Muna-Buton System Generation Expansion Planning by Considering the Interconnection System

Ahmad Fatana[1], Sarjiya[2], Lesnanto Multa Putranto[3*]

***Abstract*—Electrical energy consumption has increased annually. It is in line with the fulfillment of electricity sales for the last five years (2013-2017) with a 5.1% growth per year. Muna and Buton are large islands in Southeast Sulawesi with a population of 360,682 and an area of 7,712.18 km^2. Muna and Buton are two main cities in Southeast Sulawesi that are developing rapidly. Those two regions are relatively rich in natural potential, promoting local economic growth. The primary source of electricity for both regions is Buton. Current electricity consumption in Muna and Buton is relatively high, with a peak load of 37 MW primarily fulfilled by diesel power plants (*pembangkit listrik tenaga diesel,* PLTD) of 30.15 MW. The government's target to achieve a new renewable energy mix (NRE) of 23% in 2025 and 31% in 2050 is contrary to the situation of generations in Muna and Buton, which is currently still dominated by PLTD. The planning was conducted by looking at its effect on the cost of generation construction, reserve margin, energy mix, and total cost. The desired optimization value was achieved through several performed scenarios, i.e., an isolated or pre-interconnection scenario, assuming each system was separated, and an interconnection system, assuming that interconnection was performed in Muna and Buton system. The optimization method was carried out using mixed-integer linear programming (MILP) by employing the OSeMOSYS software platform. The optimization results show that the Muna-Buton generation expansion planning has been successfully carried out. Of the several performed scenarios, the scenario with the interconnection system can be selected as the best option. It is based on the total cost value and reduced generation costs of 1,073 IDR per kWh in 2022 and 1,362 IDR per kWh in 2047, with an average of 1,202 IDR per kWh.**

***Keywords*—Generation Expansion Planning (GEP), Power Plant Development Cost, Interconnection, Mixed Integer Linear Programming (MILP).**

I. INTRODUCTION

For the last five years (2013-2017), electrical energy consumption has increased annually following the realization of electricity sales, with a 5.1% annual growth [1]. Buton and Muna are large islands in Southeast Sulawesi with a total population of around 360,682 people and a land area of 7,712.18 km^2. Geographically, those two regions are adjacent. The main power source of those two regions is supplied from Buton. Muna and Buton presently consumes a significant amount of electricity, reaching a peak load of 32,996 kW [1].

[1,2,3] *Department of Electrical and Information Engineering, Faculty of Engineering Universitas Gadjah Mada, Jln. Grafika No. 2 Yogyakarta 55281 INDONESIA (tel.: +6285299447946, +62(274)552305; email: [1]ahmad.fatana013@mail.ugm.ac.id, [2]sarjiya@ugm.ac.id, [3]lesnanto@ugm.ac.id)*
**Corresponding Author*

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As depicted in Fig. 1 [1], the each of Muna and Buton area has an isolated electrical system. It is due to the archipelagic nature of the Muna and Buton region. In the Muna system, the electricity system is still dominated by diesel power plants (*pembangkit listrik tenaga diesel*, PLTD) with a total installed capacity of 4,7 MW with a peak load of 4.2 MW. Meanwhile, the diesel power plant continues to dominate the Buton system with a total installed power plant of 30.15 MW and a peak load of 33.2 MW [2]. This condition contradicts the government's new renewable energy (NRE) mix target of 23% by 2025 and 31% by 2050. Therefore, an economical electricity development plan is needed to achieve the government's target by utilizing the energy potential of each region.

An interconnection between the two systems has previously been carried out [3] by connecting northern Sulawesi and southern Sulawesi. The interconnection was carried out by including two voltage transmission options, 275 kV and 500 kV, and taking into account voltage economy, *N*-1 contingency, and voltage stability.

Muna and Buton have several energy potentials, especially on Buton Island, with a geothermal energy potential of 125 MW [4], hydro energy of 10 MW, and solar energy of 10 MW [2]. In the meantime, the energy potential of the Muna system is relatively small, with hydro and solar power generating only 5 MW each. The utilization of each of these potentials is expected to contribute to the government's NRE mix target of 23%.

The electricity policy planning is outlined in the National Electricity General Plan (*Rencana Umum Ketenagalistrikan Nasional*, RUKN) and the Regional Electricity General Plan (*Rencana Umum Ketenagalistrikan Daerah*, RUKD). RUKD should be prepared by taking into account the RUKN and according to guidelines issued by the government [5].

In order to achieve the energy mix target, it is necessary to carry out generation expansion planning (GEP). GEP is employed to determine the type, capacity, and construction time of generating units by taking into account the forecasting of the annual load or peak load [6]. GEP has generally been conducted in previous studies [5]-[16]. One of the platforms that previous researchers have widely used to conduct GEP is OSeMOSYS [7]-[9], [14], [15]. Reference [7] employed the Open Source Spatial Electrification Toolkit (OnSSET) and OSeMOSYS. The study is divided into three scenarios, i.e., residential electricity consumption, rural electricity consumption, and urban electricity consumption, which are divided into low and high electricity consumption, respectively. In [8], the object of the performed research was the Java-Bali System in 2016-2025. The linear programming (LP) method was selected to achieve the minimum value by applying emission and no emission limits in its settlement. In this study, three scenarios were carried out, i.e., the modeling scenario of the electricity supply business plan (*rencana usaha penyediaan tenaga listrik*, RUPTL), optimization without emission limits, and optimization with emission limits. The simulation results show that optimization without emission limits is cheaper than optimization with emission limits [8]. Meanwhile, mixed-integer linear programming (MILP) and LP methods were used in other studies [9]. This method was chosen for both isolated and interconnection schemes. Three scenarios were employed in the study, i.e., the business as usual (BAU) scenario, the NRE target scenario, and the CO_2 limit scenario. The obtained result is that the value of the electricity generation basic cost (*biaya pokok penyediaan*, BPP) in the CO_2 limitation scenario is the highest compared to other scenarios [9]. As in research [14], the case studies were in Jayapura and Sarmi. The scenario was carried out with an isolated and interconnection system. The employed method was MILP. The obtained results show that, based on generation costs and total costs, isolated system scenarios are cheaper. The generation expansion has also been carried out using PLEXOS as its interface [6], [10]. In the study, the MILP method was chosen with a long-term plan (LT) model that planned the construction of a generation for twenty to thirty years. The LT plan model provides an optimal combination of the new power plant construction, cessation of generation, and addition of transmission lines by minimizing the net present value (NPV) of the total cost in long-term planning while keep considering constraints [7].

In this study, a GEP study was conducted on Muna and Buton Islands to meet the projected load for the 2022-2047 period and the 23% energy mix target set by the government to obtain a minimum cost of electricity supply. The results of this study are expected to be a reference in preparing the Muna and Buton Island electricity master plan to support the achievement of Indonesia's renewable energy target.

II. METHODOLOGY AND DATA

The problems of generation expansion are addressed by formulating an objective function in the form of finding minimum costs in providing electricity while still paying attention to existing restraints. The cost component includes capital costs, operating and fixed maintenance costs, variable costs, as well as fuel costs. It is written in (1).

$$Z = min\left(\sum_r \sum_t \sum_y DFC_y \times [C_{inv}^t \times NC_{r,t,y}] + \sum_y DF_y \times [C_{F0\&M}^t \times (\sum_r \sum_t (RC_{r,t,y} + \sum_y^{yy} NC_{r,t,y}))] + \sum_r \sum_l \sum_f DF_y \times [\sum_t (((HR_t \times C_{fuel}^t) + C_{vo\&m}^t) \times P_{r,t,y})]\right) \quad (1)$$

where

z = total cost
y = year,
r = region,
f = fuel,
t = technology,
l = time slices,
$NC_{r,t,y}$ = new capacity,
C_{inv}^t = discount rate,

Fig. 1 Map of Muna and Buton [1].

DFC_y = discount factor for capital investment,
DF_y = discount factor for fixed and variable costs,
$C_{FO\&M}^t$ = operation and fixed maintenance cost,
$RC_{r,t,y}$ = residual capacity,
C_{fuel}^t = fuel cost,
$C_{VO\&M}^t$ = operating and variable maintenance costs,
$P_{r,t,y}$ = production,
HR_r = calorific rate.

The course of this study is shown in Fig. 2. Research began by studying various literature in the form of research and books related to generation expansion planning. In addition, data collection related to research was carried out, including information on existing plants, generation plans, energy demands, energy potential, and techno-economic costs of generation. In this study, two scenarios were carried out, i.e., isolated and interconnection scenarios. In the isolated scenario, it was assumed that in the Muna and Buton systems, the generation expansion was carried out individually. Meanwhile, in the interconnection scenario, it was assumed that the Muna and Buton systems were interconnected. Subsequently, a simulation of isolated and interconnection scenarios was carried out. The outcomes of each scenario were analyzed from the perspectives of the generation BPP, the system reliability, as well as its energy mix. Following the completion of each analysis, a comparison was made between scenarios before and after the interconnection, followed by the formulation of conclusions and recommendations.

1) Restraints: In the optimization model of this generation expansion planning, there are several considered restraints, which are shown in (2) to (6). It is assumed that the total power of the existing generation and additional new generations each year should be greater than or equal to the annual peak load plus the reserve margin. At (3), the total energy production for each time slice should be equal to the energy demand for each time slice. Equation (4) shows that in meeting the NRE mix target, NRE production must be equal to or greater than the NRE target multiplied by the total annual energy production. In the meantime, at (5), energy production is limited annually according to the capacity factor of each generation.

$$\sum_t (RC_{r,t,y} + \sum_y^{yy} NC_{r,t,y} \geq PL_{r,y} + RM_{r,y} \tag{2}$$

$$\sum_t P_{r,t,y} \geq D_{r,l,y} \tag{3}$$

$$PRE_{r,y} \geq RET_y \times P_{r,t,y} \tag{4}$$

$$P_{r,t,y} \geq AC_{t,y} \times CF_{t,y} \times 8760 \tag{5}$$

where

$PL_{r,y}$ = peak load,
$RM_{r,y}$ = reserve margin,
RET_y = renewable energy target,
$\mathrm{PRE}_{r,y}$ = renewable energy production,
$P_{r,t,y}$ = production,
D_y = demand,
$AC_{t,y}$ = available capacity,
$CF_{t,y}$ = capacity factor.

The restraint in this GEP design model is the reserve margin. It aims to ensure the achievement of reliability targets. In (6), the reserve margin is calculated as a percentage of the difference between the installed capacity with peak load to peak load.

$$RM = \frac{(IC-PL)}{PL} = \times 100\% \tag{6}$$

where *RM* is the reserve margin, *IC* is the total installed capacity, and *PL* is the peak load.

2) The Calculation of Electricity Generation Basic Cost (BPP): As shown in equation (7), the BPP is calculated by dividing the cost of electricity production by the amount of energy sold. Meanwhile, (8) demonstrates that the CRF is used to determine the return on capital in accordance with a generation's interest rate and operational life.

$$BPP = \frac{((Capital\ Cost_y \times CRF) + FOM\ Cost_y + VOM\ Cost_y + Fuel\ Cost_y)/(1+i)^y}{Energy\ sold/(1+i)^y} \tag{7}$$

$$CRF = \frac{i \times (1+i)^n}{E(1+i)^n - 1} \tag{8}$$

where *i* is the interest rate and *y* the is the *y*th year.

Based on the optimization model written in (1) to (8), a GEP simulation was performed using the OSeMOSYS platform. In the simulation, the assumptions of the techno-economic data of the generation candidates [17] and the primary energy of the generations [18], [19] were used, as shown in Table I and Table II.

III. RESULTS AND DISCUSSIONS

This section elaborates on the results of optimizations carried out on the Muna and Buton systems. The results shown include generation capacity, reliability as represented by reserve margin, energy mix, and the BPP of power plant. Simulations were performed in both the isolated and interconnection scenarios. In the isolated scenario, the GEP simulation for the Muna and Buton systems was carried out separately; however, in the interconnection scenario, both systems were assumed to be linked by transmission channels.

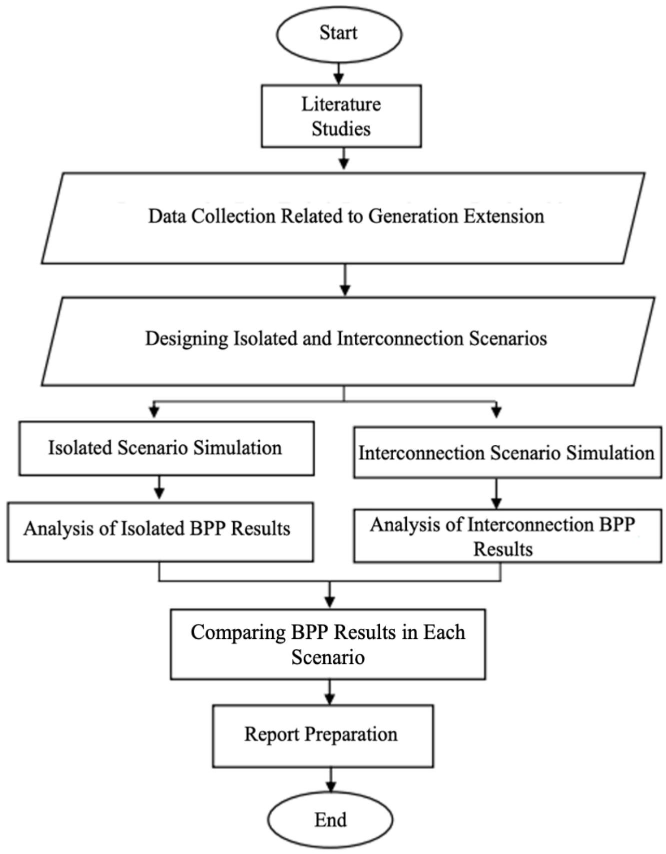

Fig. 2 Research flowchart.

A. Simulation Results of the Isolated Scenario

In this isolated system simulation scenario, the Muna and Buton systems were simulated as separate systems with the energy potential utilization of each region.

1) Simulation Results of the Muna System: The composition of generations in the Muna system from 2022 to 2047 is shown in Fig. 3. It can be seen that there is an increase in generating capacity from 2022 to 2047 to meet peak load demand that increases every year. There were four types of generation candidates selected, i.e., PLTD, micro hydro power plant (*pembangkit listrik tenaga mikrohidro*, PLTMH), gas engine power plant (*pembangkit listrik tenaga mesin gas*, PLTMG), and solar power plant (*pembangkit listrik tenaga surya*, PLTS). In addition, the initial year of installed generation percentages was PLTD of 31.58%, PLTMG of 26.32%, and PLTMH and PLTS of 21.05%, respectively. Among these four installed generations, there was only 3 MW existing PLTD in 2018, and it will be retired in 2039. Meanwhile, the reserve margin on the Muna system is shown in Fig. 4. It can be observed that the reserve margin of 35% has been met since the first year. At the

TABLE I
DATA ON TECHNO-ECONOMIC ASSUMPTIONS OF GENERATION CANDIDATES

Generation	Generation Age (years)	Capacity Factor (%)	Efficiency (%)	Capital Cost ($/kWe/y)	FO&M ($/kWe/y)	VO&M ($.MWh)
PLTD	25	40	37	1,500	38.00	6.40
PLTMG	25	55	42	400	40.00	3.80
PLTU	30	80	34	1,650	45.25	3.80
PLTMH	25	40	37	2,600	38.00	6.40
PLTS	25	16	25	830	26.00	0.40
PLTP	30	80	25	4,500	20.00	0.37

TABLE II
PRIMARY ENERGY

Primary Energy	Cost		Calorific Value		Escalation
Coal	60.00	$/ton	4,700	kcal/kg	0.012
LNG	10.00	$/MMBTU	252,000	kcal/Mscf	0.009
HSD	0.58	$/liter	9,100	kcal/liter	0.023

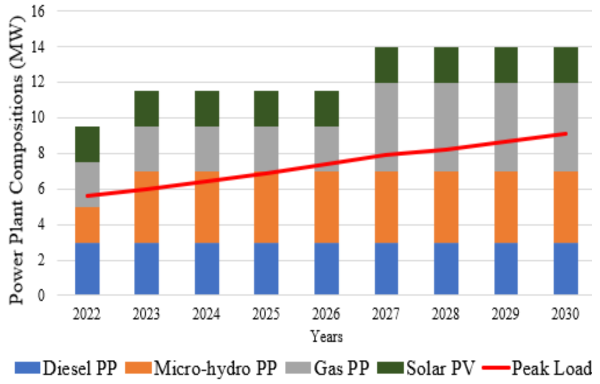

Fig. 3 Composition of the Muna system generation.

beginning of the year, the reserve margin was 69.64%. It is due to the addition of PLTMH, PLTMG, and PLTS plant types, with a total of 6.5 MW and a peak load of 5.6 MW. In 2023, 2027, 2033, 2037, 2040, and 2044 there was an increase because, in each of these years, there were generation additions, resulting in an increase in the reserve margin value.

The energy mix of the Muna system is shown in Fig. 5. It can be observed that from the optimization results, in the initial year during the planning, the PLTMG dominates the energy mix, which is 63.87%, then followed by PLTMH at 25.69% and PLTS by 10.44%. PLTMG dominates the Muna system because the system has a small primary energy potential, so the PLTMG is forced to meet electricity demand based on optimization results. The highest cost in the Muna system is fuel cost, which is 311 billion IDR, then followed by the capital cost of 178 billion IDR, fixed cost of 51 billion IDR, and the lowest cost is the variable cost of 14 billion IDR, with a total of 553 billion IDR. Fuel costs are the highest costs because, in the Muna system, there are PLTMG and PLTD type power plants, which need fuel during their operation. In the meantime, fixed costs became the second highest cost due to the addition of several generations, causing the cost of capital to increase. The reserve margin and total cost of generation BPP have been effectively determined for the Muna system as a whole, with a

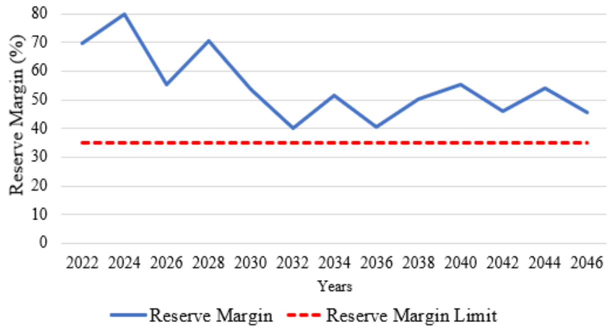

Fig. 4 Reserve margin of the Muna system.

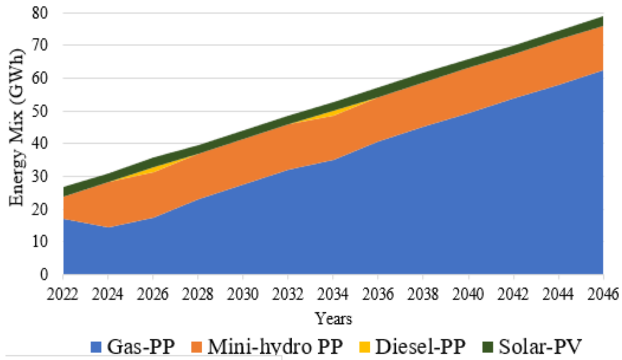

Fig. 5 Energy mix of the Muna system.

BPP value of 1,489 IDR per kWh in 2022 and 1,629 IDR per kWh in 2047, with an average of 1,529 IDR per kWh. On the other hand, the NRE mix in the Muna system was not achieved because Muna had little primary energy potential.

2) Simulation Results of the Buton System: The generation composition on the Buton system is shown in Fig. 6. It can be observed that there are five types of installed generations in the Buton NRE scenario, namely PLTMH, PLTMG, geothermal power plants (*pembangkit listrik tenaga panas bumi*, PLTP), PLTS, and steam power plants (*pembangkit listrik tenaga uap*, PLTU). The generation capacity always increases every year. It is due to the demand for electricity that is always increasing

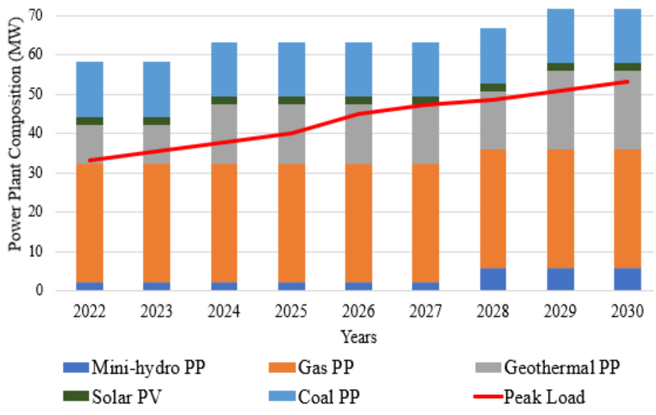

Fig. 6 Composition of the Buton system generation.

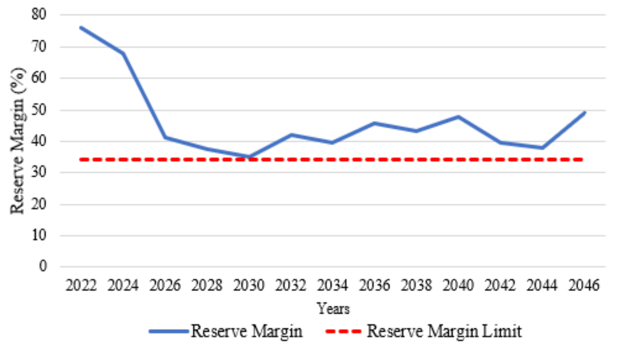

Fig. 7 Reserve margin of the Buton system.

throughout the year. The PLTM is reported to dominate expansion planning with a percentage of 51%, followed by PLTU with 24%, PLTP with 17%, PLTMH with 4%, and finally PLTS with 3%. Gas Engine Power Plant dominates throughout the planning year because it is the cheapest generation selected based on optimization results, while PLTP is the second largest due to the minimum limit of NRE production, which is set at 23% in 2025 and 31% in 2047. Meanwhile, the reserve margin is shown in Fig. 7. It can be seen that, during the planning time, the minimum reserve margin limit of 35% has been met. In the early years, reserve margins have increased by a total of 75.90%. It is due to the existence of three types of existing plants, namely PLTU, PLTMG, and PLTMH, with a total capacity of 46.4 MW and the addition of new plants of 10 MW PLTP and 2 MW PLTS types at the beginning of the year with a peak load of 32.2 MW. In general, there is an increase in the reserve margin value due to the addition of new plants in these years. Furthermore, the energy mix on the Buton system is shown in Fig. 8. It can be seen that there are five types of generations running during the planning period, namely PLTP, PLTU, PLTMG, PLTMH, and PLTS. The percentage of each generation in the initial year of planning is PLTU by 43%, PLTP by 30%, PLTMG by 22%, then PLTMH by 4%, and finally PLTS by 1%. In 2045, PLTP will experience a significant increase. It is due to the existence of a PLTU type generation that retires in 2044 so that PLTP-type generations are included in penetration based on simulation results. In this simulation result, PLTP and PLTU can be used as base loads with a total of 157.68 GWh or 73. Then, PLTMG

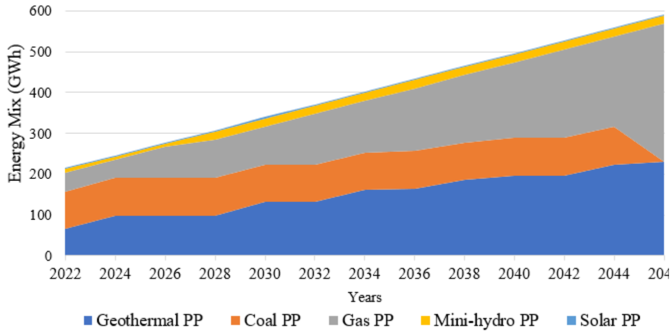

Fig. 8 Energy mix of the Buton system.

can be used as a follower by 22%, and PLTMH of 4% can be used as its peaker. Meanwhile, the highest cost of the Buton system is fuel costs, amounting to IDR 1,596 billion, followed by capital costs of IDR 1,403 billion and fixed costs of IDR 287 billion. The lowest is variable costs of IDR 56 billion, with a total cost of IDR 3,343 billion. Fuel costs and capital costs became the most dominant. It is due to the presence of PLTMG and PLTU, each of which requires fuel, so the additional fuel costs are even greater. In the meantime, capital costs became the second largest due to the addition of PLTMG, PLTP, PLTMH, and PLTS, resulting in greater capital costs.

The value in the form of reserve margin, NRE mix, and total generation BPP costs has been successfully obtained for the Buton system as a whole, with a BPP value of 1,071 IDR per kWh in 2022 and 1,546 IDR per kWh in 2047, with an average of 1,221 IDR per kWh.

3) Simulation Results of the Muna-Buton Interconnection System: In the interconnection system design, only the generation BPP was calculated as performed in the Muna and Buton isolated scenarios. The composition of the generations on the interconnection system is shown in Fig. 9. The generation capacity is increasing annually. It is in line with the increasing demand of the community, which leads to an increase in peak loads every year. The generation candidates selected based on the optimization results are PLTP, PLTU, PLTMG, PLTMH, PLTS, and PLTD. The PLTMG became the largest, at 58%. It happened because, in the early years, there was an addition of a new plant of 10 MW plus an existing type of PLTMG plant of 30 MW. The reliability of the interconnection system can be seen in Fig. 10. It can be observed that throughout the planning year, a reserve margin of 35% was met. At the beginning of the year, the reserve margin value was 68.86%. The increase in the reserve margin at the beginning of the year occurred due to the minimum restriction on the production of NRE plants by 23%, resulting in the NRE generation installation. The installed generation type is a PLTP of 10 MW, resulting in an increase in the reserve margin value. In 2026, the reserve margin increased due to the presence of new PLTP installed consecutively by 5 MW, which led to an increase in reserve margin in that year. Meanwhile, at the end of the year, the reserve margin value was 43%. The energy mix of the interconnection system is shown in Fig. 11. It can be seen that at the beginning of the planning year, coal-fired power plants dominated, at 37%, followed by PLTMG at 33%, then

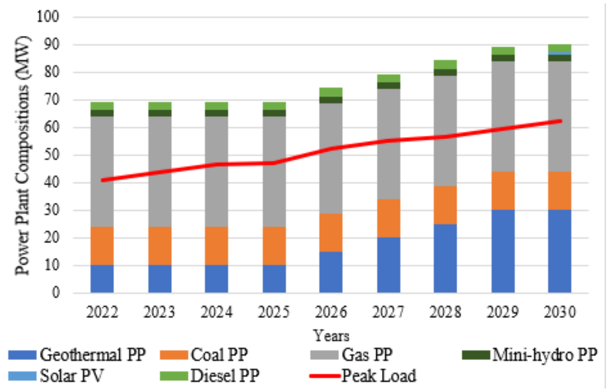

Fig. 9 Composition of the Muna-Buton interconnection system generation.

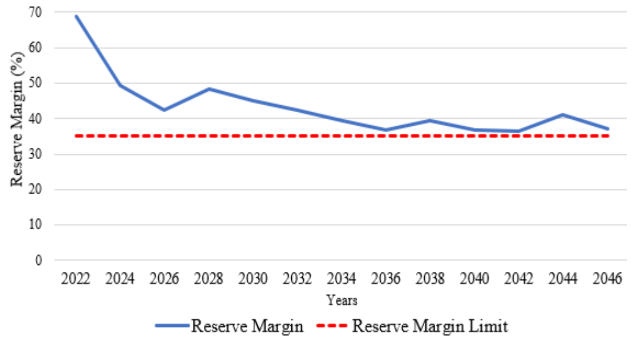

Fig. 10 Reserve margins of the Muna-Buton interconnection system.

PLTP at 27%. In 2027, PLTP will increase to 48%. The reserve margin at the beginning of the planning was relatively high because there were already several existing generations, namely PLTU, PLTMG, PLTMH, and PLTD, as well as several new power plants with a total installed capacity of 69.4 MW. In general, PLTP dominated during planning due to the addition of PLTP-type generation. In 2044, PLTP-type generation experienced a drastic increase of 84% due to the existence of a retired PLTU type plant of 14 MW in that year, resulting in the addition of a PLTP type plant of 20 MW. Based on Fig. 11, PLTP and PLTU can be used as base load, PLTMG is used as a follower, and PLTMH can be used as its peaker.

The highest cost in the Muna-Buton interconnection system is capital costs of 2,194 billion IDR, followed by fuel costs of 1,168 billion IDR, fixed costs of 326 billion IDR, and the lowest costs are variable costs of 43 billion IDR. Capital costs are the highest costs due to the addition of several types of plants dominated by PLTP, which have the greatest capital costs among other generation types. In the meantime, fuel costs are the second highest due to the penetration of PLTMG and PLTU power plants that require fuel during their operation.

IV. CONCLUSION

In this study, the generation planning in Muna-Buton from 2022 to 2047 with isolated and interconnection scenarios has been successfully implemented. In the isolated system scenario, it has been successfully carried out while maintaining its reliability. Each Muna and Buton system has met predetermined limits, such as reserve margin, NRE targets, and the energy demand fulfillment. From the analysis performed, an interconnection scenario is recommended as the best option. This recommendation is based on the total cost value of construction and more economical generation costs, which are 1,073 IDR per kWh in 2022 and 1,362 IDR per kWh in 2047, with an average of 1,202 IDR per kWh.

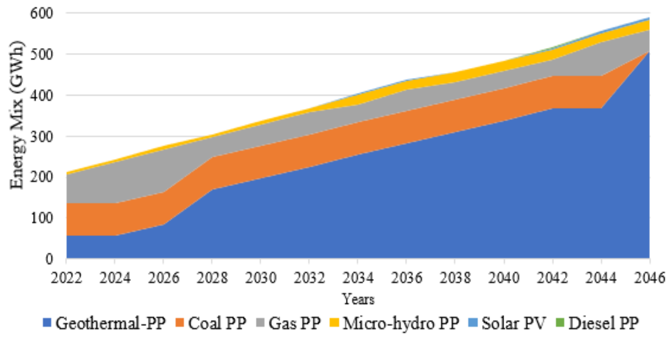

Fig. 11 Energy mix of the Muna-Buton interconnection system.

CONFLICT OF INTEREST

In the preparation of the research report, the author declares that the article entitled "Muna-Buton System Generation Expansion Planning by Considering the Interconnection System" was written and compiled without any conflict of interest.

AUTHOR CONTRIBUTION

Conceptualization, Ahmad Fatana, Sarjiya, Lesnanto Multa Putranto; methodology, Ahmad Fatana, Sarjiya, Lesnanto Multa Putranto; writing—drafting the original draft, Ahmad Fatana; writing—review and editing, Sarjiya, Lesnanto Multa Putranto.

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