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# Generation expansion planning for high-potential hydropower resources: The case of the Sulawesi electricity system

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**ABSTRACT**

To ensure sustainable development for Sulawesi Island, which has significant hydropower potential, generation expansion planning (GEP) should meet the forecast electricity demand. GEP has determined the type and capacity of generating units necessary to minimize the total cost and provide the required reserve margin and energy balance. This study used GEP with WASP-IV software to minimize costs by considering the high hydropower potential of various Sulawesi electricity regions. Regional-balanced and resources-based approaches were employed to determine the generation candidates. The resources-based approach considered all the hydropower resources in Sulawesi Island and prioritized installation of hydropower generating units close to resource locations, while the regional-balanced one considered the installation of flexible generating units close to load centers. The results showed that the resources-based approach could achieve up to 30% renewable energy in the energy mix, with total costs for the regional-balanced one being \$ 9.83 billion for low demand and \$ 13.57 billion for high demand; however, the resources-based scenario costs would be \$ 9.54 billion for low demand and \$ 13.38 billion for high demand.

***Keywords:***

generation expansion planning;
renewable energy;
hydropower;
resources-based;
regional-balanced;

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## *1. Introduction*

GEP to ensure energy sustainability has become one of the main issues in the power system planning field, especially with regard to limiting carbon emissions as the response of the environmental issue [1]. There are several factors that affect GEP, the issue of energy security, fossil fuel depletion, social-economic and environmental issue [2]. For these purposes, the use of renewable energy sources (RESs) in generating units has become popular. Some countries required their utility companies to employ a specific proportion of RES generation in their generation systems. The availability of electricity primary source is very important for ensuring sustainability, especially since many RESs have intermittent characteristics [3]. Poor electricity supply can have a detrimental effect on the economic activities of a region [4]. In a developing country like Indonesia, the yearly increase of electrical energy consumption reflects the economic growth of communities. The incremental growth in energy consumption not only comes from the residential sector, due to population growth, but also from the industrial sector. The annual average economic growth in Indonesia of 6.3% caused the annual electricity sales increment (2012–2016) to increase to 6.7%, as asserted by [5].

GEP is an important procedure for ensuring sustainable energy. GEP determines the type, size, and quantity of generating units to be deployed during a specified time horizon with minimal total costs as the objective [4]. Considering the renewable energy proportion targets, the problem can be solved with multi-objective approaches

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based on the technique presented in [6]. Another work [7] considered GEP with a high proportion of hydropower generating units, including water pumping technology. To achieve a high proportion of RES generation, systems must be more flexible than conventional generation and transmission systems [8]. With effective GEP, electricity at an affordable price can be obtained, providing economic benefits for various regions, enabling economic activities and communities' quality of life to increase significantly [7, 8, 9].

The decline of fossil fuel supplies was the most important factor constraining GEP. In developing countries, fossil fuels such as coal are a source of air pollution. To achieve carbon emission targets, RES generating units should be considered using a GEP procedure [5, 9, 10]. RES targets are supported by the Presidential Regulation of the Republic of Indonesia No. 61 of 2011, which is the national action plan for reducing greenhouse gas emissions, and Law No. 16 of 2016, concerning the Approval of Paris Agreement, by which the Government of the Republic of Indonesia commits to reducing greenhouse gas emissions by 29% by 2030 [10, 11]. Considering these regulations, the Government of Indonesia and PT Perusahaan Listrik Negara (PT PLN) have specified a minimum renewable energy mix of 23% by the end of 2025 and 31% by the end of 2050 [3, 12, 13].

The Sulawesi electricity system (SES) is one of the largest electricity systems in Indonesia, with an average projected growth of electrical energy sales in 2018–2027 of 8.7%, after Java and Sumatra systems. The economic development of this island will increase rapidly in the near future, so the electricity support systems that are the backbone of development should be put in place. Currently, the SES is divided into two sections: the North Sulawesi Region, consisting of North Sulawesi Province and Gorontalo Province, and the Southern Sulawesi Region, consisting of South Sulawesi Province, Central Sulawesi Province, Southeast Sulawesi Province, and West Sulawesi Province. The peak load of the North Sulawesi Region system in 2017 was 401 MW, while that of the Southern Sulawesi Region system was 1,556 MW [3, 13, 14]. Currently these two systems are not connected.

Primary potential RESs on Sulawesi Island include wind energy in the South, hydro energy in the central region, and natural gas on the East coast [5]. Based on Nippon Koei reports in 2011 [15], hydropower potential was 26,321 MW, of which 4,338 MW were already in operation, 5,956 MW were planned, and 16,027 MW were unplanned; however, due to geographical conditions, only about 8,000 MW of hydropower could be generated. The potential RESs in Sulawesi were determined by the Sulawesi Electricity Masterplan Study [16], which included hydropower at 5,174.3 MW, geothermal energy at 1,148 MWe, wind power at 4,104.54 MW, biomass energy at 2,086 MWe, and solar energy at 21,081,000 MW with radiation of 4.80 kWh/m$^2$/day [3, 13].

Various GEP studies have considered RESs. A statistical residual load duration curve (S-RLDC) was used to model the load for GEP in China [18], which was a technique to simplify the duration curve load method. In that study, the generation of renewable energy was included in the plan as a negative load. In another study in Kenya [19], GEP was conducted by carrying out renewable energy integration and least-cost GEP to achieve security and continuity in the supply of electrical power systems, using WASP-IV as a tool to solve GEP problems. In addition, a study of distributed centralized thermal energy generation in the long-term planning of the Iranian electricity system used WASP-IV [20]. The researcher in a further study [21] conducted GEP for the electricity system in Pakistan using WASP-IV. The selection of generating units included in the GEP could be achieved by using screening curves to determine the type of generator needed to supply the base and peak loads. Yet another study [9] analyzed and estimated the proportion of renewable energy that could be developed in the energy mix of Indonesia and Thailand. LEAP was used in the development of renewable energy, such as hydro, wind, and solar power, with the objective of increasing the use of renewable energy in those two countries, which were previously dominated by non-renewable energy power plants.

Several studies have applied GEP to Indonesia's energy mix. The researcher in [22] used OSeMOSYS for GEP to meet the demand and satisfy the load increase in the Java–Bali Electrical Power System. Another study also conducted Sulawesi GEP using OSeMOSYS [23]. In both studies, a RES generating unit was considered to be a fixed plant and used as the data input. To deal with the issue of sustainability in the electric power system, research on the energy mix in Indonesia has been conducted by a number of researchers [22, 23]. To capture the trend of the energy mix status, one study [24] introduced a dynamics modeling approach to develop a new model of the energy mix. Previous trends were used as the data input to simulate future energy mix needs. An overview of the potential resources and utilization of energy in Indonesia has also been carried out [25]. Currently, the energy mix in Indonesia still depends on fossil energy, with a contribution of RESs of around only 3%. To increase the proportion of RESs, local resources and potential RESs, one of which is hydropower, must be considered.

There are several studies to support GEP and energy planning by considering RESs, especially related to hydropower. To support the development of a hydropower plant, risk analysis and investment bidding are needed [26,27]. This is to determine the level of competitiveness of the hydropower plant. The researcher in [26], conducted an investment risk analysis of a small-hydropower (SHP) plant in a Portugal electrical system. The researcher considers and identifies several aspects of risk and determining the tariff for SHP in Portugal. For the determination of costs or bidding for hydropower in Norwegian, it is necessary to consider factors of water value, feed-in fees, technical and hydrological characteristics, and bilateral agreements outside the spot market [27].

To conduct the GEP for the SES, pre-analysis of the electrical demand projection (load forecasting) and primary energy resources was carried out. These processes, including transmission expansion planning (TEP) and transmission backbone determination, became the basis of a masterplan, which is needed to provide development guidelines for specific areas. The previous masterplan study was carried out in 2008, resulting in the installation of more hydropower generating units on Sulawesi Island [28]. The new masterplan was formulated in several stages: load forecasting, generation expansion planning, and transmission expansion planning, including the determination of the system backbone. The load forecasting stage considered two scenarios: base and high-demand scenarios. The base-demand scenario used a "business as usual" approach for normal growth, resulting in a low projection for electricity demand, but the high-demand scenario, which considered all aspects of the possible development planning (such as mining load and higher economic growth) resulted in a high projection for electricity demand.

The GEP for Sulawesi had to consider several factors, such as the system's reserve margin, the loss of load probability (LOLP) reliability index, and the possible interconnection of the northern and southern systems. The value of the reserve margin was deterministically set at 35–40%, or equivalent to the LOLP criteria of <0.274%. LOLP <0.274% meant that the probability of a system outage was less than one day per year. These two criteria needed to be fulfilled for GEP in Indonesia. The final stage in the development of the electricity system masterplan was the TEP for the SES, which had to consider economic and technical criteria, such as load flow, short circuits, and stability. In the TEP, it was necessary to set transmission voltage levels between 275 kV and 500 kV as the backbone.

This study focused on GEP for the SES by considering potential resources, including RES options. The contribution of this paper is a GEP procedure for a developing country using low-cost fossil power plants to achieve a high RES proportion in the target energy mix. Regional-balanced and resources-based approaches were applied to the optimization problem, which modified the constraints in the GEP optimization equation. The regional-balanced approach focused on installing generator units close to the load centers, while the resources-based approach focused on installing generator units close to the resource locations. The simulations were developed as an optimization problem, which was simulated in a WASP-IV environment.

## 2. Materials and methodology

This section discusses the materials and methodology used to conduct this research. Section 2 is divided into two sub-sections: the first discusses the data used in the study (namely the SES data) and the second discusses the methodology, including the assumptions about the data and the objective functions and constraints.

### 2.1. The Sulawesi electricity system

Currently, the SES is divided into two different subsystems for the northern and southern regions. The Northern Sulawesi System consists of the North Sulawesi and Gorontalo Provinces, while the Southern Sulawesi System consists of the South Sulawesi, West Sulawesi, Central Sulawesi, and Southeast Sulawesi Provinces. Based on the Rencana Usaha Penyediaan Tenaga Listrik (RUPTL) 2018–2027 document, in 2018 the peak load in the Northern Sulawesi System is expected to be 421 MW, with a total capacity of existing plants of 573 MW, while the Southern Sulawesi System's peak load is estimated at 1,413 MW, with a total capacity of existing plants of 1,977 MW. The average load growth over 10 years for the Northern Sulawesi System is 9%, while that for the Southern Sulawesi System is 9.9% [5].

Load growth in the SES is influenced by several factors, such as population growth, economic growth, growth in the number of industrial areas, and smelting industry development. The small industries and smelter factories are two particular factors that will affect the load growth in Sulawesi. In the SES, the growth of those sectors has already been planned by the regional government. The locations of the capital city, industrial areas, and smelter factories can be seen in Figure 1 [16].

The load growth for Sulawesi was divided into two scenarios: a base-demand scenario with normal load growth and a high-demand scenario with very optimistic load growth. The industrial areas and smelter factories should be gradually installed in Sulawesi between 2017 and 2026, in the North Sulawesi, Gorontalo, Central Sulawesi, West Sulawesi, and South Sulawesi Provinces, and industrial sector development has been planned close to the capital city in each province. Smelters in Sulawesi will serve the nickel mining process, with smelter factories being spread across seven potential areas: one area in South Sulawesi Province and six areas in Southeast Sulawesi Province. The requirement of a smelter in South Sulawesi is 270 MW for the base-demand scenario and 620 MW for the high-demand scenario. The requirement of a smelter in the Southeast Sulawesi Province is 710 MW for the base-demand scenario and 2,244 MW for the high-demand scenario. The construction of smelter factories in the Southeast Sulawesi Province is spread across six areas: four in the northern and western regions of the provincial capital, and two potential areas on Kabaena Island and Muna Island [16].

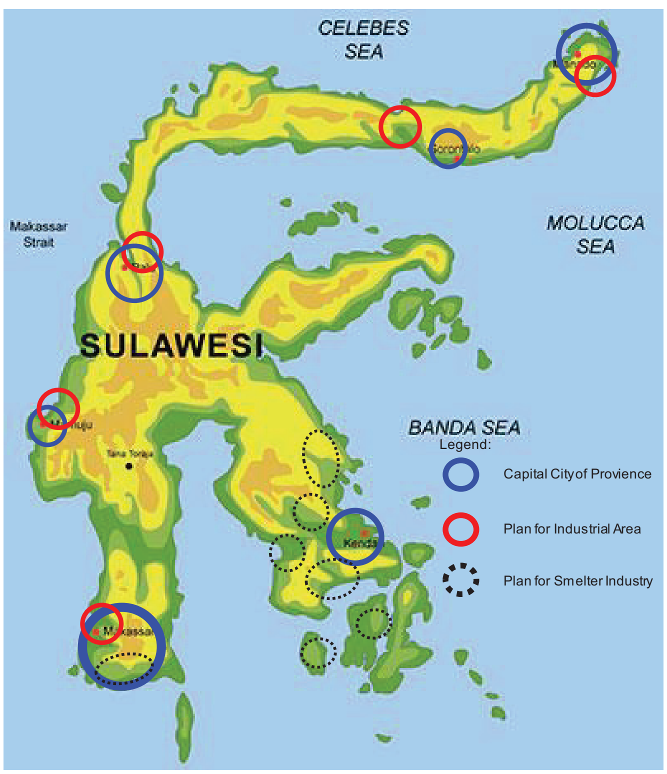


Figure 1: Map of the distribution of industrial areas and smelter factories in Sulawesi [16]

The SES has a number of potential RESs, such as hydropower. Based on the One Map Policy [29], South Sulawesi has the largest hydropower resources on Sulawesi Island at 3,826.5 MW, spread across eight locations. The largest hydropower potential is in Karama, at 1,161.1 MW, while the smallest is in Central Sulawesi, in Kerataun, at 54.5 MW. West Sulawesi has hydropower potential of 1,867.4 MW, spread across nine locations. Karama River has the largest hydropower potential in West Sulawesi, at 1,148 MW. In addition, a Nippon Koei study stated that hydropower potential in Sulawesi is abundant. North Sulawesi Province has 63.19 MW, Central Sulawesi has 1,596.7 MW, Sulawesi South has 3,269.5 MW, and Southeast Sulawesi has 276.4 MW [16].

## 2.2. Methodology

This research was conducted in several stages and the flowchart is presented in Figure 2. Data, which was crucial for the GEP Simulation, was collected by surveying and reviewing the literature and statistics relating to public policy. The data used in this study, consisting of the load duration curve, peak load, energy demand, existing generating unit technical data, and fuel costs for the SES, was obtained from PT PLN and the RUPTL document. For the load forecasting, economic growth was assumed, based on the Indonesian RAPBN 2018 data, to have a value of 5.4% in 2018 and 5.9–6.9% by 2021 [16]. The value for the SES's energy losses was based on the 2010–2016 electricity system losses data from the 2018–2027 RUPTL document. Fuel costs were assumed based on data from the Indonesian Crude Oil Price (ICP) and ESDM Regulation No. 11 of 2017, which can be seen in Table 1.

In this study, the objective function for minimizing the total cost was formulated as described in Equation (1):

$$\min B_{j,t} = \sum_{t=1}^{T} \left( \overline{I_{j,t}} - \overline{S_{j,t}} + \overline{F_{j,t}} + \overline{O\&M_{j,t}} + \overline{O_{j,t}} \right) \quad (1)$$

The optimal solution was formulated by minimizing the total cost of all the expansion plans, for each year, across the horizon plan presented by Equation (1). The minimum total cost of generation ($B_{j,t}$), attached to expansion plan j, is the sum of the discounted investment cost ($\overline{L_{j,t}}$), discounted fuel cost ($\overline{F_{j,t}}$), discounted operation & maintenance cost ($\overline{O\&M_{j,t}}$), discounted cost of energy not supplied ($\overline{O_{j,t}}$), minus the discounted residual values after depreciation during the operation period in the study (salvage value, ($\overline{S_{j,t}}$)) [30]. The calculations for the cost components of $B_{j,t}$ are presented in Equations (2)–(6).

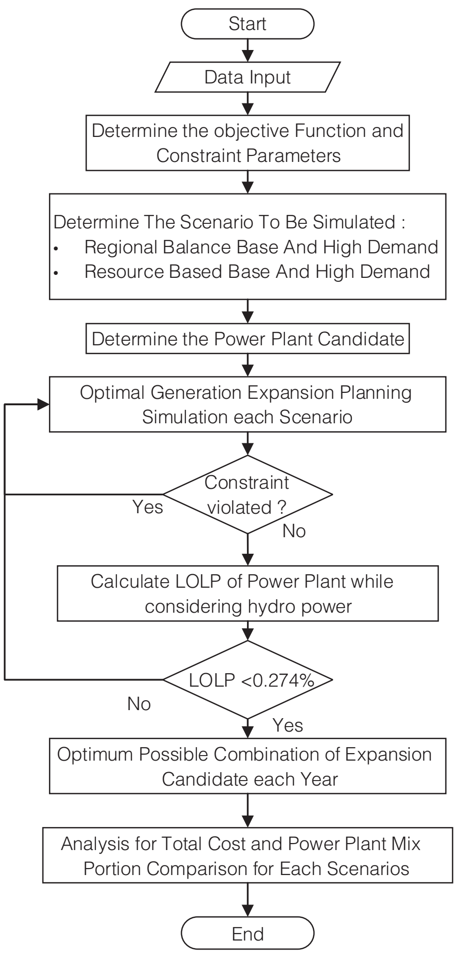


Figure 2: Research flowchart

$$\overline{I_{j,t}} = (1+i)^{-t} \times \sum_k [C_{Cap}^k \times P_{max}^k] \quad (2)$$

$$\overline{S_{j,t}} = (1+i)^{-t} \times \sum_k [\delta_{j,t} \times C_{Cap}^k \times P_{max}^k] \quad (3)$$

$$\overline{F_{j,t}} = (1+i)^{-t-0.5} \times \sum_{h=1}^{NHYD} \left[\alpha_h \times \left(\sum_k C_{Fuel}^{k,thermal} \times G_{k,thermal}^{t,h}\right)\right] \quad (4)$$

$$\overline{O\&M_{j,t}} = (1+i)^{-t-0.5} \times \sum_k \left[\left(C_{FOM}^k \times P_{max}^k\right) + \left(C_{VOM}^k \times G_k^t\right)\right] \quad (5)$$

$$\overline{O_{j,t}} = (1+i)^{-t-0.5} \times \sum_{h=1}^{NHYD} \left[a + \frac{b}{2} \times \left(\frac{ENS_{t,h}}{EA_t}\right) + \frac{c}{3} \times \left(\frac{ENS_{t,h}}{EA_t}\right)^2 \times ENS_{t,h} \times \alpha_h\right] \quad (6)$$

where i is the discount rate, t is the number of years between the reference date for discounting and the first year of the study, and T is the number of years in the study period. The investment cost, represented in Equation (2), is the sum of all the capital investment costs of units k ($C_{Cap}^k$) added in year t by expansion plan j, multiplied by the capacity of units k in MW ($P_{max}^k$). Equation (3) shows the calculation for the salvage value. The salvage value is the sum of all the capital investment costs of units k ($C_{Cap}^k$) added in year t by expansion plan j, multiplied by the capacity of units k in MW ($P_{max}^k$) and the salvage value factor at the horizon for unit k ($\delta_{k,t}$). The fuel cost calculation, represented in Equation (4), is the sum of all fuel costs for thermal units k ($C_{Fuel}^{k,thermal}$), multiplied by the generation capacity of unit k ($G_{k,thermal}^{t,h}$), considering the probability of hydro-condition ($\alpha_h$) for the number of hydro-conditions (NHYDs) in expansion plan j. Another cost component was the operation & maintenance cost (O&M), which was divided into a fixed O&M cost and a variable O&M cost. The O&M cost in Equation (5), is the sum of all the fixed O&M costs of unit k ($C_{FOM}^k$) multiplied by the unit size ($P_{max}^k$), and the variable O&M cost of unit k ($C_{VOM}^k$) multiplied by the

**Table 1: Primary energy cost and heat content assumptions**

| Fuel Type | Price | | Heat Content | | Fuel Cost | |
|---|---|---|---|---|---|---|
| | Value | Unit | Value | Unit | (USD/GJ) | (USD/MWh) |
| Coal | 0.0650 | USD/Kg | 20.92 | MJ/kg | 3.107 | 11.1852 |
| Natural Gas | 0.2613 | USD/m$^3$ | 39.34 | MJ/m$^3$ | 6.644 | 23.9184 |
| LNG | 0.3733 | USD/m$^3$ | 39.34 | MJ/m$^3$ | 9.489 | 34.1604 |

expected generation of unit k in year t ($G_k^t$), for each hydro-condition, weighted by the probabilities of the hydro-conditions. The equation for the energy not served cost, represented in Equation (6), refers to the amount of energy that is not supplied per year due to deficiencies in generating capacity and deficiencies in the energy supply of plants for each hydro-condition, where a, b, and c are constants ($/kWh), given as the input data. $ENS_{t,h}$ is the amount of energy not served (kWh) for hydro-condition h in year t, and $EA_t$ is the energy demand (kWh) on the system in year t.

In the GEP procedures, some technical constraints had to be fulfilled, as presented in equations (7)–(12) [3, 6, 22, 23].

$$N_t = N_{t-1} + N_A - N_R + N_{Cand} \tag{7}$$

$$\left(1+a_t\right)D_{tp} \geq \sum_k \left(N_k^t \times P_{max}^k\right) \geq \left(1+b_t\right)D_{tp} \tag{8}$$

$$G_t \geq EA_t + ENS_t \tag{9}$$

$$LOLP \leq C \tag{10}$$

The total number of generating units in operation in year t for the expansion plan can is given by Equation (7). The total number of all generating units ($N_t$) is sum of all the generating units in operation in the year before year t ($N_{t-1}$), the number of committed additions of units ($N_A$), and the number of candidate generating units added to the system in year t ($N_{Cand}$), subtracted from the number of committed retirements of units in year t ($N_R$). The other constraint was the reserve margin constraint represented in Equation (8). The installed capacity in the critical period, or in the peak demand period, must lie between the given maximum and minimum reserve margin, $a_t$ and $b_t$ respectively, above the peak demand $D_{tp}$ in the critical period of the year. The installed capacity is the sum of all units k in year t ($N_k^t$) multiplied by the maximum capacity of the units k ($P_{max}^k$). Total generation from all generating units in year t ($G_t$), as shown in Equation (9), must be greater than or equal to the sum of the energy demand ($EA_t$) and the energy not served ($ENS_t$) in year t. In this paper, the reliability of the generation system was considered, and represented by the LOLP (loss of load probability) reliability index, which can be seen in Equation (10). LOLP is the probability of the available capacity not meeting the load in a certain period of time (generally one year). The calculated LOLP value must be lower than or equal to the predetermined value (C). The LOLP value was obtained from the COPT (capacity outage probability table) calculation. COPT is used to calculate the probability of loss of power generation from generating units ($P_j$). COPT calculations using binomial distribution could be done using Equation (11). COPT is affected by the number of generating units (N), power plant outage conditions (OC), power plant availability (A), and plant unavailability (U). The COPT calculation can produce LOLE values, which is the amount of time when the available capacity cannot meet the load demand in a certain period of time. The LOLE calculation can be seen in Equation (12), where $Pi$ is the cumulative probability from the available generation combination and $Day_i$ is the duration of the loss load (per day) [32].

$$Prob_j = \frac{N!}{OC!N-OC!} \times A^{N-OC} \times U^{OC} \tag{11}$$

$$LOLE = \sum_{i=1}^{n} Prob_i \cdot Day_i \tag{12}$$

The scenarios' setup was designed to address the different priorities of policymakers, so the generating unit candidate options and the load forecast for the upcoming years was determined before the optimization procedure. The GEP procedure was applied separately to the two existing systems in Sulawesi, meaning that the interconnection of the two systems was not considered in the procedure. In determining the scenarios, two issues were considered: the conditions of load forecasting and the limitations of the locations of the generating unit candidates. The load forecast scenarios were used for the base-demand scenario, referring to normal business growth ("business as usual"), and the high-demand scenario used the growth of large industrial sectors, such as industrial areas and smelter factories, and the use of electric vehicles. Generating unit candidate options were divided into regional-balanced and resources-based scenarios. The regional-balanced scenario considered the construction of new generating units located close to the load centers, while the resources-based scenario considered the construction of generating units located close to resources. The overall scenario of the GEP can be seen in the Table 2. In Southern Sulawesi, there are many sources of hydropower, but the locations are far from the load centers.

In the resources-based scenario, the hydropower should be installed based on the government policy. The regional-balanced scenario considered resources located near the load centers, but Northern Sulawesi only had a demand scenario, since it has no abundant hydropower potential.

After determining the scenarios, the next step was to determine the candidates for the plants to be built. The candidates were divided into two types: thermal and renewable energy. The thermal candidates for the Northern Sulawesi system and the Southern Sulawesi system can be seen in Tables 3 and 4.

In this study, the installation of RES plants, such as those running on hydro, geothermal, and wind power, were determined as fixed units. A fixed unit was a candidate of a certain size that entered a system on a certain year. Hydropower candidates are shown in Tables 5 and 6 for the regional-balanced scenario and those for the resources-based scenario can be seen in Table 7. In addition, there were also wind power candidates of 60 MW, which should enter the system in 2027 for both scenarios.

**Table 2: GEP scenarios considering the load forecast and the generating unit candidates' aspects**

| System | Scenarios |
|---|---|
| Northern Sulawesi Region | Base Demand |
| | High Demand |
| Northern Sulawesi Region | Regional-Balanced Base Demand |
| | Regional-Balanced High Demand |
| | Resources-Based Base Demand |
| | Resources-Based High Demand |

In the GEP optimization procedure, hydropower characteristics followed the Indonesian sunny and rainy season weather patterns. The hydropower daily output was assumed to be an average value. The hydro-conditions were divided into four periods per year, with each hydropower unit having a characteristic for energy generation and an average capacity for each period. Two types of hydropower plants were used: run-of-the-river (ROR) and dam (DAM). The two types of hydropower plant had different characteristics, especially for the capacity factor of each type. The ROR hydropower plants had a higher capacity factor than the DAM plants. DAM hydropower plants could be flexibly controlled so that they could be operated as peaker units. If the GEP produced a feasible solution, the simulation result could be summarized.

## 3. Results and discussion

In this section, the GEP optimization for all the scenarios for the planning horizon from 2023 to 2050 is discussed. Simulation was carried out using the WASP-IV tool, which has proved useful for solving GEP problems.

**Table 3: Thermal generating unit candidates for the Northern Sulawesi system**

| No | Name | Code | Unit Size (MW) | Spinning Reserves (%) | FOR (%) | Scheduled Maintenance Days per Year (days) |
|---|---|---|---|---|---|---|
| 1 | Coal 100 MW | C100 | 100 | 11 | 12 | 35 |
| 2 | Coal 200 MW | C200 | 200 | 11 | 12 | 35 |
| 3 | Coal 300 MW | C300 | 300 | 10 | 12 | 35 |
| 4 | Geothermal 20 MW | P020 | 20 | 0 | 5 | 28 |
| 5 | CCGT 150 MW | CC15 | 150 | 20 | 10 | 30 |
| 6 | NGGT 200 MW | GT20 | 200 | 18 | 10 | 35 |

**Table 4: Thermal generating unit candidates for the Southern Sulawesi system**

| No | Name | Code | Unit Size (MW) | Spinning Reserves (%) | FOR (%) | Scheduled Maintenance Days per Year (days) |
|---|---|---|---|---|---|---|
| 1 | Coal 200 MW | C200 | 200 | 11 | 12 | 35 |
| 2 | Coal 300 MW | C300 | 300 | 10 | 12 | 35 |
| 3 | Coal 600 MW | C600 | 600 | 11 | 12 | 35 |
| 4 | CCGT 150 MW | CC15 | 150 | 20 | 10 | 30 |
| 5 | NGGT 200 MW | G200 | 200 | 18 | 10 | 35 |

**Table 5: Hydropower unit candidates for Northern Sulawesi System**

| No | Name | Unit Size (MW) | Unit | Plant Type | Year |
|---|---|---|---|---|---|
| 1 | Poigar 2 | 30 | 1 | ROR | 2028 |
| 2 | Sawangan | 12 | 1 | ROR | 2028 |

**Table 6: Hydropower unit candidates for Southern Sulawesi System**

| No | Name | Unit Size (MW) | Unit | Plant Type | Year |
|---|---|---|---|---|---|
| 1 | Watonohu | 15 | 1 | ROR | 2024 |
| 2 | Konawe | 21 | 1 | DAM | 2023 |
| 3 | Buttu Batu | 200 | 1 | DAM | 2025 |
| 4 | Scattered | 400 | 1 | DAM | 2025 |

The SES demand forecast is presented in Figure 3. It can be seen that the Northern Sulawesi system in 2050 will have a base-demand peak load of 3,224 MW and a high-demand peak load of 4,257 MW, whereas the southern Sulawesi system in 2050 will have a base-demand peak load of 11,373 MW and a high-demand peak load of 15,630 MW.

### 3.1. Northern Sulawesi Region GEP

The GEP for the Northern Sulawesi system was based on regional-balanced scenarios, for both the base-demand and high-demand conditions. Based on Figures 4 and 5, it can be seen that the installed generating units were dominated by thermal plants. Figure 5 shows the total capacity for the base demand to the end of 2050, which requires 4,203.4 MW total capacity, with a thermal plant capacity of 4,090 MW and a hydro power plant capacity of 113.4 MW. Figure 6 shows the high-demand scenario, in which the total capacity of the plant to the end of 2050 is 55,614 MW; the composition of the generating units is dominated by thermal plants (5,490 MW) and hydropower plants (113.4 MW).

The Northern Sulawesi System requires a high number of thermal generating units, due to its limited hydropower resources so, to meet the load requirements, there needs to be a supply of thermal generating units. The reserve margin for the Northern Sulawesi System is around 30–40%, with a reserve margin at the end of 2050 of 30.4% to satisfy the reserve margin requirement.

**Table 7: Hydropower candidates for the resources-based scenario**

| No | Name | Type | Capacity (MW) | Year |
|---|---|---|---|---|
| 1 | Watonohu | ROR | 15 | 2033 |
| 2 | Konawe | DAM | 21 | 2035 |
| 3 | Buttu Batu | DAM | 200 | 2036 |
| 4 | Tersebar | DAM | 400 | 2037 |
| 5 | Karama-1 | DAM | 640 | 2033 |
| 6 | Masuni | DAM | 320 | 2035 |
| 7 | Mong | DAM | 200 | 2036 |
| 8 | Batu | DAM | 215 | 2037 |
| 9 | Lariang-6 | DAM | 160 | 2038 |
| 10 | SR 1 (Bada)1 | DAM | 420 | 2039 |
| 11 | SR 2 (Tuare) | DAM | 720 | 2041 |
| 12 | Kulawi | ROR | 150 | 2044 |
| 13 | La’a | ROR | 160 | 2045 |
| 14 | Lariang | ROR | 127 | 2046 |
| 15 | Makale | ROR | 45 | 2047 |
| 16 | Palu-3 | DAM | 75 | 2047 |
| 17 | Wtunohu-1 | ROR | 33 | 2048 |
| 18 | Malea | ROR | 70 | 2048 |
| 19 | Tamboli | ROR | 20 | 2049 |
| 20 | Koro Yaentu | ROR | 16 | 2049 |
| 21 | Lalindu | ROR | 50 | 2049 |
| 22 | Bakaru 3 | ROR | 145 | 2050 |

### 3.2. Southern Sulawesi Region GEP

The GEP optimization results for the regional-balanced scenarios can be seen in Figures 6 and 7. Figure 6 shows that, under base-demand conditions, the total power plant capacity to the end of 2050 is 14,794.7 MW. The thermal generating unit component is 12,750 MW (86.2%) and that of the RES generating units, 2,044.7 MW (13.8%). Figure 7 shows the high-demand condition, with a total capacity of 20,344.7 MW, a thermal component of 18,300 MW (90%), and a renewable energy component of 2,044.7 MW (10%).

Figure 8 and Figure 9 show the results of the resources-based GEP optimization. In the resources-based scenario, the RES generating unit component becomes 5,610.7 MW for both the base demand and high-demand scenarios. The thermal generating unit component is 9,300 MW and 14,800 MW for the base and high-demand scenarios, respectively.

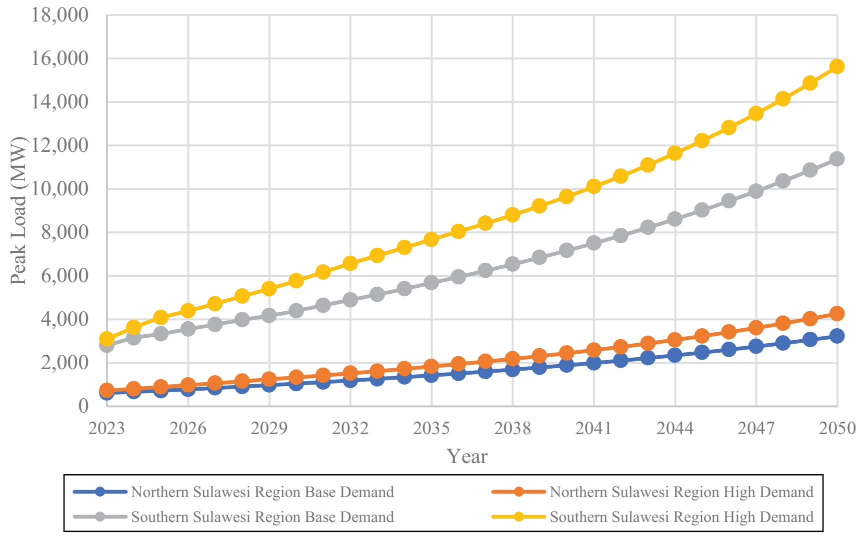


Figure 3: Base- and high-demand peak load for Northern and Southern Sulawesi

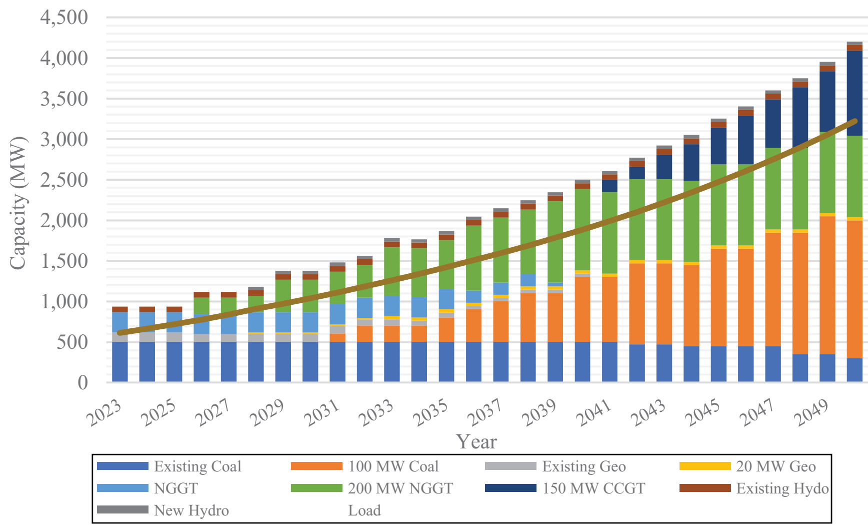


Figure 4: Northern Sulawesi System installed capacity for the base-demand scenario

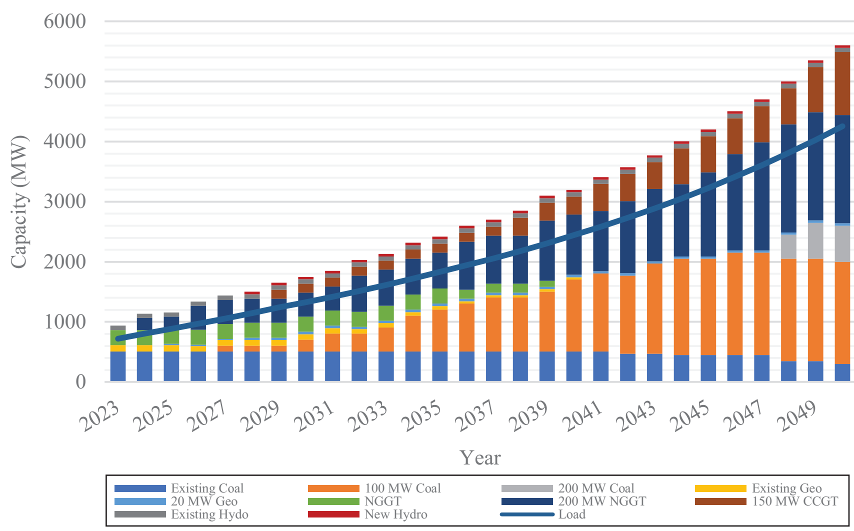


Figure 5: Northern Sulawesi System installed capacity for the high-demand scenario

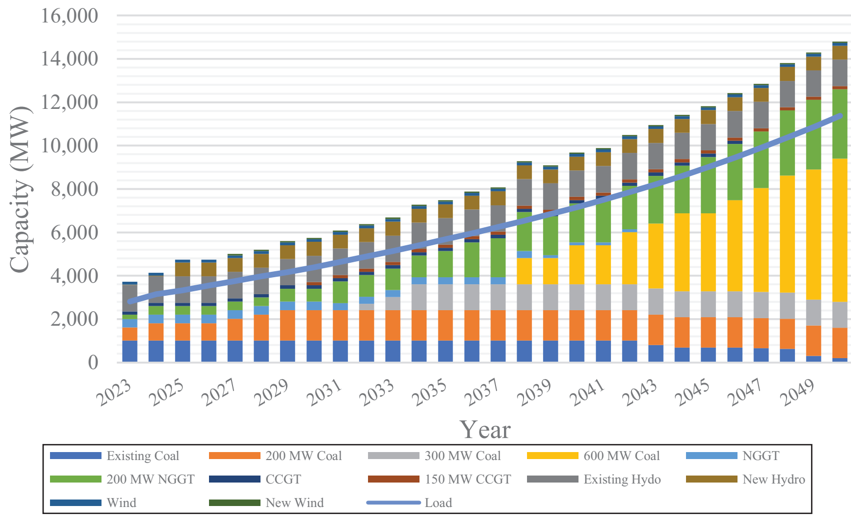


Figure 6: Southern Sulawesi System installed capacity for the regional-balanced and base-demand scenario

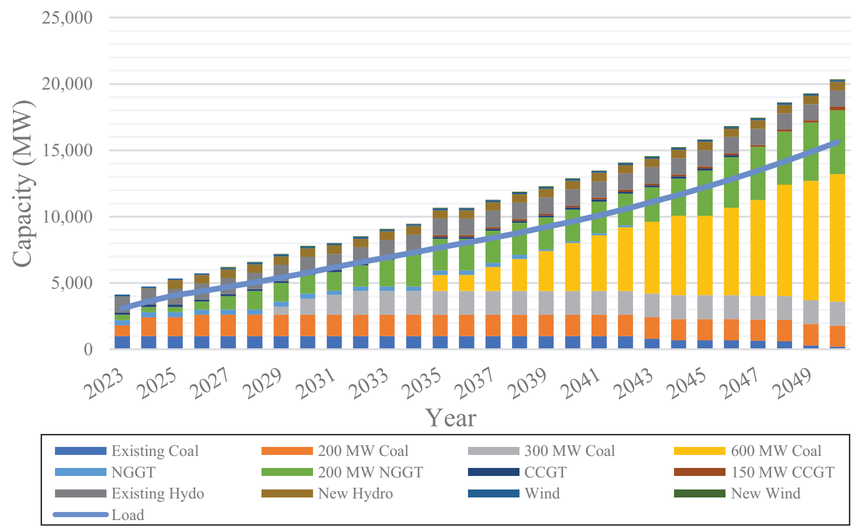


Figure 7: Southern Sulawesi System installed capacity for the regional-balanced and high-demand scenario

Based on the results of the GEP optimization, the reserve margin for each scenario is 30–40%. At the end of 2050, the regional-balanced base demand reserve margin is 30%, the regional-balanced high demand reserve margin is 30.2%, the resources-based base demand is 31.1%, and the resources-based high demand is 30.58%.

### 3.3. Comparison between scenarios

To compare the installed capacity of the scenarios, the whole SES needed to be evaluated. The installed capacity for Northern and Southern Sulawesi was aggregated, and the Northern Sulawesi GEP results were combined with the regional-balanced and resources-based scenarios for the Southern Sulawesi results.

Based on the simulation results, several comparisons could be made regarding the effect of the proportion of RESs. Applying a resources-based scenario would increase the proportion of hydropower installed capacity as presented in Figure 10. By the end of 2050, the resources-based base-demand scenario could have 30% RES generating units, thereby meeting the energy mix target set by the government.

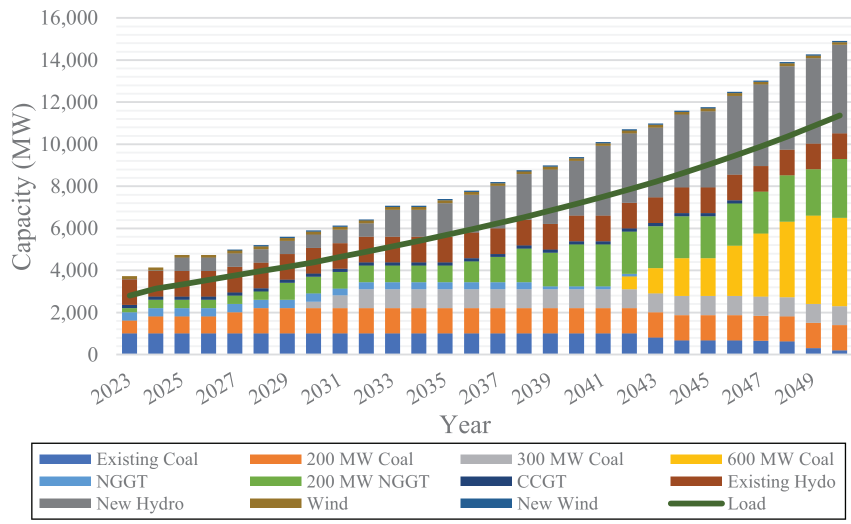


Figure 8: The Southern Sulawesi System installed capacity for the resources-based and base-demand scenario

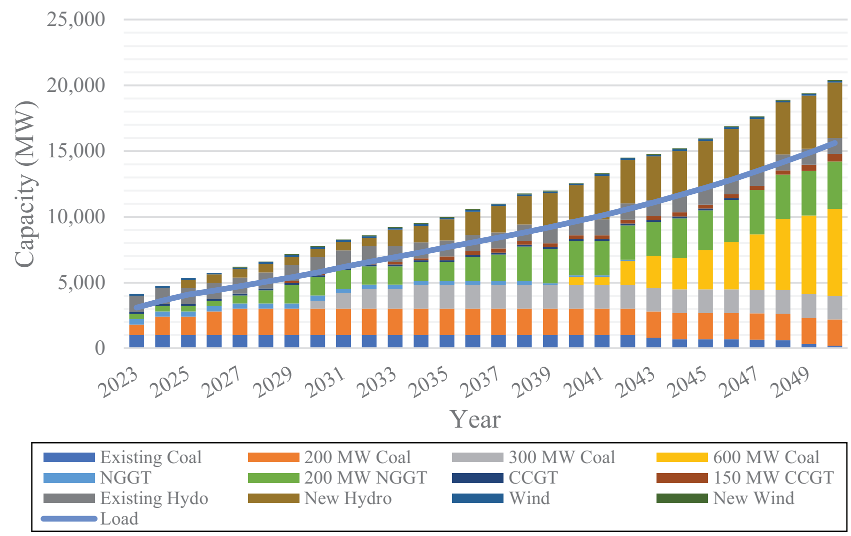


Figure 9: The Southern Sulawesi System installed capacity for the resources-based and high-demand scenario

The greater capacity of RES generating units could reduce the proportion of fossil power plants as presented in Figures 10 and 11. For the base demand, the coal proportion was 60% and the renewable power proportion was 8%. Furthermore, the proportion of coal power plant could be reduced by up to 44%. A reduction in the consumption of coal is also one of the government's targets, as set out in the 2018–2027 RUPTL document.

With the decrease of fossil-based generating units, especially those consuming coal, the results of GEP optimization could have an impact by reducing the emission levels produced by coal power plants and switching to hydropower units. In addition, it could reduce energy dependence on fossil fuels, thereby increasing energy security and sustainability for the future.

To increase the energy security and sustainability of power systems, the power plant reliability index is something that needs to be considered. The reliability of power plants must meet the standards for reliability established by the Indonesian Government and PT PLN,

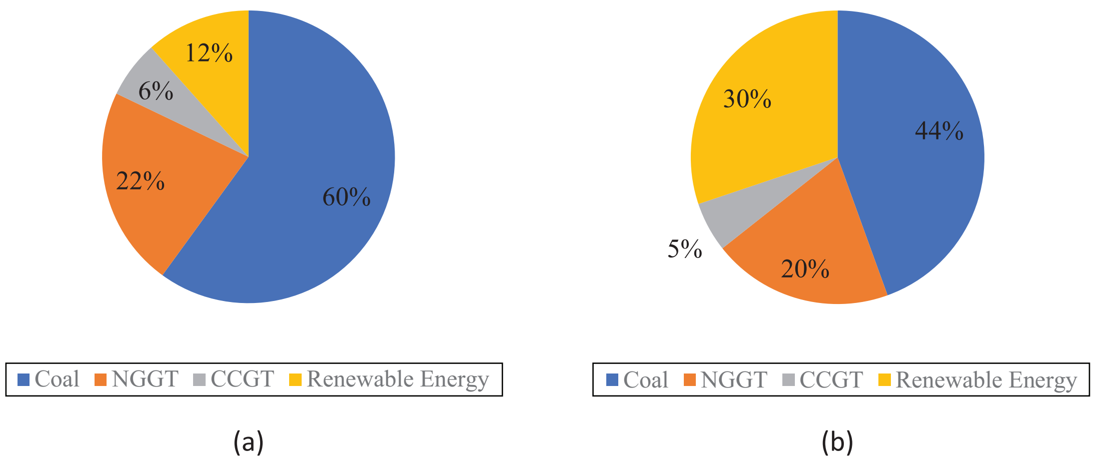


Figure 10: Installed capacity for the base-demand scenarios (a) regional-balanced (b) resources-based

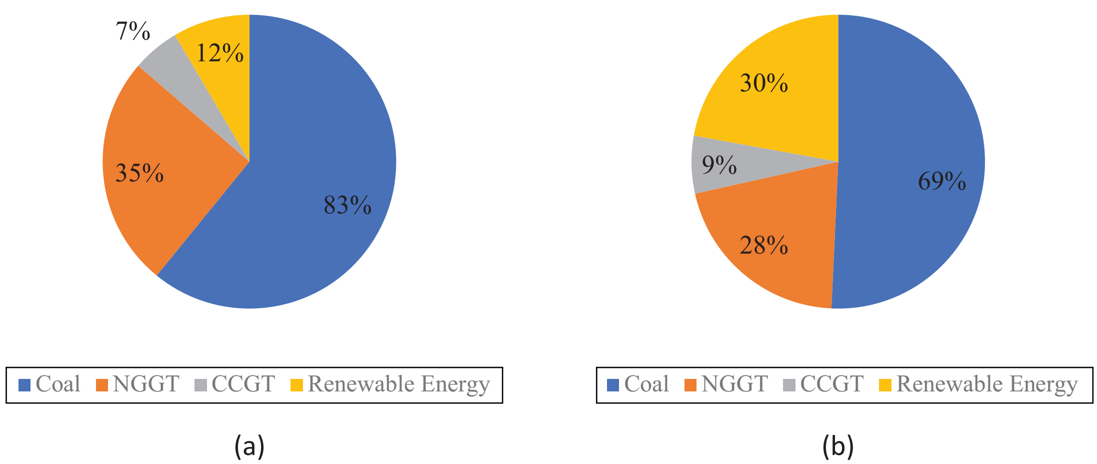


Figure 11: Installed capacity for the high-demand scenario (a) regional-balanced (b) resources-based

which is less than 0.274% for LOLP. Table 8 shows the LOLP index for each scenario, which is less than 0.274% for each year.

Another impact of increasing the number of renewable energy power plants entering the system is the decrease in total generation costs. This can be seen in Table 9. Based on these results, the inclusion of renewable energy through a resources-based scenario could provide a lower total cost for renewable energy generation (USD 9.54 billion for base demand and USD 13.38 billion for high demand) than a regional-balanced scenario, with a relatively high cost (USD 9.83 billion for base demand and USD 13.57 billion for high demand). However, it was assumed that there would be no land-acquisition costs for each power plant, and installing a hydropower plant requires a greater area of land than any other type of power plant.

**Table 8: LOLP index for each scenario**

| | Base Demand (%) | | | High Demand (%) | | |
|---|---|---|---|---|---|---|
| | Northern Sulawesi Region | Southern Sulawesi Region | | Northern Sulawesi Region | Southern Sulawesi Region | |
| Year | | Regional-Balanced | Resources-Based | | Regional-Balanced | Resources-Based |
| 2023 | 0.004 | <0.001 | <0.001 | 0.098 | <0.001 | <0.001 |
| 2024 | 0.021 | <0.001 | <0.001 | 0.068 | <0.001 | <0.001 |
| 2025 | 0.091 | <0.001 | <0.001 | 0.222 | <0.001 | <0.001 |
| 2026 | 0.056 | <0.001 | <0.001 | 0.13 | <0.001 | <0.001 |
| 2027 | 0.197 | <0.001 | <0.001 | 0.127 | <0.001 | <0.001 |
| 2028 | 0.192 | <0.001 | <0.001 | 0.172 | <0.001 | <0.001 |
| 2029 | 0.063 | <0.001 | <0.001 | 0.112 | <0.001 | <0.001 |
| 2030 | 0.172 | <0.001 | <0.001 | 0.11 | <0.001 | <0.001 |
| 2031 | 0.138 | <0.001 | <0.001 | 0.116 | <0.001 | <0.001 |
| 2032 | 0.150 | <0.001 | <0.001 | 0.071 | <0.001 | <0.001 |
| 2033 | 0.041 | <0.001 | <0.001 | 0.083 | <0.001 | <0.001 |
| 2034 | 0.142 | <0.001 | <0.001 | 0.044 | <0.001 | <0.001 |
| 2035 | 0.133 | <0.001 | <0.001 | 0.058 | <0.001 | <0.001 |
| 2036 | 0.079 | <0.001 | <0.001 | 0.047 | <0.001 | <0.001 |
| 2037 | 0.079 | <0.001 | <0.001 | 0.064 | <0.001 | <0.001 |
| 2038 | 0.083 | <0.001 | <0.001 | 0.06 | <0.001 | <0.001 |
| 2039 | 0.119 | <0.001 | <0.001 | 0.047 | <0.001 | <0.001 |
| 2040 | 0.090 | <0.001 | <0.001 | 0.051 | <0.001 | <0.001 |
| 2041 | 0.106 | 0.001 | <0.001 | 0.036 | 0.001 | <0.001 |
| 2042 | 0.076 | 0.002 | <0.001 | 0.042 | 0.002 | <0.001 |
| 2043 | 0.066 | 0.002 | <0.001 | 0.035 | 0.002 | <0.001 |
| 2044 | 0.073 | 0.001 | <0.001 | 0.026 | 0.001 | <0.001 |
| 2045 | 0.046 | 0.002 | <0.001 | 0.028 | 0.001 | <0.001 |
| 2046 | 0.049 | 0.003 | <0.001 | 0.015 | 0.001 | <0.001 |
| 2047 | 0.036 | 0.003 | <0.001 | 0.019 | 0.001 | <0.001 |
| 2048 | 0.037 | 0.003 | <0.001 | 0.013 | 0.001 | <0.001 |
| 2049 | 0.031 | 0.002 | <0.001 | 0.007 | 0.001 | <0.001 |
| 2050 | 0.020 | 0.003 | <0.001 | 0.008 | 0.001 | <0.001 |

**Table 9: Total cost comparison for each scenario**

| Scenario | Total Cost (Billion USD) |
|---|---|
| Regional-Balanced Base Demand | 9.83 |
| Resources-Based Base Demand | 9.54 |
| Regional-Balanced High Demand | 13.57 |
| Resources-Based High Demand | 13.38 |

## 4. Conclusion

To meet the 30% energy mix proportion target, the resources-based scenario should be chosen for the GEP procedure for both demand scenarios. The technical construction costs for the resources-based scenario would be lower than for the regional-balanced scenario.

However, the land-acquisition costs have not been considered in this study. Normally, hydropower plants require more land investment than other types of power plant, so that the social costs for the resources-based scenario could be higher. Furthermore, transmission lines would have be installed to transmit the electrical power from the source to the load center. In this situation, the resources-based scenario would require more transmission-line facilities than the regional-balanced one, which might increase the construction costs.

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