Decarbonization Roadmap and Energy System Scenarios for Southern Sulawesi System: Response to Demand Growth from Smelters Sector

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Abstract

This study aims to develop a decarbonization roadmap and energy system scenarios for Southern Sulawesi System in response to a sharp increase electricity demand driven by the rapid expansion of nickel smelters through 2030. While Indonesia has pledged to cut GHG emissions under the Paris Agreement, the extraordinary pace of industrialization in this region, accelerated by the national mineral downstreaming policy, presents distinctive planning challenges. Unlike other regions, Southern Sulawesi has already achieved notable renewable energy mix of approximately 30%, yet this is now threatened by the sudden rise in industrial demand. The reserve margin is projected to decline significantly, primarily due to energy-intensive smelters, which now represent the largest source of electricity consumption relative to other areas in the country. This study is the first to incorporate updated electricity demand forecasts, particularly from the smelter sector, into a decarbonization framework using the Low Emission Analysis Platform (LEAP). It evaluates three scenarios: Business as Usual, National Plan (align with RUPTL 2021-2030), and the Southern Sulawesi System scenario. Each scenario assesses pathways to optimize generation cost, ensure demand fulfillment, and reduce emissions. Results indicate a steep demand surge between 2024-2025, and show that transitioning from coal to gas, combined with renewable energy expansion and co-firing strategies, can reduce GHG emissions up to 48% while achieving a 35% renewable share. The study underscores the urgency for targeted policy actions, including updated planning mechanisms, spatial and cross-sectoral coordination, and carbon pricing instruments, to ensure energy reliability and support a realistic clean energy transition.

Keywords: Southern Sulawesi System, smelter, decarbonization, greenhouse gas emissions

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1. Introduction

Global efforts to tackle climate change have been marked by several key agreements, including the Kyoto Protocol in 1997 and the Paris Agreement in 2015. The Kyoto Protocol was an initial step that required industrialized nations to reduce greenhouse gas emissions, while the Paris Agreement reinforced global commitments to limit the global temperature rise to below 2°C, with an ambitious target of 1.5°C [1]. Given that the energy sector contributes more than three-quarters of global emissions, with 40% from power generation, decarbonizing this sector is a top priority in reducing climate change [2,3].

Indonesia faces substantial difficulties in meeting the increasing energy demand, mainly due to its extensive dependence on coal as the main source in the national energy mix. However, the country has abundant renewable energy potential, such as biomass, hydropower, and geothermal energy, including Southern Sulawesi, which comprises the provinces of South Sulawesi, Southeast Sulawesi, West Sulawesi, and Central Sulawesi.

Studies on biomass utilization for bioenergy in Indonesia, especially in Sumatra, have shown that bioenergy can support the decarbonization of the power sector, reduce coal dependence, and contribute to the goals of reducing greenhouse gases [4]. In Java-Bali, the development of renewable energy such as hydropower, geothermal, and biomass, along with the expansion of gas-fired power plants, offers a cost-effective solution for the electricity system [5]. Based on this potential, Indonesia has the opportunity to achieve 100% renewable energy through the reduction of fossil fuels, the utilization of bioenergy and the transition to clean energy such as solar and hydropower [6].

Taking these studies into account, Indonesia has the potential to establish an environmentally friendly and sustainable energy sector. However, with the increasing energy demand from the mineral industry, particularly nickel smelters, the decarbonization pathway is crucial to ensure a sustainable energy supply while supporting national clean energy transition targets.

Although the energy transition and decarbonization of the power sector have been widely studied at the national level, in Java-Bali and Sumatra, specific studies on the Sulawesi energy sector, particularly with regard to the growing demand for electricity from smelters, remain limited. The lack of such research could impede strategic planning essential to ensure reliable electricity supply while also minimizing carbon emissions in this region. Therefore, more in-depth research is needed to understand the challenges and opportunities to decarbonize the power generation sector in Southern Sulawesi.

This research seeks to examine the decarbonization pathway for the power generation sector in Southern Sulawesi, addressing the increasing demand from smelters, as part of Indonesia's commitment to achieving the targets outlined in the Paris Agreement. The main focus includes projections of energy demand considering high-voltage consumers (smelters) until 2030, the decarbonization roadmap and its costs in the system to achieve net zero emissions and the role of the renewable energy mix in supporting national renewable energy targets. Furthermore, this study will evaluate CO_2 emissions from the power generation sector in 2030 and identify the necessary policies to achieve a low-emission power generation system in Southern Sulawesi.

2. Literature Review

2.1. Decarbonization of the energy sector and energy demand projection

The decarbonization of the energy sector is a critical effort to reduce carbon emissions, primarily from fossil fuel combustion, which is a major contributor to greenhouse gases [7]. The power generation sector contributes significantly to both global and national emissions, making strategies such as renewable energy development, energy efficiency, and carbon capture technology (CCS) essential for achieving net zero emissions (NZE) [7,8]. In Indonesia, policies such as the Electricity Supply Business Plan (RUPTL) 2021-2030, focusing on the development of renewable energy, reflect a strong commitment to achieving the goals of the Paris Agreement and transitioning to a more sustainable energy system [9].

However, there are considerable challenges remaining, limited investments in renewable energy, and inadequate infrastructure [10]. In Sulawesi, the transition to energy requires multi-sector collaboration involving the government, the private sector, and local communities. Proactive policies, incentives for investors, and increased public awareness are key to accelerating an inclusive and sustainable decarbonization process, especially to address the increasing energy demands of smelters [11].

A further challenge in the energy transition in Southern Sulawesi is the rising energy demand from the smelter sector. The expansion of smelters in this region is expected to contribute 30.7% to the national electricity demand, highlighting the importance of long-term energy planning that takes into account these factors to support both economic development and the sustainability of the energy system [12].

2.2. Power generation in Indonesia and decarbonization commitments

In 2022, Indonesia's total installed power generation capacity reached 83.3 GW, with 85% sourced from fossil fuels and 55% from coal power plants, as shown in Figure 1. The national electricity provider, PLN, plans to expand capacity by 40.6 GW by 2030, with 51.6% coming from renewable energy, bringing the total installed capacity to 99.2 GW, as shown in Figure 2 [9].

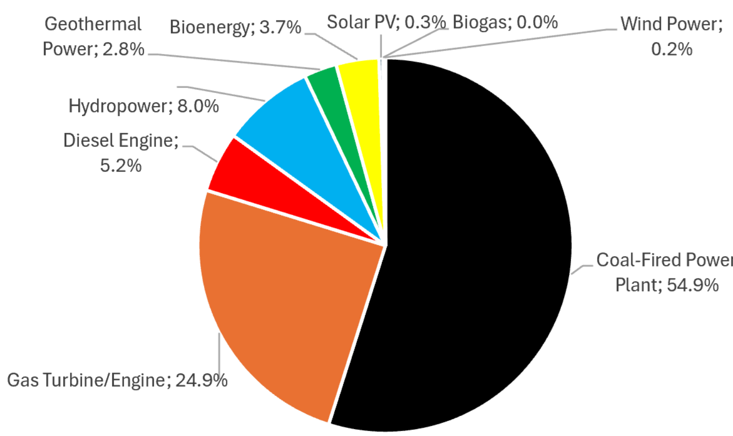

Figure 1: *Installed national power generation capacity in 2022*

The Indonesian government has also established renewable energy targets of 23% by 2025 and 31% by 2050, as described in the National Energy Plan (RUEN). The targeted renewable power generation capacity is 45.2 GW by 2025 and 167.7 GW by 2050. However, in 2023, the realization of renewable energy was only 13. 09%, falling short of the target of 17. 9%, making the acceleration of the transition of energy crucial [13]. The net zero emissions (NZE) strategy for 2060 includes the early retirement of coal-fired power plants, the development of large-scale solar photovoltaic power and the use of technologies such as co-firing and hydrogen energy. The roadmap includes

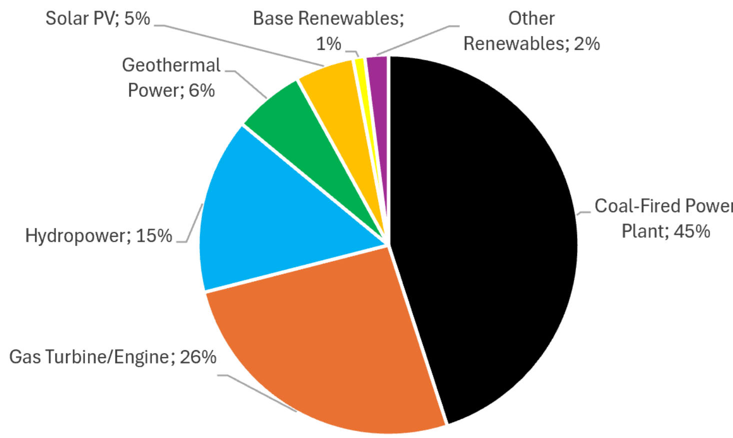

Figure 2: *Planned installed capacity by 2030*

gradual increases in the adoption of renewable energy, starting with solar and wind, followed by nuclear and ocean energy by 2045. Large-scale renewable energy projects will be continuously promoted as technology and operational costs decrease [13, 14].

2.3. Renewable energy potential in Sulawesi

Indonesia has an estimated renewable energy potential of 3,687 GW, however, its current utilization is merely 0. 3%. Sulawesi, with significant renewable energy resources, faces similar challenges in transitioning to sustainable power generation. The total renewable energy potential in Sulawesi is approximately 247 GW and the distribution is provided in Table 1 [15].

Table 1: *Renewable Energy Potential in Sulawesi*

Type of Renewable Energy	Potential (MW)	Utilization Factor	Maximum Utilization (MW)
Geothermal	2,990	0.6	1,794
Bioenergy	3,500	0.6	2,100
Wind	14,890	0.1	1,489
Hydro	3,100	0.6	1,860
Solar	222,700	0.1	22,270
Total	247,180		29,613

In 2023, the mix of renewable energy in Sulawesi reached 1,201.39 MW, representing 35% of the total power generation capacity, with contributions of 36% in Southern Sulawesi and 31% in north Sulawesi. This indicates that renewable energy in Sulawesi has yet to dominate the fossil energy mix [16]. The development of renewable energy-based power plants in the region requires the optimization of the resource potential and the adoption of more advanced technologies to support the energy transition and to achieve national targets, particularly given the increasing energy demand from smelters. Some technologies that can be developed especially in Southern Sulawesi include solar photovoltaic, hydropower, wind power, bioenergy, and municipal solid waste (MSW).

2.4. Smelters and energy demand in Sulawesi

A smelter is an industrial facility that processes raw minerals into pure products through a smelting process, which requires high-voltage electricity. In Sulawesi, the construction of smelters is expanding rapidly, especially for nickel, which adds value to mining products, creates jobs, and strengthens the local economy [17]. The distribution map of the growth of the smelter in Southern Sulawesi is shown in Figure 3 [18].

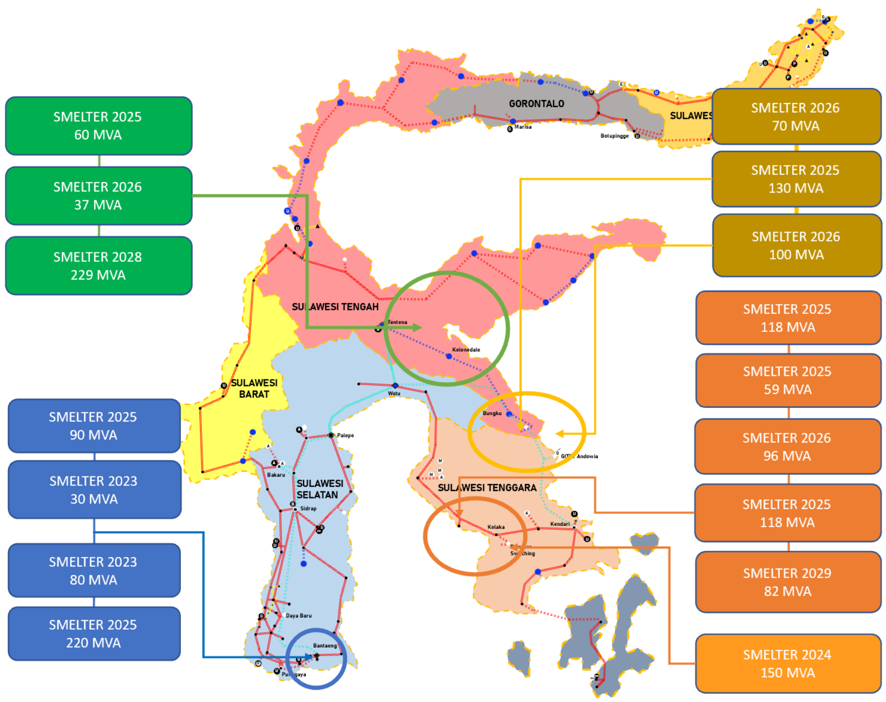

Figure 3: *Distribution map of smelter growth in Southern Sulawesi*

The high energy demand from smelters presents a challenge for PLN, which must ensure a stable and sufficient electrical supply to support operations. Limited power generation capacity and network infrastructure constraints must be addressed to allow the smelters to operate optimally without disrupting the electricity supply to the general public [19].

Government policies such as Law No. 3 of 2020 mandate mineral processing in the country prior to export, further increasing the energy demands in the region [20]. Furthermore, Presidential Regulation No. 55 of 2022 emphasizes mineral downstream processing as a national economic strategy, reinforcing the need for a sustainable energy transition [21]. Without proper energy planning, the rapid growth of smelters could strain the existing power infrastructure and hinder Indonesia's decarbonization efforts.

2.5. Current policies and development

Indonesia has also introduced various policies to support the energy transition and emission reductions, beginning with the Nationally Determined Contribution (NDC) in 2016, which aimed at a reduction of 29% emissions (unconditional) and 41% (conditional). In 2022, Indonesia updated these targets through the enhanced NDC (ENDC), setting a reduction target of 31. 89%

(unconditional) and 43. 20% (conditional) while committing to achieving net zero emissions (NZE) by 2060 or earlier [13, 22]. Furthermore, Presidential Regulation No. 22 of 2017 on National Energy Plan (RUEN) established a target 23% of renewable energy share in the national energy mix by 2025. The Regulation of the Ministry of Energy and Mineral Resources No. 12 of 2017 also supports the development of renewable energy such as geothermal, solar, wind and bioenergy. In 2022, Indonesia launched the Green Taxonomy and Presidential Regulation No. 112 of 2022 to accelerate the transition to renewable energy, which also promotes the phase-out of coal-fired power plants and prohibits the construction of new coal-fired power plants. The government has also secured funding from the Energy Transition Mechanism (ETM) of the Asian Development Bank (ADB) and the Just Energy Transition Partnership (JETP) to accelerate the clean energy transition [22–25].

2.6. State of the art and research gap

Indonesia's commitment to global climate agreements such as the Kyoto Protocol and the Paris Agreement has led to the development of national policies that emphasize power sector decarbonization and renewable energy targets. Strategic documents like the Electricity Supply Business Plan (RUPTL (2021-2030)) and the National Energy Plan (RUEN) outline Indonesia's path towards achieving 23% renewable energy by 2025 and net zero emissions by 2060. These initiatives have received support from multilateral mechanisms such as JETP and ETM. However, power generation remains dominated by fossil fuels, particularly coal, which represents more than half of the country's electricity capacity by 2022. This dependence is compounded by slow infrastructure development and underinvestment in renewable projects, especially in regions beyond Java.

Sulawesi, with a renewable energy potential exceeding 240 GW, remains underutilized, with only about 35% of its installed capacity sourced from renewables. Southern Sulawesi faces a unique challenge: a sharp increase in electricity demand driven by the construction of nickel smelters under the government's downstream mineral policy. These high-voltage industrial consumers place immense stress on the local electricity system, risking a decline in reserve margin and hindering clean energy transition efforts. Despite policy support for renewable deployment, including Presidential Regulation No. 112/2022 and the Green Taxonomy, the energy transition in Sulawesi continues to lag behind. The challenge is not only technical, but also structural, as pointed out by Lo (2017), who noted that energy governance in Asia suffers from institutional imbalances and regional inequality, where national energy priorities often overlook subnational realities [26].

In response to climate goals and shifting electricity demand patterns, several studies have employed energy system models such as LEAP and OSeMOSYS to assess Indonesia's energy transition pathways. For example, Handayani et al. (2017) examined the trade-offs between electrification and emission mitigation in the Java-Bali system, while Sani et al. (2021) analyzed biomass-based decarbonization pathways in Sumatra. Yudiartono et al. (2023) also applied the LEAP model to develop national-scale energy transition scenarios, which incorporate the expansion of renewable energy, energy efficiency and the distribution of sectoral demand [4, 5, 27]. However, while these studies address important aspects of energy planning, their approaches remain aggregated at the national level and do not explicitly examine the pressures arising from the growth of energy-intensive industries. Even Sulawesi-specific research, such as that by Sarjiya et al. (2023), focuses mainly on interconnection planning and capacity expansion, rather than the sectoral strain posed by large-scale mineral processing [28].

In addition, regional studies in Asia and Southeast Asia have highlighted uneven progress in the energy transition due to a combination of structural inefficiencies, carbon lock-in, and unequal access to financial and technical resources [29–32]. For ASEAN countries in particular, financial development and the use of renewable energy have been identified as key levers to reduce CO_2 emissions, although their effectiveness varies by institutional readiness and subnational contexts [33]. The failure to align national energy roadmaps with localized industrial dynamics (especially in rapidly industrializing zones) remains a central policy and modeling gap.

Therefore, this study contributes by developing decarbonization scenarios that integrate updated projections of electricity demand from the smelter industry in Southern Sulawesi. It examines the implications of high-voltage industrial growth on system capacity, emissions, and renewable integration.

3. Methods

To develop a roadmap for decarbonization for the Southern Sulawesi electricity system in response to the growing demand for electricity, particularly from smelters, an approach to modeling energy systems as a tool for policymaking is required. Energy system modeling consists of two main approaches: the top-down approach, which is econometric-based, and the bottom-up approach, which analyzes energy demand in detail based on activity and intensity. Bottom-up models, such as EnergyPLAN, TIMES, LUT, Oemof, OSeMOSYS, BALMOREL, PLEXOS, LEAP and NEMO, have been widely developed and used [34, 35].

Several energy system modeling studies in Indonesia, as shown in Table 2, have covered various scales. However, none of these studies specifically addresses the significant impact of the smelting industry on the electricity system. Rapid expansion of smelters has the potential to cause an energy supply deficit, deviating from previously established development plans. Therefore, immediate mitigation measures are necessary to ensure that the electricity system continues to meet the decarbonization goals and maintain the planned renewable energy mix.

Table 2: *Energy system modeling studies in Indonesia*

Coverage	Years for Modeling	Baseline	Model	Reference
Jawa-Bali	2016–2030	RUPTL 2016	LEAP	[5]
Indonesia	2010–2025	RUPTL 2016	LEAP	[36]
Sumatra	2018–2028	RUPTL 2016	LEAP	[4]
Sulawesi	2019–2050	RUPTL 2016	OSeMOSYS	[28]
Indonesia	2022–2060	RUPTL 2021	LEAP	[37]

The research scheme is illustrated in Figure 4, using the Low Emission Analysis Platform (LEAP). LEAP is a model developed by the Stockholm Environment Institute, widely used for integrated energy analysis and climate change mitigation assessments, and is freely accessible [38]. LEAP was chosen as the primary tool in this study because of its ability to model energy systems while considering both technical and economic aspects, including development costs and greenhouse gas emission estimates.

LEAP has been applied in various energy analyses for Indonesia, as reported by the National Energy Council. In the study by Handayani et al. (2017), the reliability of the LEAP model for Indonesia was also validated by comparisons with historical data [5].

3.1. Modeling parameters, assumptions and limitations

The modeling assumptions used in this study are based on 2020 as the baseline, with projections that extend to 2030 according to the national development plan (Electricity Supply Business Plan (RUPTL) 2021-2030). Key macroeconomic assumptions are derived from official electricity

Figure 4: *Research scheme showing the input parameters and outputs*

planning documents, such as the Electricity Supply Business Plan (RUPTL) and the National Electricity General Plan (RUKN). The projections of electric demand and distribution losses are based on these documents, supplemented by the latest data on the energy demand of high-voltage customers (smelters) [9,12,18]. This study considers four time periods, including the dry season, the rainy season, daytime and nighttime, using the PLN load curve 2023, which reflects post-COVID-19 conditions and future load growth as of Figure 5 [39]. Detailed key modeling parameters are presented in Table 3.

Meanwhile, electricity generation in Southern Sulawesi is modeled using various technologies, including coal power plants with pulverized boiler type and Circulating Fluidized Bed (CFB) & Stoker boiler types. Gas-fired power plants include the simple cycle gas turbine, the gas engine, and the combined cycle gas turbine. For renewable energy, the study incorporates hydropower, photovoltaic solar panels, wind power, and biomass through co-firing in CFB & Stoker boiler types, as well as Waste-to-Energy technology. The selection of technologies is based on government plans, the potential for energy resources, and local conditions, reflecting future opportunities for the electric system in the region.

Table 3: *Key modeling parameters*

Parameters	Value	Reference
Demand Projection Growth	6.8–9.12%	[9]
Smelter Demand Projection Growth	Shown in Figure 3	[18]
Transmission & Distribution Losses	6–9%	[9,12]
Load Shape	Shown in Figure 5	[39]
Reserve Margin	35%	[9,38]
Interest Rate	6.5–7.5%	[8]

Sources of technology data include the document Technology Data for the Indonesian Power

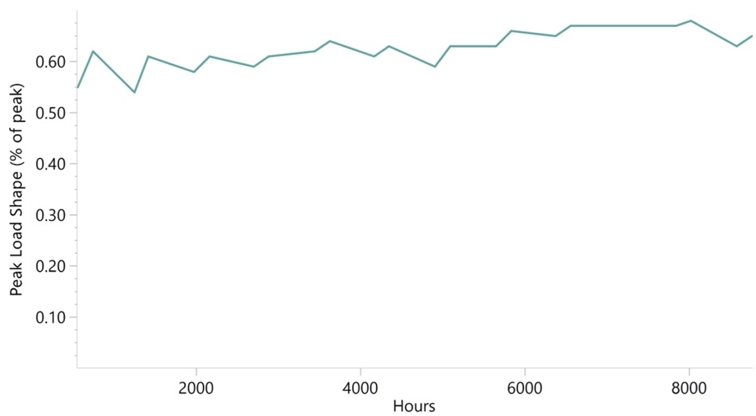

Figure 5: *Load shape electricity demand Southern Sulawesi*

Sector and PLN [9,40,41], with a focus on the development of power plants rather than investment in transmission infrastructure. Therefore, the development of transmission lines is outside the scope of simulation, and all power plants are assumed to be able to transmit their power to the entire Southern Sulawesi electricity system. Table 4 provides details of the power plant modeling parameters.

Greenhouse gas emissions from fuel combustion are calculated in the LEAP model using Tier 2 emission factors from the Indonesian Ministry of Energy, as shown in Table 5 [42]. Renewable energy sources are considered to produce zero carbon emissions and emissions from the construction of power plants are ignored. Biomass emissions are also considered zero, as waste products that would typically be discarded are utilized.

Although this study adopts a scenario-based modeling framework using fixed parameters aligned with national planning documents, it does not include formal sensitivity or uncertainty analysis. This is because the primary objective is to explore indicative pathways that align with existing policies and emerging regional challenges, rather than to forecast with precision. However, we recognize that key parameters, such as electricity demand growth, fuel prices, and capital costs of renewables, carry inherent uncertainty. Variations in these inputs could influence the mix of generation, the outcomes of emissions and the costs of the system. Future research could extend this analysis by systematically testing the model's responsiveness to such parameter changes, thus enhancing the robustness and credibility of long-term planning under uncertainty.

3.2. Scenario development

The scenario development to represent the Southern Sulawesi electricity system is shown in Table 6. The key modeling parameters remain consistent across all scenarios; however, these scenarios explore different approaches to meet electricity demand and climate targets while considering resource opportunities and system constraints.

Table 4: *Technical and economic parameters of power generation technologies*

Technology	Capacity (MW) [9]	Lifetime [41]	Efficiency [41]	Cap. Factor [4,5,38,41]	Cap. Credit [4,5,38,41]	Capital Cost (USD/kW) [40,41]			Fixed O&M (USD/kW) [40,41]			Variable O&M (USD/MWh) [40,41]		
(Year)	2020					2020	2023	2030	2020	2023	2030	2020	2023	2030
Pulverize Coal Power	450	30	34	80	100	1650	1880	1820	45.3	51.6	50	0.13	1.5	1.45
CFB and Stoker Coal Power	573	30	34	80	100	1650	1880	1820	45.3	51.6	50	0.13	1.5	1.45
Gas Turbine Combine Cycle	110	25	59	80	100	690	1080	1030	23.5	26.8	26	2.3	2.6	2.5
Gas Turbine Simple Cycle	328	25	35	80	100	770	1120	1060	23.2	26.5	25.7	1	3.6	3.5
Gas Engine	89	25	35	80	100	770	1120	1060	23.2	26.5	25.7	1	3.6	3.5
Diesel Engine	473	25	46	31	100	800	910	910	8	9.12	9.12	6.4	7.3	6.84
Hydropower Large	486	50	95	51	53	2080	2200	2110	37.7	43	41	0.65	0.74	0.71
Hydropower Medium/Small	36	50	95	51	58	2700	2500	2400	53	47.8	45.8	0.5	0.57	0.55
PV Ground-mounted	0	30	100	21	22	790	960	670	14.4	7.5	6.8	0	0	0
PV Floating	0	30	100	21	22	890	1200	740	16.2	9	7.5	0	0	0
Wind Power	130	30	100	31	40	1500	1650	1200	60	40	36	0	0	0
Coal Power (Co-firing 20%)	0	25	33	80	72	1810	2040	1980	53.1	53.1	51.5	1.5	1.55	1.49
Bioenergy	0	25	32	80	72	2010	2240	2180	54.18	54.18	52.5	1.58	1.575	1.523
Municipal Solid Waste	0	25	29	80	100	6800	5970	5520	243.7	277.8	238.3	24.1	27.5	24.80

*Capacity credit is defined as a portion of the installed capacity that is considered reliable for calculating the reserve margin. This value is determined based on the availability ratio of Variable Renewable Energy (VRE) plants (intermittent plants) compared to the availability of standard thermal power plants [38].

Table 5: *Fuel costs and GHG emission factors*

Fuel	Fuel Cost [4,9]	Unit	GHG Emission Factor [42]	Unit
Coal	67.86	USD/ton	99,718	$kgCO_2/TJ$
Natural Gas	8	USD/MMBTU	57,600	$kgCO_2/TJ$
Fuel Oil	0.81	USD/liter	74,067	$kgCO_2/TJ$
Wood Pellet (Biomass)	135	USD/ton	0	$kgCO_2/TJ$

Table 6: *Scenario development modeling*

Scenario Development	Renewable Share Target	Emission Constraint	Add Demand Constraint
Business as Usual (BaU)	No	No	Yes
National Plan (RUPTL 21)	Yes	Yes	No
Southern Sulawesi System (SUL)	Yes	Yes	Yes

The Business as Usual (BAU) scenario represents the development of the power generation sector as traditionally implemented, without considering climate change mitigation strategies. This scenario is based on Indonesia's NDC definition of "business as usual," which means development without mitigation policies. It relies on readily available domestic energy resources (coal) and focuses on cost optimization solely for electricity production, which also means that this scenario does not apply renewable energy share targets and emission constraints. However, this scenario does incorporate additional electricity demand constraints, especially from the rapidly growing smelter sector, thereby prioritizing supply expansion to meet the projected surge in industrial consumption. This scenario serves as a reference for the development of the other two scenarios and as a baseline for emission calculations.

The National Plan (RUPTL 21) scenario represents a power sector development pathway that incorporates climate change mitigation strategies, in line with the inaugural "green" RUPTL of PLN published in 2021. This scenario simulates the expansion of the power plant based on the infrastructure rollout originally scheduled. However, it does not account for the significant surge in electricity demand driven by the accelerated proliferation of smelter operations. Consequently, this scenario may not adequately capture the emerging capacity requirements and could lead to an underestimation of the adequacy of the system in meeting future industrial loads.

The Southern Sulawesi System (SUL) scenario is developed to reflect the most current and region-specific dynamics in the Southern Sulawesi electricity system. It incorporates all three critical planning constraints: renewable energy share targets, emission reduction commitments, and additional electricity demand from high-voltage consumers, particularly the rapidly expanding smelter industry. This scenario integrates updated electricity demand projections and actual power plant developments realized between 2021 and 2024, ensuring that system planning aligns with on-the-ground realities. The core principle of this scenario lies in optimizing generation costs while maintaining system reliability and accelerating the deployment of renewable-based power plants that are suited to local resource availability. By capturing both policy objectives and regional infrastructure trends, the SUL scenario enables a more realistic and adaptive assessment of future system needs, facilitating robust comparative analysis across regulatory, technical, and spatial dimensions.

4. Results and Discussion

The simulation results for all scenarios of the Southern Sulawesi System will be discussed in this section, covering demand projection, electricity generation, cumulative cost production, and GHG emissions, representing conditions from 2021 to 2030.

4.1. Demand Projection

The demand projection for the Southern Sulawesi electricity system is expected to experience a significant increase between 2024 and 2025, with a load growth of 41%. The primary factor driving this sharp increase in demand is the electricity consumption of high-voltage smelter customers, which is projected to reach 5,330.88 GWh, as shown in Figure 6. The rapid expansion of smelters in Southern Sulawesi is further reinforced by the fact that nearly 90% of Indonesia's nickel ore reserves are concentrated in Central Sulawesi, South Sulawesi, and Southeast Sulawesi, which are all part of the Southern Sulawesi electricity system [43].

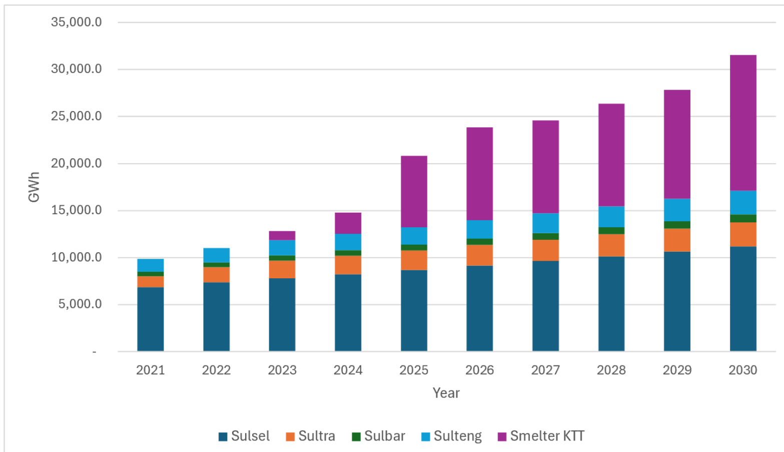

Figure 6: *Demand projection (GWh) for Southern Sulawesi's electricity system (2021-2030)*

This trend aligns with Law No. 3 of 2020, which mandates that mining companies must process and refine (smelt) minerals domestically before export, and Presidential Regulation No. 55 of 2022, which emphasizes downstream industrialization as part of a national strategy to increase the added value of mining products within Indonesia. These regulatory frameworks further strengthen the demand projection for the Southern Sulawesi electricity system in the coming years [20, 21].

The expansion of smelters is expected to continue to grow until 2030, with estimated electricity demand from smelters reaching 14,420.16 GWh, contributing to a total system demand of approximately 31,547.76 GWh in that year. This demand is primarily dominated by high-voltage smelter consumers, followed by medium- and low-voltage demand from the provinces of South Sulawesi, Southeast Sulawesi, Central Sulawesi and West Sulawesi, respectively.

4.2. Electricity generation mix

In the BAU scenario, which simulates the development of a cost-effective system without emission mitigation and renewable energy mix targets, coal-fired steam power plants are the primary option to accommodate the increasing load in Southern Sulawesi, as shown in Figure 7. As illustrated in Figure 7, pulverized coal power plants dominate the total installed capacity in the Southern Sulawesi electricity system, with 3.9 GW of coal capacity out of a total system capacity of 6.2 GW. This limits the expansion of renewable energy, which only reaches 0.7 GW.

The development of pulverized coal power plants in Southern Sulawesi aims to improve combustion efficiency and increase capacity, considering that most of the steam power plants in the region have a capacity of $\leq$ 100 MW. As a result, by 2030, renewable energy will contribute only 8% of total electricity production, which is much below the government's target and represents a significant decrease from the level of 2021.

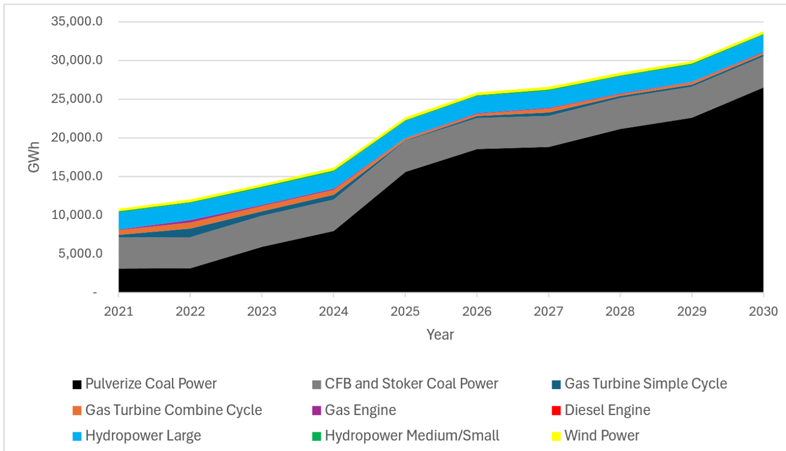

Figure 7: *Electricity generation (GWh) under the BAU scenario for Southern Sulawesi's System (2021-2030)*

In the RUPTL 21 scenario, which represents the 2021–2030 national electricity infrastructure development plan, planning was conducted before COVID-19 and before the regulations that cause significantly increased electricity demand from smelters were introduced. This scenario adopts climate mitigation strategies to reduce greenhouse gas emissions by integrating large-scale renewable energy expansion in Southern Sulawesi. However, the sudden surge in the electricity demand from the smelters makes the system vulnerable. As shown in Figure 8, by 2025, all fossil fuel power plants are operating at maximum capacity, contributing 72% of total electricity production of the system.

Focusing solely on renewable energy is insufficient to keep up with increasing electricity demand, leading to a decrease in the reserve margin of the system below the minimum threshold, as shown in Figure 10. However, PLN's efforts in this scenario should be recognized, as by 2030, installed renewable energy capacity reaches 2.5 GW, with hydropower, solar, wind, biomass, and waste-to-energy power plants being developed.

Mitigation scenarios to achieve emission reduction targets, renewable energy mix, and the massive electricity demand from high-voltage consumers in smelters during a very short and critical period focus on three key elements and are illustrated in Figure 9.

First, development of gas power plants. Given that some constructions of power plants between 2021 and 2023 did not proceed as planned due to unavoidable constraints (e.g., the COVID-19 pandemic), the reserve margin declined (Figure 10) as the post-pandemic electricity demand increased. Therefore, in 2025, an additional rapid power supply is required, but carbon emissions are kept in check, making gas-fired power plants a suitable solution. These plants not only maintain system reliability, but also respond to the massive growth of smelters. This strategy aligns with existing research suggesting that the initial stage of the energy transition involves the switch from coal to gas [4,5,15,44].

Second, timely execution of renewable energy projects – Reducing dependence on existing coal and gas power plants requires accelerated renewable energy development, including hydropower, wind, solar, bioenergy and waste-to-energy plants. The deployment of large-scale solar photovoltaic is proposed for 2027-2030, following the Indonesian energy transition roadmap. Floating

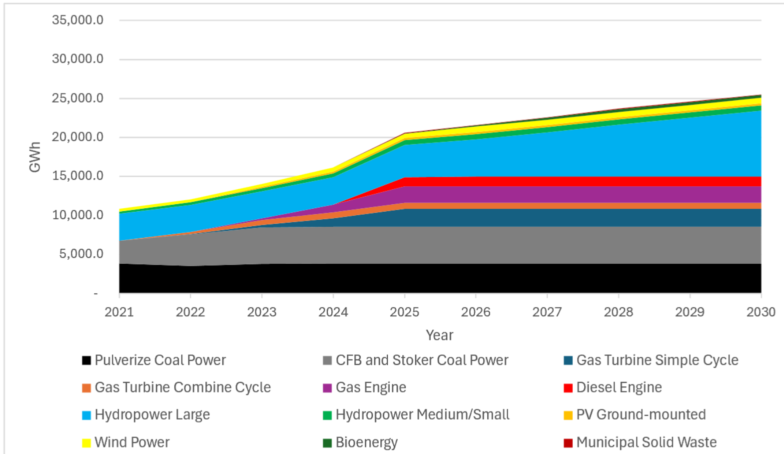

Figure 8: *Electricity generation (GWh) under the RUPTL 21 scenario for Southern Sulawesi's System (2021-2030)*

solar PV, particularly post-implementation of PLN's largest floating PV project in Cirata (192 MWp), completed in just two years, presents a viable option for further development in South Sulawesi's lakes [41].

Third, mass implementation of co-firing in coal-fired power plants – Implementing biomass co-firing in CFB and Stoker coal-fired power plants is crucial to increase the renewable energy mix and reduce coal consumption. This measure is prioritized for the CFB and Stoker boiler plants, as their implementation feasibility is higher compared to the pulverized coal power plants [41]. Since not all coal-fired power plants in Southern Sulawesi are owned by PLN, specific policy measures are required to encourage Independent Power Producers (IPPs) to adopt co-firing. A carbon tax could be a key policy incentive, pushing IPP-operated coal plants to seek emission reduction solutions, including biomass co-firing.

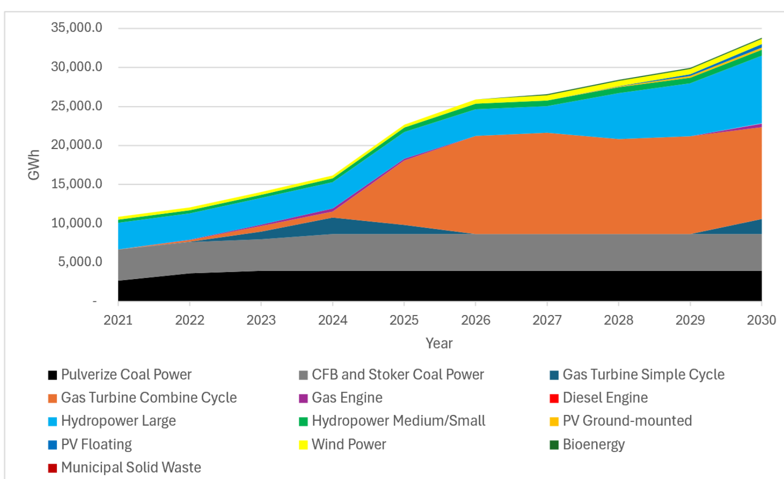

Figure 9: *Electricity generation (GWh) under the SUL scenario for Southern Sulawesi's System (2021-2030)*

Ultimately, the SUL scenario is the most viable approach to achieve emission reduction targets, meet the goal of the renewable energy mix, and meet the massive electricity demand from high-voltage smelters. In this scenario, 35% of the Southern Sulawesi electricity production comes from renewable energy.

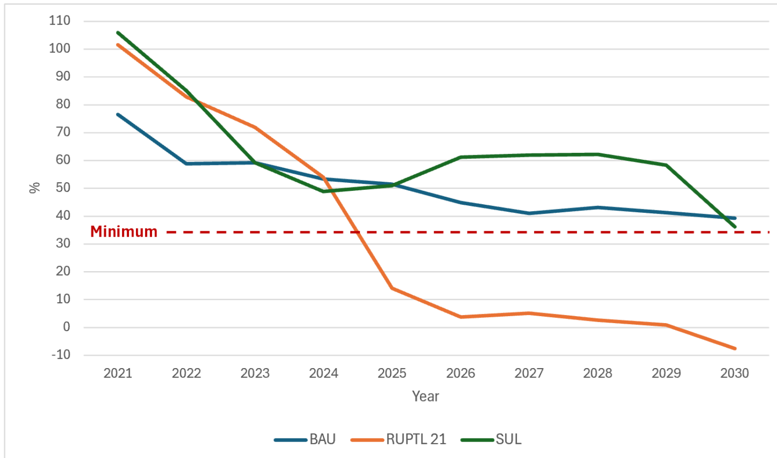

Figure 10: *Reserve margin across all scenarios for Southern Sulawesi's Electricity System (2021-2030)*

Figure 11 summarizes the total installed capacity across the three scenarios by 2030. They are 6.2 GW, 4.9 GW, and 6.9 GW for the BAU, RUPTL 21 and SUL scenarios, respectively. However, the mix of renewable energy in each scenario is as follows: BAU scenario: 10. 6%, RUPTL 21 scenario: 50. 7% and SUL scenario: 39. 8%. This shows that while the RUPTL 21 scenario has the highest share of renewable energy, the SUL scenario offers the most balanced approach by ensuring adequate energy supply, cost efficiency, and climate mitigation in response to the increasing demand for energy from smelters.

These outcomes highlight fundamental differences in the behavior of the system in each scenario. The BAU case, although cost-effective, locks the region into a carbon-intensive trajectory with minimal capacity for adaptation to climate goals or policy shifts such as carbon pricing. In contrast, the RUPTL 21 scenario, while ambitious in the deployment of renewable energy, lacks flexibility and is overwhelmed by unexpected demand spikes (illustrating the risk of rigid top-down planning that excludes dynamic industrial load).

The SUL scenario emerges as a resilient and adaptive pathway, blending gas-fired generation for flexibility and reliability with renewable energy to curb emissions. This hybrid strategy mirrors the successful transition models proposed for various countries, such as Indonesia, Vietnam, India, and Japan, where the coal-to-gas transition serves as an interim step toward deeper decarbonization [45–49]. However, the feasibility of the SUL scenario is contingent on timely project execution, supportive regulatory frameworks, and coordinated efforts between PLN and IPPs, especially in biomass co-firing and floating solar PV expansion.

Furthermore, while the SUL pathway does not achieve the highest renewable share, its configuration offers a practical system-wide compromise between affordability, security, and climate alignment, making it a potentially replicable model for other emerging industrial regions in Indonesia and ASEAN.

4.3. Cumulative cost production

Figure 12 presents the cumulative costs of the system in the three modeled scenarios. These costs include the total costs of electricity production along with investment costs for the development

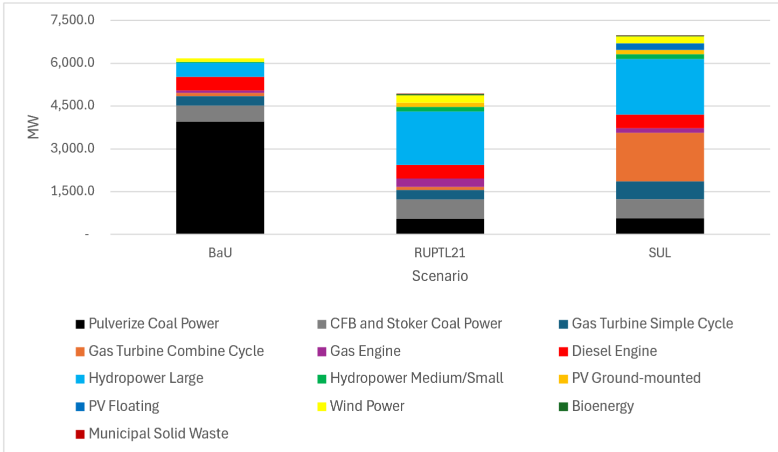

Figure 11: *Comparison of installed capacity in 2030 across all scenarios for Southern Sulawesi's System*

of the power plant during the modeling period (2021–2030). However, transmission network development costs are excluded, as they are beyond the scope of this study.

As predicted, the BAU scenario is the cheapest option for power generation and system development in this model. The most striking aspect in Figure 12 is the high cost in the RUPTL 21 scenario, which is 6.5 times (or 550%) more expensive than the BAU scenario. This occurs because the RUPTL 21 scenario does not account for the sudden surge in electricity demand from high-voltage smelters. As a result, all fossil fuel power plants operate at maximum capacity, leading to a sharp increase in fuel costs. In addition, system reliability constraints force expensive dispatching decisions, leading to inefficiencies in fuel consumption and higher operational costs.

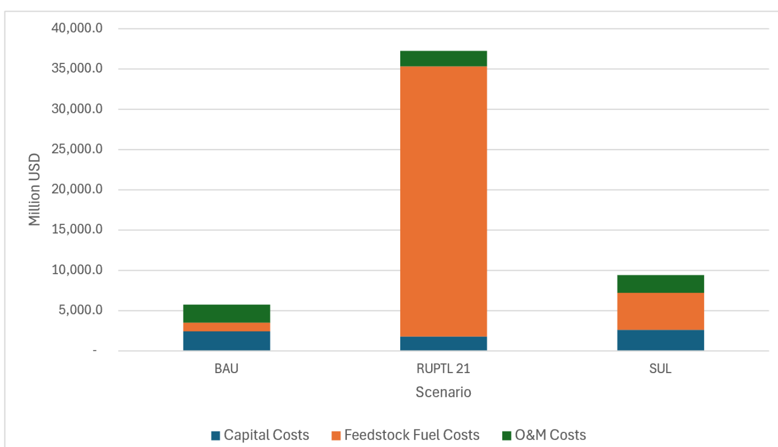

Figure 12: *Cumulative system cost (2021-2030) across all scenarios for Southern Sulawesi's System*

Meanwhile, in the SUL mitigation scenario, the total system cost is 1.6 times (or 65%) higher than in the BAU scenario. The main driver of this cost increase is fuel costs, as natural gas is more expensive than coal. However, investment costs for power plant development remain relatively similar across the scenarios, and operation and maintenance (O&M) costs in the SUL scenario are 2% lower than in the BAU scenario, thanks to the contribution of renewable energy. This cost trade-off, while significant, must be evaluated against the substantial reduction of 48% in GHG emissions achieved under this scenario, which highlights a classic tension in energy transitions between economic efficiency and environmental sustainability.

Compared to other studies, such as Sani et al. (2021) on Sumatra's power system, similar increases in cost were observed when transitioning from coal to gas and renewables [4]. However, these increases were offset by long-term savings from carbon pricing avoidance and improved public health metrics. In this study, the SUL scenario may also be economically justified if Indonesia implements carbon tax policies in the electricity sector, as planned under its enhanced NDC commitments [22].

Furthermore, the levelized electricity cost (LCOE) from solar and wind in Indonesia, based on Lazard's 2023 analysis, continues to decline and could reduce the long-term burden of renewable integration [14]. Therefore, while upfront costs in the SUL scenario are higher, they represent an investment toward system resilience and climate compliance.

4.4. Estimation of GHG emission

Figure 13 illustrates annual GHG emissions across all scenarios in the Southern Sulawesi Power Sector. Greenhouse gas emissions increase significantly in all scenarios. In the BAU scenario, GHG emissions nearly quadruple, rising from 2.8 MTonCO_2eq to 11.1 MTonCO_2eq by 2030. In this scenario, emissions are mainly contributed by coal-fired power plants, which account for 4.5 GW of the total installed capacity of 6.1 GW in 2030. This aligns with the assumption of the BAU scenario that continued expansion of coal power plants leads to severe environmental impacts, particularly in terms of global warming.

The sharp increase in GHG emissions under BAU is a direct result of the system's heavy reliance on coal, with minimal integration of renewable or low-carbon alternatives. The emission trajectory reflects a carbon-intensive pathway that contradicts Indonesia's climate goals, including its improved NDC target of 43.2% emissions reduction by 2030 [22].

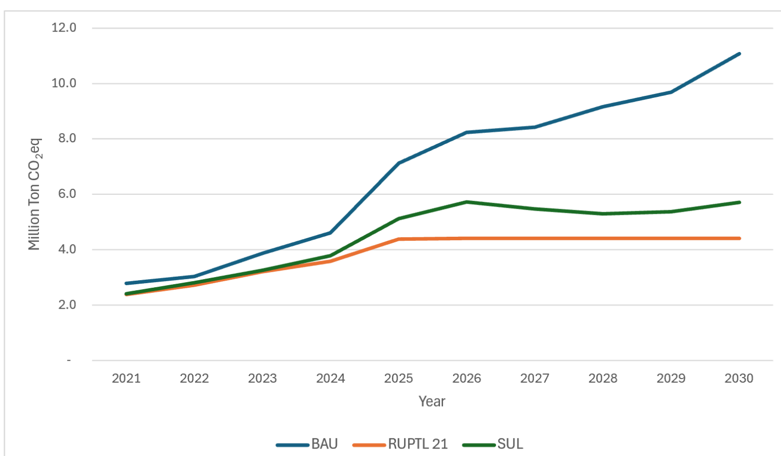

Figure 13: *Comparison of GHG emissions in the power generation sector of Southern Sulawesi's System*

In the National Plan (RUPTL 21) scenario, the emission trend follows the growth of the load in the Southern Sulawesi system. This scenario incorporates climate mitigation efforts, making it a more sustainable approach. By 2025, greenhouse gas emissions will be reduced by 38% compared to the BAU scenario. However, this reduction cannot be sustained, as the massive increase in the demand for electricity from the smelters between 2023 and 2025 strains the system, pushing the reserve margin below the minimum threshold, as shown in Figure 10.

The inability of the RUPTL 21 scenario to maintain emission reductions is mainly due to the overreliance on peak power plants based on fossil fuels, as renewable installations are behind the surge in demand. This illustrates the systemic weakness of renewables only planning when the growth of industrial loads is underestimated or excluded during the planning phase.

Meanwhile, in the SUL scenario, GHG emissions are reduced to 5.7 $MTonCO_2eq$, which is a 48% reduction compared to BAU, aligning with Indonesia's Enhanced NDC (ENDC) target of 43.2% emission reduction by 2030. This scenario reduces the generation of coal power, in accordance with Indonesia's Net Zero Emission (NZE) roadmap, and replaces it with gas-fired power plants and renewable energy sources. Due to the share of renewable energy 35% in the Southern Sulawesi electricity system, this scenario successfully meets the national renewable energy mix targets of 23% by 2025 and 31% by 2050.

These findings are consistent with studies such as Handayani et al. (2017), which highlighted that emission reductions are more robust when fossil fuel displacement is accompanied by gas integration and strategic expansion of renewables [5]. Compared to Java-Bali and Sumatra systems, the relatively high baseline share of renewable energy in Southern Sulawesi further improves the mitigation potential when properly managed.

However, the success of this scenario depends on infrastructure readiness, policy enforcement (e.g. carbon pricing), and stable gas supply (factors that require significant institutional and financial support). Thus, while technically feasible, the SUL scenario requires systemic coordination and long-term planning to ensure that its climate benefits are fully realized.

4.5. Insights

Based on the analysis conducted, several key insights have been identified for the future development of the power generation sector in the Southern Sulawesi electricity system.

First, without climate mitigation, the Southern Sulawesi power sector will remain locked into coal dependency. This is evident in the BAU scenario, where power generation in Southern Sulawesi is heavily dependent on coal-fired power plants. These plants offer the lowest-cost option with high efficiency, making the cumulative system cost significantly lower than in the other two scenarios. However, this approach leads to a continuous increase in GHG emissions and has the potential to incur additional costs if a carbon tax is implemented in Indonesia's power sector.

Second, the current development of the power sector based on the Electricity Supply Business Plan 2021-2030 has begun to adopt climate mitigation measures. This is reflected in the declining GHG emissions trend compared to the BAU scenario. The mix of renewable energy is also being aggressively developed to meet national targets. However, a major challenge arises from the significant increase in electricity demand from high-voltage smelter customers, which makes the system increasingly vulnerable. As a result, power sector planning needs to be updated to accommodate this demand.

Third, an optimal strategy is needed to balance electricity demand with climate mitigation goals, achieving a renewable energy mix of up to 35%, as shown in Figure 14. This scenario focuses on replacing coal-fired power plants with gas-fired power plants to reduce GHG emissions while simultaneously developing large-scale renewable energy projects, including hydropower, solar and wind power. The findings indicate that the adoption of renewable energy technology will be crucial for the Southern Sulawesi power system to aggressively reduce GHG emissions. However, while this scenario successfully balances emission reduction and energy adequacy, it results in a 65% higher system cost than the BAU scenario. This raises a critical question: Can domestic natural gas supply meet this demand, or will LNG imports be required for sustainability?

This transition pathway aligns with best practices globally in energy modeling, where a coal-to-gas switch serves as a practical entry point for decarbonization while maintaining the reliability of the system [4,7]. However, its feasibility hinges on affordable gas availability, strong carbon pricing policies, and the active role of Independent Power Producers (IPPs) in biomass co-firing. Without these supporting mechanisms, the energy transition may stagnate, similar to concerns raised in recent evaluations of Indonesia's Just Energy Transition Partnership (JETP) [13].

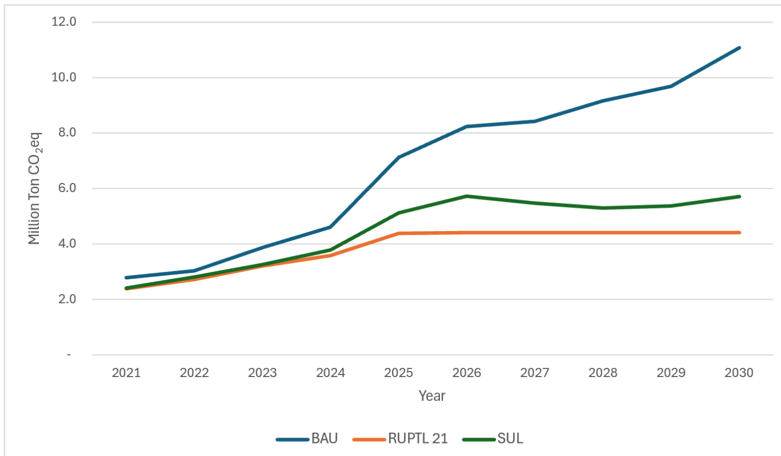

Figure 14: *Comparison of renewable energy contribution to electricity production in Southern Sulawesi's System*

Fourth, the role of renewable energy in the Southern Sulawesi power sector is crucial. In the SUL mitigation scenario, the share of renewable energy in the production of electricity in Southern Sulawesi reaches 35%, as shown in Figure 14. At the beginning of the modeling period, Southern Sulawesi already had a high share of renewable energy. However, because of the significant increase in the electricity demand from smelters, the contribution of renewable energy declined. Based on our observations, Southern Sulawesi's renewable energy potential is promising and could restore the region's renewable energy share. The development of large-scale hydropower and solar power presents a viable option to increase the mix of renewable energy, aligned with climate mitigation and national policies. The success of the Cirata floating solar photovoltaic project could serve as a reference point for similar projects in Southern Sulawesi, given the availability of large reservoirs in the region. Floating solar photovoltaic mitigates land constraints while improving the operational efficiency of the solar panel. However, further studies are required to assess the feasibility of floating solar PV deployment in Southern Sulawesi.

Compared to the Net Zero scenarios of the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) for Southeast Asia, the share of renewable energy of the SUL scenario 35% by 2030 falls within realistic mid-range targets [7,8]. This indicates that, although it is not the most ambitious option, the scenario is technically and institutionally feasible, especially if the planning and policy measures are refined accordingly.

5. Conclusion

The findings of this study highlight the urgent need for strategic planning in the Southern Sulawesi electricity system to accommodate the rapidly growing energy demand - primarily driven by the smelting industry - while ensuring a sustainable and low carbon future. The analysis demonstrates that, without targeted intervention, coal will continue to dominate electricity generation, exacerbating greenhouse gas emissions and undermining Indonesia's decarbonization commitments.

The transition from coal to natural gas, accompanied by the large-scale deployment of renewable energy and co-fire strategies using biomass in existing coal-fired power plants, is essential to achieving a cleaner and more resilient energy mix. The proposed scenario for Southern Sulawesi indicates that a share of renewable energy 35% by 2030 is achievable, with the potential to reduce emissions by 48% compared to the Business-as-Usual scenario. This hybrid pathway - which integrates the flexibility of gas, the sustainability of renewables and the contribution of biomass through co-firing - offers a technically feasible and policy-responsive roadmap.

To enable this transformation, supportive measures are required, including targeted fiscal incentives for renewable energy, improved spatial and sectoral coordination in electricity planning, and market-based mechanisms such as carbon pricing to accelerate clean technology adoption. Furthermore, the transition requires coordinated efforts from government, energy providers and industrial stakeholders to ensure timely policy implementation, investment mobilization, and the deployment of advanced energy technologies.

Although this study offers a timely assessment of possible decarbonization trajectories for Southern Sulawesi, it did not include a quantitative sensitivity or uncertainty analysis due to the exploratory nature of the scenario design and the absence of sufficient empirical data at the time of modeling. Future studies are encouraged to incorporate probabilistic sensitivity testing and parameter variation to validate and strengthen the robustness of scenario-based insights.

By taking decisive action today, Southern Sulawesi has the potential to become a national model, showcasing how rapid industrial growth can be harmonized with climate goals through strategic, adaptive, and evidence-based energy planning.

Declaration of interest: The authors declare no conflicts of interest.

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