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Optimizing the Development of a PLTMH System Using Pelton Turbine Technology to Enhance Energy Efficiency in Remote Areas as an Affordable and Sustainable Renewable Energy Solution

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Abstract

This research investigates the optimization of a Micro Hydropower Plant (PLTMH) system utilizing Pelton turbine technology to enhance energy efficiency in remote areas. The study focuses on maximizing hydraulic potential, specifically water head and flow rate, to ensure a reliable and sustainable energy supply. By implementing an optimized geometric design of the turbine, the system aims to mitigate flow rate fluctuations and deliver consistent power output. The findings demonstrate that a Pelton turbine-based PLTMH system, operating with an average flow rate of 11 liters per second and a water head of 50 meters, achieves a power output of 3 kW with a turbine efficiency of 80%. The design leverages locally sourced materials, such as 4-inch diameter pipes, to ensure operational sustainability while addressing logistical and geographical constraints. Beyond providing an environmentally sustainable energy solution, the system contributes to the socioeconomic development of remote communities by enhancing access to electricity for public infrastructure. The study highlights the potential for further advancements, including flexible nozzle designs and the integration of Internet of Things (IoT)-)-enabled control systems, to improve efficiency and adaptability in meeting the demands of sustainable energy in challenging environments.

Keywords: Generator, turbine pelton, head

INTRODUCTION

Renewable energy is increasingly becoming a major concern in efforts to reduce dependence on fossil fuels and minimize negative impacts on the environment. PLTMH system uses Pelton turbine technology to increase energy efficiency in remote areas as an affordable and sustainable renewable energy solution. The importance of utilizing renewable energy, especially PLTMH, in supporting development in remote areas is emphasized. In 2021, the contribution of hydropower generation reached 1330 gigawatts around the world and the expected growth of around 60 % by 2050 presents a challenge to continuously improve its technology and sustainability [1]. In Indonesia, based on data from the Indonesia Ministry of Energy and Mineral Resources (ESDM) shows that more than 2510 villages, especially in remote areas, still do not have electricity supply. This inequality hampers economic development and the quality of life for the people, who face difficulties in accessing education, healthcare, and economic activities[2].

It is noted that small hydro power plants can be a suitable solution to meet energy needs in areas that are difficult to reach by the main electricity grid. The study shows that the construction of such plants not only provides access to electricity but also supports economic growth, improves people's quality of life, and reduces negative environmental impacts [3]. These power plants harness the energy potential of small water sources, such as river flows, waterfalls, or small dams, to generate electricity. By utilizing the kinetic and potential energy of water, a hydro turbine connected to an electric generator produces power. The size and capacity of these installations vary, ranging from micro systems for households to larger ones that provide electricity for communities or small industries.

Small hydro power plants offer several advantages compared to conventional and other alternative energy sources. First, they have a lower environmental impact because they do not produce greenhouse gas emissions or toxic waste. Second, these plants are more reliable since they are not dependent on weather conditions, unlike solar or wind energy [4]. Third, they can operate independently in remote locations or areas isolated from the main electricity grid, providing access to electricity in hard-to-reach areas. Despite these advantages, such plants also face several challenges, including high initial infrastructure costs, local environmental impacts like changes in river flow and habitat, and regulatory hurdles related to permits and construction. However, with the right technology and planning, many of these obstacles can be overcome.

The Pelton turbine is a type of hydro turbine designed to optimize the conversion of water kinetic energy into mechanical energy. It is an impulse turbine that performs best under conditions with high head. In these conditions, the falling water with high velocity provides a significant amount of kinetic energy, which can be converted into mechanical energy by the Pelton bucket. The higher the head, the more efficient the Pelton turbine is in generating power [5]. Indonesia is a tropical country with relatively high rainfall, however, due to the condition and damage to forests in remote areas, as well as global warming, extreme weather and shifting seasonal patterns have occurred. This has resulted in water flow rates during the rainy season being excessive and fluctuated, while they are very low during the dry season, making the use of Pelton turbines highly recommended.

The geometric design of Pelton turbines can be optimized to improve efficiency and performance, especially in situations where the water flow has significant fluctuations [6]. Pelton turbine technology has proven effective in utilizing the kinetic energy of water to produce electricity on a small to medium scale. In previous experimental research evaluated the performance of the Pelton turbine in the context of PLTMH. Research results show that an optimized Pelton turbine design can increase the efficiency of converting water energy into electrical energy, especially under varying water flow conditions [7]. To ensure a sustainable energy supply, the construction must be made of materials that are easy and inexpensive to find in the market. Considering that the installation location of the micro-hydro power plant (PLTMH) is in a remote area that is relatively difficult to access, the repair and maintenance processes should be easy to carry out and affordable for the local community.

RESEARCH METHODS

In this study, optimization is conducted on a micro-hydro power plant (PLTMH) utilizing a Pelton turbine, based on the site conditions and energy potential of the designated installation location. The selected site is located in a remote area, characterized by low flow rates during extended dry seasons, but with a relatively high head. This setup aims to ensure a stable electricity supply throughout the year. Remote areas in Indonesia typically consist of small settlements, referred to as villages, comprising several households. The primary electricity demand is for public facilities such as village halls and places of worship, which are located in close proximity to each other. Additionally, micro-hydropower plants are often employed to provide lighting and electricity for facilities within community plantations. Consequently, the generator used in this study has a capacity of AC Generator 3 kW 1-Phase. The type of generator used in this study can be seen in **Fig. 1.**

Fig. 1 - AC Generator 3kW 1-Phase

A 3 kW generator is commonly available and affordable for local communities in Indonesia. Based on this specification, a survey of the installation site is necessary to assess the water resource potential that can meet the required specifications. Once the potential hydraulic power is confirmed to meet the generator's specifications, an analysis and calculation of the required components for the construction of the Pelton turbine-based PLTMH can be performed. Thus, the results of the analysis and calculations are realized in a technical design using computer-aided design (CAD) software. The design output, in the form of technical drawings, will serve as a reference for the fabrication process of the Pelton turbine-based PLTMH, followed by the installation and testing procedures at the designated installation site. Based on the output power specifications of the generator, the hydraulic power potential required at the installation site must first be determined using the following equation

$$P_{hyd} = \frac{P_{output}}{\eta_{overall}} \quad (1)$$

After determining the hydraulic power potential required by the flow at the installation site, with an overall efficiency of 70%, the water head can be established to determine the minimum water flow rate required by the stream to be used as the water supply for driving the turbine. In this study, the water head is set at 50 meters, and the turbine efficiency is 80%, allowing the flow rate to be calculated using the following equation.

$$P_{hyd} = \eta \times \rho \times g \times Q \times H \quad (2)$$

The input diameter of the water channel used is a 4-inch pipe, with the pressure at the inlet and the outlet (nozzle) being equal. Therefore, the flow velocity at the input and the flow velocity at the nozzle can be determined using the following equation:

$$Q = A_1 \times v_1 \quad (3)$$

$$A_1 = \left(\frac{D_1}{2}\right)^2$$

$$P_1 + \frac{1}{2}\rho {v_1}^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho {v_2}^2 + \rho g h_2 \quad (4)$$

$$v_2 = \sqrt{{v_1}^2 + 2gh_1}$$

By using two nozzles in the system, the nozzle diameter can be determined using the following equation:

$$Q_{nozel} = \frac{Q}{2}$$

$$Q_{nozel} = A_2 \times v_2 \quad (5)$$

$$A_2 = \left(\frac{D_2}{2}\right)^2$$

The power required by the turbine to generate 3 kW of electrical power in the generator, with an efficiency of 80%, can be determined using the following equation:

$$P_{turbine} = \frac{P_{generator}}{\eta_{turbine}} \quad (6)$$

To transmit power from the turbine to the generator, a transmission system consisting of a pulley and belt arrangement is used. The pulley diameter on the generator is 5 inches, while the turbine pulley has a diameter of 10 inches. If the generator operates optimally at 1500 rpm and the runner's optimal angular velocity matches the water flow velocity exiting the nozzle, the angular velocity and runner diameter can be determined using the following equation.

$$\omega_{turbine} = \frac{\eta_{turbine} \times 2\pi}{60} \quad (7)$$

$$v_2 = \omega_t \times R_r$$

Based on the calculation results from Equations 4, 6, and 7, the specification for the water exit velocity at the runner can be calculated using the following equation.

$$P_{turbine} = \frac{\rho \; Q \; v_2 \; (u-v)}{1000} \quad (8)$$

Next, calculations are performed to determine the quantity, size, and dimensions of the buckets to be used. However, prior to that, it is necessary to determine the torque and force required to rotate the turbine runner using the following equation.

$$T = \frac{P}{\omega_t} \quad (9)$$

$$F = \frac{T}{r}$$

After determining the force required to rotate the turbine, the surface area of the bucket needed to generate this force must be calculated. The analysis can be performed using the conservation of energy approach through Newton's laws and the conservation of momentum in dynamic fluid flow, as shown in the following equation:

$$F = \dot{m} \; (v_2 - \dot{} v_{bucket}) \quad (10)$$

$$\dot{m} = \dot{\rho} \; A_2 \; v_2$$

After performing calculations and analysis using Equations 1–11, the specifications for each component in the construction of the PLTMH using a Pelton turbine are obtained.

RESULTS AND DISCUSSION.

This study aims to optimize a Micro Hydropower Plant (PLTMH) system using Pelton turbine technology to enhance energy efficiency in remote areas. The primary focus of this research is to harness hydraulic potential, such as water head and flow rate, to produce reliable and sustainable electricity. Through optimal geometric turbine design, the system is expected to provide a stable energy supply even under fluctuating flow rate conditions. This research also seeks to support electricity access in remote areas, improve the quality of life for communities, and reduce dependence on fossil-based energy with an environmentally friendly and cost-effective approach.

The research findings indicate that the implementation of a Pelton turbine-based Micro Hydropower Plant (PLTMH) system is highly relevant for meeting energy needs in remote areas. For instance, at the study location with an average water flow rate of 50 liters per second and a water head of 50 meters, this system successfully generates 3 kW of electrical power with a turbine efficiency of 80%. This demonstrates that the PLTMH system is capable of providing sufficient energy for basic community needs, such as lighting for village halls, mosques, and local schools. The design, adapted to the geographical conditions—such as using 4-inch diameter pipes and easily accessible local components—ensures operational sustainability despite fluctuations in water flow. With this success, the Pelton turbine-based PLTMH system not only provides stable energy access but also supports economic and social development in remote areas without causing significant environmental impacts.

Location parameters are key factors in determining the feasibility and efficiency of a Pelton turbine-based Micro Hydropower Plant (PLTMH) system. In this study, the selected location has an average water flow rate of 50 liters per second with a water head of 50 meters. The stable water flow during the rainy season provides an opportunity for consistent energy generation, even though a flow rate reduction of up to 30% occurs during the dry season. This condition still meets the minimum flow rate requirement of 11 liters per second. The geographical conditions of the location include a small river flowing through hilly terrain with limited road access, necessitating a simple yet efficient system design. The use of local materials, such as 4-inch diameter pipes and support structures made from resources available in the area, offers solutions to transportation and cost challenges. With these hydrological potentials and geographical conditions, the PLTMH system can be designed to provide a reliable energy supply to meet the needs of the local community.

Based on field survey data, the hydraulic potential of the location was calculated using Equation (2), where η represents system efficiency, ρ is the density of water (1000 kg/m^3), g is gravity (9.81 m/s^2), Q_{min} is the water flow rate (11 liters per second or 0.0109 m^3/s), and H is the water head of 50 meters. With a system efficiency of 70%, the calculation results indicate a hydraulic power potential of 3.72 kW. This value demonstrates that the energy potential of the location is sufficient to meet the basic requirements of the PLTMH system, producing 3 kW of electrical power with a turbine efficiency of 80%. These calculations are also utilized to determine component specifications such as the nozzle diameter and the optimal number of turbine buckets to ensure efficient operation under the given water flow conditions.

The technical design, created using CAD software, resulted in the main component specifications for the Pelton turbine-based PLTMH system. The design includes a jet diameter of 15 mm, chosen to optimize water flow at an average rate of 50 liters per second. The turbine is designed with a runner diameter of 300 mm and equipped with 24 buckets to ensure even distribution of kinetic energy during each rotation cycle. These buckets are designed with dimensions of 8 cm in width, 6 cm in height, and 3 mm in depth to maximize efficiency in capturing water flow. Additionally, dual nozzles with a 20-degree inclination angle are employed to improve water flow distribution to the turbine. This design not only considers technical aspects but also the availability of materials at the site, enabling components to be easily fabricated and assembled using local materials. This design provides a solid foundation for ensuring optimal system performance in remote areas.

The designed PLTMH system achieves an overall efficiency of 70%, encompassing the conversion of hydraulic energy into electrical energy through the generator. In this system, the Pelton turbine efficiency is set at 80%, reflecting the turbine's ability to optimally convert water's kinetic energy into mechanical energy. For instance, with a water flow rate of 50 liters per second and a water head of 50 meters, the initial hydraulic power potential of 24.5 kW can produce a net electrical power output of 17.15 kW after accounting for overall efficiency. The high turbine efficiency is achieved through an optimal design, including an appropriate number of buckets and precise nozzle diameter, which minimizes energy losses due to friction and turbulence. This system is designed to maximize the utilization of available water resources in remote locations while ensuring a stable and reliable electricity supply to meet the needs of the local community.

The construction and implementation of the Pelton turbine-based PLTMH system are designed to ensure efficiency and ease of maintenance, particularly in remote areas with limited access. The construction process begins with the fabrication of the turbine runner using locally sourced corrosion-resistant materials to ensure durability under environmental conditions. Dual nozzles with a diameter of 15 mm are assembled to optimally distribute water flow to the 24 turbine buckets. A 3-kW generator is installed using a pulley transmission system with a 2:1 ratio, ensuring stable mechanical power transfer from the turbine. The support structures for the turbine and generator are constructed from lightweight steel, which can be easily assembled on-site. System implementation includes initial testing to verify smooth water flow, turbine rotation stability, and electrical power output as per specifications. Additionally, basic training is provided to the local community on routine maintenance, such as cleaning the nozzles and checking the transmission belts. This process ensures that the PLTMH system operates reliably and sustainably to meet the electricity needs of the local community

The performance analysis of the Pelton turbine-based PLTMH system demonstrates significant operational efficiency under varying water flow conditions. With an average flow rate of 11 liters per second and a water head of 50 meters, the system generates 3-kW of electrical power, matching the generator's capacity. The Pelton turbine exhibits an efficiency of 80%, approaching the optimal value reported in previous literature, which is 85% under similar conditions [8]. Testing results also show that the system can maintain an overall efficiency of up to 70%, even when the water flow rate decreases by up to 35% during the dry season. The turbine rotation speed remains stable at 1500 rpm, ensuring optimal generator performance. Compared to other systems using different turbines, the Pelton turbine demonstrates higher efficiency in locations with a high head, supporting that this type of turbine is highly effective for locations with significant hydraulic potential. These findings confirm that the system's design and implementation successfully meet the community's energy needs while ensuring operational efficiency and stability[9, 10].

The Pelton turbine-based PLTMH offers significant advantages, particularly for remote areas with limited access to energy. This system has minimal environmental impact, as it does not produce greenhouse gas emissions or toxic waste [9], which highlight micro-hydropower plants as an ideal clean energy solution. Additionally, the PLTMH does not rely on weather conditions like solar or wind power, making it more reliable for generating electricity year-round, especially in areas with stable water flow. Economically, the PLTMH has low operational costs after the initial installation, and raw materials such as pipes and mechanical components can be sourced locally, reducing dependence on imports. This study also demonstrates that a 3 kW PLTMH system can support lighting and basic needs for public facilities in villages, contributing to an improved quality of life for the community. Another advantage is the system's ability to operate independently without connection to the main electricity grid, making it an ideal solution for remote communities in Indonesia. These findings reinforce the position of the PLTMH as an efficient, sustainable, and environmentally friendly renewable energy alternative.

The Pelton turbine-based PLTMH system faces several challenges that need to be addressed to ensure optimal operation, particularly in remote areas. One major challenge is the significant fluctuation in water flow between the rainy and dry seasons, which can affect output power stability. As a solution, the use of dual nozzles adjustable to varying water flow rates has been implemented, to enhance turbine efficiency under unstable flow conditions. Another challenge is the difficulty of transporting large components to remote locations with limited road access [11]. To overcome this, components such as turbine runners and pipes are designed in small modules that can be assembled on-site using simple tools. Additionally, the lack of local community knowledge regarding system maintenance poses a challenge, which is addressed through basic technical training covering routine maintenance such as cleaning nozzles and checking transmission belts. Support for local materials, cost-efficient installation, and system sustainability ensures that these challenges can be overcome without compromising the system's efficiency or stability. This discussion highlights the importance of an adaptive and community-based approach for the successful implementation of PLTMH systems.

The implementation of a Pelton turbine-based PLTMH system has significant social and economic implications, particularly for communities in remote areas. Socially, access to electricity enhances the quality of life by providing lighting for homes, schools, and public facilities, enabling extended hours for learning and work activities. Furthermore, the availability of energy supports access to healthcare services, such as the operation of basic medical equipment in village health centers. Economically, the PLTMH system stimulates the growth of small and medium enterprises in local communities, such as agricultural processing that requires electricity. This study shows that with a 3-kW power output, the system can support at least 15 households and several public facilities [12]. This aligns indicate that micro-hydro systems contribute to increased economic productivity in remote areas. Additionally, the system's low operational costs allow communities to allocate their budgets for other needs, such as education and business development. Thus, the PLTMH system not only serves as a sustainable energy solution but also as a significant instrument for social and economic development in remote areas.

The findings of this study align strongly with its initial objectives, which were to optimize the Pelton turbine-based PLTMH system to provide reliable, efficient, and sustainable energy in remote areas. The designed system successfully generates 3 kW of electrical power, meeting the initial target, with a turbine efficiency of 80% and an overall system efficiency of 70%. The stability of power output, even with water flow fluctuations of up to 30%, demonstrates the success of the technical design in addressing the challenges of inconsistent water flow conditions. Additionally, the use of local materials and a modular design achieves the goal of minimizing costs and facilitating implementation in areas with limited access is recommended [13]. This success not only meets the community's energy needs but is also socially and economically relevant by providing electricity access to public facilities and improving community welfare, thereby supporting sustainable development. For future development, the focus will be on improving efficiency and adaptability to various hydrological conditions.

One recommendation is the development of flexible nozzle designs to accommodate extreme fluctuations in water flow rates, as well as the use of lightweight yet corrosion-resistant composite materials for turbine runners to enhance durability and efficiency, particularly in locations with high sediment content. Additionally, the integration of automated control systems based on the Internet of Things (IoT) is proposed to monitor and regulate water flow in real-time, ensuring optimal operational efficiency despite sudden changes in flow rates. The combination of Pelton turbines with other renewable energy systems, such as solar panels, is also suggested to create more reliable hybrid systems. With this approach, the development of Pelton turbines not only improves technical performance but also provides sustainable, relevant, and dependable energy solutions to meet the energy needs of remote areas

CONCLUSIONS.

This study successfully demonstrates that the Pelton turbine-based PLTMH system is an effective, efficient, and sustainable renewable energy solution, particularly for remote areas in Indonesia. The designed system is capable of generating 3 kW of electrical power with a turbine efficiency of 80% and an overall system efficiency of 70%, even under fluctuating water flow conditions of up to 30%. The technical design, incorporating dual nozzles, local materials, and modular components, has proven effective in overcoming geographical and technical challenges in remote locations. The implementation of this system not only meets the community's energy needs but also provides significant social and economic benefits, such as improved quality of life, access to public facilities, and the development of local economies.

For future development, the study recommends innovations in the design of more flexible nozzles, the use of lightweight and corrosion-resistant composite materials, and the integration of IoT-based control systems to enhance operational efficiency. The combination of this system with other renewable energy technologies, such as solar panels, is also suggested to create more reliable and sustainable hybrid systems. Thus, the Pelton turbine-based PLTMH can continue to evolve as a relevant energy solution for remote areas, supporting sustainable development goals and reducing dependence on fossil fuels.

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