PROCEEDINGS, 49th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2024
SGP-TR-227

Geothermal Power Plant Retrofit to Optimize Generation: A Case Study from Salak Unit 4/5/6

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Keywords: geothermal, retrofit, power generation, turbine blade, isentropic efficiency

ABSTRACT

Star Energy Geothermal (SEG) is Indonesia's largest geothermal energy company that manages and operates geothermal power plants situated at Darajat (DRJ), Wayang Windu (WW) and Salak (SLK) with a combined capacity of 886 MW. The SLK geothermal power plants are located in Sukabumi regency, West Java province, comprises three units (SLK1/2/3) 60 MW each and three units (SLK4/5/6) 67 MW each. SEG supplies geothermal steam to SLK1/2/3 those are operated by a PLN subsidiary company, while SLK4/5/6 are operated by SEG. In order to maintain safe and reliable operation as well as to optimize plant performance, SEG conducted a comprehensive study aimed at retrofitting these SLK4/5/6 units by replacing and upgrading the steam turbine rotor and stator. Several project constraints were applied, including no additional steam mass flow rate, no major upgrades to main equipment and the Balance of Plant (BOP), no significant civil or structural modifications, and no additional steam wells related to this project. Under these constraints, the retrofit project for SLK4/5/6 is expected to yield an additional power generation increase of 2.4 MW for each unit, resulting in a total increase of 7.2 MW across the three units.

The scope of the retrofit for SLK4/5/6 is primarily focused on modifying the turbine blades to enhance the isentropic efficiency parameter, while keeping other parameters unchanged. Referring to the turbine work formula, turbine output is influenced by parameters such as steam mass flow rate ($\dot{m}$), delta enthalpy (h_1-h_2), and isentropic efficiency (η_t). Notably, parameters like steam mass flow rate ($\dot{m}$), inlet enthalpy (h_1), and outlet enthalpy (h_2) remain unaltered as no additional steam mass flow or steam pressure change is required for this retrofit plan. The expected improvement in the parameter of isentropic efficiency (η_t) is anticipated to rise from the current average of 79.2% to 81.5% through the turbine blade modification, employing a new three-dimensional (3D) design as opposed to the existing two-dimensional (2D) design.

1. INTRODUCTION

Indonesia is a country with resources accounting for 40% of the world's total geothermal energy, showcasing significant potential for renewable energy sources. The utilization of geothermal energy began 20 years ago, and as of now, Indonesia has only tapped into 4-5% of its geothermal capacity. The country, particularly in non-Java islands, is facing a substantial increase in electricity demand, requiring additional power generation each year. Currently, the installed capacity of geothermal power plants is approximately 2.3 GW out of a total national capacity of around 83.8 GW. Government of Indonesia expects geothermal to enhance its important role as a renewable energy source.

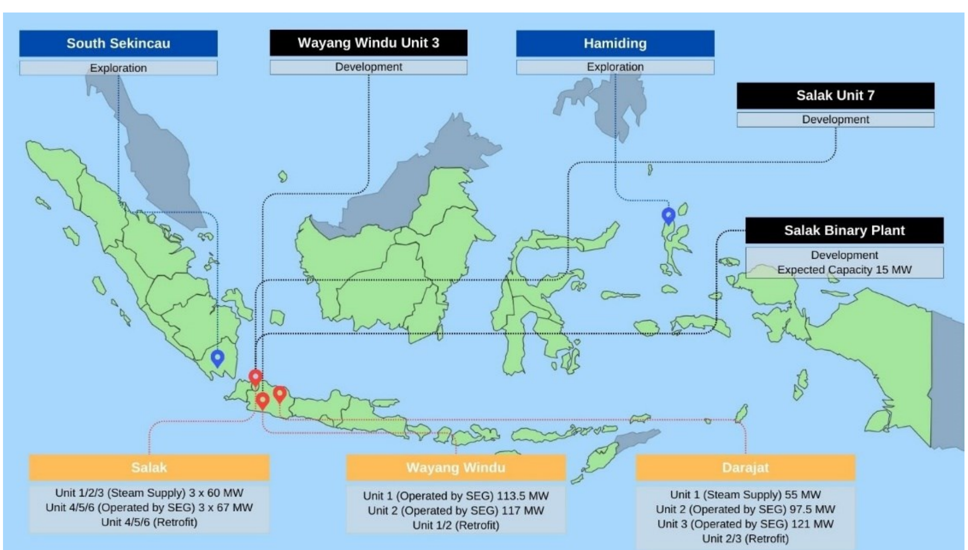

Figure 1: Star Energy Geothermal Portfolio (2024)

In partnership with two state-owned companies' PT Pertamina and PT Perusahaan Listrik Nasional (PLN), SEG operates three different assets of geothermal power plant at West Java with total capacity 886 MW (see Figure 1). Wayang Windu geothermal power plant in Pengalengan Regency generates 230.5 MW, consist of two units 1 x 113.5 MW and 1 x 117 MW. Darajat geothermal power plant generates 274.5 MW consists of 1 x 97.5 MW and 1 x 122 MW as well as to supply steam to PLN to produce 1 x 55 MW electricity. Salak geothermal power plant generates 381 MW consist of 3 x 67 MW and supply steam to PLN to produce 3 x 60 MW electricity.

Furthermore, SEG is currently developing several new geothermal power plants, including the Salak Binary Plant (15 MW), which is in the commissioning stage and expected to operate this year 2024. Other geothermal power plants in the development phase are Wayang Windu Unit 3 and Salak Unit 7, both units are anticipated to be operational in 2026-2027. SEG is also exploring geothermal areas such as South Sekincau in Lampung and Hamiding in Maluku. These new development and exploration projects are to accelerate company's generation target 1200 MW by 2028.

Considering remaining lifetime of turbine equipment and efforts to optimize power plant generation, SEG is also retrofitting existing operational assets. Ongoing studies and project development are currently being conducted on units operated by SEG, including for Darajat Unit 2/3, Wayang Windu Unit 1/2, as well as Salak Unit 4/5/6. Those retrofit projects are expected to improve plant performance and generation output by implementing advanced technology especially for steam turbine and Balance of Plant (BOP) equipment. SEG plans Commercial Operations Date (COD) of retrofit projects are executed within the timeframe of 2025-2026.

2. SALAK GEOTHERMAL POWER PLANT

This plant started operations in 1997 with 55 MW for each unit. The generation output was increased to 65.6 MW each unit in 2004. SLK4/5/6 generation output is currently 67 MW for each unit since 2021. Steam for the power plant comes mostly from water dominated resources. Brine from production wells is flashed to steam at a controlled pressure in a cyclone separator. The separated brine is then injected into the reservoir and the steam is sent through to a steam scrubber. Once solid particles and moisture droplets are removed from the steam by the scrubber, the steam flows to the power plant. Provisions in the main steam supply system continuously wash the steam upstream of the scrubbers in order to remove chlorides, rock dust and other contaminants from the steam.

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Table 1: Turbine Performance and Generation Output

Condition	Generation Output (MW)	Steam Mass Flow (kg/hr)	Steam Pressure (Bara)	Steam Temperature (°C)	Condenser Pressure (Bara)	NCG Content (wt%)	Execution Year
Case 1	55.0	393,927	5.86	159	0.083	2	1997
Case 2	59.5	421,686	6.25	161	0.083	2	N/A
Case 3	65.6	461,749	6.90	164	0.090	2	2004
Case 4	67.0	484,900	7.25	166	0.11	2	2021

The turbine is manufactured, supplied, and installed by Fuji Electric. It is a single cylinder, double flow, and dual entry condensing type unit. The rotating turbine blades are all reaction style. There are nine stages of blade on each end of the turbine. Turbine steam supply system consists of two basket style steam strainers; two swings check main steam stop valves, two butterflies main steam control valves and associated piping. Steam enters the turbine at the center of each side of the turbine casing, below the horizontal joint, through penetrations in the lower case. Steam expands as it passes through the turbine and transfers its energy to the rotor as it flows in two directions toward the governor and generator ends. After leaving the final stage, the steam is directed into exhaust ducts located under the turbine case and flows into the condenser.

The turbine oil system provides hydraulic oil pressure to open the main steam stop swing check valve and to operate the main steam turbine control valve. The oil system also provides lubrication and cooling for the turbine-generator bearings, oil pressure from the jacking oil to lift the turbine shaft off the journal bearings and a hydraulic turning device that rotates the turbine-generator rotors at a low speed in the range of 80 to 150 revolutions per minute. The oil system has provisions for storing, filtering, heating, and cooling the oil.

Steam leaves the turbine exhaust ends and flows through ducts into the condenser where it is condensed by contact with condenser tubes. The tubes are cooled by circulating cooling water which is returned to the cooling tower. The condenser has a pressure much less than atmospheric as the result of a gas removal system and by cold water circulating through the condenser tubes. The condenser is of the two pass type where the cooling water enters one end, flows through half the tubes to the far end, turns around, and flows through the remaining tubes back to exit from the end where it originally entered.

The condenser includes an after-cooler that further cools the vapors and gases before they exit to the non-condensable gas removal system. A series of valves are provided at the condenser gas outlet to obtain the proper pressure gradient in the gas removal exit area. Suspended solids in the circulating water leave deposits inside the condenser tubes. Scheduled outages to manually clean deposits from the inside of the condenser tubes are avoided with the installation of an online cleaning system that circulates sponge rubber balls through the tubes. The condenser has a vacuum breaker valve to slow the turbine after shutdowns and rupture disks that prevent over pressurization of the turbine case and condenser shell during abnormal conditions.

Condensate from the condenser is pumped by one of two, 100% capacity, vertical, canned, two stage, centrifugal pumps. One pump is intended for normal operating conditions while the other is a stand-by pump that backs up the operating pump. A recirculating line that re-routes condensate back to the condenser is provided for low load or no-load conditions to prevent damage to the pumps. Condensate from the pumps under normal operating conditions flows to the condensate injection system, the circulating water return line for cooling tower makeup, seal water supply to LRPV through Plate Heat Exchanger (PHE) the scrubber wash spray system and the turbine wash spray system. It is advantageous to send as much condensate directly to the injection system as possible to reduce corrosion to piping by avoiding contact with air, and also to reduce hydrogen sulfide gas emissions in the cooling tower.

The circulating water system and auxiliary cooling water system for each unit consists of two 50% capacity stainless steel wet pit pumps for each system. The pumps are vertical, centrifugal, single stage pumps. The circulating water pumps deliver cooling water through the condenser to the top of the cooling tower. The auxiliary cooling water is supplied to the lube oil coolers, generator air coolers, the inter-condenser outlet loop seal, inter-condenser, standby after-condenser, liquid ring vacuum pump seals, main condenser and circulating water system. Both sets of pumps are located at the cooling tower pump pit.

The crossflow induce draft cooling tower for each unit that has 6 cells and consists of a concrete structure with PVC splash type fill material. Each cooling tower is designed to handle the combined flows from the main condenser cooling water system, auxiliary cooling water system and the makeup flow from the condensate system. The cooling towers use an evaporation process to cool the water. Water falls by gravity through the cooling tower fill and is broken up into small droplets. As the warm water is passing through the cooling tower, air flow induced by large fans, passes across the droplets resulting in evaporation of a small portion of the water, which is continuously replaced with condensate. Cooling takes place primarily by latent heat transfer with sensible heat transfer having a lesser effect.

The generator for each unit is rated at 70 MVA with cooling system is a totally enclosed water-to-air cooling system. A brushless exciter is provided with the generator. The generator is furnished with internal heaters to keep it dry and filters to prevent damage from dust and hydrogen sulfide gas. Power produced from the generator is routed through iso-phase bus duct to generator circuit breaker and then to the main step-up transformer. Power from the main transformer is routed to the PLN substation, and from there through line breakers to PLN's transmission line. Voltage is stepped up by the main transformer in order to efficiently transmit power by minimizing line losses in the PLN system. The main transformer has a tap-changer that is used for line voltage control. The tap changer is operated independently from the generator automatic/manual voltage regulator.

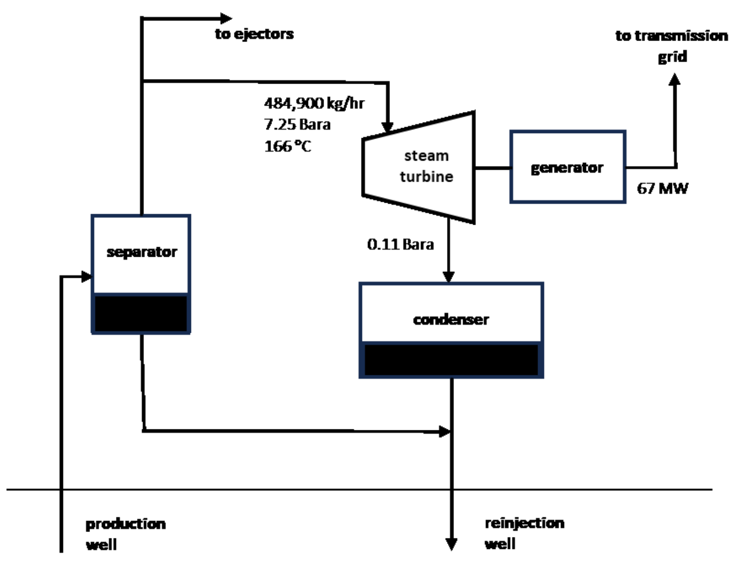

Figure 2: Simplified Schematic of SLK4/5/6 Current Operation

3. POWER PLANT RETROFIT

Based on Lifetime Assessment (LTA) conducted by OEM, turbine rotors and stators as major equipment indicated that remaining lifetime is limited up to 2026. Considering this LTA result that potentially impact to Loss Production (LPO) and safety issue, a comprehensive study and project planning is conducted with OEM support. A number of alternatives were developed and reviewed during feasibility study including potential increase of generation output by implementing advanced or new technology.

3.1 Challenges

In order to mitigate LTA result and to maintain safe and reliable operations of SLK4/5/6, project team expanded study with alternatives including any potential design and technology to optimize power plant performance and increase generation output. However, some challenges below had to be considered since these SLK4/5/6 are the running units and directly contributing electricity production in the transmission grid.

1. Project execution is scheduled during planned Shutdown Turnaround (SDTA) program.
2. No modification of turbine-generator structural and foundation, including turbine casing.
3. Use existing steam supply conditions (no additional steam mass flow and no change of steam pressure).
4. No modification of BOP (condenser, cooling towers, circulating water, gas removal and electrical systems).
5. Considering limited space available, no modification of power plant layout.
6. No amendment is required for existing commercial contracts and legal requirements.

3.2 Assessment and Selection Process

Project team generated a wide range of alternatives during feasibility study. These alternatives were assessed using selection process consist of three steps as follows:

1. Technical Review which involves assessment of basic engineering design, preliminary scope of work, timeline, estimated cost and generation output.
2. Constraints Filter is to select alternative that should pass all six constraints as mentioned above. If one alternative could not meet one or more constraint requirement above, then it will be dropped and fail to proceed to the next selection process.
3. Economic Analysis is the ultimate evaluation to decide the best selected alternative. Company defined the optimum set of IRR, NPV and PI parameters combined with COD and commercial requirements to finalize selection process.

Figure 3: Alternative Selection Process during Feasibility Study

Referring to established selection process above, various generated alternatives were narrowed down to three alternatives as follows:

1. Alternative A - Turbine Retrofit
   Scope: Replace turbines rotor & stator only.
2. Alternative B - Major Retrofit
   Scope: Replace turbines rotor & stator, transformer. Upgrade cooling tower and generator.
3. Alternative C - Total Rebuild
   Scope: Replace with new turbines, generators, transformers. Modify cooling tower structure and mechanical parts.

3.3 Resolution

Final outcome that underwent the Technical Review, Constraint Filter, and Economic Analysis stages is Alternative A, involving the replacement of the turbine rotor and stator only (Turbine Retrofit). Both alternatives B and C are basically proven for first pass Technical Review selection. However, these alternatives failed to continue to next steps selection Constraint Filter and Economic Analysis. Alternatives B and C involve significant modification/upgrade or even new development of power plant, which is unable to fit to 2nd and 3rd selection processes.

Alternative A meets all Constraint Filter above as well as provide positive value of Economic Analysis. By implementing turbine rotor and stator replacement, turbine generation will increase to 69.4 MW with an additional output 2.4 MW per unit. SLK4/5/6 total generation output increase is 7.2 MW. As shown in Table 2 below, only Alternative A (Turbine Retrofit) that meet three steps selection process and the other alternatives failed to proceed.

Table 2: Final Alternative Selection Result

Selection Process	Alternative A (Turbine Retrofit)	Alternative B (Major Retrofit)	Alternative C (Total Rebuild)
Technical Review	Pass	Pass	Pass
Constraints Filter	Pass	Fail	Fail
Economic Analysis	Pass	Fail	Fail

Considering all of these constraints and selection process result, OEM has prepared the Detail Engineering Design, which includes the scope of turbine retrofit, timeline, and technical specifications. The scope of Turbine Retrofit focused on turbines rotor and stator replacement and all others equipment remain no change. Below is the list of turbine parts will be replaced and is described in sectional drawing in Figure 4.

1. Turbine Rotor with Rotary Blades and Accessories
2. Stationary Blade Holder with Stationary Blades (Turbine Side & Generator Side)
3. Stationary Blade Rings Holder with Stationary Blades (Turbine Side & Generator Side)

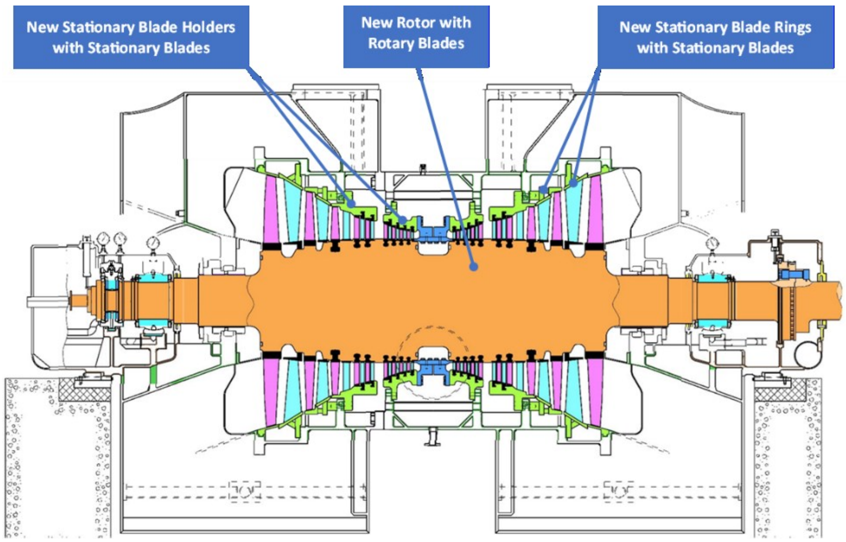

Figure 4: Turbine Parts Replacement for Retrofit Project

OEM implements three-dimensional (3D) technology in new turbine rotor and stator with focusing on efficiency improvement of turbine rotary and stationary blades design. 3D optimum design at each section will improve turbine efficiency by reducing the following losses:

1. Profile losses that usually taken to be the losses generated in the blade boundary layers well away from the end walls.
2. Secondary flows reduce turbine performance by introducing additional losses in each row, and they alter the flow field with respect to the design intent at the row exit, thus affecting the aerodynamic performance of the successive row.

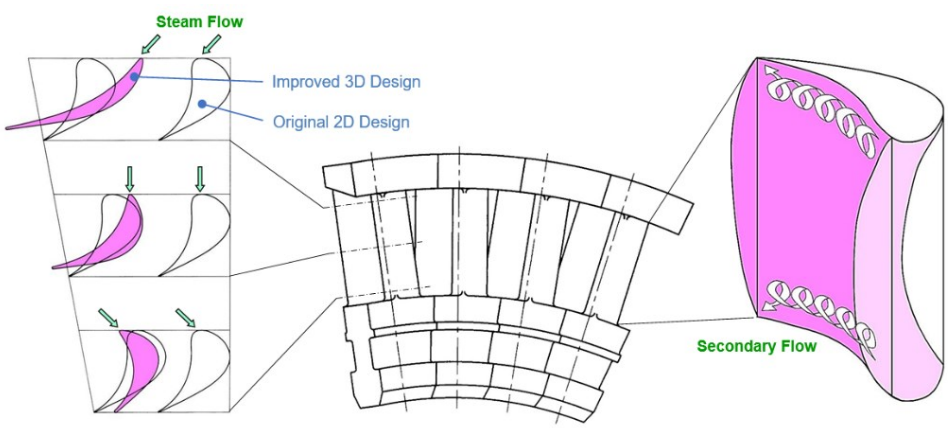

Figure 5: 3D Turbine Blade Design to Improve Efficiency

By implementing the Retrofit Project, SLK4/5/6 aims to ensure the safe and reliable operation of the system. This project resolution is designed to address the gap identified by LTA, so lifetime of turbine rotors and stators can be extended beyond end of contract schedule. Simultaneously, the project will enhance plant performance through efficiency improvements, utilizing 3D technology for the new turbine rotors and stators.

In alignment with the turbine work formula, the retrofit will focus on key parameters such as steam mass flow rate ($\dot{m}$), delta enthalpy (h1-h2), and isentropic efficiency (ηt). Notably, parameters like steam mass flow rate ($\dot{m}$), inlet enthalpy (h1), and outlet enthalpy (h2) will remain unchanged, as no additional steam mass flow or steam pressure changes are required for this retrofit plan. The anticipated improvement in isentropic efficiency (ηt) is expected to increase from the current average of 79.2% to 81.5%. Following this improvement in isentropic efficiency, the power generation output will also increase by 2.4 MW for each unit, resulting in a total increase of 7.2 MW across the three units. Figure 6 below shows simplified schematic of SLK4/5/6 after the execution of Retrofit Project. As shown below all current parameters remain the same, however, the generation output is expected to optimize to 69.4 MW per unit.

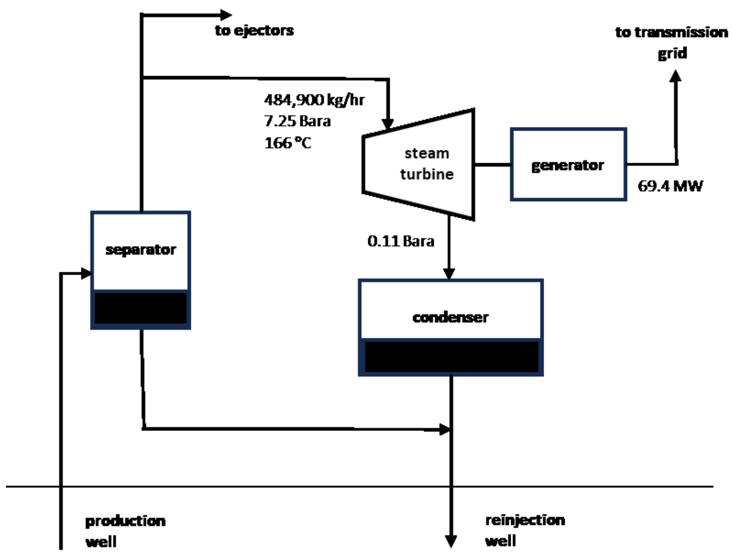

Figure 5: Simplified Schematic of SLK4/5/6 after Retrofit Project

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