



# Development of a 3D-Printed Cross-Flow Turbine Prototype for Pico-Hydro Power Generation as a Sustainable Renewable Energy Source

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**Abstract.** Hydropower remained one of the most promising renewable energy sources, particularly for rural and off-grid communities. Pico-hydro systems, typically with a capacity of less than 5 kW, offer an attractive solution for areas with limited access to electricity, with cross-flow turbines being widely applied due to their simplicity and adaptability. However, conventional fabrication methods often face challenges related to manufacturing costs, design flexibility, and modest efficiency, creating a need for alternative approaches. This study investigated the application of additive manufacturing in developing a cross-flow turbine prototype utilizing 3D printing technology. The turbine was fabricated from PLA+ filament via Fused Deposition Modeling (FDM) and required approximately 5 days, 18 hours, and 42 minutes of printing time, with a total material consumption of 1,677 grams. Mechanical evaluation through tensile testing yielded an average tensile strength of 21.2 MPa, a maximum load of 0.508 kN, and a Young's modulus of 2.18 GPa, indicating adequate strength for pico-hydro applications. Experimental testing was conducted under a flow rate of 0.00347 m<sup>3</sup>/s and a head of 3.04 m, corresponding to a theoretical hydraulic input of 93.20 W. The turbine delivered an actual output of 64 W, resulting in an overall efficiency of approximately 68,58%. These findings confirm the feasibility of 3D printing for fabricating functional pico-hydro turbines with competitive performance, reduced cost, and greater design flexibility compared to conventional methods.

**Keywords:** 3D Printing Technology, Additive Manufacturing, Cross-Flow Turbine, Pico-Hydro Power Plant, Renewable Energy

## 1 Introduction

The increasing awareness of the importance of renewable energy utilization as a means to reduce the impacts of climate change and dependence on fossil fuels has highlighted hydropower as a promising solution. Indonesia possesses a renewable energy potential of approximately 442.4 GW; however, only 11.31% of this capacity has been harnessed for electricity generation (Ma'rif et al., 2023). Among the various sources of renewable

energy, water resources offer a clean and cost-effective option for electricity production. Indonesia has abundant water resources that can be utilized as a reliable energy source (Asri & Niwes, 2016). The country is endowed with approximately 65,017 tributaries and 5,590 major rivers, encompassing a total watershed area of 1,512,466 square kilometers. The vast network of rivers indicates that Indonesia's hydropower potential is significantly greater than that of wind energy (Ma'ruf et al., 2023). According to the Ministry of Energy and Mineral Resources (MEMR), Indonesia's potential for hydropower generation reached up to 75 GW in 2020.

Small-scale hydropower plants, such as pico-hydro systems, present an attractive option for remote areas that are not connected to the main electrical grid. Pico-hydro systems, typically with power capacities of less than 5 kW, are particularly suitable for regions with low to medium water flow rates (Malik et al., 2024). The operational principle of a hydropower plant involves converting the potential energy of water into electrical energy through the use of a turbine connected to a dynamo or generator (Ma'ruf et al., 2023). Among the various components, the turbine plays a critical role in transforming the kinetic energy of water into mechanical energy, which is subsequently converted into electricity (Triyono et al., 2024). One of the most commonly employed turbines in pico-hydro applications is the cross-flow turbine (Tirono, 2012), valued for its simple design and its ability to operate efficiently under a wide range of flow conditions (Hendri et al., 2024).

However, conventional cross-flow turbines still face limitations, including restricted efficiency, high manufacturing costs, and limited flexibility in design customization (Trisasiwi et al., 2002; Saputra et al., 2017). While additive manufacturing has been widely explored in other engineering applications, its integration into pico-hydro turbine design remains underexplored. This gap highlights the need to assess whether 3D printing can produce efficient, low-cost, and customizable turbine prototypes suitable for small-scale renewable energy systems.

This study introduces the use of 3D printing technology, specifically Fused Deposition Modeling (FDM) with PLA+ filament, to fabricate a cross-flow turbine prototype for pico hydro applications. The novelty of this research lies in demonstrating the feasibility of producing complex turbine geometries with adequate mechanical strength, acceptable efficiency, and relatively low cost using additive manufacturing (Yusanto et al., 2023). The focus of this work is to examine the mechanical characteristics of the printed specimens and evaluate the turbine's experimental performance under laboratory-scale testing.

## 2 Methodology

This research was conducted through several sequential stages, including the design and fabrication of a 3D-printed cross-flow turbine prototype. The preliminary turbine design is configured to operate under a head of 3.04 meters, with an available flow rate ranging from 0.002 to 0.005 m<sup>3</sup>/s. A detailed explanation of the methodology is presented in the subsections below.

## 2.1. Turbine Design

The preliminary stage of this study involved designing a cross-flow turbine using Computer-Aided Design (CAD) software. Design parameters, such as blade angle, rotor diameter, number of blades, and nozzle geometry, were determined based on a literature review and site-specific flow conditions suitable for pico-hydro applications.

$$\text{Flow Velocity:} \quad v = \frac{s}{t} = 0,190 \frac{m}{s} \quad (1)$$

$$\text{Cross-sectional area:} \quad A = P \times L = 0,01823 \text{ m}^2 \quad (2)$$

$$\text{Flow rate:} \quad Q = v \times A = 0,00347 \text{ m}^3/s \quad (3)$$

After determining the initial design parameters of the turbine, the dimensions of key components such as the runner blades and the volute casing can be calculated. These dimensions form the basis for the geometric configuration of the cross-flow turbine to be constructed, ensuring compatibility with the available head and flow rate in the pico-hydro system (Trisasiwi et al., 2002).

$$\text{Relative flow velocity:} \quad v = C * \sqrt{2gH} = 4.247 \text{ m/s} \quad (4)$$

$$\text{Tangential velocity:} \quad u = 0.48 * v = 2.038 \text{ m/s} \quad (5)$$

$$\text{Runner Outside Diameter:} \quad D_0 = \frac{u \times 60}{\pi \times n} = 0.16 \text{ m} \quad (6)$$

$$\text{Jet thickness:} \quad S_0 = 0.17 \times D_0 = 0.0264 \text{ m} \quad (7)$$

$$\text{Blade spacing:} \quad t = \frac{s}{\sin \beta} = 0.067 \text{ m} \quad (8)$$

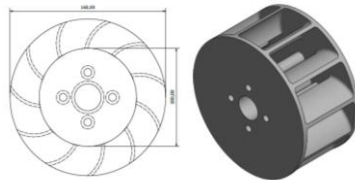
$$\text{Turbine thickness:} \quad L = \frac{Q}{S_0 * K_c * \sqrt{2gH}} = 0.07 \text{ m} \quad (9)$$

$$\text{Number of turbine blades:} \quad n = \pi \left( \frac{D_0}{t} \right) = 11 \quad (10)$$

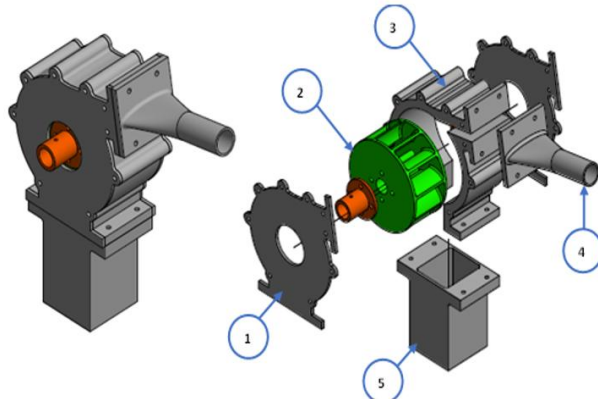
$$\text{Blade arc length:} \quad a = 0.17 \times D_0 = 0.0264 \text{ m} \quad (11)$$

$$\text{Runner Inner diameter:} \quad D_i = D_0 - (2 * a) = 0.1 \text{ m} \quad (12)$$

Following the calculation above, the runner blades can be accurately generated using Computer-Aided Design (CAD) software.



**Figure 1.** Sectional View and Isometric View of Runner Blade



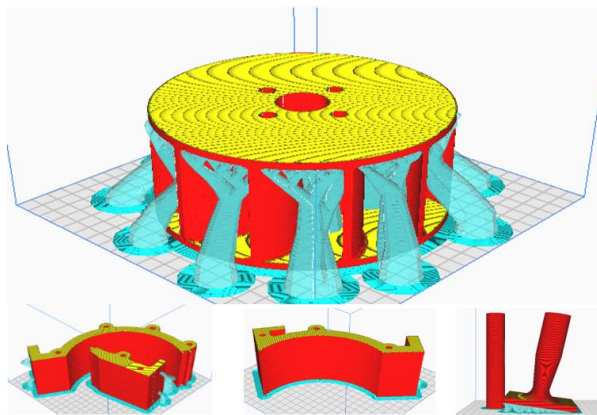
Nodal Description: (1) Cover, (2) Runner Blade, (3) Volute Case, (4) Inlet, (5) Outlet

**Figure 2.** Cross-Flow Turbine Assembly

## 2.2. 3D Printing and Fabrication

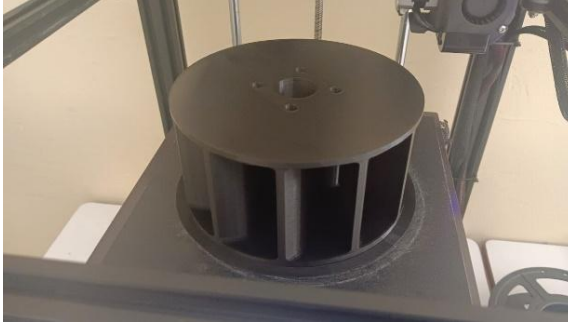
The turbine components were fabricated using Fused Deposition Modeling (FDM) technology, a widely adopted additive manufacturing method known for its cost-effectiveness and accessibility. PLA+ filament was selected due to its improved mechanical strength, dimensional stability, and environmental friendliness compared to standard PLA. The fabrication process involved several key steps.

**3D Modeling and Slicing.** The finalized CAD models of turbine components, including the runner blades, shaft, nozzle, and volute casing, were exported in STL format. These files were processed using slicing software Ultimaker Cura to generate G-code for the 3D printer. Parameters such as layer height (0.15 mm), infill density (50%), print speed (100 mm/s), and support structures were optimized to strike a balance between print quality and strength.



**Figure 3.** Slicing Process in Ultimaker Cura Design

**Printing Process.** A desktop FDM 3D printer was used to print each part individually. The nozzle temperature was maintained at 240°C, while the heated bed was set to 70°C to ensure proper adhesion. The components were printed with a 10% infill pattern using a zigzag design to reduce weight while maintaining structural integrity.



**Figure 4.** Print Result

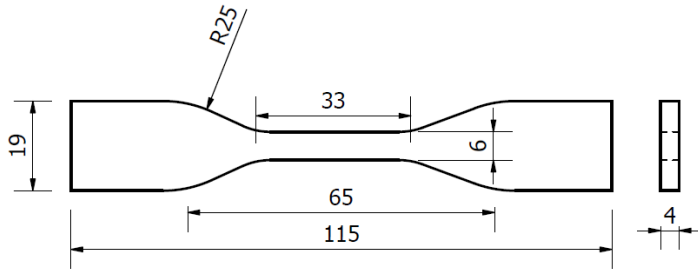
**Post-Processing and Assembly.** After printing, the components underwent post-processing steps, including the removal of support structures. The turbine parts were then assembled using bolts, adhesive, and alignment tools to ensure correct positioning and fit between components.



**Figure 5.** Assembly Cross-Flow Turbine Components

### 2.3. Tensile Test of PLA+ Filament

The tensile test is widely recognized as a fundamental method for evaluating the behavior of materials under axial tensile loading. In this study, PLA+ filament specimens were fabricated and tested according to the ASTM D638 Type IV standard (ASTM International, 2015), which is specifically designed for assessing the tensile properties of polymer-based materials. Five repeated tests were conducted to obtain the average tensile strength of the specimens.



**Figure 6.** Specimen Dimensions D638 Type IV

#### 2.4. Experimental Setup and Testing

To assess the functional performance of the 3D-printed cross-flow turbine prototype, a controlled experiment was conducted using a concrete water reservoir as the main source of potential energy. The test aimed to simulate actual pico-hydro operation conditions and evaluate how the turbine performs under different flow rates and load conditions. The experiment was conducted at a dedicated testing site equipped with a concrete water reservoir measuring approximately 1 meter in height and 2 meters in cross-section. The reservoir, constructed from reinforced concrete, was designed to store and maintain a stable water head of approximately 3.04 meters during discharge. The concrete structure ensured minimal deformation, reduced water leakage, and allowed repeatable testing with consistent hydraulic conditions. Water was supplied to the concrete reservoir through a gravity-fed system from an open drainage channel (irrigation canal), allowing continuous flow and sustainable water use throughout the experiment.



**Figure 7.** Turbine Set Up with Small Generator

### 3 Result and Discussion

#### 3.1. Result

Using Fused Deposition Modeling (FDM) with PLA+ filament, the turbine components, including the runner blade, volute casing, and nozzle, were successfully fabricated based on the design model. The printed parts demonstrated good reproducibility across multiple builds, confirming the reliability of the process. The modular capability of 3D printing enabled efficient assembly and testing of individual components, while the low-cost material provided a cost-effective solution.

**Table 1.** Time and Material for Fabrications

No	Items	Times	Material needs
1	Runner Blades	1 day 18 hours 57 minutes	459 grams
2	Volute Case	1 day 20 hours 23 minutes	824 grams
3	Intake + Long Bushing	19 hours 11 minutes	128 grams
4	Left-Right Bushing	5 hours 53 minutes	42 grams
5	Outlet	1 day 2 hours 18 minutes	224 grams
	<b>TOTAL</b>	<b>5 days 18 hours 42 minutes</b>	<b>1677 grams</b>

The total time required to 3D print all components was approximately 5 days, 18 hours, and 42 minutes, excluding the assembly process. The cross-flow turbine prototype was successfully fabricated using PLA+ filament, with a total material consumption of 1,677 grams.

**Table 2.** Tensile Test Result

Sample	Lc (mm)	Fm (kN)	Rm (MPa)	E (GPa)
1	115	0.51	21	1.8
2	115	0.46	19	2.1
3	115	0.55	23	2.3
4	115	0.5	21	2.1
5	115	0.52	22	2.6
	<b>Average</b>	<b>0.508</b>	<b>21.2</b>	<b>2.18</b>

Mechanical performance was further evaluated through tensile testing of PLA+ specimens (ASTM D638 Type IV) with five repetitions. The results are shown in Table 2 above.

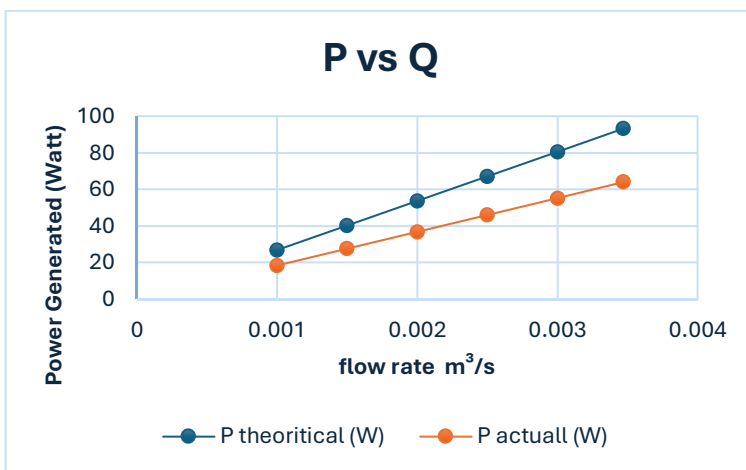
Experimental tests were conducted to evaluate the performance of the 3D-printed cross-flow turbine under controlled flow and head conditions. Key parameters, including flow rate, head, voltage, current, and output power, were recorded. At a flow rate of 0.001 - 0.00347 m<sup>3</sup>/s and a head of 3.04 m, the turbine successfully generated electrical power, as shown in Table 3 below.

**Table 3.** Power Generated

Flow rate (Q) (m <sup>3</sup> /s)	$P_{theoretical}$ (W) 90%	$P_{actual}$ (W)
0.00100	26.84	18.4
0.00150	40.26	27.6
0.00200	53.68	36.8
0.00250	67.10	46.0
0.00300	80.51	55.2
0.00347(max)	93.20	64.0

### 3.2. Discussion

From a mechanical perspective, the tensile testing of PLA+ offers key insights into its structural suitability for pico-hydro turbine applications. The specimens produced an average tensile strength ( $R_m$ ) of 21.2 MPa at a maximum load ( $F_m$ ) of 0.508 kN and a Young's modulus ( $E$ ) of 2.18 GPa, demonstrating moderate strength combined with reasonable stiffness. These findings confirm that PLA+ provides adequate load-bearing capacity for small-scale turbine components under controlled conditions. However, it is important to note that the performance of PLA+ may be influenced by environmental exposure, particularly to water and UV radiation. Studies have shown that hydrolytic degradation occurs when PLA-based materials are immersed in water, leading to chain scission that reduces tensile strength and stiffness over time (Krasowska & Heimowska, 2023). Similarly, UV exposure accelerates photodegradation, causing embrittlement and loss of ductility, which can further compromise long-term mechanical stability (Czechowski et al., 2022). PLA+ is suitable for initial turbine fabrication. However, its durability under continuous outdoor and wet conditions may be limited without the use of protective coatings or material reinforcement.

**Figure 8.** Power Generated and Flow Rate Diagram

The comparison between the theoretical turbine power (calculated at 90% hydraulic efficiency) and the actual output across a flow rate range of 0.00100–0.00300 m<sup>3</sup>/s at a constant head of 3.04 m provides important insights into the performance of the pico-hydro turbine. As expected, shown in Figure 8 above, both theoretical and actual power increased proportionally with flow rate, since turbine power is directly dependent on discharge. At lower flow rates (0.00100–0.00200 m<sup>3</sup>/s), the actual power output was significantly below the theoretical prediction, resulting in lower efficiency values. This discrepancy can be attributed to hydraulic losses, leakage, and reduced runner interaction with the incoming jet at suboptimal flow conditions. As the flow rate increased toward 0.00300 m<sup>3</sup>/s, the actual output approached a maximum value of 64 W. Based on theoretical turbine power, and actual power turbine efficiency could be calculated.

$$\eta_{eff} = \frac{P_{out}}{P_{theoretical}} = \frac{64 \text{ watt}}{93.29 \text{ watt}} = 68.58\% \quad (13)$$

The resulting efficiency at this operating point was approximately 68–70%, which is consistent with efficiency levels commonly reported for laboratory-scale cross-flow for such low-head, small-scale setups (Acharya et al., 2015).

## 4 Conclusion

This study demonstrated the feasibility of employing 3D printing technology—specifically Fused Deposition Modeling (FDM) with PLA+ filament—for the fabrication of a cross-flow turbine prototype designed for pico-hydro applications. The fabrication process required a total printing time of approximately 5 days, 18 hours, and 42 minutes, consuming 1,677 grams of material with a zigzag infill pattern at 10% infill density. Mechanical characterization of the printed specimens revealed an average tensile strength (Rm) of 21.2 MPa under a maximum load (Fm) of 0.508 kN and a Young's modulus (E) of 2.18 GPa, which confirmed adequate stiffness and moderate strength for structural applications. The use of additive manufacturing enabled the production of complex turbine geometries with acceptable dimensional accuracy at a relatively low cost. Experimental performance testing at a flow rate of 0.00347 m<sup>3</sup>/s and a head of 3.04 m, corresponding to a theoretical hydraulic input power of 93.20 W, produced an actual power output of 64 W, which resulted in an overall system efficiency of approximately 68.58%. This efficiency was consistent with the ranges commonly reported for laboratory-scale cross-flow turbines. Overall, the findings demonstrated the potential of 3D printing technology as a rapid, cost-effective, and reliable method for developing small-scale renewable energy systems, particularly for applications in remote or off-grid areas.

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