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# OPTIMAL GREEN POWER EXPANSION PLANT FOR SUSTAINABLE DYNAMIC ELECTRICITY DEMAND

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## Abstract

The increasing demand for electricity requires an expansion of power generation capacity, with a focus on sustainability. Effective planning necessitates an understanding of both current capacity and the growth potential of green energy technologies. This study presents a framework for optimizing power generation expansion through dynamic demand analysis, targeting new and renewable energy (NRE) sources, including solar, wind, hydro, biomass, and natural gas (in both steam and combined cycle configurations). Employing a Loss of Load Probability (LOLP) model, this research assesses reliability in meeting future load demands for sustainable energy production. A case study on Lombok Island, Indonesia, demonstrates the application of this model, projecting a transition from fossil-fuel-based to NRE-based generation, with NRE sources expected to contribute 79% of energy production by 2050. The LOLP approach identifies an optimal capacity reserve, enabling efficient integration of solar, wind, and biomass energy while maintaining a 21% reliance on natural gas for stability. These findings highlight the significant potential for NRE-based expansion in similar regional settings, emphasizing the role of a dynamic LOLP model in enhancing sustainable power system reliability.

Keywords: Expansion plan, Green power, LOLP, NRE, Reliability.

## 1. Introduction

The transition toward sustainable energy generation is essential to meet rising electricity demands while minimizing environmental impacts. Traditional power generation methods, heavily reliant on fossil fuels, contribute significantly to greenhouse gas emissions, with the electricity sector alone responsible for substantial $CO_2$ output [1]. A power generation development plan serves as a strategic framework for utility companies, helping to balance future demand with cost efficiency across generation plants [2, 3]. Accurate forecasting and optimization are critical in this planning process but are often complicated by the need to ensure reliability, especially in systems prone to operational issues such as outages. Consequently, aligning expansion plans with precise demand projections is vital for promoting both efficiency and sustainability, as acknowledged in recent research that stresses the importance of addressing reliability within clean energy transitions [4, 5].

Global efforts to decrease fossil fuel reliance underscore the need for integrating renewable energy sources. Indices evaluating the sustainability of power generation systems typically consider social, economic, and environmental aspects, making the move to clean energy sources not only beneficial for emissions reduction but also crucial for supporting the growing electricity demands driven by expanding economies and populations [6]. In Indonesia, like many other regions, energy demand growth calls for diversification into non-renewable energy (NRE) sources to alleviate fossil fuel dependence. Clean energy options, such as natural gas and renewable alternatives like solar and wind, provide viable pathways for sustainability in both medium- and long-term perspectives [7]. Natural gas plants, for instance, offer efficiency and lower emissions compared to coal and oil, positioning them as an optimal transitional resource in the shift toward fully renewable energy systems [8, 9].

Despite the considerable progress in clean energy, the reliability of power supply remains a significant challenge in transitioning to NRE. The LOLP (Loss of Load Probability) index, a widely recognized metric, is instrumental in evaluating an electric power system's capacity to meet demand under fluctuating conditions. Established methodologies use LOLP to quantify system adequacy and forecast reliability, a factor often overlooked in many studies focusing on sustainability alone [10]. This paper proposes a dynamic approach to power generation planning by employing a tailored LOLP model in combination with a load duration curve (LDC) and economic dispatch optimization, incorporating a range of clean energy technologies. Through this method, the study aims to assess optimal power expansion while balancing the need for sustainable energy growth and reliable supply, as demonstrated in a case study of Lombok Island, Indonesia. This approach not only facilitates the integration of renewable energy but also supports the region's growing demand through robust and adaptive energy planning frameworks [11].

## 2. Problem Formulation

Building a power generation system for large loads depends on energy sources and reliability (Fig. 1). Technology selection is influenced by fuel, investment, and environmental costs. Advances in the past decade have boosted efficiency, increasing

NRE plants' competitiveness with conventional ones. Efficiency, investment, environmental, and operating costs play key roles in expansion planning.

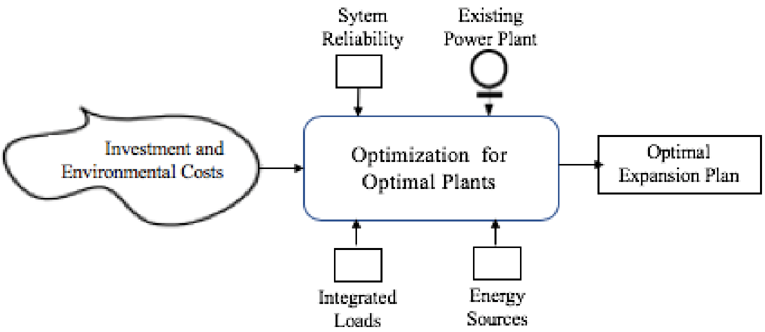


**Fig. 1. Problem formulation of optimal electricity expansion plan.**

To ensure sustainable electricity, reliability factors like LOLP control and reserve margin analyses must be integrated from 2025 to 2050. The Load Duration Curve guides LOLP and optimizing unit commitment reduces costs while supporting cleaner energy transitions. Optimal power generation is key to sustainable expansion.

## 3.Methods

The power adequacy study aims to assess the generator's ability to serve the system's load demand in the future. The optimal generating capacity is an approach to determine the optimal generating capacity of power plants based on the least cost of power plant operation.

Referring to Conny et al., the $P_j$ value had to meet the constraints of each generating unit that met the following criteria from (1) through (3) [7]. The parameter j indicates the generating capacity of generator unit j, while m is the total number of generator units supporting the load demand.

$$\sum_{j=1}^{m} P_j - P_l' - P_d = 0 \quad (1)$$

$$P_l' = \sum_{j=1}^{m} P_j^{bl} - P_{loss} \quad (2)$$

$$P_j^{min} \le P_j \le P_j^{max} \quad (3)$$

$P_d$ is defined as load demand and $P_{loss}$ measures as a power loss. $P_j^{bl}$ indicates the power loss of generator unit j based on unit operation.

After determining the optimal power based on the economic dispatch above, the reserve margin can be calculated through (4).

$$P^{rm} = NDC - P^{pl} \quad (4)$$

Equation (4) shows that the reserve margin is the difference between the Net Dependable Capacity (NDC) and the peak load. This paper calculates NDC based on the optimal power capacity for each generating unit as formulated in (5).

$$NDC = \sum_{j=1}^{m} P_j^{opt} \quad (5)$$

The NDC value meets specific reliability criteria, such as the planning LOLP index. The effect of LOLP changes is substantial on the total planned generating capacity.

The generator failure index assesses a power plant's ability to meet system demand. A system fails when the LOLP exceeds the set threshold, with reliability measured in days per year. LOLP calculations use unit capacity and forced outage rate (FOR) data (Fig. 2). Cumulative outage probabilities are computed from individual unit failures using the Fourier Transform Method for accuracy. A fifth-degree polynomial approximates the daily load curve (LDC), improving model precision [11].

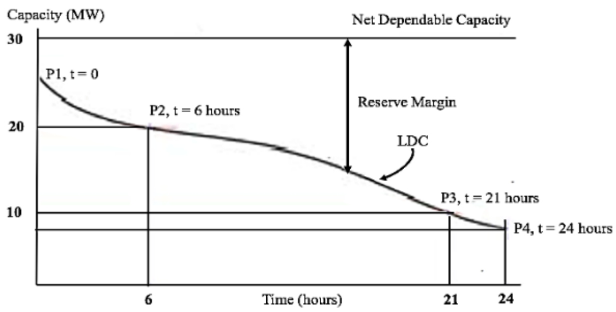


**Fig. 2. The cumulative probability of LDC [11].**

Figure 2 emphasizes the importance of determining LOLP in the electricity expansion plan to ensure system reliability. LOLP is the probability of the generator failing to serve the load and is influenced by potential outage durations at peak, middle, and base loads.

The amount of LOLP in year m is obtained from the total planned generating capacity by considering the total daily disturbance probability ($t_j$), and the loss of power probability ($P_j$) represented by (6).

$$LOLP = \sum_{j=1}^{m} P_j \, t_j \quad (6)$$

Therefore, NDC can be calculated with (7) by substituting (6) with (5).

$$NDC_j = \sum_{j=1}^{m} P_j^{opt} \, (1 + LOLP_j) \quad (7)$$

For the load duration curve (Fig. 2), The probability of LOLP in one day per year, it is assumed that the peak load lasts for 6 hours (30 MW), the middle load for 21 hours (20 MW), and the base load for 24 hours for a load of 10 MW. Assuming that FOR is 10%, it can be determined that the individual LOLP probability at P1 is 0.001, P2 is 0.027, P3 is 0.243, and P4 is 0.729. Based on this concept, the determination of LOLP for 39 generating units can be calculated based on the number of plants. The LOLP calculation in this paper uses the Fourier Transform Method approach. Meanwhile, the LDC is approximated by a fifth-power polynomial function.

## 4. Algorithm

The planning period for this study spans from 2025 to 2050. The baseline data includes operational records, information on generator technologies, and details of existing power plants. The selection of appropriate technologies for the power expansion plan is guided by the availability of both local and imported energy sources. Additionally, calculating the Loss of Load Probability (LOLP) requires specific data on the Load Duration Curve (LDC), peak load, and the LOLP standards applicable to the targeted electricity supply area.

The proposed methodology for solving the sustainability of the electricity supply expansion plan based on clean energy sources will use the following procedures.

1. Start
2. Set the time period (baseline year - to year-end)
3. Input the potential power plan.
4. Define and input the peak load for each expansion plan, FOR, and LOLP standard
5. Define the potential power plant.
6. Determine the LDC using a fifth-power polynomial function.
7. Determine LOLP
8. Calculate NDC for optimal power plant.
9. Calculate optimal green power plant expansion plan within the planning period (2025-2050).
10. Write output for each year time (green power plant expansion plan, LOLP, and reserve margin).
11. Finish.

Completing optimal power expansion planning to serve continuous load needs is done by creating a software program based on the FORTRAN language. The proposed method has been written using the FORTRAN 4.0 application software and operated on an ASUS X450J Laptop computer.

## 5. Results and Discussion

A case study on Lombok Island, Indonesia (Fig. 3) demonstrates clean energy optimization. With LOLP capped at one day per year, the system will accommodate load growth through local renewables, new sources, and imported natural gas. A 2025-2050 expansion plan, based on five-year interval sensitivity analyses, supports generator planning, LOLP management, and reserve margin assessments, enabling fast and efficient optimization.

According to the 2021 RUPTL data [12], the electricity supply for Lombok Island is provided by a combination of Steam Power Plants (PP) with 5 units, Combined Cycle Power Plants (CCPP) with 13 units, and Diesel Power Plants (DPP) comprising 21 units. Local energy resources available for power generation include solar energy, with solar irradiation ranging from 3.3 to 5.6 kWh/m$^2$, and wind energy, with average wind speeds between 6 and 7 m/s. Additionally, approximately 900,000 tons of industrial and household waste generated annually offer significant potential for biomass energy production. The installed capacity of the existing generation system is detailed in Table 1.

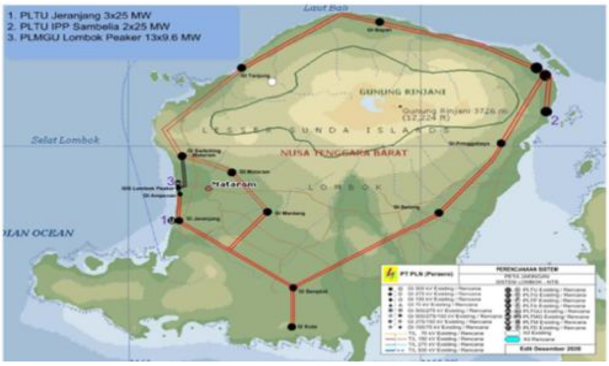


**Fig. 3. The existing power system network in Lombok Island [12].**

**Table 1. Existing of electricity supply in Lombok Island 2021 [12].**

| Electricity Supply System | Steam PP | Combined Cycle PP | Diesel PP | Total Capacity |
|---|---|---|---|---|
| **Capacity (MW)** | 125 | 124.8 | 73.5 | 323.3 |
| **Number of (Units)** | 5 | 13 | 21 | 39 |
| **Peak Load (MW)** | - | - | - | 287.0 |

Between 2025 and 2050, the competitiveness of power systems will depend on efficiency and cost per unit of electricity (Fig. 4). By 2050, alternative energy sources are projected to match coal in cost. Centralized photovoltaic systems and Concentrated Solar Power (CSP) plants will be pivotal in this shift, with CSP plants using concentrated sunlight for energy.

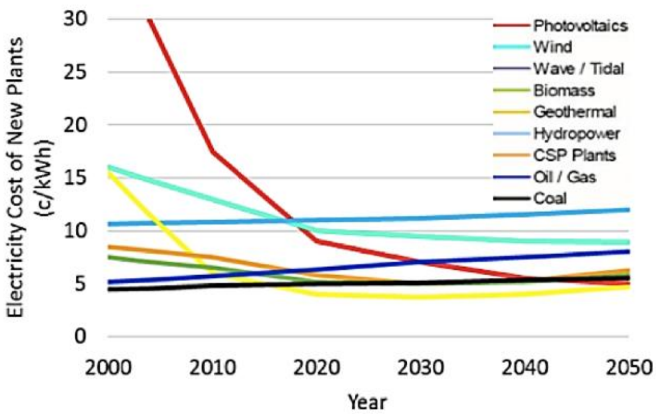


**Fig. 4. Electricity price trend 2000 to 2050.**

Table 2 shows Lombok Island's projected generation capacity growth through 2050. While diesel and natural gas plants will continue to support peak and base loads, the share of renewable energy will rise significantly, reaching 79% by 2050. Solar and wind will each contribute 29%, leveraging Lombok’s potential. Fossil fuels will be reduced by 35% yet will still account for 21% of energy in 2050, with steam and combined cycle plants transitioning to cleaner fuels and natural gas by 2030. Diesel engines will be phased out by 2030.

**Table 2. Result of electricity supply in Lombok Island.**

| Year | Power Plant Capacity (MW) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Oil | NG Steam | NG CC | Solar | Wind | Biomass | Total |
| **2021** | 73.5 | 125 | 124.8 | 0 | 0 | 0 | 323.3 |
| **2025** | 57 | 125 | 124.8 | 50 | 0 | 0 | 356.4 |
| **2030** | 22 | 125 | 124.8 | 85 | 100 | 0 | 456.8 |
| **2035** | 0 | 100 | 124.8 | 150 | 150 | 50 | 574.8 |
| **2040** | 0 | 60 | 124.8 | 150 | 250 | 150 | 734.8 |
| **2045** | 0 | 30 | 174.8 | 250 | 250 | 250 | 954.8 |
| **2050** | 0 | 30 | 224.8 | 350 | 350 | 250 | 1204.8 |

Table 3 highlights the effects of implementing a 1-day-per-year loss of load probability (LOLP) and a 10% forced outage rate (FOR) on Lombok's power system, resulting in a 10-12% reserve margin that is both technically and economically viable [13, 14]. The LOLP is calculated to range from 0.472 to 0.897 days per year, indicating reliable performance. Research has shown that maintaining a low LOLP and a steady reserve margin is essential for ensuring system stability and minimizing risks of load shedding, especially in areas with growing energy demands [15, 16]. Lombok's electricity supply is supported by a 150kV transmission network, with electrical loads primarily concentrated in coastal areas. Projected electricity supply growth is expected to increase by a factor of 3.7 from 2021 to 2050, driven by an annual load growth rate of 9.4% [17]. The most significant growth is anticipated in 2022 at 12.6%, reflecting the region's rapid economic development. The average reserve margin of 11.1% further confirms the system's reliability, in alignment with industry standards for energy security and resilience [18, 19].

**Table 3. Expansion plant capacity (NDC) and peak load.**

| Year | Peak Load (MW) | LOLP (%) | NDC (MW) | Reserve Margin (%) |
|---|---|---|---|---|
| **2021** | 287.0 | 0.472 | 323.3 | 11.2% |
| **2025** | 316.4 | 0.639 | 356.4 | 11.2% |
| **2030** | 403.8 | 0.775 | 456.8 | 11.6% |
| **2035** | 515.4 | 0.841 | 574.8 | 10.3% |
| **2040** | 657.8 | 0.897 | 734.8 | 10.5% |
| **2045** | 839.6 | 0.597 | 954.8 | 12.1% |
| **2050** | 1071.5 | 0.796 | 1204.8 | 11.1% |

## 6. Conclusions

The proposed method offers an optimal power expansion plan for Lombok Island (2025-2050). It highlights how LOLP affects the reserve margin and competition among generating units, with fuel oil remaining competitive until 2030. Natural gas, favoured for its low cost, will remain optimal for combined cycle plants and peak loads. Simulation results show a transition to 79% NRE-based generation, with natural gas contributing 21% as a cleaner alternative to fuel oil. Solar and wind each contribute 29%, and biomass 20%. The LOLP ranges from 0.472 to 0.897 days per year, indicating excellent reliability. This method also supports planning for interconnected island or national grids, with interconnection modelled as a large generating unit.

**Nomenclatures**

| | |
|---|---|
| $P_d$ | load demand |
| $P_j$ | loss of power probability |
| $P_j^{min}$ | Minimum generating capacity of generator unit j |
| $P_j^{max}$ | Maximum generating capacity of generator unit j |
| $P_j^{opt}$ | Optimal generating capacity of generator unit j |
| $P_j^{bl}$ | Power loss of generator operation of unit j |
| $P_l'$ | Total power loss |
| $P^{rm}$ | Reserve margin power |
| $P^{pl}$ | Peak load |
| $P_{loss}$ | Power loss |
| $t_j$ | Total daily disturbance probability |

**Abbreviations**

| | |
|---|---|
| CC | Combined Cycle |
| CSP | Concentrated Solar Power |
| FOR | Force Outage Rate |
| LDC | Load Duration Curve |
| LOLP | Loss of Load Probability |
| NDC | Net Dependable Capacity |
| NG | Natural Gas |
| NRE | New and Renewable Energy |
| PP | Power Plant |
| RUPTL | Rencana Umum Penyediaan Tenaga Listrik |

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