler} \tag{2}$$

$$C_i^{gas} = \sum_{h=1} Q_{ih}^{NG}\, C_{NG}\, d \tag{3}$$

$$C_i^{coll} = \alpha_i \, N_i^{coll} \, A_i^{coll} \, C_i^{CAPcoll} \quad (4)$$

$$C_i^{boiler} = \beta_i \, Q_i^{CAPboiler} \, C_i^{CAPboiler} \quad (5)$$

$$CostCons_j = C_j^{gas} + C_j^{boiler} \quad (6)$$

$$C_j^{gas} = \sum_{h=1} Q_{jh}^{NG} \, C_{NG} \, d \quad (7)$$

$$C_j^{boiler} = \beta_j \, Q_j^{CAPboiler} \, C_j^{CAPboiler} \quad (8)$$

$$C_{TES}^{coll} = \alpha \, N_{TES}^{coll} \, A_{TES}^{coll} \, C_{TES}^{CAPcoll} \quad (9)$$

$$CostTES = \gamma \, Q_{TES}^{CAP} \, C_{TES}^{CAP} \quad (10)$$

where the subscript i and j represent prosumer and consumer. Eq(11) ensures that the total surface area of solar thermal collectors, which is given by multiplying the number of installed collectors (N_i^{coll}) by the area of each collector (A_i^{coll}) is less than or equal to the amount of available area ($Area_i$). The thermal energy from the boiler and excess is calculated by using Eq(12)-Eq(16).

$$N_i^{coll} \, A_i^{coll} \leq Area_i \quad (11)$$

$$Q_{ih}^{coll} \leq N_{ih}^{coll} \, A_i^{coll} \, I_{ih}^{coll} \, \eta_i^{coll} \qquad \forall \, i, h \quad (12)$$

$$Q_{ih}^{boiler} = Q_{ih}^{NG} \, \eta_i^{boiler} \quad (13)$$

$$Q_i^{Demand} = Q_{ih}^{disch} + Q_{ih}^{boiler} + Q_{ih}^{dishcTES} \quad (14)$$

$$Q_{ih}^{Excess} = Q_{ih}^{coll} - Q_{ih}^{disch} \quad (15)$$

$$Q_{ih}^{boiler} \leq Q_i^{CAPboiler} \quad (16)$$

For the consumer, the thermal energy from the boiler is determined by Eq(16), and the demand (Q_{jh}^{Demand}) by Eq(17). Eq(18) ensures that energy generated for the boiler (Q_{jb}^{boiler}) is less than or equal to the amount of available area.

$$Q_{jh}^{boiler} = Q_{jh}^{NG} \eta_j^{boiler} \quad (16)$$

$$Q_{jh}^{Demand} = Q_{jh}^{boiler} + Q_{jh}^{dischTES} \quad (17)$$

$$Q_{jb}^{boiler} \leq Q_j^{CAPboiler} \quad (18)$$

The energy balance and capacity limit equation for the prosumer and consumer side was translated into programming language via General Algebraic Modelling System (GAMS) software using the CPLEX solver to solve the MILP problem. The main parameter for mathematical formulation in GAMS is depicted in Table 1.

Table 1: Main parameter for mathematical formulation in GAMS

Item	Unit	Value
Annualized capital cost factor for the investment cost of collector	USD/m^2/y	0.0476
Annualized capital cost factor for the investment cost of boiler	USD/kW/y	0.0667
Investment cost of solar thermal collector	USD/m^2	306
Investment cost of boiler	USD/kW	120
Investment cost of thermal energy storage	USD/kWh	10
Natural gas price	USD/kWh	0.029
Area of solar thermal collector	m^2 /collector	12.52
Efficiency of boiler to produce thermal energy	kWh output / kWh input	0.8
Energy loss factor of thermal energy storage	kWh output / kWh input	0.6

The investment cost of boiler was referred to McNeil G. (2013) while the natural gas price is based on the selling price by Gas Malaysia Energy and Services Sdn. Bhd. for the average annual gas consumption (Energy Commission, 2021).

3.3 Determination of storage capacity

The thermal storage was required to ensure the fluctuating daily thermal demand was satisfied with the limited daily excess energy supply availability. The total thermal energy for the solar collector at TES must be less than The capacity of the thermal storage tank was calculated using Eq(21)-Eq(22). Eq(23) ensures that energy stored in the thermal energy storage (Q_h^{stored}) is less than the energy generated to be stored in TES (Q_{TES}^{CAP})

$$N_{TES}^{coll}\ A_{TES}^{coll} \leq AreaTES \tag{19}$$

$$Q_{TES,h}^{coll} \leq N_{TES,h}^{coll}\ A_{TES}^{coll}\ I_{TES,h}^{coll}\ \eta_{TES,h}^{coll} \tag{20}$$

$$Q_h^{stored} = Q_{h-1}^{stored} + Q_{TES,h}^{coll} + Q_{ih}^{Excess} - Q_{ih}^{dishcTES} - Q_{jh}^{dischTES} - Q_h^{loss} \tag{21}$$

$$Q_h^{loss} = Q_{h-1}^{stored} \eta^{stored} \tag{22}$$

$$Q_h^{stored} \leq Q_{TES}^{CAP} \tag{23}$$

4. Results and discussions

4.1 GAMS coding

GAMS version 24.4.6 encodes the objective function, variables, parameters, and constraints. The mixed integer linear programming model was optimised using the CPLEX solver. This model's goal function was to minimise the total solar thermal cost of the thermal energy supply chain by determining the optimal modes of the pathway and utilization based on the cost parameters provided. The number of equations was 525, with 558 variables and a solving time of 0.031 s.

4.2 P2P feasibility evaluation

Under the optimal scenario, the total solar thermal system cost was 551,744 USD/y which the total cost of thermal energy - prosumer 1 is 111,390 USD/y, cost of natural gas purchased - prosumer 1 (93,761 USD/y), cost of solar thermal collector - prosumer 1 (14,224 USD/y) and the cost of the boiler is 3,401 USD/y. The energy capacity of boiler - prosumer 1 is 425 kW. Based on the model output, the pathway of the best route was decided based on the thermal energy supply, as shown in Table 2. Table 3 shows a detailed breakdown of the model's optimal solar thermal design for the integrated system. The optimal scenario requires 78 collectors for Prosumer 1 with a size of 976.6 m^2, 95 collectors for Prosumer 2 (1,189.4 m^2), and 100 collectors for TES with a size of 1,252 m^2. The results showed that the P2P approach could improve system operation efficiency because the P2P network reduced the cost of heat generation from the boiler by 3.73 % for Prosumer 2, Consumer 1 (19.76 %) and Consumer 2 (27.50 %) via getting the thermal energy supply from TES. However, all prosumers and consumers still rely on the boiler for thermal energy supply for their process due to the limitation of solar collector area and higher cost of solar collectors.

Table 2: The percentage of thermal energy supply from the optimal integrated system

Heat supply	Prosumer 1	Prosumer 2	Consumer 1	Consumer 2
Solar Thermal	30.53 %	28.70 %	-	-
TES	0	3.73 %	19.76 %	27.50 %
Boiler	69.5 %	67.6 %	80.2 %	72.5 %

Table 3: The optimal solar thermal design for the integrated system

	Number of collectors	Area (m^2)
Prosumer 1	78	976.6
Prosumer 2	95	1,189.4
TES	100	1,252.0

5. Conclusions

This study developed an economic model for the P2P decision analysis to manage thermal energy transactions in an integrated solar thermal system. The model output shows that the annualized total cost for the integrated thermal system is 551,744 USD/y. In the case study, the centralized thermal energy storage operator bought the energy surplus from prosumers at low prices and resold it to other consumers at variable prices. As a result, peer-to-peer heat networks on local energy markets can provide socio-economic incentives that promote local renewable generation while also serving as an alternative incentive for prospective prosumers. P2P heat networks enable customers to trade heat energy at a lower P2P marginal price than the price of heat energy generated from fossil fuels. The mathematical modelling results demonstrated that the proposed decision analysis was practical. Not only did all consumers and prosumers benefit from market participation, but the third party was also regarded as the price maker operator. This decision-making analysis model would obtain the centralized operator's optimal strategy and operation and manage the heat transactions between prosumers and consumers using a previously explained iterative market analysis. The application of P2P technology in energy transactions in an integrated heat-thermal system enables decentralized transactions, improves network and congestion management, helps a more efficient trading process, aids in the renewable generation intermittency issue, and increases social capital in the energy sector.

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