Tanah Merah Electricity System Development Considering New Renewable Energy and CO_2 Emissions

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ABSTRACT — The condition of the electricity system in the Papua region still has an electrification ratio of 94% with a high electricity generation cost of IDR3,041/kWh. In addition, the existing electricity system still consists of over 100 small systems, the majority of which are diesel power plants. One of the systems is the Tanah Merah area, with a population of 19,136 people and an energy demand of 6.89 GWh. The region is projected to experience expansion and population growth, resulting in a corresponding rise in the demand for electrical energy. Therefore, planning for the development of power plant systems needs to be done to meet the growing demand for electrical energy. Planning in remote areas is typically done for a short-term timeframe spanning from 2025 to 2030, involving the optimization process of several proposed power plant candidates. The proposed candidate power plants consider gas and fuel supply, as well as the availability of local primary energy and technology. Optimization will minimize the total cost of the to-be-selected power plant, which has features including initial investment costs, ongoing operation and maintenance costs, fuel expenses, and the residual value of the assets throughout the planned duration. In planning, a greenhouse gas emission reduction of 29% and an energy mix proportion of 23% need to be considered in accordance with government policy. Therefore, two scenarios covering both economic and environmental aspects were considered in the simulation process, namely the business as usual (BaU) scenario and the nationally determined contributions (NDC) scenario for emission limitation. Optimization was developed based on mixed-integer linear programming (MILP) performed in HOMER software. The simulation results indicate that the electricity generation cost for the BaU scenario is more economical compared to the NDC scenario at IDR2,559.8/kWh versus IDR3,104.64/kWh.

KEYWORDS — Power Generation System Planning, Remote Area Planning, New and Renewable Energy, Emission Limitation, HOMER.

I. INTRODUCTION

In an electricity system, the demand for a system that will continue to increase must be balanced with an increase in the power plant capacity. The advancement of power plants in Indonesia is still being carried out because the electrification ratio reached only 99.2% in 2020. The electrification ratio remains low, especially in the Eastern Indonesia region [1]. The development of power plants must also align with the national energy policy by paying attention to the energy mix from renewable energy [2].

The Eastern Indonesia region exhibits a low and dispersed load profile yet possesses a substantial primary energy capacity, with the Papua region being one notable example. Currently, existing load centers are supported by many isolated systems. The utilization of new renewable energy (NRE) in the Papua region is currently not being maximized to its full potential. For instance, the solar power capacity in the region is estimated to reach 2,020 MW, yet only approximately 202 MW is currently being utilized [3]. The use of renewable energy needs to be pursued in the planning of electric power systems to achieve the national energy mix target of 23% by 2025 [2].

Power plant development planning is done based on the extent of the area, the number of customers, and the electrical energy demands of a given area. These values are reflected in the peak load magnitude to be served. The system is divided into three categories based on its size: large systems > 100 MW, medium systems 10 – 100 MW, and small systems 10 MW [4]. The planning approach varies depending on the type of system.

Electricity system planning on large systems has been widely studied by modeling optimization with the objective functions of minimizing total costs, maximizing NRE penetration, and minimizing CO_2 emissions. In developing the optimization model, the three objectives can be combined into a multi-objective model. Several large system plans that have been developed take renewable energy into account, such as one in Brazil [5], with a system size of 152 MW. In addition, planning for developing a 2,350 MW system with a 100 MW wind power plant penetration by considering seasonal variations has been discussed [6].

Planning for multiregional power plant development by considering fossil and NRE generation candidates with a system size of 1931 GW has also been discussed [7]. Generation development in a 2,000 MW system in Chile by considering hydropower and nuclear power plant candidates has been discussed [8]. Similarly, a system of 8,000 MW has been developed [9]. In all three studies, the main target of system planning is to reduce greenhouse gas emissions, which is currently the focus of research in several countries. In addition, carbon capture storage (CCS) technology in the steam power plant was also considered [10], with a system size of 103 GW.

In optimizing large systems, linear programming or mixed integer linear programming (MILP) models are often used to solve optimization problems. The control variables determined are the type and size of the power plant to be built each year. In large systems, the time-step for plant planning is usually made one year for 20 to 40 years.

In contrast to large system planning, small and medium system planning is carried out in a shorter planning duration of 5 to 10 years with different time-step ranging from per year to every 5 years. Linear programming-based models have also been developed in HOMER software to plan these systems including a biomass solar microgrid system in Sharjah [11], a small-scale hybrid system based on biomass, wind power, solar power and batteries [12], a 50 MW medium-scale hybrid system (solar power plant-battery-diesel power plant) in Sabah [13], a 41 kW small-scale solar power plant-biomass-diesel power plant system in a remote area [14], 17.08 kW off-grid solar power plant-biomass power plant system in Punjab, Pakistan [15], small-scale hybrid biomass power plant system in peninsula Malaysia [16], determination of stand-alone system or grid-connected in remote areas [17], a small-scale hybrid solar power plant-biomass power plant-battery system in Chhattisgarh, India [18], 1 kW residential electricity system based on solar power plant-biomass power plant-battery [19].

Based on the development of methods carried out in previous studies, a plant development optimization model was developed with the object of the Tanah Merah electricity system. This system has a peak load of 3 MW which is included in the small system category. The electricity system development considers seasonal variations that affect energy production from renewable energy plants. Therefore, planning was carried out for 2025-2030 with a 5-year time-step that considered local primary energy potential, technological support, emission restrictions, and the contribution of existing plants. Simulations for planning were conducted using HOMER software. The optimization model is developed by minimizing the total planning cost including investment cost, operation and maintenance (O&M) cost, fuel cost, and residual asset value. This study developed two optimization scenarios: the business as usual (BaU) scenario to obtain the most economical plant configuration and the nationally determined contributions (NDC) scenario for emission limitation to obtain the most environmentally friendly plant configuration.

II. CONCEPT OF THE POWER PLANT DEVELOPMENT PLANNING

A. POWER PLANT DEVELOPMENT PLANNING

System development needs to be planned so that an increased supply of electrical energy can be prepared to meet the increasing load demand from year to year. Planned plant development will result in an economical total cost of electrical energy generation. In addition, targets mandated by the government, especially on environmental aspects can also be met through a planned planning process. Currently, power plants from renewable energy sources are part of the planning process of power plant development.

The planning of power plant development will determine the configuration of the power plant type and capacity that will be built in a given planning duration including the fuel requirements for fossil power plants. Such power plant configuration must meet the demands of electrical energy throughout the planning year, meet the system load profile, and meet the target of fulfilling environmental aspects. An optimization process needs to be applied to plan such power plant development to obtain optimal and economical power plant configuration. Optimization is built by minimizing the

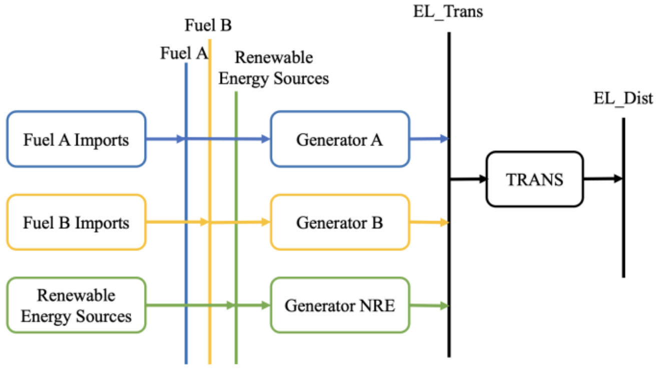

Figure 1. Energy chain of power plant development planning.

total cost, including investment costs, O&M costs, fuel costs, and residual value of assets at the end of the planning year. The limits on meeting the needs of electrical energy, load profile, and environmental aspects are arranged as constraints on the formulation of the optimization function.

B. ISOLATED SYSTEM POWER PLANT PLANNING

The modeling of power plant development planning, starting from identifying primary energy availability, selecting candidate plants, and distributing the assumption model, is illustrated by the energy chain in Figure 1 [20]. The figure explains that it is necessary to look at the availability of primary energy to determine the candidate generator. It is very suitable for remote/isolated areas where fuel transportation for power plants is still constrained due to limited transportation facilities and infrastructure. In the end, the energy needs that must be provided within the planning period must meet the energy needs required each year.

In the energy planning chain model, a distribution network configuration fulfills the energy distribution from the generator to the load. The determination of the configuration is done through a power system analysis study. This study focuses on optimizing power plant development by considering the available primary energy sources, assuming the network configuration is already available. Power system analysis to obtain the optimal configuration is not part of this study.

C. TOTAL COST OF ENERGY PRODUCTION

The total cost of energy production is the total cost used to produce electricity, which includes investment costs, O&M costs, fuel costs, component replacement costs, and asset residual values. These costs are accumulated annually according to the planning duration. The planning duration can usually be done according to the technical age of the plant.

Investment costs are the initial capital costs required to build a new plant. Investment costs include land costs, construction costs, and generator equipment costs. These costs depend on the type of generator and the output of the generator, but not on the operating conditions of the system.

O&M costs are the costs required for the operation and maintenance of the generation system, and depend on the type of plant and the size of the power plant capacity. It includes the costs of management, employee salaries, insurance, and scheduled maintenance.

Fuel cost is the cost incurred for the use of fuel in the plant. The factors affecting the amount of such costs are the type of fuel used and the plant's ability to convert energy.

Replacement cost is the cost of replacing generation system components, as determined by their technical lifecycle parameters within each component. The residual asset value is the value remaining in a power system component at the end of the planning year. A component will experience depreciation which is modeled linearly over time. The total cost value is shown in (1).

$$Z = CC + OMC + FC + RC + SV \quad (1)$$

where Z is the total production cost, CC is the investment cost, OMC is the O&M costs, FC is the fuel cost, RC is the component replacement cost, and SV is the asset's residual value.

D. ELECTRICITY GENERATION COST

The cost of electricity supply is all the costs used in the process of distributing energy from electricity suppliers to consumers for energy sold per unit of energy. This electricity generation cost is used as a reference for the purchase price of electricity from the generator [21] and will affect the determination of electricity tariffs and subsidies.

The amount of electricity generation cost can be written in (2).

$$Electricity\ Generation\ Cost = \frac{Total\ Cost\ of\ Energy\ Production}{Energy\ produced} \quad (2)$$

E. CO2 GAS EMISSIONS

Currently, most of the power plants in Indonesia are still thermal plants with fossil fuels as energy sources that produce greenhouse gas emissions. One type of gas is CO_2. Increasing emissions will impact the environment, one of which is the increase in global temperature. The production of CO_2 gas emissions at the power plant can be calculated using the fuel emission factor which can be written in (3).

$$ET = EP \times EF \quad (3)$$

where ET is the total emission, EP is the thermal generation energy, and EF is the emission factor of each plant. To realize the reduction of CO_2 gas emissions, the government has limited the emission reduction to a minimum of 29% by 2030 [22]-[24]. The target applies nationally, so any system planning in Indonesia needs to take this into account, including small/isolated systems.

III. METHODOLOGY

A. RESEARCH FLOW CHART

The research flowchart is presented in Figure 2. The necessary data for the Tanah Merah electricity system is collected in the first stage. These data are related to load characteristics, load profile, projected energy growth, primary energy potential, solar irradiation data, and wind speed. After that, generation and energy storage candidates are determined in the next stage, including collecting techno-economic data.

Mathematical function modeling is determined based on two scenarios, namely BaU and NDC, to determine the most economical and environmentally compliant plant configuration. In the NDC scenario, optimization was performed by limiting the production of greenhouse gas emissions, namely CO_2. In this scenario, the reduction of CO_2 emissions is at least 29% by 2030.

Mathematical function modeling was used to select the optimum candidate generation technology at a later stage. Then the objective functions of the two predetermined scenarios were organized based on their supporting constraints. The optimization process was carried out using HOMER software. Generation candidates, techno-economic parameters, NRE profile, load profile, and load forecast are the input variables for the process. Simulations are conducted for both scenarios until all constraints are met and the most economical value is achieved. In this research, the emission constraints checking needs to be carried out outside the HOMER optimization software.

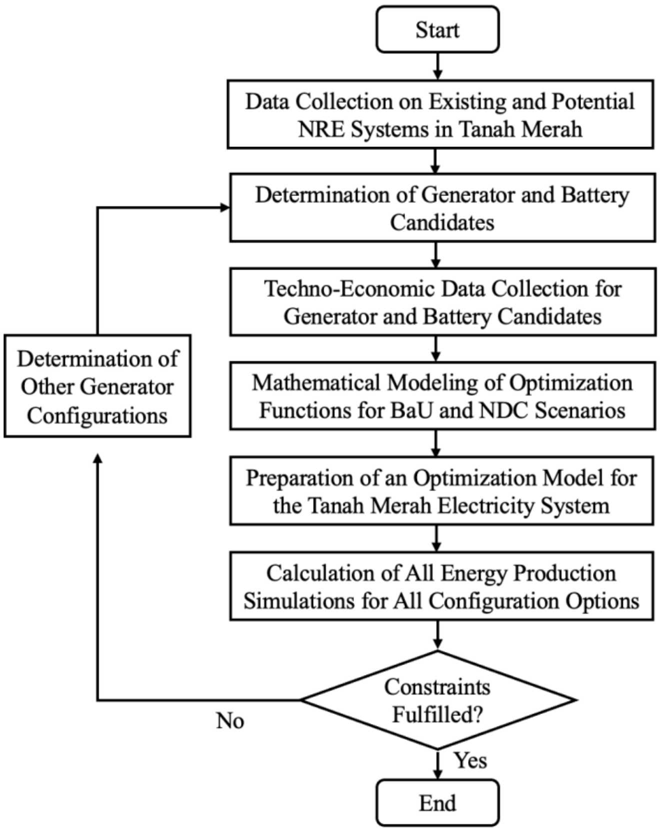

Figure 2. Research flowchart.

B. ELECTRICAL ENERGY DEMANDS

Tanah Merah is an area that is also the capital of Boven Digoel Regency, located in Papua Province, shown in Figure 3 [22]. The population is approximately 19,136 with an area of 1,301.97 km² and latitude and longitude coordinates of 6°4.8`S, 140°16.6`E. The Tanah Merah system has a peak load of 2.73 MW and is currently supplied by one diesel generator with a capacity of 4 MW.

The load profile in 2020 is shown in Figure 4 [25]. The load profile style is used as the basis for determining the load profile style for the planning year 2025-2030. The peak load forecasting for 2025-2030 for this electricity system is shown in Figure 5 [25]. The load in Tanah Merah is assumed to have linear growth. Most of the livelihoods in this area are dominated by the agricultural sector which is a residential customer so it can be observed that the high load is located after 17:00 WIT to 21:00 WIT. During these hours, electricity is mostly used for lighting.

In order to meet these electrical energy needs, the selection of power plant candidates is based on the potential of local primary energy sources. The region has sufficient solar, wind and biomass potential [3].

Figure 3. Location of Tanah Merah system.

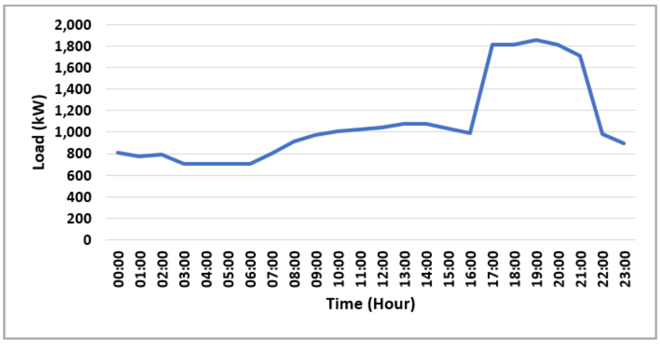

Figure 4. Daily load profile in 2020.

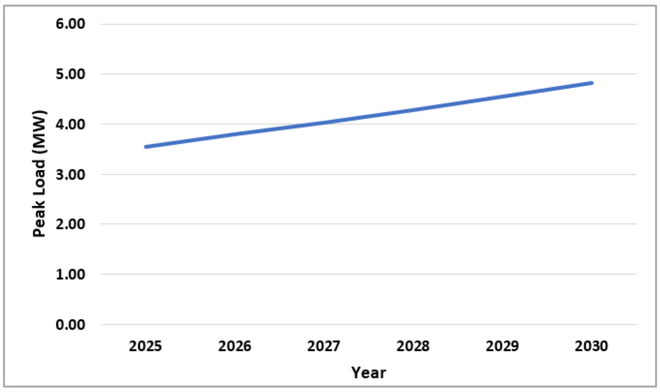

Figure 5. Load forecasting of Tanah Merah.

The optimal power plant type for 2025 to 2030 will be determined. The selected options of power plant system development are diesel power plant, gas engine power plant, biomass power plant, wind power plant, solar power plant, and batteries whose parameters are shown in Table I. This table describes the techno-economic parameters, namely investment cost, replacement cost, O&M costs, and technical lifecycle of components [26].

C. AVAILABILITY OF PRIMARY ENERGY

Fuels for fossil plants used in this study include high speed diesel (HSD), liquefied natural gas (LNG), and biomass for the needs of diesel, gas engine, and biomass power plants. The fuel cost data and its escalation are shown in Table II [27]. The monthly profiles for solar irradiation are shown in Figure 6 [26] and wind speed is shown in Figure 7 [2]. Solar irradiation and wind speed data were obtained from the National Aeronautics and Space Administration (NASA) by entering the latitude and longitude data of the Tanah Merah system [28].

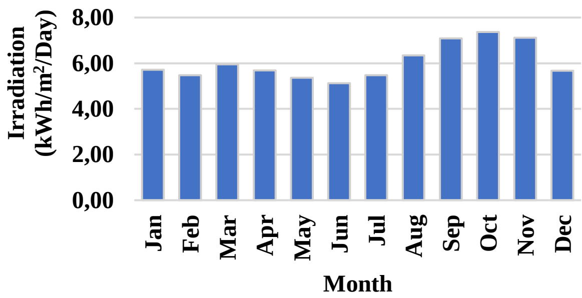

Figure 6. Monthly average of solar global horizontal irradiance (GHI) [3].

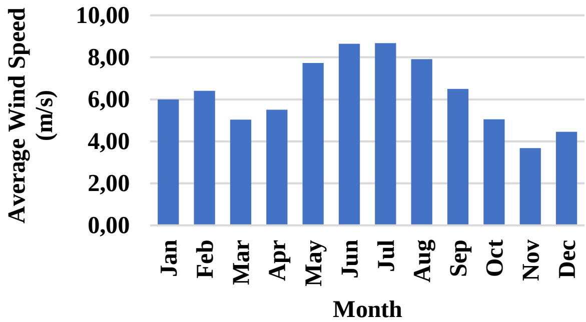

Figure 7. Monthly average wind speed [3].

TABLE I
TECHNO-ECONOMIC PARAMETER OF GENERATOR TECHNOLOGY [26]

Technology	Investment (Rp/kW) × 1.000	Replacement (Rp) × 1.000	O&M (Rp/kW/year) ×1000	Technical Lifecycle (year)
Diesel Power Plant	12,440	12,440	124	25
Gas Engine Power Plant	10,108	10,108	435	25
Biomass Power Plant	26,435	26,435	740	25
Wind Power Plant	62,200	62,200	1,138	27
Solar Power Plant	12,907	12,907	233	25
Battery	3,312	2,955	156	4

Rate IDR15,550/US$

The objective function of this study is to minimize the total cost value written in (4).

$$\frac{\sum_{Ng} UC_g(NCA_g)}{(1+d)^{Ny}} + \frac{\sum_{Ng} OM_g Pd_g OPhr_g}{(1+d)^{Ny}} + \frac{\sum_{Ng} CC_g}{(1+d)^{Ny}} + \frac{Fcost\left(\sum_{Ng} Fcon_g\left(Pd_g \times OPhr_g\right)\right)}{(1+d)^{Ny}} - \frac{\sum_{Ng} Crep_g \left({Rrem_g}/{Rcomp_g}\right)}{(1+d)^{Ny}} \quad (4)$$

subject to

$$\sum_{Ng} Pd_g OPhr_g \geq EDtot \quad (5)$$

$$Pd_g \leq Cap_g \quad (6)$$

$$NCA_g \leq MaxUcap_g \quad (7)$$

where g is the type of plant g (unit), y is the year, d is the discount rate (%), N is the considered number, N_y is the number

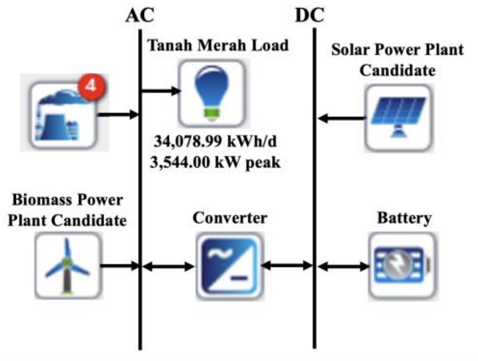

Figure 8. Option scheme of the hybrid system development planning [28].

TABLE II
FUEL PARAMETERS [25]

Type	Fuel Cost	Escalation (%/year)
HSD	Rp7,775/liter	2.3
LNG	Rp155,500/MMBtu	0.9
Biomass	Rp 500/kg	1.2

Rate IDR15,550/US$

of the considered year, N_g is the number of considered plants, OM^g is the operation and maintenance cost of plant type g ($), $Crep^g$ is the replacement cost of plant type components g ($), $Rrem^g$ is the remaining lifecycle of the generating type component g (years) $Rcomp^g$ is the lifecycle of the generating type component g (years), ED is demand (kW), Cap^g is the total capacity of plant type g (kW), CC^g is the investment cost of plant type g ($), $Fcon^g$ is the fuel consumption of plant type g (L/kWh), NCA^g is the capacity of plant type g added (kW), Pd^g is the power generated by the generation type g (kW), $OPhr^g$ is the operating hours of the generation type g (hours), and $MaxUcap^g$ is the maximum unit capacity of generation type g (kW). The objective functions and constraints from (4) to (7) are used in both BaU and NDC scenarios in each optimization scenario. For the NDC scenario, some additional constraints are used in the optimization as shown in (8):

$$\sum_{Ng} EF_g \times Pd_g OPhr_g \leq (1-29\%) EFBAU_g \times PdBAU_g OPhrBAU_g \quad (8)$$

where EF_g is the emission factor of generation type g (kg/MWh).

IV. RESULT AND DISCUSSION

A. PLANT CONFIGURATION CANDIDATES

The Tanah Merah system is predicted to have a peak load of 3.54 MW and is supplied by two diesel power plants with a capacity of 6 MW in 2025. The system development model in HOMER is carried out by considering predetermined technology candidates, as shown in Figure 8 [28]. There are several plant configuration options considering the existing combinations shown in Table III.

From several combination options given, one combination option can be selected that is the most optimal or has the lowest total cost value, namely the combination of the existing diesel power plant (6 MW) with 2.5 MW gas engine power plant and 1.5 MW biomass power plant for the BaU scenario and the combination of 2.5 MW gas engine power plant, 1 MW biomass power plant, 3 MW solar power plant, and 1,512 MWh battery for the NDC scenario as shown in Table III. Based on this combination, the total system cost and cost per type of cost component can be seen in Figure 9.

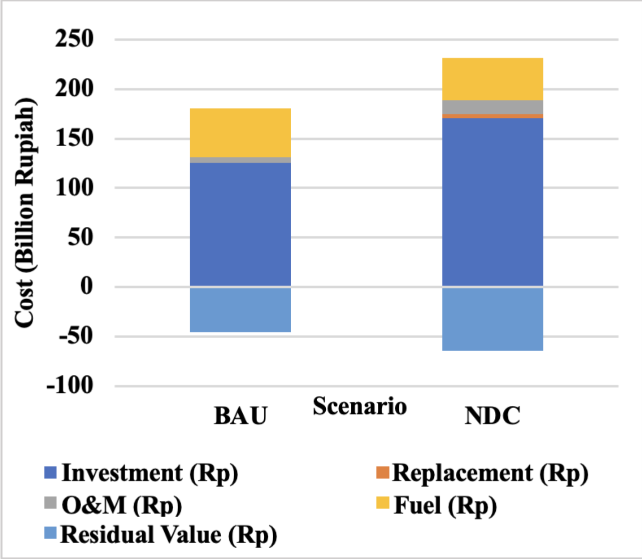

Figure 9. Total costs of power plant planning.

TABLE III
FUEL PARAMETERS OF THE CHEAPEST GENERATION COMBINATION OPTION FOR EACH SCENARIO

Scenario	Plant Composition of Tanah Merah					
	Combination Options	*Diesel*	*Gas Engine*	*Biomass*	*Solar*	*Battery*
BaU	Diesel-Gas Engine-Biomass	6 MW	2.5 MW	1.5 MW	-	-
NDC	Diesel-Gas Engine-Biomass-Solar	6 MW	2.5 MW	1 MW	3 MW	1,512 MWh

Table III shows that the most economical electrical energy plant is obtained by operating more biomass power plants compared to being dominated by gas engine power plant and diesel power plant in the BaU scenario. In the NDC scenario, a solar power plant with a capacity of 3 MW is required to fulfill the environmental aspects. It is because a solar plant has a lower emission factor when compared to biomass, LNG and diesel. Batteries are needed in this scenario to overcome the intermittent nature of solar power plants so that the electrical energy from solar power plants can be used at more flexible times.

B. ENERGY MIX

The energy mix for each scenario for the Tanah Merah system can be seen in Figure 10 (BaU) and Figure 11 (NDC). In the BaU scenario, electrical energy needs are met by 84% from the biomass power plant, 15% from the gas engine power plant, and the rest from the diesel power plant. This configuration is the most economical and meets the national energy mix target (> 23%) but the fulfillment of emissions has not been fulfilled because emissions are still produced from the biomass power plant.

For the NDC scenario, the biomass power plant is selected as the baseload plant since it has cheaper fuel costs. In addition, 3 MW of solar power plants can fulfill environmental aspects. Of the total electrical energy production per year, the solar power plant can produce 5.4 GWh/year or 39.7% electrical energy at the beginning of the planning year and 5.3 GWh/year

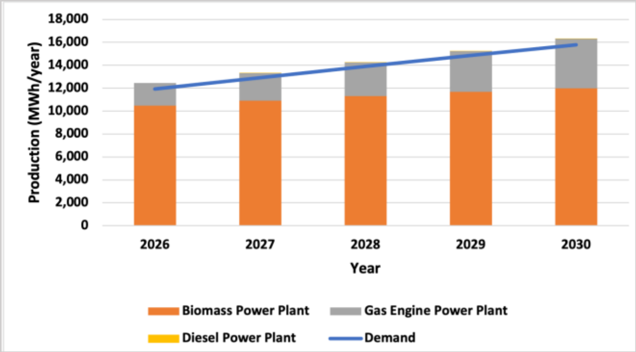

Figure 10. Electrical energy production from power plants in each year for BaU scenario.

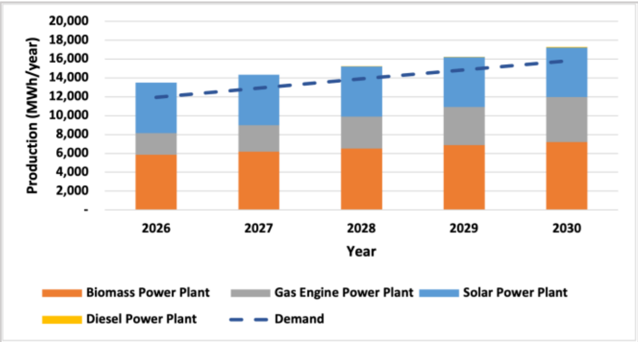

Figure 11. Electrical energy production from power plants in each year for NDC scenario.

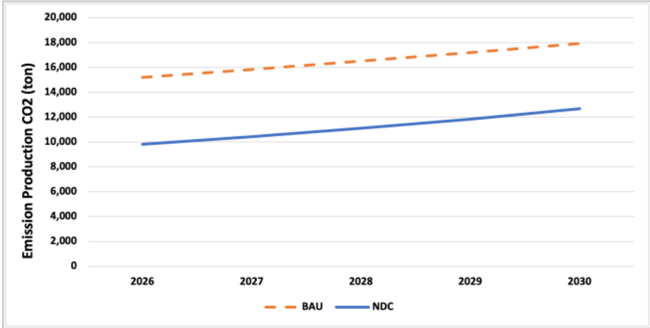

Figure 12. CO_2 emission production tons/MWh per scenario for Tanah Merah system.

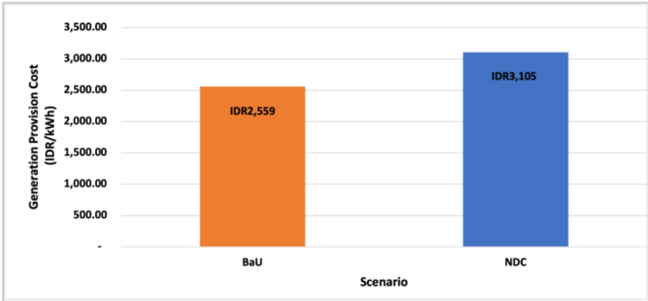

Figure 13. Total generation cost of average main cost of Tanah Merah power plant system for each scenario.

or about 30.5% of the total energy produced by the system at the end of the planning year. The biomass power plant produced electrical energy of 5.9 GWh/year or 44% of the energy at the beginning of the planning year and 7.3 GWh/year or about 42.3% of the total energy produced by the system in the last year of planning. Being add up, the renewable energy mix in the NDC scenario reaches 83.7% in 2026.

C. PRODUCTION OF CO_2 GAS EMISSIONS

A comparison of CO_2 gas emission production for the Tanah Merah system and each scenario can be seen in Figure 12. The CO_2 emissions of the Tanah Merah system in the initial year of the period were 15 thousand tons for the BaU scenario. After that, it will continue to increase until it reaches 17 thousand tons in 2030. Biomass power plants emit the largest greenhouse gas. It is because the biomass power plant as a baseload generator continues to produce electrical energy for 24 hours which results in greater fuel consumption and also because the emission factor produced by the biomass power plant is high.

In the NDC scenario, the amount of CO_2 emissions is lower than in the BaU scenario, due to the CO_2 production limit being 29% in 2030. This restriction minimizes the mix of thermal power generation to achieve the annual emission target and is also due to the presence of the 3 MW solar power plant. It proves that the NDC scenario is capable to meet the 29% emission reduction target by 2030. The decrease is measured from the optimization results of the BaU scenario.

D. TOTAL PRODUCTION COST

In the BaU scenario, the system requires funds of IDR135.4 billion, with details of IDR125 billion for investment costs, IDR5.9 billion for O&M costs, IDR49.7 billion for fuel costs, and IDR45.2 billion for residual value as previously illustrated in Figure 9. Meanwhile, the NDC scenario spent more total funds than the BaU scenario, which amounted to IDR167.1 billion, with details of IDR170.9 billion for investment costs, IDR3.6 billion for replacement costs, IDR13.9 billion for O&M costs, IDR42.9 billion for fuel costs, and IDR64.3 billion for residual value. High investment costs for NRE power plants, especially solar power plants, result in higher investment costs in the NDC scenario.

A comparison of the average electricity generation cost for the Tanah Merah system and each scenario can be seen in Figure 13. The BaU scenario has a cheaper average power plant main generation cost. It shows that, for now, the investment cost of solar power plants is still higher than conventional plants.

V. CONCLUSION

Based on the results and discussion of simulations in this study, it is concluded that the load requirements in the Tanah Merah system can be met at the most economical cost with the composition of diesel power plant and gas engine power plant with an average electricity generation cost of IDR2,598.08/kWh. With this configuration, the national energy mix target of 23% can already be met from biomass power plants. However, the target of reducing CO_2 emissions has still not been achieved. Therefore, an option from the NDC scenario results in a diesel power plant, biomass power plant, and solar power plant configuration with an average electricity generation cost of IDR3,104.64/kWh. It indicates that fulfilling environmental aspects to meet electrical energy needs still requires high costs for now. Further research by adding network constraints can be done to plan network requirements.

CONFLICT OF INTEREST

The authors declare that the "Tanah Merah Electricity System Development Considering New Renewable Energy and CO_2 Emissions" article is free from conflict of interest.

AUTHOR CONTRIBUTION

Conceptualization, Amrisal Kamal Fajri, Sarjiya, and Lesnanto Multa Putranto; methodology, Amrisal Kamal Fajri, Sarjiya, and Lesnanto Multa Putranto; software, Amrisal Kamal Fajri and Adlan Bagus Pradana; writing—original draft preparation, Amrisal Kamal Fajri; writing— review and editing, Sarjiya, Fransisco Danang Wijaya and Lesnanto Multa Putranto.

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