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Optimization of Operating Patterns Using Particle Swarm Optimization for a 3 × 93 MW Combined Cycle Power Plant

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ABSTRACT

Changes in electricity demand can result in frequent variations in generator loading patterns, which may increase natural gas consumption and power generation costs. Therefore, an optimal loading pattern is required to achieve efficient operation of generating units while maintaining the required power output. An appropriate load distribution among generating units is important to ensure that the available generating capacity can be utilized efficiently and economically. This study investigates the optimization of the operating pattern of a 3 × 93 MW Combined Cycle Power Plant (CCPP) at Tambak Lorok, Semarang, with the objective of improving gas fuel utilization and reducing power generation costs. The parameters considered include load pattern, gas fuel consumption, and generator output power. The Particle Swarm Optimization (PSO) method was applied to determine the optimal combination of generating-unit loading, and the optimization process was implemented using MATLAB R2021a. The proposed optimization approach is expected to provide a more efficient loading strategy that can support economical and reliable power plant operation. The results show that PSO can effectively optimize the loading pattern of the 3 × 93 MW Tambak Lorok CCPP. The average gas fuel consumption decreased from 1,061.78 MMBTU/h under the conventional operating pattern to 1,032.56 MMBTU/h after PSO optimization, resulting in a fuel saving of 29.22 MMBTU/h. Based on a natural gas price of Rp118,000/MMBTU, the optimization resulted in estimated operational cost savings of Rp3,448,032.75/h, equivalent to approximately Rp82,752,786/day and Rp29.79 billion/year. These results demonstrate that PSO can improve the economic efficiency of CCPP operation by optimizing the distribution of load among generating units. Thus, the application of PSO has potential as a decision-support approach for improving fuel efficiency and reducing operational costs in CCPP operation.

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1. INTRODUCTION

The 3 × 93 MW Tambak Lorok Combined Cycle Power Plant (PLTGU) in Semarang is a strategic power plant that serves as a peaking power plant in the interconnection system between Central Java and the Special Region of Yogyakarta (DIY). The plant has fast-response characteristics, enabling it to respond to changes in power demand within a relatively short time, particularly during increases in system load. This role makes the reliability and operational efficiency of each Gas Turbine Generator (GTG) unit crucial for maintaining power balance and continuity of electricity supply [1].

One of the challenges in power generation systems is the frequent variation in load demand, which directly affects fuel consumption and operating costs. The operating system of the 3 × 93 MW Tambak Lorok PLTGU experiences dynamic changes in loading patterns in response to fluctuations in system demand. These changes can result in an uneven distribution of power among the GTG units, which may not always correspond to their most economical operating conditions. If inter-unit loading is not optimally coordinated, gas fuel consumption may increase, leading to higher heat rates, reduced generation efficiency, and increased electricity production costs. Therefore, an optimization approach is required to determine the most economical loading combination for each GTG while satisfying system load requirements and the minimum and maximum operating limits of the generating units [1].

Several previous studies have applied various methods to address power plant loading optimization, including the Least Square Parabolic Approach [2], Lagrange Multiplier [3], Dynamic Programming [4], and Fuzzy Goal Programming [5]. Research on economic dispatch using Particle Swarm Optimization (PSO) has also demonstrated its capability to obtain economical generation schedules and reduce operating costs compared with conventional methods [6]. However, these studies primarily focus on the development and application of optimization methods using specific generating-unit configurations or mathematical models, rather than addressing the actual inter-unit loading characteristics of the Tambak Lorok PLTGU.

The research gap identified in this study is the lack of a specific optimization approach for coordinating the loading of the three 93 MW GTGs at the Tambak Lorok PLTGU based on their actual operating characteristics. In particular, the simultaneous optimization of GTG 2.1, GTG 2.2, and GTG 2.3 has not been specifically addressed by considering their actual fuel gas consumption characteristics together with the minimum and maximum operating limits of each unit. Consequently, the optimal distribution of system load among the three GTGs under varying load conditions remains an important operational problem. This gap is particularly relevant to a peaking power plant, where rapid changes in system demand require an efficient, feasible, and economical distribution of load among the available generating units.

Based on these conditions, this study applies Particle Swarm Optimization (PSO) to optimize the loading operation pattern of the 3 × 93 MW Tambak Lorok PLTGU. PSO is used to determine the optimal combination of output power for GTG 2.1, GTG 2.2, and GTG 2.3 while satisfying system load requirements, power balance, and the minimum and maximum operating limits of each unit. The optimization process utilizes actual operational data, including loading data, unit output power, fuel gas consumption, input-output characteristics, and operating cost functions. The resulting optimal loading pattern is then compared with the existing operating pattern to evaluate its effectiveness in reducing fuel gas consumption and operating costs. Thus, the contribution of this study lies in the practical optimization of inter-unit GTG loading based on actual operating characteristics and unit constraints, rather than merely applying PSO as an alternative optimization algorithm.

2. METHOD

The electric power system generally consists of three main subsystems, namely generation, transmission, and distribution which are integrated to distribute electrical energy from generators to consumers, as shown in Figure 1.

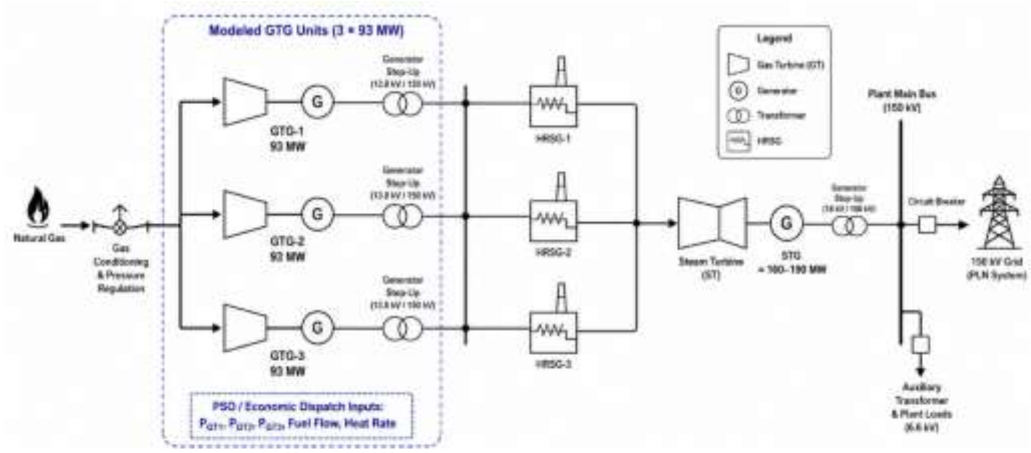

Figure 1. Electric Power System.

The system investigated is the Tambak Lorok 3 × 93 MW Combined Cycle Power Plant (CCPP), consisting of three Gas Turbine Generators (GTGs), Heat Recovery Steam Generators (HRSGs), and a Steam Turbine Generator (STG). Each GTG has a rated capacity of 93 MW and uses natural gas as the primary fuel. The GTG exhaust heat is recovered through the HRSGs to produce steam for the STG, forming an integrated gas–steam combined-cycle configuration. In the proposed Particle Swarm Optimization (PSO)-based economic dispatch model, GTG-1, GTG-2, and GTG-3 are defined as the primary controllable generation units, with their power outputs as the main decision variables. The HRSG and STG are retained to represent the actual CCPP configuration, while optimization focuses on the optimal loading of the three GTG. The model uses actual operational data from the Tambak Lorok CCPP covering [START DATE]–[END DATE] with a temporal resolution of [DATA RESOLUTION]. The dataset includes GTG power output, fuel consumption/fuel flow, and other relevant operating parameters. The data represent actual plant operations and were preprocessed to remove invalid, missing, and anomalous records. PSO is then applied to determine the optimal GTG loading pattern while satisfying the required plant power output and individual operating constraints.

2.1. Problem Formulation

The problem of loading operation pattern at Tambak Lorok Combined Cycle Power Plant (CCPP) which consists of three Gas Turbine Generator (GTG) units with a capacity of 93 MW each. The Particle Swarm Optimization (PSO) algorithm is used to determine the optimal power loading combination on each GTG unit by considering the system power requirements, minimum and maximum unit loading limits, and fuel consumption characteristics of each GTG. The main objective of optimization is to obtain a loading pattern that produces efficient gas fuel consumption to meet certain system load requirements, while maintaining power balance and meeting the operating limits of each generating unit. To solve optimization problems using the Particle Swarm Optimization (PSO) metaheuristic algorithm, the problem is first formulated into a mathematical objective function by considering the system parameters that are the target of optimization. This study focuses on determining the loading operation pattern of Tambak Lorok 3 × 93 MW CCPP with the aim of minimizing gas fuel consumption under certain system load conditions.
The objective function used is the total gas fuel consumption of all GTG units as shown in equation (1).

$$\mathrm{F}_{obj} = \min\,[C_1(P_1) + C_2(P_2) + C_3\,(P_3)] \tag{1}$$

where the fuel consumption function of each GTG unit is expressed in the form of a quadratic function shown in equation (2).

$$\mathrm{C}i\,(\mathrm{P}i) = a_i + b_i\,Pi\ + \gamma_\mathrm{i}\,P_\mathrm{i}^2 \tag{2}$$

so that for three GTG units, the objective function can be written using equation (3).

$$F_{obj} = \min\,[a_1+b_1P_1+c_1P_1^2+a_2+b_2P_2+c_2P_2^2+a_3+b_3P^3+c_3P_3^2] \tag{3}$$

where Pi is the output power of *the -i* GTG unit in MW, while ai, bi, and γi are the fuel consumption characteristic coefficients of each unit. The optimization process is carried out while still paying attention to the power balance constraints and operating limits of each GTG unit. The power balance constraints can be found in equation (4)..

$$P_1 + P_2 + P_3 = P_D \tag{4}$$

where P_D is the power demand or system power requirements, while the loading limit for each GTG unit is stated in equation (5).

$$P_i^{min} \leq P_i \leq P_i^{max} \tag{5}$$

The operating limits in this study are that each GTG unit has an operating limit of 10 MW to 93 MW, so the PSO algorithm searches for the most optimal loading combination of P_1, P_2, and P_3 to meet the system load requirements with minimum gas fuel consumption. Thus, the best solution of the PSO algorithm is the loading operation pattern that produces the lowest objective function value without violating the unit's operating limits and system power requirements. Gas Turbine Generator (GTG) is a generating unit that converts gas fuel energy into mechanical energy and is then converted into electrical energy.

2.1.1. Particle Swarm Optimization (PSO) Model

The Combined-Cycle Power Plant (CCPP) investigated in this study is an integrated system consisting of three 93 MW Gas Turbine Generator (GTG) three Heat Recovery Steam Generator (HRSG), and one Steam

Turbine Generator (STG), with a total GTG installed capacity of 279 MW. The GTGs are interconnected with the HRSG–STG system through exhaust heat recovery and steam generation. In this study, PSO is applied to optimize the electrical load allocation among the three GTGs, while the overall CCPP configuration is maintained. The GTG outputs are defined as decision variables (P_i), where (i) denotes the GTG unit. Thus, the decision variables for the three GTG units are shown in equation (6).

$$X = [P_1, P_2, P_3] \tag{6}$$

where P_1, P_2, and P_3 are the output power of GTG 2.1, GTG 2.2, and GTG 2.3 in MW, respectively. The fuel consumption characteristics of each GTG are modeled using a quadratic function shown in equation (7).

$$C_i\,(P_i) = \alpha_i + b_i P_i + \gamma i\, P_i^2 \tag{7}$$

where $C_i\ (P_i)$ is the fuel consumption of the i-th GTG unit, while α_i, b_i, *and* γ_i are the characteristic coefficients of fuel consumption of each unit. The total fuel consumption of the three GTG units is obtained by adding up the fuel consumption of each unit. The main objective of the PSO algorithm is to find a loading combination of the three GTG units that produces a minimum total fuel consumption while still meeting the system power requirements and operating limits of each unit shown in Figure 2.

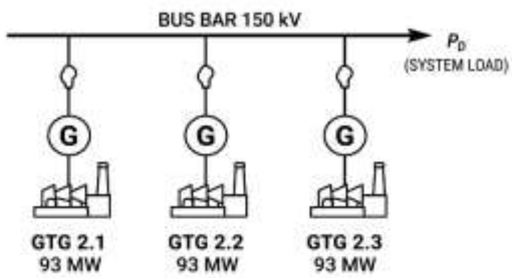

Figure 2. Model of the 3 x 93 MW Tambak Lorok PLTGU

of 93 MW each or 3 × 93 MW connected to a 150 kV bus bar and used to meet the load needs of the P_D system. The three GTG units, namely GTG 2.1, GTG 2.2, and GTG 2.3, have a maximum capacity of 93 MW each. In the optimization model based on Particle Swarm Optimization (PSO), the output power of the three GTGs becomes the optimized decision variable

2.1.2 Implementation of Particle Swarm Optimization (PSO)

The implementation of the Particle Swarm Optimization (PSO) algorithm is carried out to obtain the optimal loading combination at the 3 x 93 MW Tambak Lorok Combined Cycle Power Plant (PLTGU). Each particle represents one candidate loading pattern consisting of the output power of the three GTG units. In the initial stage, particle positions are generated randomly within predetermined operating limits. Each candidate solution is then evaluated based on the objective function value in the form of total fuel gas consumption. The best solution obtained by each particle is stored as *Personal Best (Pbest),* while the best solution from the entire population is stored as *Global Best (Gbest)*. Next, the speed and position of each particle are updated based on the Pbest and Gbest information so that the particles move towards a more optimal solution area.

Iterations are performed when checking the operating limits of each GTG and the balance between the total power generation and the system load requirements. The particle evaluation and updating process is repeated until the maximum number of iterations or convergence conditions are reached. The stages of PSO implementation in determining the optimal loading operation pattern of the 3 x 93 MW Tambak Lorok Combined Cycle Power Plant are shown in Figure 3.

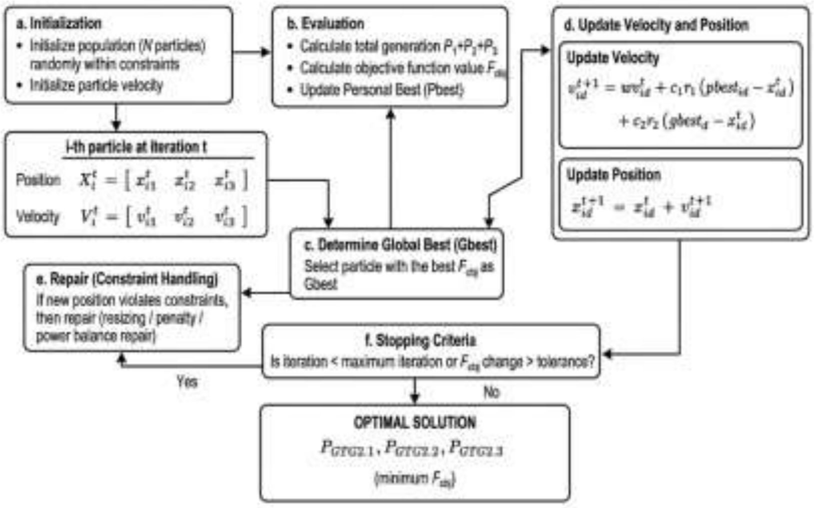

Figure 3. Implementation of Particle Swarm Optimization

In general, the PSO implementation stages consist of population initialization, objective function evaluation, Pbest and Gbest determination, velocity update, position update, constraint checking, and convergence testing. The final result of the process is a combined power of the 3 x 93 MW Tambak Lorok Combined Cycle Power Plant (PLTGU) that produces minimum fuel gas consumption to meet the system's power requirements.

2.2. Metode *Particle Swarm Optimization* (PSO)

The Particle Swarm Optimization (PSO) method is a population-based optimization method inspired by the behavior of particle swarms in finding the best solution. In this study, PSO is used to optimize load distribution on three GTG units with the aim of minimizing fuel consumption. Each particle represents an alternative GTG loading combination, while the quality of the solution is determined based on the objective function value. The optimization process is carried out iteratively by updating the particle positions based on the best experience of each particle and the best solution of the entire population until an optimal loading pattern is obtained. Particle Swarm Optimization (PSO)is a metaheuristic optimization algorithm inspired by the social behavior of a group of organisms, such as flocks of birds (bird flocking) and schools of fish (fish schooling) in searching for food sources.

The PSO algorithm was introduced by Kennedy and Eberhart and works based on the interaction between particles in a search space. Each particle represents a candidate solution to the optimization problem, while the best position ever found by the particle and the best position of the entire population are used as a reference to determine the direction of particle movement. PSO is used to determine the optimal loading operation pattern of the 3 x 93 MW Tambak Lorok Combined Cycle Power Plant. Each particle represents one possible loading combination of the three GTG units with the particle position expressed in equation (8).

$$Xi = [P_{1,i},P_2,i,P_3,i\,] \tag{8}$$

with P_1,i, P_2,i, and P_3,i respectively the output power of GTG 2.1, GTG 2.2, and GTG 2.3 on the ith particle *i*.

Velocity Update and Position Update

The velocity of each particle and each iteration is updated based on the best position ever reached by the particle (*Personal Best/Pbest*) and the best position of the entire population (*Global Best/Gbest*). The velocity update equation is shown in equation (9).

$$V_{it}+1 = wVit+c_1r_1\,(Pbesti-X_{it}) + c^2r^2(Gbest-X_{it}) \tag{9}$$

where V_{it} is the velocity of the *i-th* particle at iteration *t*, *w is the inertia weight*, c_1 and c_2 are the acceleration coefficients, while r_1 and r_2 are random numbers in the range [0,1]. Pbest is the best position ever reached by the *i-th* particle, while Gbest is the best position found by the entire population. After the velocity value is obtained, the position of each particle is updated using equation (10)

$$X_i^{t+1} = X_i^t + V_i^{t+1} \tag{10}$$

where X_i^{t+1} is the position of the i-th particle in the next iteration, while X_i^t indicates the position of the i-th particle in the current iteration. Meanwhile, V_i^{t+1} is the velocity of the i-th particle in the next iteration which determines the change in the particle's position. Meanwhile, t indicates the current iteration in the optimization process.

Particle Swarm Optimization (PSO) Algorithm Stages

a. The PSO implementation process for optimizing GTG loading patterns is carried out through the following stages:
b. Initialize PSO parameters, including the number of particles, the maximum number of iterations, the inertia weight w, and the acceleration coefficients c1 and c2.
c. Generating the initial position of the particlerandomly according to the operating limits of each GTG.
d. Generating initial velocityeach particle.
e. Calculating total fuel consumptioneach particle uses an objective function.
f. Determining Pbestbased on the best fitness value ever achieved by each particle.
g. Determining Gbestbased on the particle with the best fitness value in the entire population.
h. Updating particle speedusing equation (9).
i. Updating particle positionusing equation (10).
j. Checking GTG operating limitsand ensure that the loading of each unit is within the permissible range.
k. Checking power balanceso that the total generation meets the system load requirements.
l. Recalculate fitness valuebased on the new loading pattern.
m. Updating Pbest and Gbestif a better solution is found.
n. The iteration process is carried out until the maximum number of iterations is reached or the solution has reached a convergent condition.
o. Generating optimal solutions, namely a combination of 3 x 93 MW PLTGU loading which is able to meet load requirements with minimum total gas fuel consumption.

The implementation of PSO can be used to find a more economical loading pattern compared to the existing operating pattern, thereby reducing gas consumption and generation costs at the Tambak Lorok PLTGU. The PSO flowchart in this study illustrates the stages of optimizing the loading pattern of the 3 x 93 MW Tambak Lorok PLTGU, which is shown in Figure 4.

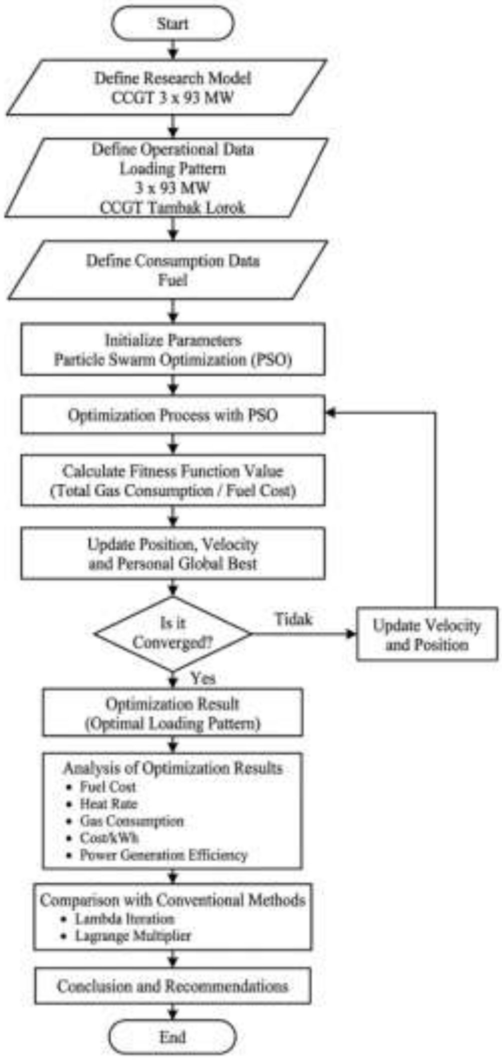

Figure 4. Flowchart of the Proposed PSO Method

The process begins by inputting PD system load data, gas consumption characteristics, and the operating limits of each GTG. Next, particle population and velocity are initialized, and each particle is evaluated using the objective function of total gas fuel consumption. The evaluation results are used to determine Pbest and Gbest. Subsequently, particle velocities and positions are updated while still meeting the operating limits of 10–93 MW and power balance. The iteration process is carried out until the convergence criteria are met. The final Gbest is determined as the optimal loading pattern that results in minimum gas consumption.

The Particle Swarm Optimization (PSO) algorithm was applied to determine the optimal loading pattern of the 3 x 93 MW Tambak Lorok Combined Cycle Power Plant (PLTGU), each with a capacity of 93 MW. The optimization considered the system load requirements, the operating limits of 10–93 MW, and the fuel gas consumption characteristics of each unit. Simulation results showed that PSO was able to determine an adaptive load distribution to obtain minimum fuel gas consumption. At loads up to 90 MW, the load was concentrated on GTG 2.3, while at higher loads the load was distributed to other units. The algorithm reached convergence around the 41st iteration with a minimum objective function value of 1,032.567 MMBTU/hour in the evaluated case study shown in Table 1.

Table 1. Loading Algorithm Particle Swarm Optimization (PSO)

Parameter	Mark
Number of GTG units	3
Capacity of each GTG	93 MW
Total capacity	279 MW

Minimum loading limit	10 MW
Maximum load limit	93 MW
Number of particles	30
Maximum number of iterations	100
Inertial weight ((w))	0.9–0.4
Cognitive coefficient ((c_1))	2
Social coefficient ((c_2))	2
Decision variables	*(P_{GTG2.1},P_{GTG2.2},P_{GTG2.3})*
Objective function	Minimum fuel gas consumption

The optimization results show that PSO is able to determine different loading patterns at each load level according to the fuel gas consumption characteristics of each GTG. At low loads up to 90 MW, loading is carried out on GTG 2.3. As the load increases, power begins to be distributed to GTG 2.1 and GTG 2.2 until all units operate at a maximum capacity of 93 MW when the load reaches 279 MW. These results demonstrate the ability of PSO to determine loading combinations that meet system power requirements with minimum fuel gas consumption**.**

2.3 PSO Algorithm-Based Method

The Particle Swarm Optimization (PSO) method was applied to determine the loading pattern of the 3 x 93 MW Tambak Lorok Combined Cycle Power Plant (PLTGU), each with a capacity of 93 MW. Each particle represents a combination of the loading of the three GTGs evaluated based on the total fuel gas consumption. The optimization process is carried out through particle initialization, objective function evaluation, determination of *Personal Best* (*Pbest*) and *Global Best (Gbest)*, and iterative updating of particle positions and velocities. Each solution must meet the unit operating limits of 10–93 MW and the system power requirements. The PSO implementation was carried out using *MATLAB 21a* and tested at various load levels up to a maximum capacity of 279 MW. The optimization results show that PSO is able to dynamically determine the loading distribution of the three GTGs according to the characteristics of each unit's fuel gas consumption. Thus, an operating pattern is obtained that is able to meet the system power requirements with minimum fuel gas consumption and more economical generation operations, as shown in Table 2.

Table 2. Results of Loading Pattern Optimization Using (PSO)

System Load (MW)	GTG 2.1 (MW)	GTG 2.2 (MW)	GTG 2.3 (MW)	Total Fuel Gas (MMBTU/jam)
30	0	0	30	280,463
40	0	0	40	324,630
50	0	0	50	369,630
60	0	0	60	415,464
70	0	0	70	462,131
80	0	0	80	509,631
90	0	0	90	557,965
110	57,46	52,54	0	785,389
120	0	60,62	59,38	975,000
150	70,32	0	79,68	972,875
180	93	30,65	56,35	1.255,360
210	93	30	87	1.397,110
240	56,07	93	90,93	1.533,770
260	93	86,11	80,89	1.626,620
279	93	93	93	1.718,530

The optimization results show that PSO is able to determine different loading patterns at each load level according to the fuel gas consumption characteristics of each GTG. At low loads up to 90 MW, loading is carried out on GTG 2.3. As the load increases, power begins to be distributed to GTG 2.1 and GTG 2.2 until all units operate at a maximum capacity of 93 MW when the load reaches 279 MW. These results demonstrate the ability of PSO to determine loading combinations that meet system power requirements with minimum fuel gas consumption.

3. RESULTS AND DISCUSSION

The results of the optimization simulation of the loading pattern of a 3 × 93 MW Gas Turbine Generator (GTG) using the Particle Swarm Optimization (PSO) algorithm are presented to evaluate the algorithm's ability to obtain an optimal loading pattern. Testing is carried out by considering the system load requirements, the minimum and maximum loading limits of each GTG, and the fuel consumption characteristics of each unit. The PSO optimization results are then compared with the existing loading pattern to determine the effect of optimization on gas fuel consumption and generation costs. In addition, the algorithm convergence process is analyzed to determine the ability of PSO to find an optimal solution during the iteration process.

3.1. Results of GTG Loading Pattern Optimization Using PSO

The PSO algorithm is implemented using MATLAB 21a to obtain the optimal load combination of the 3 x 93 MW Tambak Lorok Combined Cycle Power Plant. Each particle represents the combined output power of the three GTG units, while the fitness value is determined based on the total gas fuel consumption. At each iteration, the particle position and velocity are updated based on the Personal Best (Pbest) and Global Best (Gbest) until convergence is achieved.
The objective function is used to minimize total fuel consumption while still meeting the power balance and operating limits of each unit, namely 10–93 MW. The optimization results show that PSO is able to determine the load distribution of the three GTGs according to the fuel consumption characteristics of each unit. A summary of the optimization results at several load levels is shown in Table 3.

Table 3. Results of Loading Pattern Optimization Using PSO

System Load (MW)	GTG 2.1 (MW)	GTG 2.2 (MW)	GTG 2.3 (MW)	Total Fuel Gas (MMBTU/jam)
30	0	0	30	280,463
40	0	0	40	324,630
50	0	0	50	369,630
60	0	0	60	415,464
70	0	0	70	462,131
80	0	0	80	509,631
90	0	0	90	557,965
110	57,46	52,54	0	785,389
120	0	60,62	59,38	975,000
150	70,32	0	79,68	972,875
180	93,00	30,65	56,35	1.255,360
210	93,00	30,00	87,00	1.397,110
240	56,07	93,00	90,93	1.533,770
260	93,00	86,11	80,89	1.626,620
279	93,00	93,00	93,00	1.718,530

Optimal loading of up to 90 MW was performed on GTG 2.3. As power demand increased, the PSO began distributing the load to GTG 2.1 and GTG 2.2 until all units reached their maximum capacity of 279 MW. These results demonstrate that the PSO is capable of generating adaptive loading patterns to meet system power requirements by considering the fuel gas consumption characteristics of each unit.

3.2. Comparison of Existing Loading Patterns and PSO Results

A comparison of existing conditions and PSO optimization results was conducted to evaluate the increase in the efficiency of the power plant operation. The simulation results show that fuel gas consumption in existing conditions is 1,061.788 MMBTU/hour, while the PSO optimization results are 1,032.567 MMBTU/hour. Thus, a savings of 29.221 MMBTU/hour is obtained. In terms of generation costs, the existing conditions require a cost of Rp125,290,984/hour, while the PSO results are Rp121,841,220/hour, resulting in a cost savings of Rp3,449,764/hour. The comparison of these results is shown in Table 4.

Table 4. Comparison of Existing Conditions and PSO Optimization Results

Parameter	Existing	PSO	Savings	Decline
Fuel Gas Consumption (MMBTU/hour)	1,061,788	1,032,567	29,221	2.75%
Generation Cost (Rp/hour)	125,290,984	121,841,220	3,449,764	2.75%

The PSO optimization results provide increased efficiency compared to the existing operating pattern. The reduction in fuel gas consumption of 29.221 MMBTU/hour indicates that the algorithm is able to find a more economical loading combination. In addition, the cost savings of IDR 3.45 million/hour indicate the potential for significant economic benefits if the optimized loading pattern can be consistently applied in power plant operations. Thus, PSO can be used as a decision-making support method in determining the loading pattern of the 3 × 93 MW GTG, especially to obtain more efficient operations in terms of fuel consumption and generation costs.

3.3. PSO Algorithm Convergence Analysis

Convergence analysis was performed to determine the development of fitness values during the iteration process. A decreasing fitness value indicates that the PSO is getting closer to the optimal solution. In the initial stage, the fitness value is relatively high because the particle positions are generated randomly. As the number of iterations increases, the particles move towards a better solution region based on the Pbest and Gbest information. The decreasing fitness value indicates that the total fuel consumption is decreasing, as shown in Table 5.

Table 5. Results of PSO Algorithm Convergence Analysis

Iteration	Fitness Value (MMBTU/hour)	Optimization Conditions	Information
1	Tall	Exploration	Particles are randomly initialized
10	Decrease	Exploration	Particles start to find better solutions
20	Decrease	Exploration–Exploitation	Pbest and Gbest start directing particles
30	Approaching optimum	Exploitation	The change in fitness value starts to decrease
40	Approaching optimum	Exploitation	Particles increasingly gather at the best solution
41	**≈ 1,032,567**	**Convergent**	**The optimal solution starts to stabilize**
50	≈ 1,032,567	Stable	The changes in fitness are relatively small
75	≈ 1,032,567	Stable	The best solution is maintained
100	≈ 1,032,567	Stable	Convergence condition until the final iteration

The fitness value decreased in the initial iterations and began to stabilize around the 41st iteration. This condition indicates that the particles have moved towards the best solution region based on the Pbest and Gbest information. After reaching the convergence condition, the change in fitness value is relatively small until the maximum iteration, with the best value around 1,032.567 MMBTU/hour. These results indicate that PSO is able to achieve the optimal solution effectively through the balance of exploration and exploitation processes as shown in Figure 5.

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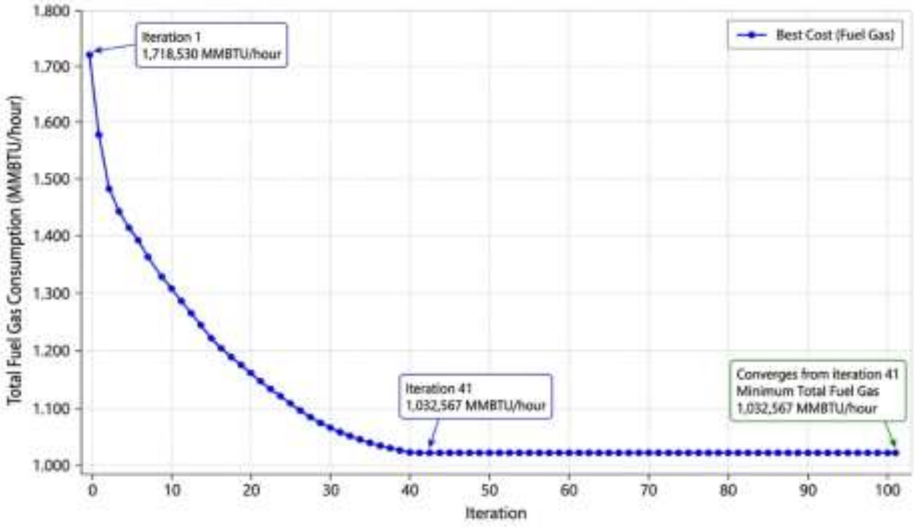

Figure 5. The convergence curve shows that PSO

The convergence curve shows that PSO experienced a significant decrease in fitness value in the initial iterations and then reached a relatively stable state in subsequent iterations. This condition indicates that the particle population has converged around the best solution and the optimization process has reached a convergent state. Thus, the PSO algorithm is able to effectively search for solutions by balancing exploration of the search space and exploitation of the best solution found.

3.4. Discussion of Optimization Results

The results of the 3 × 93 MW GTG loading pattern optimization using the Particle Swarm Optimization (PSO) algorithm were then compared with existing operating conditions to determine the level of increase in generation efficiency. The evaluation was carried out based on fuel gas consumption, generation costs, and the algorithm's ability to obtain optimal solutions while still meeting the system load requirements and operating limits of each unit is shown in Table 6.

Table 6. Summary of PSO Optimization Results

Performance Parameters	Existing Conditions	PSO Results	Change
Fuel Gas Consumption (MMBTU/hour)	1,061,788	1,032,567	−29,221
Reduction in fuel gas consumption	–	–	2.75%
Generation Cost (Rp/hour)	125,290,984	121,841,220	−3,449,764
Reduction in generation costs	–	–	2.75%
Total GTG capacity	279 MW	279 MW	Still
Optimization method	Existing	PSO	–
Convergence conditions	–	41st Iteration	Stable

The implementation of PSO resulted in a reduction in fuel gas consumption of 29.221 MMBTU/hour, or 2.75%, compared to existing conditions. This reduction in fuel consumption is in line with a decrease in generation costs of Rp3,449,764/hour. These results indicate that PSO is able to determine a more economical loading pattern by allocating power based on the fuel consumption characteristics of each GTG.

In addition to the economic aspect, the convergence results at the 41st iteration indicate that the algorithm is able to find a stable solution in the search process. The optimized loading pattern also maintains the total generation capacity of 279 MW and meets the system power requirements and unit operating limits. Overall, the results of the study indicate that PSO has the potential to be an effective optimization method for regulating the loading pattern of the 3 × 93 MW GTG Tambak Lorok Combined Cycle Power Plant. The application of this method can support efforts to increase the efficiency of fuel gas use while reducing generation costs. The optimization results can be used as a reference to support operational decision-making, with its application still considering the actual conditions of the generator, unit reliability, technical operating limits, and system requirements.

3.5. Evaluation of Optimization Result Efficiency

The optimization results show that the implementation of PSO has a positive impact on the operational efficiency of the GTG. The reduction in fuel consumption of 29.221 MMBTU/hour indicates that the PSO loading pattern is more economical than the existing condition. The reduction in fuel consumption also has a direct impact on generation costs. Based on the simulation results, savings of approximately Rp3,449,764/hour were obtained. If these optimal operating conditions can be maintained consistently, the potential savings over a longer operating period will be even greater. In addition to the economic aspect, optimizing the loading pattern can also provide benefits by reducing fuel consumption and emissions due to the generation process. Therefore, the implementation of PSO is not only reviewed from a cost aspect, but can also support increased operational efficiency of the power plant is shown in Table 7.

Table 7. Summary of PSO Optimization Results

Efficiency Parameters	Existing Conditions	PSO Optimization Results	Change
Fuel Gas Consumption (MMBTU/hour)	1,061,788	1,032,567	−29,221
Fuel Gas Consumption Efficiency	100%	97.25%	2.75%
Generation Cost (Rp/hour)	125,290,984	121,841,220	−3,449,764
Cost Savings	–	–	Rp3,449,764/hour
Generating Capacity (MW)	150	150	Still
Optimization Status	Existing	PSO	More economical

The evaluation results show that the application of the PSO algorithm can improve the efficiency of the 3 × 93 MW GTG operating pattern through more optimal load allocation to each unit. The reduction in fuel gas consumption and generation costs indicates that the PSO method can be an effective approach in supporting more economical power plant operations. By considering power requirements, unit capacity limits, and fuel consumption characteristics, the optimization results can be used as a reference in determining an efficient loading strategy and supporting the optimal operation of the Tambak Lorok Combined Cycle Power Plant (PLTGU).

3.6. Comparison of PSO with Conventional Methods

A comparison was conducted to evaluate the performance of the Particle Swarm Optimization (PSO) algorithm against existing loading patterns and the conventional Lambda Iteration method under the same system load conditions. The evaluation focused on fuel gas consumption and generation costs. The comparison results were used to determine the ability of each method to determine the loading distribution of GTG 2.1, GTG 2.2, and GTG 2.3 economically. The loading graph is shown in Figure 6.

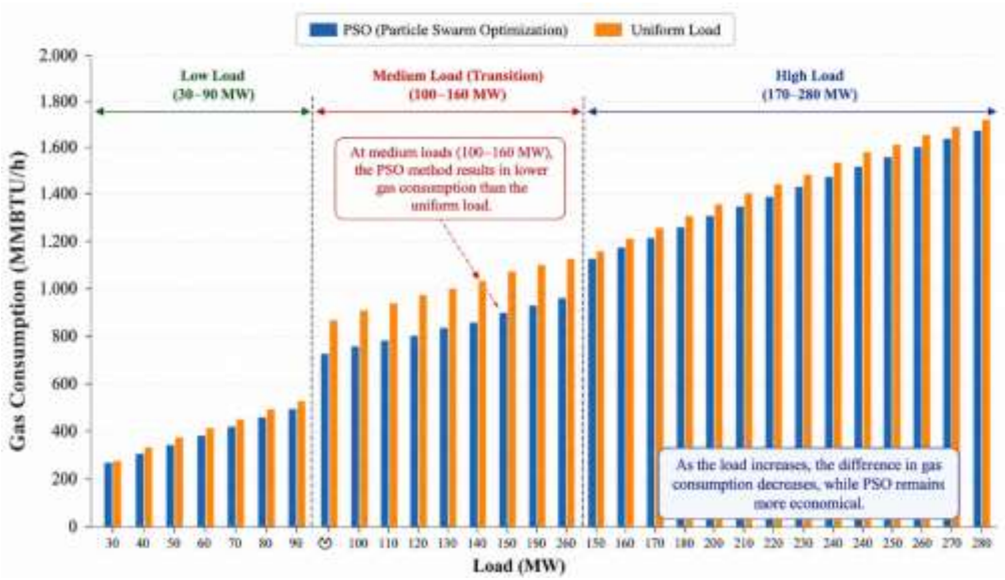

Figure 6. PSO Optimization Graph with Even Load Distribution

Figure 6 illustrates the comparison of gas consumption between the PSO-based optimization method and the uniform-load strategy across different load levels (30–280 MW). The results show that PSO consistently achieves lower gas consumption, with the most significant reduction observed in the medium-load transition range (100–160 MW).

Comparison of natural gas (CNG) consumption between the Particle Swarm Optimization (PSO) method and uniform load distribution at various loading levels of the 3 × 93 MW GTG. In general, CNG consumption increases with increasing power plant load. At loads of 100–160 MW, the PSO method produces lower CNG consumption than uniform load distribution. Meanwhile, at high loads (170–280 MW), the difference in consumption between the two methods becomes smaller, but PSO still shows more efficient fuel use. These results indicate that the PSO algorithm is more effective in determining load distribution, thereby increasing the efficiency of power plant operations is shown in Table 8.

Table 8. Comparison of Loading Results

Method	Fuel Gas (MMBTU/hour)	Generation Cost (Rp/hour)	Fuel Gas Savings (MMBTU/hour)	Cost Savings (Rp/hour)
Existing	1,061,788	125,290,984	–	–
Lambda Iteration	[simulation results]	[simulation results]	[results]	[results]
PSO	1,032,567	121,841,220	29,221	3,449,764

Based on Table 7, the PSO optimization results show fuel gas consumption of 1,032.567 MMBTU/hour, lower than the existing condition of 1,061.788 MMBTU/hour. The reduction in consumption of 29.221 MMBTU/hour indicates that PSO is capable of producing a more economical loading pattern.

In terms of generation costs, PSO generates a cost of Rp121,841,220/hour, or Rp3,449,764/hour lower than the existing condition. These results indicate that PSO has the potential to improve operational efficiency through more optimal load distribution across the three GTG units. The Lambda Iteration value needs to be entered based on actual simulation results so that comparisons between methods can be made objectively. By comparing the three methods under the same load conditions, the method with the lowest fuel gas consumption and generation costs can be determined as the method that provides the best economic performance.

4. CONCLUSION

Based on the research results, the Particle Swarm Optimization (PSO) algorithm successfully determined the optimal loading pattern for the three 93 MW Gas Turbine Generator (GTG) units, namely GTG 2.1, GTG 2.2, and GTG 2.3, at the Tambak Lorok Combined Cycle Power Plant (PLTGU). The optimization was formulated to minimize fuel gas consumption while satisfying the required power demand and the operating constraints of each GTG unit. The optimization results demonstrate that the PSO algorithm can effectively redistribute the generation load among the GTG units to obtain a more efficient operating condition. Under the existing operating condition, the total fuel gas consumption was 1,061.788 MMBTU/hour. After optimization using PSO, the fuel gas consumption decreased to 1,032.567 MMBTU/hour, resulting in a saving of 29.221 MMBTU/hour, equivalent to approximately 2.75% of the existing fuel consumption. This reduction indicates that the optimized loading pattern can improve the utilization of fuel gas while maintaining the required power generation within the specified operating limits. From an economic perspective, the optimized loading pattern also reduced the estimated generation cost from Rp125,290,984/hour under the existing condition to Rp121,841,220/hour. This represents a cost saving of Rp3,449,764/hour, demonstrating the economic benefit of applying PSO to GTG load allocation. The results therefore indicate that optimization of the loading pattern can simultaneously contribute to fuel efficiency and reduction in generation costs. Overall, the results confirm that PSO is capable of obtaining a converged and feasible loading solution for the three GTG units based on the defined operational constraints. The proposed optimization approach provides a quantitative basis for evaluating alternative GTG loading patterns and may support operational decision-making for more efficient operation of the Tambak Lorok PLTGU.

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