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Design and Thermodynamic Modeling of a Recuperative ORC Binary System for Double Flasher Geothermal Power Plant

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Abstract. This research evaluates the thermodynamic performance of a recuperative binary Organic Rankine Cycle (ORC) integrated with a double-flash geothermal power plant, modeled using Aspen HYSYS for medium-enthalpy resources (200°C) common in Indonesia, such as Lahendong or Wayang Windu fields. Configurations compared include standalone double-flash (baseline), double-flash + simple ORC, and double-flash + recuperative ORC, with n-pentane selected as the optimal working fluid for its superior net power output, thermal efficiency, and low specific investment cost among alternatives like isopentane and isobutane. Fixed geothermal brine inputs (180°C, 15 bar, ~144-146 kg/s) simulate real Indonesian conditions. Results demonstrate the recuperative design's superiority: ORC efficiency rises by ~2% (13.71% vs. 11.71%), overall plant efficiency by 3.26% (21.5% vs. 18.24%), and net power output by 168% (5229 kW vs. 1514.6 kW baseline), driven by recuperator-enabled heat recovery that cuts evaporator duty by 15-25% and condenser rejection. Geothermal segment efficiency improves to 5.62% from 4.55%. Recuperator design features shell-and-tube units (e.g., 5181 mm tube length, 2100 mm shell diameter, U = 65 W/m^{2}K, area ~1889 m^2) with minimal pressure drops. Findings align with global benchmarks (e.g., 3-4% efficiency gains, 35% power boosts) and support Indonesia's 40 GW geothermal potential via modular ORC for brine utilization. Recommendations emphasize economic optimization and scaling for Lahendong expansions.

Keywords: *Aspen HYSYS, double-flash geothermal, efficiency enhancement, n-pentane, recuperative ORC.*

1 Introduction

Geothermal energy constitutes one of Indonesia's premier renewable resources, harnessing subsurface heat for reliable baseload power generation. The

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archipelago nation possesses an estimated geothermal potential of 40 GW, positioning it as the global leader in untapped reserves, equivalent to about 40% of worldwide resources. This endowment furnishes a sustainable avenue for fulfilling national electricity requirements, particularly amid escalating demand projected to reach 400 GW by 2050 and net-zero emissions commitments by 2060. Geothermal's dispatchable nature complements intermittent renewables like solar and wind, mitigating grid instability while curtailing fossil fuel reliance.

Not withstanding this expansive reserve, exploitation lingers at roughly 2.7 GW of installed capacity as of early 2026, harnessing less than 7% of viable potential. Development impediments include technical drilling risks (success rates ~70-80% in high-enthalpy fields), high CAPEX ($3.2-5.5 million/MW for flash plants), regulatory/social delays in protected forests (70% sites), and remote access challenges in volcanic regions [1]. Double-flash geothermal power plants represent an evolutionary advancement in geothermal power plant configurations, utilizing sequential flashing at high-pressure (HP, ~5-15 bar) and low-pressure (LP, ~1-3 bar) stages to maximize steam yield from separated geothermal brine. This process extracts additional vapor from the HP liquid flash product, boosting gross power output by 20-60% over single-flash systems while reducing reinjection entropy generation. Empirical data indicate gross thermal efficiencies of 12-18% for double-flash plants (e.g., 14.09% in Dieng, Indonesia, post-conversion), compared to 8-12% for single-flash equivalents under comparable reservoir conditions (geofluid 150-250°C). Such gains stem from minimized flashing irreversibilities and higher utilization factors (~0.25-0.35 kg steam/kg geofluid vs. 0.15-0.25), though parasitic loads (pumps ~2-5% net) temper net efficiencies to 10-15%. These metrics underscore double-flash dominance in medium-high enthalpy fields (>150°C), as deployed in ~30% of global capacity [2].

The performance of a geothermal power plant depends not only on the reservoir condition, but also on how effectively the available heat is converted into useful power. In flash geothermal systems, a double-flash configuration can improve the use of geothermal fluid by expanding steam at two pressure levels. The liquid from the first separator is flashed again at a lower pressure, producing additional steam for the low-pressure turbine. This makes the double-flash system more effective than a single-flash system under suitable resource conditions. Previous studies on geothermal power systems and the conversion of single-flash plants to double-flash configurations have shown that this approach can increase power output by recovering more energy from the geothermal fluid before reinjection [2,3]. However, even after the second flashing process, some thermal energy remains in the separated brine or exhaust stream.

This remaining heat can be used by adding a binary bottoming cycle. The Organic Rankine Cycle (ORC) is suitable for this purpose because it uses organic working fluids with lower boiling points than water, allowing power generation from low- to medium-temperature heat sources. In geothermal applications, the ORC can recover heat that is not fully utilized by the flash system. The selection of the working fluid and the ORC configuration is important because both affect heat absorption, turbine work, and thermal efficiency [4]. A recuperator can also be added to the ORC to reuse part of the heat from the turbine outlet stream before it reaches the condenser. This reduces the heat demand in the main heat exchanger and lowers the condenser heat rejection. Recuperative ORC systems have been reported to improve the use of low-grade heat, especially when the turbine exhaust temperature is still high enough for internal heat recovery [5,6].

Based on this consideration, this study models a recuperative binary ORC integrated with a double-flash geothermal power plant using Aspen HYSYS. The system is compared with two other configurations: a standalone double-flash geothermal power plant and a double-flash geothermal power plant with a simple ORC. The comparison is carried out under the same geothermal inlet conditions so that the effect of the ORC and recuperator can be evaluated clearly. Similar combined flash-binary and geothermal bottoming-cycle studies have shown that adding a secondary cycle can improve geothermal heat utilization and plant performance [7–9]. Therefore, this study focuses on turbine power output, pump power consumption, condenser heat rejection, ORC efficiency, and overall plant thermal efficiency to evaluate whether the recuperative ORC configuration can improve the use of medium-enthalpy geothermal resources in Indonesia.

2 Methodology

2.1 Basic Analytical Theory

The Organic Rankine Cycle (ORC) is a technology that utilizes organic fluids with low boiling points to convert low- to medium-temperature heat into electricity. ORC is highly suitable for geothermal power plants due to its efficiency at temperatures suboptimal for conventional steam Rankine cycles. The recuperator in ORC systems enhances thermal efficiency by recovering heat from the exhaust stream. Hidayah et al. emphasize the critical role of optimal working fluid selection and cycle configuration in maximizing ORC efficiency in geothermal power plant applications [4].

Research on ORC implementation in geothermal power plants emphasizes power output and efficiency optimization. Integration of recuperative cycles has proven to significantly enhance system performance. Surendran & Seshadri introduce an innovative two-stage transcritical-recuperative ORC, effective for dual/multi-source heat recovery applications, thereby augmenting geothermal power plant capability to utilize energy from multiple heat sources simultaneously.

Analyses of ORC system performance and optimization have been extensively researched. Li et al. conducted an experimental investigation of a recuperative ORC system for electricity generation from low-grade thermal energy, demonstrating superior efficiency and power output compared to basic ORC configurations, rendering it highly suitable for geothermal applications [1]. Yilmaz et al. focused on modeling and designing combined double-flash and binary geothermal power plants, revealing that ORC integration significantly enhances thermodynamic performance [7].

Several case studies demonstrate the successful implementation of ORC systems in geothermal power plants. Adi et al. investigated the use of the Kalina cycle as a bottoming cycle in geothermal power plants, highlighting the potential for efficiency and power output improvements when integrated with advanced cycles such as recuperative ORC [8]. This study illustrates practical applications and benefits of sophisticated thermal cycles in enhancing geothermal power generation.

2.2 Information and Data Collection

Data for the recuperative binary ORC-double-flash geothermal power plant design were comprehensively gathered, including geofluid compositions/properties (water, steam, non-condensables), reservoir conditions (temperature, pressure, enthalpy), and specifications for turbines, generators, pumps, heat exchangers, ORC working fluids, and recuperator design parameters. Actual operational data from geothermal power plants, such as geofluid mass flow rates, temperatures/pressures at system points, and turbine/generator outputs, were collected for model validation. Literature reviews sourced suitable thermodynamic models and comparable case studies.

2.3 Plant and System Design

The review encompassed foundational concepts and recent advances in geothermal power generation and binary ORC systems. Key aspects included: double-flash geothermal power plant operating principles; recuperative binary ORC mechanisms and advantages; case studies from Indonesian and international geothermal power plants; and critical parameters/variables influencing system efficiency and performance.

PFDs for the double-flash geothermal power plant with ORC and recuperator were constructed in Aspen HYSYS. Major components (separators, turbines, pumps, heat exchangers, recuperators) were interconnected per material/energy flows. Geofluid and ORC working fluid properties were defined using Aspen databases or external sources; operating conditions were derived from design data, literature, and reasonable assumptions.

Simulations verified design-condition outputs (power, performance parameters). Three systems were compared at constant well/operational variables but varying heat exchanger states:

1. Double-flash only;
2. Double-flash + simple ORC;
3. Double-flash + recuperative binary ORC.

Metrics included utilizable power and thermal efficiencies (cycle-specific and overall). Simulation results were benchmarked against similar actual operational data to validate accuracy. Model adjustments addressed discrepancies, accounting for influencing factors.

3 Data and Analysis

3.1 Operational Data Collection

Operational data collection was pivotal for developing and validating the thermodynamic model of the recuperative binary ORC-double-flash geothermal power plant. Essential parameters encompassed geofluid conditions from production wells (temperature, pressure, enthalpy, compositions of water, steam, and non-condensables), component specifications (turbines, generators, pumps, heat exchanger capacities and efficiencies, ORC working fluids), actual operational outputs (geofluid mass flow rates at system points, temperatures/pressures, turbine and generator power), and literature-derived thermodynamic models alongside relevant case studies.

3.2 System and Plant Concept Design

Process flow diagrams (PFDs) in Figure 1, were developed for the recuperative binary ORC integrated with the double-flash geothermal power plant, with stream states detailed subsequently; these aligned with established PFDs for double-flash geothermal power plants and existing ORC implementations [4,9].

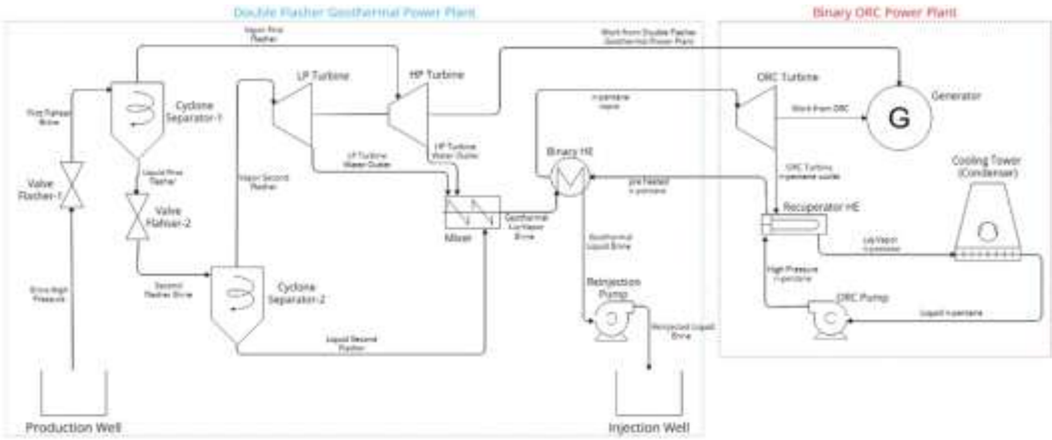

Figure 1 PFD of ORC binary system with recuperator at the geothermal plant double flasher

3.2.1 Operational Data in Double-Flash Geothermal Plant

Stream states for each flow in the double-flash geothermal power plant-ORC design process were determined from multiple sources, with reasonable assumptions where needed. The value of each simulating parameter is shown in Table 1. Production well mass flow averaged from Adi et al.; temperatures/pressures adjusted for medium-enthalpy ORC suitability (<200°C) [7].

Table 1 Stream states in the double-flash geothermal plant

Stream	Description	Vapour Fraction	Temperature (°C)	Pressure (kPa)	Molar Flow ($\frac{kgmol}{h}$)	Mass Flow ($\frac{kg}{h}$)	Liquid Volume Flow ($\frac{m^3}{h}$)
1	Production Well	0,0	180,0	1500,0	7993,3	144000,0	144,3
2	Post-1st Flash Separator	0,1	151,8	500,0	7993,3	8895,0	144,3
3	HP Turbine Inlet	1,0	151,8	500,0	493,8	135105,0	8,9
4	Liquid from 1st Separator	0,0	151,8	500,0	7499,5	135105,0	135,4
5	Post 2nd Flash Separator	0,1	99,6	100,0	7499,5	13899,0	135,4
6	LP Turbine Inlet	1,0	99,6	100,0	771,5	13899,0	13,9

Stream	Description	Vapour Fraction	Temperature (°C)	Pressure (kPa)	Molar Flow ($\frac{kgmol}{h}$)	Mass Flow ($\frac{kg}{h}$)	Liquid Volume Flow ($\frac{m^3}{h}$)
7	LP Turbine Outlet	0,9	46,0	10,0	771,5	8895,0	13,9
10	HP Turbine Outlet	0,9	99,6	100,0	493,8	121206,0	8,9
13	Liquid From 2nd Separator	0,0	99,6	100,0	6728,0	144000,0	121,5
23	Mixer Inlet	0,2	46,0	10,0	7993,3	144000,0	144,3
14	Mixer Outlet	0,0	46,0	10,0	7993,3	144000,0	144,3
15	Reinjection Pump Outlet	0,0	46,2	1500,0	7993,3	144000,0	144,3

3.2.2 Operational Data in ORC Plant

Stream states adjusted to binary heat exchanger duty, converting mixer vapor-liquid mixture to full liquid via Aspen HYSYS dynamic rating model, determining required ORC flow rate; fluid selection detailed in 3.5 [9]. All values of the steam and water mass flowrate are denoted in Table 2.

Table 2 Steam states in ORC

Stream	Description	Vapour Fraction	Temperature (°C)	Pressure (kPa)	Molar Flow ($\frac{kgmol}{h}$)	Mass Flow ($\frac{kg}{h}$)	Liquid Volume Flow ($\frac{m^3}{h}$)
22	Inlet to Binary HE	0,0	61,1	500,0	2831,5	204297,0	324,4
16	Outlet from Binary HE	1,0	92,1	500,0	2831,5	204297,0	324,4
17	Outlet from Recuperator HE	0,9	35,8	100,0	2831,5	204297,0	324,4
18	ORC Condenser Outlet	0,0	30,0	100,0	2831,5	204297,0	324,4
19	ORC Pump Outlet	0,0	30,2	500,0	2831,5	204297,0	324,4
20	ORC Turbine Outlet	1,0	60,6	100,0	2831,5	204297,0	324,4

3.3 Thermodynamic Model Development in Aspen HYSYS

The thermodynamic model development in Aspen HYSYS was conducted through a structured multi-step process. First, process flow diagrams (PFDs) were constructed to illustrate material and energy flows within the double-flash geothermal power plant integrated with ORC and recuperator systems. Major components, including separators, turbines, pumps, heat exchangers, and the recuperator, were interconnected according to actual system flows, with Figure 2 presenting the designed system PFD.

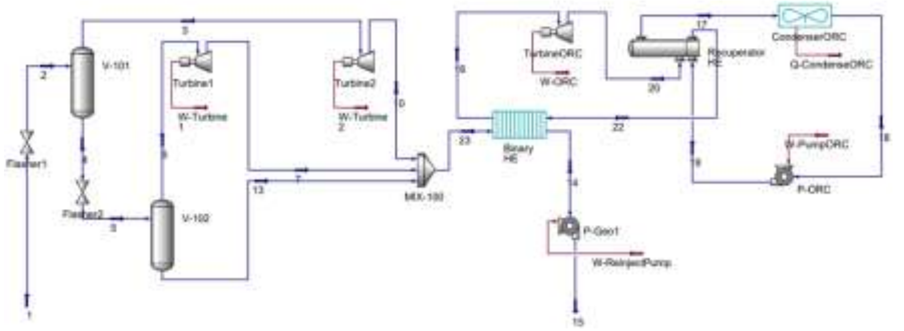

Figure 2 PFD of ORC binary system at geothermal plant double flasher on Aspen HYSYS

Comparator system PFDs were similarly developed for the standalone double-flash geothermal power plant and the double-flash with simple ORC configurations. Figure 3 depicts the double-flash geothermal power plant PFD, while Figure 4 shows the double-flash schematic model with simple ORC PFD.

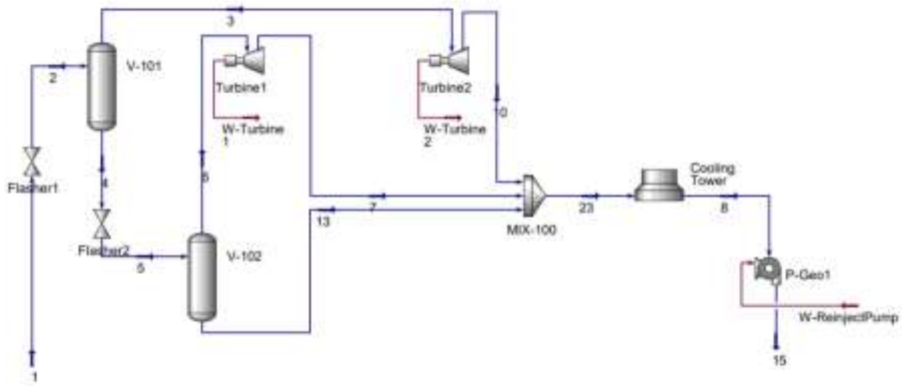

Figure 3 PFD of the geothermal system double flasher on Aspen HYSYS

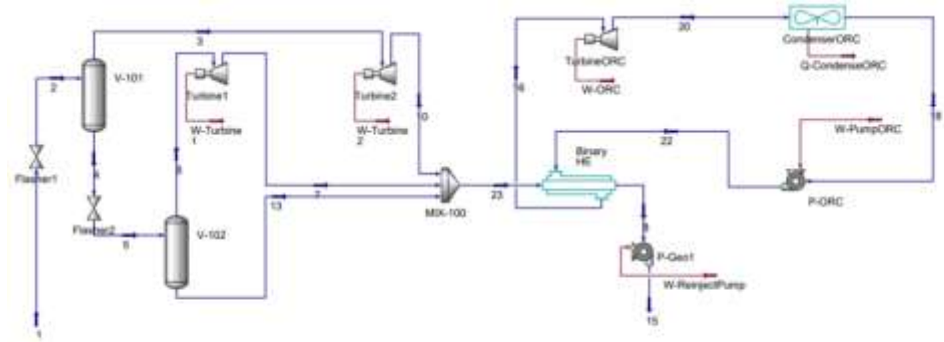

Figure 4 PFD of the geothermal plant double flasher with a simple ORC

Geothermal fluid and n-pentane working fluid properties were determined using Aspen HYSYS component databases. The Peng-Robinson equation of state was applied for the double-flash Rankine cycle analysis, whereas the Soave-Redlich-Kwong package was selected for the ORC hydrocarbon streams, consistent with previous study [9]. Determined parameters encompassed molar mass, boiling point, critical pressure and temperature, and specific heat capacity.

Operating conditions for each component were established based on design data, literature sources, and reasonable assumptions outlined in Section 3.2. Primary operational parameters included pressure, temperature, and fluid mass flow rates.

3.4 Thermodynamic Assumptions

Several thermodynamic assumptions underpinned the simulations to ensure model realism and computational feasibility. All turbines operated at 80% isentropic efficiency, pumps at 75% efficiency, and generators at 100% efficiency. No pressure drops were assumed across heat exchangers, coolers, pipelines, or separators; processes proceeded under steady-state conditions with negligible heat losses from heat exchangers.

3.5 ORC Working Fluid Selection

Optimal working fluid selection is crucial for maximizing ORC system efficiency and performance. Several candidates were evaluated based on thermophysical properties tabulated from NIST data (Table 3). n-Pentane was selected owing to Hidayah et al. and property assessment, offering: suitable boiling point for medium-temperature geothermal heat utilization; high specific heat capacity for efficient transfer; and good thermal stability within operational ranges [10].

Table 3 Properties of candidate ORC working fluids [10]

Property	n-Pentane	n-Butane	Isopentane	Propane
Formula	C_5H_{12}	C_4H_{10}	C_5H_{12}	C_3H_8
Molar Mass (g/mol)	72.15	58.12	72.15	44.1
Boiling Point (℃)	36.1	-0.5	27.8	-42.1
Critical Temperature (℃)	33.7	37.5	33.8	42.5
Critical Pressure (bar)	196.6	152.0	187.8	96.7
Specific Heat Capacity ($\frac{kJ}{kg.K}$)	2.39	2.38	2.45	2.31

3.6 Simulation Result

Simulation results from the recuperative binary ORC-double-flash geothermal power plant in Aspen HYSYS are aligned with data in Section 4.2. Obtained results for the designed and comparator systems covered turbine-generated powers, condenser-heats rejected, and pump-required powers. Simulated turbine powers per system are tabulated in Table 4; condenser heats rejected in Table 5; and pump powers in Table 6. Calculations for all equipment (turbines, condensers, pumps) followed the equations:

$$\dot{Q} - \dot{W} = \dot{m} \times (h_{outlet} - h_{inlet}) \quad (1)$$

$$\dot{W}_T = \dot{m} \times (h_{inlet} - h_{outlet}) \quad (2)$$

$$\dot{W}_P = \dot{m} \times (h_{outlet} - h_{inlet}) \quad (3)$$

$$\dot{Q} = \dot{m} \times (h_{outlet} - h_{inlet}) \quad (4)$$

Table 4 Simulated turbine powers (kW)

System	Turbine	Power (kW)
ORC binary with recuperator on double-flash geothermal power plant	High-pressure turbine	548.6
	Low-pressure turbine	1066.1
	ORC turbine	2714.5
Double-flash geothermal power plant with simple ORC	High-pressure turbine	1066.1
	Low-pressure turbine	548.6
	ORC turbine	2714.5
Double-flash geothermal plant only	High-pressure turbine	548.6
	Low-pressure turbine	1066.1

Table 5 Simulated condenser heats rejected (kW)

System	Condenser	Power (kW)
Recuperative ORC + double-flash	ORC condenser	19680.5
Simple ORC + double-flash	ORC condenser	23181.6
Double-flash only	Geothermal cooling tower	22344.4

Table 6 Simulated pump powers (kW)

System	Pump	Power (kW)
ORC binary with recuperator on double-flash geothermal plant	Geothermal reinjection pump	80.16
	ORC pump	49.17
Double-flash geothermal plant with simple ORC	Geothermal reinjection pump	78.93
	ORC pump	49.65
Double-flash geothermal only	Geothermal reinjection pump	80.16

3.7 Result Analysis and Representation

Simulation results from Subsection 4.6 were subsequently processed by calculating thermal efficiencies for each system—both overall system thermal efficiency as well as for individual cycles. Thermal efficiencies were also computed for each system segment, namely the double-flash/geothermal power plant portion and the standalone ORC portion. The primary focus was on overall plant efficiency across systems. Efficiencies for each system were calculated according to the equation:

$$\eta = \frac{\sum \dot{W}_T - \sum \dot{W}_P}{\sum \dot{Q}_C} \tag{5}$$

Thermal efficiency denoted by η; $\sum \dot{W}_T$ mean the total power generated by all turbines; $\sum \dot{W}_P$ is the total power required by all pumps; and $\sum \dot{Q}_C$ show the total heats rejected by condensers.

From the efficiency equation, thermal efficiency was then calculated for each system, considering only the geothermal power plant (double-flash unit), as shown in Figure 5. It can be seen that the efficiency decreases for the double-flash geothermal power plant with a simple ORC configuration. This occurs because the efficiencies in Figure 5 are based on the heat exchanged in the binary heat exchanger (HE duty), and in the simple ORC case, this duty increases; compared with the recuperative ORC system, while the heat input to the binary HE is larger, so a higher duty is required.

Thermal efficiencies for the ORC cycle alone in each system are presented in Figure 6. The figure shows a 2% efficiency increase for the ORC with a recuperator compared with the simple ORC. This indicates that, for the same turbine work, the recuperative ORC exhibits lower condenser work, since the working fluid (n-pentane) is first routed through the recuperator HE before entering the binary HE, thereby reducing condenser heat rejection and increasing overall ORC cycle efficiency. At the same time, the heat that must be supplied by the binary HE is reduced because part of the working-fluid heating is accomplished in the recuperator HE. The ORC turbine power of 2714.5 kW is also observed, in contrast to the double-flash-only geothermal power plant, which has no ORC turbine and thus no associated ORC efficiency. Consequently, the power gain obtained by using the ORC cycle relative to the geothermal power plant-only system is 168%, i.e., turbine power becomes 1.68 times higher.

The key efficiency indicator is shown in Figure 7, which presents bar charts of overall plant efficiency for each system. The highest efficiency is achieved by the binary ORC with recuperator on the double-flash geothermal power plant (Figure 2), at 21.5%, compared with 18.24% for the double-flash geothermal power plant with simple ORC (Figure 4) and 6.87% for the double-flash-only geothermal power plant (Figure 3). The improvement associated with adding ORC indicates that exchanging heat between the turbine exhaust and the stream entering the binary HE increases system efficiency by 3.26% relative to the simple ORC configuration, consistent with ref. [4,6]. This enhancement arises from reduced ORC condenser duty and binary HE duty due to internal heat recovery. The double-flash-only system exhibits the lowest efficiency because it does not utilize ORC to recover additional power from the geothermal fluid, resulting in much lower turbine output, in agreement with previous study [7]. These results show that incorporating an ORC cycle with a hydrocarbon working fluid, such as n-pentane, to exploit residual heat prior to reinjection can significantly increase overall system efficiency and the recoverable power from medium-enthalpy production wells.

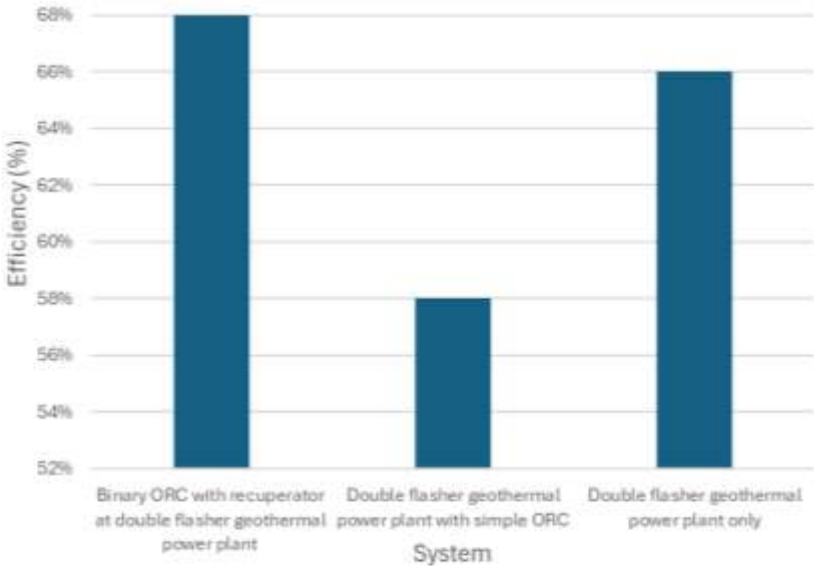

Figure 5 Efficiency of the geothermal power plant only system

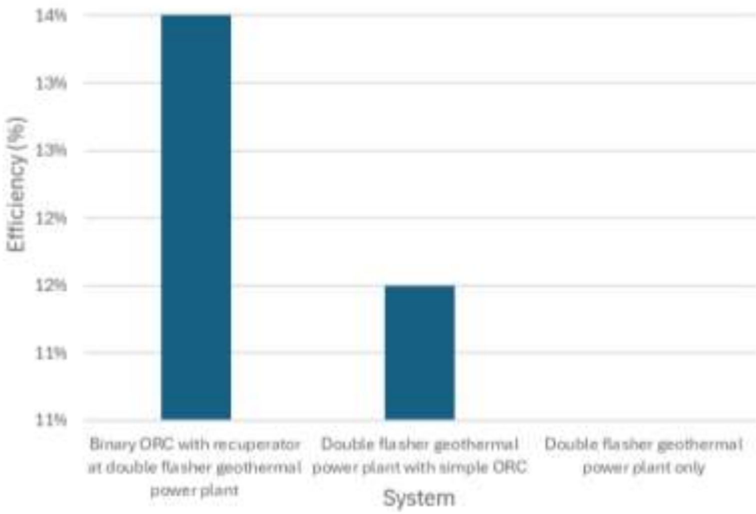

Figure 6 Efficiency of the ORC system

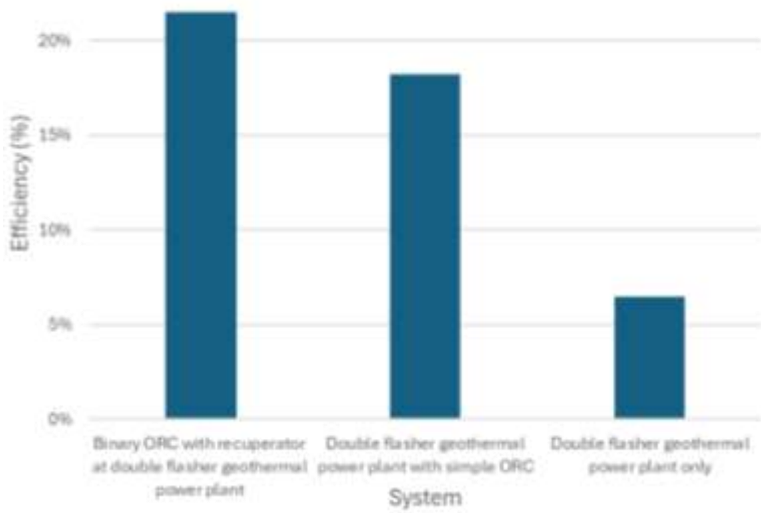

Figure 7 Efficiency of the overall power plant system

4 Conclusion

The results of the design and thermodynamic modeling of the recuperative binary ORC system integrated with the double-flash geothermal plant produced designed outcomes where the state conditions of each stream presented in Tables 1 and 2 proved highly advantageous, positively impacting the overall system. Simulation results, coupled with comparative studies against existing or alternative systems, demonstrated the superiority of the proposed design over others.

The adoption or selection of the double-flash process in the geothermal plant already confers advantages through increased turbine power output. Results further indicate that the recuperative ORC cycle delivers higher thermal efficiencies, both for the standalone ORC cycle and the overall system (Figures 6 and 7), compared with the double-flash geothermal plant with simple ORC, yielding sequential thermal efficiency improvements of 2% and 3.26%, respectively, consistent with studies [6,7].

In terms of overall plant power generation capacity, the designed system, binary ORC with recuperator on double-flash geothermal plant, produced 2714.5 kW more power than the double-flash geothermal plant alone, representing a 168% increase. This demonstrates that geothermal plants employing ORC are highly advantageous for power output.

In summary, the results indicate that the recuperative binary ORC design integrated with the double-flash geothermal plant is highly advantageous, achieving a 3.26% efficiency increase and an overall system power generation uplift of 168% (1.68 times) compared with alternatives, including double-flash with simple ORC or double-flash alone.

Nomenclature

CAPEX	=	Capital expenditure
h	=	Enthalpy
HE	=	Heat Exchanger
HP	=	High-pressure
LP	=	Low-pressure
$\dot{m}$	=	Mass flow rate
NIST	=	National Institute of Standards and Technology
ORC	=	Organic Rankine Cycle
PFD	=	Process Flow Diagram
$\dot{Q}$	=	Heat transfer rate
T	=	Temperature
U	=	Overall heat transfer coefficient
$\dot{W}$	=	Power
η	=	Thermal efficiency

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