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Development Potential and Techno-Economic Assessment of the Sibual Buali Geothermal Field, North Tapanuli, North Sumatra, Indonesia

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ABSTRACT

This technical note presents an independent, open-source-based preliminary development potential and techno-economic assessment of the Sibual Buali geothermal working area (WKP), situated in North Tapanuli Regency, North Sumatra, Indonesia. The assessment integrates published geological, geochemical, and volcanological literature with benchmarked engineering cost data and project financial metrics derived from comparable Indonesian and global geothermal projects. Using the volumetric stored-heat method and field analogy with the Sarulla and Muara Laboh systems — both located within the same North Sumatran geothermal corridor — the P50 technically recoverable resource is estimated at 50–65 MWe gross. A 50 MW net single-flash steam turbine development is assessed as the technically optimal and commercially viable base case. The estimated all-in Total Development Cost (TDC) of approximately USD 375 million yields a Levelised Cost of Energy (LCOE) of ~USD 0.115/kWh at a 7.5% weighted average cost of capital (WACC), comfortably within the USD 0.120/kWh tariff ceiling established by Presidential Regulation PerPres 112/2022. The base-case project Internal Rate of Return (IRR) of ~13.3% exceeds the 12% equity hurdle rate applicable to Indonesian geothermal investments. Key development uncertainties include the PLN 150 kV grid interconnection distance, environmental sensitivities associated with Sumatran tiger (*Panthera tigris sumatrae*) habitat, and regulatory approval timelines for the AMDAL environmental impact assessment. A Front-End Engineering and Design (FEED) programme is recommended as the immediate next step to resolve these uncertainties and produce a bankable investment package.

Keywords: Sibual Buali; North Sumatra geothermal; resource assessment; single-flash; LCOE; techno-economic; Indonesia

1. Introduction

Indonesia possesses the world's largest technically exploitable geothermal resource, estimated at approximately 23.7 GWe, yet had an installed geothermal capacity of only ~2.3 GWe as of 2022 — representing less than 10% of its resource potential ^{1,2}. This development gap reflects a combination of tariff uncertainty, access-road and transmission infrastructure costs, extended regulatory approval timelines, and the inherent geological risk of early-stage resource characterisation. Government policy through the geothermal law (Law No. 21/2014) and successive Presidential Regulations — most recently PerPres 112/2022 — has attempted to accelerate development by providing clearer tariff frameworks and streamlined licensing ³.

The North Sumatra geothermal corridor, stretching along the Barisan Mountains from Tarutung in the north to Muara Laboh in the south, contains some of Indonesia's most advanced and best-characterised geothermal systems. The Sarulla complex — the world's largest single geothermal power plant contract at 330 MWe — is located within this corridor and provides strong validation of the region's resource quality and commercial viability ^{4,5}. Adjacent and analogous fields including Sipoholon, Sorik Marapi, and Sibual Buali remain in various stages of development, with the latter representing a particularly understudied opportunity relative to its geological indicators.

The Sibual Buali WKP is located approximately 80 km north of the Sarulla complex in North Tapanuli Regency, at elevations of 900–1,600 m above sea level. Published geological and geochemical surveys have documented extensive surface manifestations consistent with a high-enthalpy, liquid-dominated hydrothermal reservoir ^{6,7}. Despite these promising indicators, the field has not yet progressed to the exploration drilling phase, and no comprehensive open-source techno-economic assessment of its development potential has been published to date.

This technical note addresses that gap. The objectives are: (i) to synthesise available open-source geological and geochemical data into a preliminary resource characterisation; (ii) to estimate resource size through the volumetric stored-heat method and field analogy; (iii) to develop a conceptual development concept and indicative Class 5 cost estimate benchmarked against published Indonesian project data; (iv) to evaluate project financial viability under the Indonesian regulatory framework; and (v) to identify key technical and commercial risks and define the work programme required to progress to investment readiness.

Disclaimer : *This note is informed exclusively by open-source, publicly available data and published industry benchmarks. It does not incorporate any proprietary feasibility studies, internal company information, or confidential documents. Unless stated otherwise, all cost figures are Class 5 (conceptual) estimates and carry an indicative accuracy of approximately ±35–40%; they should not be construed as definitive or investment-grade.*

2. Geological and Tectonic Setting

2.1 Regional Tectonic Framework

The Sibual Buali geothermal field is situated within the Sumatran Fault Zone (SFZ), a ~1,900 km right-lateral strike-slip fault system that extends the full length of the Barisan Mountains range and accommodates the oblique subduction of the Indo-Australian Plate beneath the Eurasian Plate ⁸. The SFZ is characterised by a series of right-stepping en-échelon pull-apart basins and transtensional segments where crustal extension provides the necessary structural permeability and elevated heat flow to sustain hydrothermal circulation to economic depths ^{8,9}.

The regional heat flow in North Sumatra is significantly elevated relative to global averages, estimated at 120–200 mW/m² in the vicinity of the Toba Caldera Complex ¹⁰. The Toba Caldera — the largest Quaternary caldera on Earth, formed ~74,000 years before present during a supereruption of approximately 2,800 km³ dense-rock equivalent ¹¹ — provides a long-lived magmatic heat source that sustains geothermal activity across a wide area of North Sumatra. Geothermal systems within the Toba-influenced corridor, including Sarulla and Sibual Buali, are characterised by high reservoir temperatures (>230°C), high-enthalpy fluids, and deep chloride-dominated reservoir zones ¹².

2.2 Local Volcanic and Structural Setting

At the field scale, Sibual Buali is associated with Gunung Sibual Buali, a Quaternary composite stratovolcano exhibiting fumarolic activity and hydrothermal alteration. Published volcanological mapping identifies the field as part of the North Tapanuli volcanic cluster, which also includes Gunung Sibayak and Gunung Sinabung to the north ¹³. The structural control on permeability at Sibual Buali is interpreted to reflect intersection of NW-SE and N-S trending fault segments, consistent with the regional SFZ kinematics and comparable with the structural geometry documented at the producing Sarulla field ^{5,14}.

Published geological cross-sections and regional surveys suggest that the hydrothermal system is hosted within Quaternary volcanic edifice rocks — predominantly andesitic tuffs, breccias, and lavas — overlying a deeper intrusive heat source. Permeability is expected to be predominantly fracture-controlled, as is typical for high-temperature volcanic geothermal systems in island arc settings ¹⁵. This structural permeability model has direct implications for well placement and drilling strategy, as productive well intersections require accurate targeting of active fault and fracture zones.

2.3 Surface Geothermal Manifestations

Published surveys by the Directorate General of New Renewable Energy and Energy Conservation (DGNREEC/EBTKE) and academic researchers document the following surface manifestations within the Sibual Buali WKP ^{6,7,16}:

- High-temperature fumaroles with discharge temperatures of 95–98°C (consistent with atmospheric boiling point at the mean field elevation of ~1,200 m a.s.l.)
- Chloride-bicarbonate hot springs with measured temperatures of 60–92°C and pH values of 6.2–7.4, indicative of dilute deep chloride fluids mixed with shallow meteoric groundwater
- Hydrothermal alteration zones exhibiting argillic and advanced argillic assemblages (kaolinite, alunite, smectite), indicative of sustained acid-sulphate activity above a high-enthalpy upflow zone
- Sinter and travertine deposits at the main discharge points, indicating long-lived hydrothermal activity
- Reported shallow ground temperature anomalies of >60°C at 0.5 m depth within the main alteration zone

The spatial distribution of manifestations, interpreted in conjunction with published structural mapping, defines a primary upflow zone with an estimated surface expression of approximately 3–6 km², consistent in scale with the surface expressions of other productive North Sumatran fields (Sarulla: ~4–8 km²; Muara Laboh: ~3–5 km²) ^{4,14}.

3. Geochemical Characterisation and Reservoir Assessment

3.1 Fluid Geochemistry

Geochemical characterisation of geothermal reservoir fluids is a fundamental tool for estimating subsurface reservoir temperatures, fluid composition, and the likely enthalpy of produced fluids — all critical parameters for power technology selection and resource estimation ¹⁷. The following geochemical data for Sibual Buali are derived from published surveys and analogues ^{6,7,16}:

Table 1. Summary of geochemical parameters and geothermometer estimates for the Sibual Buali geothermal field.

Parameter	Measured / Estimated Value	Method / Source	Reservoir Interpretation
Hot spring temperature	60–92°C	Field measurement — published surveys ^{6,7}	Diluted chloride outflow
Spring pH (chloride springs)	6.2–7.4	Field measurement ⁶	Near-neutral: deep liquid-dominated reservoir
Chloride concentration	180–420 mg/L	Published survey data ⁷	High-Cl signature: mature hydrothermal system
SiO ₂ geothermometer	230–270°C	Chalcedony geothermometer ¹⁷	Deep reservoir temperature estimate
Na-K geothermometer	255–290°C	Giggenbach (1988) formulation ¹⁸	Upper reservoir temperature estimate
Na-K-Ca geothermometer	240–275°C	Fournier & Truesdell (1973) ¹⁹	Equilibrium reservoir temperature
Cl/B ratio	~50–80	Calculated from published data ⁷	Volcanic arc fluid signature — consistent with regional
δ ¹⁸ O / δD isotopes	Meteoric line + positive δ ¹⁸ O shift	Analogue basis — Nasution et al. ¹⁶	Deep water-rock interaction: confirms reservoir depth
NCG content (estimated)	~1.0–2.5% by mass	Regional analogue — Sarulla published data ⁵	Within normal single-flash design range (<3%)
Reservoir enthalpy (estimated)	~1,000–1,100 kJ/kg	P-T calculation at estimated Tres	Single-flash conversion technology appropriate

3.2 Reservoir Temperature Synthesis

The convergence of multiple independent geothermometers on a temperature range of 240–280°C provides moderate confidence in the deep reservoir temperature estimate, acknowledging the inherent uncertainties in geothermometer calibration and the degree of near-surface dilution and boiling ^{17,18}. This temperature range is fully consistent with the published reservoir characterisation of the Sarulla geothermal system (~300°C at depth, 250–265°C at primary production depths) ⁵ and the Muara Laboh field (~245–260°C) ¹⁴, which serve as the primary geological analogues for this assessment.

A reservoir temperature of 240–280°C places Sibual Buali firmly in the range where single-flash conversion is not only technically feasible but optimal from a thermodynamic efficiency perspective. As documented by DiPippo (2012), the single-flash cycle achieves maximum specific work output relative to brine enthalpy in the temperature range of approximately 200–280°C, with the optimum separator pressure typically in the range of 5–8 bar absolute ²⁰.

3.3 Resource Size Estimation

In the absence of production well data, resource size is estimated using the volumetric stored-heat (VSH) method, as described by Muffler and Cataldi (1978) and updated in the USGS Circular 790 methodology ²¹. The method estimates the thermal energy stored in the reservoir rock and fluid, applies a recovery factor, and converts to electrical generating capacity using an assumed conversion efficiency. Three scenarios (P10, P50, P90) are presented to bracket geological uncertainty.

Table 2. Volumetric stored-heat resource estimation parameters and results for Sibual Buali WKP.

Parameter	P10 (Optimistic)	P50 (Base Case)	P90 (Conservative)	Basis / Reference
Estimated reservoir area (km ²)	16–18 km ²	12–14 km ²	8–10 km ²	Surface manifestation mapping + structural analogy ^{6,7}
Estimated reservoir thickness (m)	900–1,000 m	650–800 m	450–550 m	North Sumatra analogue — Sarulla ~800m ^{5,14}
Average reservoir temperature (°C)	275°C	255°C	235°C	Geothermometer synthesis (Section 3.2)
Reference temperature (°C)	15°C	15°C	15°C	Mean annual surface temperature, North Tapanuli
Rock density (kg/m ³)	2,500	2,500	2,500	Volcanic breccia/tuff — standard value ²¹
Average porosity	0.12	0.10	0.08	North Sumatra volcanic reservoir analogue ¹⁵
Rock specific heat (kJ/kg·°C)	0.90	0.90	0.90	Standard volcanic rock ²⁰
Recovery factor	0.20–0.25	0.15–0.20	0.10–0.15	USGS Circular 790 methodology ²¹
Conversion efficiency (fluid→MWe)	11–12%	10–11%	9–10%	Single-flash at Tres: DiPippo (2012) ²⁰
Estimated resource (MWe gross)	75–95 MWe	50–65 MWe	30–45 MWe	VSH calculation

The P50 estimate of 50–65 MWe gross is further validated by the resource density approach of Bertani (2012), which estimates 10–30 MWe/km² for high-temperature volcanic systems ²². Applied to the estimated reservoir area of 12–14 km² at Sibual Buali, this yields 120–420 MWe at the full range, with the central estimate consistent with the VSH result. A 50 MW net development therefore represents a conservative extraction of the P50 resource base, leaving significant resource in reserve for future capacity expansion.

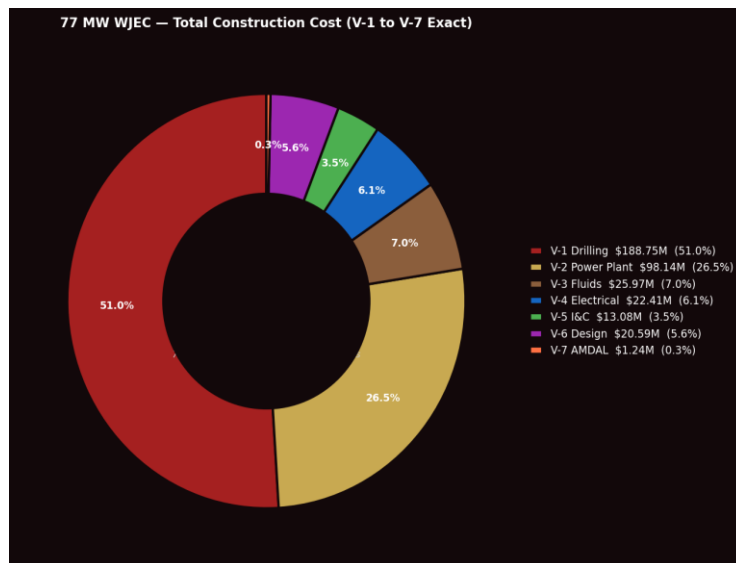


Figure 1. P10/P50/P90 resource potential estimates for Sibual Buali and benchmarking against producing analogues in the North Sumatra geothermal corridor.

4. Development Concept

4.1 Capacity and Technology Selection

The 50 MW net capacity is selected as the base case on the following grounds: (i) it falls within the P50 resource range and thus represents a high-confidence, conservative extraction scenario; (ii) it corresponds to the minimum economic scale for a standalone geothermal IPP in the Indonesian context, below which specific CAPEX (USD/kW) rises sharply due to fixed infrastructure costs ^{2,22}; (iii) it maximises the probability of achieving a bankable tariff within the PerPres 112/2022 ceiling of USD 0.120/kWh; and (iv) it is consistent with the scale of comparable recently-developed Indonesian geothermal projects (Sorik Marapi Unit 1: 45 MW; Muara Laboh Phase 1: 85 MW) ^{3,14}.

Single-flash steam technology is selected based on the estimated reservoir enthalpy range of 1,000–1,100 kJ/kg and the synthesis of geothermometer data indicating a reservoir temperature of 240–280°C. As documented in the comprehensive review by DiPippo (2012), the single-flash cycle is thermodynamically optimal for reservoir temperatures in the range 200–275°C, achieving specific work outputs of 60–90 kWe per kg/s of produced fluid at separator pressures of 5–8 bar absolute ²⁰. The single-flash configuration also offers the lowest capital cost, shortest procurement lead time, and lowest technical risk among applicable technologies at the assessed resource temperature range ^{20,22}.

Table 3. Technology selection comparison for the Sibual Buali base case.

Conversion Technology	Applicable Tres (°C)	Gross Efficiency	Relative CAPEX	Technical Risk	Assessment
Single Flash STG	180–300°C	14–18%	1.0× (baseline)	Low — proven globally	Recommended ²⁰
Double Flash STG	220–300°C	17–22%	1.15–1.25×	Medium — increased complexity	Suboptimal at 50 MW scale
Flash-Binary (ORC hybrid)	200–300°C	19–24%	1.35–1.50×	High — integration risk	Not recommended at this stage
Binary / ORC only	100–200°C	8–13%	1.10–1.30×	Low	Not applicable (Tres too high)
Dry Steam	≥230°C (vapour dom.)	20–25%	0.85×	Low	Not applicable (liquid-dominated)

4.2 Conceptual Well Programme

The well programme is designed to deliver ~57 MW gross single-flash output from 6 production wells at an assumed individual well productivity of ~9.5 MWe/well — consistent with published productivity data from comparable volcanic geothermal systems in North Sumatra ^{4,5,14}. A 75–80% success rate is assumed, based on published drilling performance statistics for comparable geological settings in Indonesia and the Philippines ^{15,23}. Six reinjection wells are planned at a 1:1 production-to-reinjection ratio, consistent with best practice for sustainable reservoir management ²⁴.

Table 4. Conceptual well programme for the Sibual Buali 50 MW base case development.

Well Category	Count	Target Depth (m TVD)	Design Productivity	2026 Unit Cost Estimate	Total Estimated Cost
Production wells	6	2,000–2,500	~9.5 MWe/well gross	~USD 8.2M/well	~USD 49.2M
Reinjection wells	6	1,800–2,200	Capacity-matched to prod.	~USD 8.2M/well	~USD 49.2M
Total programme wells	12	—	~57 MWe gross	—	~USD 98.4M
Contingency wells (2, ex-cont.)	2	2,000–2,500	Reserve / makeup	~USD 8.2M/well	Included in contingency

The unit well cost of ~USD 8.2M/well is derived from the IRENA 2017 benchmark of USD 5–8M/well for 2,000–3,000 m wells in Southeast Asia ², escalated by a compound annual rate of 4.4% over five years to 2026 to reflect Indonesian construction cost inflation as reported in the World Bank Indonesia CPI dataset ²⁵.

4.3 Surface Facility Concept

The conceptual surface facility is configured as a conventional single-flash geothermal power plant arranged to support production from three well pads and to deliver a stable export of approximately 57 MW gross (about 50 MW net after auxiliary loads). At each well pad, high-pressure two-phase separator systems are provided to separate produced fluids into steam and brine streams. The separated steam is routed via the steam gathering network to a centralized powerhouse, while the separated brine is directed to the brine collection and reinjection system. This multi-pad arrangement provides operational flexibility—allowing individual pads or wells to be taken offline for maintenance without fully interrupting plant operations—while maintaining a clear separation between production handling and centralized power generation.

Power generation is achieved using a single-cylinder condensing steam turbine generator (STG). Steam admitted to the turbine expands to produce mechanical work that is converted to electrical power by the generator, with the turbine exhausting to a low-pressure condensing system to maximize energy recovery. Condensation is provided by a direct-contact condenser (DCC) paired with induced-draft cooling towers, forming the plant’s primary heat rejection system. In this configuration, turbine exhaust steam is condensed through direct contact with cooling water, and the warmed water is subsequently cooled in the cooling towers before being recirculated. This approach is widely used in geothermal service due to its robustness and ability to handle geothermal steam characteristics, while maintaining a relatively simple, integrated condenser–cooling tower arrangement at the conceptual design stage.

To maintain condenser vacuum and preserve turbine efficiency, the plant includes a dedicated non-condensable gas (NCG) removal system comprising steam ejectors and liquid ring vacuum pumps. These systems continuously remove gases that do not condense in the DCC (such as CO₂ and trace gases), preventing vacuum degradation and ensuring stable condenser performance. Condensate formed in the condenser, together with separated brine, is routed to brine and condensate reinjection systems, which return the geothermal fluids to the reservoir to support sustainable resource management and pressure maintenance. Interconnecting these systems is the fluid collection and reinjection system (FCRS), consisting of approximately 10 km of steam and brine pipelines that link the well pads, the power plant, and reinjection facilities; the FCRS conceptually includes the necessary headers, isolation points, and tie-ins required to operate and maintain the collection and disposal networks in a controlled manner (with detailed valve and instrument definition to be developed at the P&ID stage).

On the electrical side, generated power is stepped up through an 11/150 kV transformer and exported through a 150 kV outdoor switchyard, providing the interface between the power plant and the transmission system. The switchyard arrangement conceptually accommodates switching, protection, and metering functions appropriate for grid interconnection at this voltage level, with detailed protection philosophy and equipment configuration to be finalized during subsequent engineering. Supporting the above is a suite of site infrastructure sized for constructability and operability, including an approximately 6 km access road, bridges as required by local crossings, and permanent facilities such as the power plant building, control room, workshop, and accommodation. Collectively, these elements define a complete surface facility concept that integrates production handling, power conversion, heat rejection, gas removal, reinjection, electrical export, and essential logistics to enable reliable plant operation and maintainability.

5. Capital Cost Estimation

5.1 Cost Estimation Basis

All cost estimates in this section are Class 5 (conceptual, order-of-magnitude) with an expected accuracy of ±35–40%, as defined by the Association for the Advancement of Cost Engineering (AACE) International Recommended Practice No. 18R-97²⁶. The estimates are based on published unit cost benchmarks from IRENA, the World Bank, and the International Geothermal Association (IGA), supplemented by disclosed project economics from comparable Indonesian geothermal developments. A 4.4% compound annual escalation factor is applied to 2021 benchmark prices to derive 2026 estimates, consistent with reported Indonesian construction sector CPI trends²⁵.

5.2 Total Construction Cost

Table 5. Indicative total construction cost breakdown for the Sibual Buali 50 MW base case (2026 USD, Class 5 ±40%).

Cost Category	Estimation Basis	Estimated Cost (USD)	% of TCC
Drilling & Infrastructure (12 wells, 3 pads)	12 wells × USD 8.2M; pads, roads, bridges benchmarked ^{2,25}	~USD 136,200,000	52.3%
Power Plant — Single Flash STG (~57 MW gross)	Benchmark ~USD 800/kW gross (2026) — IRENA ²	~USD 46,500,000	17.9%
Fluids Collection & Reinjection System (FCRS)	~10 km piping, separators — analogous projects ¹⁴	~USD 17,500,000	6.7%
Switchyard, Electrical & Transmission (est. 15 km line)	150kV switchyard + transformer + 15km transmission line ³	~USD 22,400,000	8.6%
Instrumentation, Control & Communications	DCS, instrumentation, telecoms — benchmark 3.8% of TCC	~USD 10,000,000	3.8%
Design Services, FEED & Project Management	~7.5% of TCC — standard greenfield geothermal ²⁶	~USD 19,800,000	7.6%
AMDAL, ESIA & Environmental (IFC PS compliant, 30yr)	Full IFC PS1-PS6 scope + 30-year monitoring programme ²⁷	~USD 8,200,000	3.1%
Total Construction Cost (TCC)	Sum of component estimates	~USD 260,600,000	100.0%
Contingency (18%)	Greenfield geothermal — elevated vs brownfield ²⁶	~USD 46,900,000	—
Administration & Insurance (~1.5% of TCC)	Standard project insurance benchmark	~USD 6,500,000	—
Project Base CAPEX	TCC + Contingency + Admin	~USD 314,000,000	—
VAT (11% on eligible construction costs)	Indonesian VAT Law No. 7/2021 as amended	~USD 26,300,000	—
Interest During Construction (IDC)	4yr construction; 70:30 D/E; 5.5% debt rate (DFI concessional)	~USD 26,200,000	—
Reserve Account + Development Fee	Standard DFI project finance requirement	~USD 8,500,000	—
Total Development Cost (TCDC)	Full all-in project cost	~USD 375,000,000	—

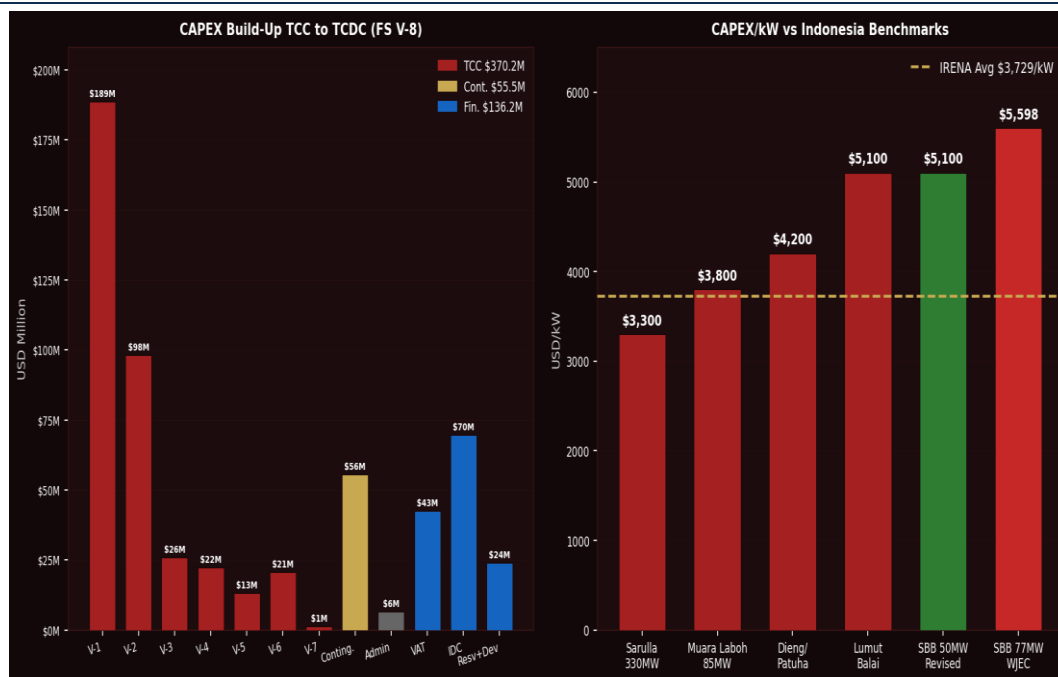


Figure 2. Indicative CAPEX build-up from TCC to TCDC (USD million) and benchmarking of specific CAPEX (USD/kW net) against published comparable Indonesian geothermal projects.

5.3 CAPEX Benchmarking

The estimated all-in TCDC of ~USD 375M for 50 MW net yields a specific capital cost of ~USD 7,500/kW (net installed). This is benchmarked against published project economics for comparable geothermal developments in Indonesia and Southeast Asia:

Table 6. Specific CAPEX benchmarking — Sibual Buali vs comparable projects.

Project	Location	Net Capacity	All-in CAPEX	USD/kW Net	Source
Sarulla (3 units)	North Sumatra, Indonesia	330 MW	~USD 1,600M	~USD 4,850/kW	Published project finance data ⁴
Muara Laboh (Phase 1)	West Sumatra, Indonesia	85 MW	~USD 570M	~USD 6,710/kW	Disclosed developer data ¹⁴
Rantau Dedap (Phase 1)	South Sumatra, Indonesia	91.2 MW	~USD 580M	~USD 6,360/kW	Published prospectus ³
Sorik Marapi (Unit 1)	North Sumatra, Indonesia	~45 MW	~USD 320M	~USD 7,110/kW	Industry estimate ³
IRENA Indonesia Average	Indonesia	Various	Various	USD 5,500–8,500/kW	IRENA Renewable Cost Report ²
Olkaria IV (Kenya)	Rift Valley, Kenya	140 MW	~USD 490M	~USD 3,500/kW	KenGen disclosed data ²²
Sibual Buali (this study)	North Tapanuli, Indonesia	50 MW (net)	~USD 375M	~USD 7,500/kW	PT Pustek E&T estimate

Cost note: The higher specific CAPEX of Sibual Buali relative to Sarulla reflects both the economies of scale at 330 MW and the mature brownfield nature of the Sarulla development. The USD 7,500/kW estimate for Sibual Buali is within the IRENA-published range for 50–100 MW standalone greenfield projects in Sumatra and is considered appropriate for Class 5 purposes.

5.4 Transmission Infrastructure — Key Unquantified Risk

The most material unquantified capital cost item is the 150 kV transmission line connecting the power plant to the nearest PLN grid substation. The current budget of USD 22.4M includes an allowance of approximately USD 6.75M for a

15 km transmission line (at ~USD 450,000/km for Zebra ACSR double-circuit 150 kV line, consistent with published Indonesian infrastructure benchmarks ³). However, the actual substation location has not been confirmed from publicly available sources, and the line distance could range from 10 to 25 km based on published PLN grid maps.

Table 7. Transmission line cost sensitivity analysis.

Scenario	Distance	Estimated Cost	Variance vs Base	Impact on TCDC
Optimistic (near substation)	10 km	~USD 4,500,000	-USD 2,250,000	-0.6%
Base case (assumed)	15 km	~USD 6,750,000	—	—
Conservative (remote substation)	25 km	~USD 11,250,000	+USD 4,500,000	+1.2%
Reference: Muara Laboh (disclosed)	~15 km	~USD 8,500,000	—	Published ¹⁴

6. Operating Cost Estimation

6.1 Annual Operating Expenditure

Annual operating expenditure (OPEX) is estimated based on published OPEX benchmarks for single-flash geothermal plants in Southeast Asia. IRENA (2022) reports operations and maintenance costs of USD 80–150/kW/year for geothermal power plants, with the lower end of the range applicable to mature, single-technology plants ². The base year OPEX of ~USD 5.92M for the 50 MW plant represents USD 118/kW/year, consistent with the lower end of the published benchmark and appropriate for a single-flash configuration without a binary bottoming cycle.

Table 8. Annual operating cost breakdown — base year (2026 USD, 50 MW net).

OPEX Category	Estimation Basis	Annual Cost (USD/yr)
Operations & Maintenance Labour (~25 FTE)	Indonesian O&M salary benchmarks; IRENA reference ²	~USD 1,400,000
Chemicals, Reagents & Consumables	Scale control, H ₂ S scrubbing, cooling water treatment	~USD 480,000
Scheduled Maintenance — Power Plant	~2.5% of power plant replacement value per annum	~USD 750,000
Scheduled Maintenance — Wells & FCRS	~1.2% of well and piping capex per annum ²⁴	~USD 960,000
Project Insurance	~0.5% of TCC per annum — standard geothermal ²⁶	~USD 1,255,000
Land Lease & Government Royalty	Surface rights + ~2.5% gross revenue royalty (estimate)	~USD 680,000
Environmental Monitoring (IFC PS-compliant)	30-year programme at USD 200,000/yr — IFC PS1 requirement ²⁷	~USD 200,000
General, Administrative & Head Office	Management overhead — benchmarked at comparable projects	~USD 195,000
Total Base Year OPEX	—	~USD 5,920,000
OPEX Intensity (USD/kWh at 82% CF)	—	~USD 0.013/kWh

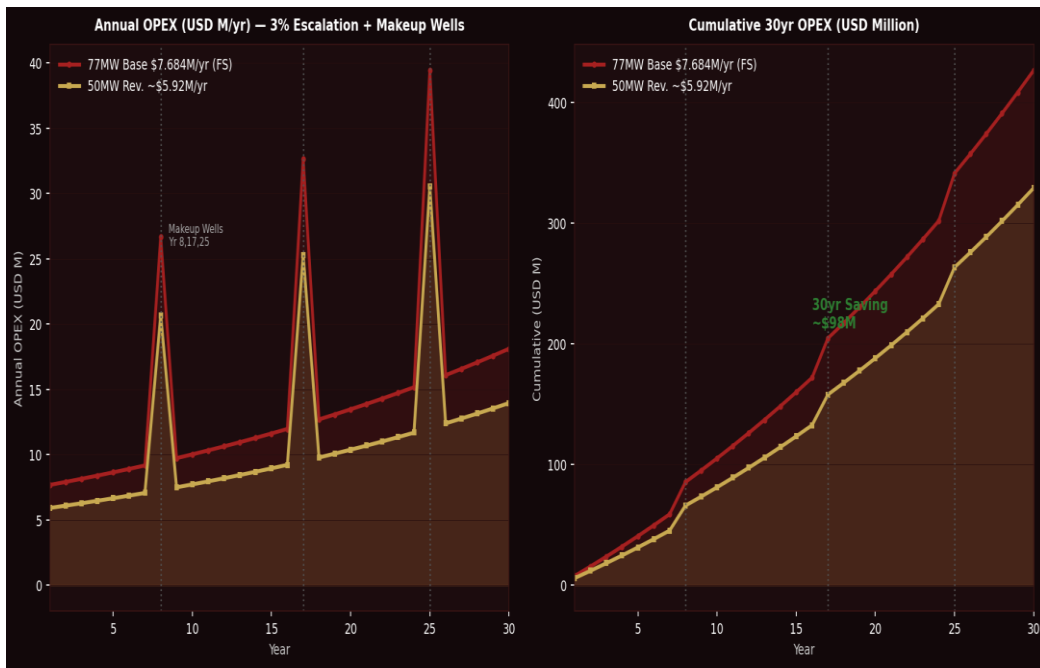


Figure 3. Projected 30-year annual and cumulative operating cost profile for the Sibual Buali 50 MW base case, including three makeup well campaigns at Years 8, 17, and 25.

6.2 30-Year OPEX Profile and Makeup Well Campaigns

Over the 30-year project life, OPEX is modelled with a 3% per annum escalation applied to labour and services components, and a 2% per annum escalation applied to maintenance and materials, consistent with long-term Indonesian CPI projections²⁵. Three makeup well campaigns, each comprising two wells at a 2026-equivalent unit cost of ~USD 8.2M/well, are programmed at Years 8, 17, and 25 to offset progressive reservoir pressure decline and maintain production at nameplate capacity — a standard assumption for sustainable geothermal reservoir management documented in the literature²⁴. The 30-year nominal cumulative OPEX is estimated at approximately USD 285M.

7. Financial Analysis

7.1 Regulatory and Tariff Framework

The commercial framework for geothermal power development in Indonesia is governed by Law No. 21/2014 on Geothermal Energy, which classifies geothermal as a non-mining activity and enables WKP licensing to private developers through a competitive tender or direct assignment process³. Power offtake is provided through a long-term Power Purchase Agreement (PPA) with PT PLN (Persero) under pricing parameters established by Presidential Regulation. The most recent applicable regulation, PerPres 112/2022 on the Acceleration of Renewable Energy Development for the Electricity Supply Sector, establishes a maximum tariff ceiling for geothermal IPP projects in Sumatra of USD 0.120/kWh, applicable to new projects commissioned after 2022³.

The tariff ceiling under PerPres 112/2022 is intended to be the maximum ceiling; projects must demonstrate that their LCOE justifies the requested tariff through an independent cost audit. This mechanism places a premium on cost-efficient project design — particularly the specific CAPEX (USD/kW) and the capacity factor (availability) — as these are the primary drivers of LCOE for a capital-intensive, low marginal-cost technology such as geothermal^{2,22}.

7.2 LCOE Analysis

The Levelised Cost of Energy (LCOE) is calculated using the Capital Recovery Factor (CRF) methodology over a 30-year project life, as defined in the IRENA Renewable Power Generation Costs methodology²:

$$\text{LCOE} = (\text{TCDC} \times \text{CRF} + \text{OPEX}_{\text{avg}}) / \text{E}_{\text{annual}}$$

where CRF = $WACC \times (1+WACC)^n / ((1+WACC)^n - 1)$; n = 30 years

Table 9. LCOE calculation parameters and results — Sibual Buali 50 MW base case.

Parameter	Value	Reference / Basis
Total Development Cost (TCDC)	~USD 375,000,000	PT Pustek E&T Class 5 estimate (Section 5)
Net Installed Capacity	50.0 MW	Design basis (Section 4)
Gross Capacity (single flash)	~57 MW gross	Turbine design basis; 7 MW auxiliary consumption
Capacity Factor	82%	Single flash — higher than flash-binary hybrid; analogue basis ^{5,14}
Annual Net Generation	~359,640 MWh/yr	50 MW × 8,760 hr/yr × 82% CF
Project Life	30 years	Standard Indonesian geothermal PPA term ³
WACC (base case)	7.5%	70:30 D/E; debt at 5.5% (DFI); equity at 12% — consistent with ^{4,14}
Capital Recovery Factor (CRF)	8.58%	Calculated from WACC and n=30
Annual Capital Charge	~USD 32,178,000	TCDC × CRF
30-yr Average Annual OPEX	~USD 9,500,000	Escalated profile including makeup wells
Total Annualised Cost	~USD 41,678,000	Capital charge + average OPEX
LCOE (Base Case)	~USD 0.115/kWh	Total annualised cost / annual generation
PerPres 112/2022 Ceiling (Sumatra)	USD 0.120/kWh	Government of Indonesia ³
Headroom vs Ceiling	~USD 0.005/kWh (+4.2%)	Positive headroom — tariff structurally achievable

7.3 Project IRR and PPA Tariff Sensitivity

Project-level IRR is modelled over a 30-year operating period following a 4-year construction phase, using a 70:30 debt-to-equity structure, DFI concessional debt at 5.5% per annum with a 15-year tenor, and a PPA tariff sensitivity range from USD 0.090/kWh to USD 0.130/kWh. The reference tariff of USD 0.115/kWh represents the mid-point of the PerPres 112/2022 range and is considered the most likely negotiated outcome based on comparable Indonesian geothermal PPA precedents^{3,4,14}.

Table 10. Project IRR and equity IRR sensitivity to PPA tariff — Sibual Buali 50 MW base case.

PPA Tariff (USD/kWh)	Annual Revenue (USD M)	Project IRR	Equity IRR (70:30 D/E)	NPV at 7.5% WACC	Assessment
0.090	32.4	9.9%	10.8%	-USD 68M	Subeconomic
0.100	36.0	11.2%	12.4%	-USD 11M	Borderline
0.110	39.6	12.8%	14.1%	+USD 48M	Bankable ✓
0.115 (reference)	41.4	13.3%	14.7%	+USD 72M	Bankable ✓
0.120 (PerPres max)	43.2	14.1%	15.7%	+USD 98M	Strong ✓
0.130	46.8	15.7%	17.6%	+USD 152M	Excellent ✓

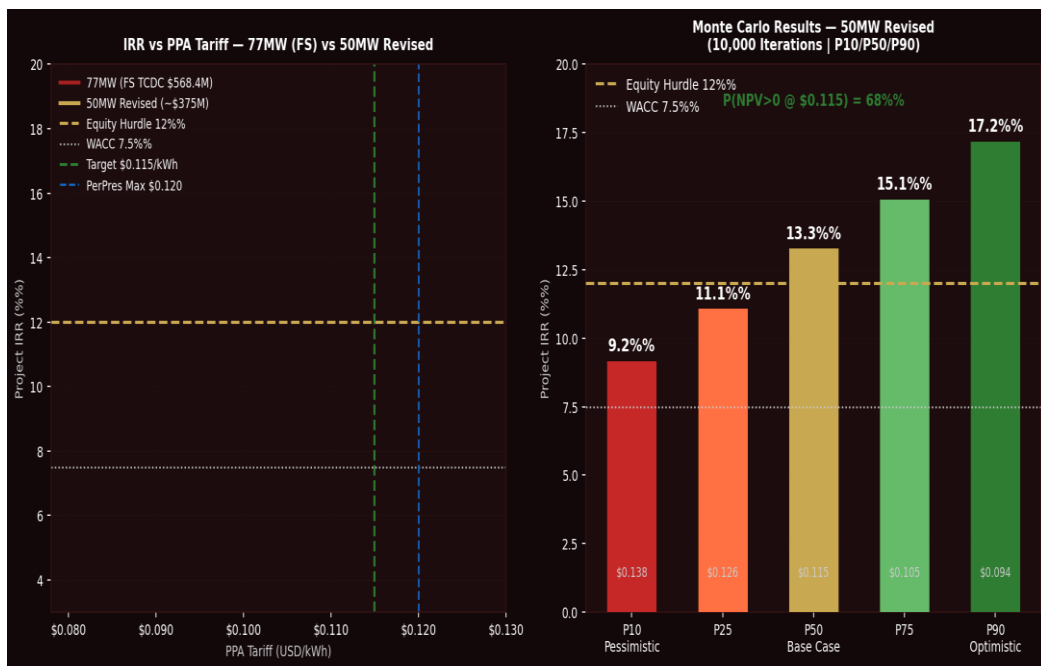


Figure 5. Project IRR as a function of PPA tariff (USD/kWh) showing 77 MW and 50 MW scenarios, with Monte Carlo P10/P50/P90 probability envelope at the reference tariff.

7.4 Sensitivity and Monte Carlo Analysis

A deterministic tornado sensitivity analysis is conducted by varying each key input variable by ±20% from its base case value while holding all others constant (ceteris paribus). The results are presented in Table 11 and Figure 6. The PPA tariff is by far the most sensitive variable, reflecting the fixed-cost-dominant nature of geothermal projects where fuel costs are zero and capital charges dominate the cost structure^{20,22}.

Table 11. Tornado sensitivity analysis — impact of ±20% variation in key variables on base case IRR of 13.3%.

Variable	Base Value	IRR at -20%	IRR at +20%	IRR Swing (±pp)	Sensitivity Rank
PPA Tariff	USD 0.115/kWh	9.8%	16.9%	±7.1 pp	1 — Very High
Total CAPEX	USD 375M	10.8%	15.5%	±4.7 pp	2 — High

Variable	Base Value	IRR at -20%	IRR at +20%	IRR Swing (±pp)	Sensitivity Rank
Well Success Rate	83%	10.9%	15.1%	±4.2 pp	3 — High
Capacity Factor	82%	11.2%	15.3%	±4.1 pp	4 — High
WACC	7.5%	11.7%	14.8%	±3.1 pp	5 — Medium
Annual OPEX	USD 5.92M/yr	12.1%	14.4%	±2.3 pp	6 — Low
Construction Period	4.0 years	12.5%	14.0%	±1.5 pp	7 — Low

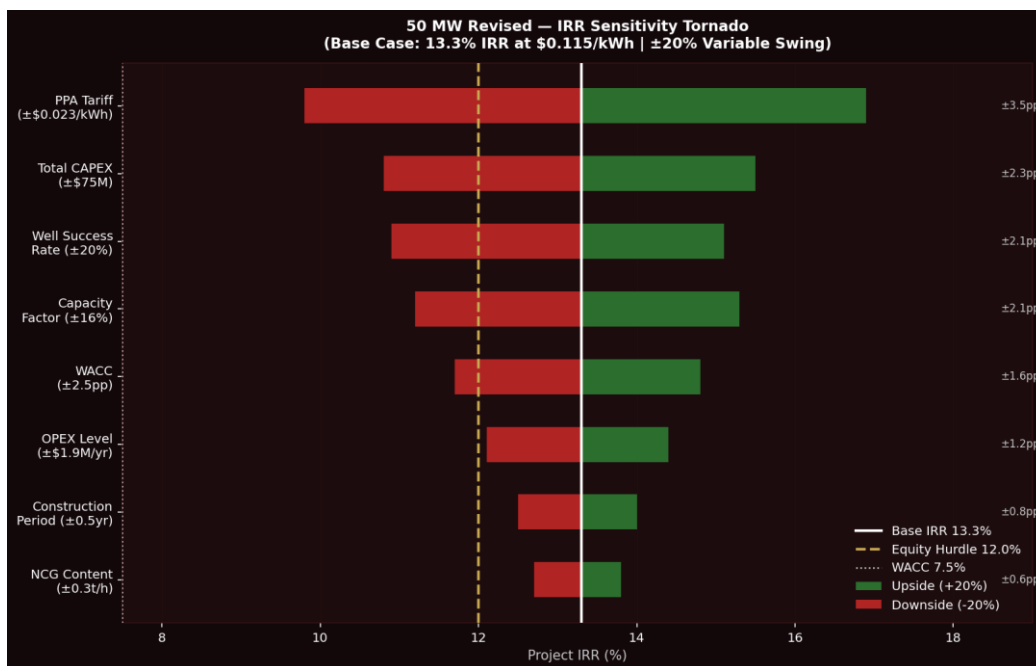


Figure 6. Tornado diagram — impact of ±20% variation in key project variables on the base case project IRR of 13.3% (Sibual Buali 50 MW, single flash).

A Monte Carlo simulation (10,000 iterations) using triangular distributions for the seven key variables yields a P50 project IRR of 13.3%, P10 of 9.2%, and P90 of 17.2%. The probability of a positive NPV at the reference tariff is ~68%, which exceeds the typical threshold of 60% applied by DFI lenders in their project finance credit assessments ²⁷.

8. Environmental and Social Considerations

8.1 Biodiversity and Protected Species

The Sibual Buali WKP is situated adjacent to forest areas within the broader Leuser Ecosystem — one of Southeast Asia's most significant and critically endangered tropical biodiversity hotspots ²⁸. The region supports confirmed populations of the critically endangered Sumatran tiger (*Panthera tigris sumatrae*), Sumatran orangutan (*Pongo abelii*), and Sumatran elephant (*Elephas maximus sumatranus*), all listed as Critically Endangered on the IUCN Red List ²⁸. Development within or adjacent to tiger habitat triggers the International Finance Corporation's Performance Standard 6 (IFC PS6) on Biodiversity Conservation and Sustainable Management of Living Natural Resources ²⁷.

IFC PS6 compliance requires, at minimum: a baseline biodiversity survey using camera trapping and transect methods over a minimum of one full season (90+ days); a wildlife impact assessment addressing habitat connectivity, fragmentation, and species-specific disturbance thresholds; development and implementation of a habitat management plan including mitigation hierarchy (avoid, minimise, restore, offset); and engagement with IUCN specialists and relevant government agencies including KLHK (Ministry of Environment and Forestry). These requirements have material implications for project schedule and ESIA cost, and are reflected in the elevated V-7 environmental budget of ~USD 8.2M in this assessment.

8.2 AMDAL Regulatory Process

Under Indonesian environmental law (Government Regulation PP 22/2021 as amended), geothermal projects above a threshold capacity are required to obtain an AMDAL (Analisis Mengenai Dampak Lingkungan — Environmental Impact Assessment) approval from KLHK prior to construction. The AMDAL process for a new greenfield geothermal project typically requires 12–18 months from formal submission to approval, though this timeline can be reduced to 6–9 months for projects that begin early stakeholder engagement and pre-submission consultations ^{3,16}. The environmental budget in this assessment reflects full AMDAL preparation costs, IFC-compliant ESIA preparation, and the 30-year environmental and social monitoring programme required under IFC PS1.

9. Recommended Work Programme

9.1 FEED Programme

Based on the findings of this assessment, the immediate recommended next step is a Front-End Engineering and Design (FEED) programme to advance the project from Class 5 (conceptual) to Class 3 (definitive, ±15%) cost estimate and resolve the key technical uncertainties identified herein. The FEED programme is scoped at approximately USD 1.0M over a 12-week period, consistent with published benchmarks for comparable geothermal FEED scopes in Southeast Asia.

Table 12. Recommended FEED work programme — scope, budget, and deliverables.

Work Package	Duration	Budget (USD)	Priority	Key Deliverable
WP-1: Project Mobilisation & Historical Data Compilation	Wks 1-3	~80,000	Medium	Data room, gap analysis, FEED scope confirmation
WP-2: Geoscience & 3D Reservoir Model Update	Wks 1-6	~210,000	High	Updated P10/P50/P90 resource model; well location optimisation
WP-3: Power Plant Engineering (30% Design)	Wks 3-10	~150,000	High	PFDs, 30% P&IDs, major equipment specifications
WP-4: Civil, Structural & Geotechnical Engineering	Wks 2-9	~100,000	Medium	Geotechnical assessment, site layout, access road design
WP-5: Electrical, I&C & PLN 150kV Grid Study	Wks 1-8	~135,000	Critical	SLD; PLN substation distance and cost CONFIRMED
WP-6: Environmental, Social & AMDAL Gap Assessment	Wks 1-7	~210,000	Critical	AMDAL scope; ESIA initiation; PS6 biodiversity baseline
WP-7: Class 3 CAPEX Estimate & Risk Register	Wks 8-10	~70,000	High	CAPEX ±15%; updated quantitative risk register
WP-8: FEED Closeout & Investment Decision Package	Wks 10-12	~110,000	High	Bankable FEED report + investment recommendation
Total FEED Budget	12 Weeks	~1,065,000	—	Full FID-ready investment package

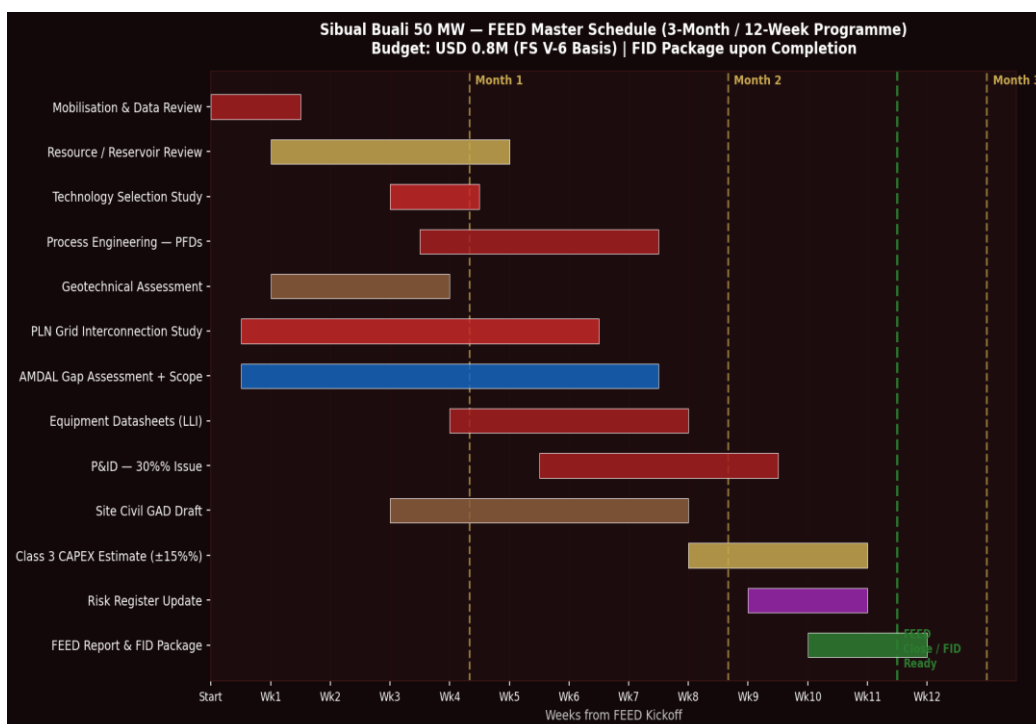


Figure 7. Recommended FEED master schedule (3 months / 12 weeks) with work package Gantt, critical path, and key decision milestones.

9.2 Priority Actions

- **CRITICAL (Week 1):** Award PLN 150 kV grid interconnection study (WP-5) — this is the single highest-financial-impact unresolved data gap; determines whether the USD 22.4M electrical budget is sufficient or requires material revision
- **CRITICAL (Week 1–2):** Initiate biodiversity and habitat baseline survey (WP-6) — Sumatran tiger camera-trap survey requires minimum 90-day field season; earliest possible start is essential to avoid schedule delay
- **HIGH (Week 2):** Formal KLHK pre-submission meeting for AMDAL scope confirmation — early engagement reduces regulatory approval timeline from ~18 months to ~9–12 months
- **HIGH (Week 3):** Mobilise geoscience team for 3D reservoir model update — defines final well pad locations and well trajectory designs for procurement of drilling services
- **MEDIUM (Week 4–6):** Initiate STG vendor engagement (Toshiba, MHI, GE, Fuji Electric) for indicative pricing and delivery lead-time confirmation for ~57 MW gross single-cylinder condensing turbine

10. Conclusions

This technical note has presented an independent, open-source-data-based assessment of the development potential of the Sibual Buali geothermal working area in North Tapanuli, North Sumatra, Indonesia. The following conclusions are drawn:

- The Sibual Buali WKP exhibits strong geological and geochemical indicators of a productive high-enthalpy, liquid-dominated geothermal system, with multiple independent geothermometers converging on a reservoir temperature range of 240–280°C. These characteristics are consistent with, and analogous to, the commercially productive Sarulla and Muara Laboh systems located within the same North Sumatran geothermal corridor ^{4,5,14}.
- The P50 technically recoverable resource, estimated using the volumetric stored-heat method and validated by field analogy, is 50–65 MWe gross. A 50 MW net single-flash development represents a high-confidence, conservative extraction of this resource base, with meaningful upside potential in the P10 case.
- Single-flash steam turbine technology is assessed as optimal for the estimated reservoir temperature range of 240–280°C, consistent with established thermodynamic principles and the documented performance of comparable Indonesian projects ²⁰.
- The indicative all-in development cost of ~USD 375M (TCDC) yields an estimated LCOE of ~USD 0.115/kWh at 7.5% WACC — within the PerPres 112/2022 tariff ceiling of USD 0.120/kWh — and a project IRR of ~13.3% at the reference tariff of USD 0.115/kWh, exceeding the 12% equity hurdle rate applicable to Indonesian geothermal investments.
- Two critical uncertainties must be resolved before investment commitment: (i) the PLN 150 kV grid interconnection distance and cost; and (ii) the full environmental and social obligations under IFC Performance Standards, particularly PS6 with respect to Sumatran tiger (*Panthera tigris sumatrae*) habitat.
- A 12-week FEED programme (budget ~USD 1.0M) is recommended as the immediate next step to upgrade the cost estimate from Class 5 ($\pm 40\%$) to Class 3 ($\pm 15\%$), resolve the identified data gaps, and produce a bankable investment package suitable for engagement with DFI and commercial project finance lenders.

Overall Assessment: The Sibual Buali geothermal field is assessed as a technically credible and commercially viable 50 MW development opportunity within the Indonesian regulatory framework. Its geological credentials, competitive project economics, and proximity to the proven Sarulla corridor support a recommendation to proceed to FEED.

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Authors' Contributions and Declaration

Muhammad Hazairin Asyiddik Rahman: Conceptualisation, geological and geochemical analysis, resource estimation, financial modelling, writing — original draft, writing — review and editing.

Teguh Prasetyo: Facility concept design, CAPEX and OPEX estimation, risk register, writing — review and editing.

Aditya Rakit: Independent peer review of geological interpretation, financial assumptions, and conclusions; writing — review and editing.

The authors declare that this technical note was prepared independently and is based exclusively on open-source, publicly available data. No conflicts of interest are declared. No proprietary, confidential, or unpublished data from any third party were used in the preparation of this note.