Inflow Prediction System and Grindulu Hydropower Production Optimization using The Bi-LSTM Seq2Seq Quantile Regression Model

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The Grindulu PS Hydroelectric Power Plant is one of the hydroelectric power plants that relies on the flow of the Grindulu River as its primary energy source. Due to the irregularity of water discharge, particularly at its lowest point during the dry season, the Grindulu PS Hydroelectric Power Plant is planned to be constructed using variable speed drive (VSD) technology [1], [2]. The objective of this study is to analyze the hydrological and hydraulic data of the Grindulu River to determine the annual water discharge profile, particularly during the dry season; to analyze the minimum potential for electricity generation from the Grindulu PS Hydroelectric Power Plant based on the lowest available discharge; and to analyze the Variable Speed Drive (VSD) system of the Grindulu PS Hydroelectric Power Plant in optimizing electricity generation under minimum discharge conditions during the dry season. This study is a quantitative-predictive analysis aimed at modeling inflow predictions at the proposed site for the Grindulu Hydropower Plant, which is planned to utilize a pumped-storage system. The prediction model used is the Bi-Directional Long Short-Term Memory Sequence-to-Sequence (Bi-LSTM Seq2Seq) with a Quantile Regression (QR) approach to generate inflow estimates at various levels of uncertainty (q10, q50, and q90) [3]. The research results show that the flow characteristics of the Grindulu watershed are dominated by relatively constant low-flow conditions throughout the year, particularly during the dry season, as indicated by the q50 and q90 flow values, which are both 1.021 m^3/s. This indicates that the flow is dominated by baseflow and that high-flow events occur only for limited periods. With a minimum flow potential and a reservoir system design flow of 242 m^3/s, a generation capacity of +1,000 MW can be achieved by utilizing the water stored in the upper reservoir. At the Grindulu River Basin hydroelectric power plant, the VSD system allows for more flexible and efficient operation of the pump-turbines, ensuring that power generation remains normal even under minimum flow conditions. The analysis results indicate that the hydraulic technical parameters that need to be considered in supporting the implementation of the VSD system under minimum flow conditions are water flow, effective head, reservoir water level fluctuations, turbine efficiency, and flow stability [2].

Keywords: Variable Speed Drive, Hydropower, Bi-LSTM Seq2Seq.

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1. Introduction

The Indonesian government is committed to reducing greenhouse gas emissions and addressing the decline in fossil fuel production by accelerating the transition toward new and renewable energy (NRE) [4], [5]. This commitment is aligned with the National Energy Policy (PP No. 79 of 2014), which targets an NRE mix of 23-31% by 2050. As electricity demand continues to rise, the government is prioritizing the development of hydropower as a reliable energy source and storage system [2], [1]. In the Java-Bali region, the RUPTL 2025-2034 outlines the strategic development of Pumped Storage (PS) hydropower plants, such as the Grindulu PS project in Pacitan, East Java, to improve load factors and support the integration of variable renewable energy (VRE) into the national grid. The urgency of this research lies in the significant operational challenges posed by hydrological fluctuations of the Grindulu River. During the dry season, water discharge drops to its lowest levels, which severely limits the capacity of conventional fixed-speed turbines that cannot adapt to varying flow rates. This technical limitation results in energy inefficiency and threatens the reliability of peak load supply. To address this, the implementation of Variable Speed Drive (VSD) technology is proposed for the Grindulu PS project. VSD allows for dynamic adjustments of turbine and generator speeds, ensuring that even at minimum discharge, the hydropower plant can maintain high efficiency and a better ramping rate, which is critical for modern grid stability.

The scope of this research is specifically focused on the technical integration of hydrological and hydraulic data for the Grindulu PS Hydropower Plant. While previous studies have explored VSD in electrical control or general micro-hydro feasibility, there is a lack of technical analysis that specifically bridges the gap between seasonal river discharge profiles and VSD operational effectiveness. This study limits its focus to the hydraulic performance and simulation of VSD systems during the dry season's critical low-flow scenarios. By excluding non-technical factors such as economic or social-environmental impacts, the research maintains a rigorous focus on the feasibility of VSD as a solution for fluctuating river inflows in the Indonesian context.

The objectives of this research are clearly defined to provide a comprehensive technical evaluation of the proposed system. First, the study aims to analyze the hydrological and hydraulic data of the Grindulu River to establish a discharge profile, particularly during the dry season. Second, it seeks to evaluate the minimum electrical power generation potential based on the lowest available discharge data. Finally, the research aims to analyze the effectiveness of the Variable Speed Drive (VSD) system in optimizing power output and operational continuity during these minimum discharge conditions. The results are expected to serve as a vital technical reference for stakeholders and contribute to the scientific understanding of flexible hydropower operations.

2. Literature Review And Problem Statement

Current research in the hydropower sector highlights the critical impact of hydrological variability on energy reliability, particularly under the influence of climate change. Previous studies have shown that the efficiency of small-scale hydropower plants can be significantly improved under low-flow conditions by utilizing advanced control systems, such as Permanent Magnet Synchronous Generators (PMSGs), which offer better stability than conventional systems [6]. Other findings also identify that seasonal variability and prolonged dry seasons in Southeast Asia act as major constraints, leading to a significant reduction in hydropower generation capacity for facilities reliant on surface water. On the other hand, some studies suggest that Seasonal Pumped Hydro Storage (SPHS) can mitigate these risks by enhancing grid flexibility; however, most existing literature focuses on large-scale climate modeling or specific power control issues [7]. There is a striking contradiction in the literature regarding the most effective mitigation strategies; while some emphasize hybrid battery systems to reduce mechanical wear [8], others focus on reservoir management to increase river flow [1].

Despite these advancements, a significant research gap exists in the technical integration of high- resolution hydrological forecasting with the specific application of Variable Speed Drive (VSD) technology for pumped-storage systems in basins with extreme seasonal fluctuations like the Grindulu River. Previous studies evaluate micro-hydropower performance using general tools like GEOGloWS but often overlook the dynamic interaction between real-time inflow uncertainty and variable turbine speeds [9]. Consequently, the problem addressed in this study is the lack of a technical framework that utilizes advanced predictive modelling, specifically the Bi-LSTM Seq2Seq with Quantile Regression, to optimize the operational efficiency of the Grindulu PS plant under minimum discharge conditions. This research aims to solve the inefficiency of conventional fixed-speed systems by analyzing how VSD can adapt to quantified inflow uncertainties (q10, q50, and q90), thereby ensuring the sustainability of power generation during the dry season.

3. Method

The research method employed in this study is a quantitative-predictive approach, specifically chosen for its capability to provide accurate and stable inflow forecasts that align with the highly stochastic characteristics of hydrological data. Given that the Grindulu PS Hydropower infrastructure is in the pre- construction phase, this study relies on a combination of historical hydrometeorological data, Digital Elevation Models (DEM), and pre-feasibility estimates. The core of this methodology is the implementation of the Bi-Directional Long Short-Term Memory Sequence-to-Sequence (Bi-LSTM Seq2Seq) architecture combined with Quantile Regression (QR). This specific method was selected because it effectively captures long-term dependencies and bi-directional temporal patterns in rainfall-runoff cycles while quantifying hydrological uncertainties through probabilistic intervals (q10, q50, and q90). This ensures the model remains robust against the irregular discharge patterns typical of the Grindulu watershed, particularly during critical dry seasons.

The analysis process begins with watershed delineation and proxy inflow construction. Using GIS- based flow direction and accumulation analysis, the catchment area is identified to calculate estimated runoff. Since actual inflow data is unavailable, rainfall data from the last 10 years is converted into a proxy inflow dataset using the SCS Curve Number (CN) method and rainfall-runoff transformation. Before modeling, the data undergoes rigorous pre-processing, including outlier removal, Min-Max scaling normalization, and segmentation into look-back windows and forecast horizons. The dataset is partitioned into training (70%), validation (15%), and testing (15%) sets. The Bi-LSTM Seq2Seq model is then trained using the Pinball Loss function and the Adam optimizer to maintain stability. The evaluation approach utilizes probabilistic metrics such as Continuous Ranked Probability Score (CRPS) and Prediction Interval Coverage Probability (PICP) to validate the consistency of the forecasts against seasonal hydrological ranges.

The research samples consist of secondary hydrometeorological and geospatial data specifically focused on the Grindulu Watershed in Pacitan, East Java. The primary data samples include 10 years of daily rainfall records from BMKG, which serve as the main runoff indicator. Additionally, estimated reservoir parameters such as Elevation Area Volume (EAV) curves, planned water levels (EL upper and EL lower), and effective storage capacities are integrated as focus variables. The spatial samples are derived from Digital Elevation Models (DEM), soil type maps, and land-use maps to determine the Curve Number coefficients. Each data sample is identified and screened for relevance based on its proximity to the planned site, ensuring that the input variables accurately reflect the specific topographical and hydrological conditions required for a reliable pumped-storage simulation.

4. Results And Discussion

The study area for this research is located within the Grindulu River Basin (DAS), situated in Pacitan Regency, East Java Province. The Grindulu PS hydroelectric dam is situated at coordinates 08° 04' 42.16" S and 111° 19' 36.24" E. The total area of the Grindulu Watershed is approximately 655.40 km², with some literature citing a range of 600–800 km². The analysis focuses on the inflow discharge entering the hydroelectric power plant reservoir; therefore, this study uses the Grindulu River watershed area with a planned catchment area at the dam site of 127.86 km² and a river length of 23.07 km. According to PLN's 2025–2034 Long-Term Power System Plan (RUPTL), the development of the Grindulu Hydroelectric Power Plant is planned to strengthen the Java-Bali power system. The projected power balance for the Grindulu Hydroelectric Power Plant in 2033 is 1,000 MW. This capacity is determined based on system design and grid operational requirements, specifically to meet peak loads and to enhance the system's flexibility in accommodating renewable energy integration.

Rainfall data analysis was conducted to obtain an overview of rainfall characteristics in the Grindulu watershed as a basis for further hydrological analysis. A total of 6 stations with the same observation period, namely from 2014 to 2024, were used in this study. The rainfall data used in this study were obtained from 6 rainfall observation stations located around the Grindulu watershed area, namely the Pacitan, Nawangan, Kebon Agung, Bandar, Tegalombo, and Tulakan stations. The data used consisted of daily rainfall data obtained from relevant agencies.

Table 1. Rainfall in the Grindulu PS Watershed Bulan (mm)

No	Tahun	Jan	Feb	Mar	Apr	Mei	Jun	Jul	Agu	Sep	Okt	Nov	Des	Jumlah
1	2014	456	167	125	145	40	149	137	16	0	5	256	574	2069
2	2015	285	305	376	311	101	4	0	0	1	0	142	219	1744
3	2016	255	343	428	319	230	226	102	206	323	257	468	345	3502
4	2017	418	394	238	369	84	58	53	20	107	286	784	277	3087
5	2018	611	308	327	133	37	15	0	8	28	21	440	322	2251
6	2019	394	220	480	156	31	1	3	0	0	15	60	198	1557
7	2020	425	363	484	176	248	124	10	27	87	306	428	330	3008
8	2021	415	371	273	254	53	212	84	53	92	102	603	358	2870
9	2022	245	353	331	222	189	182	30	134	253	665	562	402	3568
10	2023	270	575	249	211	88	123	95	3	2	7	125	153	1900
11	2024	392	313	374	261	20	61	66	3	86	110	505	637	2828

No	Tahun	Jan	Feb	Mar	Apr	Mei	Jun	Jul	Agu	Sep	Okt	Nov	Des	Jumlah
Rata-Rata		379	337	335	232	102	105	53	43	89	161	398	347	2580
Maksimum		611	575	484	369	248	226	137	206	323	665	784	637	3568
Minimum		245	167	125	133	20	1	0	0	0	0	60	153	1557

Table 1. shows that average rainfall in the Grindulu watershed ranges from 43 mm/month to 398 mm/month. November through April are months with relatively high rainfall, while May through October have relatively low average monthly rainfall.

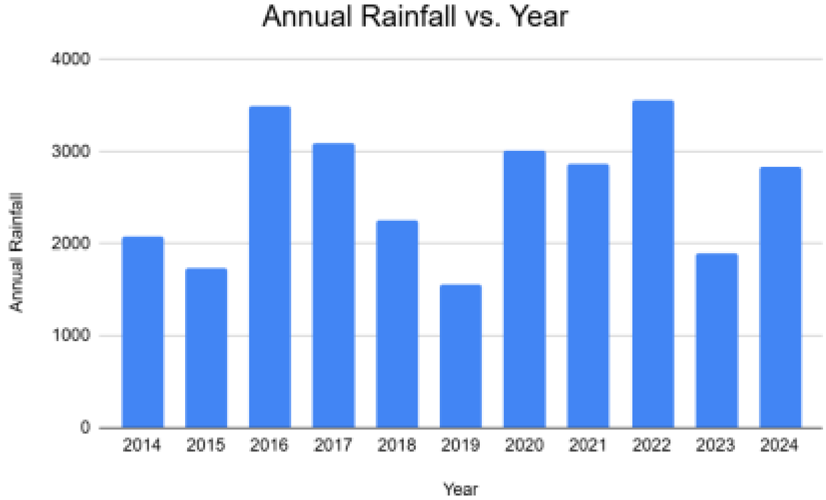

Figure 1. Annual Rainfall DAS Grindulu

Figure 1 above shows that, for the period 2014–2024, 2019 was the year with the lowest annual rainfall, at 1,557 mm, while 2022 was the year with the highest annual rainfall, reaching 3,568 mm. The calculated regional rainfall data is then used as the basis for hydrological analysis to determine inflow discharge.

A return period analysis (RPA) was then conducted to determine the design rainfall characteristics for the Grindulu Watershed based on specific rainfall events. This calculation was performed as a supporting hydrological analysis for the hydropower plant's inflow conditions. The results of the rainfall recurrence interval analysis are as follows:

Table 2. Results of the Design Rainfall Analysis

Recurrence Interval (T)	Xr	SD	K	Xt (mm)
2 year	72,41	23,67	-0,14	69,14
5 year			1,03	96,88
10 year			1,18	100,36
25 year			2,79	138,42
50 year			3,52	155,63

The next step is to calculate the rainfall intensity to determine the amount of rainfall per unit of time for a specific return period. The results of the rainfall intensity calculation are as follows:

Table 3. Analysis of Rainfall Intensity

Recurrence Interval (T)	Xt (mm)	I (mm/jam)
2 year	69,14	23,97
5 year	96,88	33,59
10 year	100,36	34,79
25 year	138,42	47,99
50 year	155,63	53,96

Furthermore, the SCS method was used to calculate the amount of direct runoff from a rainfall event. The primary parameter in this method is the Curve Number (CN), which serves to estimate a land area's potential to generate runoff. CN values range from 0 to 100 and are used because of their simplicity in estimating the amount of rainfall that will become runoff. Based on the Grindulu Watershed spatial plan map, the area designated for the Grindulu PS hydroelectric power plant is dominated by moderate to dense vegetation, consisting largely of forested areas. Meanwhile, surrounding the site are areas of dryland fields and agricultural land owned by local residents, as well as relatively low-density settlements. Given these conditions, land cover is assumed to be dominated by forest (70%), dryland fields (15%), agricultural land (8%), and settlements (7%).

Table 4. CN Value of the Grindulu Watershed

Land	Condition	% Area	CN	%Area*CN
Forest	Fair	70,00%	73	51,10
Grassland	Poor	15%	85	12,75
Agricultural	Fair	8%	85	6,80
Residential	Good	7%	83	5,81
Total		100,00%		76,46

In the SCS CN method, a composite CN value of 76.46 (>75) is considered high, indicating that the watershed has a relatively high runoff potential (**Soulis**). This is due to a combination of land cover, soil type with low infiltration capacity (HSG C), and hilly topography, so that most of the rainfall becomes surface runoff rather than infiltrating into the soil. High CN value correlates with low infiltration capacity, thereby increasing the volume of direct runoff. A CN value of 76.49 indicates a hydrological response where runoff increases significantly during rainfall and decreases significantly during dry periods. This CN value is also used to determine the Initial Abstraction (Ia) value, which is the portion of rainfall retained by vegetation, stored on the surface, or collected in specific basins before runoff occurs [10]. The Ia value is obtained by multiplying the value 0.2 the USDA's empirical runoff assumption by the potential maximum retention (S). In this study, the runoff value was below the Initial Abstraction (Ia) value, at 15.6 mm; thus, although the Grindulu Watershed has high runoff potential, the rainfall that occurred was insufficient to trigger surface flow, resulting in runoff values that tend to be low or zero. Runoff data is used to calculate inflow discharge by considering the catchment area of the Grindulu watershed.

Next, the total discharge value is calculated, which is the sum of the daily runoff discharge and the baseflow discharge. This total discharge value is used to determine the design discharge values q10,

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q50, and q90 through probabilistic analysis. The q10 value can also be interpreted as the value representing the highest flow condition that still occurs relatively frequently. Meanwhile, the q50 value is the median discharge exceeded 50% of the time, reflecting normal river flow conditions. Then, q90 describes the discharge that remains reliable 90% of the time, where q90 represents low-flow conditions that generally occur during the dry season [11]. In hydropower plant planning, the q90 value is often used as a reference to determine the minimum reliable flow rate that can ensure the plant's operational sustainability. This inflow dataset is then used as input for inflow prediction modeling using the BiLSTM Seq2Seq method with a Quantile Regression approach.

Figure 2. Historical Inflow Data for the Grindulu Watershed

The results of the inflow prediction using the BiLSTM Seq2Seq model are shown in Figure 2, which demonstrates that the prediction model is able to closely follow historical inflow patterns. The historical inflow data was derived from daily rainfall data for the years 2014–2024, comprising a total of 4,018 days. From this data, an average flow rate of 1.65 m³/s was obtained, a maximum flow rate of 115.84 m³/s indicating flow conditions during heavy rainfall, and a minimum flow rate of 1.021 m³/s indicating baseflow conditions during the dry season. The graph shows that the highest rainfall occurred in 2018, while in other years there were no significant differences in rainfall patterns. In the graph, the maximum discharge is defined as the highest recorded discharge during the 2014-2024 period or the highest extreme event. The historical inflow results, dominated by baseflow where the average discharge is not significantly different from the minimum discharge indicate that the flow system in the Grindulu Watershed is characterized by low-discharge conditions, with high-discharge events being transient. These historical inflow modelling results can serve as a basis for water availability analysis in hydropower plant planning.

Furthermore, the modelling results show that the BiLSTM Seq2Seq model is capable of capturing inflow variations in the Grindulu watershed. The prediction results graph shows a pattern match between historical inflow data and the model's predicted inflow values, particularly in depicting the flow fluctuations that occur between the rainy and dry seasons.

igure 3. 2025 Annual Inflow Simulation

Figure 3 shows that the q10, q50, and q90 values in the 7-day forecast range show no significant differences and are relatively constant for each quartile. In the rainfall forecast for May 15-21, 2025, the total average inflow volume is 0.62 million m³ with an average discharge of 1.025 m³/s.

Figure 4. 7-Day Pumped Storage Simulation

After determining the estimated inflow, a model was created to determine how long it would take for the upper reservoir to fill to capacity with the available natural inflow. The initial upper reservoir level for this model was set at 90%. This means that once the upper reservoir reaches 90% of its capacity, the power plant can begin operations. The storage volume of the upper reservoir is 5.42 million m³. Figure 4. shows that the estimated time required to fill the upper reservoir to a level sufficient to drive the turbine is approximately 7 days, with a total energy output of 28,000 MWh. The calculation is based on the flow rate obtained from previous calculations, with an average planned power plant production time of 4 hours. Based on the results of this modeling, it is also estimated that the minimum reservoir level is 37.3%.

An analysis of the power potential at the Grindulu Hydroelectric Power Plant was then conducted to determine the amount of electrical energy that can be generated based on the available inflow data obtained from the inflow prediction modelling in the previous stage. In this study, the power potential calculation focused on minimum flow conditions occurring during the dry season, which represent the conditions when the lowest operational threshold is reached. The calculation of electrical power potential was performed by considering several key parameters in the hydroelectric power generation system, namely flow rate, for which data was derived from rainfall. The volume of flow in the Grindulu watershed will influence the sustainability of electricity production within the power generation system. The results of the previous flow rate analysis showed that the q50 value (average flow rate) and the q90 value (flow rate during the dry season) do not differ significantly because rainfall in the Grindulu watershed is dominated by base flow; therefore, the predicted average inflow value (q50) is used as a reference in the analysis of electricity generation potential.

Total Energi (Q50)	Rata-rata Jam Bangkit/Hari	Hari Kapasitas Penuh	Level Reservoir Min
28,000 MWh	4.0 jam	7 hari	37.3%

Tabel Detail Pumped Storage per Hari

Tanggal	Q50 Inflow (m^3/s)	Jam Bangkit (Q50)	Energi Q50 (MWh)	Energi Q90/Kering (MWh)	Energi Q10/Basah (MWh)	Upper Reservoir (%)	Lower Reservoir (%
2026-05-15	1.029	4	4000	4000	4000	37.3	64.
2026-05-16	1.025	4	4000	4000	4000	37.3	64.
2026-05-17	1.024	4	4000	4000	4000	37.3	64.
2026-05-18	1.024	4	4000	4000	4000	37.3	63.
2026-05-19	1.024	4	4000	4000	4000	37.3	63.
2026-05-20	1.025	4	4000	4000	4000	37.3	63.
2026-05-21	1.025	4	4000	4000	4000	37.3	63.

Figure 5. Prediction of Power Plant Capacity

Based on Figure 5, it can be seen that the power generation potential for low, average, and high flows will consistently produce 4,000 MWh with a run duration of 4 hours. In the design of this hydroelectric power plant, the upper reservoir and lower reservoir will be used as dams in a pumped-storage system, where water flowing from the upper reservoir to the lower reservoir will be pumped back to the upper reservoir. In this study, the storage volume of the upper reservoir is assumed to be 5.42 million m³, which is deemed sufficient to support power generation operations with a design flow rate of 242 m³/s and an operating duration of 4 hours. It is known that the required water volume is approximately 3.48 million m³ per cycle. Based on the planning results, the storage capacity of the upper reservoir is 5.42 million m³, which is sufficient to support one power generation cycle. The difference between the storage capacity and the operational requirement is +1.94 million m³. This volume serves as a reserve to support the stability of the system.

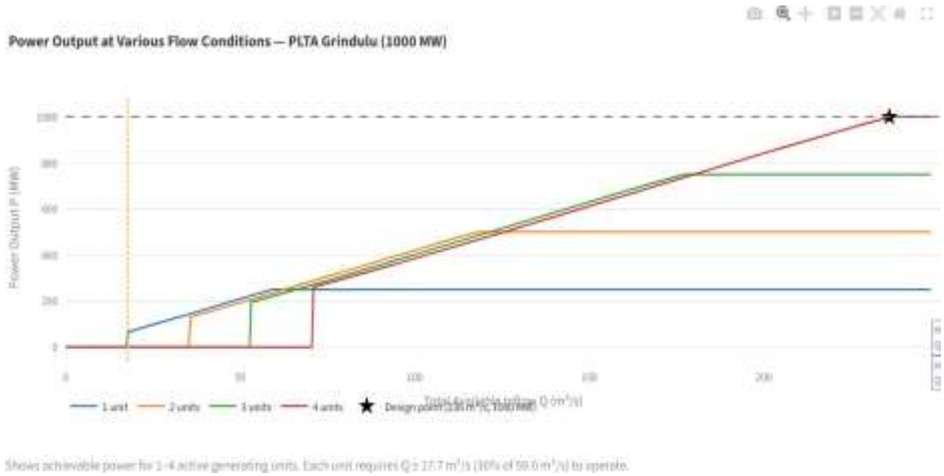

Figure 6. Power Output Under Various Flow Conditions

Figure 6 shows the relationship between total available flow and the electrical power generated by the Grindulu PS hydroelectric power plant based on modeling results for the operation of 1 to 4 active turbine units. The orange dashed line on the left indicates the minimum inflow required for the turbines to operate. This line indicates that under low inflow conditions, most units cannot yet be operated because the flow rate has not met the minimum operational threshold for the turbines; this suggests that multi-unit operation is highly dependent on the availability of a sufficiently large flow rate. The graph illustrates the importance of unit commitment strategy, adjusting the number of active units based on available flow to maintain power plant operational efficiency and reduce energy losses resulting from partial operation. In this study, it is assumed that the Grindulu PS hydroelectric power plant is designed with 4 turbines, each having a rated power or maximum achievable output of 250 MW, an average head of 500 m, and a speed of 500 RPM. The intake velocity for drawing water from the upper reservoir is assumed to be limited to 12 m/s, while the water flow in the tunnel ranges between 2.5-3 m³/s. The blue, orange, green, and red curves in Figure X represent the number of active turbine units operating simultaneously.

For the power plant to generate electricity, each turbine requires a minimum flow rate of 17.7 m³/s. This means that the turbines can operate only if the flow rate exceeds this minimum threshold. This condition aligns with the characteristics of Francis turbines, where efficiency and operational stability are significantly influenced by the adequacy of the flow rate relative to the design flow rate. When considering the natural inflow rate of 1,021 m³/s, this flow rate is still far below the required flow rate for power plant operations. Therefore, the reservoir system, the VSD system, and pumped storage are critical components to ensure the power plant operates optimally. This aligns with the concept of storage-based hydropower plants, where operational continuity is heavily influenced by the reservoir's ability to accumulate flow before it is utilized for power generation [12]. ability to optimize electricity production under fluctuating inflow conditions, particularly during periods of minimum flow in the dry season. The VSD system allows the turbine and generator to operate at varying rotational speeds in accordance with available water flow conditions.

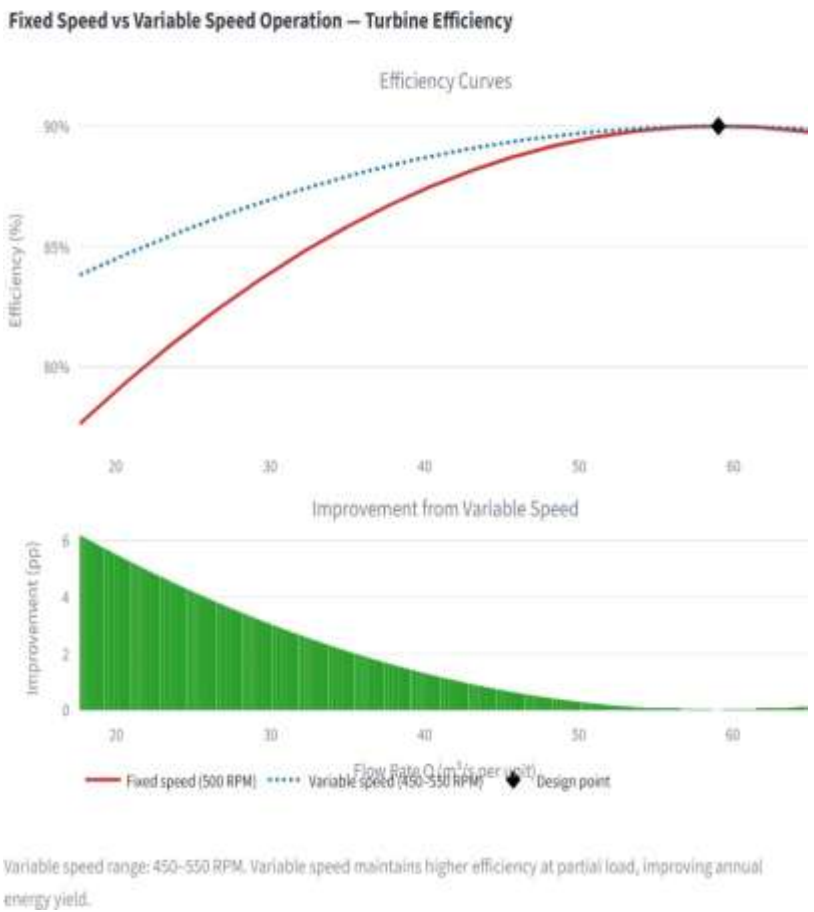

Figure 7. Efficiency of Conventional Turbines vs. VSD

The orange FS curve shows that turbine efficiency increases to a maximum as flow rate rises. However, the curve drops significantly at low flow rates. At low flow rates of approximately 17–20 m³/s, the efficiency of the turbine with the FS system is around 78% and continues to increase until it reaches its maximum. The blue VSD curve indicates that turbine efficiency tends to be higher across nearly the entire flow range, particularly under low-to-medium flow conditions. This is due to the VSD system's ability to adjust turbine speed to various water flow conditions, thereby maintaining turbine efficiency close to optimal levels. At low flow rates, the VSD efficiency is approximately 84% and continues to increase until reaching a maximum point. The graph in Figure 7 shows that the turbine efficiency with the VSD system is 6% higher than that of the FS system under low-flow conditions. This indicates that the VSD system enables more optimal utilization of water energy compared to conventional systems, which typically experience a decrease in efficiency or may even be unable to operate under certain flow conditions.

Figure 7 shows a green curve at the bottom. This graph represents the difference between the efficiency curves of the VSD and FS systems, where the improvement in efficiency is indicated by percentage points (pp). The graph shows a difference of up to 6 pp. This means that using a VSD can increase turbine efficiency by up to 6% at every flow rate. At low flow rates ranging from 17-20 m³/s, the VSD system can improve turbine efficiency by 4-6% under the same operating conditions. These percentage point values are used to distinguish absolute changes from relative changes in percentage, thereby avoiding ambiguity in data interpretation.

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Figure 7 shows that the use of a VSD can help maintain the stability of power generation by expanding the turbine's operating range under various flow conditions. Under minimum flow conditions, the VSD system still allows the turbine to operate at a relatively higher efficiency level compared to conventional systems. Thus, the application of VSD technology at the Grindulu hydroelectric power plant has the potential to optimize the utilization of hydropower, particularly during the dry season when water flow is at its lowest.

An evaluation of the inflow prediction model was conducted to assess the ability of the BiLSTM Seq2Seq model to represent patterns of flow variation in the Grindulu watershed. The model was designed to analyze temporal relationships in the inflow time series data so that it could capture patterns of flow fluctuations influenced by changes in hydrological conditions and capable of identifying temporal patterns in time-series data also can predict potential inflow values through quartile estimation [13].

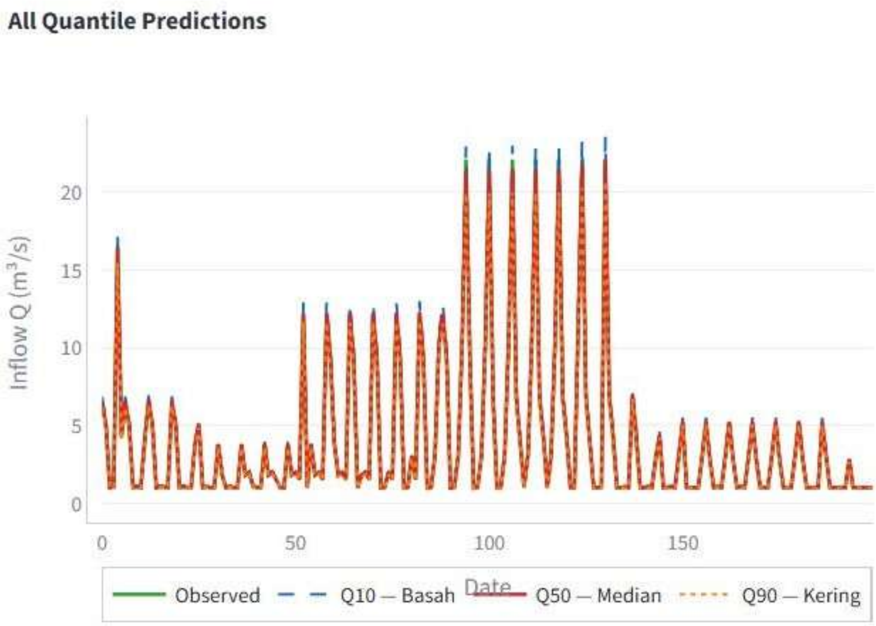

Figure 8. All Quantile Predictions

The prediction plots for all quantiles show that the BiLSTM model using the Quantile Regression approach is capable of generating predicted inflow distributions at several probability levels, namely the high quantile (q10), median quantile (q50), and low quantile (q90). The q50 value appears capable of following the pattern of the observed data, including capturing flow fluctuations such as peak flows during specific periods. This demonstrates the model's ability to represent the nonlinear relationship between rainfall and flow discharge, which is a critical aspect of hydrological systems [3]. Meanwhile, the q10 and q90 values define the boundaries of the prediction interval, where q10 and q90 represent wet and dry extreme conditions. This approach offers an advantage over conventional prediction methods because it not only produces a single predicted value but also provides an indication of the uncertainty in discharge that may occur, allowing the inflow prediction results to be used to identify potential discharge variations that could affect the operation of the hydroelectric power plant system.

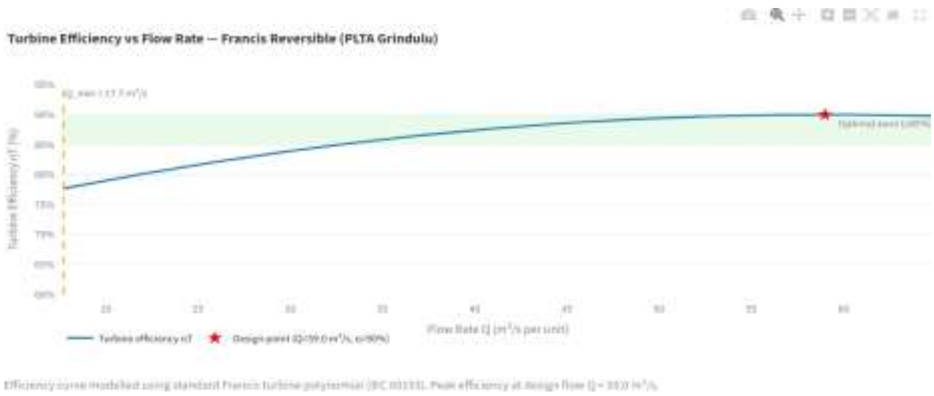

Figure 9. Turbine Efficiency and Flow Rate

Figure 9 illustrates the relationship between flow rate (Q) and turbine efficiency. The curve shows that turbine efficiency (blue line) increases as the flow rate increases until it reaches an optimal point, after which it tends to level off. The graph shows that turbine efficiency at the minimum flow rate of 17.7 m³/s is approximately 78%. This efficiency value increases until it reaches maximum efficiency at the design flow rate of 59 m³/s, corresponding to an efficiency level of 90%. The green-shaded area represents the optimal operating zone with turbine efficiency >85%, a value that is generally the operational target for hydroelectric power plants to achieve optimal performance. Figure 9 shows that the turbine at the Grindulu hydroelectric power plant performs best when the actual flow rate is close to the design flow rate. Therefore, to ensure the turbine maintains optimal efficiency, its operation should be maintained within the optimal flow range of 85–100% of the design flow rate, as recommended in the hydro turbine performance standards.

5. Conclusion

The hydrological and hydraulic analysis of the Grindulu River reveals that the flow characteristics are dominated by baseflow, with a constant discharge of 1,021 m3/s (q50 and q90) and limited high-flow events (q10 = 1,604 m3/s), indicating minimal surface runoff. While the natural discharge only yields a potential of +4,2 MW, the implementation of a reservoir system with a design discharge of 242 m3/s significantly elevates the generation potential to +1000 MW. These findings demonstrate that natural discharge limitations can be effectively mitigated through a closed-loop water circulation mechanism and Variable Speed Drive (VSD) technology. The VSD system provides essential operational flexibility for pump turbines to adjust to load variations, ensuring stable power generation even during the low-flow conditions of the dry season. Scientifically, this pattern confirms that integrating circulation systems with VSD technology offers a practical solution for optimizing hydropower potential in rivers with low-flow characteristics. The implications of this research contribute to the development of more efficient, large-scale hydroelectric methods that are resilient to seasonal hydrological fluctuations. To improve the sensitivity of the BiLTSM Seq2Seq model to daily fluctuations in future research, further developments could be undertaken, such as adding input variables (such as soil moisture and temperature) or using higher-resolution data and longer observation periods. Additionally, sensitivity analyses can be conducted on hydrological parameters such as CN and Ia values to determine their impact on runoff calculations and discharge estimates. Further studies are also needed regarding reservoir operation optimization through water balance analysis, including water losses due to evaporation and seepage. Furthermore, an economic analysis is necessary to ensure the long-term operational feasibility of the turbines.

6. Referensi

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