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Peer-to-Peer Control Strategy for the Optimal Trading Price of Integrated Solar Thermal Systems

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Huge potential exists for an integrated solar thermal system that connects several solar thermal plants at various locations to a single centralized energy generation (CEG) system network to meet the demand for heat from various businesses. Effective energy management via optimization has become crucial to increase economic competitiveness, provide more cost-effective energy services, and reduce environmental impacts. Planning and energy management issues include linking every user to a distributed energy resource, a third-party monopoly, and the limited ability of distributed energy resources to compete on pricing and services and set their trading price. The use of locally produced energy is encouraged, and a Peer-to-peer (P2P) competitive energy system is suggested to balance supply and demand. P2P interactions at a larger distribution level are utilized to determine the optimal trading price for an integrated solar thermal system by addressing the financial mechanism. The economic optimization amongst P2P network participants was assessed in terms of the net present value (NPV) and the levelized cost of heat (LCOH). The proposed energy network can enable the model to evaluate transactions, prevent monopolies, and ease access to new distributed energy providers. To demonstrate the suggested approach, a case study of a decentralised competitive heating system at a distribution level is presented. Model simulations were then run to confirm the logic and potential value of the proposed design. In the results, a series of sensitivity analyses were undertaken to investigate the magnitude of the effect of the parameter variation on cost calculation. Simulation findings indicate a minimum solar radiation level of 1,800 kWh/m², a discount rate below 10 %, a lifetime beyond 15 years, and an optimal trading price of 336 USD/m² gross for the system acquisition cost. The study found LCOH with positive NPV values between 55 and 82 MYR/MWh . Hot water trade prices from an integrated solar thermal system can be enhanced by 40 % of the LCOH compared to conventional production. All of these results suggest that an integrated solar thermal system in this context could be promising.

1. Introduction

The integration of multiple solar thermal plants into a single centralized energy generation (CEG) system offers a promising solution to meet the growing demand for heat across various industries. However, effective planning and management are essential to maximize the potential of these integrated systems. Energy optimization has emerged as a critical aspect of modern energy management, aimed at enhancing economic competitiveness, cost-effective energy services, and environmental sustainability.

The viability of solar thermal systems in industries has been investigated in several studies. The technological aspects of a system that simultaneously generates solar thermal heat and power for industrial purposes were also studied by Martínez-Rodríguez et al. (2021). Dáz-de-León et al. (2022) also assessed the effectiveness and practicality of a solar thermal heat pump in an industrial batch process. Martnez-Rodrguez et al. (2022) researched the evaluation of electric power and refrigeration production using solar thermal energy for industrial applications where the information on the potential for integrating solar thermal energy is discussed. A feasibility study on a solar power system based on Stirling Dish (SD) technology was published by Tsoutsos et al. (2003).

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The authors also reviewed and compared the various Stirling engines from the perspective of a solar Stirling system.
Peer-to-peer (P2P) energy trading business models were reviewed by Muhsen et al. (2022) based on various aspects of P2P energy trading, including its sustainability, economic viability, and regulatory considerations which can be adapted to the thermal energy trading context. A decentralised P2P control system for trading in heating and cooling within distributed energy systems was discussed by Li et al. (2021). The research explored a novel technique for managing energy transactions in distributed energy systems for optimal heating and cooling resource usage. Babagheibi et al. (2023) discussed the development of an integrated energy system that combines heat and power markets within the framework of energy hubs. The study places a particular emphasis on addressing security constraints in the system.
The majority of previous research on solar thermal energy concentrates on single solar thermal plants rather than integrated solar thermal systems' economic analyses. Chee et al. (2022) studied the economics of cogeneration in the pulp and paper sector using a natural gas boiler and solar photovoltaic systems. The paper discussed the benefits of combining these energy sources for industrial applications. Martnez-Rodrguez (2023) conducted a thorough thermo-economic analysis of a heat pump created for industrial purposes. The analysis explored the technical and financial facets of heat pumps, examining their effectiveness, affordability, and suitability for industrial processes.
Andika et al. (2017) conducted a comprehensive evaluation of advancements in thermal energy storage for concentrated solar power (CSP) systems. In the study, the authors evaluated the feasibility and economic viability of these technological enhancements, aiming to improve the efficiency and reliability of CSP systems. The study also explored various aspects of thermal energy storage, considering factors such as cost-effectiveness, performance improvements, and their impact on the overall CSP system. Rashid et al. (2019) presented a comprehensive analysis of various hybridization schemes for a solar thermal/gas power plant. The study assessed the technical and economic aspects of these hybrid configurations, focusing on their feasibility and cost-effectiveness. It investigated different system parameters, including the integration of solar thermal and gas power, to determine the optimal configuration for sustainable power generation.
Prior research in solar thermal energy mainly emphasizes standalone solar thermal plants, neglecting economic analyses of integrated solar thermal systems. Conventional control methods often rely on a third party to manage the flow of heating energy between prosumers and consumers, leading to potential inefficiencies and higher costs. Third-party monopolies, restricted access to dispersed energy supplies, and issues competing on pricing and services are challenges for the implementation of optimal integrated facilities. To address these issues, the proposed approach introduces a P2P competitive energy system, enabling optimal trading price determination between multiple stakeholders within the larger distribution network.
The research gap in this study revolves around the limited focus on economic analyses of integrated solar thermal systems. Additionally, the need for efficient management and trading mechanisms within integrated solar thermal systems, particularly through P2P approaches, is highlighted to address potential inefficiencies and challenges in integrated solar thermal systems. This paper represents an extension and advancement of a previous case study that was published by Ismail et al. (2022). The emphasis of this extension is on the efficient application and optimization of trading prices. By harnessing P2P interactions, the study aims to establish a robust financial mechanism that allows integrated solar thermal systems to determine the optimal trading price for their energy offerings. The proposed multi-layer competitive energy system approach incorporates an operating mechanism, enabling participants to evaluate economic optimization through a multi-energy management system.
One of the primary advantages of this P2P approach is the promotion of locally-produced energy utilization and effective supply-demand balance. By facilitating direct transactions and preventing monopolies, the proposed energy network opens avenues for new distributed energy providers to penetrate the market. To demonstrate the practicality of the concept, the paper provides a full case study of a decentralized competitive heating system at a larger distribution level, particularly in terms of determining the optimal trading price for energy transactions. Extensive model simulations were developed to validate the approach's rationale and potential utility. A number of sensitivity analyses were carried out and the findings were presented in the results. These analyses explore the extent to which the variation in the parameters affects the trading prices estimate for the economic evaluation.

2. Case study description

This case study illustrates a decentralized competitive heating system constructed at a larger distribution level to demonstrate the viability and effectiveness of the suggested architecture for integrated solar thermal systems. The aim is to validate the rationality and potential utility of the P2P control strategy in determining optimal trading prices for energy transactions within the system based on economic evaluation. Extended model simulations based on an integrated solar thermal network as reported by Ismail et al. (2022) compare the user trading price (MYR/MWh) and system efficiency of the decentralised competitive heating system to conventional central heating systems.

2.1 System description

The decentralized competitive heating system comprises an integrated solar thermal plants within prosumers and consumers, all linked to a single CEG network with a thermal energy storage (TES). The P2P energy trading mechanism facilitates direct interactions between these distributed energy resources and prosumers and consumers, allowing them to negotiate and determine the optimal trading price for heating energy. The variables consist of the following: the capital cost for system acquisition, the discount rate, annual solar radiation, system lifespan, annual system efficiency, and solar thermal market price.

3. Methodology

3.1 System design and simulation setup

A thorough system design was created for the larger solar thermal integrated system, which included the network of connected solar thermal plants. The simulation setup was created to test the system's performance under different scenarios using a General Algebraic Modelling System (GAMS) and SHIP tools as the simulation software. The SHIP Tools developed by AEE - Institute for Sustainable Technologies, serve to simulate the yearly energy generated. This software is specifically designed for modeling and evaluating the utilization of solar heat in industrial operations, while also providing calculations of annual expenses, taking into account climate conditions and hourly demand patterns. The system is evaluated based on LCOH and NPV as the parameters to alleviate the optimal trading price of the integrated solar system. The main parameters for the economic evaluation of the optimal integrated solar thermal system is shown in Table 1.

Table 1: The economic characteristics of an integrated solar thermal system

Parameter	Unit	Value
Investment Costs	MYR	2,234,164.80
Subsidy of initial investment	% of investment	0.20
Annual O&M costs	% of investment	0.01
Residual value	% of investment	0.05
Cost of substituted final energy (NG)	MYR/MWh	171.00
Efficiency of existing system	%	0.80

3.2 Data collection

Data related to solar energy generation, heat demand profiles of various businesses, geographical information of solar plants and CEG network locations, historical energy prices, and other necessary parameters for the cost estimation. The optimal design of the TES system from Ismail et al. (2022) was utilized to evaluate the optimal trading price of the integrated solar thermal systems. The study suggested that TES required 6,420 kWh of total demand to supply to consumers and prosumers. This TES intended to substitute the hot water production using a natural gas boiler. The cost of natural gas considered in this study is assumed to be 171 MYR/MWh (Energy Commission, 2023).

3.2 Economic evaluation

The chosen economic indicators are the net present value (NPV) and the levelized cost of heat (LCOH) as depicted in Eq(1) and Eq(2).

$$NPV = (E - O)\frac{1-(1+i)^{-N}}{i} - CC \tag{1}$$

where *E* is the annual income, *O* is the annual operating and maintenance cost, i is the discount rate and CC is the capital cost. This study also estimated the LCOH, which determined the minimum heat thermal trading price necessary for energy consumers to generate a profit. The LCOH is computed by dividing all costs incurred over the lifetime of the solar collector by the total amount of heat generated.

$$LCOH = \frac{I_C - S_O + \sum_{t=1}^{n}\frac{A_t}{(1+i)^t} - \frac{RV}{(1+i)^n}}{\sum_{t=1}^{n}\frac{M_{th}}{(1+r)^t}} \tag{2}$$

where I_c represents the initial investment cost, A_t signifies the annual operating cost, RV denotes the residual value of the investment, M_{th} stands for the substituted energy, r represents the annual reduction in yield, *i* signifies the discount rate, and *t* denotes the service life of the solar collector when referring to the annual heat thermal generation.

3.3 Simulation and validation

The proposed decentralized competitive heating system was simulated based on different case studies. The simulation result compared the performance of the P2P system with conventional central heating systems in terms of user cost and system efficiency.

3.4 Sensitivity analysis

A sequence of sensitivity analyses is conducted to assess the scale of the impact resulting from variations in key parameters on the calculation of heating generation costs. These parameters encompass factors such as solar radiation levels (Scenario 1), the projected project lifetime (Scenario 2), the applied discount rate (scenario 3), and the purchase price of the system (Scenario 4). For Scenario 1, the regional factor was considered and three locations to represent the selected industrial complex location in Peninsular Malaysia. The yearly average value of solar irradiance identified for the North region was Bayan Lepas, Kuantan for the central region, and Johor Bahru which is near Pasir Gudang represents the South region. The project lifetime in Scenario 2 was evaluated at 13 y, 15 y, and 21 y because it represents a long-duration project to ensure their successful planning, execution, and completion. For Scenario 3, the discount rates of 5 %, 10 %, and 15 % were applied to evaluate the present value of future cash flows at several rates and allow for the comparison of costs and benefits occurring at different points in time. Finally, the purchase prices of three common types of solar collectors based on their efficiency, namely Arcon HT-A, Arcon HT-SA, and Ritter XL Solar - Aqua Plasma were Scenario 4. The collector-specific system costs encompass all its components, such as collectors, storage, and process integration, the cost was retrieved from SHIP Tools. These costs can exhibit substantial variations where simpler or larger systems tend to have lower specific system costs compared to more complex or smaller systems. The basis for the base case evaluation was Johor Baharu for the region, 21 y for project lifetime, 10% discount rate, and Arcon HT-SA for the solar collector. This sensitivity analysis aims to unveil the degree to which alterations in these elements influence the overall calculation of heating generation costs, providing valuable insights for informed decision-making and planning within the context of the project or system under examination.

Table 4: Basis for the base case evaluation

Variable	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Location/region	Bayan Lepas, Kuantan, Johor Bahru	Johor Bahru	Johor Bahru	Johor Bahru
Discount rate (%)	10	5, 10, 15	10	10
Project Lifetime (y)	21	21	13, 15, 21	21
Type of collector	Arcon HT-SA	Arcon HT-SA	Arcon HT-SA	Arcon HT-A, Arcon HT-SA, Ritter XL Solar - Aqua Plasma

4. Results and discussions

The sensitivity analysis for economic analysis for all scenarios for the optimal solar thermal systems was evaluated to study the impact of the variation changes on economic performance as shown in Tables 4 to 7. As shown in Table 4, Scenario 1A has a higher yearly average solar radiance resulting higher in solar heat delivery (1,373 MWh/y) and also a higher annual final energy savings. This results in a lower cost for the hot water production based on LCOH and subsequently provides a higher NPV. It can be concluded that the location with higher solar radiance will affect the cost of hot water generation. Scenario 2 results shown in Table 5 indicated that the discount rate must not be less than 10 % in order to have a positive NPV value. A negative NPV of -222,742 at a 15 % discount rate for Scenario 2C indicates that the project being evaluated is not financially viable under the given assumptions and conditions.

Table 4: Results of sensitivity analysis based on variation in solar radiance for Scenario 1

Parameter	Unit	Scenario 1A	Scenario 1B	Scenario 1C
Location/region	-	Bayan Lepas	Kuantan	Pasir Gudang
Average solar radiance	kWh/m².y	1,971	1,804	1,822
Solar heat delivery	MWh/y	1,373	1,232	1,236
Installed aperture area	m²aperture	1227	1227	1227
Annual final energy savings	MYR/y	293,539	263,481	264,290
Simple payback	y	6.2	7.0	6.9
LCOH	MYR/MWh	55	61	61
NPV	MYR	57,3267	31,3305	320,301

Table 5: Results of sensitivity analysis based on variation in the discount rate for Scenario 2

Parameter	Unit	Scenario 2A	Scenario 2B	Scenario 2C
Discount Rate	%	5	10	15
Annual final energy savings	MYR/y	269,259	269,259	269,259
Simple payback	y	6.8	6.8	6.8
LCOH	MYR/MWh	62	59	58
NPV	MYR	1,418,525	363,272	-222,742

Table 6: Results of sensitivity analysis based on variation in project lifetime for Scenario 3

Parameter	Unit	Scenario 3A	Scenario 3B	Scenario 3C
Project lifetime	y	13	15	21
Annual final energy savings	MYR/y	269,258	269,258	269,258
Simple payback	y	6.8	6.8	6.8
LCOH	MYR/MWh	93	82	59
NPV	MYR	-1,034	117,480	363,272

Table 7: Results of sensitivity analysis based on variation in the collector system cost for Scenario 4

Parameter	Unit	Scenario 4A	Scenario 4B	Scenario 4C
Types of solar collectors	-	Arcon HT-SA	Arcon HT-A	Ritter XL Solar - Aqua Plasma
Collector system costs	USD/m².gross	358	336	485
Solar heat delivery	MWh/y	1,260	1,120	1,181
Installed gross area	m²gross	1,330	1,330	1,192
Annual final energy savings	MYR/y	269,258	252,459	239,304
Simple payback	y	6.79	6.79	9.59
LCOH	MYR/MWh	59	59	81
NPV	MYR	363,272	340,824	-316,740

Table 6 shows the results of the project lifetime based on several variations. The highest LCOH was obtained for Scenario 3A, however, it gave a negative NPV value. The system is identified as profitable if the project lifetime is more than 15 y and should not be less than 13 y. Another sensitivity analysis was conducted for Scenario 4 to determine the effect of several types of solar collectors based on different collector system costs. The result in Table 7 shows that both Arcon HT-SA and Arcon HT-A collectors provide a similar LCOH with a slightly different NPV value. Therefore, both Ritter XL Solar - Aqua Plasma in Scenario 4C have higher specific system costs resulting from a negative NPV and high LCOH. This is similar to the results by Asbdelhady 2021 where the author reported that the LCOE and NPV are very highly sensitive to the collector cost. The range of LCOH with positive NPV value in the study is between 55 to 82 MYR/MWh. The cost of hot water production using the integrated solar thermal systems is considered lower than the of natural gas which is 171 MYR/MWh. The trading selling price of hot water can be increased by 40 % of the LCOH compared to production by conventional method.

5. Conclusions

This paper represents a deeper exploration about a broader field of P2P thermal energy trading. It likely leverages the insights and knowledge gained from the initial case study while narrowing the focus to address the optimal trading price control strategy for larger solar thermal integrated systems. Through this extension, a more comprehensive understanding of the economic and technical intricacies associated with the optimal trading price was studied. The results show that the optimal integrated solar thermal system generated based on the simulation proves advantageous when considering specific conditions, including, a solar radiation level of at least 1,800 kWh/m².y, a discount rate must be lower than 10 %, the operational lifespan more than 15 y, and a system purchase price of 336 USD/m².gross. These parameters collectively highlight the favourable prospects of a larger integrated solar thermal system within this context, emphasizing its feasibility and economic viability. To summarize, the cost of producing hot water using integrated solar thermal systems is less than that of natural gas. The commercial selling price of hot water can be enhanced by 40 % of the LCOH as compared to a boiler powered by natural gas. The research showcases the benefits of adopting a peer-to-peer control strategy for determining the optimal trading price in larger solar thermal integrated systems. By addressing financial mechanisms and promoting direct interactions among stakeholders, the proposed optimization model holds great promise in transforming the energy landscape and fostering the widespread adoption of sustainable, locally produced energy sources. Future works stemming from this study could encompass the dynamic market conditions and validate the findings by scaling the proposed P2P control strategy to real-world, large-scale integrated solar thermal systems and assessing its practicality.

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