Analysis of energy efficiency and financial feasibility of using solar panels technology for paddle aerators in shrimp ponds

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Abstract. The use of solar panel technology for paddle aerators represents a new innovation being developed in the field of shrimp farming. The objective of this study was to analyze the level of energy efficiency and the financial feasibility of shrimp farming enterprises that use solar panel technology. The research method employed is a causal ex-post facto design with purposive sampling for data collection. The results show that ponds using solar panel technology have better harvest productivity, although this requires a slightly higher investment. However, the high investment cost does not affect the amount of operational capital needed. This results in a significantly improved financial feasibility of enterprises using solar panels. The use of solar panel technology also significantly impacts energy efficiency, with an 89% efficiency and an 11% risk of energy loss. These results correlate with the progressive performance of shrimp farming, as seen in growth trends and survival rates. The conclusion of this study indicates that the use of solar panel technology can significantly enhance electricity energy efficiency through the conversion to renewable energy systems, positively affecting the financial feasibility of shrimp farming enterprises in terms of both harvest productivity and economic profitability.

Key Words: growth, harvest, mechanical, shrimp, technology.

Introduction. Shrimp farming is an agribusiness activity widely developed in tropical aquatic regions. In Indonesia, shrimp farming has been practiced since the mid-1980s with the *Penaeus monodon* species (Hukom et al 2020). In 2001, *Penaeus vannamei* species began to be developed as a new commodity considered to have more advantages (Larson et al 2021). Shrimp farming in Indonesian waters has been developed using various cultivation patterns, including traditional, semi-intensive, intensive, and super-intensive systems (Ariadi et al 2023c).

One crucial tool in shrimp farming is the paddle aerator. Paddle aerators are aquaculture engineering devices with multiple functions in shrimp pond ecosystems (Ariadi et al 2023b). The primary function of a paddle aerator is to assist in supplying dissolved oxygen in the pond (Ramesh et al 2024). Additionally, paddle aerators help create currents, homogenize water temperature, and collect waste at the pond's bottom (Ariadi et al 2020). *P. vannamei* shrimp cannot withstand hypoxic conditions, thus requiring intensive use of paddle aerators for oxygen supply (Nguyen et al 2022).

Electricity usage for paddle aerators is a significant contributor to the production costs in shrimp farming cycles (Ramesh et al 2024). Energy consumption for oxygen production by paddle aerators accounts for 23% of operational costs (Moulick et al 2022). Therefore, alternative technologies are needed to reduce the impact of electricity waste on paddle aerators. One approach is the use of solar panels (Patel et al 2024). Solar panels have an energy production capacity of around 404 kWh m^{-3}, depending on the panel capacity used (Cannone et al 2024). Solar panel technology is also considered more efficient and environmentally friendly for integrated aquaculture activities (Ikram et al 2022). The use of solar cells also impacts the reduction of excess electricity use in ponds (Cannone et al 2024; Patel et al 2024).

However, there has been little information showing the correlation between renewable energy use and shrimp production history and financial profitability. Therefore, the aim of this study is to analyze the energy efficiency and financial feasibility of *P. vannamei* shrimp farming in ponds using solar panel technology. This research is expected to provide empirical evidence on the efficiency of energy use in ponds through the use of solar panel technology.

Material and Method

Description of the study sites. This study was conducted at an intensive shrimp farming pond in Probolinggo, Indonesia (6°52′04″S 109°37′27″E/6.8677°S 109.6243°E). Data sampling was carried out from June to August 2024. The research method used was a causal *ex-post facto* design with purposive sampling.

Research procedures. The ponds used in this study are HDPE ponds covering 1500 m^2 each, with a total of 20 ponds: 10 ponds using solar panel technology and 10 conventional ponds. The solar panels have a capacity of 150 megawatts. The stocking density of shrimp is 100 individuals m^{-2} across the 20 ponds. The shrimp farming cycle lasts for 90-95 days. During the study period, shrimp growth data was collected every ten days. Shrimps were fed an artificial pelleted feed with a predetermined feeding rate. To control the level of feed consumption, observations were carried out on the feeding tray every 09.00, 13.00, 16.00, and 20.00, routinely.

The production parameters analyzed include the total shrimp harvest during the farming period. At harvest, the survival rate (SR) was calculated using the formula $SR=N_t/N_0 \times 100$, where N_t is the number of shrimp at the end of the study, and N_0 is the number of shrimp at the start of the study. Subsequently, harvest productivity was calculated based on the quantity of harvest per ha. Shrimp growth rate measurements were carried out every seven days.

Financial feasibility analysis. The financial feasibility of the enterprise was assessed based on indicators such as profit margin, benefit cost ratio (B/C ratio), break-even point (BEP), and business profitability. These values were derived from data on investment costs, fixed capital, working capital, selling price, acceptance costs, production costs, technical lifespan, and production volume. Additionally, the financial feasibility analysis included net present value (NPV), internal rate of return (IRR), B/C ratio, profitability index (PI), and Revenue/Cost Ratio (R/C Ratio), following the formulas proposed by Diatin et al (2021). Financial feasibility analysis is a technique used to determine the sustainability of an enterprise based on anticipated future profits. Through this analysis, we can estimate the potential sustainability of the business.

Profit (P) is the result of revenue from production (TR) minus the cost of production (TC) of a business conducted at a constant level (Diatin et al 2021).

$$P = TR - TC$$

The R/C ratio is the conversion value of total revenue (TR) divided by the cost of production (TC) within the operational system (Diatin et al 2021).

$$R/C=TR/TC$$

Net present value is a reference value for project feasibility based on the difference between gross revenue and expenditure costs, with the discount factor in the context of investment (Diatin et al 2021).

$$NPV = \sum_{i=1}^{n} \left(\frac{(Bt - Ct)}{(1+i)t} Ko \right)$$

Where: Bt - project profit in t year; Ct - project costs in t year; t - project age; i - interest rate; Ko - financial standards.

The IRR is a technique for assessing the internal rate of return based on the Net Present Value and the current interest rate (Diatin et al 2021). The formula for IRR is as follows:

$$\mathrm{IRR} = i' + \frac{NPV}{NPV' - NPV"}(i" - i')$$

Where: i' - discount rate that produces positive NPV; i'' - discount rate that produces negative NPV.

The B/C ratio is a measure of the percentage of NPV compared to investment expenditure during the business period (Diatin et al 2021).

$$\text{B/C Ratio} = \frac{\sum PV\ Net\ cash}{\sum PV\ Investment} \times 100\%$$

To determine the energy efficiency produced from using solar panel technology in the ponds, the production level and energy efficiency are calculated based on the following formula (Dizaj 2024):

$$\mathrm{PCE} = \frac{\boldsymbol{Voc.Jsc.FF}}{\boldsymbol{Pin}}$$

$$\mathrm{FF} = \frac{\boldsymbol{Pmax}}{\boldsymbol{Voc.Jsc}} \times 100\%$$

$$\mathrm{E} = (\mathrm{PCE}-\mathrm{FF})*100\%$$

Where: Voc - open circuit voltage; Jsc - short circuit current density; FF - fill factor; Pin - incident power; PCE – power conversion efficiency; E - efficiency; Pmax – maximum power output of the solar cell.

Data analysis. Field sample data were tabulated based on time and research variables, then descriptive analysis was carried out.

Results and Discussion. The production data of shrimp reared in ponds using solar panel technology is presented in Table 1. A high survival rate impacts the total shrimp biomass, leading to an increase of shrimp harvest productivity (Alam et al 2021).

Table 1

Production performance comparison of shrimp culture using solar panel technology and conventional technology

Indicators	*Solar panel technology*	*Conventional technology*
Rearing duration (day)	90	120
Total cycle (cycle year^{-1})	2	2
Stocking density (shrimp m^{-2})	100	100
Survival rate (%)	93.0±1.4	91.12±2.0
Total yield (kg)	4211.9±3.2	3921.4±2.8
Productivity (kg m^{-2})	633.0±1.2	572.0±1.3

The length of the shrimp farming cycle affects the performance level of the harvested production. The study results confirm that the use of solar panel technology has a positive impact on survival rate (93%) and total productivity (4211 kg) compared to conventional farming. The use of solar panel technology provides energy efficiency and ecological benefits for the pond ecosystem (Malik et al 2011; Erdemir & Dincer 2024).

The concept of using solar panel technology in ponds is highly recommended for the future development of the aquaculture industry (Erdemir & Dincer 2024).

Financial feasibility analysis. The components of investment required for intensive shrimp farming using solar panel technology compared to conventional systems are described in Table 2. The operational costs for constructing pipe channels and installing pumps are the most expensive investment components. The main difference is that in ponds using solar panel technology, solar cells are employed as a source of electrical energy. This use of solar panel technology is aimed at developing renewable energy in the field of aquaculture (Gorjian et al 2022).

Table 2

Shrimp aquaculture investment using solar panel and conventional technology

Indicators	*Solar panel technology (USD)*	*Conventional technology (USD)*
Pond	142.24	142.24
Pump	275.25	275.25
Pipe canals	619.21	619.21
Equipment	86.71	36.71
Paddle aerator	104.71	104.71
Total investment	1228.12	1178.12

The operational cost components used in shrimp farming activities are presented in Table 3. The percentage of fixed costs ranges from 24.48 to 30.07%, while variable costs range from 69.93 to 75.82%, operational costs being higher than fixed costs. The largest portion of production costs in shrimp farming is allocated to feed, accounting for 59.69 to 65.39%. Feed is the largest production factor that must be considered in intensive shrimp farming (Madusari et al 2022). Comparatively, the total cost for conventional farming is slightly higher (1408.8 USD) than for ponds using solar panel technology (1307.90 USD).

Table 3

Operational cost of shrimp culture using solar panel and conventional technology

Indicators		*Solar panel technology*		*Conventional technology*	
		USD	*%*	*USD*	*%*
Fixed cost	Land rent	19.35	1.48%	19.35	1.37%
	Labor	293.45	22.44%	287.55	20.41%
	Electricity	-	-	109.33	7.76%
	Depreciation	7.40	0.57%	7.42	0.53%
Total fixed cost		320.20	24.48%	423.65	30.07%
Variable cost	Fry	85.00	6.50%	85.00	6.03%
	Feed	855.22	65.39%	840.85	59.69%
	Probiotic	32.25	2.47%	40.15	2.85%
	Molasses	15.23	1.16%	19.15	1.36%
Total variable cost		987.70	75.52%	985.15	69.93%
Total cost		1307.90	100.00%	1408.80	100.00%

The shrimp sales results at harvest are presented in Table 4. The revenue from ponds using solar panel technology is higher (14741.65 USD) compared to conventional ponds (13724.9 USD). The higher total revenue in the solar panel technology ponds is due to a greater harvest biomass. The increased biomass is influenced by a good SR (Estrada-Perez et al 2016).

Table 4

The annual profit for shrimp culture using solar panel and conventional technology

Items	*Solar panel technology*	*Conventional technology*
Yield shrimp (kg)	4211.90	3921.40
Price of shrimp (USD)	3.50	3.50
Total revenue (USD)	14741.65	13724.90

The results of the shrimp farming business feasibility analysis are presented in Table 5. The analysis indicates that both conventional shrimp farming systems and those using solar panel technology are categorized as feasible and profitable for development. A profitable feasibility value suggests a good opportunity for long-term business success (Wafi & Ariadi 2024).

Table 5 shows that the ponds using solar panel technology have a profit level of 14741.65 USD, associated with the R/C ratio, NPV, and IRR. The high profit value is influenced by the shrimp's weight and the amount of biomass harvested. Solar panel technology ponds are considered very suitable for productive and sustainable shrimp farming models. Additionally, farming patterns and management practices will significantly affect harvest productivity (Ariadi et al 2021). High business profitability will impact the feasibility parameters of the R/C ratio, NPV, B/C ratio, and IRR.

Table 5

Financial feasibility analysis of shrimp culture using solar panel and conventional technology

Items	*Solar panel technology*	*Conventional technology*
Total investment (USD$)	1178.12	1178.12
Fixed cost (USD)	320.20	423.65
Variable cost (USD)	987.70	985.15
Total cost (USD)	1307.90	1408.80
Total revenue (USD)	14741.65	13724.90
Profit (USD)	13753.95	12739.75
Average cost/kg (USD)	3.05	3.01
R/C ratio	1.39	1.25
NPV (USD)	985.17	962.39
BCR	11.31	11.01
IRR (%)	313.18	284.17

Note: R/C ratio – revenue/cost ratio; NPV – net present value; BCR – benefit cost ratio; IRR – internal rate of return.

Energy efficiency using solar panel in shrimp ponds. The use of solar panel technology can provide energy support of 281 kWh, which is greater compared to the electrical support of 117 kWh. This means that the use of solar panel technology can achieve an energy efficiency of 89% and reduce energy loss in the operational system of paddle aerators to just 11% (Table 6). Additionally, the use of solar panel technology impacts the operational costs of paddle aerators, reducing them to 9.1 USD, which is 5.6 USD less compared to conventional farming systems.

The statistics on energy efficiency and lower operational costs for paddle aerators using solar panel technology indicate that the use of renewable energy in aquaculture is highly recommended. Paddle aerators are essential tools in shrimp farming that require ongoing technological innovation (Ariadi et al 2023b). Renewable energy represents a green concept that is worth exploring in the field of aquaculture.

Table 6

Production and efficiency of energy on shrimp culture using solar panel and conventional technology

Items	*Solar panel technology*	*Conventional technology*
Energy support (kW/hour)	281	117
Efficient energy (%)	89	43
Energy lost (%)	11	57
Cost loss estimate (USD/day)	9.1	14.7

***Shrimp growth rate*.** The comparison of shrimp growth rates in conventional ponds and those using solar panel technology is described in Figure 1. Overall, the shrimp growth rates in both types of ponds exhibit similar trends. The difference lies in the biomass values, where the ponds using solar panel technology (1.06-18.06 g) show better results compared to conventional ponds (0.06-16.51 g). Good environmental conditions and proper management practices contribute to optimal growth of the organisms (Linayati et al 2024).

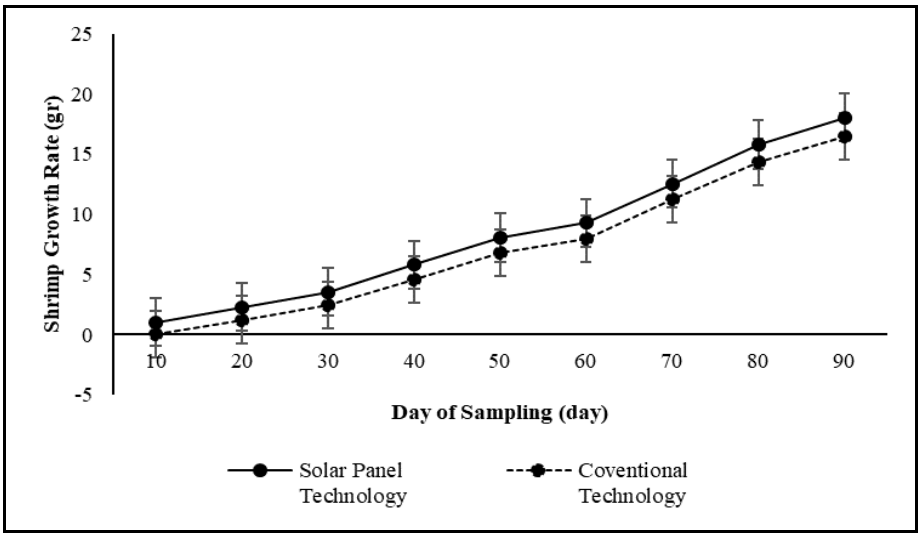

Figure 1. Fish growth rate of shrimp on solar panel pond and conventional pond.

The shrimp biomass production in ponds using solar panel technology is higher compared to conventional ponds. The high shrimp biomass is influenced by the SR and the management practices of shrimp farming (Wafi & Ariadi 2024). Proper farming methods, such as the number of seedings, feed provision, and application of relevant technologies, will impact the productivity of harvested shrimp biomass (Ariadi et al 2023a; Madusari et al 2024). Intensive shrimp farming with innovative technology applications will support farming performance (Pinto et al 2020; AftabUddin et al 2020).

In terms of investment costs, the use of solar panel technology is considered relatively inexpensive to develop, adding only 50 USD per 2 HP (horse power). The use of solar panel technology can provide long-term benefits for the development of shrimp farming production cycles (Tien et al 2019). Additionally, the capital analysis for shrimp farming with solar panel energy is generally cheaper. The affordability and simplicity of the components make shrimp farming a preferred choice for many farmers (Ariadi et al 2023b).

The profit margins in solar panel technology ponds are seen as more advantageous compared to conventional ponds. The revenue from solar panel technology ponds is also higher compared to the study by Muqsith et al (2021), which reported 6860 USD. The profitable revenue level impacts the financial feasibility of the business, making it a viable and profitable option for development (Wafi & Ariadi 2024).

The use of solar panel technology impacts energy efficiency and reduces energy loss in the operational system of paddle aerators (Phu & Nguyen 2022). Solar panel technology, acting as an energy substitute, affects the effectiveness of the equipment (Yaghoubi et al 2024). This system influences energy consumption, leading to savings by paddle aerators (Tien et al 2019). Paddle aerators operating 24 hours a day are particularly prone to energy loss (Ramesh et al 2024). Effective use of solar panel technology in paddle aerators suggests potential for future innovations in this equipment.

Regarding shrimp growth, ponds using solar panel technology show progressive growth rates. This indicates a correlation between energy efficiency and the performance of the reared shrimp. Shrimp are sensitive to changes in environmental conditions (Xu et al 2022; Lao et al 2024). Shrimp with good growth performance reflect a very good and ideal farming ecosystem (Ariadi et al 2023a; de Almeida et al 2024).

Overall, the use of solar panel technology in paddle aerators is considered to have many positive impacts. It enhances energy consumption efficiency, reduces operational costs, stabilizes pond ecosystems, and improves shrimp production performance. The use of renewable energy concepts in shrimp farming is currently one of the most developed areas (Tien et al 2019; Phu & Nguyen 2022). This is part of the adaptive implementation of precision technology in aquaculture activities (Zhang et al 2022; Wu et al 2022; Mangano et al 2023).

Conclusions. This study concludes that the use of solar panel technology can significantly enhance electrical energy efficiency through the conversion to renewable energy systems. The application of solar panel technology in paddle aerators can also mitigate potential energy loss, which impacts the efficiency and technical lifespan of the paddle aerators. The efficiency of using solar panel technology correlates positively with the financial viability of shrimp farming operations, showing much better results compared to conventional shrimp farming systems.

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Conflict of Interest. The authors declare that there is no conflict of interest.

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