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Economic Scheduling of Thermal Power Plants in the West Sumatra System Using Genetic Algorithms

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Abstract

Fuel cost is the largest component of operating expenses for thermal power plants; consequently, suboptimal scheduling increases system costs. This study determines a minimum-cost 24-hour generation schedule for the West Sumatra electrical system by optimizing four thermal units—specifically at the Teluk Sirih and Ombilin power plants—while assuming the Muara Labuh geothermal unit operates at a capacity of 85 MW. A genetic algorithm is employed to generate candidate schedules, evaluate total fuel costs and power balance constraints, convert feasible solutions into fitness values, and improve the population through selection, crossover, and mutation. The algorithm uses a population size of 20,000, a crossover probability of 0.9, a mutation probability of 0.1, and 100 generations. The genetic algorithm yields a total 24-hour cost of Rp3,202,331,042.71, representing a 2.9% cost reduction compared to the actual schedule. Compared to the lambda iteration method, the cost is lower by Rp25,365.40, or 0.0008%. These findings demonstrate the effectiveness of the genetic algorithm for economic scheduling in a real-world thermal system, although its numerical advantage over the lambda iteration method in this specific case is relatively small.

Keywords: *Fuel Cost, Genetic Algorithm, Lambda Iteration, Thermal Power Plant.*

Abstrak

Biaya bahan bakar merupakan komponen biaya operasi terbesar pada pembangkit listrik tenaga termal, sehingga penjadwalan menjadi tidak optimal meningkatkan biaya system. Penelitian ini menentukan jadwal pembangkitan 24 jam dengan biaya minimum pada sistem kelistrikan Sumatera Barat dengan mengoptimalkan empat unit pembangkit PLTU Teluk Sirih dan PLTU Ombilin, sedangkan unit panas bumi Muara Labuh diasumsikan beroperasi pada kapasitas 85 MW. Algoritma genetika digunakan untuk membangkitkan kandidat jadwal, mengevaluasi total biaya bahan bakar dan kendala keseimbangan daya, mengubah solusi layak menjadi nilai fitness, serta memperbaiki populasi melalui seleksi, crossover, dan mutasi. Algoritma menggunakan ukuran populasi 20.000, probabilitas crossover 0,9, probabilitas mutasi 0,1, dan 100 generasi. Algoritma genetika menghasilkan total biaya 24 jam sebesar Rp3.202.331.042,71 dan menurunkan biaya sebesar 2,9% dibandingkan penjadwalan aktual. Dibandingkan iterasi lambda, biaya berkurang Rp25.365,40 atau 0,0008%. Temuan ini menunjukkan bahwa algoritma genetika efektif untuk penjadwalan ekonomis pada sistem termal nyata, meskipun keunggulan numeriknya terhadap iterasi lambda pada kasus ini relatif kecil.

Kata kunci: Biaya Bahan Bakar, Algoritma Genetika, Iterasi Lambda, Pembangkit Termal.

Introduction

An electric power system comprises generating units that supply electrical loads [1]. Because load demand varies over time [3], each unit in a large, dynamic system must be scheduled carefully to ensure economical operation [2], [17], [20]. Generation must be balanced with demand so that power plants operate optimally at minimum cost [4]. Economic operation depends on plant characteristics, unit output limits, fuel prices, and proper scheduling [21], [22]. Fuel may account for up to 60% of total operating costs; therefore, even a 1% reduction can yield annual savings of billions of rupiah in a large-scale system [5], [6], [18].

Economic dispatch allocates the required load among generating units while satisfying operational constraints and minimizing total generation cost [1]. Precisely matching the number of committed units and their outputs to system demand is also essential for smart-grid operation [7], [19]. The West Sumatra electricity system requires periodic scheduling optimization because load demand and unit availability may change. Previous work analyzed the economic operation of thermal power plants serving the system's peak load using the lambda-iteration method [8].

Building on [8], this study applies a genetic algorithm to optimize the scheduling of thermal generating units in the West Sumatra system under dynamic load conditions. Unlike the conventional lambda-iteration method used in [8], the GA employs probabilistic search rather than a deterministic iterative procedure. This approach is expected to represent practical operating conditions more flexibly.

Genetic algorithms can search for near-global solutions and are not restricted by the form of generator characteristic curves because they use probabilistic rather than deterministic search [9]-[11]. Early studies demonstrated the suitability of GA-based search for valve-point loading, unit commitment, and economic dispatch [23], [24]. Related evolutionary and swarm-intelligence methods have subsequently addressed nonconvex cost functions, prohibited operating zones, ramp-rate limits, multiple fuels, and other practical generator constraints [25]-[28]. Evolutionary formulations have also been extended to combined unit-commitment and economic-dispatch problems in microgrids [29], while hybrid population-based methods have shown competitive performance for nonconvex dispatch [30]. In this study, the GA results are compared with lambda iteration and actual PLN scheduling to validate the proposed optimization.

Method

a. Data Collection

This study used operational data from the Ombilin and Teluk Sirih coal-fired power plants and the Muara Labuh geothermal power plant in the West Sumatra system. The collected data included hourly output, fuel consumption, minimum and maximum output limits, and technical specifications for each generating unit.

b. Genetic Algorithm Calculation

In the initial stage, the input-output characteristic of each generating unit was estimated using the least-squares method in MATLAB.

The input-output characteristic is essential for analyzing the economic operation of a thermal generating unit. It describes the relationship between fuel input (liters/hour) and electrical output (MW). Figure 1 illustrates a typical input-output characteristic curve.

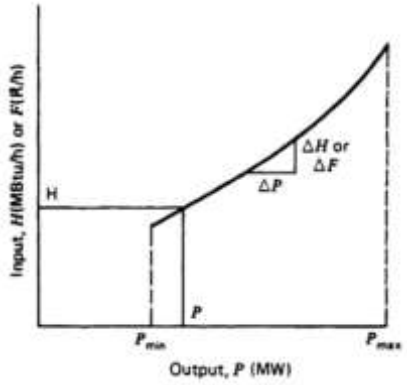


Figure 1. Input-output characteristics of a thermal generating unit

The input-output characteristic is expressed by (1) [12]:

$$H_i = \alpha_i + \beta_i PT_i + \gamma PT^2{}_i \quad \text{.....(1)}$$

where:

H_i = Fuel consumption of unit i (liters/hour).
PT_i = Electrical power generated by unit i (MW).
α, β, γ = Fuel-cost coefficients of unit i.

The fuel-cost function is obtained by multiplying the unit's input-output characteristic by the fuel price, as expressed in (2) [5]:

$$F_i = \text{Fuel costs } \left(\frac{\text{Rp}}{\text{MBtu}}\right) \text{x } H_i \quad \text{.....(2)}$$

The GA is a metaheuristic inspired by natural selection and can solve a wide range of optimization problems. Its fitness function guides the search toward a near-global optimum and reduces the risk of becoming trapped in a local optimum. The method can also address nonconvex economic-dispatch problems and is not restricted by the form of the generator characteristic curve because it uses probabilistic search [9]-[11], [23], [24], [29]. Moreover, the GA requires relatively few explicit mathematical calculations [13]. Figure 2 presents the flowchart for scheduling generating units using the GA.

As shown in Figure 2, the procedure begins by reading the input data and randomly generating an initial population of a predetermined size. Each chromosome is encoded as a binary string and evaluated according to the operational constraints. This population represents the initial candidate solutions.

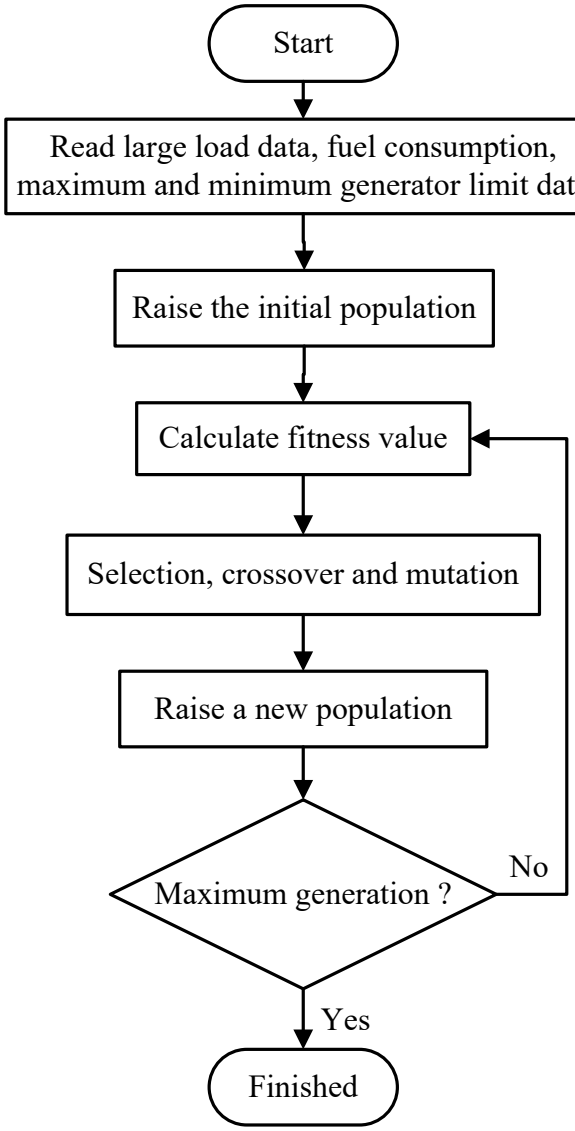


Figure 2. Flowchart of the Optimal Scheduling Procedure

The fitness value indicates the quality of each candidate solution and is used to identify the best schedule. The objective function is first calculated as the total generation cost, as given by (3) and (4) [14].

$$F_T = F_1 + F_2 + F_3 + \cdots + F_N \quad \text{.....(3)}$$

$$F_T = \sum_{i=1}^{N} F_i\,(P_i) \quad \text{.....(4)}$$

The power-balance constraint is then calculated using (5) [4]:

$$\sum_{i=1}^{n} P_i - P_D^t = 0 \quad \text{.....(5)}$$

The generation cost is mapped to a fitness value. In (3)-(5), F_T is the total fuel cost, F_i(P_i) is the fuel-cost function of unit i, N is the number of generating units, P_i is the output of unit i, and P_Dt is the demand at time t. The evolutionary stage consists of selection, crossover, and mutation, which produce the next generation of offspring [9], [10], [15]. The main parameters are the maximum number of generations (Maxgen), population size (popsize), crossover probability (P_c), and mutation probability (P_m). A population that is too small may cause premature convergence and provide insufficient coverage of the search space. The crossover probability controls how

frequently new structures are introduced into the population and is commonly set between 0.6 and 0.9. The mutation probability increases population diversity; a typical value is approximately the reciprocal of the number of genes in a chromosome [10], [13]. After the evolutionary operators are applied, the objective and fitness values of the new population are recalculated. The process continues until the maximum number of generations is reached or the highest fitness value, corresponding to the lowest generation cost, is obtained.

Results and Discussion

a. West Sumatra Electric Power System

The West Sumatra power system is connected to the 150-kV Central Sumatra interconnection (Jambi-West Sumatra-Riau), excluding the Mentawai Islands system. To meet demand, each generating unit receives dispatch instructions from the Unit Pelaksana Pengatur Beban (UP2B) and generates power according to the requested output. To validate the optimization results, the GA schedule was compared with both the lambda-iteration schedule and the actual PLN schedule.

Table 1. Generator Specifications

No.	Generating Unit	Machine Brand	Installed Power (MW)	Capability (MW)	Status	Remarks
1	PLTU Teluk Sirih Unit 1	Nanjing Turbine & Electric Machinery (Group Co., Ltd.)	112	112	RUN	Routine maintenance
2	PLTU Teluk Sirih Unit 2	Nanjing Turbine & Electric Machinery (Group Co., Ltd.)	112	112	RUN	Routine maintenance
3	PLTU Ombilin Unit 1	GEC Alsthom Rateau	100	97	RUN	Routine maintenance
4	PLTU Ombilin Unit 2	GEC Alsthom Rateau	100	97	RUN	Routine maintenance
5	PLTP Muara Labuh	Fuji Electric	85	85	RUN	Routine maintenance

The West Sumatra system includes three power plants: Teluk Sirih PLTU with two 112-MW units, Ombilin PLTU with two 100-MW units (97-MW capability each), and Muara Labuh PLTP with one 85-MW unit. Table 1 summarizes the specifications of these units.

b. Actual 24-Hour Load Data

Table 2 presents the thermal-generation load to be optimized using PLN data for August 21, 2020. Because detailed operating data for the Muara Labuh geothermal power plant were unavailable, the unit was assumed to operate at its maximum output of 85 MW. The remaining load was allocated among the four coal-fired units.

Table 2. Load Data for Optimization on August 21, 2020

Time	Total Load (MW)	Muara Labuh PLTP Assumed at Maximum Capacity (MW)	Load to be Optimized (MW)
01:00	434.4	85	349.4
02:00	412	85	327
03:00	410.3	85	325.3
04:00	410.9	85	325.9
05:00	410.6	85	325.6
06:00	410.6	85	325.6
07:00	410.2	85	325.2
08:00	410.4	85	325.4
09:00	396.3	85	311.3
10:00	396.3	85	311.3
11:00	396.3	85	311.3
12:00	396.3	85	311.3
13:00	396.3	85	311.3
14:00	396.3	85	311.3
15:00	396.3	85	311.3
16:00	396.3	85	311.3
17:00	406.7	85	321.7
18:00	427.77	85	342.77
19:00	427.09	85	342.09
20:00	427.05	85	342.05
21:00	427.34	85	342.34
22:00	427.31	85	342.31
23:00	436	85	351
24:00	435.4	85	350.4

Table 3 presents the actual 24-hour loading schedule used to meet system demand on August 21, 2020.

Table 3. Actual Loading Schedule on August 21, 2020

Time (Hour)	PLTU Teluk Sirih Unit 1 (MW)	PLTU Teluk Sirih Unit 2 (MW)	PLTU Ombilin Unit 1 (MW)	PLTU Ombilin Unit 2 (MW)	Total Load (MW)	Total Cost (IDR/hour)
01:00	98,60	97,80	76,00	77,00	349.4	144.968.291,52
02:00	87,00	87,00	76,00	77,00	327	135.192.038,49
03:00	86,30	86,00	76,00	77,00	325.3	135.072.997,36
04:00	86,80	86,10	76,00	77,00	325.9	135.296.199,48
05:00	86,50	86,10	76,00	77,00	325.6	135.445.000,90
06:00	86,60	86,00	76,00	77,00	325.6	135.519.401,61
07:00	86,40	85,80	76,00	77,00	325.2	135.519.401,61
08:00	86,40	86,00	76,00	77,00	325.4	135.519.401,61
09:00	88,20	88,10	67,50	67,50	311.3	130.227.279,25
10:00	88,20	88,10	67,50	67,50	311.3	130.227.279,25
11:00	88,20	88,10	67,50	67,50	311.3	130.227.279,25
12:00	88,20	88,10	67,50	67,50	311.3	130.227.279,25
13:00	88,20	88,10	67,50	67,50	311.3	130.227.279,25
14:00	88,20	88,10	67,50	67,50	311.3	130.227.279,25
15:00	88,20	88,10	67,50	67,50	311.3	130.227.279,25
16:00	88,20	88,10	67,50	67,50	311.3	130.227.279,25
17:00	89,00	87,70	80,00	65,00	321.7	133.973.354,90
18:00	99,00	98,77	80,00	65,00	342.77	148.124.369,56

Time (Hour)	PLTU Teluk Sirih Unit 1 (MW)	PLTU Teluk Sirih Unit 2 (MW)	PLTU Ombilin Unit 1 (MW)	PLTU Ombilin Unit 2 (MW)	Total Load (MW)	Total Cost (IDR/hour)
19:00	99,00	98,09	80,00	65,00	342.09	150.579.592,92
20:00	99,00	98,05	80,00	65,00	342.05	150.014.147,54
21:00	99,00	98,34	80,00	65,00	342.34	150.021.587,61
22:00	99,00	98,31	80,00	65,00	342.31	150.185.269,17
23:00	100,00	98,00	76,00	77,00	351	144.745.089,40
24:00	99,20	98,20	76,00	77,00	350.4	145.489.096,48

Table 3 indicates that the peak-load period occurs from 17:00 to 01:00. Figure 3 presents the load profile graphically.

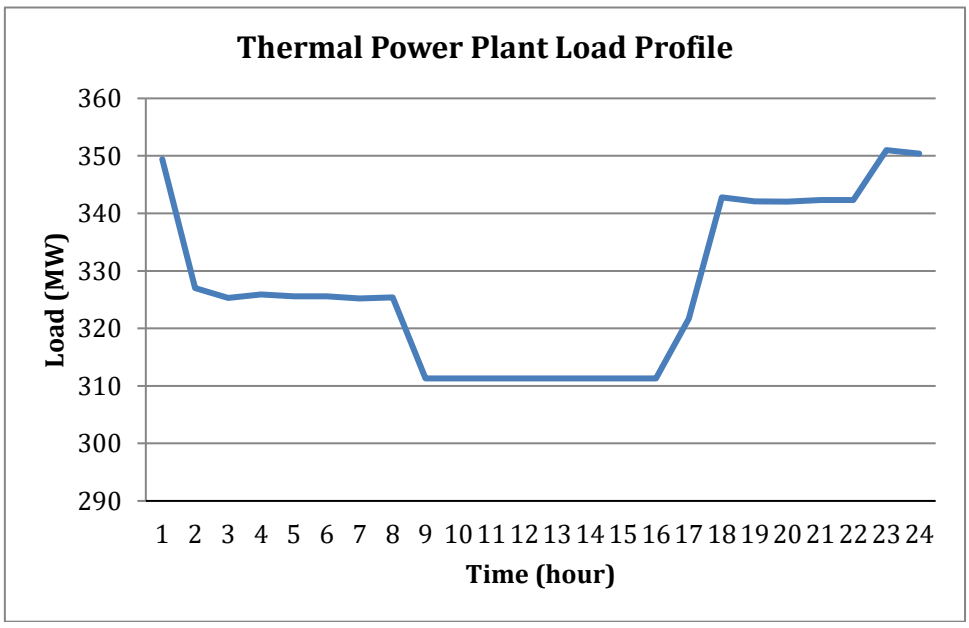


Figure 3. Actual thermal-generation load profile

Figure 3 shows that the load exceeds 340 MW from 18:00 to 01:00 and decreases outside this period.

c. Input-Output Characteristics of Thermal Generating Units

Table 4 presents the input-output characteristic equation for each thermal generating unit.

Table 4. Input-output Characteristic Equations of Thermal Generating Units

No.	Generating Unit	Input-Output Characteristic Equation of Generator
1	PLTU Teluk Sirih Unit 1	$H(P) = 737{,}3441 - 15{,}3211PT_1 + 0{,}0862PT_1^2$
2	PLTU Teluk Sirih Unit 2	$H(P) = 644{,}5535 - 13{,}2967PT_2 + 0{,}0753PT_2^2$
3	PLTU Ombilin Unit 1	$H(P) = 574{,}6447 - 15{,}4061PT_3 + 0{,}1089PT_3^2$
4	PLTU Ombilin Unit 2	$H(P) = 171{,}8667 - 4{,}2776PT_4 + 0{,}0322PT_4^2$

d. Fuel-Cost Function of Each Generating Unit

Based on the industry price on August 21, 2020, coal cost USD 50.34/ton, equivalent to IDR 744,007.08/ton. The fuel-cost function for each unit was obtained by multiplying its input-output characteristic by the fuel price, as shown in Table 5.

Table 5. Fuel-cost Functions of Thermal Generating Units

No.	Generating Unit	Fuel Cost Function Equation for Generator (Rp/Hour)
1	PLTU Teluk Sirih Unit 1	F_1 = 548.589.230,7962 -11.399.006,8733 PT_1 +64.133,4102 PT_1^2
2	PLTU Teluk Sirih Unit 2	F_2 = 479.552.367,4387-9.892.838,9406 PT_2 +56.023,7331 PT_2^2
3	PLTU Ombilin Unit 1	F_3 = 427.539.725,2844 - 11.462.247,4751 PT_3 +81.022,3710 PT_3^2
4	PLTU Ombilin Unit 2	F_4 = 127.870.041,6162-3.182.564,6854 PT_4 +23.957,0279 PT_4^2

e. Thermal Power Plant Optimization

The optimization incorporated the minimum and maximum output constraints of each generating unit, as listed in Table 6.

Table 6. Generator Capacity Limits

No.	Generating Unit	P_{min} (MW)	P_{max} (MW)
1	PLTU Teluk Sirih Unit 1	70	112
2	PLTU Teluk Sirih Unit 2	70	112
3	PLTU Ombilin Unit 1	50	97
4	PLTU Ombilin Unit 2	50	97

The lambda-iteration calculation was performed for the 01:00 demand of 349.4 MW. The procedure began by determining an initial lambda value of 801,628.57 using (6).

$$\lambda = \frac{P_D + \sum \frac{\beta_i}{2\gamma_i}}{\sum \frac{1}{2\gamma_i}} \quad \text{.....(6)}$$

The output of each generating unit was then determined using (7):

$$P_i^{(k)} = \frac{\lambda^{(k)} - \beta_i}{2\gamma_i} \quad \text{.....(7)}$$

If total generation did not equal the required demand (P_D), the calculation proceeded to the next iteration using an updated lambda value. This process continued until total generation matched demand while each unit remained within its output limits. Table 7 presents the 24-hour lambda-iteration results. In (6) and (7), lambda is the incremental cost, beta_i and gamma_i are fuel-cost coefficients, and P_i is the output of unit i.

Table 7. Twenty-four-hour Optimization Results Using the Lambda-iteration Method

Time	PLTU Teluk Sirih Unit 1 (MW)	PLTU Teluk Sirih Unit 2 (MW)	PLTU Ombilin Unit 1 (MW)	PLTU Ombilin Unit 2 (MW)	Total Load (MW)
01:00	95,119	95,446	75,682	83,153	349,4
02:00	91,129	90,878	72,523	72,47	327
03:00	90,826	90,531	72,284	71,66	325,3
04:00	90,933	90,653	72,368	71,946	325,9
05:00	90,879	90,592	72,326	71,803	325,6
06:00	90,879	90,592	72,326	71,803	325,6
07:00	90,808	90,511	72,27	71,612	325,2
08:00	90,844	90,551	72,298	71,707	325,4
09:00	88,332	87,676	70,309	64,983	311,3

Time	PLTU Teluk Sirih Unit 1 (MW)	PLTU Teluk Sirih Unit 2 (MW)	PLTU Ombilin Unit 1 (MW)	PLTU Ombilin Unit 2 (MW)	Total Load (MW)
10:00	88,332	87,676	70,309	64,983	311,3
11:00	88,332	87,676	70,309	64,983	311,3
12:00	88,332	87,676	70,309	64,983	311,3
13:00	88,332	87,676	70,309	64,983	311,3
14:00	88,332	87,676	70,309	64,983	311,3
15:00	88,332	87,676	70,309	64,983	311,3
16:00	88,332	87,676	70,309	64,983	311,3
17:00	90,184	89,797	71,776	69,943	321,7
18:00	93,938	94,094	74,747	79,991	342,77
19:00	93,817	93,955	74,651	79,667	342,09
20:00	93,817	93,955	74,651	79,667	342,05
21:00	93,861	94,006	74,686	79,786	342,34
22:00	93,856	94	74,682	79,772	342,31
23:00	95,404	95,772	75,908	83,916	351
24:00	95,297	95,65	75,823	83,63	350,4
Total	2.188,247	2.182,391	1.741,473	1.742,390	
Average	91,177	90,933	72,561	72,600	

The cost of each unit was obtained by substituting its optimized output into the corresponding fuel-cost function. Table 8 presents the unit costs and total generation cost.

Table 8. Unit and Total Generation Costs Using the Lambda-iteration Method

Time	PLTU Teluk Sirih Unit 1 (MW)	PLTU Teluk Sirih Unit 2 (MW)	PLTU Ombilin Unit 1 (MW)	PLTU Ombilin Unit 2 (MW)	Total (IDR/
01:00	44.582.236,1385102	45.693.141,3774398	24.131.051,8604298	28.879.156,2796064	143.285.58
02:00	42.404.602,1226217	43.200.285,4415962	22.407.341,5581672	23.049.589,4322742	131.061.81
03:00	42.322.724,4822767	43.106.555,6595219	22.342.531,1579081	22.830.401,4630334	130.602.2
04:00	42.350.279,1268853	43.138.098,9578316	22.364.342,0886891	22.904.165,7602146	130.756.88
05:00	42.336.318,6210217	43.122.117,6085069	22.353.291,6240076	22.866.793,2258216	130.678.52
06:00	42.336.318,6210217	43.122.117,6085069	22.353.291,6240076	22.866.793,2258216	130.678.52
07:00	42.318.274,5176104	43.101.461,5432691	22.339.008,7800042	22.818.488,8246828	130.577.23
08:00	42.327.215,1544008	43.111.696,3758125	22.346.085,7578766	22.842.423,0760067	130.627.42
09:00	42.095.812,9916095	42.846.797,7514924	22.162.918,9405605	22.222.955,1733348	129.328.48
10:00	42.095.812,9916095	42.846.797,7514924	22.162.918,9405605	22.222.955,1733348	129.328.48
11:00	42.095.812,9916095	42.846.797,7514924	22.162.918,9405605	22.222.955,1733348	129.328.48
12:00	42.095.812,9916095	42.846.797,7514924	22.162.918,9405605	22.222.955,1733348	129.328.48
13:00	42.095.812,9916095	42.846.797,7514924	22.162.918,9405605	22.222.955,1733348	129.328.48
14:00	42.095.812,9916095	42.846.797,7514924	22.162.918,9405605	22.222.955,1733348	129.328.48
15:00	42.095.812,9916095	42.846.797,7514924	22.162.918,9405605	22.222.955,1733348	129.328.48
16:00	42.095.812,9916095	42.846.797,7514924	22.162.918,9405605	22.222.955,1733348	129.328.48
17:00	42.188.171,4525855	42.952.525,4982073	22.236.025,4541088	22.470.200,4947468	129.846.92
18:00	43.724.886,7410244	44.711.686,9553372	23.452.415,3318384	26.584.015,9632367	138.473.00
19:00	43.647.070,901004	44.622.606,9367105	23.390.820,057268	26.375.701,5091684	138.036.19
20:00	43.647.070,901004	44.622.606,9367105	23.390.820,057268	26.375.701,5091684	138.036.19
21:00	43.675.460,8631326	44.655.106,4683558	23.413.292,1852037	26.451.701,9669198	138.195.56
22:00	43.672.040,6342162	44.651.191,1465458	23.410.584,89657	26.442.545,9503641	138.176.36
23:00	44.815.939,7439877	45.960.674,5882051	24.316.040,3890339	29.504.785,1872434	144.597.4
24:00	44.727.079,6682050	45.858.951,6330355	24.245.703,0288674	29.266.905,108197	144.098.63
Total	1.027.842.193,62238	1.048.405.206,74753	545.795.997,375733	580.313.010,363184	3.202.356.
Average	42.826.758,0675993	43.683.550,2811472	22.741.499,8906555	24.179.708,7651327	133.431.51

The GA parameters were set to a population size of 20,000, a crossover probability (P_c) of 0.9, a mutation probability (P_m) of 0.1, and a maximum of 100 generations (Maxgen). Table 9 presents the 24-hour optimization results.

Table 9. Twenty-four-hour Optimization Results Using the Genetic Algorithm

Time	PLTU Teluk Sirih Unit 1 (MW)	PLTU Teluk Sirih Unit 2 (MW)	PLTU Ombilin Unit 1 (MW)	PLTU Ombilin Unit 2 (MW)	Total Load (MW)
01:00	95,119	95,446	75,682	83,153	349,4
02:00	91,129	90,878	72,523	72,47	327
03:00	90,826	90,531	72,284	71,66	325,3
04:00	90,933	90,653	72,368	71,946	325,9
05:00	90,879	90,592	72,326	71,803	325,6
06:00	90,879	90,592	72,326	71,803	325,6
07:00	90,808	90,511	72,27	71,612	325,2
08:00	90,844	90,551	72,298	71,707	325,4
09:00	88,332	87,676	70,309	64,983	311,3
10:00	88,332	87,676	70,309	64,983	311,3
11:00	88,332	87,676	70,309	64,983	311,3
12:00	88,332	87,676	70,309	64,983	311,3
13:00	88,332	87,676	70,309	64,983	311,3
14:00	88,332	87,676	70,309	64,983	311,3
15:00	88,332	87,676	70,309	64,983	311,3
16:00	88,332	87,676	70,309	64,983	311,3
17:00	90,184	89,797	71,776	69,943	321,7
18:00	93,938	94,094	74,747	79,991	342,77
19:00	93,817	93,955	74,651	79,667	342,09
20:00	93,81	93,947	74,646	79,648	342,05
21:00	93,861	94,006	74,686	79,786	342,34
22:00	93,856	94	74,682	79,772	342,31
23:00	95,404	95,772	75,908	83,916	351
24:00	95,297	95,65	75,823	83,63	350,4
Total	**2.188,24**	**2.182,38**	**1.741,47**	**1.742,37**	**7854,462**
Average	91,1767	90,9326	72,5612	72,5988	

Table 10 presents the cost of each unit and the total generation cost obtained using the GA.

Table 10. Unit and Total Generation Costs Using the Genetic Algorithm

Time	PLTU Teluk Sirih Unit 1 (MW)	PLTU Teluk Sirih Unit 2 (MW)	PLTU Ombilin Unit 1 (MW)	PLTU Ombilin Unit 2 (MW)	Total Cost (IDR/hour)
01:00	44.582.236,2536458	45.693.141,3036127	24.131.051,7811924	28.879.156,3175348	143.285.585,655986
02:00	42.404.602,1084743	43.200.285,5161147	22.407.341,5280318	23.049.589,4020382	131.061.818,554659
03:00	42.322.724,5733882	43.106.555,6312276	22.342.531,1651632	22.830.401,3929608	130.602.212,76274
04:00	42.350.279,0865323	43.138.098,9528647	22.364.342,1229652	22.904.165,7712581	130.756.885,93362
05:00	42.336.318,7537825	43.122.117,5292485	22.353.291,6469119	22.866.793,1494145	130.678.521,079357
06:00	42.336.318,6593577	43.122.117,6128950	22.353.291,6055232	22.866.793,2015815	130.678.521,079357
07:00	42.318.274,5198869	43.101.461,5224747	22.339.008,7801802	22.818.488,8430244	130.577.233,665566
08:00	42.327.215,1932884	43.111.696,4452543	22.346.085,6898472	22.842.423,0357063	130.627.420,364096
09:00	42.095.813,0140401	42.846.797,7525026	22.162.918,9573548	22.222.955,1330995	129.328.484,856997
10:00	42.095.812,9607692	42.846.797,7860278	22.162.918,9324451	22.222.955,1777548	129.328.484,856997
11:00	42.095.812,9877715	42.846.797,7533289	22.162.918,9370518	22.222.955,1788447	129.328.484,856997
12:00	42.095.813,0212476	42.846.797,7380375	22.162.918,9478964	22.222.955,1498154	129.328.484,856997
13:00	42.095.812,9968365	42.846.797,7307893	22.162.918,9592264	22.222.955,1701447	129.328.484,856997
14:00	42.095.812,9750506	42.846.797,7602510	22.162.918,9398776	22.222.955,1818177	129.328.484,856997
15:00	42.095.812,9538047	42.846.797,7461708	22.162.918,9600513	22.222.955,1969703	129.328.484,856997
16:00	42.095.812,9825115	42.846.797,7486152	22.162.918,9439682	22.222.955,1819021	129.328.484,856997
17:00	42.188.171,4808881	42.952.525,4197887	22.236.025,4789355	22.470.200,5200356	129.846.922,899648
18:00	43.724.886,5436205	44.711.686,8761626	23.452.415,3359981	26.584.016,2356551	138.473.004,991436
19:00	43.647.071,1035221	44.622.606,8140808	23.390.819,9111254	26.375.701,5754224	138.036.199,404151
20:00	43.642.552,1212485	44.617.433,9622699	23.387.243,3482735	26.363.604,572071	138.010.834,003863

Time	PLTU Teluk Sirih Unit 1 (MW)	PLTU Teluk Sirih Unit 2 (MW)	PLTU Ombilin Unit 1 (MW)	PLTU Ombilin Unit 2 (MW)	Total Cost (IDR/hour)
21:00	43.675.460,8588396	44.655.106,6901854	23.413.292,2538154	26.451.701,6807710	138.195.561,483611
22:00	43.672.040,8393519	44.651.190,5346522	23.410.584,4299989	26.442.546,8236929	138.176.362,627696
23:00	44.815.939,635173	45.960.674,6515132	24.316.040,6703324	29.504.784,9514513	144.597.439,90847
24:00	44.727.079,7123483	45.858.951,6987126	24.245.702,7971724	29.266.905,2300712	144.098.639,438305
Total	1.027.837.675,3353	1.048.400.033,17678	545.792.420,123338	580.300.914,073038	3.202.331.042,70854
Average	42.826.569,8056408	43.683.334,7156992	22.741.350,8384724	24.179.204,7530433	133.430.460,112856

Table 9 shows average outputs of 91.1767 MW for Teluk Sirih Unit 1, 90.9326 MW for Teluk Sirih Unit 2, 72.5612 MW for Ombilin Unit 1, and 72.5988 MW for Ombilin Unit 2. Total generation over 24 hours was 7,854.462 MWh. As shown in Table 10, the corresponding total generation cost was IDR 3,202,331,042.71, with an average hourly cost of IDR 133,430,460.11.

The lowest generation cost occurred from 09:00 to 16:00, when the average cost was IDR 129,328,484.86/hour. The highest cost occurred at 23:00, at IDR 144,597,439.91/hour, because this time remained within the peak-load period. Under both the GA and lambda-iteration methods, Teluk Sirih Unit 2 had the highest unit cost, whereas Ombilin Unit 1 had the lowest.

f. Comparison of Actual Scheduling, Lambda Iteration, and Genetic Algorithm

Table 11 compares the fuel costs obtained from actual PLN scheduling, lambda iteration, and the GA.

Table 11. Fuel-cost Comparison Among Actual Scheduling, Lambda Iteration, and the Genetic Algorithm

Time	Actual PLN Scheduling (IDR/hour)	Lambda-Iteration Method (IDR/hour)	Genetic Algorithm (IDR/hour)
01:00	144.893.890,82	143.285.585,655986	143.285.585,655986
02:00	135.192.038,49	131.061.818,554659	131.061.818,554659
03:00	135.072.997,36	130.602.212,76274	130.602.212,76274
04:00	135.296.199,48	130.756.885,933621	130.756.885,93362
05:00	135.445.000,90	130.678.521,079358	130.678.521,079357
06:00	135.519.401,61	130.678.521,079358	130.678.521,079357
07:00	135.519.401,61	130.577.233,665567	130.577.233,665566
08:00	135.519.401,61	130.627.420,364097	130.627.420,364096
09:00	130.227.279,25	129.328.484,856997	129.328.484,856997
10:00	130.227.279,25	129.328.484,856997	129.328.484,856997
11:00	130.227.279,25	129.328.484,856997	129.328.484,856997
12:00	130.227.279,25	129.328.484,856997	129.328.484,856997
13:00	130.227.279,25	129.328.484,856997	129.328.484,856997
14:00	130.227.279,25	129.328.484,856997	129.328.484,856997
15:00	130.227.279,25	129.328.484,856997	129.328.484,856997
16:00	130.227.279,25	129.328.484,856997	129.328.484,856997
17:00	133.973.354,90	129.846.922,899648	129.846.922,899648
18:00	148.124.369,56	138.473.004,991437	138.473.004,991436
19:00	150.579.592,92	138.036.199,404151	138.036.199,404151
20:00	150.014.147,54	138.036.199,404151	138.010.834,003863
21:00	150.021.587,61	138.195.561,483612	138.195.561,483611
22:00	150.185.269,17	138.176.362,627696	138.176.362,627696
23:00	144.745.089,40	144.597.439,90847	144.597.439,90847
24:00	145.489.096,48	144.098.639,438305	144.098.639,438305
Total	3.307.409.073,46	3.202.356.408,10883	3.202.331.042,70854
Average	137.808.711,39417	133.431.517,0045350	133.430.460,112856

Table 11 shows that the GA produced the lowest 24-hour fuel cost. Compared with lambda iteration, the GA reduced the daily cost by IDR 25,365.40. Compared with actual PLN scheduling, the reduction was IDR 105,078,030.75. Figure 4 illustrates the hourly difference between the GA and actual PLN scheduling.

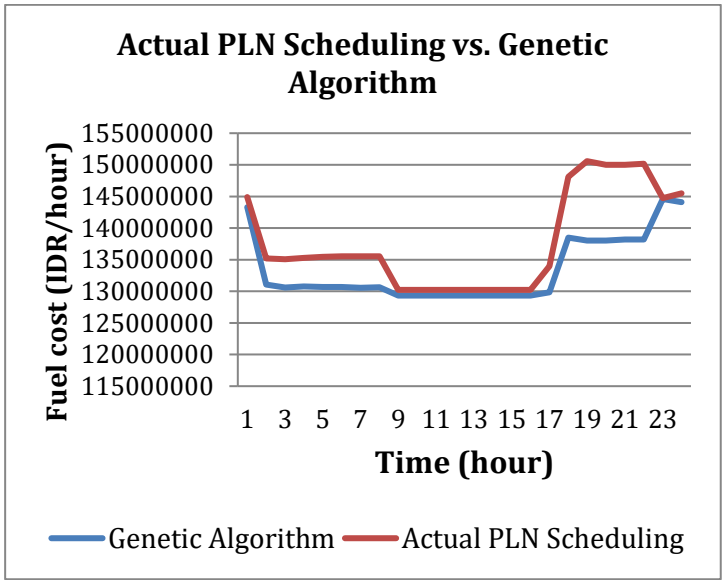


Figure 4. Hourly fuel-cost Comparison Between Actual PLN Scheduling And The Genetic Algorithm

Although the daily difference between the GA and lambda iteration was small, the projected annual saving was approximately IDR 9.26 million. Compared with actual PLN scheduling, the projected annual saving was approximately IDR 38.35 billion. Figure 5 provides a direct comparison of the hourly fuel costs for all three methods.

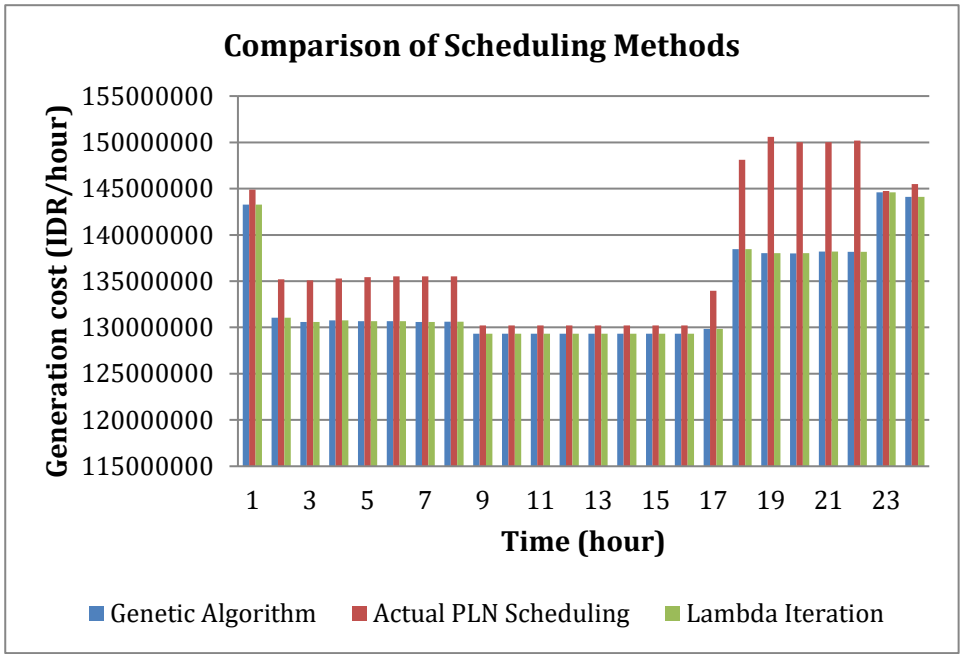


Figure 5. Hourly Generation-Cost Comparison Among Actual Scheduling, Lambda Iteration, and the Genetic Algorithm

Figure 5 shows that the largest differences among the three methods occurred during peak-load periods. The GA consistently produced the lowest or equal generation cost. Therefore, optimizing the output allocation among generating units can reduce operating costs.

Conclusion

The GA-based schedule produced a 24-hour generation cost of IDR 3,202,331,042.71, compared with IDR 3,307,409,073.46 for actual PLN scheduling. The resulting daily saving was IDR 105,078,030.75, reported as 2.9% for August 21, 2020, with a projected annual saving of approximately IDR 38.35 billion. Compared with lambda iteration, the GA reduced the daily cost by IDR 25,365.40, equivalent to 0.0008%, with a projected annual saving of approximately IDR 9.26 million. These results show that the GA can identify a slightly lower-cost schedule than lambda iteration and a substantially lower-cost schedule than the actual PLN dispatch. Its probabilistic search is suitable for large optimization problems and can converge toward a global optimum.

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