Optimization of Power Plant Operation Scheduling in Tahuna 1 Isolated System to Minimize the Levelized Cost of Electricity

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Abstract: The Tahuna 1 System which is located on Sangihe Island, North Sulawesi, Indonesia consists of 4 power plants, namely the Tahuna Diesel Power Plant, Tamako Diesel Power Plant, Sangihe Solar Power Plant, and Ulung Peliang Micro Hydro Power Plant are synchronized through the 20 kV medium voltage network with a total net power capacity of 15,358 kW. The cumulative value of the Levelized Cost of Electricity (LCOE) of the Tahuna 1 System in 2023 reached Rp4,210.86/kWh, because there is no normal operation scheduling for the generating units per hour as a reference in operating the system. Until now, the dispatcher of the Tahuna Command Center must coordinate with the power plant operator to operate the generating units without any priority order of operation, but only the availability and readiness of each unit. In this research, a scheme for hourly generating unit operation scheduling was designed on the Tahuna 1 System to minimize the LCOE by considering the system load profile, generating unit capacity, and spinning reserve with a modification of the Merit Order and Priority Listing method to increase the selectivity of determining the priority list of generating unit operations based on the cheapest LCOE ranking (Rp/kWh) according to the range of generating zones created from the intersection of the cost function equation between all diesel generating units. The design of the hourly operation scheduling scheme of generating units was carried out on 12 units of Tahuna Diesel Power Plant, and 6 units of Tamako Diesel Power Plant as independent variables. Based on the results of the operation scheduling scheme with consideration of two spinning reserve units, there is a decrease in the LCOE value of the Tahuna 1 System from the initial Rp4,210.86/kWh to Rp2,913.66/kWh or 30.81% more economical compared to the current conditions. This scheduling scheme is also a better choice to implement when viewed from the operational reliability of the 20 kV distribution system.

Keywords: isolated system; power plant operation scheduling; levelized cost of electricity

1. Introduction

Tahuna (3.6111059, 125.4751878) is the capital of Sangihe Islands Regency located on Sangihe Island, North Sulawesi, Indonesia. There are twelve sub-districts on Sangihe Island with a total area of 692.67 km^2 [1]. Sangihe Island has a population of 130,458 people as of 2023 [1], with a population growth ratio of 0.29% from 2020 to 2023 [1]. The electricity system on this island is categorized as an isolated system because it is not yet connected to the Minahasa System which is the grid of North Sulawesi and Gorontalo. The Tahuna 1 System consists of 4 power plants, namely the Tahuna Diesel Power Plant, Tamako Diesel Power Plant, Sangihe Solar Power Plant, and Ulung Peliang Micro Hydro Power Plant which are synchronized through the 20 kV medium voltage network with a total power capacity of 15,358 kW [2]. During 2023, the peak load of the Tahuna 1 System was 5,710 kW which occurred at 07:00 PM [3] because many household consumers use electricity for lighting simultaneously.

The cumulative LCOE value of the Tahuna 1 System in 2023 reached Rp4,210.86/kWh [4] or 81.65% higher than the average LCOE of the Northern Sulawesi region, which was Rp2,318/kWh [4]. This is because there is no normal operation scheduling for the generating units per hour as a reference in operating the system. Until now, the dispatcher of the Tahuna Command Center must coordinate with the power plant operator to operate the generating units without any priority order of operation, but only the availability and readiness of each unit.

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Research on the scheduling of thermal generating unit operations has been conducted throughout the world. In previous research, Ananda R et al. [5] analyzed the operation scheduling of 4 geothermal generating units with maximum power capacities varying from 32 MW to 55.5 MW to meet the system's power needs for 24 hours with a system load of 159.59 MW to 163.79 MW using the Forward Dynamic Programming method, the results obtained were a reduction in operating costs from Rp 4,885,715 to Rp3,036,492 or 30% more economical compared to current conditions. Another research by Raj, Vinod and Saurabh Chanana [6] discussed the scheduling of 10 thermal generating unit operations with varying maximum power capacities from 55 MW to 455 MW to meet the system load from 700 MW to 1,500 MW using the Priority Listing and Lagrange Relaxation methods, the results obtained there is a decrease in the value of total generation cost of $1,480 in the daily period using the Lagrange Relaxation method compared to the Priority Listing method which was initially from $566,760 to $565,280. Meanwhile Hanafi, Ikhsan and Rinaldy Dalimi [7] conducted research related to the scheduling of operations of 6 thermal generating units using the Merit Order method with variations in maximum power capacity from 32 MW to 650 MW to supply the system with load fluctuations from 1,317 MW to 1,774 MW, a decrease in the value of generation costs in the daily period was obtained from the initial $1,988,410 to $1,696,770.

From several research that have been described above, it was found that each design of the generating unit operation schedule aims to minimize the generation cost which consists of objective function equations and constraint functions based on existing parameters. In this research, a scheme for hourly operation scheduling of generating units in the Tahuna 1 System will be designed to minimize LCOE by considering the system load profile, generating unit capacity, and spinning reserve with a modification of the Merit Order and Priority Listing method to increase the selectivity of determining the priority list of generating unit operations based on the cheapest LCOE ranking (Rp/kWh) according to the range of generating zones created from the intersection of the cost function equation between all diesel generating units. This method is also used because it can be formulated using a formula with an appropriate algorithm.

1. Methodology

To optimize the operating pattern of all generating units in the Tahuna 1 System, a scheduling scheme is required by determining the on and off status and the loading value of generating units by considering the system load profile, generating unit capacity, and spinning reserve based on performance data from each generating unit. To assist the calculation and data processing process starting from the regression of Specific Fuel Consumption (SFC) performance data and fuel consumption of each generating unit, the formulation of generating unit cost functions, generation costs ramping starting from minimum to maximum capacity of each diesel generating unit as an independent variable, until the final hourly operation scheduling scheme in this research, Microsoft Excel software is used by compiling several formulas in each process. The output results of this research will be in the form of a file with the format (*.xlxs) from Microsoft Excel so that it can be used by all stakeholders easily without any additional plugins to be installed, starting from dispatcher of the Tahuna Command Center to operators at each power plant in determining the priority order of unit operations in real time according to the estimated hourly system load. The process of working on this research is explained in the research flow diagram as shown in Figure 1 as follows.

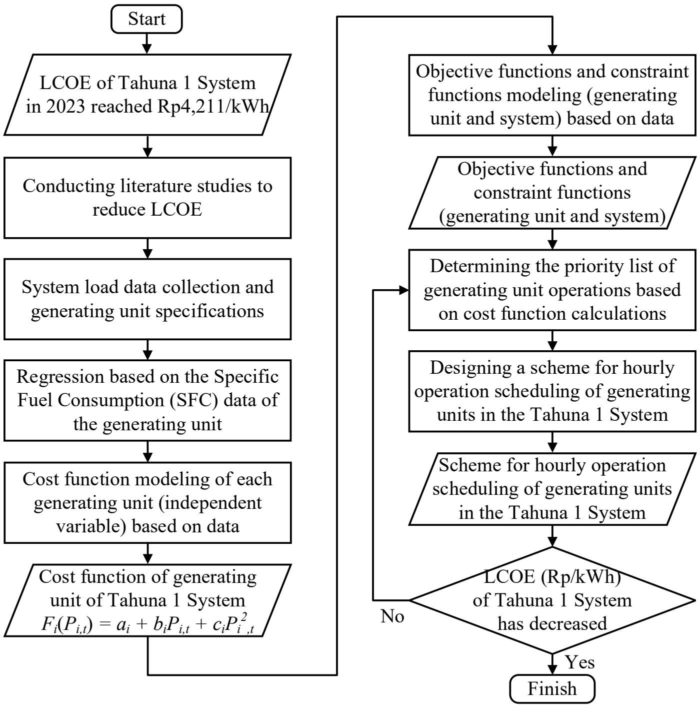

Figure 1. Research flow diagram

A. System Load Profile

One important aspect in designing a generating unit operation scheduling scheme is to know the average trend of the system load per hour within a certain period. This aims to ensure that the designed scheme can fulfill the system's hourly power needs for 24 hours. In this research, only data for the year 2023 was used to represent the hourly system load profile in the Tahuna 1 System. This is because in the previous year there were no additional generating units in the Tahuna Diesel Power Plant (Unit #10, Unit #11, and Unit #12) and Tamako Diesel Power Plant (Unit #5, Unit #6, and Unit #7), so that optimal scheduling could not be made. In Figure 2 below is the average system load profile per hour of the Tahuna 1 System period of 2023 [3].

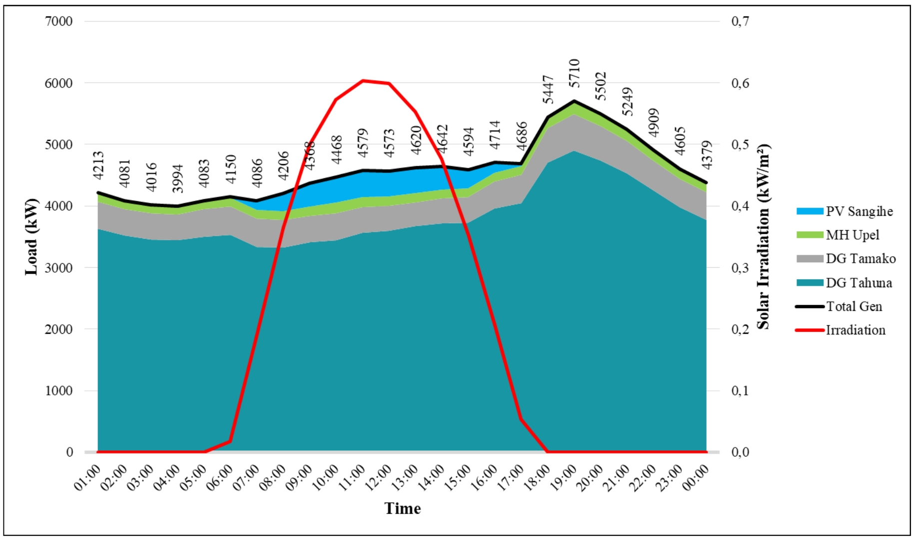

Figure 2. Average system load profile per hour of the Tahuna 1 System 2023 [3]

From Figure 2, it is explained that the average load on the Tahuna 1 System for the period of 2023 is 4,578 kW with the peak load value of 5,710 kW at 07:00 PM [3]. The peak load of the system occurs at that hour because many household consumers use electricity for lighting simultaneously. It is also known from Figure 2 that the order of the largest composition of the Tahuna 1 System load is borne by the Tahuna Diesel Power Plant, then continued by the Tamako Diesel Power Plant, Sangihe Solar Power Plant, and Ulung Peliang Micro Hydro Power Plant.

Based on Figure 2, it can also be seen that the operating hours of the Sangihe Solar Power Plant only occur at 06:00 AM-05.00 PM along with the availability of solar irradiation. Based on direct measurement data at the location, during 2023, the average daily irradiation at the Sangihe Solar Power Plant reached 4.49 kWh/m^2/day with the highest solar irradiation occurring at 11:00 AM with a value of 0.604 kW/m^2 [8]. Since the Sangihe Solar Power Plant and Ulung Peliang Micro Hydro Power Plant are renewable energy-based power plants which cause the system load to be unpredictable (intermittent), the average load of these power plants in this research is used as a control variable.

B. Existing Generating Unit

The Tahuna 1 System consists of the Tahuna Diesel Power Plant, Tamako Diesel Power Plant, Sangihe Solar Power Plant, and Ulung Peliang Micro Hydro Power Plant which are synchronized through the 20 kV medium voltage with a total installed power of 21,101 kW. However, due to age factors, the total net power that can be generated by all these generating units is 15,358 kW as described in Table 1 below [2].

Table 1. Generating units installed on Tahuna 1 System [2]

No	Generating Units	Power Capacity (kW)		
		Installed	Minimum	Netto
#1	Unit #1 Diesel Generator (DG) Tahuna	765	145	425
#2	Unit #4 DG Tahuna	500	35	150
#3	Unit #5 DG Tahuna	500	50	300
#4	Unit #6 DG Tahuna	1,300	168	850
#5	Unit #7 DG Tahuna	1,300	196	1,000
#6	Unit #8 DG Tahuna	1,120	377	850
#7	Unit #9 DG Tahuna	1,120	450	850
#8	Unit #10 DG Tahuna (Ex UIW MMU)	1,292	207	904
#9	Unit #11 DG Tahuna (Ex UIW MMU)	1,292	378	904
#10	Unit #12 DG Tahuna (Ex UIW MMU)	1,292	202	904
#11	Unit #1 DG Tahuna (KIP 1)	1,600	225	1,100
#12	Unit #1 DG Tahuna (KIP 2)	3,720	203	2,250
#13	Unit #1 DG Tamako	700	172	630
#14	Unit #2 DG Tamako	500	23	450
#15	Unit #4 DG Tamako	1,300	255	1,170
#16	Unit #5 DG Tamako (Genset Mobile)	200	20	180
#17	Unit #6 DG Tamako (Genset Mobile)	200	40	180
#18	Unit #7 DG Tamako (Genset Mobile)	100	20	90

Table 1. Continued

#19	Unit #1 Micro Hydro (MH) Ulung Peliang (Upel)	1,000	120	1,000
#20	Unit #1 Photovoltaic (PV) Sangihe	1,300	14	1,170
Total (kW)		21,101	-	15,358

From Table 1, it is known that the Tahuna Diesel Power Plant consists of 12 generating units, the Tamako Diesel Power Plant consists of 6 generating units, and the Ulung Peliang Micro Hydro Power Plant and Sangihe Solar Power Plant each consist of one generating unit.

In this research, the design of the hourly generating unit operation scheduling scheme will only be carried out on the Tahuna Diesel Power Plant and Tamako Diesel Power Plant as independent variables. While the Sangihe Solar Power Plant and Ulung Peliang Micro Hydro Power Plant are used as control variables, because the loading of these generating units on the Tahuna 1 System depends on natural conditions so that it cannot be predicted (intermittent). Figure 3 below is the Single Line Diagram (SLD) of the Tahuna 1 System [9].

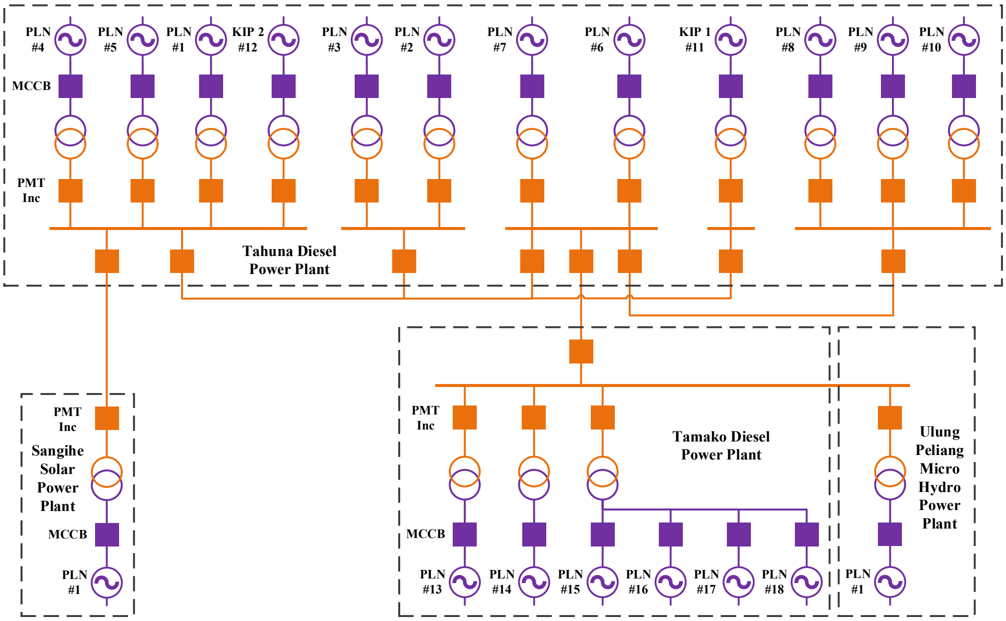

Figure 3. Single line diagram 20 kV of the Tahuna 1 System [9]

C. *Economic Dispatch Modeling*

1) *Generation Cost Function*

In designing a generating unit scheduling scheme, there are two main topics, namely determining the generating unit to be operated and the total generation costs of the operating unit [10]. In the process of designing the operating scheduling scheme for generating units, the generation cost function of each thermal generating unit is used in the form of a second-order polynomial as in (1) below [11].

$$F_i(P_{i,t}) = a_i + b_iP_{i,t} + c_iP_{i,t}^2 \quad (1)$$

where:

$F_i(P_{i,t})$ = cost function of generating unit-i

a_i, b_i, c_i = coefficient of cost function of generating unit-i

$P_{i,t}$ = generated power of generating unit-i at hour-t (kW)

Based on the results of the regression of SFC performance data and fuel consumption of each generating unit, by referring to (1), the cost function for each installed diesel generating units of the Tahuna 1 System can be obtained as in Table 2.

Table 2. Generating unit cost function in Tahuna 1 System

No	Diesel Generating Units	Generation Cost Function
#1	Unit #1 DG Tahuna	$F_1 = 110,601.086 + 3,501.193P_1 + 0.1197P_1^2$
#2	Unit #4 DG Tahuna	$F_2 = 39,539.790 + 4,289.739P_2 - 1.1966P_2^2$
#3	Unit #5 DG Tahuna	$F_3 = 62,254.468 + 3,641.193P_3 - 1.1966P_3^2$
#4	Unit #6 DG Tahuna	$F_4 = 287,095.439 + 3,427.005P_4 - 0.7179P_4^2$
#5	Unit #7 DG Tahuna	$F_5 = 299,001.410 + 3,482.048P_5 - 0.8376P_5^2$
#6	Unit #8 DG Tahuna	$F_6 = 240,680.101 + 3,332.475P_6 - 0.3590P_6^2$
#7	Unit #9 DG Tahuna	$F_7 = 78,134.281 + 3,502.390P_7 - 0.3590P_7^2$
#8	Unit #10 DG Tahuna (Ex UIW MMU)	$F_8 = 425,743.164 + 4,087.517P_8 - 1.1966P_8^2$
#9	Unit #11 DG Tahuna (Ex PLN UIW MMU)	$F_9 = 411,527.794 + 4,105.466P_9 - 1.1966P_9^2$
#10	Unit #12 DG Tahuna (Ex PLN UIW MMU)	$F_{10} = 186,953.659 + 3,707.005P_{10} - 0.5983P_{10}^2$
#11	Unit #1 DG Tahuna (KIP 1)	$F_{11} = 228,104.045 + 3,303.757P_{11} - 0.7179P_{11}^2$
#12	Unit #1 DG Tahuna (KIP 2)	$F_{12} = 310,117.639 + 3,432.988P_{12} - 0.3590P_{12}^2$
#13	Unit #1 DG Tamako	$F_{13} = 6,358.626 + 2,788.031P_{13} - 0.0957P_{13}^2$
#14	Unit #2 DG Tamako	$F_{14} = 289,991.163 + 4,439.312P_{14} - 2.3932P_{14}^2$
#15	Unit #4 DG Tamako	$F_{15} = 201,288.688 + 3,605.296P_{15} - 0.8376P_{15}^2$
#16	Unit #5 DG Tamako (Genset Mobile)	$F_{16} = 92,091.190 + 2,924.442P_{16} - 1.1966P_{16}^2$
#17	Unit #6 DG Tamako (Genset Mobile)	$F_{17} = 35,273.982 + 3,954.697P_{17} - 5.9829P_{17}^2$
#18	Unit #7 DG Tamako (Genset Mobile)	$F_{18} = 33,700.479 + 3,509.569P_{18} - 5.9829P_{18}^2$

Based on Table 2, the F_i variable represents the total generation cost of each diesel generating unit (Rp), while the P_i variable represents the power generated of each diesel generating unit (kW). Apart from the Tahuna 1 System, the cost function of the diesel generating unit can be varied according to data on other isolated systems in Indonesia to be further calculated using the same research method. So, it can be calculated further to minimize generation costs according to the needs of each system as a continuous improvement.

2) Objective Function and Constraint Function Modeling

Optimization of the generating unit operation scheduling scheme aims to minimize the LCOE. Based on the generation cost function for each generating unit from Table 2, the objective function can be formulated through (2).

$$min\ F(P_{i,t}, U_{i,t}) = \sum_{i=1}^{N} \sum_{t=1}^{T} [F_i(P_{i,t})U_{i,t}] \quad (2)$$

where:

$min\ F(P_{i,t})$ = objective function
F_i = cost function of generating unit-i
$P_{i,t}$ = generated power of generating unit-i at hour-t (kW)
$U_{i,t}$ = on/off status of generating unit-i at hour-t

There are several constraints that must be met in designing the diesel generating unit operation scheduling scheme in the Tahuna 1 System which are divided into system constraints and diesel generating unit constraints. When viewed from a system perspective, the constraints used in this research are shown in (3), (4), and (5) below.

$$P_{load,t} = P_{PV,t} + P_{MH,t} + \sum P_{DG,t} \quad (3)$$

where:

$P_{load,t}$ = system load at hour-t (kW)
$P_{PV,t}$ = output power of solar power plant at hour-t (kW)
$P_{MH,t}$ = output power of micro hydro power plant at hour-t (kW)
$P_{DG,t}$ = output power of diesel power plant at hour-t (kW)

Equation (3) is used as a constraint of the total load of the Tahuna 1 System at hour-t for 24 hours. The system load at hour-t is the accumulation of the output power of the Tahuna Diesel Power Plant, Tamako Diesel Power Plant, Sangihe Solar Power Plant, and Ulung Peliang Micro Hydro Power Plant. Meanwhile, other system constraints are explained in (4) and (5) as follows.

$$P_{reserve\ DG,t} \geq P_{PV,t} + P_{MH,t} \quad (4)$$

$$\sum_{i=1}^{N} (P_{i\ max\ DG} - P_{i,t\ DG}) U_{i,t\ DG} \geq P_{PV,t} + P_{MH,t} \quad (5)$$

where:

$P_{reserve\ DG,t}$ = spinning reserve of diesel generating unit at hour-t (kW)
$P_{i\ max\ DG}$ = maximum operating power of diesel generating unit (kW)
$P_{i,t\ DG}$ = generated power of diesel generating unit at hour-t (kW)
$U_{i,t\ DG}$ = on/off status of diesel generating unit-i at hour-t

Equation (4) is the constraint of the total spinning reserves of the diesel generating unit which must be more than or equal to the accumulated power generated by the solar and micro hydro power plant at hour-t. Spinning reserves of diesel generating unit are needed as a form of mitigation if the power generated from solar and micro hydro power plant decreases or is lost due to the dependence of renewable energy generators on natural conditions. Meanwhile, (5) explained that spinning reserves of diesel generating unit are the accumulation of the difference in its maximum capacity to the power generated at hour-t. Another constraint that must be met in this research is the net power capacity of the diesel generating unit as shown in Table 2, which is modeled into the (6).

$$P_{i\ min} \leq P_{i,t} \leq P_{i\ max} \quad (6)$$

where:

$P_{i\ min}$ = minimum output power of generating unit (kW)
$P_{i,t}$ = generated power of generating unit at hour-t (kW)
$P_{i\ max}$ = maximum output power of generating unit (kW)

3) Priority Order of Generating Unit Operations

Dynamic changes in the priority list of diesel generating unit operations along with the increase in power generated due to the characteristics of non-linear generation costs per kWh. In this research, the unit Rp/kWh is used in the generation cost ramping of diesel generating unit to make it easier to determine the generation cost ranking when producing the same power. The results of the roots of the equation of the generation cost function per kWh of diesel generating units that intersect are used as the limits of the generation zone range, so that variations in operation combinations can be obtained based on range of the generation zone. In Figure 4 below is the intersection of 18 graphs of the generation cost function per kWh of the diesel generating unit.

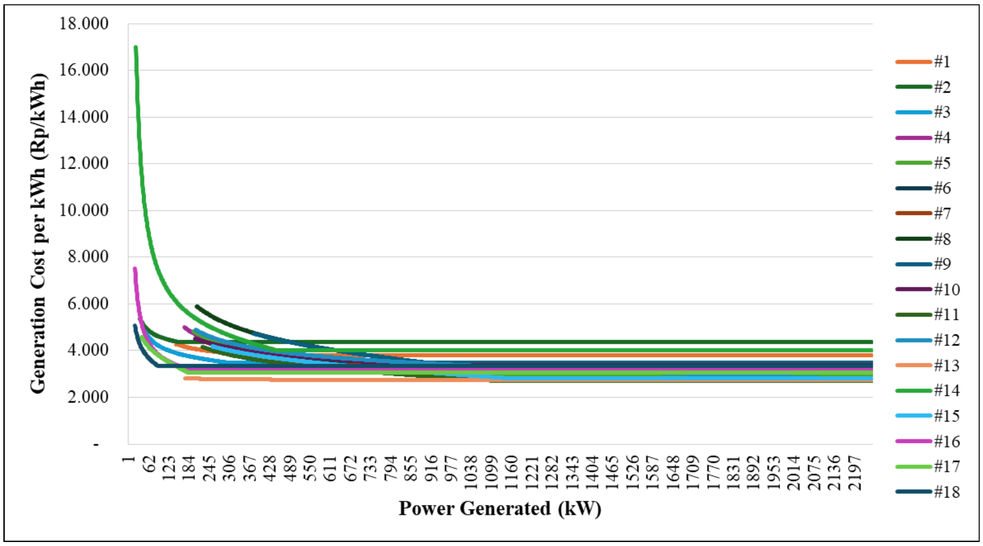

Figure 4. Intersection of the generation cost function per kWh

Figure 4 explains that the graphs of the generation cost function per kWh of each diesel generating unit intersect each other as the power generated increases. From the two results of the roots of the generation cost function equation per kWh obtained, the root with a positive value is selected to be used as the boundary of the generation zone range. In each generation zone, there are variations in the combination of the priority order of diesel generating unit operations according to the amount of power generated, along with calculations of generation costs per kWh. The list of priority order of operations in each generation zone is then used as a reference in preparing the schedule of the generating unit operation schedule per hour in the Tahuna 1 System to obtain a more optimal LCOE value compared to the current condition.

2. Result and Analysis

A. Scheduling Scheme with Consideration of Spinning Reserves on One Operating Unit

After obtaining a list of priority order of the diesel generating unit operations in the Tahuna 1 System according to their respective generation zone boundaries, an hourly operation scheduling scheme can be prepared to fulfill the system's power needs. As a comparison of research results, the scheduling of diesel generating unit operations will be divided into two schemes, namely consideration of spinning reserve on one and two operating units. As explained in (3) which is one of the constraint functions, the total load of the Tahuna 1 System at hour-t is the accumulation of the output power of the solar power plant, micro hydro power plant, and diesel power plant. The hourly loading value of the diesel generating unit can be obtained which will be optimized through the operation scheduling scheme as in Table 3 below [3].

Table 3. Load profile per hour of the Tahuna 1 System 2023 [3]

Time	Load (kW)		
	Total System	Solar + Micro Hydro (Control Variables)	Diesel (Independent Variables)
01:00	4,213	147	4,066
02:00	4,081	137	3,944
03:00	4,016	134	3,882
04:00	3,994	129	3,865
05:00	4,083	132	3,951
06:00	4,150	152	3,998
07:00	4,086	289	3,797
08:00	4,206	433	3,773
09:00	4,368	527	3,841
10:00	4,468	582	3,886
11:00	4,579	597	3,982
12:00	4,573	574	3,999
13:00	4,620	559	4,061
14:00	4,642	518	4,124
15:00	4,594	447	4,147
16:00	4,714	315	4,399
17:00	4,686	178	4,508
18:00	5,447	185	5,262
19:00	5,710	218	5,492
20:00	5,502	206	5,296
21:00	5,249	195	5,054
22:00	4,909	175	4,734
23:00	4,605	166	4,439
00:00	4,379	158	4,221

Based on Table 3, the hourly loading value on the diesel generating unit is obtained which will be used to schedule operations as independent variables. Based on the ramping data of the cheapest to most expensive LCOE values of the generating unit and the generation zone range, as well as the constraint function of the generating unit's net power capacity from Table 1, the operation scheduling scheme for the diesel generating unit of the Tahuna 1 System can be designed with consideration of the spinning reserves on one operating unit in the Table 4 below.

Table 4. Operation scheduling scheme with one spinning reserve unit in Tahuna 1 System

Time	Operating Generating Units							
	I	II	III	IV	V	VI	VII	VIII
01:00	#11	#13	#12	#17	#16	OFF	OFF	OFF
02:00	#11	#13	#12	#18	OFF	OFF	OFF	OFF
03:00	#11	#13	#12	#18	OFF	OFF	OFF	OFF
04:00	#11	#13	#12	OFF	OFF	OFF	OFF	OFF
05:00	#11	#13	#12	#18	OFF	OFF	OFF	OFF
06:00	#11	#13	#12	#17	OFF	OFF	OFF	OFF
07:00	#11	#13	#12	#18	OFF	OFF	OFF	OFF
08:00	#11	#13	#12	#17	#16	OFF	OFF	OFF
09:00	#11	#13	#12	#17	#16	#18	OFF	OFF

Table 4. Continued

Time	Operating Generating Units							
	I	II	III	IV	V	VI	VII	VIII
10:00	#11	#13	#12	#17	#16	#18	#14	OFF
11:00	#11	#13	#12	#17	#16	#18	#3	OFF
12:00	#11	#13	#12	#17	#16	#18	#3	OFF
13:00	#11	#13	#12	#17	#16	#18	#3	OFF
14:00	#11	#13	#12	#17	#16	#18	#3	OFF
15:00	#11	#13	#12	#17	#16	#18	#3	OFF
16:00	#11	#13	#12	#17	#16	#18	#3	OFF
17:00	#11	#13	#12	#17	#16	#18	#3	OFF
18:00	#11	#13	#12	#15	#17	#18	#14	OFF
19:00	#11	#13	#12	#15	#17	#16	#18	#3
20:00	#11	#13	#12	#15	#17	#16	OFF	OFF
21:00	#11	#13	#12	#15	#18	OFF	OFF	OFF
22:00	#11	#13	#12	#5	OFF	OFF	OFF	OFF
23:00	#11	#13	#12	#17	#16	#18	#3	OFF
00:00	#11	#13	#12	#17	#16	#18	OFF	OFF

Based on Table 4, it is known that Unit #11 and Unit #13 are always the priority generating units to be operated in the hourly scheduling scheme with consideration of the spinning reserve on one operating unit. This is because both units have the lowest LCOE value sequentially within their generation zone range. In this scheme, Unit #11 functions as the spinning reserve because it is always the priority of operation and fulfills the capacity constraint function as (6). Meanwhile, the loading value of each generating unit operating per hour is shown in Table 5.

Table 5. Loading value of the operating generating units with one spinning reserve

Time	Loading Value of Operating Generating Units (kW)								Total (kW)
	I	II	III	IV	V	VI	VII	VIII	
01:00	953	630	2,250	180	53	OFF	OFF	OFF	4,066
02:00	974	630	2,250	90	OFF	OFF	OFF	OFF	3,944
03:00	966	630	2,250	36	OFF	OFF	OFF	OFF	3,882
04:00	985	630	2,250	OFF	OFF	OFF	OFF	OFF	3,865
05:00	981	630	2,250	90	OFF	OFF	OFF	OFF	3,951
06:00	948	630	2,250	170	OFF	OFF	OFF	OFF	3,998
07:00	827	630	2,250	90	OFF	OFF	OFF	OFF	3,797
08:00	667	630	2,250	180	46	OFF	OFF	OFF	3,773
09:00	573	630	2,250	180	180	28	OFF	OFF	3,841
10:00	518	630	2,250	180	180	90	38	OFF	3,886
11:00	503	630	2,250	180	180	90	149	OFF	3,982
12:00	526	630	2,250	180	180	90	143	OFF	3,999
13:00	541	630	2,250	180	180	90	190	OFF	4,061
14:00	582	630	2,250	180	180	90	212	OFF	4,124
15:00	653	630	2,250	180	180	90	164	OFF	4,147
16:00	785	630	2,250	180	180	90	284	OFF	4,399
17:00	922	630	2,250	180	180	90	256	OFF	4,508

Table 5. Continued

Time	Loading Value of Operating Generating Units (kW)								Total (kW)
	I	II	III	IV	V	VI	VII	VIII	
18:00	915	630	2,250	1170	180	90	27	OFF	5,262
19:00	882	630	2,250	1170	180	180	90	110	5,492
20:00	894	630	2,250	1170	180	172	OFF	OFF	5,296
21:00	914	630	2,250	1170	90	OFF	OFF	OFF	5,054
22:00	925	630	2,250	929	OFF	OFF	OFF	OFF	4,734
23:00	934	630	2,250	180	180	90	175	OFF	4,439
00:00	942	630	2,250	180	180	39	OFF	OFF	4,221

From Table 5, it is known that the operation scheduling scheme with consideration of the spinning reserve on Unit #11 can be met. This can be proven by the total scheduled hourly load (kW) in accordance with the loading value of the diesel generating unit of Tahuna 1 System as an independent variable as shown in Table 3 before. After determining the loading value per hour, the generation cost per hour for each diesel generating unit can be calculated in Table 6.

Table 6. Generation cost of the operating generating units with one spinning reserve

Time	Generation Cost of Operating Generating Units (Rp)								Total Cost (Rp)	LCOE (Rp/kWh)
	I	II	III	IV	V	VI	VII	VIII		
01:00	2,724,538	1,724,825	6,217,035	553,273	243,725	OFF	OFF	OFF	11,463,396	2,819.33
02:00	2,764,864	1,724,825	6,217,035	301,100	OFF	OFF	OFF	OFF	11,007,823	2,791.03
03:00	2,749,576	1,724,825	6,217,035	152,291	OFF	OFF	OFF	OFF	10,843,727	2,793.34
04:00	2,785,734	1,724,825	6,217,035	OFF	OFF	OFF	OFF	OFF	10,727,593	2,775.57
05:00	2,778,165	1,724,825	6,217,035	301,100	OFF	OFF	OFF	OFF	11,021,125	2,789.45
06:00	2,714,843	1,724,825	6,217,035	534,667	OFF	OFF	OFF	OFF	11,191,369	2,799.24
07:00	2,469,286	1,724,825	6,217,035	301,100	OFF	OFF	OFF	OFF	10,712,246	2,821.24
08:00	2,112,303	1,724,825	6,217,035	553,273	224,084	OFF	OFF	OFF	10,831,519	2,870.80
09:00	1,885,434	1,724,825	6,217,035	553,273	579,721	127,278	OFF	OFF	11,087,566	2,886.64
10:00	1,746,808	1,724,825	6,217,035	553,273	579,721	301,100	455,229	OFF	11,577,992	2,979.41
11:00	1,708,247	1,724,825	6,217,035	553,273	579,721	301,100	578,227	OFF	11,662,428	2,928.79
12:00	1,767,241	1,724,825	6,217,035	553,273	579,721	301,100	558,476	OFF	11,701,672	2,926.15
13:00	1,805,307	1,724,825	6,217,035	553,273	579,721	301,100	710,885	OFF	11,892,146	2,928.38
14:00	1,907,705	1,724,825	6,217,035	553,273	579,721	301,100	780,408	OFF	12,064,067	2,925.33
15:00	2,079,318	1,724,825	6,217,035	553,273	579,721	301,100	627,227	OFF	12,082,500	2,913.55
16:00	2,379,136	1,724,825	6,217,035	553,273	579,721	301,100	999,842	OFF	12,754,933	2,899.51
17:00	2,663,852	1,724,825	6,217,035	553,273	579,721	301,100	915,981	OFF	12,955,788	2,873.95
18:00	2,649,958	1,724,825	6,217,035	3,272,886	553,273	301,100	408,108	OFF	15,127,185	2,874.80
19:00	2,583,509	1,724,825	6,217,035	3,272,886	553,273	579,721	301,100	448,307	15,680,656	2,855.18
20:00	2,607,853	1,724,825	6,217,035	3,272,886	553,273	559,696	OFF	OFF	14,935,567	2,820.16
21:00	2,647,967	1,724,825	6,217,035	3,272,886	301,100	OFF	OFF	OFF	14,163,813	2,802.50
22:00	2,669,785	1,724,825	6,217,035	2,810,935	OFF	OFF	OFF	OFF	13,422,580	2,835.36
23:00	2,687,507	1,724,825	6,217,035	553,273	579,721	301,100	662,818	OFF	12,726,280	2,866.92
00:00	2,703,162	1,724,825	6,217,035	553,273	579,721	161,474	OFF	OFF	11,939,490	2,828.59
Total Daily Generation Cost (Rp)									293,573,461	2,857.97
Total Daily Energy Production (kWh)									102,721	

Table 6 is the result of the calculation of the generation cost of the diesel generating units of Tahuna 1 System per hour considering the spinning reserve on one operating unit. In one day, the total generation cost required from all diesel generating units in the Tahuna 1 System is Rp293,573,461 to produce 102,721 kWh of electrical energy. Based on these two calculation results, the daily LCOE value of the diesel generating unit can also be obtained, namely Rp2,857.97/kWh.

B. Scheduling Scheme with Consideration of Spinning Reserves on Two Operating Units

After the scheduling scheme for the diesel generating units of Tahuna 1 System has been prepared with consideration of the spinning reserves on one operating unit, the next step is to prepare a scheduling scheme for the operation of the diesel generating units according to the hourly system loading requirements with consideration of the spinning reserves on two operating units as in Table 7 below.

Table 7. Operation scheduling scheme with two spinning reserve units in Tahuna 1 System

Time	Operating Generating Units							
	I	II	III	IV	V	VI	VII	VIII
01:00	#11	#13	#12	#17	#16	#18	OFF	OFF
02:00	#11	#13	#12	#17	#16	OFF	OFF	OFF
03:00	#11	#13	#12	#17	OFF	OFF	OFF	OFF
04:00	#11	#13	#12	#18	#17	OFF	OFF	OFF
05:00	#11	#13	#12	#17	#16	OFF	OFF	OFF
06:00	#11	#13	#12	#17	#16	OFF	OFF	OFF
07:00	#11	#13	#12	#17	#16	#18	OFF	OFF
08:00	#11	#13	#12	#17	#16	#18	#3	OFF
09:00	#11	#13	#12	#5	OFF	OFF	OFF	OFF
10:00	#11	#13	#12	#15	OFF	OFF	OFF	OFF
11:00	#11	#13	#12	#15	#18	OFF	OFF	OFF
12:00	#11	#13	#12	#15	OFF	OFF	OFF	OFF
13:00	#11	#13	#12	#15	#18	OFF	OFF	OFF
14:00	#11	#13	#12	#15	OFF	OFF	OFF	OFF
15:00	#11	#13	#12	#15	OFF	OFF	OFF	OFF
16:00	#11	#13	#12	#15	OFF	OFF	OFF	OFF
17:00	#11	#13	#12	#17	#16	#18	#3	#2
18:00	#11	#13	#12	#15	#17	#16	#18	#14
19:00	#11	#13	#12	#15	#17	#16	#18	#3
20:00	#11	#13	#12	#15	#17	#16	#18	#3
21:00	#11	#13	#12	#15	#17	#18	#14	OFF
22:00	#11	#13	#12	#15	OFF	OFF	OFF	OFF
23:00	#11	#13	#12	#17	#16	#18	#3	#2
00:00	#11	#13	#12	#17	#16	#18	#3	OFF

Based on Table 7, it is known that in this scheduling scheme Unit #11 and Unit #12 are used as spinning reserves because they are always the priority of operations for 24 hours and fulfill the constraint function of the power capacity as (6). Meanwhile, Unit #13 cannot be operated as a spinning reserve unit because this diesel generating unit does not fulfill the constraint function. The loading value for each diesel generating unit operating per hour is shown in Table 8 as follows.

Table 8. Loading value of the operating generating units with two spinning reserves

Time	Loading Value of Operating Generating Units (kW)								Total (kW)
	I	II	III	IV	V	VI	VII	VIII	
01:00	953	630	2,103	180	180	20	OFF	OFF	4,066
02:00	963	630	2,113	180	58	OFF	OFF	OFF	3,944
03:00	966	630	2,116	170	OFF	OFF	OFF	OFF	3,882
04:00	971	630	2,121	90	53	OFF	OFF	OFF	3,865
05:00	968	630	2,118	180	55	OFF	OFF	OFF	3,951
06:00	948	630	2,098	180	142	OFF	OFF	OFF	3,998
07:00	811	630	1,961	180	180	35	OFF	OFF	3,797
08:00	667	630	1,817	180	180	90	209	OFF	3,773
09:00	573	630	1,723	915	OFF	OFF	OFF	OFF	3,841
10:00	518	630	1,668	1,070	OFF	OFF	OFF	OFF	3,886
11:00	503	630	1,653	1,170	26	OFF	OFF	OFF	3,982
12:00	526	630	1,676	1,167	OFF	OFF	OFF	OFF	3,999
13:00	541	630	1,691	1,170	29	OFF	OFF	OFF	4,061
14:00	587	630	1,737	1,170	OFF	OFF	OFF	OFF	4,124
15:00	653	630	1,803	1,061	OFF	OFF	OFF	OFF	4,147
16:00	785	630	1,935	1,049	OFF	OFF	OFF	OFF	4,399
17:00	922	630	2,072	180	180	90	300	134	4,508
18:00	915	630	2,065	1,170	180	180	90	32	5,262
19:00	896	630	2,046	1,170	180	180	90	300	5,492
20:00	894	630	2,044	1,170	180	180	90	108	5,296
21:00	905	630	2,055	1,170	180	90	24	OFF	5,054
22:00	925	630	2,075	1,104	OFF	OFF	OFF	OFF	4,734
23:00	934	630	2,084	180	180	90	300	41	4,439
00:00	942	630	2,092	180	180	90	107	OFF	4,221

It is known from Table 8, the hourly scheduling scheme with consideration of spinning reserves on two operating units, namely Unit #11 and Unit #12, can be fulfilled. This can be proven by the total scheduled hourly load (kW) in accordance with the loading value of the diesel generating unit of Tahuna 1 System as an independent variable. The generation cost per hour for each diesel generating unit is calculated in Table 9.

Table 9. Generation cost of the operating generating units with two spinning reserves

Time	Generation Cost of Operating Generating Units (Rp)								Total Cost (Rp)	LCOE (Rp/kWh)
	I	II	III	IV	V	VI	VII	VIII		
01:00	2,724,538	1,724,825	5,942,090	553,273	579,721	101,499	OFF	OFF	11,625,946	2,859.31
02:00	2,743,820	1,724,825	5,961,285	553,273	257,684	OFF	OFF	OFF	11,240,887	2,850.12
03:00	2,749,576	1,724,825	5,967,030	534,667	OFF	OFF	OFF	OFF	10,976,097	2,827.43
04:00	2,759,142	1,724,825	5,976,590	301,100	228,067	OFF	OFF	OFF	10,989,723	2,843.40
05:00	2,753,407	1,724,825	5,970,856	553,273	249,316	OFF	OFF	OFF	11,251,677	2,847.80
06:00	2,714,843	1,724,825	5,932,465	553,273	483,234	OFF	OFF	OFF	11,408,641	2,853.59
07:00	2,435,242	1,724,825	5,661,765	553,273	579,721	149,206	OFF	OFF	11,104,033	2,924.42
08:00	2,112,303	1,724,825	5,362,708	553,273	579,721	301,100	770,996	OFF	11,404,927	3,022.77
09:00	1,885,434	1,724,825	5,159,459	2,783,810	OFF	OFF	OFF	OFF	11,553,528	3,007.95

Table 9. Continued

Time	Generation Cost of Operating Generating Units (Rp)								Total Cost (Rp)	LCOE (Rp/kWh)
	I	II	III	IV	V	VI	VII	VIII		
10:00	1,746,808	1,724,825	5,037,596	3,099,980	OFF	OFF	OFF	OFF	11,609,208	2,987.44
11:00	1,708,247	1,724,825	5,003,983	3,272,886	120,905	OFF	OFF	OFF	11,830,845	2,971.08
12:00	1,767,241	1,724,825	5,055,456	3,267,942	OFF	OFF	OFF	OFF	11,815,464	2,954.60
13:00	1,805,307	1,724,825	5,088,821	3,272,886	130,446	OFF	OFF	OFF	12,022,285	2,960.42
14:00	1,920,027	1,724,825	5,190,133	3,272,886	OFF	OFF	OFF	OFF	12,107,870	2,935.95
15:00	2,079,318	1,724,825	5,332,839	3,083,597	OFF	OFF	OFF	OFF	12,220,578	2,946.85
16:00	2,379,136	1,724,825	5,608,870	3,061,541	OFF	OFF	OFF	OFF	12,774,372	2,903.93
17:00	2,663,852	1,724,825	5,882,127	553,273	579,721	301,100	1,046,920	592,879	13,344,699	2,960.23
18:00	2,649,958	1,724,825	5,868,492	3,272,886	553,273	579,721	301,100	429,599	15,379,854	2,922.82
19:00	2,611,891	1,724,825	5,831,304	3,272,886	553,273	579,721	301,100	1,046,920	15,921,920	2,899.11
20:00	2,607,853	1,724,825	5,827,375	3,272,886	553,273	579,721	301,100	441,546	15,308,580	2,890.59
21:00	2,629,987	1,724,825	5,848,952	3,272,886	553,273	301,100	395,156	OFF	14,726,179	2,913.77
22:00	2,669,785	1,724,825	5,887,960	3,160,647	OFF	OFF	OFF	OFF	13,443,218	2,839.72
23:00	2,687,507	1,724,825	5,905,420	553,273	579,721	301,100	1,046,920	213,408	13,012,175	2,931.33
00:00	2,703,162	1,724,825	5,920,892	553,273	579,721	301,100	438,162	OFF	12,221,136	2,895.32
Total Daily Generation Cost (Rp)									299,293,842	2,913.66
Total Daily Energy Production (kWh)									102,721	

Table 9 is the result of the calculation of the hourly generation costs of the generating units of Tahuna 1 System with consideration of the spinning reserves on the two operating units. The total daily generation cost required from all diesel generating units in the Tahuna 1 System is Rp299,293,842 to produce 102,721 kWh of electrical energy. Based on the calculation results, the daily LCOE value can also be obtained, namely Rp2,913.66/kWh.

C. Comparison of Levelized Cost of Electricity

The diesel generating unit operation scheduling scheme per hour has been designed in sub-chapter 3A and 3B in accordance with all the constraint functions that have been set. Next, a comparison graph can be made of the average daily LCOE value between the existing conditions and two new schemes as shown in Figure 5 below.

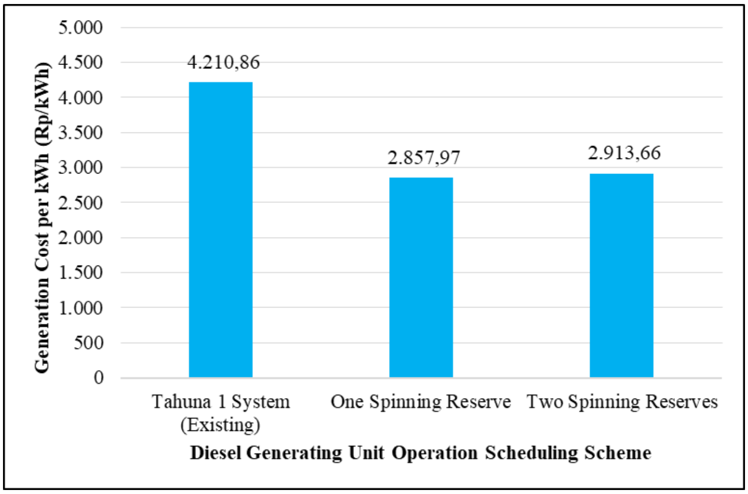

Figure 5. Comparison of average daily LCOE value of the Tahuna 1 System between schemes

Based on Figure 5, the LCOE value of the Tahuna 1 System experienced a significant decrease after designing two types of hourly diesel generating unit operation scheduling schemes. In the first new scheduling scheme, namely by considering one spinning reserve unit, there was a decrease in the LCOE value from the initial Rp4,210.86/kWh to Rp2,857.97/kWh or 32.13% more efficient. Meanwhile, in the diesel generating unit operation scheduling scheme by considering two spinning reserve units, the calculated LCOE value was Rp2,913.66/kWh or 30.81% more economical when compared to the average cumulative LCOE value of the Tahuna 1 System for the period 2023.

Since the average LCOE value of the Tahuna 1 System in existing condition is the result of calculations based on cumulative data of 2023, by assuming the total daily electrical energy production between all the diesel generating unit operational scheduling schemes is the same, namely 102,721 kWh, the daily generation cost can then be calculated as in Figure 6 below.

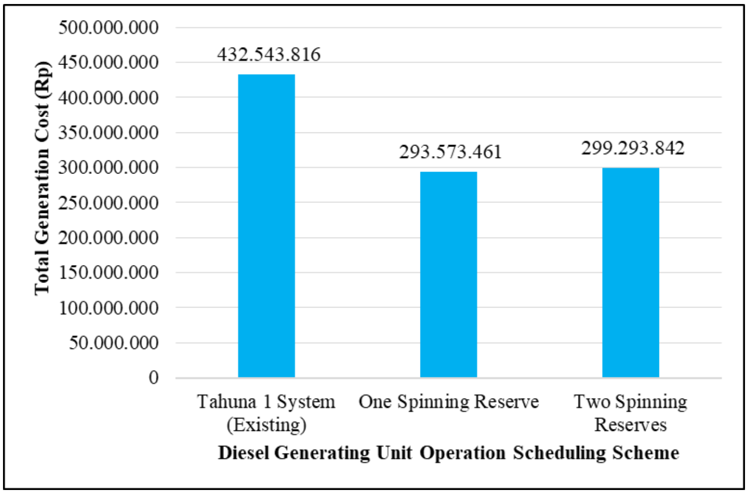

Figure 6. Comparison of daily generation costs of the Tahuna 1 System between schemes

Figure 6 explains that there was a decrease in the total daily generation costs in the Tahuna 1 System after designing two types of hourly diesel generating unit operation scheduling schemes. In the first new scheduling scheme, which considers one spinning reserve unit, there was a decrease in the total daily generation costs from the initial Rp432,543,816 to Rp293,573,461 in producing 102,721 kWh of electrical energy. Meanwhile, from the calculation results of the diesel generating unit operation scheduling scheme considering two spinning reserve units, there was a decrease in the total daily generation costs to Rp299,293,842.

In the diesel generating unit operation scheduling scheme with the consideration of one spinning reserve unit, only Unit #11 is used as a spinning reserve because this unit is always the main priority in the operation scheduling scheme. Based on performance data, during 2023 there were a total of 7 blackouts in the Tahuna 1 System caused by a decrease in the Sangihe Solar Power Palant load due to a sudden decrease in solar irradiation accompanied by a malfunction of the spinning reserve unit in responding to system frequency fluctuations [12]. Therefore, in the scheduling scheme with the consideration of two spinning reserve units, Unit #11 and Unit #12 will be used as spinning reserves because both engine units are the priority of operation for 24 hours and fulfill the constraint function of the capable power capacity.

With the difference in LCOE value of two new scheduling schemes are relatively small, namely Rp55.69/kWh, the scheduling scheme with consideration of two spinning reserve units is a better choice to implement when viewed from the aspect of the reliability of the operation of the 20 kV distribution system. This is because there is still a backup diesel generating unit (Unit #12) as a form of mitigation if the main spinning reserve (Unit #11) fails to respond to the solar and/or micro hydro power plant which experiences a decrease or loss of load.

D. Research Results Product

The results of this research are in the form of a file with the format (*.xlxs) from Microsoft Excel so that it can be used by all stakeholders easily without any additional plugins to be installed, starting from dispatcher of the Tahuna Command Center to operators at each power plant in determining the priority order of unit operations in real time according to the estimated hourly system load. Figure 7 below shows a display of Microsoft Excel which can be used in the operation of the Tahuna 1 System as the result of this research.

Time	Load (kW)			Unit Commitment							
	System	Spin Reserve	UC DG	I	II	III	IV	V	VI	VII	VIII
01:00	4213	147	4066	#11	#13	#12	#17	#16	#18	OFF	OFF
02:00	4081	137	3944	#11	#13	#12	#17	#16	OFF	OFF	OFF
03:00	4016	134	3882	#11	#13	#12	#17	OFF	OFF	OFF	OFF
04:00	3994	129	3865	#11	#13	#12	#18	#17	OFF	OFF	OFF
05:00	4083	132	3951	#11	#13	#12	#17	#16	OFF	OFF	OFF
06:00	4150	152	3998	#11	#13	#12	#17	#16	OFF	OFF	OFF
07:00	4086	289	3797	#11	#13	#12	#17	#16	#18	OFF	OFF
08:00	4206	433	3773	#11	#13	#12	#17	#16	#18	#3	OFF
09:00	4368	527	3841	#11	#13	#12	#5	OFF	OFF	OFF	OFF
10:00	4468	582	3886	#11	#13	#12	#15	OFF	OFF	OFF	OFF
11:00	4579	597	3982	#11	#13	#12	#15	#18	OFF	OFF	OFF
12:00	4573	574	3999	#11	#13	#12	#15	OFF	OFF	OFF	OFF
13:00	4620	559	4061	#11	#13	#12	#15	#18	OFF	OFF	OFF
14:00	4642	518	4124	#11	#13	#12	#15	OFF	OFF	OFF	OFF
15:00	4594	447	4147	#11	#13	#12	#15	OFF	OFF	OFF	OFF
16:00	4714	315	4399	#11	#13	#12	#15	OFF	OFF	OFF	OFF
17:00	4686	178	4508	#11	#13	#12	#17	#16	#18	#3	#2
18:00	5447	185	5262	#11	#13	#12	#15	#17	#16	#18	#14
19:00	5710	218	5492	#11	#13	#12	#15	#17	#16	#18	#3
20:00	5502	206	5296	#11	#13	#12	#15	#17	#16	#18	#3
21:00	5249	195	5054	#11	#13	#12	#15	#17	#18	#14	OFF
22:00	4909	175	4734	#11	#13	#12	#15	OFF	OFF	OFF	OFF
23:00	4605	166	4439	#11	#13	#12	#17	#16	#18	#3	#2
00:00	4379	158	4221	#11	#13	#12	#17	#16	#18	#3	OFF

Figure 7. Display of research results product (*.xlxs)

The red box in Figure 7 represents the hourly load estimation form for the Tahuna 1 System, which can be filled in dynamically and in real time by the dispatcher of the Tahuna Command Center and power plant operator as needed. Furthermore, a formula implemented in Microsoft Excel will automatically determine the priority order for generating unit operations to achieve the lowest generation cost without compromising system reliability by providing spinning reserve units.

3. Conclusions

Based on the results of the design, simulation, and analysis that have been carried out to reduce the LCOE value in the Tahuna 1 System, the following conclusions can be obtained:

1. Two hourly diesel generating unit operation scheduling schemes for the Tahuna 1 System have been designed on 12 generating units of Tahuna Diesel Power Plant and 6 generating units of Tamako Diesel Power Plant by considering the system load profile, generating unit capacity, and spinning reserve as a constraint function.

2. There is a decrease in the total daily generation costs of the Tahuna 1 System on the scheduling scheme with one spinning reserve unit from Rp432,543,816 to Rp293,573,461 to produce 102,721 kWh of electrical energy, and the decrease in the LCOE value from Rp4,210.86/kWh to Rp2,857.97/kWh or 32.13% more economical compared to current conditions. Meanwhile, the scheduling scheme with two spinning reserve units shows that there is a decrease in the total daily generation costs from Rp432,543,816 to Rp299,293,842, and the decrease in the LCOE value from Rp4,210.86/kWh to Rp2,913.66/kWh or 30.81% more efficient compared to current conditions.
3. With the difference in LCOE value of two new scheduling schemes are relatively small, namely Rp55.69/kWh, the scheduling scheme with consideration of two spinning reserve units is a better choice to implement from the aspect of the reliability of the operation of the 20 kV distribution system, because there is still a backup generating unit (Unit #12) which functions as mitigation if the main spinning reserve (Unit #11) fails to respond to the solar and/or micro hydro power plant when decrease or loss of load.
4. Apart from the Tahuna 1 System, the cost function of the diesel generating unit can be varied according to data on other isolated systems in Indonesia to be further calculated using the same research method. So, it can be calculated further to minimize generation costs according to the needs of each system as a continuous improvement.

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