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Performance and Economic Analysis of Solar Tracking Systems for Renewable Energy-based Water Aeration

Kasama Sirisomboon*[1], Trannatee Papharawiwan*, and Patipan Charoensuk*

Abstract – *This study develops a solar-powered water treatment aerator using single-axis tracking to evaluate energy generation and dissolved oxygen (DO) levels. The performance of three solar panel configurations was compared: an LDR-based light-tracking system, an RTC-based time-tracking system, and a fixed-angle panel. Experimental Tests conducted under partial shading from 24 March to 2 April 2025 demonstrated that the RTC-based tracking system delivered the highest daily energy output of 1.119 kWh, corresponding to the highest DO level at the end of the day at 9.2 mg/L. In comparison, the LDR-based system produced 0.845 kWh/day, and the fixed panel produced 0.754 kWh/day. The RTC tracking system also offered a short payback period for tracking system of 1.29 years and a competitive LCC of 42,830 THB, while the LDR system was less economically viable, with a 5.20-year payback and higher LCC. Overall, the RTC system provides the best balance of cost and energy gain over the 20-year lifespan.*

Keywords – Dissolved oxygen, fife cycle cost, partial shading, solar panel, solar tracking system.

1. INTRODUCTION

In Thailand, the initial phase of implementing a water treatment system via aeration, solar panels were selected as the primary energy source due to their environmental sustainability, cost-effectiveness, and potential for long-term operational efficiency [1]-[3]. The energy output of solar panels is significantly influenced by the angle of solar incidence; optimal performance is achieved when the panels are oriented perpendicular to the sun's rays. However, with the sun's position changing throughout the day, fixed solar panels are unable to maintain this optimal orientation, resulting in reduced energy efficiency [4]-[6].

The research by Sneineh and Salah [6] studied a solar tracking system implemented using a PIC16F877A microcontroller that processes signals from four LDR photo-sensors mounted at a 45° tilt to detect sunlight intensity. The microcontroller controls DC motors through an L298 H-bridge driver to adjust the photovoltaic panel's position, ensuring it continuously faces the sun for optimal energy capture. Chin *et al.* [7] developed and validated a compact, wall-mountable single-axis solar tracker using dual LDR sensors and MATLAB™/Simulink™ modeling. The system improved PV efficiency by adjusting panel orientation in real time and reducing power use at night, with experimental results closely matching simulations despite minor environmental disturbances. Additionally, the comparative study for the power generation of the single-axis, dual-axis, and fixed solar tracking systems was investigate by Kishore *et al.,* [8]. The research found that the single-axis system generated, on average, 23.28% more electricity per year than the fixed system, while the dual-axis system yielded a 27.64% increase. However, the additional gain from the dual-axis system over the single-axis system was only 4.36%. Therefore, the single-axis tracking system was considered the most cost-effective and efficient solution.

Based on these insights, this study developed a single-axis solar tracking system capable of horizontal rotation to follow the sun's path throughout the day. Two tracking mechanisms were implemented: (1) a light-based tracker using LDR sensors to detect peak light intensity, and (2) a time-based tracker employing an RTC module to guide panel rotation based on a preprogrammed schedule.

The objective of this study is to evaluate the performance of these three solar panel configurations-light-tracking, time-tracking, and fixed-by monitoring and comparing electrical output parameters (current, voltage, and power), dissolved oxygen levels in the aeration system, life cycle cost and payback period for determining the most efficient and cost-effective configuration for practical implementation in sustainable water treatment applications.

2. EXPERIMENTAL SET-UP

2.1 System Configuration and Operation

The structure of the solar-powered water treatment system is illustrated in Figure 1. Solar radiation is converted into electricity via solar panels and directed through an inverter to power an air blower. The oxygen is then delivered into the water through air tubes. The tracking mechanism is powered by a 100-watt solar panel, with the rotating motion controlled by a shaft and bearing system.

The total system weight is 209.5 kilograms, comprising the following components: a structural frame weighing 115 kilograms; two 550 W monocrystalline solar panels weighing a total of 57 kilograms; one 100

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W monocrystalline solar panel weighing 12 kilograms; a 0.2 kW single-stage ring blower (maximum air flow rate 55 m^3/h) weighing 5 kilograms; an inverter weighing 5 kilograms; and a control unit with an integrated battery (used for storing energy from the 100 W panel and powering the control system), also weighing 5 kilograms.

Additionally, the system includes six UCP205-16 pillow block bearings with a combined weight of 7 kilograms, and a 1.5-meter solid round shaft weighing 3.5 kilograms. The floating platform comprises six 200-liter plastic tanks, providing a total displacement volume of 1.2 m^3. At a water temperature of 30°C, the density is approximately 997 kg/m^3, enabling the tanks to support up to 1,198.4 kilograms. Given the system's total weight of 209.5 kilograms, the resulting submersion is approximately 18% of the tank volume, corresponding to a depth of 0.10 m.

2.2 Solar Panel Movement and Sensor Configuration

Figure 2. shows the power control system consisting of (1) a 100 W monocrystalline solar panel, (2) a 12V 30A solar charge controller, (3) a 12V 12Ah battery, (4) an Arduino-compatible UNO R3A microcontroller, (5) an L298N motor driver module, and (6) a linear actuator rated at 1500 N with a 450 mm stroke. Solar energy captured by the panel is regulated by the charge controller and stored in the battery, which serves as the primary power source for the control system. The UNO R3A microcontroller executes programmed logic to control the actuator's movement based on sensor input or scheduled commands. Signals from the microcontroller are sent to the L298N driver, which supplies the necessary current to operate the actuator.

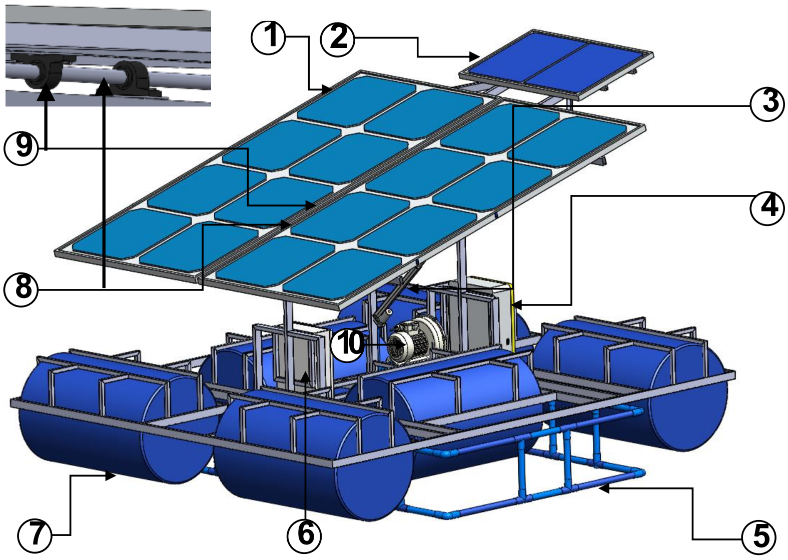


Fig. 1. Structural components of the solar-powered water treatment system including: (1) two 550 W solar panels, (2) a100 W monocrystalline solar panel, (3) a 1500 N linear actuator with 450 mm stroke, (4) a Sonner SN-2200 hybrid solar pump inverter, (5) one set of PVC and corrugated flexible piping (150 cm × 250 cm × 30 cm), (6) a control cabinet, (7) six 200-liter plastic tanks, (8) a solid round shaft (7/8 inch diameter, 150 cm length), (9) six UCP205-16 ball bearings, and (10) a 0.2 kW single-stage ring blower.

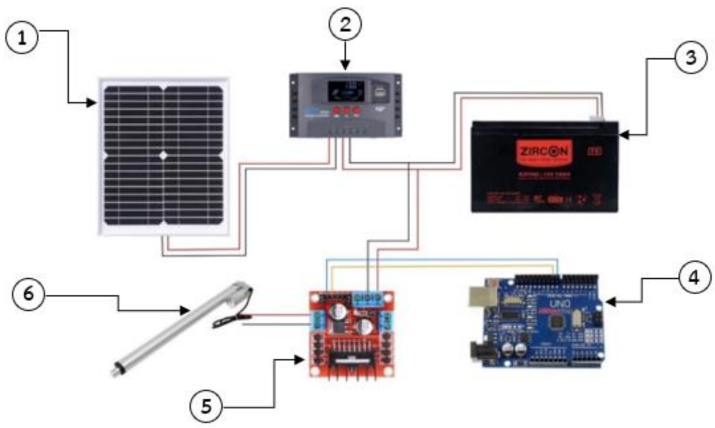


Fig. 2. Power control system.

The solar panel position control system, shown in Figure 3, including two control systems 1) a Light Dependent Resistor (LDR) sensor and 2) a Real-Time Clock (RTC) module. The location for actuator, pivot point and LDR for this solar tracking systems are shown in Figure 4.

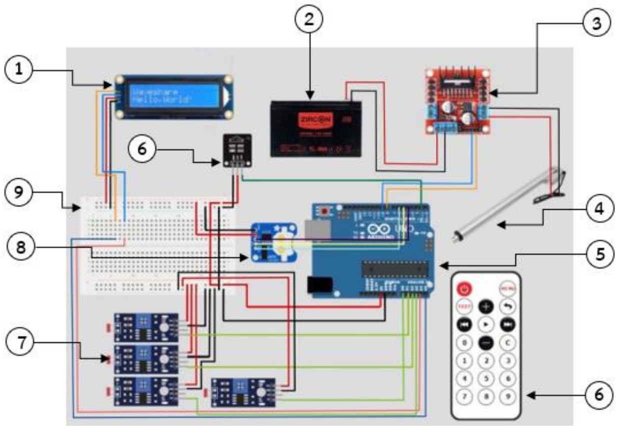
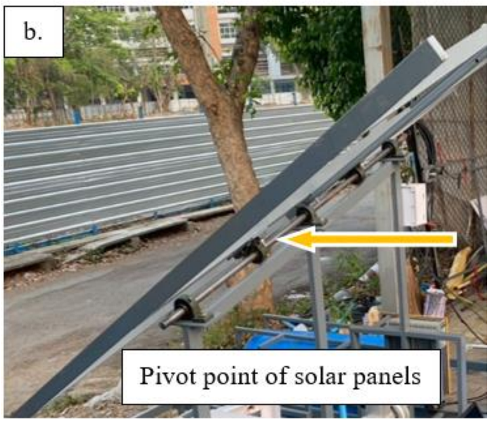


Fig. 3. Solar panel position control system including (1) one LCD1602 display module, (2) one 12V 12Ah battery, (3) one L298N motor driver module, (4) one linear actuator rated at 1500 N with a 450 mm stroke length, (5) one UNO R3A microcontroller board, (6) one infrared (IR) remote control, (7) four LDR (Light Dependent Resistor) sensor modules, (8) one Real-Time Clock (RTC) module, and (9) one protoboard for circuit assembly.



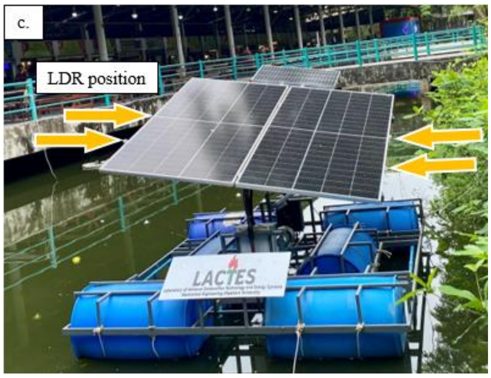


Fig. 4. Location of (a) actuator, (b) pivot point and c) LDR sensors for solar panels used in this study.

In the LDR-based control system, four LDR modules are strategically positioned—two facing east and two facing west—to detect differences in sunlight intensity. These sensors generate analogy signals that are processed by the UNO R3A microcontroller. When a significant imbalance in light intensity is detected between the east- and west-facing sensors, the microcontroller sends a signal to the L298N motor driver, which then activates the linear actuator. The actuator adjusts the solar panel's orientation toward the direction with greater light intensity. Once the panel is aligned such that the light intensity readings from both directions are nearly equal, the system enters a standby mode for a defined delay period (*e.g.,* five minutes) before initiating a new reading cycle. This feedback-driven mechanism allows the panel to continuously track the sun's position and maximize energy capture throughout the day.

In the RTC-based control system, the RTC module provides accurate timekeeping, allowing the UNO R3A microcontroller to execute solar tracking based on a pre-programmed schedule. The system begins moving the solar panel at 09:00 AM, initiating rotation from an eastward angle of 30°, and then adjusts the panel's position by 2.73° every 15 minutes. This continues until it reaches a westward angle of 330° by 2:30 PM, resulting in a total of 22 incremental movements covering a 60.06° arc. The RTC module ensures precise timing of each movement regardless of environmental light conditions. This time-based approach is particularly beneficial in environments where sunlight is intermittent or obstructed.

In the present study, the system was installed on a floating platform in a pond surrounded by trees, where partial shading frequently occurred. Under these conditions, the LDR-based tracking system—relying on light intensity differences detected by four sensors—was prone to misjudging the optimal direction due to shadows cast by nearby foliage. This often led to unnecessary or inaccurate panel movements, reducing tracking efficiency. In contrast, the RTC-based method proved more stable and effective, as it followed a fixed time-driven sequence rather than real-time light variability

2.3 Measurement Instruments

The dissolved oxygen (DO) meter used in this study is the YSI Model 51B, a widely adopted instrument in both research and industry. It operates based on the electrochemical (polarographic) principle, where oxygen interacts with the probe's electrode behind a semi-permeable membrane. The device displays the result in mg/L with an accuracy of ±0.1 mg/L for DO and ±0.3 ºC for temperature.

Electrical measurements were obtained using the TENMARS TM-28E TRUE RMS watt clamp meter, which measures parameters such as voltage, current, resistance, and power. Accuracy specifications are ±1.0% + 3 digits for DC voltage, ±1.5% + 5 digits for DC current, and ±5.0% + 5 digits for both DC and AC power measurements.

2.4 Initial Cost

The cost analysis for the three configurations, as shown in Table 1, indicates that the fixed system was the most economical at 39,750 THB. The RTC-based system totalled 45,880 THB due to the added cost of the RTC module, while the LDR-based system was slightly higher at 45,905 THB. These figures provided the basis for evaluating the economic feasibility of each setup.

Table 1. Summarizes the cost comparison among three configurations: RTC, LDR, and fixed-angle systems.

Item	RTC (THB)	LDR (THB)	Fixed (THB)
Solar panel, controlling and water treatment systems	31,900	31,900	31,900
Floating platform and structural support system	7,850	7,850	7,850
RTC module	6,130	-	-
LDR sensor	-	6,155	-
Total Cost	45,880	45,905	39,750

3. EXPERIMENTAL PROCEDURE

3.1 Solar Panel Voltage and Current Measurement

Voltage and current output from the solar panels were recorded using the clamp meter every 30 minutes from 09:00 AM to 05:00 PM for seven consecutive days (March 25 to April 1, 2025), yielding 17 readings per day. These data were used to assess the system's power generation efficiency under real sunlight conditions.

3.2 Dissolved Oxygen (DO) Measurement

Dissolved oxygen levels were monitored over a five-day period from March 25–30, 2025, for four-time intervals from 10:00 AM to 4:00 PM. According to water quality standards, DO values between 5–7 mg/L indicate good water quality, while values below 3 mg/L represent poor water quality. The DO values were measured at four sampling points (Figure 5) between 10:00 AM to 4:00 PM at two-hour intervals, totaling four readings per day. Measurements were conducted over a five-day period to evaluate water quality improvement due to aeration.

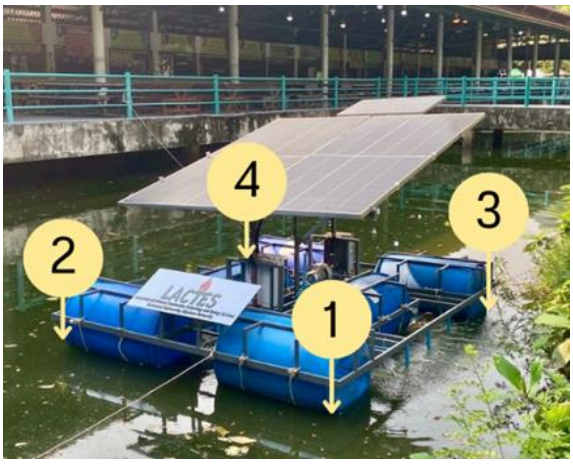


Fig. 5. Sampling locations for dissolved oxygen measurement.

4. RESULTS AND DISCUSSION

4.1 Solar Irradiance and Power Generation

Figure 6 shows the solar irradiance measured from March 25 to April 2, 2025, at Silpakorn University, Nakhon Pathom, Thailand. Between 24 March and 1 April, solar irradiance exhibited a typical diurnal pattern, rising steadily from around 450–550 W/m² at 09:00, reaching peak values near 850–990 W/m² between 11:30 and 13:00, and then gradually declining to 200–300 W/m² by 17:00. The highest midday irradiance was recorded on 28–29 March, exceeding 970 W/m², which indicates stable clear-sky conditions. In contrast, markedly lower values were observed on 31 March and 1 April, where peak irradiance reached only ~600–750 W/m². In contrast, 2 April experienced markedly reduced irradiance (200–650 W/m²) throughout the day, suggesting heavier cloud cover or unfavorable weather conditions, making it the day with the lowest solar energy potential in the period observed.

Figure 7 illustrates the performance of three solar panel configurations—RTC-based, LDR-based, and fixed (NORMAL)—in terms of (a) current, (b) voltage, and (c) power output measured throughout the day. As shown in Figure 7(a), the RTC configuration consistently produced higher current values, peaking around midday, with a maximum of 2.91 A recorded on March 25, 2025. The LDR and fixed systems generated lower and more fluctuating currents, indicating less effective sunlight tracking.

In Figure 7(b), voltage remained relatively stable across all configurations, ranging between 60–70 V, with occasional dips due to partial shading or load variations. The fixed system showed slightly more consistent voltage values, while RTC and LDR experienced minor fluctuations as the actuator adjusted the panel orientation.

Figure 7(c) presents power output trends, where the RTC system again outperformed the others, reaching a peak of 200 W at midday. The LDR system showed moderate performance, while the fixed panel delivered the lowest power generation across all measurement days. These results confirm the RTC-based system's superior ability to maximize solar energy capture through efficient sun-tracking, thereby enhancing electrical performance.

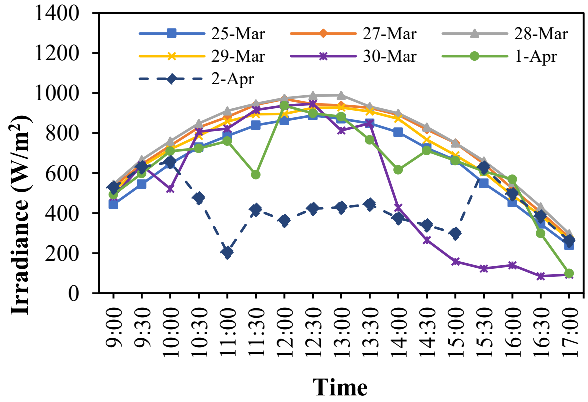
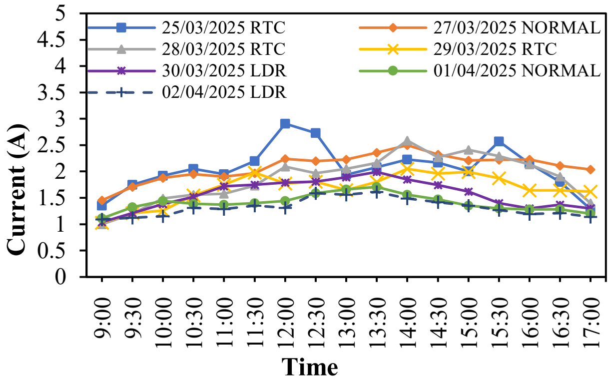
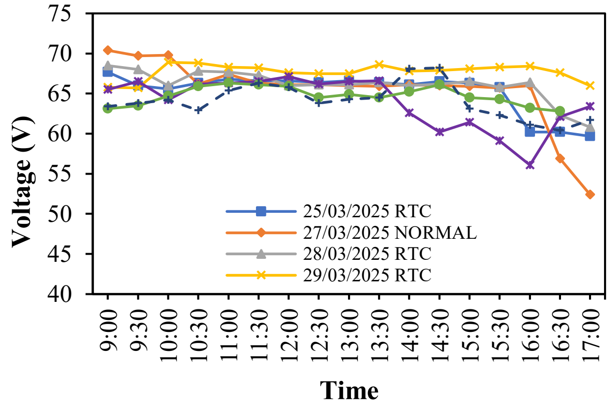


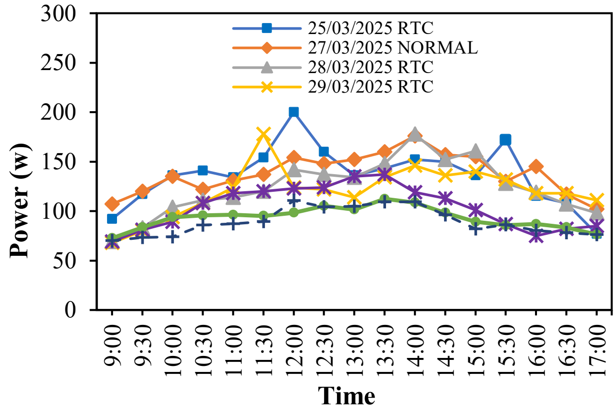
Fig. 6. Solar irradiance from March 25 to April 1, 2025 at Silpakorn University, Nakhon Pathom, Thailand.



(a)



(b)



(c)

Fig. 7. Comparison of current (a), voltage (b), and power output (c) of solar panel systems using RTC-based tracking, LDR-based tracking, and fixed configuration over a typical day.

4.2 Dissolved Oxygen (DO) Levels

Figure 8 illustrates the variation in dissolved oxygen (DO) levels measured at 10:00, 12:00, 14:00, and 16:00 across five different days, comparing systems with RTC-based tracking, LDR-based tracking, and a fixed (normal) solar panel configuration. The results demonstrate a consistent increase in DO levels throughout the day, with the highest values recorded at 16:00. The RTC-based tracking system shows the most significant increase, reaching nearly 9 mg/L, while the LDR and fixed systems exhibited lower DO values.

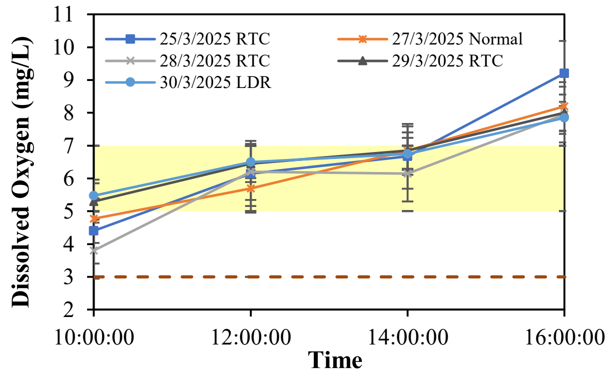


Fig. 8. Dissolved oxygen levels at different times of day under RTC, LDR, and fixed solar panel configurations.

The shaded yellow region represents the optimal DO range of 5–7 mg/L for good water quality, and the red dashed line marks the lower threshold for poor quality at 3 mg/L. From the experimental results, it was found that the RTC system significantly improved water quality, increasing the DO level by up to 109% (from 4.4 to 9.2 mg/L on 25 March and 3.8 to 8.0 mg/L on 28 March), while the LDR system achieved about a 51% increase from 5.3 to 8.0 mg/L) on 29 March. Notably, all systems stayed above the poor-quality threshold, with the RTC system consistently maintaining DO levels within or above the good quality zone at the end of the day. These results confirm that enhanced solar tracking performance positively correlates with improved water aeration efficiency.

4.3 Life Cycle Cost and Payback Period

In this study, a life-cycle cost (LCC) and the payback period analysis were carried out over a 20-year project lifespan using a discount rate of 5% (r = 0.05), taking into account the present value (PV) of the initial investment, periodic replacement costs for control modules, and projected income from energy generation. Considering (1) an expected annual price decrease of 5% for electronic components, the replacement costs for the RTC and LDR control modules—scheduled every five years—were adjusted accordingly, and (2) an anticipated annual electricity cost increase of 4%, derived from a 10-year historical average, was also incorporated into the calculations. For the cost savings (or revenue from power generation) analysis, the data from 2 April and 30 March were excluded due to their strong deviation from the normal pattern, with markedly reduced irradiance levels (200–650 W/m²) throughout the day. As a result, the present value of total replacement costs over the project duration was calculated at 13,622 THB for the RTC system and 13,678 THB for the LDR system as shown in Table 2.

Table 2. Comparison of payback period and life-cycle cost (LCC) for fixed, LDR, and RTC solar panel configurations.

Item	RTC (THB)	LDR (THB)	Fixed (THB)
Tracking system cost at the 1st year	6,130	6,155	-
PV cost for tracking system replacement	13,622	13,678	-
PV of total cost including sensor replacement	53,372	53,428	39,750
Daily energy output (kWh/day)	1.119	0.845	0.754
Annual income	1,695	1,280	1,142
Annual saving from tracking system installation	553	138	0
PV of saving from tracking system installation	5,171	1,718	0
Payback period for tracking system (year)	1.29	5.20	-
LCC	42,839	50,799	39,750

PV = present value

The RTC system incurred an initial tracking system cost of 6,130 THB and produced an average of 1.119 kWh/day, which is 0.365 kWh/day more than the fixed system. At an electricity rate of 4.15 THB/kWh [9], this corresponds to an additional annual income of approximately 553 THB, resulting in a payback period of around 1.29 years. The LDR system required a similar upfront cost of 6,155 THB but yielded only 0.091 kWh/day more than the fixed system, generating an annual savings of 138 THB and leading to a longer payback period of approximately 5.20 years, making it less economically attractive.

The fixed configuration exhibited the lowest LCC at approximately 39,750 THB. The RTC system followed at 42,830 THB, offering a favorable balance between cost and energy gain, while the LDR system had the highest LCC at 50,799 THB. These findings highlight the RTC system as the more cost-effective tracking solution despite its higher upfront and maintenance costs.

Finally, to enhance the reliability of the economic analysis, the authors may extend the testing period beyond the initial short-term observations for more comprehensive data across varying weather conditions, seasonal changes, and system performance fluctuations. This extended dataset would improve the accuracy of energy yield estimations and operational stability, thereby providing a more realistic assessment of cost savings, payback period and return on investment.

5. CONCLUSION

Based on the experimental results conducted under the partial shading environment, the Real-Time Clock (RTC)-based solar tracking system consistently demonstrated superior performance in both power generation and water quality improvement. It achieved the highest current and power outputs, peaking at 2.91 A and 200 W, with relatively stable voltage levels. This enhanced energy production directly contributed to improved aeration, as evidenced by dissolved oxygen (DO) levels rising throughout the day-reaching up to 9.2 mg/L by 4:00 PM. In contrast, the Light Dependent Resistor (LDR)-based tracking and fixed-angle systems produced lower power outputs and correspondingly reduced DO levels, reinforcing the link between energy capture and water treatment effectiveness. The RTC tracking system proved the most cost-effective, offering a short payback period for tracking system of 1.29 years and a competitive LCC of 42,830 THB, while the LDR system was less economically viable with a 5.20-year payback and higher LCC. Overall, the RTC system provides the best balance of cost and energy gain over the 20-year lifespan.

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