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The Technical and Environmental Assesements of The Microhydro Power Plant of Werba

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The escalating global demand for renewable energy solutions necessitates comprehensive assessments to ensure technical and environmental sustainability. This study evaluates the technical and environmental performance of the microhydro power (MHPP) of Werba, located in Fakfak, Papua, Indonesia, which generates 1.6 MW of electricity for the Fakfak grid. The primary objective of this research is to assess how the integration of the Werba MHPP influences grid stability, reduces power losses, and contributes to GHG emission reductions. The research design integrates advanced power flow simulations using the Newton-Raphson method alongside detailed environmental impact assessments. The results show that the Werba MHPP improves the voltage profile by 0.103 pu at Bus 7 and reduces total power loss by 0.0783 MW, lowering losses from 0.3822 MW to 0.3039 MW. In addition to these technical improvements, the Werba MHPP has a substantial environmental impact, reducing CO_2e emissions by approximately 9,247.50 tons annually. This emission reduction underscores the plant's role in displacing diesel-generated electricity and promoting cleaner energy alternatives in remote regions. The findings confirm that the integration of MHPPs like Werba can enhance grid reliability and contribute meaningfully to climate change mitigation efforts. These findings underscore the potential of MHPPs as scalable solutions for grid enhancement and climate change mitigation, especially in remote regions.

Keywords: MHPP; Werba; voltage profile; power loss; GHG.

1. Introduction

The surge in global energy demand, predicted to rise by 25% by 2040 [1], highlights the urgent need for innovative solutions in renewable energy. This trend has heightened concerns about the long-term sustainability of the world's energy systems, particularly those heavily reliant on fossil fuels. Fossil fuel-based energy production is a leading source of greenhouse gas (GHG) emissions, contributing significantly to global warming and environmental degradation. As a result, there is a pressing need for cleaner, more sustainable energy sources that can meet increasing energy demands while mitigating harmful environmental impacts. Renewable energy, particularly hydropower, offers a promising alternative to traditional fossil fuel sources [2], [3].

Hydropower, one of the most reliable forms of renewable energy, has long been utilized to generate clean electricity. Microhydro power plants (MHPPs) are a decentralized, small-scale solution that harnesses the energy from flowing water to generate electricity, making them especially suitable for remote and off-grid areas. MHPPs not only offer environmental benefits by reducing GHG emissions but also contribute to improving energy access in

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underserved regions. By replacing diesel-powered electricity generation, MHPPs reduce reliance on fossil fuels, thus lowering overall carbon emissions [2], [4].

The Werba microhydro power plant, located in Fakfak, Papua, Indonesia, was commissioned in 2015 to meet local energy needs and reduce dependence on diesel generators [5]. The plant, with a capacity of 1.6 MW, supplies power to the Fakfak grid, which serves several rural communities. However, the impact of the Werba plant on the grid's technical performance and its contribution to environmental sustainability have not been thoroughly evaluated. To date, few studies have addressed the effectiveness of integrating such plants into local energy systems, especially in remote areas like Fakfak. There is a need to assess the operational effectiveness of MHPPs in improving grid stability, reducing power losses, and mitigating GHG emissions.

This study hypothesizes that the Werba MHPP enhances grid reliability by improving voltage profiles and reducing transmission losses while significantly reducing GHG emissions. The research aims to quantify the technical and environmental benefits of the Werba plant through simulations and performance analysis, offering valuable insights into the role of MHPPs in promoting sustainable energy solutions.

2. Problem formulation

2.1. Power flow analysis

Power flow analysis is essential for studying the steady-state behavior of electrical power systems, such as determining voltages, currents, and power flows in a network [6]. The Newton-Raphson method is one of the most widely used techniques for solving these power flow equations. The Newton-Raphson method works by iteratively improving an initial guess of the system's voltages until a set of equations representing the power flow is satisfied. The power flow equations are typically nonlinear, making it challenging to obtain an analytical solution. In each iteration of the Newton-Raphson method, it approximates the nonlinear equations with a linearized system of equations called the Jacobian matrix. The Jacobian matrix represents the sensitivity of each equation with respect to changes in system variables, such as voltages [7].

The Newton-Raphson method starts with an initial guess of the voltages and then updates them iteratively. At each iteration, it computes the mismatch between the calculated and desired values of the power flow equations. By using the Jacobian matrix, it determines the direction and magnitude of the voltage corrections needed to reduce the mismatch. This process continues until the solution converges, meaning the mismatch becomes small enough to meet a predefined convergence criterion. The Newton-Raphson power flow method is known for its efficiency and accuracy in solving power flow problems.

The active (P) and reactive power (Q) in bus i can be calculated based on equation (1) and (2) [7].

$$P_i = \sum_{i=1}^{n} \left| Y_{ij} V_j Y_{ij} \right| \cos\left(\theta_{ij} + \delta_j - \delta_i\right) \tag{1}$$

$$Q_i = \sum_{i=1}^{n} \left| Y_{ij} V_j Y_{ij} \right| \sin\left(\theta_{ij} + \delta_j - \delta_i\right) \tag{2}$$

Because these power flow equations are nonlinear, the Newton-Raphson method employs an iterative process that linearizes them at each step. The key to the Newton-Raphson approach is to approximate the nonlinear power flow equations using a first-order Taylor expansion. This requires the computation of the Jacobian matrix, which contains the partial derivatives of the power mismatch equations with respect to the voltage magnitudes and angles.

The Jacobian matrix can be broken into four submatrices:

$\frac{\partial P}{\partial \theta}$: Sensitivity of real power to voltage angles

$\frac{\partial P}{\partial V}$: Sensitivity of real power to voltage magnitudes

$\frac{\partial Q}{\partial \theta}$: Sensitivity of reactive power to voltage angles

$\frac{\partial Q}{\partial V}$: Sensitivity of reactive power to voltage magnitudes

Thus, the system of equations at each iteration can be expressed as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \partial P/\partial \theta & \partial P/\partial V \\ \partial Q/\partial \theta & \partial Q/\partial V \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \tag{3}$$

where ΔP and ΔQ represent the mismatch between the calculated and specified power values, and $\Delta\theta$ and ΔV are the corrections to the voltage angles and magnitudes.

At each iteration, the Newton-Raphson method updates the voltage angles and magnitudes by solving the linear system involving the Jacobian matrix. The new voltage values are then used to compute the updated power flow mismatches, and the process is repeated until the mismatches are within an acceptable tolerance, indicating convergence. The iterative updates can be written as:

$$\theta^{k+1} = \theta^k + \Delta\theta^k \tag{4}$$

$$V^{k+1} = V^k + \Delta V^k \tag{5}$$

where k denotes the iteration number.

The Newton-Raphson method converges quadratically, meaning that the error decreases very rapidly as the solution approaches the correct values. This makes it particularly efficient for solving large power systems, where other methods such as the Gauss-Seidel may require significantly more iterations. However, one drawback is the need to compute the Jacobian matrix and solve a linear system at each iteration, which can be computationally intensive for very large networks.

2.2. Greenhouse gas emission

Greenhouse gas emissions are the release of gases into the Earth's atmosphere that have the ability to trap heat and contribute to the greenhouse effect. The greenhouse effect is a natural process that helps regulate the Earth's temperature by trapping some of the sun's energy, keeping the planet warm enough to support life. However, human activities have increased the concentration of greenhouse gases in the atmosphere, leading to an enhanced greenhouse effect and causing global warming.

Some of the major greenhouse gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases. These gases are released into the atmosphere through various human activities, such as burning fossil fuels (coal, oil, and natural gas) for energy production, deforestation, industrial processes, agriculture, and waste management.

Carbon dioxide is the most significant greenhouse gas emitted by human activities. It primarily comes from burning fossil fuels for transportation, electricity generation, and heating, as well as from deforestation and land-use changes. Methane is mainly produced by the decomposition of organic waste in landfills, agriculture (such as rice cultivation and livestock), and the extraction and transport of fossil fuels. Nitrous oxide is released from agricultural and industrial activities, as well as during the combustion of fossil fuels. Fluorinated gases are synthetic compounds used in various industrial applications, including refrigeration and air conditioning.

The accumulation of greenhouse gases in the atmosphere leads to the intensification of the greenhouse effect, resulting in global warming and climate change. The increased average global temperatures have far-reaching impacts, including rising sea levels, altered weather patterns, more frequent and severe extreme weather events, shifts in ecosystems, and disruptions to agriculture and water resources.

To address the issue of greenhouse gas emissions and mitigate climate change, international efforts have been made to reduce emissions and transition to cleaner and renewable energy sources. The Paris Agreement, for example, aims to limit global warming well below 2 degrees Celsius above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 degrees Celsius. This requires countries to set and achieve targets for reducing their greenhouse gas emissions, as well as promote sustainable practices and technologies.

Various strategies and initiatives are being implemented to reduce greenhouse gas emissions, including transitioning to renewable energy sources, improving energy efficiency, promoting sustainable transportation, adopting carbon capture and storage technologies, and implementing policies and regulations to incentivize emission reductions. Additionally, individuals can contribute by adopting energy-saving practices, reducing waste, and making sustainable choices in their daily lives.

In calculating greenhouse gas (GHG) emissions, references [8], [9], [10] have provided a detailed calculation of the resulting emissions based on the energy produced. However, other references provide faster calculation results based on the direct conversion of generated energy to exhaust gas, as given in the following table.

Table 1. Emission factor

No	**Type of primary sources**	**Emission factor (kg CO_2/kWh)**
1	Fossil fuel (general) [8]	0.321
2	Fossil fuel (general) [9]	0.509
3	Natural gas [10]	0.457
4	Light diesel fuel [10]	0.602

5	Heavy diesel fuel [10]	0.629

Total greenhouse gas reduction in tons of CO_2e is calculated based on production energy (P_{out}) and the amount of power loss (P_{loss}) in hours operations (t) multiplied by the conversion values (v) in Table 1. This reduction is formulated in equation (6) as follows.

$$GHG = t(P_{out} + P_{loss})v \tag{6}$$

3. Case study

3.1. The Grid of Fakfak

The Fakfak grid is a grid that serves the load needs of the city of Fakfak. This grid is a distribution grid that distributes around 4 MW of power to loads installed on 7 buses and 6 distribution lines. The single-line diagram of this grid is shown in Figure 1, while the load and line data are given in Tables 2 and 3.

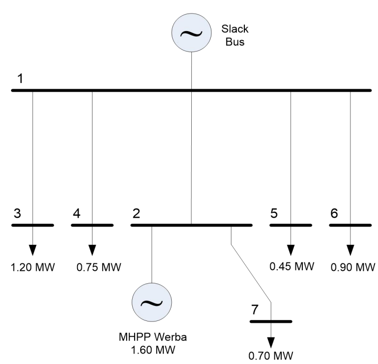

Figure 1: Single line diagram.

Table 2: Bus data

Bus no.	Bus Name	Voltage (p.u)	Generator (MW)		Load	
			Nominal	Installed	P (MW)	Q (MVAr)
1	Kebun Kapas	$1.06\angle 0°$	3.50	4.78	-	-
2	Werba	$1.04\angle 0°$	1.60	2.00	-	-
3	Wagom	$1.00\angle 0°$	-	-	1.20	0.58
4	Danaweria	$1.00\angle 0°$	-	-	0.75	0.36
5	RRI	$1.00\angle 0°$	-	-	0.45	0.22
6	Kota	$1.00\angle 0°$	-	-	0.90	0.44
7	Distribusi	$1.00\angle 0°$	-	-	0.70	0.34

Table 3: Line data

Line no.	Line from-to	Impedance (Ω)	
		R	jX
1	1-2	8.2944	6.4296
2	1-3	1.6128	1.2502
3	1-4	17.6026	13.6450

4	1-5	18.9619	14.6988
5	1-6	0.7243	1.1072
6	2-7	9.1930	7.1261

The integration of the Werba microhydro power plant (MHPP) into the Fakfak grid demonstrated significant improvements in grid performance, particularly in terms of voltage stability and reduction of power losses. The power flow analysis, conducted using the Newton-Raphson method, revealed notable changes in the voltage profiles of the buses and the power losses across the lines before and after the plant's operation.

3.2. Voltage Profile

The results of the power flow simulation indicate a considerable enhancement in the voltage stability across the grid. The most significant improvement was observed at Bus 7, where the voltage increased by approximately 0.103 pu, or 2.06 kV at a base voltage of 20 kV, following the integration of the Werba MHPP (Table 4). This improvement in voltage profile suggests that the Werba plant effectively stabilizes the grid by providing additional generation capacity at critical points. Moreover, the voltage at Bus 2, which is connected to the plant, matched the slack bus voltage, further indicating the plant's positive influence on grid stability.

Table 4: Voltage profile.

Bus no.	Voltage (p.u)		Load	
	Before	After	P (MW)	Q (MVAr)
1	1.0600∠0.0000°	1.0600∠0.0000°	4.9338	-2.2472
2	0.9675∠-0.0165°	1.0600∠0.1193°	0.0000	0.0000
3	1.0343∠-0.0051°	1.0343∠-0.0051°	-1.2000	0.5812
4	0.8449∠-0.0427°	0.8449∠-0.0427°	-0.7500	0.3633
5	0.9340∠-0.0251°	0.9340∠-0.0251°	-0.4500	0.2180
6	1.0492∠-0.0061°	1.0492∠-0.0061°	-0.9000	0.4359
7	0.8654∠-0.0387°	0.9684∠0.1011°	-0.7000	0.3390
Σ			0.9338	-0.3098

3.3. Power Loss Reduction

In terms of transmission efficiency, the total power loss across the Fakfak grid decreased from 0.3822 MW to 0.3039 MW, a reduction of approximately 0.0783 MW (Table 5). Notably, the power losses on the 1-2 transmission line were completely eliminated following the integration of the Werba MHPP, while other lines saw a substantial reduction in losses. These results confirm that the inclusion of the Werba plant not only improves the overall energy efficiency of the grid but also reduces the strain on the transmission system, leading to fewer losses and more reliable power distribution.

Table 5: Line flow.

No	Line From-to	Line flow		Line flow	
		P (MW)	Q (MVAr)	P (MW)	Q (MVAr)
1	1-2	-0.7383	-0.5723	0.0000	0.0000
2	1-3	-1.0571	-0.8196	-1.0571	-0.8196
3	1-4	-0.8091	-0.6272	-0.8091	-0.6272
4	1-5	-0.4399	-0.3410	-0.4399	-0.3410
5	1-6	-0.4749	-0.7259	-0.4749	-0.7259
6	2-7	-0.6713	-0.5204	-0.6595	-0.5112
7	2-1	0.6738	0.5223	0.0000	0.0000
8	3-1	1.0314	0.7996	1.0314	0.7996
9	4-1	0.6449	0.4999	0.6449	0.4999
10	5-1	0.3876	0.3005	0.3876	0.3005
11	6-1	0.4700	0.7185	0.4700	0.7185
12	7-2	0.6005	0.4655	0.6026	0.4671
Σ		-0.3822	-0.3000	-0.3039	-0.2393

3.4. Environmental Impact

The Werba MHPP also demonstrated a significant contribution to reducing greenhouse gas (GHG) emissions. By displacing diesel-powered electricity generation, the plant reduced CO_2e emissions by approximately 9,247.50 tons per year (Table 1). This reduction was calculated based on the plant's output and the emission factors associated with diesel fuel combustion using equation (6).

While the daily reduction of 25.34 ton CO_2e may appear modest, the annual total reflects a substantial environmental benefit, particularly in a region that previously relied heavily on diesel power generation. Over the long term, this reduction contributes meaningfully to Indonesia's goals of lowering emissions in accordance with the Paris Agreement.

3.5. Discussion

The findings of this study support the hypothesis that the integration of microhydro power plants like Werba can improve grid reliability while simultaneously reducing environmental impacts. The technical benefits, such as enhanced voltage profiles and reduced power losses, highlight the plant's role in stabilizing the local energy system. In parallel, the environmental assessment demonstrates the plant's effectiveness in curbing GHG emissions, providing a cleaner energy alternative to diesel-based systems.

These results align with broader global efforts to transition toward renewable energy, particularly in remote regions where conventional grid access is limited. The technical and environmental improvements observed in this study suggest that MHPPs can play a critical role in both enhancing energy security and meeting climate change mitigation goals.

4. Conclusion

This study has demonstrated that the integration of the Werba microhydro power plant (MHPP) into the Fakfak grid offers significant technical and environmental advantages. Through comprehensive power flow simulations, the Werba MHPP was shown to enhance voltage stability and reduce power losses, thereby improving the overall efficiency and reliability of the local power system. The voltage profile of the grid improved notably, particularly at Bus 7, with an increase of 0.103 pu, reflecting the positive impact of the plant on grid stability. Moreover, the reduction in total power losses by 0.0783 MW underscores the plant's role in minimizing energy waste and improving transmission efficiency.

In addition to these technical benefits, the Werba MHPP has proven to be an effective solution for reducing greenhouse gas (GHG) emissions. The plant's operation resulted in an annual reduction of approximately 9,247.50 tons of CO_2e, displacing diesel-generated electricity and contributing to the region’s shift toward cleaner, renewable energy sources. This finding aligns with global efforts to reduce emissions and combat climate change, particularly in regions where fossil fuels remain the dominant source of power.

The results of this study support the hypothesis that MHPPs can play a crucial role in both enhancing grid reliability and reducing environmental impact. By improving energy efficiency and contributing to GHG reduction, the Werba MHPP serves as a model for similar renewable energy projects in remote and off-grid areas.

Future research should explore the scalability of microhydro power plants in different geographic contexts, as well as their long-term sustainability in meeting both local energy needs and global environmental goals. Expanding on these findings will further solidify the role of MHPPs in the transition toward a more sustainable and resilient energy future.

Declaration of Generative AI in Scientific Writing

During the preparation of this work the authors used ChatGPT in order to improve grammar and paraphrase some paragraphs. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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