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Accelerating Renewable Energy Integration in Energy Planning Considering the PV Techno-Economics and Hourly Profile, Case Study: Indonesian Power Sector

Ahmad Adhiim Muthahhari[1]*, Candra Febri Nugraha[1], Naufal Hilmi Fauzan[2], Lukman Subekti[1], Rizki Firmansyah Setya Budi[3]

[1]Electrical Engineering Technology, Universitas Gadjah Mada, Yogyakarta, Indonesia, [2]Department of Electrical and Information Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia. [3]Research Center for Nuclear Reactor Technology, National Research and Innovation Agency Banten, Indonesia. *Email: ahmad.adhiim.m@ugm.ac.id

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ABSTRACT

In planning for the generation capacity expansion planning, it is crucial to consider the economics of scale and the availability of primary energy sources. Solar power generation or PV PP is a plant that is very dependent on the availability of solar irradiance and land. To achieve Net Zero Emission by 2060, the Indonesian government aims to increase PV capacity to 4.68 GW. To support the accelerated integration of PV power plants into the electrical system and fulfill economic and sustainable aspects, the ideal capacity of PV power plants needs to be considered. This study involves optimization and comparison with various scenarios to determine the optimal combination for PV power plant planning. In the optimization process, Mixed Integer Linear Programming (MILP) is used, assuming a load of 100 MW and various PV profiles. Based on the optimization results, to meet a 100 MW load, 138 MW of PV power plants are required, with a configuration of 125 MW for large-scale PV PP, 10 MW for medium-scale PV PP, and 3 MW for rooftop PV PP. The total cost needed is 11,445 thousand dollars, with an levelized cost of electricity (LCOE) of 4.75 c$/kWh. This value is significantly lower compared to other scenarios. To supply for 24 h, PV PP can utilize BESS, with an LCOE reaching 7.79 c$/kWh when optimal capacity and generation are achieved. The recommendation for determining the capacity of PV PP is to use the large-scale capacity scheme, both for daytime supply systems and for the 24-h scheme.

Keywords: Photovoltaic Power Plant, Economic of Scale Photovoltaic Power Plant, Net Zero Emission, RE Integration, levelized cost of electricity, Battery energy storage systems
JEL Classifications: D24, K32, Q21, Q42, Q48

1. INTRODUCTION

The electricity demand needs continue to increase each year. The increment of demand needs is evident worldwide, including in Indonesia which has an average growth of 4.97–6.29% (PLN, 2021). In 2022, electricity demand in Indonesia reached 273.76 TWh with 41.8 GW peak load, this figure is expected to rise annually in line with population and economic growth (PLN, 2023).

The escalating growth in electricity demand needs to be addressed seriously, and one effective approach is through GEP (Muthahhari et al., 2019, 2020; Muttaqien, 2017). The GEP aims to meet the demand of electricity by considering various aspect and economic value (IRENA, 2017; Khan et al., 2014; Muthahhari et al., 2019, 2020; Pereira et al., 2017). However, the capacity planning for power generation that has been carried out, now face the issue of CO_2 emission and climate changes (IRENA, 2022). The rise in global temperatures and the threat of climate change require swift action, with various countries, including Indonesia, committing to achieving Net Zero Emission (NZE) by the year 2060. The NZE in 2060 can be achieved with the Indonesian government targets with 23% of renewable energy in 2025 and 31% in 2050 (DEN, 2020). Throughout this transitional process, the Indonesian government, acting through state-owned enterprises in the electricity sector, particularly PT PLN (Persero), has strategically planned power generation by prioritizing the utilization of renewable energy sources in (PLN, 2021).

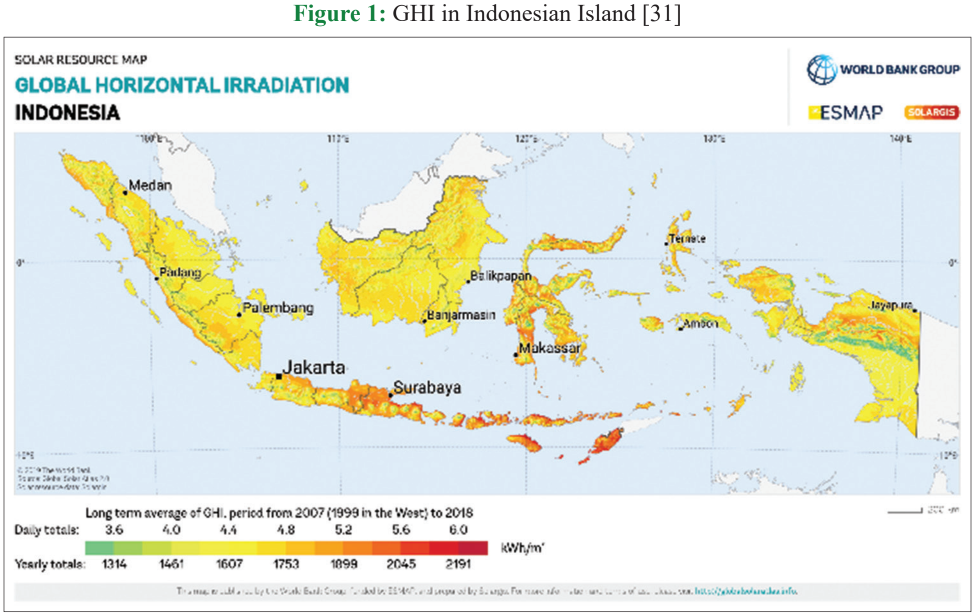
The environmental impact of CO_2 emission and the future availability of fossil fuel resources must be taken into account in generation capacity expansion planning. In order to uphold environmental sustainability and prepare for potential future dependencies on fossil fuel supplies, its need to considers the incorporation of renewable energy, including intermittent sources (Muttaqien, 2017; Pereira et al., 2017; Zhan et al., 2017). The focus of research and planning for generation expansion planning by considering renewable energy has been carried out in various countries, both baseload or variable renewable energy. For the example, in the USA (Nguyen and Felder, 2020), Ireland (Fitiwi et al., 2020), France (Seck et al., 2020), China (Chen et al., 2010; Khan et al., 2014; Shengyu et al., 2015), Brazil (Luz et al., 2018), Portugal (Pereira et al., 2017), Egypt (Rady et al., 2018), Pakistan (Shinwari, 2012), Oman (Malik and Kuba, 2015), South Africa (Wright et al., 2019), Bangladesh (Khan, 2019), Malaysia (Shirley and Kammen, 2015) and Indonesia (Budi, 2017; Muthahhari et al., 2019; Muttaqien, 2017; Putranto et al., 2023; Putrisia, 2017; Tumiran et al., 2020, 2021) have considered the environmentally friendly resource or renewable energy sources (RES) in their generation expansion planning model.

Given the current situation, there is a need for efforts to provide environmentally friendly and sustainable energy. By utilizing locally-based energy sources, such as solar energy hydro and biomass, it is expected that this can support the transition process towards cleaner and more sustainable energy (Pusat Kajian LKFT Universitas Gadjah Mada, 2023). However, the use of renewable energy sources has the potential to increase the LCOE of the system as in (Sarjiya et al., 2022).

Drawing on prior research on RES and considering Indonesia's archipelagic characteristic, there is a clear need for alternative solutions in electricity generation using local energy sources. Enhancing the utilization of local energy involves strategically placing power plants (PP) as close as possible to the energy source, and the distribution is tailored according to the source's location. In the utilization of RES, especially PV PP, the benefits of environmental factors must be accompanied by affordable and sustainable electricity prices. Currently, the cost of providing electrical energy in Indonesia varies widely, ranging from around 6 c$/kWh to 19 c$/kWh (Kementerian ESDM RI, 2021). Additionally, Indonesia also sets the LCOE for PV PP through Presidential Regulation No 112, with prices determined by the capacity of PV PP and the use of Battery Energy Storage Systems (BESS) technology (Peraturan Presiden (PERPRES) Nomor 112 Tahun 2022 Tentang Percepatan Pengembangan Energi Terbarukan Untuk Penyediaan Tenaga Listrik, 2022). However, based on this information, the government has not yet provided an optimal capacity alternative for power generation with an optimal LCOE.

Based on this condition, optimizing the planning of integrating the RES generation, such as photovoltaic (PV) PP, in the power system becomes imperative. Considering the uneven distribution of solar energy sources, as illustrated in Figure 1 (World Bank Group, 2023), and the centralized locations of demand loads at various points, this paper will focus on efforts to determine the optimal capacity of PV PP for integration into the electrical system. This is aimed at supporting government initiatives in establishing the optimal PV power plant capacity to realize the planned 4.68 GW PV power plants in (PLN, 2021). In the optimization process, this paper will consider factors such as the scale of generator capacity, generation profiles, and the availability of solar energy sources. The contribution of this paper is providing an insight into the optimal capacity scale schemes of PV PP in planning to enhance the integration of PV PP.

Figure 1: GHI in Indonesian Island [31]



2. DEVELOPING THE FRAMEWORK OF THE PROPOSED MODEL

Based on the background of the problem, an overview of this research can be seen in Figure 2. To develop the proposed framework, it is necessary to be based on the proposed novelty. This research focuses on providing information to support existing regulations, to provide planning, especially for the unclear capacity distribution of unallocated power plants. In addition, the recommendations provided are expected to serve as a basis for determining the ideal capacity of power plants to integrate into the electrical system to provide clean, sustainable, and affordable electricity generation. It is expected that the proposed model and the implementation of the case study can be used to analyse and assess current or future planning, as well as policy decisions.

In this research, it is also expected to support the SDGs in Indonesia by accelerating the integration of PV PP. An overview of the framework's desired outcome can be seen in Figure 3. In this model, there are two stages to obtain the ideal capacity for PV PP, namely, PV PP exclusively for daytime supply or PV PP operating 24 hours using BESS.

3. RESEARCH METHODS

This paper will conduct optimization to determine the PV PP capacity in efforts to accelerate the integration of renewable energy, particularly PV PP. The research flow is illustrated in Figure 2. This study will primarily focus on determining the capacity needed to meet a peak load of 100 MW during daylight hours. The optimization process will consider various aspects, including generator locations, the availability of energy sources, and generator capacity sizes. The system design is depicted in Figure 4.

Based on these assumed data (Ministry of Energy and Mineral Resources; Danish Energy Agency, 2021), a comparison will be made among scenarios: full optimization, optimization of only large-scale PV, medium-scale PV, or rooftop PV with specific locations for each candidate as depicted in Figure 5.

The optimization process will consider load profiles and solar profiles, as shown in Figure 6. The solar profile comprises three categories with high, medium, and low irradiance values, each with capacity factors of 25.8%, 16.2%, and 11%, respectively. For the

Figure 2: Research overview

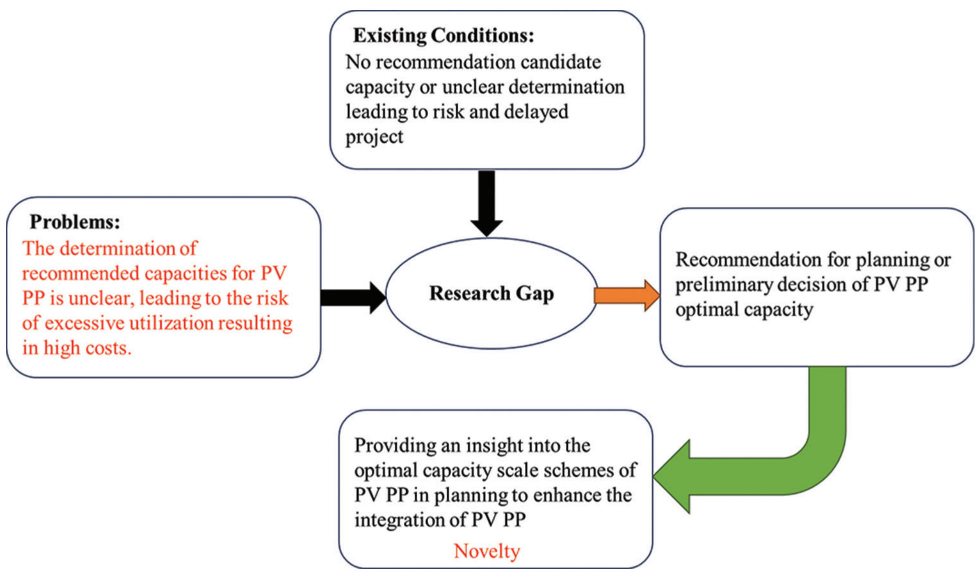


Figure 3: The framework of proposed novelty

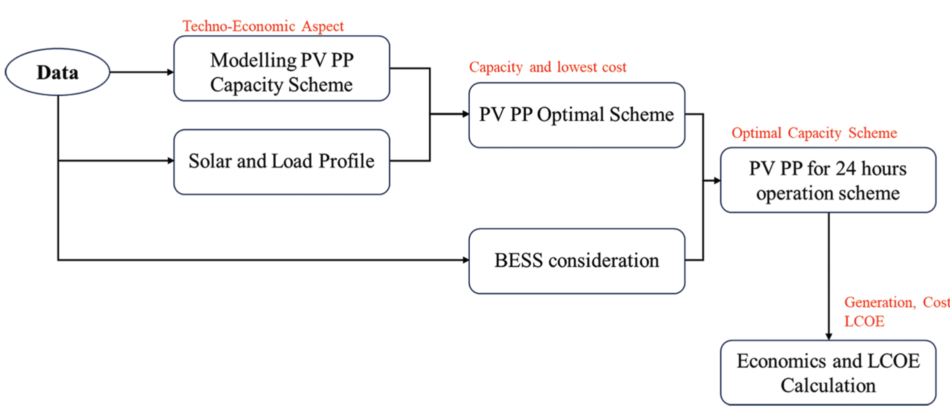


Figure 4: Research flowchart

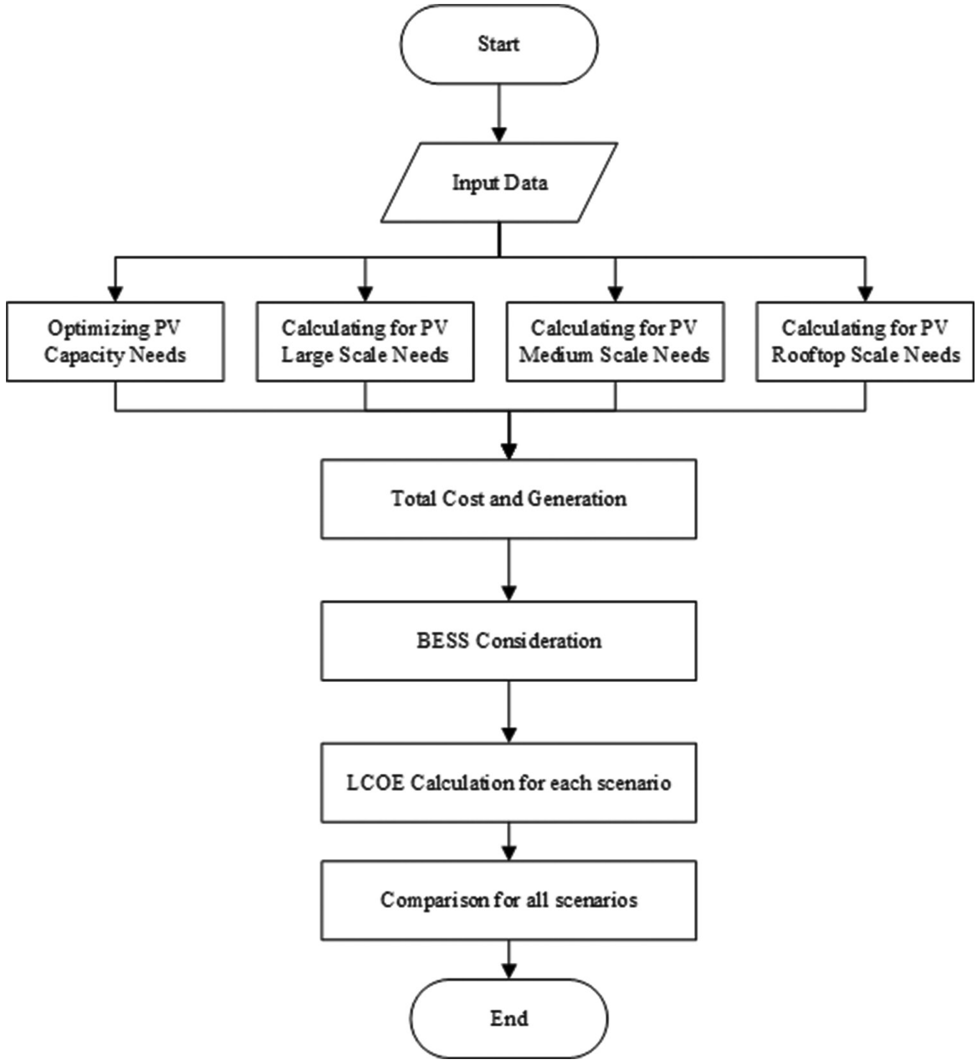
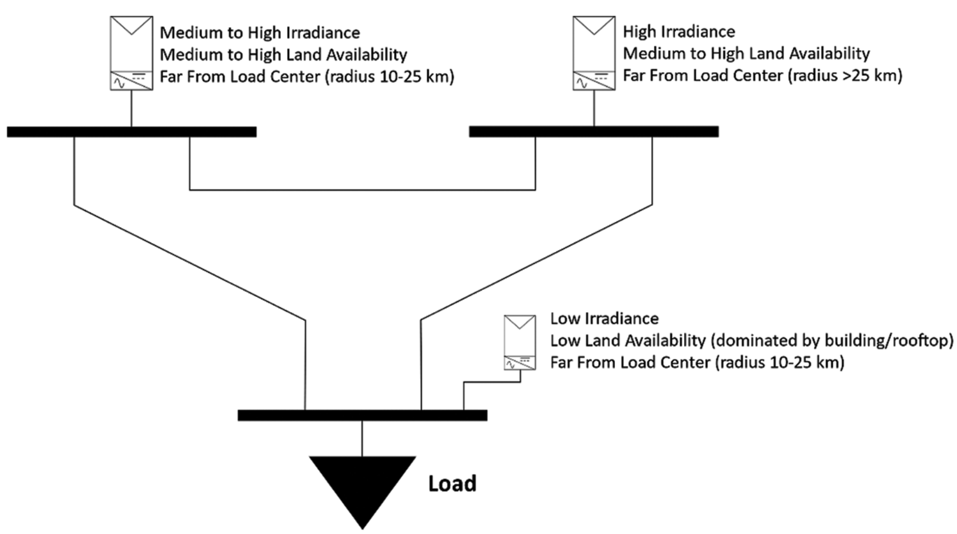


Figure 5: The system design of this research



24-h load simulation, it is assumed that the peak load of 100 MW occurs in the afternoon or evening, with the hourly generation profile as in Figure 7.

3.1. Modeling Capacity Expansion Planning

The objective of generation capacity expansion planning is to determine the optimal installed power plants, including

Figure 6: The system solar and load profile

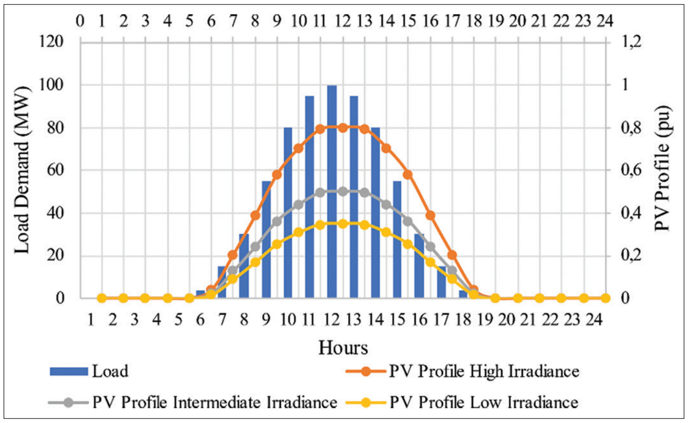
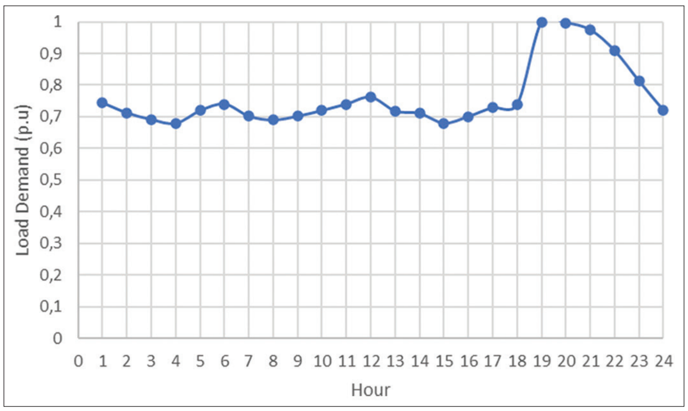


Figure 7: The 24-h load profile



the type of generator, capacity, and construction timeline, to minimize the discounted generation costs while adhering to certain constraints (Muthahhari et al., 2019, 2020; Tumiran et al., 2020, 2022). The objective function of this paper is presented in equation (1).

$$minCost = C_{Fix}^{total} + C_{VO\&M}^{total} + C_{Fuel}^{total} \tag{1}$$

The calculation of GEP is based on the total fixed cost (2), variable operating and maintenance cost in (6), and fuel cost (7). The calculation of total fixed cost considers the total annualized investment and fixed operating and maintenance costs, as in equation (3)-(5).

$$C_{Fix}^{total} = C_{Annual}^{total} + C_{FO\&M}^{total} \tag{2}$$

$$C_{Annual}^{total} = C_{Inv}^{total} \times \frac{(1-Tax)\times\dfrac{NAF}{EcoLife}}{RAF} \tag{3}$$

$$C_{Inv}^{total} = \sum_y \sum_g DF_y \times \left(C_{inv}^g \times 1000 \times P_{max}^g NB_g^y\right) \tag{4}$$

$$C_{FO\&M}^{total} = \sum_y \sum_g DF_y \times [C_{FO\&M}^g \times P_{max}^g (N_g + \sum_{i\le y} NB_g^i)] \tag{5}$$

$$C_{VO\&M}^{total} = \sum_t \sum_g DF_{t\in y} \times L_t \times (C_{VO\&M}^g \times G_g^t) \tag{6}$$

$$C_{Fuel}^{total} = \sum_t \sum_g DF_{t\in y} \times L_t \times (Heat\,Rate \times C_{fuel}^g \times G_g^t) \tag{7}$$

$$DF = \frac{1}{(1+D)^y} \tag{8}$$

$$NAF = \frac{1-(1+WACC+Infation\,rate)^{-Ecolife}}{WACC+Infation\,rate} \tag{9}$$

$$RAF = \frac{1-(1+WACC)^{-Ecolife}}{WACC} \tag{10}$$

With,

C_{Fix}^{total} : Total fixed cost ($/kW/year)
C_{Annual}^{total} : Total annualized build cost ($/kW/yr)
C_{Inv}^{total} : Total build cost ($/kW)
$C_{FO\&M}^{total}$: Total fixed O&M cost ($/kW/yr)
$C_{VO\&M}^{total}$: Total var O&M cost ($/MWh/yr)
C_{Fuel}^{total} : Total fuel cost ($/MWh)
DF_y: Discount factor
D: Discounted Rate (%)
P_{max}^g : Generator max capacity (MW)
NB_g^y : Number of generator
G_g^t : Generation of generator g in t period (MWh)
C_{inv}^g : Build cost of generator g ($/kW)
$C_{FO\&M}^g$: FO&M cost generator g ($/kW/yr)
$C_{VO\&M}^g$: VO&M cost generator g ($/MWh/yr)
C_{fuel}^g : Fuel cost generator g ($/MWh/yr)

During the optimization process, several constraints are taken into consideration. The power balance constraint ensures that the total generation during a specific period must meet or exceed the load demand at that time, as depicted in equation (11). Additionally, the total generation is limited by the available installed generating capacity, as stated in equation (12). The number of new power plants constructed cannot surpass the maximum potential, as outlined in equation (13). However, the total installed capacity must be adequate to meet the yearly peak load plus a reserve margin specified in equation (14).

$$\sum_{g=1}^{NG} G_g^t \ge D^t, \forall t \tag{11}$$

$$G_g^t \le P_{maxg}\left(N_g + \sum_{i\le y, y=1}^{NY} NB_g^i\right), \forall g, t \tag{12}$$

$$\sum_{i\le y, y=1}^{NY} NB_g^i \le NB_{maxg}^{\ i}, \forall g \tag{13}$$

$$\sum_{g=1}^{NG} P_{max\,g}\left(N_g + \sum_{i\leq y, y=1}^{NY} NB_g^i\right) \geq PL^y\left(1+RM\right), \forall y \quad (14)$$

With,
D^t: Demand in t period (MWh)
$NB_{max\,g}^{i}$: Max Number of generator g that can be built
PL^y: Peak load (MW)
RM: Reserve margin (%)

3.2. Energy Production of PV PP Systems

The GHI value determines the optimal PV capacity and energy production. The optimal capacity is estimated using the minimize cost objective while meeting the demand need as in 2.1. The calculation for PV PP energy output considers the profile of GHI profile as in (15). equation (15). $GHI_{profile}$ represents the hourly GHI (kWyr/m^2) in per unit from the historical data.

$$PV\ PP\ Energy\ Production = GHI_{profile} \times PV\ Cap \quad (15)$$

3.3. Financial-economic and LCOE Aspect

The financial-economic parameters are used to determine the PV investment's attractiveness. In this research, the value of the weighted average cost of capital (WACC) is obtained. The WACC is calculated using equation (16). *Ep* refers to the equity portion, *CoE* refers to the cost of equity (%), *Dp* refers to the debt portion, and *CoD* refers to the cost of debt (%) (Budi et al., 2022).

$$WACC = \left[Ep \times CoE\right] + \left[Dp \times CoD \times (1 - tax)\right] \quad (16)$$

The WACC is used as a discount rate when calculating the LCOE of PV PP systems. The LCOE calculation is shown in equation (17). $Investment_t$ refers to the investment cost in the tth year. $O\&M_t$ refers to the summation of fixed and variable O&M costs in the tth year. $Fuel_t$ refers to the fuel cost in the tth year. *r* refers to the WACC.

$$COE = \frac{\sum_{t=0}^{n} \frac{Investment_t + O\&M_t + Fuel_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{Energy\ production_t}{(1+r)^t}} \quad (17)$$

3.4. Data Assumption

In conducting optimization, considerations will be given to the capacity scale and economic viability of PV PP candidates, as outlined in Table 1.

4. RESULTS AND DISCUSSION

Table 1: Techno-economic data [33]

PV PP candidate	Capacity (MW)	Techno-economic assumption			
		Invest Cost ($/kW)	Fix O&M ($/kW/year)	Fixed Cost ($/kW/year)	Var O&M ($/MWh)
Large-scale PV PP	25	560	14.4	80	-
Medium-scale PV PP	10	790	14.4	107	-
Rooftop PV PP	0.5	940	14.4	125	-
BESS	100/700 MWh	320	8.5	258	2.3

Table 2: Optimization capacity results

Scenario	Load (MW)	Installed Cap (MW)		
		Large-scale	Medium-scale	Rooftop
Fully optimization	100	125	10	3
Large-scale PV PP only		150	-	-
Medium-scale PV PP only		-	220	-
Rooftop PV PP only		-	-	300

Table 3: Economics calculation

Scenario	Gen (GWh)	Total Cost ($000)	LCOE (c$/kWh)
Fully optimization	240.9	11,445	4.75
Large-scale PV PP only		12,000	4.98
Medium-scale PV PP only		23,540	9.77
Rooftop PV PP only		37,500	15.57

Table 4: A 24-h scheme

Scenario	Capacity (MW)	Energy Cap (MWh)	Generation (GWh)	Charing (GWh)
Large-scale PV PP	350	-	665.3	-
Medium-scale PV PP	-	-	-	-
Rooftop PV PP	2.5	-	2.5	-
BESS	200	1400	381.3	381.3

Based on the research that has been conducted, various combinations of PV PP capacities and scheme have been identified. The optimization results and other scenarios are presented in Tables 2 and 3. From these findings, it is evident that the combination with the lowest cost is derived from the full optimization scenario. The full optimization scenario indicates that to meet the 100 MW daytime load, a capacity of 125 MW large-scale PV power plant, 10 MW medium-scale PV power plant, and 3 MW rooftop PV are required. This combination, as in Figure 8, represents the scenario with the lowest Levelized Cost of Electricity (LCOE) due to several factors. The first factor is that large-scale PV power plants have a lower investment cost compared to other schemes. The second factor assumes in this study that the construction of large-scale PV power plants is carried out in areas sufficiently distant from the load and with relatively high irradiance values.

The optimum combination results in a total cost of 11,445 thousand dollars and an LCOE of 4.75 cents$/kWh. These values represent the lowest among the three other scenarios. The most expensive scenario involves installing rooftop PV entirely to meet the 100 MW demand, requiring 300 MW of rooftop PV. This combination represents the scenario with the highest LCOE due to several factors. The first factor is that rooftop PV has a higher investment cost compared to large-scale PV power plants. The second factor is that rooftop PV power plants have lower irradiance values, assuming they are in urban areas and subject to various shading factors from the surrounding environment.

All the results of the PV PP capacity planning required to supply a peak daytime load of 100 MW; it was found that the results of all scenarios showed that a larger capacity was needed than the load that had to be supplied. This is attributed to several factors, such as the average capacity factor of PV PP ranging only from 11% to 25%, and the generation profile of PV PP is not reaching 1 pu. These two factors contribute to the need for larger capacities to fulfill the generation requirements. Hourly generation of fully optimization scenario can be seen in Figure 9.

After determining that the optimal capacity of PV PP to supply the daytime load of 100 MW is 138 MW, with a composition of 90.5% Large Scale PV PP, 7.3% Medium Scale PV PP, and 2.2% rooftop PV, the next step is to analyze the capacity required for PV PP to supply the system for 24 h. Based on the obtained results as in Table 4, to supply the system with a peak load of 100 MW, and the system operates 24 h with load variations as shown in Figure 7, the PV PP capacity increases drastically from 138 MW to 352.5 MW with the addition of 200 MW/1400 MWh BESS. This additional capacity is necessary to ensure a 24-h supply, as illustrated in Figure 10.

Based on the overall results that can be seen in Table 5, the generation cost from PV PP can be below 5 c$/kWh and below the LCOE price set in (Kementerian ESDM RI, 2021). However, it's important to note that this PV PP can only supply electricity during the daytime. In the search for optimal generation for 24 h, the LCOE of PV PP with BESS is higher than the optimal PV PP, with a value of 7.79c$/kWh. Nevertheless, this is cheaper compared to using a medium-scale or rooftop scheme.

Figure 8: Optimum system design

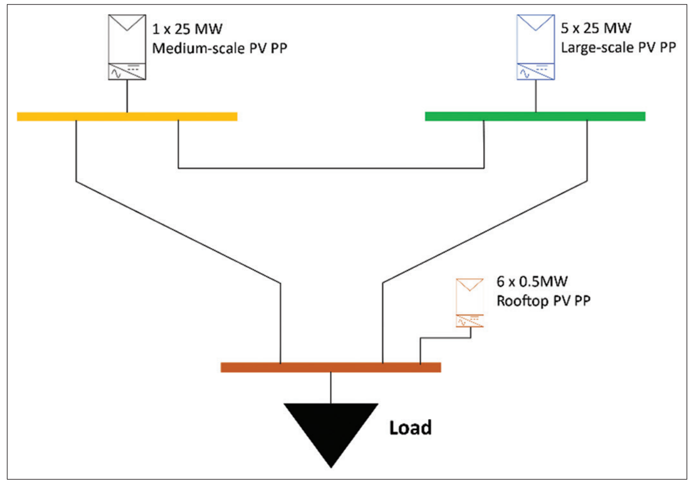


Figure 9: Hourly generation in simulation

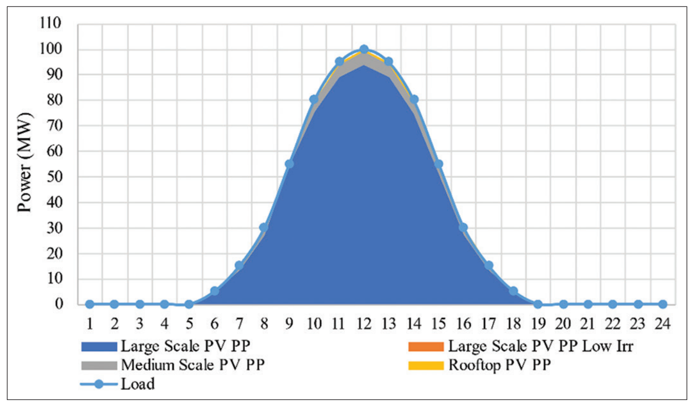


Figure 10: A 24-h generation scheme

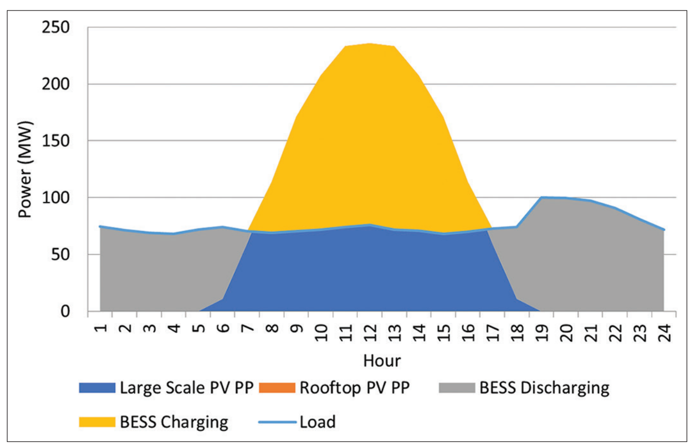


Table 5: LCOE comparation

Scenario	LCOE (c$/kWh)
Fully optimization (PV PP only)	4.75
Large-scale PV PP only	4.98
Medium-scale PV PP only	9.77
Rooftop PV PP only	15.57
PV PP+BESS	7.79

5. CONCLUSION

In planning for the generation capacity expansion planning, it is crucial to consider the economics of scale and the availability of primary energy sources. To support the accelerated integration of PV power plants into the electrical system and fulfill economic and sustainable aspects, the ideal capacity of PV power plants needs to be considered. This study involves optimization using MILP and comparison with various scenarios to determine the optimal combination for planned PV PP. Based on the optimization results, to meet a 100 MW load, 138 MW of PV power plants are required, with a configuration of 125 MW for large-scale PV PP, 10 MW for medium-scale PV PP, and 3 MW for rooftop PV PP. The total cost needed is 11,445 thousand dollars, with an LCOE of 4.75 c$/kWh. This value is significantly lower compared to other scenarios. To supply for 24 h, PV PP can utilize BESS, with an LCOE reaching 7.79 c$/kWh when optimal capacity and generation are achieved. The recommendation for determining the capacity of PV PP is to use the large-scale capacity scheme, both for daytime supply systems and for the 24-h scheme.

6. ACKNOWLEDGMENT

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