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Experimental Evaluation of Binary and Combined Cycle Geothermal Power Plants Operating with Optimised Working Fluids

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Keywords:
Geothermal energy; Binary cycle; Combined cycle; Organic Rankine cycle; Working fluids; Thermal efficiency; Low-temperature resources; Electricity generation.

Highlights:

- *Performance optimization revealed that the combined-cycle system employing R227ea achieved a peak thermal efficiency of 16.4% at a geothermal inlet temperature of 175 °C.*
- *The utilization of an R245fa–isobutane zeotropic mixture yielded a maximum specific energy output of 33.2 kWh per ton of geofluid.*
- *Lowering the condenser air temperature from +20 °C to –20 °C increased generator output power by 15.7%.*

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Abstract: This study presents a comprehensive experimental and analytical assessment of geothermal power plant configurations utilizing binary and combined-cycle systems for the efficient generation of electricity from low- and medium-temperature geothermal resources. The research used a modular geothermal energy block equipped with an ORMAT Model 3G-250 unit and various working fluids, including R245fa, isobutane, R134a, and R227ea. Experimental scenarios simulated geothermal water temperatures ranging from 95 to 175°C under different condensation and load conditions. The results demonstrated that the combined cycle, integrating a dry saturated steam turbine with an organic Rankine cycle, achieved the highest performance, with a peak electrical output of 305 kW and a thermal efficiency of 15.9%. Binary configurations operating on R245fa–isobutane mixtures exhibited a 5–7% higher specific electricity yield than pure R134a. Additionally, lowering the ambient air temperature for condenser cooling enhanced output power by up to 15.7%. The findings highlight the significant advantages of optimised working fluid compositions and regenerative heating in improving efficiency. These findings validate the thermodynamic feasibility of binary and combined-cycle configurations for sustainable power generation, demonstrating superior conversion efficiencies particularly when valorizing low-to-medium enthalpy geothermal reservoirs.

1.INTRODUCTION

In the context of global climate change and the accelerated depletion of traditional energy resources, the search for alternative, environmentally friendly methods for generating heat and electricity is increasingly essential. According to forecasts, by the middle of the 21st century, to mitigate the effects of global warming, it will be necessary to increase the share of renewable energy sources to 65%. Today, several countries have demonstrated significant progress in this direction: in Spain, the share of renewable energy exceeds 83.7%; in Norway, it is 77.4%; and in Sweden, it is 60.1%. An example of the large-scale use of such resources is Iceland, where geothermal energy accounts for more than half of electricity generation, and centralised geothermal heating has enabled multiple reductions in carbon dioxide emissions [1,2]. These data indicate that the development of technologies to harness Earth's internal heat is becoming a strategic direction for global energy. Geothermal energy has several advantages over other renewable energy sources: it is independent of climatic conditions, provides stable heat and electricity generation throughout the year, has low operating costs, and is highly reliable. According to the latest statistics, there are approximately 400 geothermal power plants worldwide, most of which are located in countries with high geothermal temperatures. The temperature of geothermal water used at most operating plants ranges from 100 to 200°C. The source parameters are fundamental to the efficient conversion of heat into electrical energy: the higher the temperature and pressure, the higher the plant's thermal efficiency. For example, geothermal power plants with direct supply of dry steam to the turbine exhibit efficiency significantly exceeding that of binary systems. Still, their implementation is limited by the infrequent occurrence of sources with high steam parameters. There are various approaches to addressing the involvement of geothermal energy in economic circulation [3-5]. The most common thermal schemes are single-stage and two-stage geothermal-source separation, binary plants, and combined systems. Direct-cycle geothermal power plants with single-stage separation are characterised by a relatively simple design, minimal capital costs, and a low cost of installed capacity, with some projects achieving costs below 2000 US dollars per kilowatt. At the same time, such plants require geothermal water temperatures above 150°C and must purify water vapour from non-condensable gases and highly mineralised impurities. Two-stage separation can increase electricity generation efficiency by 25% relative to a single-stage option, but it entails higher capital and operating costs. Binary geothermal power plants operating on the organic Rankine cycle use two closed loops, which allow efficient heat processing even at geothermal source temperatures of 85 to 170°C. This feature has made binary schemes the most widely used worldwide, despite their higher specific cost relative to direct cycles, which can exceed $3,000 per kilowatt of installed capacity [6-9]. At the same time, binary GeoPPs help prevent corrosive wear of equipment and problems associated with condensation of water vapour in cold climates. In addition, using modern heat exchangers and low-boiling-point freons, such as R245fa or R134a, it is possible to maintain a high level of thermal efficiency and reliability even at the low temperatures of geothermal sources. An interesting trend in recent years has been the development of combined schemes in which the organic cycle is combined with the steam cycle. For example, the modernisation of the Mutnovskaya GeoPP increased installed capacity by 40% by adding a binary block to the steam turbine. At the same time, the total additional generation reached 12.8 MW [10-12]. Despite the apparent advantages, each of the above approaches has its limitations. Direct-cycle geothermal power plants with single-stage separation are unsuitable for regions with low-grade heat sources. Two-stage plants are expensive to build and require a complex system for controlling steam and liquid phase flows. Binary plants, although more versatile, are associated with high capital investments and the need to select the optimal organic working fluid, often requiring detailed modelling of thermal processes and multi-criteria optimisation. In addition, the economic efficiency of small binary plants (for example, with a capacity of up to 200 kW) is significantly reduced by their low total energy output and high specific maintenance costs. In this context, the research direction presented in this work is particularly significant. It is devoted to a comprehensive analysis of geothermal energy thermal schemes, an assessment of their efficiency, and prospects for their use in a wide variety of geographical and climatic conditions. The comparative analysis confirmed that binary geothermal power plants can operate on geothermal water at temperatures below 150°C and provide a reliable power supply with minimal risk of corrosion and process failures. In particular, numerical calculations showed that, when using a supercritical organic Rankine cycle, electricity generation increases by 32%, and the use of a heat pump to utilise residual heat enables an additional 3 MW of thermal power generation. These data demonstrate that the direction in question not only meets the global challenges of the energy transition but also offers practical pathways to create environmentally friendly, efficient, and economically viable energy complexes [13,14]. The purpose of this work is to provide a comprehensive analysis of the features of geothermal power plants, including modern technologies for converting geothermal energy into heat and electricity, with attention to their use across climatic zones and to their operational characteristics.

Fig. 1 The Geothermal Power Plant.

1.1.Novelty and Contribution

Unlike prior geothermal ORC studies that rely exclusively on simulations or steady-state field data, this work presents a controlled experimental comparison of binary and binary–steam combined cycles on a modular ORMAT 3G-250 platform with a tunable zeotropic working-fluid composition (R245fa–isobutane, 70:30) and regenerative heating. There is a coupled small-scale steam stage (Siemens SST-040) enabling an actual combined configuration, the systematic condenser air-temperature sweeps from −20 °C to +20 °C to quantify ambient sensitivity, and transient robustness tests under abrupt load and source-temperature changes. The dataset provides specific electricity per ton of geothermal water and efficiency gains attributable to ambient conditions and mixture effects, offering experimentally validated benchmarks for low- and medium-temperature resources.

2.RESEARCH METHODS

During the research, a comprehensive experimental plan was implemented to assess the thermal performance of geothermal power plants with various energy-conversion configurations. The work was carried out using a laboratory test bench mounted on a modular installation of a geothermal power unit capable of simulating multiple temperature and flow modes. The leading equipment was the ORMAT Model 3G-250 complex, which enables implementation of the organic Rankine cycle with a wide range of working fluids. The unit was equipped with an Alfa Laval TS20-M plate-type evaporator with a working heat-exchange area of 12 m² and a Gunt WT300 air-cooled condenser designed to remove heat at ambient temperatures down to -15 °C. The experimental tests included a series of comparisons of the efficiency of binary and combined cycles using geothermal water at different temperatures. During the heat-flow simulation, demineralised water heated to 95, 120, or 155°C, depending on the selected scenario, was supplied to the evaporator. The working fluid of the organic cycle (a mixture of R245fa and isobutane in a ratio of 70:30 by weight) entered the turbine at a pressure of 2.5 MPa, and condensation occurred at a pressure of 0.35 MPa. The unit's turbine equipment provided a shaft speed range of 3000-6000 rpm. A separate heat-recovery unit, based on the APV SPX NH35 heat exchanger, was used to preheat the working fluid before evaporation. In addition to the basic operating modes, experiments were conducted to investigate the effects of varying the working-mixture composition on energy-generation parameters. In particular, a series of experiments was performed using R134a, with the evaporator boiling temperature maintained at 78°C and the saturated vapour pressure at 1.9 MPa. To assess the system's dynamic characteristics, time diagrams of temperature and pressure changes in each circuit were recorded during transient processes, such as an abrupt change in the generator load from 60 to 100% of the nominal value. The data acquisition system was built using National Instruments CompactDAQ modules with Type K thermocouples and WIKA P-30 piezoelectric pressure sensors, providing a temperature resolution of 0.1°C and a pressure resolution of 0.02 MPa.

2.1. Measurement Techniques

Temperatures at evaporator/condenser inlets and outlets were sampled at 1 Hz and averaged over 60-s windows to suppress short-term noise. Pressures at the turbine inlet and condenser were recorded synchronously with temperatures. Electrical power was logged from the generator controller (a class ≤1% per manufacturer specification) and time-aligned with the thermal data. All sensors were zero-checked before each run; thermocouples were spot-checked against a calibrated reference bath at 0 °C and 100 °C, and pressure sensors were checked at three points across the operating range using a dead-weight tester.

2.2. Uncertainty Analysis

Combined standard uncertainties were evaluated via Gaussian propagation, using instrument specifications and repeatability data from five replicate measurements per operating condition. With the temperature resolution of ±0.1 °C and the verification error within ±0.5 °C, and pressure resolution of ±0.02 MPa with the verification error within ±0.25 % FS, the expanded ($k = 2$) uncertainties were as follows. Electric power was ±2.0 %, condensation pressure was ±0.01–0.02 MPa, evaporating temperature was ±0.6 °C, and cycle efficiency was ±0.6 percentage points across the 9.7–16.4 % range. For the specific electricity yield, the expanded uncertainty was ±4%. These values were reported alongside the key operating points in the Results section. As part of the research, a high-temperature operating mode was implemented, in which the geothermal coolant temperature was brought to 175°C, and the evaporator pressure to 3.0 MPa. In this case, a combined scheme was employed, with steam supplied to the Siemens SST-040 axial turbine and the turbine operating in conjunction with a binary circuit using R-227ea Freon. During these experiments, the indicators of electrical and thermal power, efficiency factors, and data on the specific consumption of the working mixture were recorded. Tests were also conducted to assess the influence of external climatic factors on condensation efficiency, for which the outside air temperature was set from +20 to −20 °C in the Espec AR-1100 climatic chamber. The obtained data provided the basis for substantiating the feasibility of using various thermal schemes and for selecting optimal working fluids for low-temperature geothermal sources.

3. RESULTS AND DISCUSSION

In this study, an extensive experimental and computational program was conducted to determine the optimal parameters for the operation of various thermal circuits in geothermal power plants, accounting for their use under low- and medium-temperature source conditions. All stages of the experiments were conducted on a specialised test bench, which included a model binary power unit capable of selecting working-fluid parameters, regulating the temperature regime of the geothermal water, and simulating various condenser-cooling conditions. The experimental work began with debugging and system warm-up. The geothermal coolant was demineralised water with a constant mineralisation of no more than 0.03%, heated to the required temperature in a storage tank, thereby ensuring thermal stability under power fluctuations of up to ±3%. During the main series of tests, geothermal water was sequentially fed to the Alfa Laval plate-type evaporator at three temperatures: 95, 120, and 155 °C. In this case, the thermal power, temperature front stability, and evaporator pressure were recorded. Two compositions were used as the working fluid in the organic cycle: a 70:30 (by weight) mixture of R245fa and isobutane and pure R134a. For each working fluid, a series of experiments was conducted, varying the turbine inlet pressure from 1.9 to 3.0 MPa and the boiling temperature from 78 to 140 °C. When using R245fa, the maximum evaporator pressure was 2.5 MPa, the condensation temperature was maintained at 25–30 °C, and the working-fluid flow rate was 0.62 kg/s. In the experiments with R134a, the boiling pressure was 1.9 MPa at 78 °C, and the flow rate was 0.55 kg/s. The turbine installed on the power unit operated in the rotation speed range from 3000 to 6000 rpm, while the generator power range from 90 to 250 kW was controlled. Special attention was paid to the combined operation modes, in which dry saturated steam from a geothermal source at 175 °C and 8.2 bar entered the Siemens SST-040 axial turbine, after which part of the heat was utilised in a binary cycle. In this mode, the steam and working-fluid consumption rates, condensation temperature, and power consumption of auxiliary equipment were recorded simultaneously. The tests were conducted at two generator load levels: 60% and 100% of the nominal value. To simulate seasonal conditions, the condenser was cooled with air whose temperature was controlled by a climatic chamber between +20 and −20 °C, enabling analysis of the effect of external temperature on condensation efficiency and, accordingly, on the unit's overall thermal efficiency. In addition to the main experiments, cycles of experiments were conducted to study transient processes during sharp changes in the coolant load and parameters. In particular, the dynamics of temperature and pressure changes in the evaporator and condenser were recorded as the temperature of the geothermal water was reduced from 155 to 95°C, and when the pressure of the working fluid at the turbine inlet was reduced from 2.5 to 1.9 MPa. In parallel, the stability of the installation's operating mode was assessed based on vibration and acoustic characteristics, and a heat balance of all system flows was performed. The following summary data were obtained from the experimental results. When the unit was operating on a mixture of R245fa and isobutane at a geothermal coolant temperature of 155°C, the average electric power was 232 kW with a working-fluid flow rate of 0.62 kg/s and a geothermal water flow rate of 7.3 kg/s. At the same time, the specific electrical energy production reached 31.8 kWh per 1 ton of supplied geothermal water. The efficiency of the organic cycle in this mode was 13.2%, 1.5% higher than that in a similar experiment using pure R134a. At a geothermal water temperature of 120°C, the average electric power was 188 kW, with a specific production of 25.4 kW · h/t. When the temperature dropped to 95°C, the power output decreased to 134 kW and the efficiency to 9.7% (Table 1).

Table 1 Parameters of Operation of a Binary Cycle at Different Temperatures of the Geothermal Heat Carrier and Compositions of Working Fluids.

No.	Working fluid	Heat carrier temperature, °C	Boiling pressure, MPa	Working fluid flow rate, kg/s	Condensation temperature, °C	Electric power, kW	Efficiency, %
1	R245fa + isobutane (70:30)	155	2.5	0.62	28	232	13.2
2	R134a	155	1.9	0.55	27	218	11.7
3	R245fa + isobutane (70:30)	120	2.2	0.58	26	188	11.4
4	R245fa + isobutane (70:30)	95	1.8	0.49	25	134	9.7

In the combined operation mode with dry saturated steam supplied to the Siemens SST-040 turbine, the capacity was 305 kW, 30% higher than the binary-circuit parameters. The overall plant's thermal efficiency was 15.9%, and the power factor (the ratio of actual energy production to the calculated value based on the nominal parameters) was 0.91. For the binary circuit operating on R134a Freon, the power factor averaged 0.85, attributable to the significant temperature difference during condensation. Analysis of the effect of the air temperature in the climatic chamber showed that reducing the temperature of the cooling medium to −20°C made it possible to reduce the condensation pressure from 0.38 to 0.28 MPa, which increased the heat drop and increased the generator capacity by an average of 7.8% (Table 2).

Table 2 The Effect of Cooling Air Temperature on Electrical Power and Efficiency.

Air temperature, °C	Condensation pressure, MPa	Electric power, kW	Power increase, %	Efficiency, %
+20	0.38	216	–	12.8
+10	0.35	223	+3.2	13.4
0	0.32	231	+6.9	13.9
−10	0.29	242	+12.0	14.6
−20	0.28	250	+15.7	15.2

Comparing the data with the results of other studies confirms the high efficiency of the combined scheme incorporating the organic Rankine cycle. Therefore, in similar studies on the operation of power units with binary cycles using R245fa freon at source temperatures of 145–155°C, the thermal efficiency was 11.9–12.5%, approximately 1–2% lower than the values obtained. In addition, a comparison with the indicators achieved at the ORMAT Model 3G-250 units in a project in Turkey, where the geothermal coolant temperature was 160°C, showed that the specific energy production per 1 kg of the working fluid in this study exceeded international data by 8–12%. This was due to the use of regenerative heating and optimisation of the working-mixture composition (Table 3).

Table 3 Results of Dynamic Tests of Transient Processes with a Sharp Decrease in the Coolant Temperature.

Parameter	Initial value	Value after temperature reduction	Stabilisation time, s
Heat carrier temperature, °C	155	95	70
Boiling pressure, MPa	2.3	1,5	90
Electric power, kW	228	132	120
Turbine vibration level, % of nominal	100	118	180
Condensation temperature, °C	28	26	60

Our combined configuration yielded a ~30% higher net electric output than the binary-only case (305 kW vs. 232 kW under comparable resource conditions), consistent with independent reports that binary-flashing/combined layouts can deliver ~32% more net power than standalone ORC under similar source temperatures and flow rates. Moreover, the observed 15.7% increase in generator output when lowering the condenser air temperature from +20 °C to −20 °C aligns with the literature documenting the strong sensitivity of air-cooled geothermal ORCs to ambient temperature and the effectiveness of mitigating strategies (e.g., evaporative pre-cooling) at high ambient temperatures. These agreements support the generalizability of our findings across sites and technologies. The results of dynamic tests of transient processes showed that, with a sharp decrease in the geothermal water temperature by 40°C, the boiling pressure decreased from 2.3 to 1.5 MPa within 70 s, and the electric power decreased by 42%. At the same time, the parameters were restored once the source temperature returned, on average, within 8–9 minutes. Measurement of the turbine's vibration characteristics showed that vibration levels at sharp changes in heat flow increased by no more than 18% relative to the nominal values. During additional tests using R227ea freon at a source temperature of 175°C, a maximum electrical power of 258 kW was achieved with a working-fluid flow rate of 0.73 kg/s and a condensation temperature of 28°C. This mode exhibits the highest efficiency among the tests conducted (16.4%). During tests at high turbine speed (6000 rpm), an acoustic pressure level of 86 dB was recorded 2 m from the turbine, which corresponded to the permissible noise standards. In a comparative analysis of the obtained results with the data of large industrial installations, in particular, at a geothermal power plant in Nevada (USA), where a binary scheme on R245fa was used at a source temperature of 150 ° C, the specific cost of the installed capacity was 3150 US dollars per kilowatt. And the average efficiency was 12.1% (Table 4). Therefore, the studied installation demonstrated the best energy-efficiency indicators and comparable cost values, despite the laboratory-scale of the experiments.

Table 4 The Comparison of Installation Indicators with Data from Foreign Projects.

Project (Country)	Coolant temperature, °C	Working fluid	Efficiency, %	Specific cost, $/kW	Specific output, kWh/t
Current Study	155	R245fa + isobutane (70:30)	13.2	2950	31.8
Nevada (USA)	150	R245fa	12.1	3150	28.7
Turkey	160	R245fa	12.5	3250	29.3
Germany	145	R134a	11.9	3100	27.4

Analysis of the influence of condensation parameters showed that a 10°C decrease in ambient air temperature resulted in a 2–3% increase in generator power, attributable to a corresponding rise in the condenser temperature difference. It was also found that regenerative heating of the working fluid increases efficiency by 1.2–1.5% in the source temperature range of 120–155°C. At the same time, the use of Freon mixtures instead of pure working fluids increased energy production by 5–7% due to a broader range of phase-transition temperatures. Summarising the experimental data, the highest indicators were achieved with a combined circuit with a two-circuit cycle organisation, a mixture of R245fa and isobutane, and intermediate heating. These conditions ensured a maximum specific electrical energy production of 33.2 kWh/t of coolant and an efficiency of 16.4%. The results confirm the potential of binary and combined schemes under low-temperature geothermal conditions and support their further scaling and integration into industrial operations.

4.CONCLUSION

This research delivers a comparative analysis of diverse geothermal cycle architectures, quantifying their influence on thermodynamic performance and power generation metrics specifically for low-to-medium enthalpy reservoirs. The main results confirmed the high energy efficiency of binary and combined cycles, in which the organic Rankine cycle was used to utilise the heat of a geothermal coolant at 95-175 °C. The highest indicators were recorded for a combined circuit with the supply of dry saturated steam to the axial turbine Siemens SST-040 and subsequent utilization of residual heat in a binary circuit with a working mixture of freons R245fa and isobutane in a ratio of 70:30. In this mode, the average electric power reached 305 kW, and the thermal efficiency was 15.9%, which was 2.7–4.0% higher than the values typical of traditional binary circuits. Experiments on varying the temperature of geothermal water revealed a steady decrease in productivity with decreasing temperature: for example, when the coolant temperature dropped from 155 to 95°C, the electric power decreased from 232 to 134 kW, and the efficiency decreased from 13.2 to 9.7%. These data show that even at low source temperatures, binary cycles remain operational and provide specific energy production in the range of 19–32 kWh per ton of coolant. The use of a mixture of R245fa and isobutane, on average, increased specific output by 5–7% relative to pure R134a, attributable to a more favourable phase-transition temperature range. The temperature conditions of the cooling medium had a noticeable effect on condensation efficiency. When the air temperature dropped from +20 to −20°C, the condensation pressure decreased from 0.38 to 0.28 MPa, resulting in a 15.7% increase in generator power and a corresponding increase in plant efficiency from 12.8% to 15.2%. This circumstance supports the feasibility of operating binary and combined-cycle circuits in cold-climate regions, where natural cooling can increase the efficiency of energy generation. Dynamic tests with a sharp decrease in the geothermal source temperature revealed high system stability: when the temperature dropped from 155 to 95°C, power decreased by 42%, but the operating parameters returned to their original values within 8–9 minutes after the source temperature reached the original value. The turbine vibration level increased by no more than 18% relative to the nominal values, and the acoustic characteristics remained within the permissible limits (no higher than 86 dB at a distance of 2 m). When operating with R227ea freon at high temperature (175°C), the maximum efficiency of 16.4% was achieved, and the average generation power was 258 kW with a working fluid flow rate of 0.73 kg/s. These data are comparable to or superior to results from similar foreign projects: for example, for a station in Nevada with a coolant temperature of 150°C and a binary circuit on R245fa, the efficiency was 12.1%, and the specific energy production was 28.7 kWh/t. In this study, the particular output ranged from 31.8–33.2 kWh/t, depending on the temperature conditions and the composition of the working fluid. Hence, the generalised results of the experiments demonstrate that the use of combined schemes with regenerative heating of the working fluid and the selection of optimal Freon mixtures enables a significant increase in the efficiency of heat conversion to electrical power when operating on low- and medium-temperature geothermal sources. Considering the reported expanded uncertainties (±2 % for P_{el} and ±0.6 pp for η_{th}), the efficiency gains of 1.5–4 % and the 8–12 % increase in specific electricity output remain statistically significant across the tested operating window. These configurations demonstrate a thermal efficiency enhancement of 1.5–4% over conventional binary systems and an 8–12% increase in specific power output relative to commercial counterparts, thereby validating their viability for large-scale industrial deployment.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

E.P. Khaleeva: Conceptualisation, Methodology, Writing – original draft, Supervision, Project administration, Formal analysis, Validation.
N.A. Ashurov: Investigation, Data curation, Software, Visualisation, Writing – review & editing. B. Uzokov: Methodology, Investigation, Data curation, Resources. Yu.V. Daus: Software, Formal analysis, Writing – review & editing.
M.S. Demchenko: Experimental setup design, Investigation, Validation, Visualisation. S.V. Sargsyan: Funding acquisition, Resources, Writing – review & editing, Supervision.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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