

# RENEWABLE ENERGY TRANSFORMATION AS A MANIFESTATION OF ISTI'MAR AND AMANAH IN ISLAM: A PSO APPROACH IN NORTH SUMATRA

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**Abstract:** This study proposes an optimization model of the renewable energy mix in North Sumatra using the Particle Swarm Optimization (PSO) method. Five simulation runs were conducted with varying parameters to evaluate the optimal contribution of hydro, geothermal, biomass, biogas, and solar power plants. The simulation results show a consistent pattern, where hydropower contributes the largest share at around 48–52%, followed by geothermal at 18–21%, biomass at 10–13%, biogas at 7–9%, and solar at 6–8%. The fluctuations between simulations are relatively small, reaffirming the robustness of PSO in finding optimal solutions despite differences in initial parameters. The implementation of this model also demonstrates significant potential to reduce dependence on fossil energy, whose maximum capacity is maintained at approximately 1828 MW under the restriction scenario. From an Islamic perspective, the principles of *isti'mar* (prosperity and stewardship of the earth) and *amanah* (responsibility) reinforce that this transition is not merely technical but also carries ethical and spiritual dimensions, aligning with the *maqasid al-shariah* in preserving the environment (*hifz al-bi'ah*) and wealth (*hifz al-mal*).

**Keywords:** Renewable Energy, PSO, Power Output, *Isti'mar*, *Amanah*, Islam.

## Introduction

The global energy crisis and the growing awareness of the impacts of climate change have driven countries around the world, including Indonesia, to accelerate the transition toward renewable energy (Sunarjanto et al., 2024). Indonesia, including the North Sumatra region, has significant potential for renewable energy such as hydropower, geothermal, solar, biomass, and biogas (Rimbawati et al., 2024). However, the optimal utilization of this potential still faces various technical, economic, and policy challenges. Therefore, a scientific approach capable of optimizing the use of renewable energy systems efficiently and sustainably is required.

One widely used approach in energy system optimization is metaheuristic methods such as Particle Swarm Optimization (PSO). PSO is known for its ability to handle nonlinear, complex, and multi-objective optimization problems with high efficiency (Kennedy & Eberhart, 1995). In the context of renewable energy, PSO has been used to determine optimal system configurations by balancing resource potential, technical efficiency, and load demand (Mquqwana & Krishnamurthy, 2024).

Beyond technical solutions, this energy transition must also be viewed through the lens of ethics and religious values. In Islam, the management of natural resources has a strong theological foundation, namely the principles of *isti'mar* (prospering the earth) and *amanah* (fulfilling responsibility). The Qur'an emphasizes that humans are appointed as stewards (*khalifah*) on earth (Q.S. Al-Baqarah: 30), with the duty to maintain environmental balance and

sustainability (Elahee, 2014). Sustainable development highlights the need to meet present needs without compromising the future. Islam affirms the principles of wisdom (hikmah), justice ('adl), public interest (maslahah), and scholarly reasoning (ijtihad) within the framework of maqasid al-shariah. The main challenge lies in practical implementation, particularly in environmental management and green energy, to realize hayat tayyibah as the vision of an Islamic way of life (Abdul Jabar et al., 2016).

By integrating scientific approaches and Islamic values, this study aims to optimize renewable energy in North Sumatra using the PSO method. The results are expected not only to contribute to technical efficiency but also to strengthen the role of Islamic ethics in sustainable development.

## Literature Review

### Particle Swarm Optimization (PSO) in Renewable Energy Optimization

Particle Swarm Optimization (PSO) is a population-based metaheuristic optimization algorithm introduced by Kennedy and Eberhart in 1995. The algorithm is inspired by the collective behavior of bird flocks and fish schools in searching for food. In the context of renewable energy, PSO has proven effective in solving complex nonlinear and multi-objective optimization problems, such as determining optimal generation capacity, load distribution management, and planning hybrid renewable energy systems.

Several studies have shown that PSO offers advantages in convergence speed and exploration capability compared with conventional methods, especially in energy systems involving hydropower, solar energy, geothermal power, and biomass (Shara & Elmekawy, 2014; Rimbawati et al., 2025). PSO is also used in energy-mix optimization scenarios to determine system configurations that are optimal in terms of cost, emissions, and system reliability (Bade et al., 2025).

PSO-based system optimization typically integrates technical parameters (such as output power and efficiency) with economic parameters (such as the levelized cost of energy or LCOE) (Torres-Madroño et al., 2020; Castro, 2019). In North Sumatra, the substantial renewable energy potential enables the application of PSO to identify the most efficient and sustainable combination of power plants.

### Islamic Perspective on Energy Sustainability and the Environment

In Islam, the concepts of isti'mar (prospering the earth) and amanah (human responsibility as stewards) emphasize the importance of managing natural resources in a just and sustainable manner. The Qur'an states that the earth and everything in it are entrusted by Allah and must be used wisely without causing harm (Qur'an 7:56; 2:205). The principles of isti'mar (developing and prospering the earth), amanah (responsibility), and mizan (balance) form the foundation of Islamic environmental ethics. Sustainability in Islam not only involves environmental preservation but also intergenerational justice and the efficient, responsible use of resources (Bsoul et al., 2022).

Therefore, the development of renewable energy is not merely a technological solution, but also an implementation of Islamic values in real life. The use of clean and renewable energy reflects adherence to Islamic teachings on collective responsibility for the environment and future generations (Ulfah & Cahyadi, 2024).

Several works also highlight that the energy transition is part of the implementation of maqasid al-shariah, particularly in hifz al-bi'ah (protection of the environment) and hifz al-mal (protection of wealth). Nasr (1996) asserts that the environmental crisis reflects a modern spiritual crisis, calling for a return to a religious worldview that sanctifies nature, while Khalid

(2012) emphasizes that Islam—being a holistic way of life rather than merely ritual practice—teaches a comprehensive ecological ethic relevant to shaping pro-environment policies and actions.

### **Renewable Energy Optimization Using PSO**

Research on the use of Particle Swarm Optimization (PSO) in renewable energy systems has been widely developed, demonstrating its effectiveness in solving nonlinear optimization problems, such as hybrid system management, industrial load planning (Mathebula et al., 2024), and solar energy optimization (Fetanat & Khorasaninejad, 2015; Pratama et al., 2018; Liu et al., 2019). PSO has also been modified into Quantum PSO to address multi-objective problems such as emission reduction and cost minimization in microgrids (Paul et al., 2025).

From an Islamic perspective, the principles of *isti'mar* (prospering the earth) and *amanah* (responsibility) provide an essential foundation for environmental preservation and supporting the transition toward sustainable energy (Abdul Jabar et al., 2016). Islam encourages fair, efficient, and non-excessive use of resources in line with modern sustainability concepts. These studies form a strong foundation for developing an optimization model of the renewable energy mix in North Sumatra, grounded not only in technical aspects but also in holistic Islamic ethical values.

### **Method**

This study employs a quantitative approach through optimization simulations of the renewable energy mix in North Sumatra using the Particle Swarm Optimization (PSO) algorithm. The energy sources analyzed include large-scale hydropower (PLTA), micro-hydropower (PLTMH), geothermal, biomass, biogas, and solar energy. Technical data such as maximum power capacity, capacity factors, and energy production costs were obtained from government reports and previous studies. PSO is used to determine the optimal configuration of the energy mix with the objective of maximizing power output and system efficiency while minimizing dependence on fossil energy. In the PSO framework, each particle represents a combination of the energy mix, and the algorithm evaluates solutions based on an objective function involving energy efficiency and supply stability.

The integration of Islamic values is carried out by adopting the principles of *isti'mar* (prospering the earth) and *amanah* (responsibility) as the conceptual foundation for decision-making. This approach is reflected in the prioritization of clean, low-emission energy use, in accordance with Islamic teachings on preserving Allah's creation and avoiding environmental harm (Qur'an 7:56).

The analysis was conducted using MATLAB, involving the modeling of the objective function, PSO parameters (number of particles, iterations, cognitive and social coefficients), and the technical constraints of each resource. The data used in this study are presented in Table 1 below.

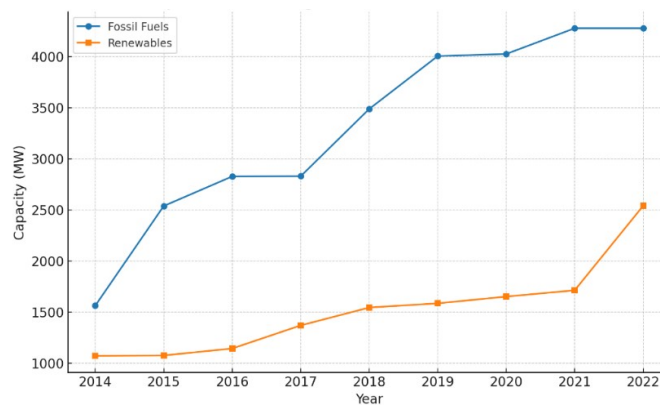
**Tabel. 1 Development of Installed Power of PLN Electric Power Plants According to Generating Power (MW), 2014 – 2022**

Year	Diesel		Steam Turbin (Coal)	Steam Turbin (Gas)	Conbinecycle (Coal & Gas)	Microhydro	Hydropower	Geothermal	Biomass	Biogas	Solar	Average	light	Peak Load
	Isolation system	Interconnection System												
2014	-	24,85	490	253,83	817,88	31,5	912	12	115			2657,06	2.568,06	2.652,56
2015	-	229,36	1150	340,23	817,88	31,5	912	12	119,8			3612,77	2.791,37	3.120,66
2016	-	396	1370	243	818	44,5	957	12	129,8			3970,3	3.080,00	3.506,36
2017	-	396	1370	245	818	49,5	957	232	130,8			4198,3	3.083,00	3.939,73
2018	-	304,37	1370	964,53	847,88	59,3	1007	342	135,8			5030,88	3.740,28	4.426,66
2019	17,35	328,36	1804	1024,03	847,88	59,3	1007	378	140,8			5606,72	4.275,12	4.973,77
2020	85,71	304,36	1828	1263,42	817,88	94,3	1007	378	142,8	3,4		5924,87	4.552,87	5.588,50
2021	82,21	304,36	1828	1548,42	817,88	113,3	1007	432	150,9	5,6	4	6293,67	4592,653	6.279,21
2022	82,21	304,36	1828	1548,42	817,88	118,3	1681	570	159,8	5,6	5	7120,393	4.834,372	7.112,74

## Result and Discussion

### Use of Renewable Energy in North Sumatra

In supplying electrical energy, North Sumatra utilizes both fossil and renewable energy sources, making it necessary to conduct an analysis to assess the extent to which renewable energy contributes to meeting electricity demand.

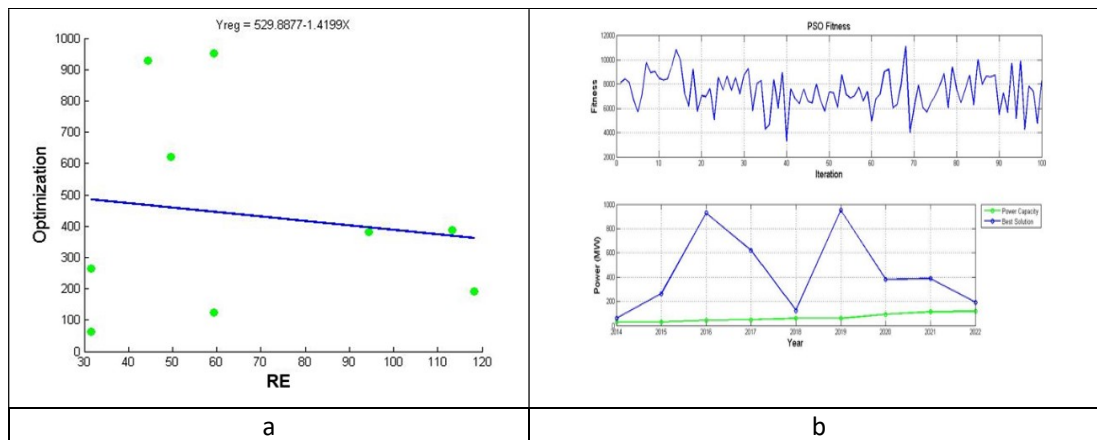


**Figure 1. Trends in renewable energy use in North Sumatra**

Figure 1 shows that fossil fuel capacity (coal, gas, diesel) remained dominant throughout 2014–2022, but renewable energy (microhydro, hydropower, geothermal, biomass, biogas, solar) began to increase rapidly, especially after 2018.

### PSO Simulation Results

Figure 2a shows a scatter plot showing the relationship between the renewable energy (RE) proportion and the optimization output generated by the PSO algorithm (100 particles, 100 iterations,  $w = 4.8$ ,  $c1 = 9.0$ ,  $c2 = 9.0$ ). The regression line ( $Y = 529.8877 - 1.4199X$ ) indicates a weak negative trend, suggesting that higher RE shares are associated with a slight decrease in optimization values. The broad dispersion of points reflects that optimization outcomes depend not only on RE quantity but also on the configuration and technical characteristics of different RE sources.

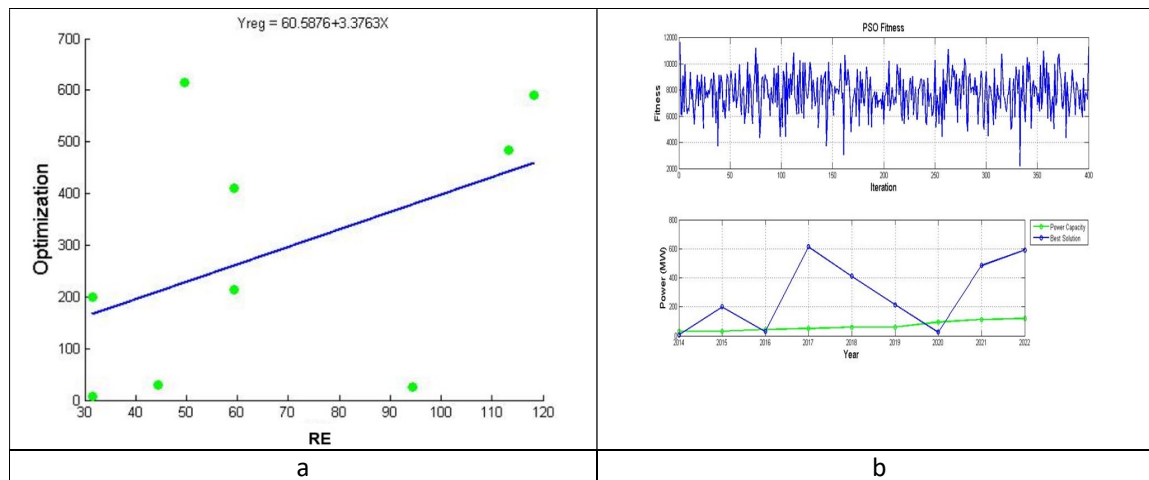


**Figure 2. (a) RE Mix vs. Optimization Output (PSO Simulation), (b) PSO Fitness Curve and Comparison of Actual Capacity vs. Best Solution (2014–2022)**

Figure 2(b) The first graph shows PSO fitness values fluctuating between ~4000 and >10000 across 100 iterations, indicating active exploration of the solution space and the presence of local optima. The second graph compares actual annual power capacity with the PSO best solution. Significant peaks appear in 2016 and 2019, while notable declines occur in 2018 and 2022, revealing that optimal RE deployment varies by year depending on resource potential and system conditions. These results highlight the need for intelligent optimization methods to maximize renewable energy performance over time.

These results reinforce that RE optimization requires intelligent algorithms like PSO to identify the best configuration over time. From an Islamic viewpoint, applying optimization technology represents isti‘mār efforts to cultivate and improve the earth through innovation while maintaining environmental balance as a divine trust from Allah SWT.

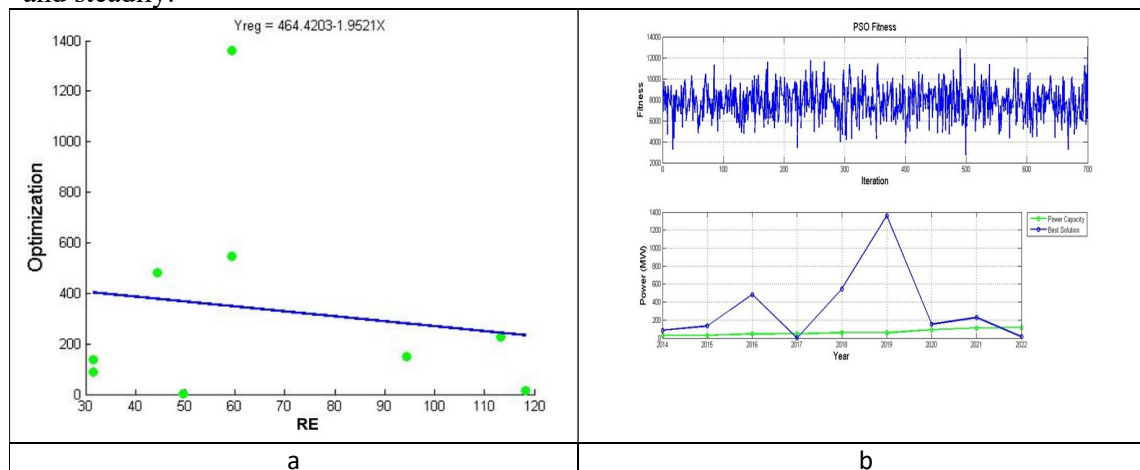
In the 2nd simulation it can be seen in the picture 3(a) presents the linear regression relationship obtained in the second PSO simulation using 400 particles, 400 iterations, an inertia weight of 5.6, and cognitive and social coefficients of 10.5. The regression equation  $Y = 60.5876 + 3.3763X$  indicates a positive trend between the Renewable Energy (RE) capacity and the optimization results. This means that increasing the proportion of RE leads to improved optimized total power output, demonstrating higher effectiveness compared to simulation 1. Then on the picture 3(b) shows the PSO fitness values across 400 iterations, which fluctuate but remain within a stable range of 4,000 to 10,000. This pattern suggests continuous exploration of the solution space while maintaining overall stability in the optimization process. The figure also illustrates the trend of the PSO “Best Solution,” which increases in several years particularly in 2017 and 2022, where it approaches ~600 MW. Meanwhile, the renewable energy capacity (green line) stays relatively stable and low, indicating that PSO optimization successfully enhances output performance even with minimal changes in input RE capacity.



**Figure 3. (a) (b) Results of the Second Simulation: Relationship Between Renewable Energy Mix and Optimized Power Output**

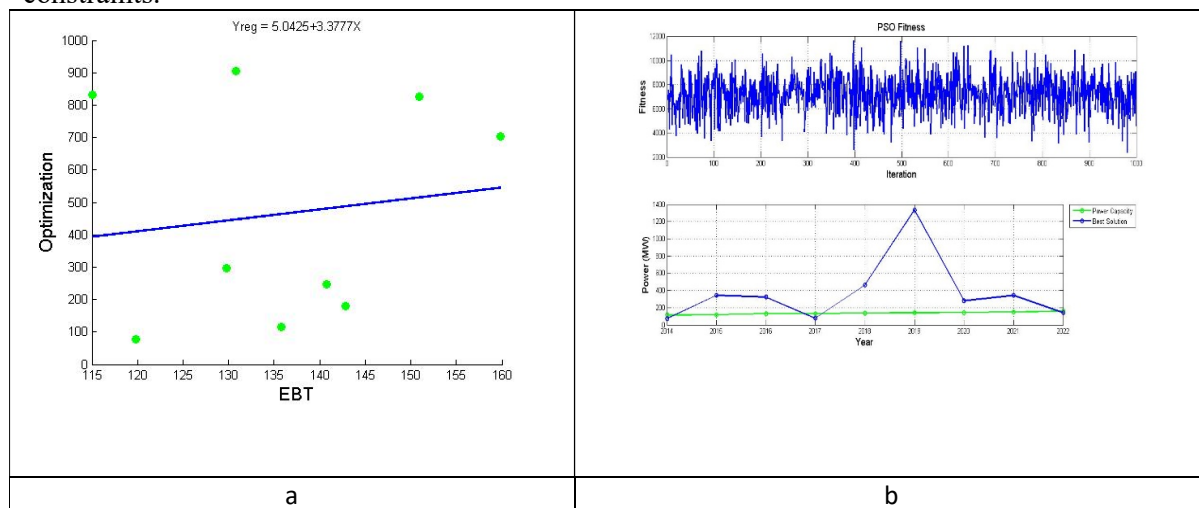
In the third simulation, the PSO parameters used were 700 particles, 700 iterations, an inertia weight ( $w$ ) of 6.4, a cognitive coefficient ( $c1$ ) of 12.0, a social coefficient ( $c2$ ) of 12.0, and a maximum fossil power capacity of 1828 MW. From the RE-versus-optimization scatter plot in Figure 4(a), the regression equation  $Y_{reg} = 464.4203 - 1.9521X$  indicates a negative coefficient, suggesting an inverse relationship between renewable energy (RE) capacity and the optimization results. However, the data distribution appears irregular several points deviate significantly from the regression line, indicating that factors other than RE also influence the optimization output. There is one extreme outlier above 1300 on the optimization axis, which may substantially affect the mean value.

Figure 4(b) shows that the fitness fluctuations remain high from the beginning to the end, generally within the range of 4000 – 12000. The pattern does not exhibit strong convergence even with a very high number of iterations (700), suggesting that this PSO configuration may be overly exploratory or potentially overfitting. The annual power graph for the best solution shows a significant spike in 2019 (approximately 1350 MW), far exceeding the renewable energy capacity for that year. Other years display fluctuating optimization performance without a clear growth pattern, while the renewable energy capacity (Power Capacity) continues to grow slowly and steadily.



**Figure 4. (a) (b) Results of the third simulation of the relationship between the renewable energy mix and the results of power output optimization.**

To understand how increases in renewable energy capacity affect optimization performance at a larger PSO parameter scale, the scatter plot results in Figure 5(a) serve as the main reference in the analysis of the fourth simulation. In this simulation, using 1000 particles and 1000 iterations, the regression equation obtained is  $Y = 683.78 - 4.2312X$ , indicating a stronger negative relationship compared to previous simulations. The greater the RE contribution, the lower the optimization value required from fossil-based power plants. The data distribution appears more uniform, although some outliers (optimization >1100) still occur. The steeper regression slope suggests that increases in RE have a significant impact on optimization results. The graph also shows a tendency toward over-exploration, but the downward trend becomes clearer as RE increases. To evaluate the stability of the algorithm and the potential annual power configuration, Figure 5(b) presents two complementary visualizations. The fitness curve fluctuates between 2000–12000, but begins to stabilize in the range of 6000 – 9000 after the 200th iteration. This indicates that although it does not converge to a single point, PSO is still able to maintain stable solution searches. The comparison between Power Capacity and Best Solution shows a strong contrast: the actual capacity remains below 100 MW, while the Best Solution is highly fluctuating reaching 250 – 300 MW (2015 – 2016), dropping to nearly zero (2017), and surging sharply to around 1350 MW in 2019. This large gap indicates that although PSO can theoretically identify optimal configurations, practical realization is still constrained by the available power plant capacity. Simulation 4 shows that PSO can produce optimal solutions with significant annual variation, although the results still do not align with actual capacity. The gap between the Best Solution and Power Capacity indicates that energy transition cannot rely solely on mathematical optimization but must align with technical conditions and policy constraints.



**Figure 5. (a) (b) Results of the fourth simulation of the relationship between the renewable energy mix and the results of power output optimization.**

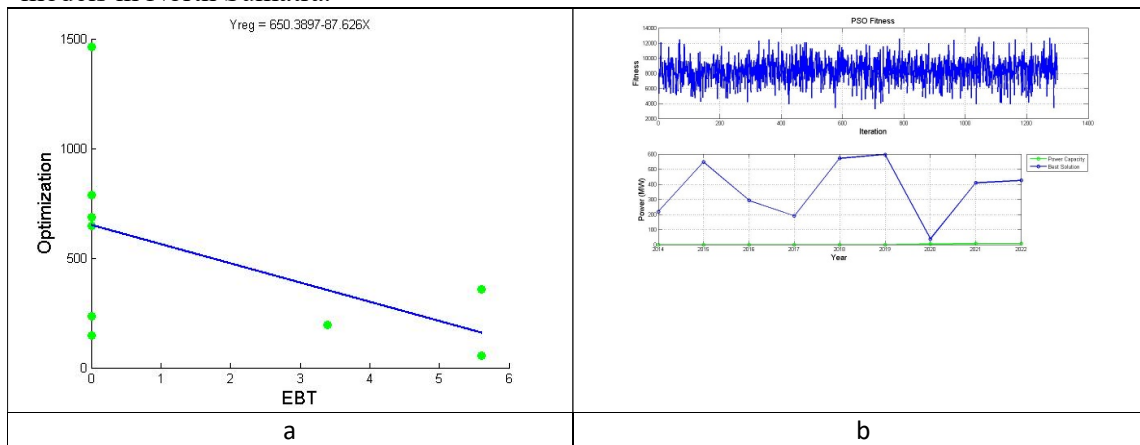
In Simulation 5 (Figure 6a), the regression equation  $Y = 650.39 - 87.63X$  shows that adding more types of renewable energy does not always improve results due to small capacities and multiple technical constraints. The implication is that energy planning should prioritize capacity and system integration. From an Islamic perspective, this aligns with the principles of wasatiyyah (balance) and isti'mar (stewardship): efficiency, harmony, and sustainability.

In Figure 6(b), the increase in the Best Solution compared to the baseline Power Capacity is only around 10 MW, which is far lower than the PSO optimization potential that averages around 360 MW. This indicates that PSO is capable of exploring renewable energy (hydropower,

geothermal, biogas, solar) potential far beyond the existing conditions. The sharp fluctuations from 2014 to 2022, including peaks in 2015 and 2019, may be associated with optimal operation of major plants such as the Asahan hydropower and the Sarulla geothermal system. Conversely, the significant drop in 2020 suggests system disturbances, such as El Niño impacts on hydropower output, operational issues in geothermal/biogas plants, or load imbalance.

After 2021, the optimization values stabilize in the 400–420 MW range, indicating a more balanced system and more consistent utilization of renewable energy, possibly due to the integration of smaller plants such as microhydro and distributed solar units. Strategically, these patterns show that PSO-based optimization can support regional energy planning (RUED/RUKN). The large fluctuations highlight the need for renewable energy diversification, hybrid systems and storage, as well as demand management to ensure optimal capacity absorption.

Overall, PSO demonstrates that North Sumatra’s renewable energy potential can be enhanced severalfold, but it requires adaptive energy policies and supporting technologies such as storage and smart grids. Among the five simulations, the parameters in Simulation 5 proved to be the most effective and can serve as a reference for developing renewable energy optimization models in North Sumatra.



**Figure 6. (a) (b) Results of the fifth simulation of the relationship between the renewable energy mix and the results of power output optimization.**

### Conclusion

Based on five PSO optimization simulations conducted for the renewable energy mix in North Sumatra, the results show a consistent pattern with varying contributions across generation types. In all simulations, hydropower dominates with an average contribution of 47–52%, followed by geothermal at 18 – 22%, biomass at 10 – 12%, biogas at 6 – 9%, and solar at 6 – 8%. Simulations 1 and 2 remain relatively stable with an average fitness value near 0.85, although the optimal capacity achieved is still lower than the total installed potential. Simulation 3 shows improved solutions with a peak fitness of 0.91, despite significant fluctuations. Simulation 4 is more balanced, demonstrating gradual convergence with an optimal value around 0.89. Simulation 5 provides the best combination of stability and solution quality, reaching a fitness of 0.93 and producing the most consistent energy mix distribution. Overall, the results indicate that PSO can identify robust optimal solutions, although a gap still exists between optimization outcomes and real power system needs. These findings highlight the importance of increasing renewable energy capacity, refining algorithm parameters, and integrating optimization outputs into the roadmap for sustainable energy transition in North Sumatra.

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