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Feasibility of Implementing Hybrid Powerplant in Matenggeng Dam

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Abstract

Indonesia's is focusing the electricity power production from non-renewable sources to renewable energy resources. Hydropower might be promising; however, its production is highly affected by seasonal variability. Matenggeng dam is designed as multipurpose dam, namely for supplying the irrigation system, flood control, and utilization in a hydropower system. Based on its design report, the Matenggeng Dam is planned to produce power of about 11.74 MWac at water elevation of +194 m. Due to seasonal variability, the power production decreases to 5.74 MWac at the lowest water elevation. Solar energy, on the other hand, has a great potential in Indonesia, this study is aimed to optimize the decrease in existing electricity production in Matenggeng Dam by hybridization of hydropower with floating solar power plants. According to the regulation of Indonesia's public affair only 20% of the water surface area at normal condition can be used. By taking into account the reservoir operation pattern and the reservoir various conditions, the optimum water surface area that can be used for FPV installation is 295.7 hectare. The result showed that, the solar power plant successfully produces 14 GWh of energy annually, where the monthly generation is stable at 1,200 MWh per month.

Keywords: *Floating solar panels, hybrid power plant, hydropower, Matenggeng Dam*

Abstrak

Indonesia mengalihkan produksi tenaga listrik dari sumber tak terbarukan ke sumber energi terbarukan. PLTA memiliki potensi yang menjanjikan, namun produksi listrik dari PLTA sangat dipengaruhi oleh musim. Bendungan Matenggeng didesain sebagai bendungan multiguna, yaitu untuk memasok sistem irigasi, pengendali banjir, dan digunakan sebagai pembangkit listrik tenaga air. Berdasarkan laporan desainnya, Bendungan Matenggeng direncanakan menghasilkan listrik sekitar 11,74 MWac pada elevasi air +194 m. Karena fluktuasi muka air, produksi listrik menurun menjadi 5,74 MWac pada elevasi air terendah. Energi surya, di sisi lain, memiliki potensi yang besar di Indonesia, penelitian ini bertujuan untuk mengoptimalkan penurunan produksi listrik yang ada di Bendungan Matenggeng dengan hibridisasi PLTA dengan PLTS terapung. Berdasarkan peraturan pemerintah Indonesia, hanya 20% dari luas permukaan air pada kondisi normal yang dapat digunakan. Dengan mempertimbangkan pola operasi waduk dan berbagai kondisi waduk, maka luas permukaan air optimum yang dapat digunakan untuk instalasi FPV adalah 295,7 hektar. Hasil penelitian menunjukkan bahwa PLTS ini berhasil menghasilkan energi sebesar 14 GWh per tahun, dimana produksi bulanannya stabil di angka 1.200 MWh per bulan.

Kata kunci: *PLTS terapung, sistem tenaga hybrid, PLTA, Bendungan Matenggeng*

Introduction

Indonesia's electricity sector remains heavily reliant on non-renewable energy resources, which poses significant challenges for the country as it seeks to transition toward a more sustainable and environmentally friendly energy system. As of early 2022, the majority of Indonesia's electricity generation—76%—was derived from fossil fuels, specifically coal and natural gas. In contrast, renewable energy sources, which are crucial for mitigating climate change and ensuring long-term energy sustainability, contributed only 12% to the national electricity mix (Total Energies Renewables

Distributed Generation (DG), 2023). This heavy dependence on coal and gas not only exacerbates greenhouse gas emissions but also makes the country vulnerable to the volatility of global fossil fuel markets. In response to these challenges, Indonesia has set ambitious targets to increase the share of renewable energy in its energy mix. The country aims to achieve a renewable energy share of 31% by 2050 (Ardiansyah, 2022). This target reflects a broader recognition of the need to transition towards cleaner energy sources to combat climate change, improve energy security, and promote sustainable development.

In light of these goals, integrating renewable energy sources into Indonesia's energy grid has become crucially important. The integration of renewable energy is essential for reducing greenhouse gas emissions and ensuring that energy systems are resilient and capable of supporting long-term economic growth. Among the renewable energy options available to Indonesia, hydropower and floating photovoltaic (FPV) systems stand out as particularly promising. Indonesia is endowed with significant hydropower resources due to its abundant rivers and rainfall. Additionally, the country's geographical conditions present substantial potential for the development of floating solar power systems. The concept of hybrid power plants, which combine hydropower with FPV systems, offers a compelling solution for enhancing Indonesia’s renewable energy capacity and achieving its sustainability objectives.

A hybrid powerplant combining floating PV and hydropower plants could be considered. It can be one of the most effective innovations for floating PV to compensate for the electricity production in that area. This option is best conceived as a way to maximize the utility of existing hydropower stations rather than as a way to justify the building of new dams (Gadzanku et al, 2022). Where rainfall patterns are highly seasonal, as in monsoon areas, there is an additional advantage of complementarity over the year: More solar power is generated during the dry season, where water levels and hydropower output are low. The reverse is true for the rainy season. These systems make the Floating PV and Hydropower plants work optimally. Where water resources and solar energy can compensate for each other (World Bank Group et al, 2019). Due to the season the energy compensation may differs in tropical areas.

The integration of FPV systems with existing hydropower facilities in Indonesia holds significant promise. FPV systems, which involve installing solar panels on floating platforms on bodies of water such as reservoirs, offer several advantages. First, FPV systems can generate electricity even when hydropower generation is intermittent, due to seasonal variations in water flow. This complementary nature of FPV systems helps to stabilize the electricity supply and improve the reliability of power generation (Lee et al., 2020). Moreover, the presence of floating solar panels on reservoirs can reduce water evaporation, which is particularly beneficial in regions facing water scarcity (Vourdoubas, J., 2023). These are the benefits of energy generation and water conservation makes FPV systems an attractive option for Indonesia.

The potential benefits of integrating FPV systems with hydropower facilities extend beyond increased energy generation and improved grid stability. FPV is a renewable energy, where this can also contribute to the reduction of greenhouse gas emissions and support climate change mitigation efforts (Popa, B., 2021). By generating renewable energy from solar power, FPV systems help to reduce reliance on fossil fuels and decrease carbon emissions. Additionally, the dual use of reservoir areas for both hydropower and solar power generation can enhance the overall efficiency of water resource management (Anandhi, R.J., 2024).

The potential for FPV systems in Indonesia is substantial. According to recent estimates, there are over 5,807 potential reservoirs in the country that could be suitable for FPV installations. Additionally, there are 26 existing hydropower plants with reservoir areas that could be utilized for floating solar power projects (Aminuddin et al., 2022). This substantial potential aligns with Indonesia’s broader renewable energy targets. For example, the country has set a goal to achieve 4,680 megawatts (MW) of solar power capacity by 2030 (Karyza, 2024). Integrating FPV systems with hydropower facilities could help Indonesia achieve this target more efficiently by utilizing existing infrastructure and maximizing the energy output from available water resources.

Earlier studies on hybrid systems primarily focused on FPV energy production potential and performance. However, many of these studies did not address important hydrological aspects, such as water level fluctuations in the reservoir or the impact of hydropower energy production that are going to be projected for FPV to generate. Additionally, these studies often relied on several assumptions; for instance, they typically calculated FPV production based solely on the area of installed photovoltaic panels, rather than using site-specific global irradiation data.
According to previous study with hybridizing FPV systems with hydropower facilities provides

valuable insights into the potential benefits and challenges of this approach. A notable example is the successful implementation of FPV systems in China, where floating solar panels have been integrated with existing hydropower dams (Rosa-Clot, M., 2020). According to a study published in Cell (2019), the integration of FPV systems with conventional photovoltaic (PV) technology has proven effective in increasing overall energy generation. The study highlighted the success of hybrid systems in various dam locations around the world, demonstrating that FPV systems can significantly enhance energy output when combined with traditional hydropower facilities. The research suggests that FPV systems typically generate around 120 watts per square meter (Wp/m^2) of energy, which can substantially complement the energy produced by hydropower facilities (Rosa-Clot, M., 2020).

In the context of Indonesia, implementing FPV systems at existing or planned hydropower dams involves several considerations. According to Aminuddin (2022) study, it only calculates the potential of the FPV generation based on the regulation and the inundation area available. The area of the FPV array is 5% of the reservoir inundation area at normal conditions. Furthermore, it only assumes the energy production is 1 MWp every 34.5 Ha. The ratio is based on the area size of Cirata Dam used by the 145 MWp floating PV array is around 250 Ha. This requires a further analysis of the energy output of FPV systems based on global horizontal irradiance (GHI) at specific sites. GHI measures the total solar radiation received per unit area on a horizontal surface, and it is a key determinant of the potential energy generation from FPV systems. By calculating the energy output from GHI data, it is possible to estimate the number of FPV units required to meet the energy needs of a particular site. Also, the inundation area needs to be seen by the dam operational data at lowest water elevation to find the suitable site for FPV.

Overall, the integration of FPV systems with hydropower facilities represents a promising pathway for Indonesia to enhance its renewable energy capacity and achieve its sustainability goals. The hybrid approach leverages the strengths of both technologies to provide a reliable and efficient source of renewable energy. By addressing the technical, logistical, and economic challenges associated with FPV implementation, Indonesia can make significant progress towards a more sustainable and resilient energy system. As highlighted in the abstract, this study specifically focuses in assessing how the integration of floating solar photovoltaic (FPV) systems with hydropower at Matenggeng Dam can help stabilize electricity production and support Indonesia's renewable energi transition. By conducting a comprehensive analysis of the energy output and site suitability.

The study will provide valuable insights into how Indonesia can effectively integrate these technologies into its energy mix. The findings will contribute to the development of strategies for enhancing the country's renewable energy capacity, reducing greenhouse gas emissions, and promoting sustainable development.

Materials and Methods

Methodology

The study's methodology is illustrated in Figure 1, beginning with the process of data collection. The necessary data encompasses solar irradiation levels, dam operation patterns, and topographic maps. Utilizing this data, the required energy generation capacity of the floating photovoltaic (FPV) system can be estimated. Based on the solar irradiation data and the selected FPV island configuration, the number of solar panels and the area required for installation are determined. Subsequently, the FPV system is positioned in alignment with the available topographic map and established guidelines. The study ultimately evaluates the energy generation potential of the FPV system, taking into account the site's feasibility.

Figure 1. Flow diagram of the study

Study location

Matenggeng Dam is located in Dayeuhluhur District, Cilacap Regency, Central Java Province, and Tambaksari District, Ciamis Regency, West Java Province. Geographically, it is positioned at coordinates 7°15'12.68" S and 108°34'35.46" E, as shown in Figure 2. The dam has a capacity of 383.5 million m3 at the elevation of +194 m and serves the dual purposes of irrigation and hydropower generation, with a capacity of 19 m³/s (Figure 2). At the elevation of +194 m the dam had an inundation area of 14.8 million m2 where 20% of the area can be utilized for FPV installment (PUPR, 2022). Matenggeng have two intakes which are installed at elevation of +128m and +148 m with a diameter of 3.5 m. Taking the opportunity that the reservoir will never empty along the year, it becomes very suitable for FPV placement.

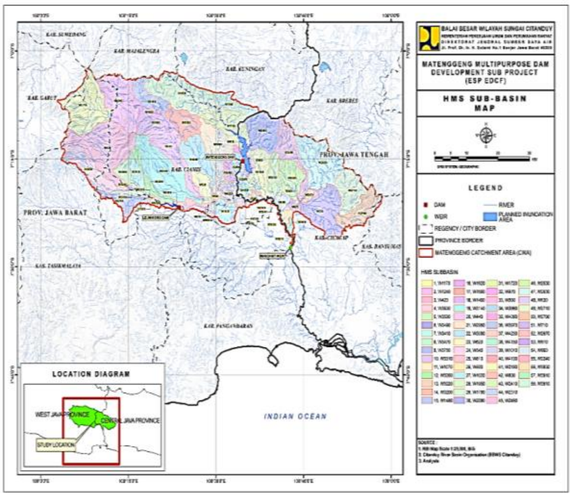

Figure 2. Map of Matenggeng Dam

Floating PV Mechanism

The floating system for the PV panels works in the following way, (Ikhennicheu, 2021). 1) The floating platforms support the solar panels and keep them a float on the water by modular floaters. 2) Mooring lines are attached to the floating platform and anchors at the bottom of the water body.

Floating PV typically deployed on man-made water bodies, industrial ponds, agriculture ponds, and off-shore environments. A floating system must be designed to withstand the challenges brought by such an environment, including a frozen water surface, snow coverage of panels, possible large fluctuations in water levels, and the constant movement caused by winds. There are some key components and system designs for an ideal Floating PV.

FPV sizing and placement

The required amount of the solar panels is based on the Global Horizontal Irradiance (GHI) data of the site and the specifications of the solar panels. GHI refers to the total amount of solar radiation received on a horizontal surface from the sun, including both direct and diffuse components. It is a crucial metric in solar energy applications, particularly for photovoltaic (PV) systems. GHI is made up of three main parts: Direct Normal Irradiance (DNI), which is the sunlight coming directly from the sun when the surface is facing straight at it; Diffuse Horizontal Irradiance (DHI), which is sunlight that has been scattered by the atmosphere and arrives from all directions except directly from the sun; and Ground-reflected Radiation, which is sunlight that bounces off surfaces like the ground or water (Homer Energy, 2020). GHI values are essential for estimating the potential energy output of solar panels installed on flat surfaces.

Accurate GHI measurements help in optimizing the design and placement of solar energy systems (Vaisala, 2018). GHI is converted by solar cells within a photovoltaic system. This system consists of solar modules, each containing multiple solar cells that generate electrical energy. During operation, these solar cells transform GHI into direct current (DC) power. An array of solar modules is grouped and packaged together, and the generated DC is directed to an inverter, where it is converted into alternating current (AC) for integration into the power grid. However, this process may involve some energy losses from the absorption of light to the electricity conversion (World Bank Group et al., 2019).

Another component of FPV system is the floaters. To enable PV panels to float on the water's surface, they are mounted on floating platforms and locked by mooring and anchor. Various types of floating platforms can be selected based on the specific conditions of the water body. The most commonly used type is the pure-float design, where the floaters directly support the PV panels. These pure-float configurations utilize specially designed buoyant structures to hold the PV panels in place on the water.

Pure-float design uses modular technology with medium density polyethene (MDPE), where this plastic does not harm the water. This modular floating system consists of two types of floats: the "main floats," which support the PV modules and can be tilted at various angles based on the model, and the "secondary floats," which attach to the main floats. The secondary floats create sufficient spacing to minimize shading on the PV modules, serve as walkways for maintenance, and enhance buoyancy (World Bank Group et al., 2019). These floats enable various configurations across the PV island. The study employs a two-row configuration as illustrated in Figure 3, deemed the most cost-effective for PV maintenance. Where this configuration affects the size of the FPV island.

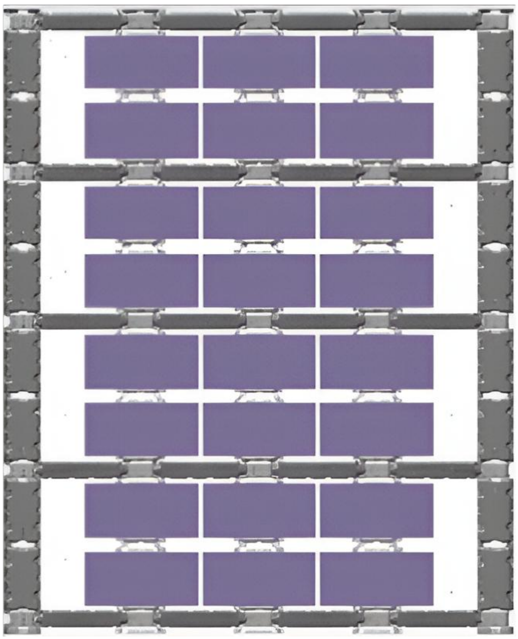

Figure 3. Configuration of FPV island

Anchoring and mooring secure the FPV array in place and ensure the stability in water, which makes it the most important part of FPV. Key considerations include the environmental forces such as wind, waves, and currents, as well as the distribution of forces to ensure the longevity of the entire system, including the floats and anchors. The mooring system is designed to prevent the floating solar islands from drifting or changing position, and it must be adapted to local water conditions and standards. The design and installation of the mooring and anchoring system are essential for the overall success and durability of floating PV installations (Helali, 2021).

Anchors will be positioned to maintain a maximum angle of 45° for the mooring lines, ensuring strong lateral resistance. The most common used type of anchoring is bottom anchoring, in the type on concrete sinkers. To ensure the degree of the mooring lines, these anchors must be placed through trigonometry calculation. The anchoring footing also affects the FPV array placement where the anchors have to be placed on a considerably empty field. Furthermore, each concrete block may be connected to multiple mooring lines.

Water level fluctuation can affect the length of the mooring lines and FPV placement. The mooring lines must withstand any condition for the next 25 years, accounting for exceptional event such as floods and storms. If water level fluctuations exceed 10 meters, alternative mooring solutions should be explored (Kanotra and Shankar, 2022). The mooring lines had to keep in tension even when the water level is low. When the mooring lines is loose, and the wind is blowing the FPV array might crash to the reservoir bed. These movement is not allowable where this might damage the FPV system. The water level fluctuation also affects the FPV placement, the lowest water elevation of the reservoir is required. Through topography data, the FPV arrays must be placed on a flat surface or did not exceed 15°. If not, this might trigger the FPV to break when it hits the bottom of the reservoir (PLN UPDL Bogor, 2021).

Dam operation pattern data

Reservoirs store water that is later used for flood catchment areas, as a source of water for irrigation, as rain catchment areas, or to change the flow rate of a river. The main parameters of a reservoir are its storage size, storage area, and intake elevation. Based on its function, reservoirs can be classified as single-purpose reservoirs and multi-purpose reservoirs, where Matenggeng is classified as a multi-purpose dam (Pusat Pendidikan dan Pelatihan Sumber Daya Air dan Konstruksi, 2017). This is based on the various water demands that must be fulfilled, such as irrigation, raw water, and hydropower. The combination of these various needs is intended to optimize the function of the reservoir and increase the feasibility of building a reservoir.

The normal water elevation is the maximum elevation reached by the reservoir surface rise under ordinary operating conditions. For most reservoirs, normal elevation is determined by the elevation of the spillway or spillway core crest. The lowest water elevation is the lowest elevation that can be obtained when inundation is released under normal conditions. This surface may be determined by the elevation of the intake in the dam. The amount of storage that lies between the minimum and normal inundation surfaces is referred dead storage. The operational pattern of the Matenggeng Dam is essential to determine the lowest water level, which was recorded at 148 meters as seen in Figure 4 (PT. Intimulya, 2022).

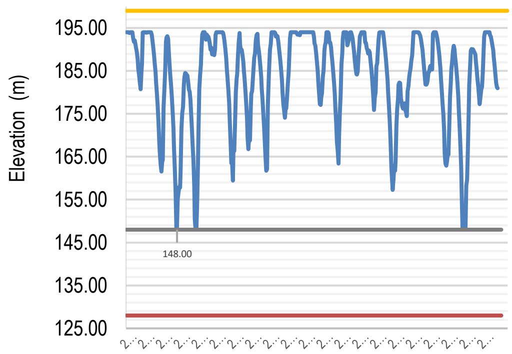

Figure 4. Matenggeng dam operation pattern

This data also provides insight into the dam's hydroelectric power generation. Hydropower utilizes the potential energy contained in water to be converted into kinetic energy through turbines. The kinetic energy in the turbine is then used to generate electricity through the generator. The power generated is calculated using the Equation 1.

$$P = \eta \, \rho \, Q \, g \, H_e \quad (1)$$

The factors in Equation (1) work like this. The power generated by a hydropower system is directly proportional to the flow rate (Q, in cubic meters per second or m³/s), the height of the water drop (H_e in meters or m), the efficiency (η, in percentage or %), also with water density (ρ, in kilograms per cubic meter or kg/m³) and gravity acceleration (g, in meters per second square or m/s²). Essentially, the water's potential energy (determined by its height and volume) is converted into kinetic energy as it flows through the turbine, which then converts it into mechanical energy and ultimately electrical energy. The efficiency η ensures that the system accounts for energy losses and determines how much of that energy is actually harnessed (Regulation of the Minister of Energy and Mineral Resources of Indonesia No. 12 of 2014).

By increasing the flow rate or the head, more energy can be extracted, leading to a higher power output, assuming the turbine and generator are capable of handling the additional load efficiently. The result shown that the highest output of electricity is at 11.74 MWac and the lowest at 5.74 MWac. Based on Figure 5, the projected capacity for the Floating Photovoltaic (FPV) system is estimated at 6 MWac.

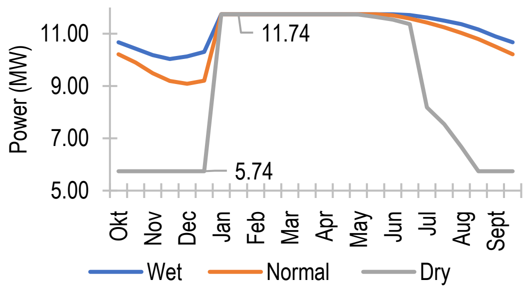

Figure 5. Matenggeng hydropower generation pattern

Global horizontal irradiation data

The GHI data is acquired from SolCast by inputting the location of the study. Solcast recorded the data for 17 years. Solcast measures the GHI with the help of the satellite. The Irradiation itself for the past 17 years has not changed significantly. Thus, Figure 6 shows the average data for the past 17 years. The GHI data at Matenggeng is considered very stable throughout the year, this proves that the reservoir's location has a good potential in solar panel energy generation.

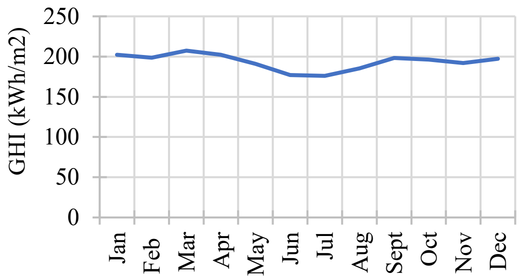

Figure 6. Matenggeng average GHI data

Topography map

The map shown the inundation area by its elevation. To find the eligible location of FPV arrays, the topography map with the lowest water elevation is needed. Figure 7 shown that in Matenggeng there are only one area that can be used for FPV arrays. Where this area is considered empty and safe for FPV installation, it does not affect the function of the spillway and intake of the dam. Also, take into account of the bathymetry measurement path (PUPR, 2020).

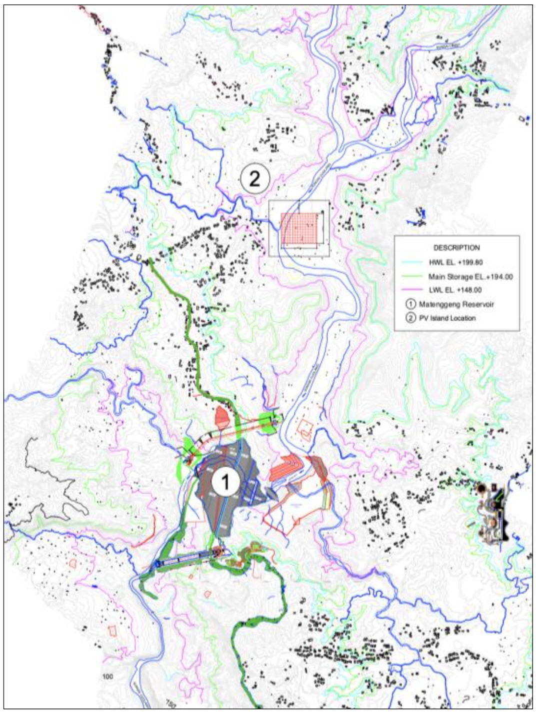

Figure 7. Topography map of Matenggeng dam

Results and Discussion

FPV sizing

In this study, the solar panel is manufactured by PGT, a company from the United Arab Emirates

(UAE). The panels used have a monocrystalline panel. Where this panels, are known for their efficiency, with efficiency ratings typically exceeding 20%. This high efficiency allows for more power generation in a smaller area. It also has a long lifespan, exceeding 25 years. The solar panels used in this study each have an area of 2.58 m^2 and a capacity of 560 Wp per unit. The island configuration is set up with two panels in a row. Based on the hydropower gap, the study projects a capacity of 6 MWac. As shown in Figure 4.6, achieving this capacity requires a total of 12,960 solar panels, with the island's dimensions being 236 meters in width (Lx) and 291 meters in length (Ly). The size of the island is also influenced by the arrangement of the solar panels and the floaters, as illustrated in Figure 8.

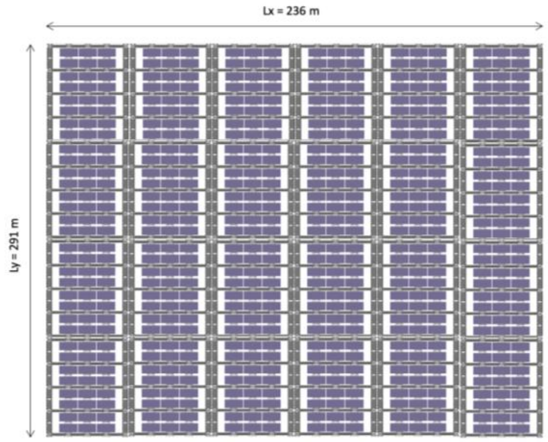

Figure 8. Schematic of FPV array size with floaters

Anchor Footing

The available area for the Floating Photovoltaic (FPV) system at the lowest water level (LWL) has a depth of 64 meters below the normal water level. Based on trigonometric calculations, the distance from the anchoring point to the panels is 102.5 meters, with the maximum mooring line tension occurring at a 30° angle. Consequently, the mooring lines will have a length of 121 meters. This angle is chosen to ensure the mooring lines when there are challenges by the environment. In this study the most catastrophic challenges are probable maximum flood (PMF), where the water elevates at 199 m, the angle occurs at PMF is 34.8°, which is still below the maximum tension of the mooring lines (45°). Thus, the anchor footing is illustrated in Figure 9.

Mooring lines modification

The water level fluctuation exceeds 10 meters, necessitating modifications to the mooring lines to prevent excessive movement of the island. To accommodate these significant changes in water level, a buoy will be added to the mooring lines. Where this buoy can adapt to significant water level variation, they keep the mooring lines in tension, making the movement of the FPV limited.

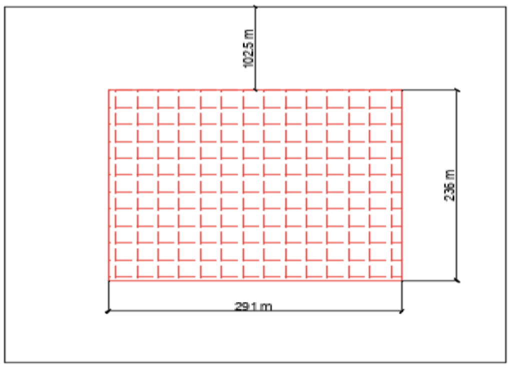

Figure 9. Schematic of the FPV island and the anchor footing

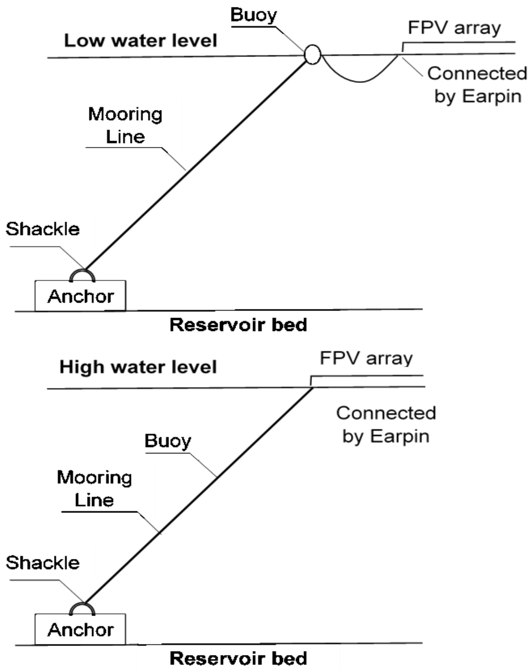

Figure 10. Schematic of mooring lines modification with buoy

Figure 10 likely illustrates the design of the mooring lines, including the placement and role of the buoy within the system. The addition of a buoy to the mooring lines is a critical modification to address the water level fluctuations that exceed 10 meters in this FPV installation. These fluctuations could otherwise cause excessive movement of the FPV island, leading to potential damage and reduced energy production. By incorporating a buoy, the mooring system gains the flexibility needed to adapt to changing water levels, ensuring the FPV island remains securely anchored and properly aligned for optimal energy generation.

FPV Placement

The selection of a suitable location for the installation of Floating Photovoltaic (FPV) panels is a critical aspect of project planning, particularly in environments where water levels fluctuate significantly throughout the year. One of the most important factors influencing the decision is the available water surface area at the Lowest Water Level (LWL). The LWL represents the point during the dry season or periods of reduced water inflow when the water level in the reservoir or lake is at its minimum. Since the water body's size can shrink considerably during these times, it is crucial to ensure that there is still enough surface area to accommodate the floating solar panels without compromising their performance or stability.

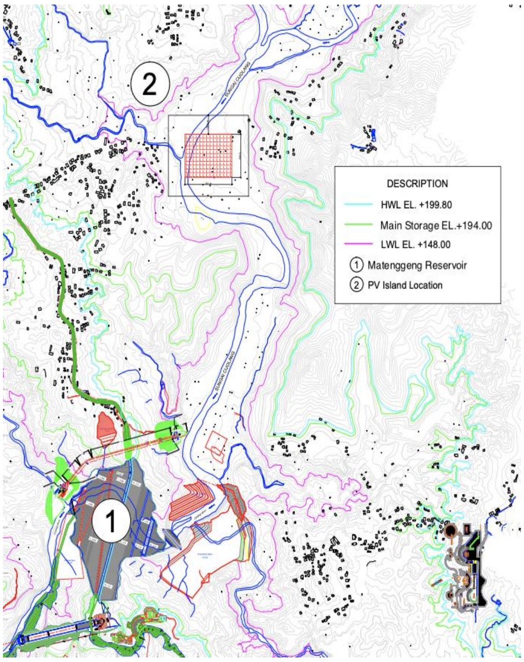

Figure 11. Schematic of the FPV island location to the dam

In this case, the location for the FPV installation is specifically determined based on the water surface available at the LWL, rather than the normal or high-water levels. This consideration ensures that the floating PV panels will continue to operate effectively even during the driest periods of the year when water levels are at their lowest. If the installation were based solely on normal or high-water levels, there would be a risk that the system could become non-functional or face structural issues during the dry season when water levels recede, potentially exposing the floating structures to the shore or even causing them to run aground. This could lead to damage to the panels, interruptions in energy production, and higher maintenance costs.

The specific location identified in Figure 11 is the only site that meets all the necessary criteria for FPV installation, given the constraints posed by the LWL. This means that after careful evaluation of the water body's surface area, depth, and the natural changes in water level, this location was deemed the most appropriate for the project. The figure likely illustrates how the LWL affects the size and shape of the water body and highlights the specific area that remains suitable for the FPV system during low-water periods.

Hybrid operation of hydropower and floating PV

Unlike hydropower, which is highly susceptible to seasonal variations, Floating Photovoltaic (FPV) energy production remains relatively stable throughout the year. Hydropower generation is often impacted by fluctuations in water availability, with periods of drought or low rainfall leading to reduced water flow and consequently lower energy output. In contrast, solar energy harnessed through FPV systems is far less dependent on such factors. While seasonal changes in sunlight intensity do exist, especially between the dry and rainy seasons, these variations are generally less pronounced than those affecting hydropower, making FPV a more consistent source of renewable energy.

In this study, the FPV system is designed to generate approximately 14 GWh of energy annually. This translates into a fairly consistent monthly output of about 1.2 GWh, ensuring a steady contribution to the overall energy mix. The regularity of this energy generation is an important advantage of FPV systems, as it helps stabilize the overall energy supply, which is particularly beneficial for regions or countries that rely heavily on hydropower. By providing a predictable and reliable source of energy, FPV can help offset the seasonal dips in hydropower production, during dry periods when water levels in reservoirs are low.

The additional energy provided by the solar panels is illustrated in Figure 12, which highlights the monthly energy contribution from the FPV system. While the FPV system does not completely close the gap between energy demand and the shortfall in hydropower generation, it plays a crucial role in enhancing the overall energy output of the combined system. The hybrid model, which integrates both hydropower and solar energy, leverages the strengths of both technologies, providing a more resilient and diversified renewable energy solution.

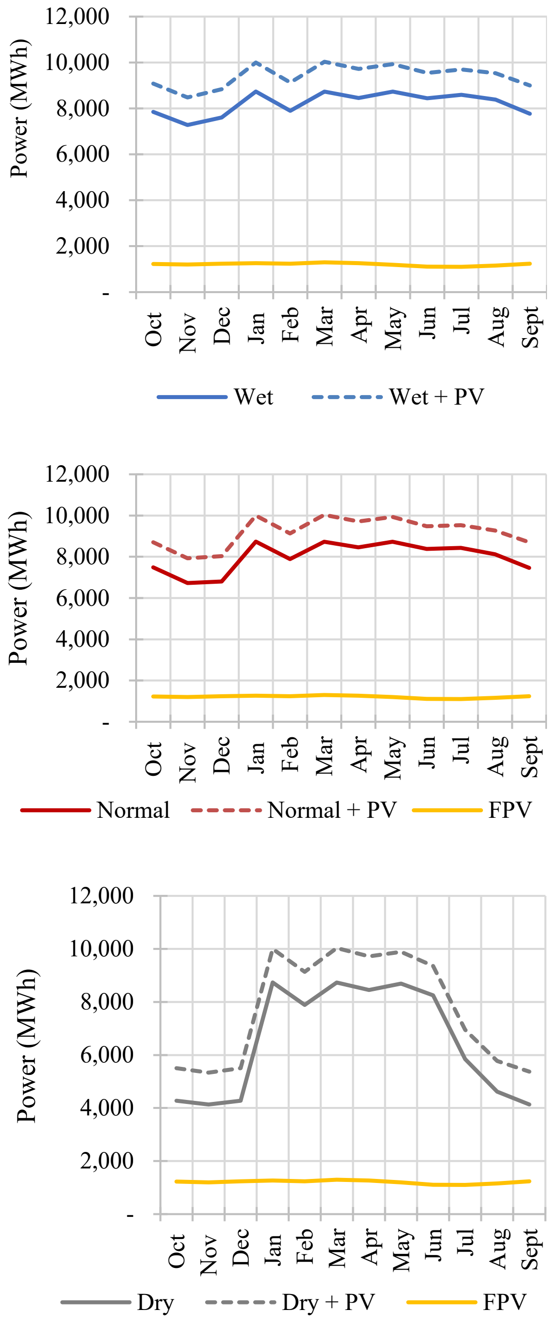

Figure 12. Electricity generation of hybrid operation in wet season

Conclusions

Floating Photovoltaic (FPV) systems are emerging as an innovative solution for expanding renewable energy capacity by utilizing available water surfaces, especially in regions with limited land resources. While this study focuses on Matenggeng Dam, the approach of the potential applicability of similar hybrid systems to other reservoirs in Indonesia, contributing to the national renewable energy strategy. Although up to 20% of the normal inundation zone could theoretically be used for FPV installations, in this case, it translates to only 68,676 m² of usable space. While this area may seem small compared to the dam's overall surface, its strategic use has proven highly effective.

The placement of the FPV panels has been meticulously planned to comply with all applicable regulations and guidelines, ensuring the installation does not interfere with the dam's primary functions or cause environmental disruption. These standards govern the dam's structural integrity, water quality, and ecosystem preservation. By following these guidelines, the study ensures that the integration of FPV technology on existing dams is both safe and sustainable.

Despite the relatively limited surface area, the study demonstrates that the FPV installation effectively addresses a critical challenge: the energy shortfall from the existing hydropower plant, which generates 6 MWac of energy. The FPV system compensates for the energy deficit during periods when hydropower alone cannot meet demand, optimizing the overall energy output of the dam. This hybrid renewable energy solution leverages both water and solar resources in a complementary way, combining hydropower and FPV systems.

This study shows that FPV systems, even when limited by space constraints, can provide a meaningful contribution to renewable energy production. By compensating for the limitations of hydropower and optimizing the use of existing infrastructure, FPV offers a promising avenue for sustainable energy development. Moreover, by introducing a more nuanced and technically sound approach to FPV placement, this study sets a new benchmark for future research and project implementations in the field of renewable energy.

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