



Operational Planning Study of Sulawesi Grid

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Abbreviations

AC	Alternating Current	PLTB	Wind Power Plant
AGC	Automatic Generation Control	PLTBG	Biogas Power Plant
ACSR	Aluminum Conductor Steel-Reinforced	PLTBM	Biomass Power Plant
BESS	Battery Energy Storage System	PLTD	Diesel Engine Power Plant
BPP	Generation cost in IDR/kWh	PLTG	Gas Turbine Power Plant
CAPEX	Capital Expenditure	PLTGM	Gas Engine Power Plant
CCGT	Combined Cycle Gas Turbine	PLTGU	Combined Cycle Power Plant
CF	Capacity Factor	PLTM	Microhydro Power Plant
COD	Commercial Operation Date	PLTMG	Gas Engine Power Plant
DC	Direct Current	PLTP	Geothermal Power Plant
DFR	Digital Fault Recorder	PLTS	Photovoltaic Power Plant
DPL	DIgSILENT Programming Language	PLTU	Steam (most often coal-fired) Power Plant
DSL	DIgSILENT Simulation Language	PPA	Power Purchase Agreement
DSM	Demand Side Management	PSS	Power System Stabilizer
DSO	Distribution System Operator	PV	Photovoltaic
ECE	Executive Committed Energy	PyPSA	Python for Power System Analysis
EMS	Energy Management System	RE	Renewable Energy
FACTS	Flexible AC Transmission Systems	REEP	Renewable Energy for Electrification, GIZ programme
FIT	Feed-In Tarriff	RKEF	Rotary Kiln - Electric Furnace
FLISR	Fault Location Isolation	RoCoF	Rate of Change of Frequency
FO&M	Fixed Operation and Maintenance Cost	RUPTL	Indonesian national 10 year energy plan
GDP	Gross Domestic Product	SCADA	Supervisory Control and Data Acquisition
GI	Substation	SCOPF	Security Constrained Optimal Power Flow
GI	Gardu Induk, substation	SLD	Single Line Diagram
IBT	Inter Bus Transformer	SPC	Static Power Compensator
IPP	Independent Power Producer	SPJBTL	Contract for industrial load
LNG	Liquified Natural Gas	STATCOM	Static Synchronous Compensator
LVRT	Low Voltage Ride Through	Sulbagsel	Southern Sulawesi subsystem
MFO	Marine Fuel Oil	Sulutgo	Norther Sulawesi subsystem
MILP	Mixed Integer Linear Programming	SVC	Static Var Compensators
MoU	Memorandum of Understanding	TOP	Take or Pay
NPI	Nickel Pig Iron	UIKL	PLN transmission and generation unit
OCGT	Open Cycle Gas Turbine	UIP3B	PLN transmission operation unit
OPEX	Operational Expenditure	VO&M	Variable Operation and Maintenance Cost
OPF	Optimal Power Flow	VRE	Variable Renewable Energy
PLN	Perusahaan Listrik Negara (Indonesian DSO)		
PLTA	Hydro Power Plant		

Executive Summary

Background and Introduction

An operational planning study of the two Sulawesi main power systems was undertaken from 2021 to 2023 by Energynautics. It was commissioned by the Federal Ministry for Economic Cooperation and Development (BMZ)-funded GIZ Implemented Project, 1,000 Islands - Renewable Energy for Electrification Programme Phase 2 (REEP2) to support the Government of Indonesia to achieve the national 23% Renewable Energy (RE) target by 2025.

Indonesian state electricity company PT. PLN (Persero) will face challenges in power system operation in Sulawesi as industrial load from nickel smelter operations is expected to grow significantly, while additional variable renewable energy (VRE) and hydro power capacities are added to the system.

Status Quo

The 20 million inhabitants of the island of Sulawesi are supplied with two transmission systems using mainly 150 kV transmission voltage, with some 275 kV backbone structures recently added (Figure 1). In 2021, the southern subsystem, Sulbagsel, had a peak load of 1600 MW and total generation of 9334 GWh. The northern subsystem, Sulutgo, had a peak load of 430 MW and a total generation of 2755 GWh.

Generation in both Sulawesi subsystems are on the one hand dominated by coal, which contributes approx. 50% of generation capacity, but on the other hand, both systems already exceed the 23% renewable electricity target the government has set for 2025. Coal capacity is supplemented by hydro, wind and gas-fired generation in Sulbagsel (approximately 32% RE share), and geothermal, hydro and PV in Sulutgo (41% RE share) (Figure 2).

Figure 1: Sulawesi transmission grid, status 2022.

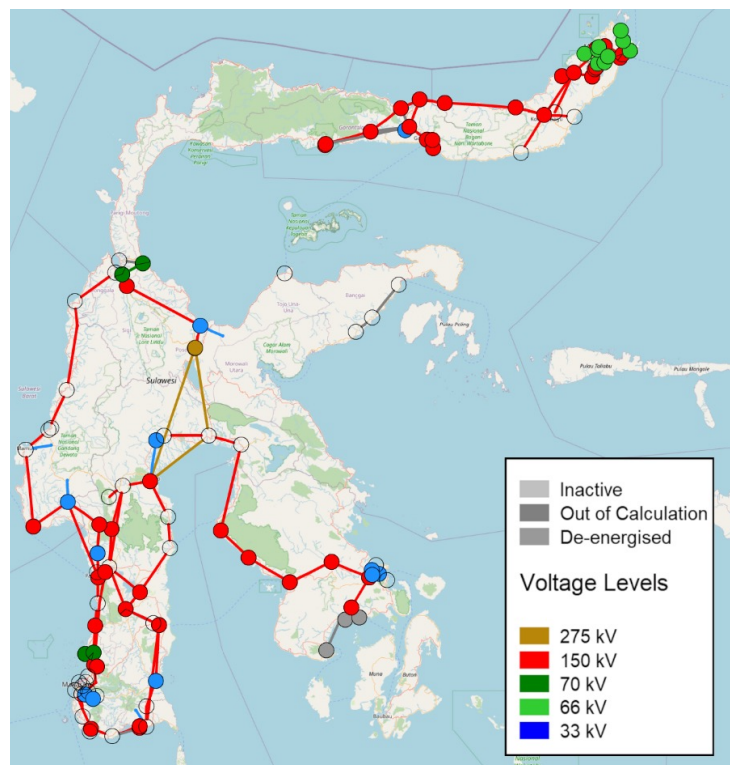
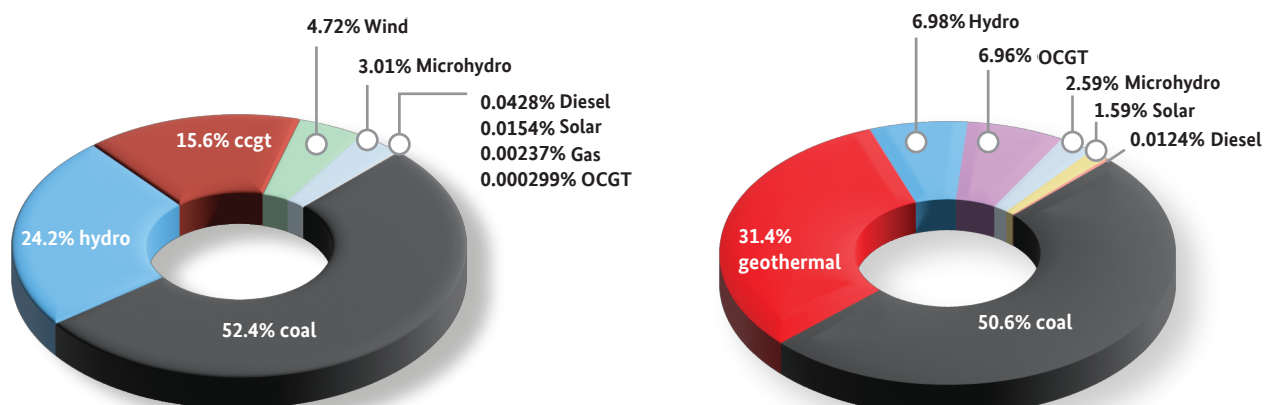


Figure 2: Generation mix in Sulbagsel (left) and Sulutgo (right).



Methodology and Inputs

The objective of the study is the development of recommendations for PLN UIP3B Sulawesi on how to operate the two Sulawesi power systems at increased variable renewable energy (VRE) and smelter penetration levels until 2025 and which strategies and technologies to use.

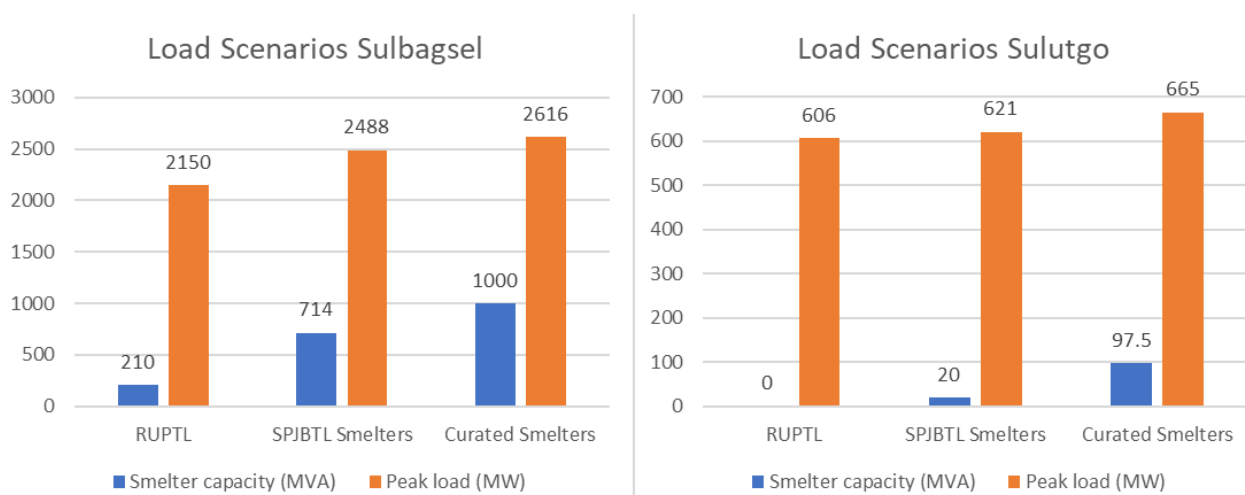
Expected challenges include both system adequacy (the capability of the system to supply the load with sufficient generation and grid capacity) as well as system stability (the capability of the system to maintain stable operation at disturbances). The operational study hence incorporates the following parts:

- Production simulation for a whole year in annual resolution, using mixed-integer linear programming (MILP) optimisation in the grid simulation framework PyPSA
- Steady state electrical analysis (load flow calculation) of key situations in DIgSILENT PowerFactory
- Dynamic stability analysis for key events in DIgSILENT PowerFactory

This analysis was conducted for a number of different demand growth scenarios for each of the two subsystems as well as for a case in which both are connected to form an all-Sulawesi transmission system (this interconnection is currently planned for 2026/27).

The scenarios hence included three systems – Solutgo, Sulbagsel and interconnected – as well as three different demand projections (Figure 3). A high smelter scenario was curated based on current connection applications.

Figure 3: Load scenarios considered in the study for both subsystems in 2025

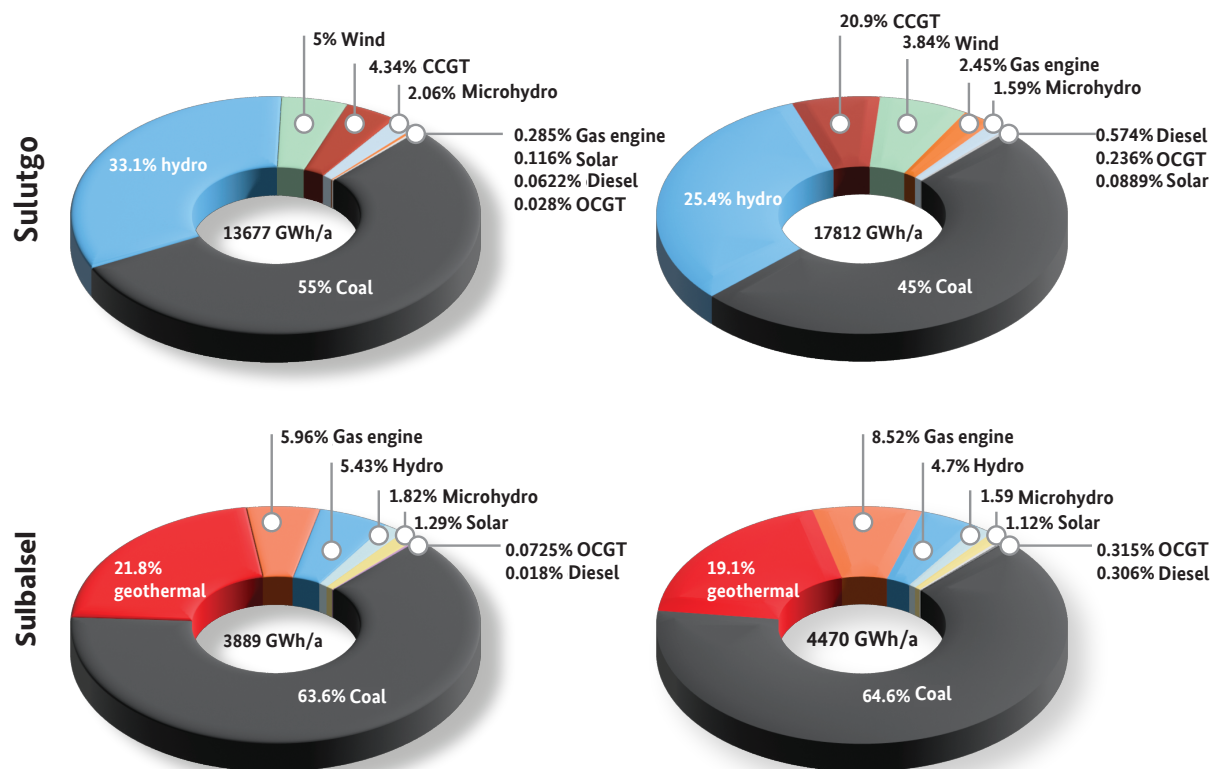


Generation capacity in both subsystems was expanded according to the RUPTL 2021-2030, with the most notable additions being a gas engine powerplant in Solutgo and a large CCGT, some additional hydro capacities and a new wind power plant in Sulbagsel.

Results

The impact of increasing industrial demand on the generation mix in both systems is shown in Figure 4. **Without more smelters, renewable energy share in Sulbagsel increases from 32% in 2021 to approximately 40% in 2025, mainly owing to new hydro resources and optimised use of existing hydro reservoirs. Rising smelter demand is, however, mainly covered by gas-fired generation, reducing the overall RE share.** For Solutgo, the impact is less severe, but rising demand tends to reduce the RE share there as well, as currently underutilised coal capacities. The generation cost (BPP) remains relatively stable in both systems, approx. 1000 IDR/kWh in Sulbagsel and approx. 1700 IDR/kWh in Solutgo.

Figure 4: Total annual generation and electricity mix in both systems for the RUPTL scenario (no additional smelter load) and Curated Smelters scenario (highest additional smelter load) in 2025



The transmission grid in both systems is generally adequate to cover rising demand, especially with the planned expansion of 150 and 275 kV transmission grid in the eastern part of the Sulbagsel system, where most smelters are expected to be connected. Minor congestion is observed in western Sulbagsel, but it can be resolved via redispatch at relatively low cost. Sulutgo is congestion free. **Both systems, however, show a need for reactive power compensation to mitigate voltage issues.** These largely come from low grid utilisation, especially in newly expanded grid areas and in scenarios with low smelter demand (Figure 5, Figure 6). Some smelter connections to existing 150 kV structures also require compensation to mitigate undervoltage.

Figure 5: Generation and load distribution 2025 (RUPTL scenario) and 2021, to show voltage issues in eastern Sulawesi.

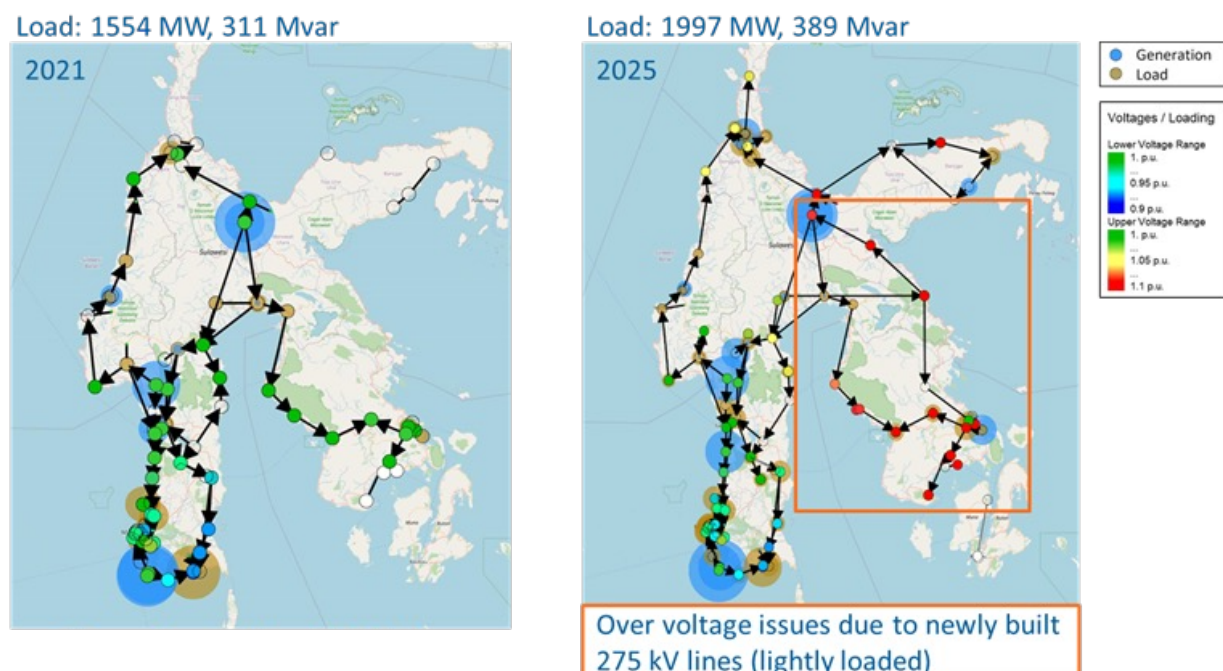
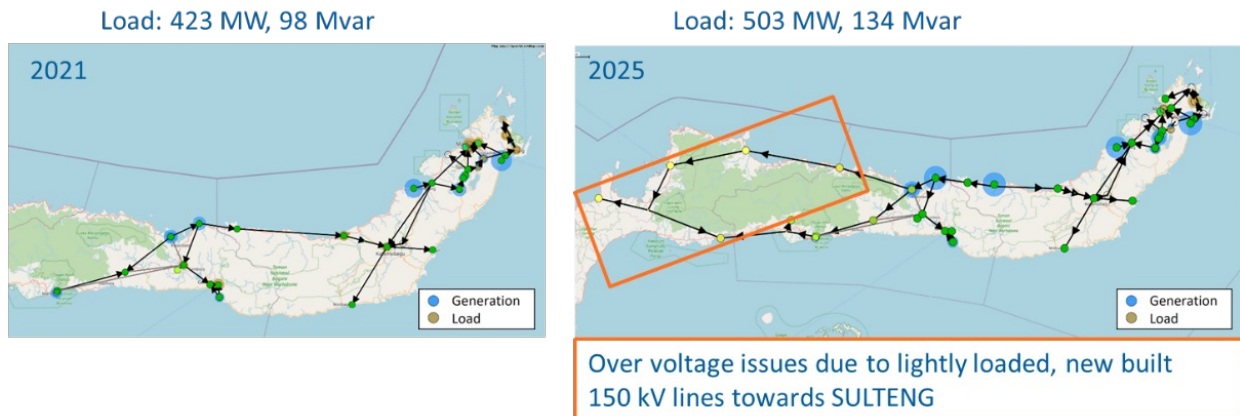
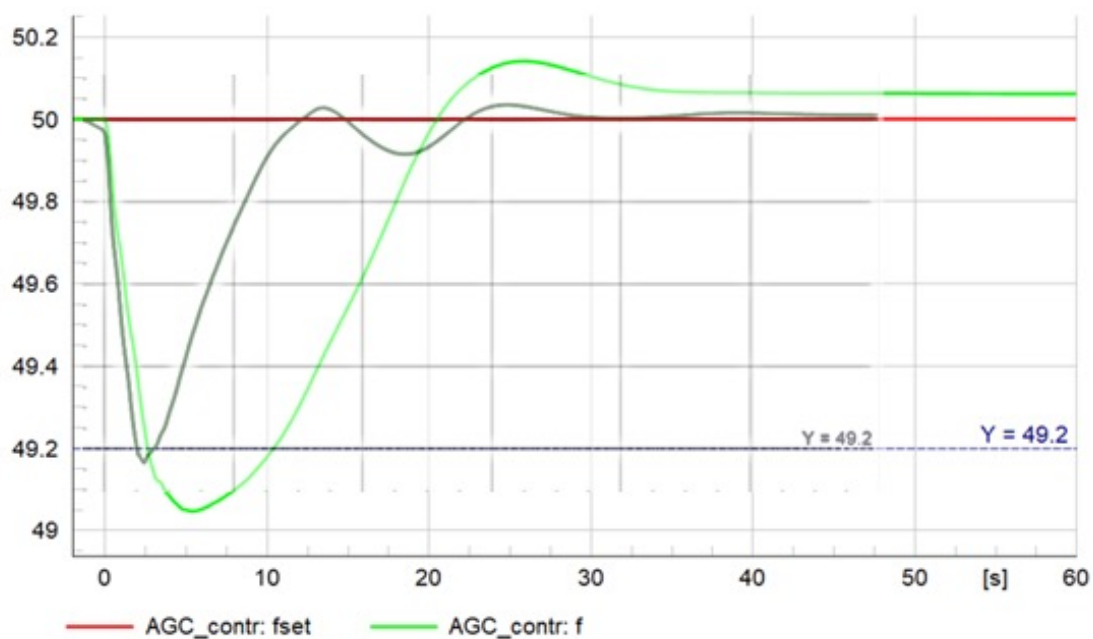


Figure 6: Overvoltage issues in the western part of the Sulutgo grid.



With the given scenarios and the current frequency control strategy carried over into 2025, **both systems can maintain their stability and operational security level**. Large generation contingencies continue to be the most critical cases and often lead to underfrequency load shedding. As shown in dynamic stability analyses, **frequency stability in both systems greatly profits from PLN's current efforts to activate primary control governors on all large generation units**, including IPPs (Figure 7). The improved frequency response also **enables the integration of larger shares of VRE** – in fact, progress in the activation scheme is one of the key factors for the successful integration of the existing wind power plants in Sulbagsel since 2019. This strategy achieves better frequency stability at relatively low cost. No extra large reserve capacities are needed if all units display the frequency sensitivity as outlined in the current Sulawesi grid code.

Figure 7: Frequency trace at large generation loss, with governors active on all units (grey) and with governors active only on hydro units that are dispatched for primary control (green).



No further significant stability issues were found for separate operation of both systems. **If the two systems are connected with a double 150 kV transmission line to form an all-Sulawesi power system, which is currently targeted for 2026/27, stability problems, however, arise.** Dispatch results show that the interconnection, theoretically allowing for transfer of up to 150 MW between the systems, has relatively little economic benefit in the short term (Table 1).

Table 1: Generation cost evaluation of individual and interconnected scenarios in 2025

	RUPTL		SPJBTL		Curated	
	Demand (GWh)	BPP (IDR/kWh)	Demand (GWh)	BPP (IDR/kWh)	Demand (GWh)	BPP (IDR/kWh)
Sulutgo ind.	3889	1641.74	4008	1620.75	4470	153695
Sulbagsel ind.	13677	997.7	16707	968.92	17812	993.18
Combined	17566	1140	20715	1095	22282	1102
Interconnected	17566	1130	20715	1079	22282	1093

This small benefit is reduced even further as dynamic stability analysis shows **that interconnector flows of more than 50 MW make the system highly dynamically unstable** (Figure 8). Generation groups in Sulutgo and Sulbagsel tend to lose synchronicity especially in short circuit cases. This is a result of bridging a fairly long distance with a comparatively low-voltage 150 kV interconnector. **It is recommended to reconsider the interconnector design and potentially use a 275 kV structure – or to continue separate operation.**

Figure 8: Loss of stability on the interconnector after a fault in Sulbagsel, interconnected SPJBTL scenario 2025. From top to bottom: Active power flow on interconnector, voltage at interconnector terminals, voltage against active power, voltage angle across interconnector.



Key Results: Sulbagsel 2025



Generation Cost (BPP):

990 – 1000 IDR/kWh, no significant deviation from today



Generation Adequacy: Planned generation fleet can supply all committed and planned smelters, but is not sufficient to cover the load of all potential smelters. Calculations assume optimised operation of PLTA Poso and PLTA Malea, increasing their capacity factors.



Grid Adequacy: Grid is generally adequate to supply the load in all cases. The additional cost of (n-1) security is 5-10 IDR/kWh (0.5-1% of BPP), indicating only minor congestion, mainly in the southwest. A 150 kV line reinforcement is required in Palu if a large smelter is connected there. Some 150 kV connected smelter installations require capacitors, and the new 275 kV structure requires reactors to keep voltage within boundaries.



Stability: No major stability issues. Large generation contingencies trigger underfrequency load shedding, but the system remains stable. Activation of free governors on all large units has an observable positive impact. Minor oscillations between eastern and western generation groups can be observed, but remain damped.



RE Share: 40% RE share (mainly by optimisation of hydro resources) without additional smelter demand, but share drops with rising demand that is covered primarily with gas (30% RE in high smelter scenario).



VRE Integration Issues: Wind fluctuations introduce major frequency swings if only designated hydro units provide primary control. Free governor activation on all large units eliminates this problem without explicitly dispatching more spinning reserve or load-following generation.

Key Results: Sulutgo 2025



Generation Cost (BPP): 1550 – 1650 IDR/kWh, no significant deviation from today, but additional cost of coal TOP is neglected due to lack of information.



Generation Adequacy: Planned generation fleet can supply all potential smelters. System is overinstalled with baseload capacity.



Grid Adequacy: Grid is adequate to supply the load in all cases. No additional cost of (n-1) security, indicating no congestion. The 150 kV expansion in the western system either needs reactors for voltage control, or can only be operated as single circuits.



Stability: No major stability issues. Large generation contingencies trigger underfrequency load shedding, but system remains stable. Free governor contribution from all major generation units required.



RE Share: 30% RE share without additional smelter demand, but share drops with rising demand that is covered primarily with coal (26% RE in high smelter scenario). Coal share > 60% in all scenarios.



VRE Integration Issues: With free governors on all units, the system can absorb higher shares of PV. VRE shares are low in all investigated scenarios.

Key Results: Interconnection



Transfer Capacity: Interconnector initially assumed to be limited to 150 MW to retain (n-1) security (trip of one of the two circuits).



Power Transfers: Sulutgo increasingly exports baseload power to Sulbagsel as smelter load increases (150 – 550 GWh/a). Sulbagsel exports in peak situations (100 – 380 GWh/a).



Economic Impact: Only very slight savings in overall BPP (< 1 %) in 2025, total impact requires multi-year analysis which was not conducted.



Stability: Transient stability issues limit interconnector flows to less than 50 MW. System will go into blackout at almost any disturbance if the interconnector runs at a higher loading. This eliminates all economic benefit of the interconnector. Redesign with higher voltage level as well as series compensation and other stabilizing measures is highly recommended.





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