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Research Article

# Techno-Economic Analysis of the Integration of Floating Photovoltaic (FPV) Solar Power Plant and Pumped Hydro Storage (PHS) Hydroelectric Power Plant at Matenggeng

**Muhammad Nuri[1*]; Sonia Putri[1]; Taufiq Hidayat[1]; Winda Puspadimiati[1]; Bambang Priyono[1]**
[1] Universitas Indonesia, Fakultas Teknik, Teknik Sistem Energi
***Corresponding author:** ***Muhammad Nuri, Muhammad,zaki23@ui.ac.id***

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**Abstract:** The increasing energy demand in Indonesia caused by population growth and industrialization, has prompted the government to accelerate the transition to renewable energy. The national energy mix target sets 23% contribution of renewable energy by 2025. Solar photovoltaic is considered as one of the potential renewable energy, although it has a fluctuating production nature. The integration of floating solar photovoltaic (FPV) and pumped hydro storage (PHS) is a solution which able to improve the stability of electricity supply. PHS stores excess energy from FPV by pumping water to an upper reservoir and uses it for electricity generation when needed, such as at night or during cloudy weather. This study aims to analyse the technical and economical aspect of the integration of FPV and hydro electric generator with PHS in Matenggeng, West Java. This study evaluates the potential for operational cost savings, increased electricity supply reliability, and reduced carbon emissions compared to fossil fuel power plants. The results show that the integration of FPV and hydro electric generator with PHS in Matenggeng able to reduce the LCOE to $0,08431/kWh, which is lower than the scenario without the integration of PLTS and conventional systems. In addition, this system contributes to reducing carbon emissions by up to 4% per year. Thus, this integration offers a sustainable solution that supports the clean energy transition in Indonesia.

**Keywords:** FPV, PHS, LCOE, Carbon Emission

## 1. Introduction

Energy demand in Indonesia continues to increase significantly, along with rapid population growth and industrialization. The Indonesian government, through the National Energy General Plan (RUEN), is committed to increasing the contribution of renewable energy in the national energy mix to 23% by 2025 and 31% by 2050 [2]. One of the strategies to achieve this target is to maximize the potential of renewable energy resources such as Solar Power Plants (PLTS) and Hydroelectric Power Plants (PLTA) [1].

PLTS has great potential in Indonesia, especially because the country is located in a tropical region with high solar radiation throughout the year. According to a Geographic Information System (GIS) study conducted by the Institute for Essential Services Reform (IESR), the technical potential for solar energy capacity in Indonesia ranges from 3,396 GWp to 19,835 GWp, depending on the land use scenario applied. This potential is equivalent to a power generation capacity of 4,705 TWh to 26,791 TWh per year. However, PLTS has a drawback, which is its intermittent or unstable production, depending on weather conditions and time of day [2]. As of 2024, the installed solar capacity in Indonesia is still low, at 717.7 MW, with the largest

contribution coming from on-grid PLN installations [15]. One major obstacle in developing PLTS is the limited availability of open land suitable for installing solar panels, as well as the high cost of land [13]. This challenge also includes the complexity of permits and land acquisition. Floating Photovoltaic (FPV) systems have been developed as a solution to overcome land limitations [7].

One potential solution to address the fluctuation in PLTS production is integration with Pumped Hydro Storage (PHS) technology. PHS, or energy storage using hydroelectric power, has been in use for more than a hundred years. This technology has become the largest grid energy storage system in the world, contributing about 95% of the total global electricity storage capacity. The basic principle of PHS involves pumping large amounts of water to a higher reservoir when excess electricity is available. When electricity demand is high, water is released to a lower reservoir through turbines to generate electricity. This system has a round trip efficiency of about 70-80%, depending on the design and age of the facility. PHS is used to address the variation in output from intermittent renewable energy sources, such as PLTS. PHS technology helps manage the instability of solar energy production by storing excess energy when production is high and releasing it when production is low or demand increases [3]. This technology enables the optimization of renewable energy utilization by minimizing reliance on fossil-fuel-based power plants [2,3].

The PHS capacity in Indonesia, both existing and planned, is 3.74 GW based on the PLN 2021-2030 Power Supply Business Plan (RUPTL) [4]. Some of the PHS projects in this development plan include: the Cisokan PHS project (1000 MW) in West Java, the Matenggeng PHS project (943 MW) in West Java, the Grindulu PHS project (1000 MW) in East Java, and the development of the 4 X 250 MW PHES system in Sumatra, which is expected to be connected to the power grid between 2029-2032 [5]. The Matenggeng Hydroelectric Power Plant is the second hydroelectric plant after the Upper Cisokan PHS that will use the PHS system, where there will be two reservoirs: the upper and lower reservoirs. The Matenggeng location in West Java and Central Java was chosen as a case study in this research because of its large energy potential from both water and solar sources [6]. By utilizing these two renewable energy sources, operational cost savings can be achieved while reducing carbon emissions from the use of fossil energy in the area. Previous research has shown that the integration of PHS and FPV can achieve an efficiency of cUSD 0.033/kWh [7].

The objective of this study is to conduct a technical and economic analysis of the integration of FPV and PHS Hydroelectric Power Plants at Matenggeng. From a technical perspective, this study will examine how the integration of these two systems can optimize a sustainable energy supply throughout the day, as well as how effectively this system can address fluctuations in energy supply. From an economic perspective, this study will analyze the initial investment costs, operational costs, and potential savings generated by the integration of these technologies compared to conventional power plants. The results of this study are expected to serve as a reference for further development in utilizing renewable energy in Indonesia and supporting the transition to clean energy.

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## 2. Materials and methods

### 2.1. Application of Technology

The combination of PHS Hydroelectric Power Plant (PLTA PHS) technology and FPV (Floating Photovoltaic) will address challenges related to the availability of additional land, reduce water evaporation, and enhance efficiency through natural cooling [7]. Here are some reasons for implementing FPV and PLTA PHS:

a. Energy Efficiency
   FPV can increase the efficiency of PV modules by up to 12% compared to land-based systems (OPVS). The water beneath the panels serves as a natural coolant, lowering the panel temperature and boosting energy output.
b. Integration with Pumped Hydro Storage (PLTA PHS)
   In conditions of electricity oversupply from coal-fired power plants, the excess energy is used to pump water from the lower reservoir (lower dam) to the upper reservoir (upper dam). During peak load, the water is released back through turbines to generate electricity.
c. Cost Savings
   The integration of FPV with PLTA PHS is more cost-effective compared to conventional power plants during peak load periods. This is due to the use of excess energy from coal-fired power plants during off-peak times, which is then utilized for the water pumping process.
d. Sustainability
   FPV supports the development of an environmentally friendly and sustainable PLTA PHS. This technology is expected to reduce dependence on fossil fuel-based power plants during peak load times.

China is one of the largest adopters of PHS technology. Several PHS systems in China have higher efficiencies, reaching around 80-85%. This is made possible by China's hydro resources and highly efficient energy management infrastructure [8].

A PLTA PHS system like the one at Matenggeng typically has an efficiency of around 75-80%, similar to other projects in Indonesia, such as the Upper Cisokan Hydroelectric Power Plant. The total losses in the PHS system include factors like transformer losses (3%), motor losses (3%), pump losses (6%), pipeline losses (5%), turbine losses (6%), and generator losses (2%), with total system losses reaching 25% [9].

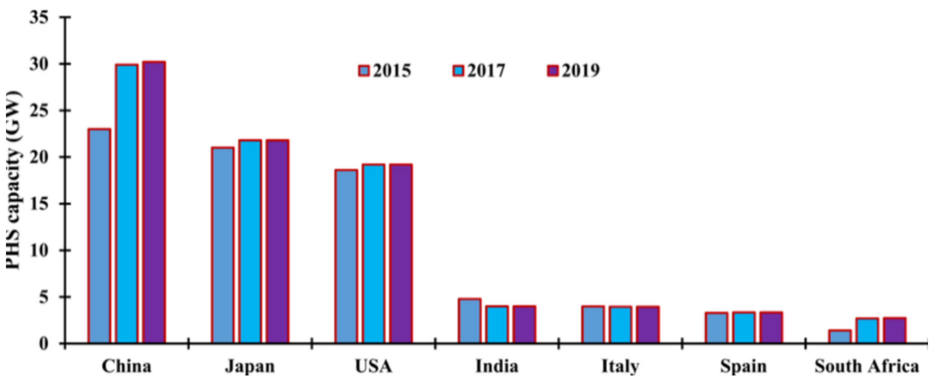


**Figure 1.** Comparison of PHS Capacity (GW) Among Countries [8]

### 2.2. Matenggeng Pumped Storage Hydroelectric Power Plant (PLTA PHS) Project

The Matenggeng Pumped Storage Hydroelectric Power Plant (MPSPP) is located on the border between West Java and Central Java. The electricity generated will be connected to the 500 kV transmission network in the southern corridor, utilizing electricity from coal-fired power plants during low load periods (off-peak). This energy will then be used to meet electricity demands during peak load times [14].

Matenggeng Pumped Storage Hydroelectric Power Plant is designed as a pumped storage power plant operating in a cyclic manner. During off-peak periods, MPSPP uses electricity from the grid to pump water from the lower dam to the upper dam. When electricity demand is high (peak load), electrical energy is generated by releasing water from the upper dam to the lower dam through turbines, which will then meet electricity demand during peak periods. The generated electricity is then transmitted through the 500 kV transmission network with a double circuit, connecting this system to the existing transmission network.

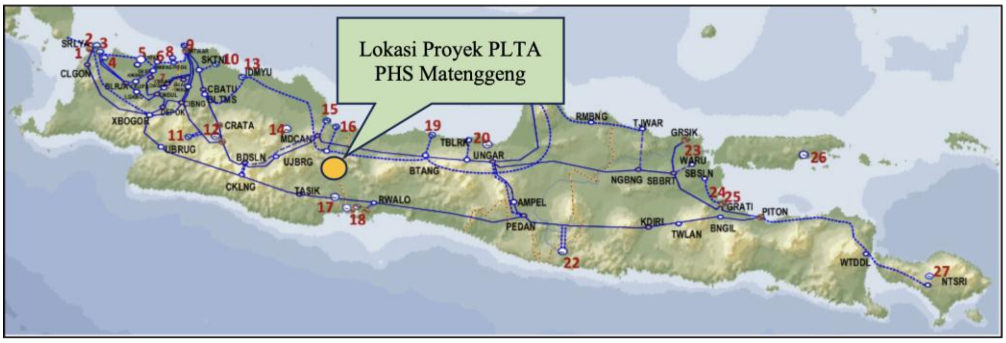


**Figure 2.** Location of the Matenggeng Pumped Storage Hydroelectric Power Plant Project

### 2.3. Research Flow Diagram

The techno-economic analysis of the integration of Floating Photovoltaic (FPV) and Pumped Storage Hydroelectric Power Plants (PLTA PHS) at Matenggeng involves several stages, including literature study, sensitivity analysis of demand load and FPV area, technical design of PLTA PHS and FPV, power plant capacity & system operation, cost estimation considering investment units and incentives, and financial feasibility analysis. The research flow diagram can be seen in Figure 1 below.

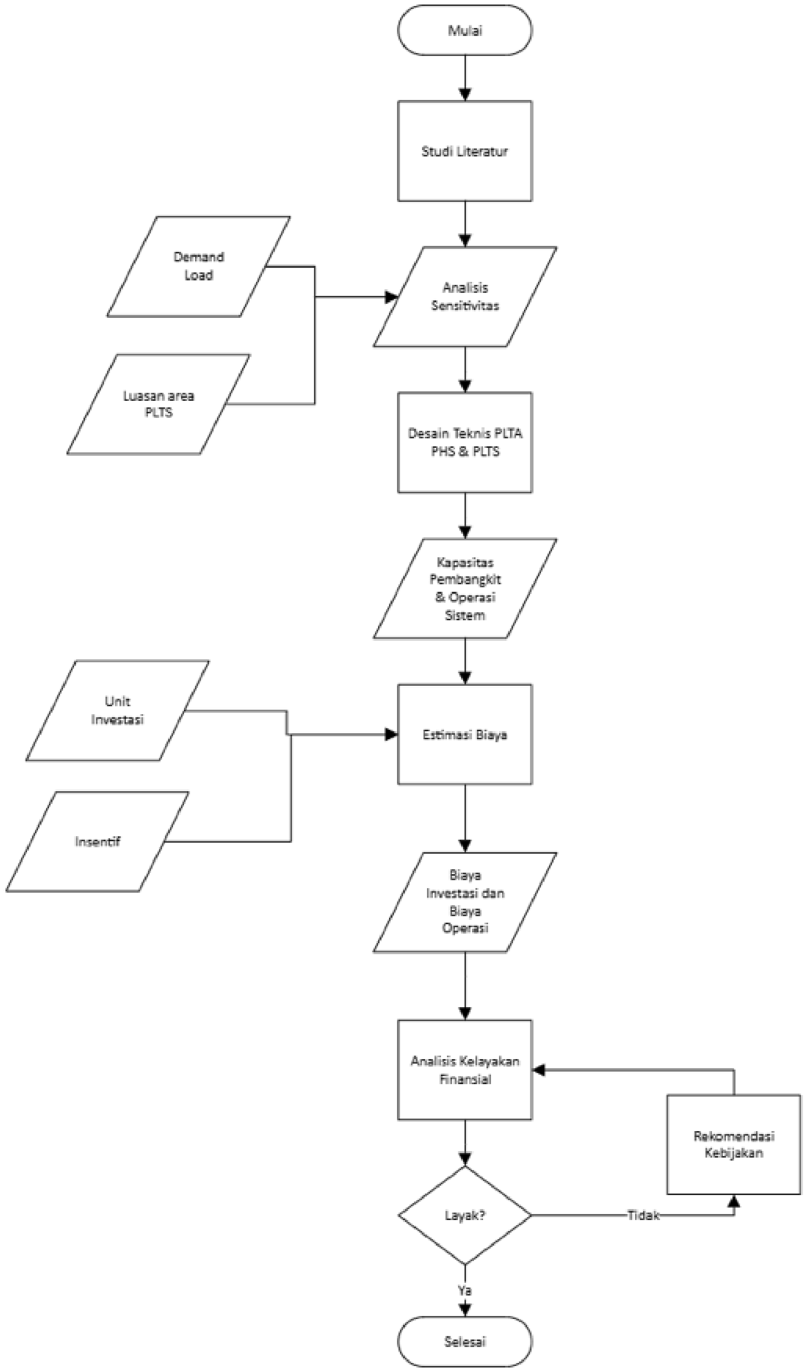


**Figure 3.** Research Flow Diagram

## 2.4. System Modeling

After obtaining energy demand data and technical parameters for the selected location, the PLTA PHS system with standalone and FPV integration scenarios can be designed to generate the required capacity and power plant operation system. The researchers used the Homer Pro software, which offers several advantages, such as providing GHI, temperature, and cloud conditions (shading) trends based on NASA's historical data from previous years. This data can be used as potential energy, which can be adjusted with key components such as solar panels, inverters, and others available in the software's library. Homer Pro is also one of the most accurate tools for power plant modeling and is useful in the techno-economic analysis process of the power generation system.

1. Electricity Load
   The electricity load used is based on a total load of 943 MW from 4 Pump Turbine units, each with a capacity of 235.75 MW. The total energy per day during 8 hours, from 09:00 AM to 04:00 PM, is 7,544,000 kWh per day.

**Table 1.** Daily Electricity Load Calculation

| Jumlah pump Turbin | 4 | Unit |
|---|---|---|
| **Kapasitas Pump Turbin** | 235,75 | MW |
| **Total beban** | 943 | MW |
| **Durasi** | 8 | Jam (09.00 hingga 16.00) |
| **Total Energi** | 7.544.000 | kWh per hari |

2. Technical and Financial Parameters
   The technical parameters of the PLTA PHS to be used as entries in the HOMER Pro software are shown in **Table 2**. The technical parameters of the PLTA PHS were obtained from the feasibility report of the Matenggeng PHS.

**Table 2.** Technical Parameters of PLTA PHS

| Parameter | Nilai |
|---|---|
| **Kapasitas (MW)** | 943 |
| ***Available head (m)*** | 450 |
| ***Design flow rate (L/s)*** | 264 |
| ***Minimum flow ratio (%)*** | 50 |
| ***Maximum flow ratio (%)*** | 150 |
| ***Efficiency (%)*** | 80,92 |

For the FPV, the first is placed at the upper dam, which is the Cimancing River, with an area of 85 hectares, while the second FPV is located at the lower dam, which is the Citeuteul River, with an area of 307 hectares. The capacity of each is 17 MW and 61.4 MW, respectively. This capacity is based on assumptions following the provisions of the Minister of Public Works and Public Housing Regulation Number 7 of 2023, which limits the maximum utilization to 20% of the normal water surface area. In this study, sensitivity analysis will be carried out with variations in the surface area of the dam utilized, increasing to 25% and 30%.

**Table 3.** Financial Parameters of the PHS and FPV Hydroelectric Power Plants

| Parameter | Nilai |
|---|---|
| CAPEX PLTA PHES ($) | 660.109.067 |
| OPEX PLTA PHES ($/year) | 33.005.453 |
| CAPEX PV ($/kWp) | 441 |
| CAPEX Inverter ($/kWp) | 400 |
| OPEX PV ($/kWp/year) | 4,41 |

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The financial parameters of the PHS and FPV Hydroelectric Power Plants, which will be used as inputs in the HOMER Pro software, can be seen in Table 3. These parameters are taken from previous studies, but for the CAPEX and OPEX values of PHS, a comparison is made with the capacities of PHS Matenggeng and PHS Cisokan [7].

3. System Modeling Scenarios
   a. Scenario 1:
      Pumped Hydro Storage Hydroelectric Power Plant In this scenario, a model is developed for the implementation of the PHS Matenggeng Hydroelectric Power Plant. The electricity required for pumping water from the lower reservoir to the upper reservoir will be fully supplied by the grid. The electrical load of the turbine used is 943 MW, with a total energy of 7,543,900 kWh per day, operating for 8 hours from 09:00 to 16:00.

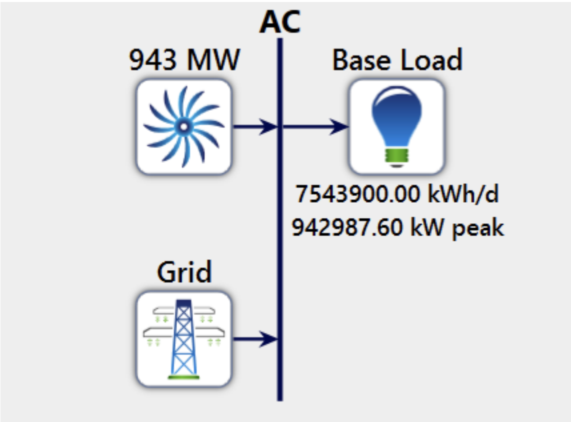


**Figure 4.** Matenggeng Hydroelectric Power Plant Scenario with PHS

   b. Scenario 2: Integration of PHS with FPV In this scenario, a model is developed for the integration of the Matenggeng PHS Hydroelectric Power Plant with an FPV located in the river flow. The energy produced by the FPV will be used to meet the electricity needs for pumping water from the lower reservoir to the upper reservoir for storage. The electrical load of the turbine used is 943 MW, with a total energy of 7,543,900 kWh per day, operating for 8 hours from 09:00 to 16:00.

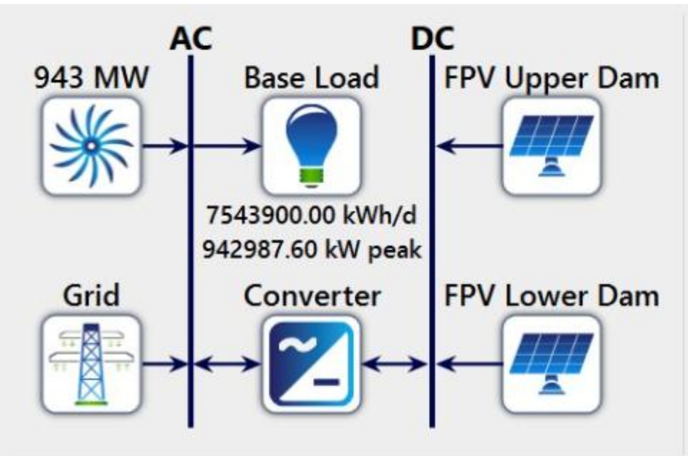


**Figure 5.** Scenario of PHS Integration with FPV

## 3. Results and discussion

The simulation results from Scenario 1 can be seen in the following Figure 6. The PHS Hydro Power Plant system scenario results in an LCOE of $0.08511/kWh. In this PHS configuration, there are two cost parameters used: CAPEX of $660,109,067 and operational costs of $3,502,385,743.65 over the lifetime of the plant, resulting in a total cost of $4,162,494,810.65. This value can be considered large, as there are operational costs for electricity supply from the grid, which amount to $2,917,496,231.94, significantly higher than the operational cost of the PHS plant itself, which is $584,889,511.71. This is because when the turbine requires energy to move water from the lower dam to the upper dam, electricity is supplied from the grid, and thus this cost is accounted for in the system's operational costs.

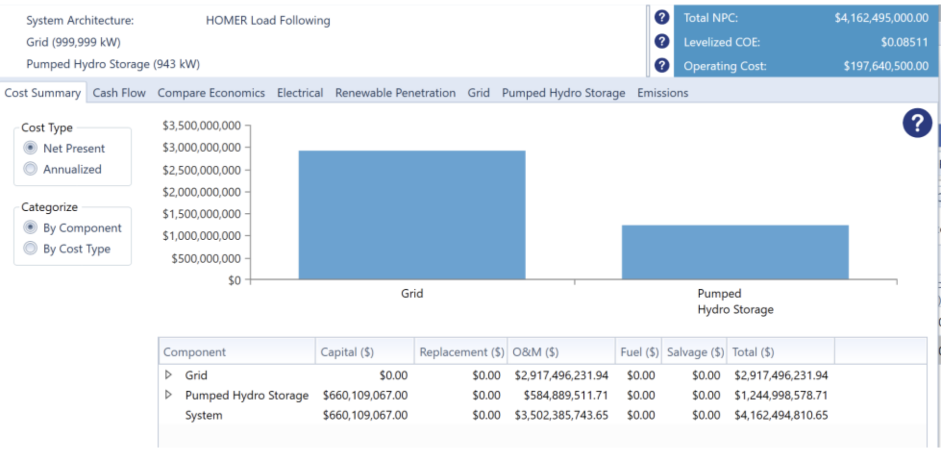


**Figure 6.** Simulation Results of Scenario 1

Meanwhile, the simulation results from Scenario 2 can be seen in Figure 7. The Integrated PHS System with FPV scenario results in an LCOE of $0.08431/kWh. In this PHS configuration, there are three cost parameters used: CAPEX of $732,315,467, operational costs of $3,395,592,711.05, and converter replacement costs of $21,509,554.38 over the lifetime of the plant, resulting in a total cost of $4,149,417,732.43.

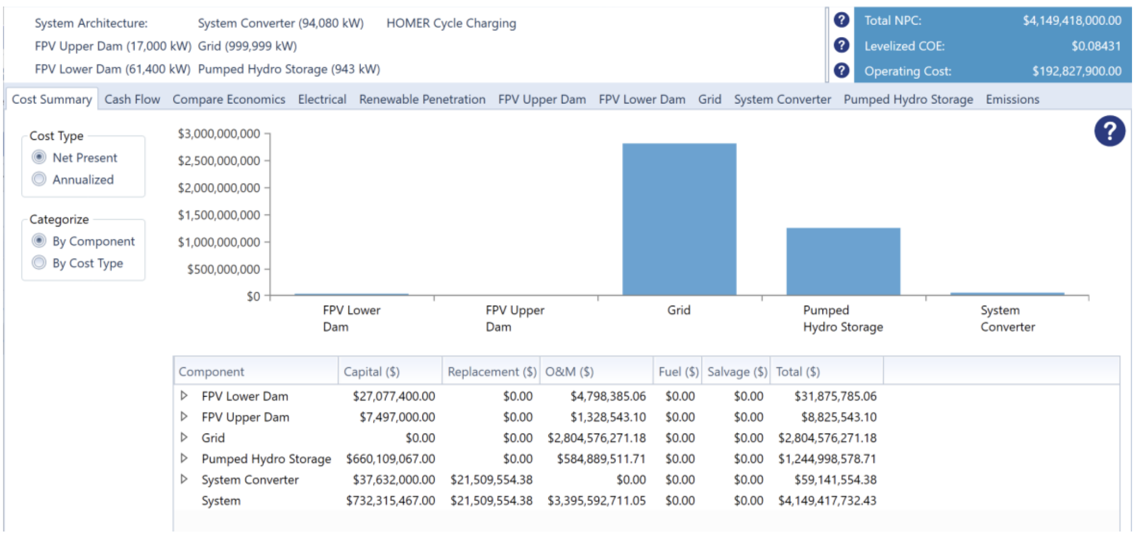


**Figure 7.** Simulation Results of Scenario 2

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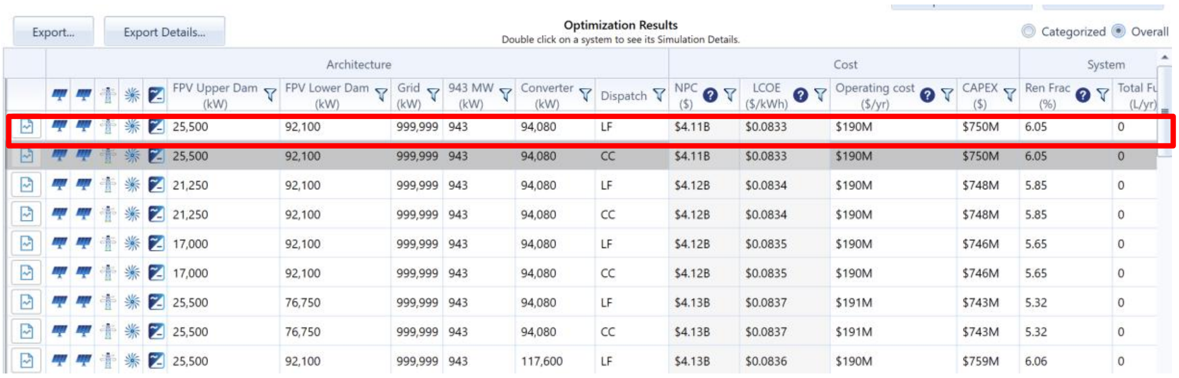
This value is lower compared to the PHS scenario without FPV integration, indicating that the scenario with FPV integration can be used to meet the energy needs of the PHS plant. With the use of FPV integration, network operating costs can be reduced because energy demands during off-peak times can be met by the existing FPV. In this scenario, network operating costs decrease to $2,804,576,271.18, resulting in a savings of $112,919,960.76 over the plant's lifetime, which provides significant cost savings. However, in this scenario, the need for converter material replacement during the plant's lifetime must also be considered, which may result in costs in the middle of the period.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Double click on a system to see its Simulation Details. Categorized Overall

| Architecture | | | | | | Cost | | | | System | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| FPV Upper Dam (kW) | FPV Lower Dam (kW) | Grid (kW) | 943 MW (kW) | Converter (kW) | Dispatch | NPC ($) | LCOE ($/kWh) | Operating cost ($/yr) | CAPEX ($) | Ren Frac (%) | Total Fu (L/yr) |
| 25,500 | 92,100 | 999,999 | 943 | 94,080 | LF | $4.11B | $0.0833 | $190M | $750M | 6.05 | 0 |
| 25,500 | 92,100 | 999,999 | 943 | 94,080 | CC | $4.11B | $0.0833 | $190M | $750M | 6.05 | 0 |
| 21,250 | 92,100 | 999,999 | 943 | 94,080 | LF | $4.12B | $0.0834 | $190M | $748M | 5.85 | 0 |
| 21,250 | 92,100 | 999,999 | 943 | 94,080 | CC | $4.12B | $0.0834 | $190M | $748M | 5.85 | 0 |
| 17,000 | 92,100 | 999,999 | 943 | 94,080 | LF | $4.12B | $0.0835 | $190M | $746M | 5.65 | 0 |
| 17,000 | 92,100 | 999,999 | 943 | 94,080 | CC | $4.12B | $0.0835 | $190M | $746M | 5.65 | 0 |
| 25,500 | 76,750 | 999,999 | 943 | 94,080 | LF | $4.13B | $0.0837 | $191M | $743M | 5.32 | 0 |
| 25,500 | 76,750 | 999,999 | 943 | 94,080 | CC | $4.13B | $0.0837 | $191M | $743M | 5.32 | 0 |
| 25,500 | 92,100 | 999,999 | 943 | 117,600 | LF | $4.13B | $0.0836 | $190M | $759M | 6.06 | 0 |

**Figure 8.** Integration of PHES with FPV with Sensitivity to PV Area Size

From the integration scenario of PHES with FPV, a sensitivity analysis was conducted based on the area size used for the FPV. In this sensitivity analysis, the FPV area sizes of 20%, 25%, and 30% of the total available area in the Matenggeng PHES region were considered. From the analysis results shown in Figure 6, it is known that with an area size of 30% and an FPV capacity of 25,500 kW at the upper dam and 92,100 kW at the lower dam, the most optimal system cost is achieved, with an LCOE of $0.0833/kWh. However, with a larger FPV area, there are also higher CAPEX and OPEX costs.

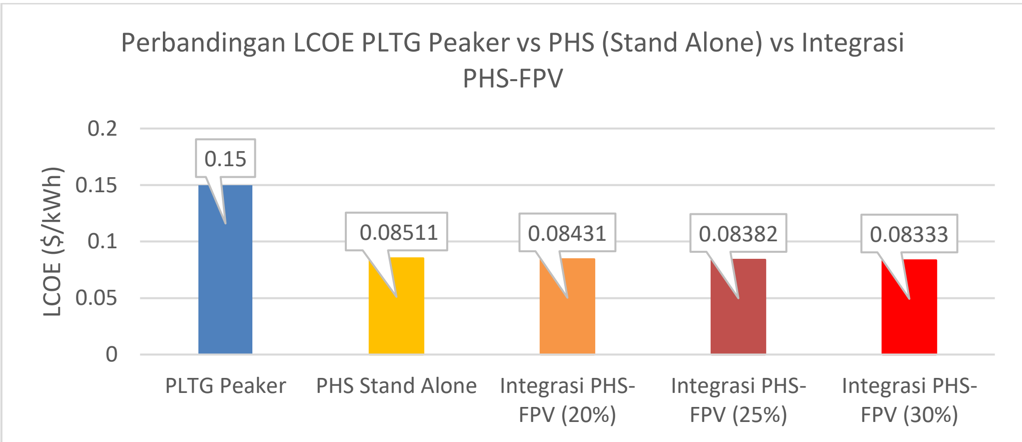

**Figure 7.** Integration of PHES with FPV with Sensitivity to PV Area Size

From Figure 7, a comparison of the LCOE between Peaker Gas Power Plants (PLTG), Stand Alone PHS, and PHS-FPV Integration is presented. It was found that the Peaker Gas Power Plant has the highest LCOE value of $0.15/kWh. With the application of Stand Alone PHS, the LCOE value significantly decreases to \$0.08511/kWh. This is due to the use of PHS technology, where the operational costs are lower compared to the operational costs of the grid. After integrating PHS-FPV, the LCOE becomes even more optimal, with a value of \$0.08333/kWh for a 30% area, thanks to the utilization of solar energy in the operation of PHS. The area of the river used for FPV affects the capacity of the FPV used. From the simulation results, it was found that the larger the installed FPV capacity, the more optimal the LCOE becomes.

The PHS configuration uses electricity from the PLN grid, which predominantly comes from coal-fired power plants, resulting in CO2 emissions. In this study's design, the PHS system is modeled using surplus coal-fired power from the 500 kV Java-Bali-Madura transmission network (Jamali). The simulation results from HOMER Pro for the Stand Alone PHS scenario show CO2 emissions of 1,734,155,761 kg/yr, while the PHS-FPV integration scenario results in CO2 emissions of 1,667,035,827 kg/yr, a decrease of 67,119,934 kg/yr. Therefore, the integration of PHS and FPV can reduce carbon emissions by up to 4% per year.

## 4. Conclusion

This research successfully analyzed the technical and economic integration of Floating Photovoltaic (FPV) Solar Power Plants with Pumped Hydro Storage (PHS) Hydroelectric Power Plants in Matenggeng. The modeling results show that this integrated system can increase energy efficiency and reduce operational costs compared to conventional systems. In the integration scenario of PHS with FPV, the Levelized Cost of Energy (LCOE) was successfully reduced to \$0.08494 /kWh, which is lower than the scenario without PLTS integration. This LCOE value, when compared to the LCOE of coal-fired power plants (PLTU), results in savings of \$0.065 /kWh. Additionally, the scenario with PLTS integration also successfully reduced the electricity grid operation costs by \$112,919,961, providing significant savings during the plant's operational period.

The use of this technology also successfully reduced carbon emissions by up to 4% per year, making it an environmentally friendly and sustainable solution. Overall, the integration of PLTS and PLTA with PHS in Matenggeng offers significant economic benefits, particularly in terms of operational cost savings and contributing to the achievement of clean energy transition targets in Indonesia.

The recommendation from this study is the need to optimize the area of the PLTS to achieve a more efficient system cost. Based on the sensitivity results, an area of 30% provides the optimal result with the lowest LCOE value of \$0.0833 /kWh.

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