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Photovoltaic Penetration with MILP Method and Technical Minimum Loading Consideration

Alfi Bahar[1], Muhammad Yasirroni[2], Sarjiya[3], M. Isnaeni Bambang Setyonegoro[4]

[1,2] Department of Electrical and Information Engineering, Faculty of Engineering Universitas Gadjah Mada, Jl. Grafika no. 2 Bulaksumur, Yogyakarta 55281 (tel.: 0274-552305; fax: 0274-552305; email: [1]alfibahar@mail.ugm.ac.id, [2]muhammad.yasirroni@mail.ugm.ac.id, [3]sarjiya@ugm.ac.id, [4]isnaeni@ugm.ac.id)

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Corresponding Author: Alfi Bahar

ABSTRACT — Technological development and the reduction of installation costs have caused a rapid growth of solar power plants in Indonesia. The National Electricity Company (Perusahaan Listrik Negara, PLN) strives to achieve the energy mix of renewable energy to 23% by 2025. Solar power plants are unique in that they only supply their power during the daytime. It makes solar power plants connected to the power system change the load profile of the Java-Bali system. In this study, the penetration of solar power plants changed the scheduling of the Java-Bali system because the penetration was installed to the technical minimum loading of existing power plants. When penetration is too big, thermal generator scheduling failure is possible. Unit commitment and economic dispatch with mixed-integer linear programming (MILP) method using CPLEX and Python were carried out to calculate the fuel and generation costs per kWh before and after the penetration. MILP was used to solve the cost fuel equation, namely an integer and nonlinear mix equations, that are challenging to be solved using standar nonlinear programming methods. Due to the use of the MILP-UC, all objective function equations and restraint functions must be linear functions. The tests were conducted for three years, from 2023 to 2025. Simulation results on the Java-Bali system show that the capacity of solar power plants penetrating the Java-Bali system against the peak load will be 52%, 52%, and 50% in 2023, 2024, and 2025, respectively. Meanwhile, penetration of solar power plants to technical minimum loading of existing power plants resulted in the fuel cost falling by 23% in 2023 and 22% in 2024 and 2025. Lastly, the cost of generation per kWh will be decreased by 8% in 2023 and will be as low as 7% in 2024 and 2025.

KEYWORDS — PV Penetration, MILP, Technical Minimum Loading, Unit Commitment, Economic Dispatch.

I. INTRODUCTION

Electricity growth in the Java-Bali system experiences an increase of 3.9% per year [1], [2]. Coal power plants currently dominate the Java-Bali electricity system, and by 2025 they will dominate the Java-Bali electricity system by 67% [3].

On the national scale, the National Electricity Company (Perusahaan Listrik Negara, PLN) is trying to achieve the energy mix of renewable energy to 23% by 2025. PLN also supports the portion of renewable energy up to more than 50%. In the Java-Bali regions, PLN is attempting to meet the solar energy mix of 6% by 2025 as a part of PLN's 2025 plan. Other targets include renewable new energy generation by 17.1%, gas plants by 15.3%, steam power plants by 67.4%, and fuel by 0.2%. By 2030, PLN targets renewable new energy generation by 16.1% and gas generation by 17.1%. On the other hand, the percentage of coal power plants decreased by 0.8% to only 66.6%, and fuel by 0.2% [4]. The addition of solar power plants has decreased in price due to technological and investment development, resulting in remarkable installation growth [5]-[8]. Solar power plants are an effort to accelerate the construction of new renewable energy power plants [9] as the Indonesian government plans to reduce emissions production by 29% by 2030 [10]. PLN is currently striving to achieve carbon neutrality by 2060, implemented in the 2021-2030 National Electricity Supply Business Plan (Rencana Usaha Penyediaan Tenaga Listrik, RUPTL). PLN will utilize various renewable energy sources from water, biofuels, geothermal (including small-scale/modular), sunlight, wind, biomass, and waste as well as support Renewable Energy Based on Industrial Development (REBID) programs.

PLN also continues to maintain the amount of the renewable energy mix so that it exceeds 23% after 2025 [11] and 24% by the end of 2030. The number of coal power plants is expected to decrease in 2026. Meanwhile, diesel power plants are expected to remain in minimal condition, even after 2025, and only for peak demand supply and remote areas.

In the penetration of solar power plants in existing plants, PLN requires when solar power plants start operating. Other plants must reduce their production and stay within the trip limit (technical minimum loading). Solar power plants will experience a decrease in production in the afternoon, so there will be an increased load. Existing power plants must meet power requirements quickly, so that they will need significant peaking capabilities.

The load profile will change due to the penetrations of solar power plants. The solar power plants will produce a negative load, and the system demand reduced by negative load results in a net load [12], [13]. Greater penetration of solar power plants will cause a lower demand during the day [14], [15]. Unit commitment and economic dispatches indicate the status of power plants that are online and offline each hour. The objective of unit commitment and economic dispatches is to minimize the operational costs of the power plant. However, due to its complex mix-integer nonlinear formulation, unit commitment is a difficult problem.

On the other hand, many different studies have been done to determine solar power plant penetration into the system. Previous works have studied power quality improvement from PV penetration [16], [17]. Other previous works have studied PV penetration for a specific goal, such as electric vehicle charge [18], [19].

A previous study on the actual case of PV penetration in multiple countries and cities showed that in Texas, USA, the output voltage could drop dramatically when the converter capacity was exhausted [20]. In Malta, the Monte Carlo simulation showed no issue until 40% of PV penetration [21].

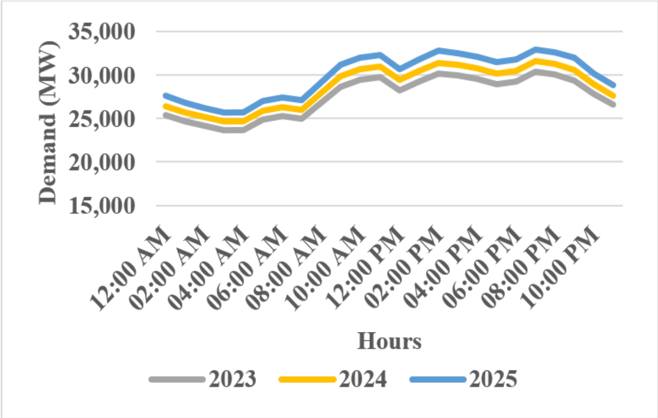

Figure 1. Java-Bali load profile 2023-2025.

In Jordan, with a growth rate of 7% of the electrical energy demand and using DIgSILENT, the maximum PV penetration was 26.5% in 2020 [22]. In Vietnam, 35MW of PV penetration showed a positive side to maintaining the existing powerplant's frequency and voltage stability [23]. In Cyprus, a combination of 25 kWp PV and 50Kwh batteries was installed to make a community storage system [24]. Another study showed that using MIQP, the limit of PV penetration could reach 68% of demand before the load ramping was higher than the maximum ramping capability. The generator cost also decreased by 40% due to PV installation [25].

This study used the MILP method because previous studies have shown there are numerous sorts of optimization methods to solve unit commitment issues, genetic algorithms (GA); Lagrangian relaxation (LR); evolutionary programming (EP); hybrid of LR and GA (LRGA); enhanced adaptive Lagrangian relaxation (ELR); and priority list (PL). MILP has the most excellent efficiency in computing in terms of computing speed. In addition, the most negligible operational costs are also generated by the MILP method [26]. Finally, solar power plant penetration can reduce the fuel cost of the existing power plants [27], [28].

This study aims to find the penetration limits of a solar power plant based on technical minimum loading (TML). At the same time, scheduling generators must stay within system operational and generator physical constraints.

II. MATERIAL

A. POWER PLANT CONDITION IN JAVA-BALI

The Java-Bali system consists of 244 power plants, including coal, geothermal, gas, steam gas, hydroelectric power plants, and a small part of diesel power plants. Coal power plants still dominate Java-Bali as the power plant with the largest capacity. The PV specification commonly used as a solar power plant in Indonesia is 230 WP - 500 WP. Characteristic data minimum power or TML (Pmin), maximum power (Pmax), ramp-up (RU), ramp-down (RD), minimum uptime (MUT), and minimum downtime (MDT) from the Java-Bali power plant that used in this paper are the restraint in calculating and optimizing the unit commitment and economic dispatch.

B. THE 2023-2025 JAVA-BALI LOAD

The operation of the Java-Bali electric power system produced 187,726 GWh of energy in December 2020. Meanwhile, Java-Bali experienced the highest peak load of 27,927 MW in 2020. Java-Bali is expected to experience electricity growth of 4.02% in 2021-2025 and will experience a growth of 3.98% in 2030 [1].

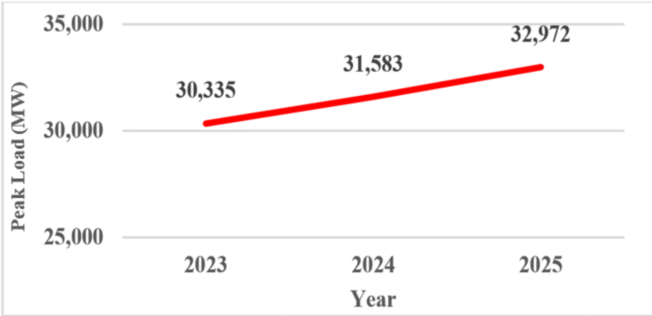

Figure 2. Increased peak load in 2023–2025.

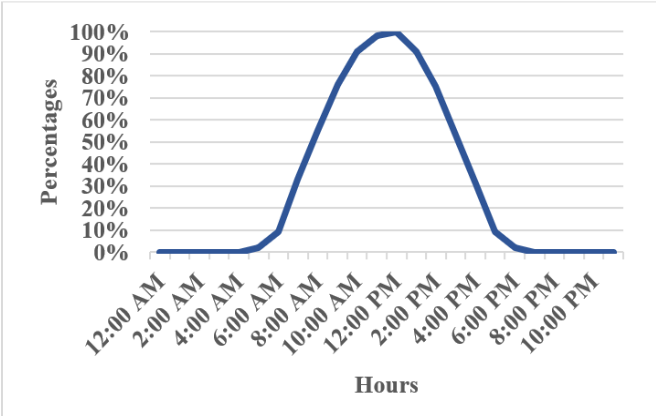

Figure 3. Solar irradiation profile.

The Java-Bali system load characteristics include peak load occurring at 7:00 PM and lowest load occurring at 04:00 AM. This study's Java Bali load profile data were the highest peak load data in 3 years, from 2023 to 2025, with a load duration of one hour. Java-Bali load profile can be seen in Figure 1, while Java-Bali increased load can be seen in Figure 2.

This study used the highest peak load profile each year, from which the highest peak load depreciated into an hourly load based on the daily load profile curve. The hourly load profile will be the reference of this study as solar power plants penetrate the load.

C. SOLAR POWER PLANTS PENETRATION

Solar power plant penetration used in this study was a profile PV typical system. Profile PV generates power from 06:00 AM to 6:00 PM and reaches its peak at 12:00 PM [29]. PV penetration to the system can be seen in Figure 3.

III. METHODOLOGY

A. SYSTEM DESIGN

This study began with a literature review to discover previous studies on solar power plant penetration in existing Java-Bali power plants. This result was used as a reference used to validate this research. Literature studies were also used to determine the theoretical basis to support this research.

Furthermore, the formulation of existing problems was carried out and then caused into a mathematical model. After that, source code unit commitment and economic dispatch were created and run with Python software. This stage started from creating MILP to determine the optimal fuel cost which later could be processed by the Phyton program. In this study, the MILP method used CPLEX and Python to obtain an optimal solution for unit commitment and economic dispatch.

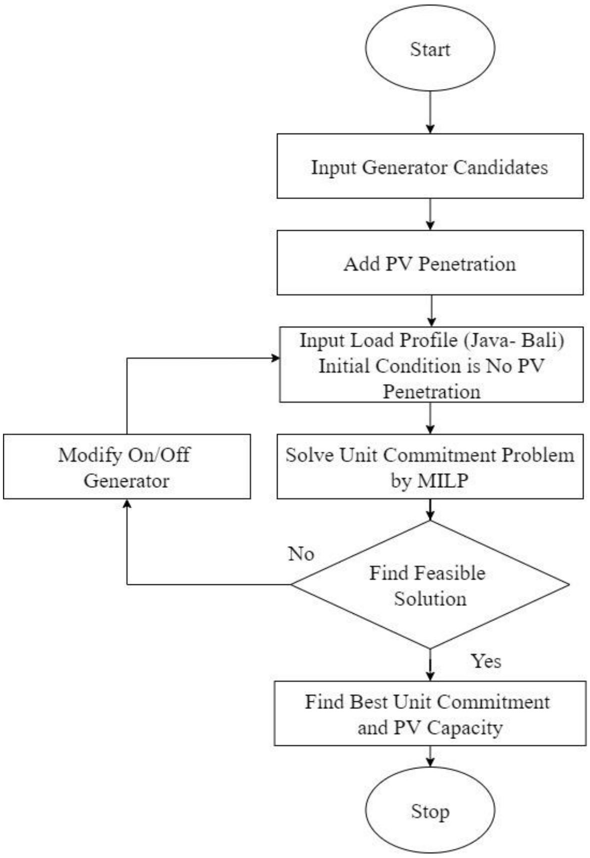

Figure 4. Flowchart penetration of solar power plants.

Unit commitment and economic dispatch were first carried out without solar power plant penetration. The results of this commitment and economic dispatch unit were used as a reference for comparison data before solar and after solar power plant penetrations.

The first thing in the penetration of solar power plants was determining the amount of TML of the entire Java-Bali system baseload power plant. The amount of TML was used as a reference for how much penetration of solar power plants against the peak load in this study.

After the amount of TML from the baseload power plant and solar power generation capacity were known, unit commitment and economic dispatch were carried out on the existing plant to find out how much different from the power generated, changes in power due to the penetration of solar power plants, and the cost of a generation before and after penetration of solar power plants.

Then, conducting unit commitment and economic dispatch at the plant after the penetration of the solar power plant is checked against the constraints of existing restraints, both in terms of system restraints and the power control side of the plant, especially in coal power plants, because the coal power plants have many restraints such as relatively slow ramping and MUT/MDT which is longer than other plants.

Suppose there was a power plant constraint violation, and no feasible solution was found; in that case, the simulation must stop, and the generator must conduct online/offline modifications. Until there is no power plant constraint violation (MUT/MDT, ramp-up ramp-down, power balance, and generation limit) and a feasible solution is found. Finally, after a feasible solution was found, the maximum PV penetration was documented. The flowchart of this study can be seen in Figure 4.

B. OBJECTIVE FUNCTION

The objective function of economic dispatch optimization can be seen as a function of fuel cost from the generator unit.

$$Minimize\ \sum_{t=1}^{T}\sum_{i=1}^{I}\left(\left(f\left(P_{i,t}\right)U_{i,t}\right)+SU_{i,t}+SD_{i,t}\right). \quad (1)$$

$P_{i,t}$ denotes the generation of unit i at time t in MW. $U_{i,t}$ denotes the status of unit i at time t. U will be 1 if the generator is on and will be 0 if the generator is off. t is an index showing the time, stated in hours, from 1 to the specified time interval and i is an index showing the number of thermal generator units. $f\left(P_{i,t}\right)$ is the fuel cost of unit i (Rp/h), which is a function of the generator power output function shown in (2).

$$f(P_{i,t}) = a_i(P_{i,t})^2 + b_i(P_{i,t}) + c_i \quad (2)$$

where a_i, b_i, and c_i represent the fuel cost coefficient of unit i.

$SU_{i,t}$ and $SD_{i,t}$ express the cost of starting up and shutting down the generator i at time t. When status of $U_{i,t}$ is “1” and $U_{i,t-1}$ is “0”, $SU_{i,t}$ value is calculated with (3). If the status of $U_{i,t}$ is “0” and $U_{i,t-1}$ is “1”, then $SD_{i,t}$ value is calculated using (4).

$$SU_{i,t} = C_{start}\left(U_{i,t} - U_{i,t-1}\right) \quad (3)$$

$$SD_{i,t} = C_{down}\left(U_{i,t-1} - U_{i,t}\right). \quad (4)$$

The cost fuel equation is an integer and nonlinear mix equation that is difficult to solve with standard nonlinear programming methods. Then, the cost fuel equation must be changed to MILP - unit commitment. Since it uses the MILP-unit commitment method, all objective function equations and restraint functions must be linear functions. Therefore, the cost fuel equation must first be projected into a linear function using the piecewise method.

C. SPINNING RESERVE

Spinning reserve is the amount of generating power available from all units synchronized with the system minus the load supplied at that time, just in case there is a problem with other plants.

$$\sum_{i=1}^{I} Pmaks_i\, U_{i,t} > D_t + SR_t \quad (5)$$

here, $Pmaks_i$ is the maximum power limit of generator. D_t is the load demand at time t. SR_t is the reserved power provided at time t.

D. POWER BALANCE CONSTRAINT

The total active power generated each hour must meet the demand of load at that hour.

$$\sum_{i=1}^{I} P_{i,t}\, U_{i,t} = D_t \quad (6)$$

where, $P_{i,t}$ is the power of generator. D_t is the load demand at time t.

E. GENERATION LIMIT

The active power generated by a generator unit must be within the minimum active power limit and the maximum active power limit generated by a generator unit.

$$Pmin_i \le P_{i,t} \le Pmaks_i \quad (7)$$

here, $Pmin_i$ is minimum power limit of unit i. $P_{i,t}$ is the power output of unit i at time t. $Pmaks_i$ is the maximum output of unit i.

F. MINIMUM UP-TIME AND MINIMUM DOWN-TIME

The minimum up-time is a generating unit that must be online or “on” for a certain time after the startup unit. On the contrary, the minimum downtime is a condition where the generator must be “offline” for a certain time before the generator can turn on.

$$T_{on\,i} \geq MUT_i \tag{8}$$

$$T_{off\,i} \geq MDT_i \tag{9}$$

where, T_{on} is the duration when unit i is “on”. T_{off} is the duration when unit i is “off”. MUT_i is the minimum uptime of unit i, and MDT_i is the minimum downtime of unit i.

G. RAMP-UP AND RAMP-DOWN

Ramp-up and ramp-down are conditions that a power plant can increase and decrease power output in MW units during a certain interval of time.

$$P_{i,t} - P_{i,t-1} \leq RU_i \tag{10}$$

$$P_{i,t-1} - P_{i,t} \leq RD_i \tag{11}$$

Here, $P_{i,t}$ represents the power of generator i at time t. $P_{i,t-1}$ denotes the power of generator i at time $t-1$. RU_i denotes the ramp-up limit of generator i. RD_i is the ramp-down unit of generator i.

H. PV Power

The maximum power released by PV depends on the condition of the sun. This condition makes the PV power limited from the PV capacity installed.

$$P_s \leq P_{s\,max} \tag{12}$$

where, P_s is the PV generator power output. $P_{s\,max}$ is the maximum capacity of a PV.

IV. ANALYSIS

A. UNIT COMMITMENT OF JAVA-BALI BEFORE SOLAR POWER PLANT PENETRATION

The first stage of this study was to conduct a unit commitment and economic dispatch on the Java-Bali system without penetration from the solar power plant. This stage used three load profiles that were the highest peak of load profiles from 2023 to 2025.

The Java-Bali load profile showed that the peak load occurred at 07:00 PM, and the lowest load occurred at 04:00 AM. The increase in load profile occurred from 05:00 AM to 12:00 PM. On the other hand, the temporary decrease in load occurred within one hour from 12:00 PM to 01:00 PM. The load profile increased in load again from 01:00 PM to 03:00 PM, then gradually dropped until 05:00 PM. The load profile to the peak load started to occur after 05:00 PM, and the peak load occurred at 07:00 PM. Then, the load gradually declined until it returned to the lowest load at 04:00 AM.

B. CHANGES IN THE LOAD PROFILE OF THE JAVA-BALI SYSTEM DUE TO SOLAR POWER PLANT PENETRATION OF THE TML LIMITS

Penetration of solar power plants to the limit of the TML Java-Bali power plant is done to maximize the capacity of solar power plants that can be installed to reduce the dependence on thermal plants (existing). The greater the capacity of solar power plants installed, the greater the generation capacity of thermal power plants that can turn off. With the smaller thermal generating capacity (running on TML limit), existing Java-Bali power plant fuel costs and generation costs per kWh are expected to be reduced.

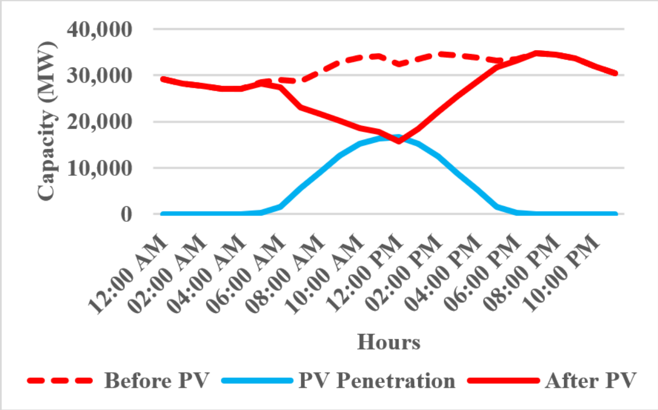

Figure 5. Penetration of PV in Java-Bali system.

TABLE I
PENETRATION OF SOLAR POWER PLANT

Year	2023	2024	2025
Demand (MW)	30,335	31,583	32,972
TML Total (MW)	12,483	12,873	14,063
Max PV Installed (MW)	15,772	16,544	16,648
Percentages	52%	52%	50%

The total TML of Java-Bali solar plants was taken from the baseload power plant specification data. Meanwhile, the highest solar power plant penetration occurred at 12:00 PM and penetrated the demand of Java-Bali. The total TML of baseload power plants was used as reference data to determine the amount of solar power plant penetration, expressed by a percentage.

The entry of solar power plant penetration changed the load profile of the Java-Bali system. Incoming solar power plants are categorized as negative loads. A negative load can cause system demand to be reduced. The change in demand began at 05:00 AM when the solar power plant entered the system. The demand for existing plants could gradually decrease because the penetration of solar power plants began to increase by noon.

During the day, at 12:00 PM, it became the system’s highest penetration peak of solar power plants. The highest solar power plant penetration caused the demand for existing power plants to be at the lowest point (reaching TML of existing baseload power plants) in one day.

After passing 12:00 PM, the intensity of sunlight begins to decrease, causing the penetration of solar power plants to drop. The decrease in penetration of solar power plants caused the existing generation demand graph began to move up. The increase in generating demand continued until the solar power plant was released from the site at sunset. The exit of solar power plants from the system bore demand from existing power plants. The increase in load continued from sunset (the release of solar power plant penetration from the system) until 07:00 PM, when there was a peak load on the system. The amount of penetration of solar power plants can be seen in Table I and Figure 5.

C. UNIT COMMITMENT OF JAVA-BALI AFTER SOLAR POWER PLANT PENETRATION

Solar power plants in large capacities that enter the Java-Bali system will make the unit commitment and economic dispatch change. Follower power plants operating in the

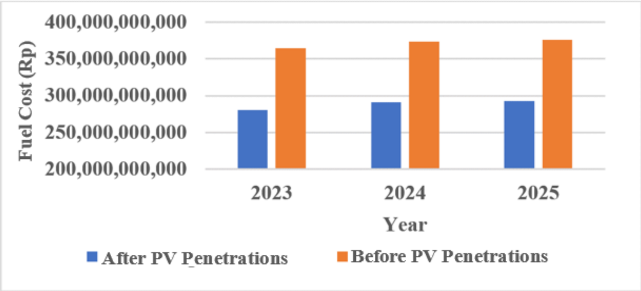

Figure 6. Fuel cost Java-Bali power plants.

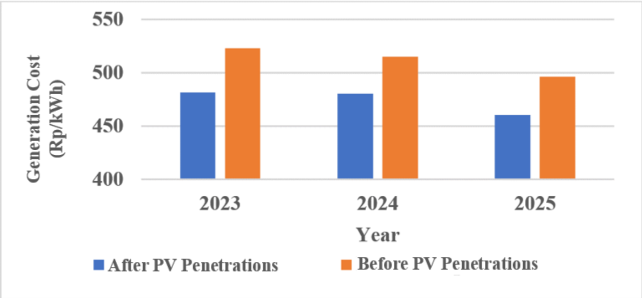

Figure 7. Generation costs per kWh.

morning began to be turned off due to the penetration of solar power plants. By noon, more follower power plants were turned off, and the baseload power plants also reduced the amount of production until it reached TML. At 12:00 PM, the solar power plant reached its peak. When the solar power plant was in peak condition, all follower generation demands were replaced by a solar power plant, resulting in the entire follower power plant going offline. Penetration of solar power plants up to the limit of TML baseload plants also caused the baseload plant to turn on its production only to the limit of TML.

In the afternoon, the production of solar power plants decreased, causing electricity production in solar power plants to decline. The baseload power plant started to increase its production beyond the TML limit, and the follower power plant began to be turned on to help the baseload power plant. The solar power plant was offline at sunset. With the solar power plant released from the system, the entire existing plant operated, as usual, to meet the system's demand and continue to increase its production to meet the peak load demand at 07:00 PM.

Simulation results show that in 2023, fuel cost for existing power plants will be 364.2 billion rupiahs, and the generation cost will be 523 rupiahs. After the PV penetration, the fuel cost is reduced by 23% to 280.4 billion rupiahs, and the generation cost is reduced by 8% to 481 rupiahs/kWh. In 2024, the fuel cost for existing power plants will be 373.5 billion rupiahs, and the generation cost will be 515 rupiahs. After the PV penetration, the fuel cost was reduced by 22% to 290.8 billion rupiahs, and the generation cost was reduced by 8% to 480 rupiahs/kWh. In 2025, fuel cost for existing power plants will be 375.7 billion rupiahs, and the generation cost will be 496 rupiahs. After the PV penetration, the fuel cost is reduced by 22% to 293.1 billion rupiahs, and the generation cost is reduced by 7% to 460 rupiahs/kWh. The decline of cost fuel and generation costs per kWh of Java-Bali can be seen in from Figure 6 and Figure 7.

D. SPINNING RESERVE CONSTRAIN

This study used a 5% reserve of the load. System reserve and max gen can be seen in Table II. The peak load and reserves

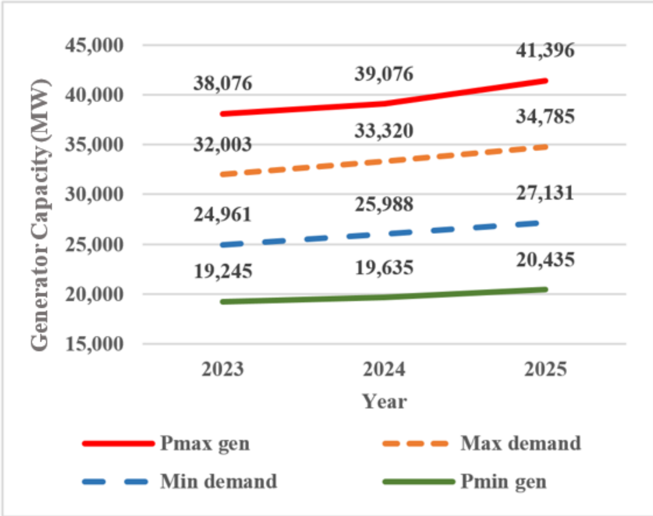

Figure 8. Java-Bali generation limit.

TABLE II
SPINNING RESERVE

Year	2023	2024	2025
Demand (MW)	30,335	31,583	32,972
Demand + Reserve (MW)	32,003	33,320	34,785
Max Gen (MW)	38,076	39,076	41,396

summary are still below the maximum capacity of all power plants in three years.

E. POWER BALANCE CONSTRAINT

The total active power generated each hour must meet the load demand at that hour. The peak load occurred at 07:00 PM. All generating capacity of the peak load must remain below the maximum capacity of the power plants. Based on Figure 5 and Figure 8, the solar power plants do not affect the power balance of the Java-Bali system.

F. GENERATION LIMIT

The generator has an upper and lower limit of operation. If all generators are turned on, the total load demand must be below the generator's total capacity. The maximum load occurred at 07:00 PM, and the maximum load remained below the maximum output capacity of all generators. Meanwhile, the minimum load occurred at 04:00 AM; the minimum load remained above the minimum output capacity of all generators.

In 2023, the maximum load will be 32,003 MW, which is still below the total output capacity of all generators of 38.076 MW. At the same time, the minimum load will be 24,961 MW, that is still above the minimum output capacity of all generators of 19,245 MW. In 2024, the maximum load will be 33,320 MW, which is still below the total output capacity of all generators of 39,076 MW. Meanwhile, the minimum load will be 25,988 MW, that still above the minimum output capacity of all generators of 19,635 MW. In 2025, the maximum load will be 34,785 MW, that still below the total output capacity of all generators of 41,396 MW. The minimum load will be 27,131 MW, which remains greater than the minimum output capacity of all generators of 20,435 MW. The generation limit of Java-Bali can be seen in Figure 8.

V. CONCLUSION

This study solved the unit commitment and economic dispatches using the MILP method. Unit commitment solutions must meet load requirements and simultaneously respect generator physical and system operational constraints. Using the TML approach, the percentage of solar power plant capacity that penetrated the Java-Bali system against peak load is an average of 50% over three years. This study has showed that the possibility of maximum PV capacity that can penetrate Java-Bali is greater than 6% that PLN has planned.

The effect of solar power plant penetration on the load profile of the Java-Bali system is that the solar power plants can suppress the operation of baseload power plants to the limit of TML. The solar power plant will turn off follower power plants because solar power plants have supplied the demand. The baseload power plant will generate power only as much as the TML limit. The greater the installed solar power generation capacity, the greater the negative load experienced by the Java-Bali system. In addition, a greater negative load will reduce the demand for existing Java-Bali power plants.

The penetration of solar power plants can reduce the fuel cost of existing power plants by 23% by 2023 and 22% by 2024 and 2025. Meanwhile, the cost of generating per-kWh of existing plants decreased due to the penetration of solar power plants by 8% in 2023, 7% in 2024, and 2025.

CONFLICT OF INTEREST

The authors of this paper, “Photovoltaic Penetration with MILP Method and Technical Minimum Loading Consideration” declare that this paper is free from conflicts of interest.

AUTHOR CONTRIBUTION

Conceptualization, Alfi Bahar, Muhammad Yasirroni, M. Isnaeni Bambang Setyonegoro, Sarjiya; methodology, Alfi Bahar, Muhammad Yasirroni, M. Isnaeni Bambang Setyonegoro, Sarjiya; software, Muhammad Yasirroni; writing—original draft preparation, Alfi Bahar; writing—review and editing, Muhammad Yasirroni, M. Isnaeni Bambang Setyonegoro, Sarjiya.

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