SWOT Analysis of Geothermal Power Plants

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ABSTRACT

Electricity generation from geothermal resources is achieved through various power plant technologies, including flash steam plants (single, double, or triple), binary cycle systems (ORC or Kalina), dry steam plants, back-pressure turbines, and combined plants that integrate multiple cycles. The selection of the power plant type is primarily determined by the temperature and characteristics of the resource, along with efficiency considerations of each technology. However, each type of plant presents its own set of challenges and advantages. This study employs a SWOT analysis to identify and evaluate the specific strengths, weaknesses, opportunities, and threats relevant to each plant type. A case study is presented from the Alaşehir geothermal field in western Anatolia, Türkiye. Furthermore, the research provides an in-depth technical perspective on power plant technologies and their implications for resource management. The findings indicate that although combined geothermal power plants offer the highest efficiency, substantial changes in the resource can lead to significant reductions in operational efficiency due to the use of specialized equipment. In contrast, binary power plants demonstrate greater operational stability and safety from both resource management and operational perspectives.

1. INTRODUCTION

Geothermal energy provides sustainable base-load power to the grid when managed by effective reservoir management practices. Due to geological heterogeneity and reservoir uncertainties, geothermal wells may exhibit a natural decline in behavior over the production period. Geothermal wells may experience declines in pressure, temperature, and flow rate, which can adversely affect the power output of the power plant.

Geothermal power plants are designed based on resource production characteristics, including fluid phase (liquid, steam, or two-phase) and reservoir temperature. As these properties change over time, power plants can operate outside their optimal design parameters, resulting in reduced efficiency. To maintain reliable operations under changing conditions, modifications to key components may become necessary. For instance, Aydin et al. (2025) reported such modifications in turbines, pumps, fans, and the NCG removal system at a double-flash geothermal power plant in the Alaşehir field, Türkiye, following significant changes in the resource. To minimise the additional revision costs, power plant design should incorporate projected resource characteristics using forecasts from numerical reservoir simulations.

Geothermal power plant technology has lower efficiency compared to conventional thermal power plants, fueled by natural gas, oil, coal, and nuclear power (Zarrouk & Moon, 2014). Nevertheless, one of the main advantages of geothermal plants is their ability to deliver reliable base-load power, similar to nuclear plants. The first commercial geothermal power plant, Larderello 1 in Italy, began operation in 1904 with a capacity of 250 kW, using pure steam in a back-pressure steam turbine (DiPippo, 2012). The early exploration at The Geysers started in 1922, but the project was halted due to the lack of advanced piping and turbine technology (Kabeyi, 2019). By the onset of World War II, Italy's installed geothermal power capacity had reached 136. 8 MW, but all the plants were destroyed during the war (DiPippo, 2012). Post-war reconstruction rapidly restored and was completed with more modern facilities, increasing the capacity to 300 MW by 1959. In the 1950s, commercial use of geothermal resources expanded to other regions worldwide, primarily utilizing high-temperature sources with dry steam or single-flash steam turbines. A key technological breakthrough enabling this expansion was the invention of the steam-water separator in New Zealand, which allowed for efficient utilisation of two-phase geothermal fluids. The Wairakei geothermal plant in New Zealand began operations in 1958, and in 1959, an experimental geothermal plant was launched in Pathe, Mexico. During the 1960s, the first large-scale geothermal power plant in San Francisco, USA, with an 11 MW capacity, was commissioned (Kabyi, 2019). With the exception of Wairakei, these early plants utilised dry steam facilities. In the 1980s, Ormat developed the first ORC binary technology targeting low-temperature geothermal resources. This binary technology significantly increased the potential for electricity generation from geothermal sources. The Kalina cycle, using a water and ammonia mixture, was later developed to offer theoretically higher thermodynamic performance. However, due to its complexity and technical challenges in commercial applications, the Organic Rankine Cycle (ORC) system became more widely adopted (Lund, 2007; Kabyi, 2019). According to Gutierrez-Negrin (2024), the global geothermal capacity stands at 16,318 MW, derived from 198 geothermal fields and 673 individual power plants.

The share of each power plant type in terms of global installed capacity and actual electricity generation is given in Figure 1 (based on the data provided Gutierrz-Negrin,2024). The proportions differ, reflecting variations in capacity factors among plant types. Based on installed capacity, flash-type plants contribute 8,598 MW, making up 52.7%. 7% of the total, while binary ORC units account for 25.1% of the capacity.

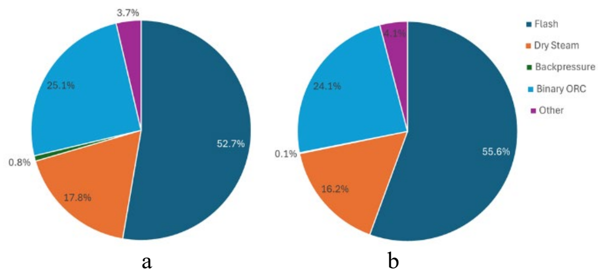

Figure 1: Global distribution (in 2021-2022) of geothermal a) installed capacity and b) actual generation by power plant type (data retrieved from Gutierrz-Negrin, 2024).

Zarrouk & Moon, 2014 simplified the schematics for geothermal power plants. These include single-flash, double-flash, binary, and combined system plants. The average conversion efficiency is reported to be only 10%, but it may reach 21% depending on various factors. The binary power plant at Chena Hot Springs has a conversion efficiency of 1% (Holdmann and List, 2007). A vapor-dominated geothermal system in Darajat has an efficiency factor of 21% (Kaya et al., 2011). The large difference in conversion efficiency between Chena Hot Springs and Darajat is mainly due to the significant discrepancy in their fluid temperatures. E.g., the Chena is a low-temperature system (~73 °C), while the Darajat is vapor-dominated with much higher reservoir temperatures (~240–245 °C). Higher geothermal fluid temperatures allow for greater thermodynamic efficiency, thus explaining the much higher efficiency achieved at Darajat compared to Chena Hot Springs.

Reinjection temperature is a critical factor affecting the efficiency of a power plant. It is typically determined based on the saturation index of minerals to prevent scaling. If the temperature is reduced below the threshold set by the mineral saturation index, heat exchangers, brine injection pumps, injection lines, and reinjection wells may experience significant scaling issues. Given this restriction, binary power plants may utilise only steam heat exchangers or operate steam and brine vaporizers in parallel to enhance net output. If the use of a brine vaporizer is not feasible due to scaling issues, steam condensate from the heat exchanger outlet is typically used in preheaters to enhance overall efficiency (see Zarrouk and Moon, 2014).

Another important factor is the cooling tower's efficiency. Typically, a dry-type cooling tower is used in binary plants, while a wet-type cooling tower is used in flashing-type or combined plants. Although both systems perform similarly during winter, dry-type cooling towers can experience a 20-40% reduction in power output during summer, due to higher ambient temperature conditions. On the other hand, wet-type cooling systems generally see a smaller reduction in power output, typically ~10-15% under similar summer conditions.

The selection of an optimal power plant type is typically determined based on key reservoir parameters, such as resource temperature, fluid phase, minimum allowable re-injection temperature, which is governed by mineral scaling risks and reservoir sustainability, as well as economic and environmental factors at the site. Power generation efficiency, shaped by thermodynamic cycle selection, heat exchanger performance, and cooling system configuration, is also a critical factor.In addition to these technical factors, operational reliability, resource management strategies, and site-specific uncertainties introduce further risks and opportunities that must be systematically addressed. A SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis provides a structured approach to evaluate these multidimensional factors, enabling identification of the most technically and economically suitable power plant configuration for a specific geothermal resource. This study employs a SWOT analysis to compare operational performance efficiency, adaptability to resource changes, and long-term sustainability of various geothermal power plants. This comparative assessment aims to understand the risks, opportunities, and benefits associated with each type. Our focus has been on binary, flashing-type, and combined geothermal power plants. Our analysis is contextualised with a case study from the Alaşehir geothermal field in western Anatolia, Türkiye.

2. MATERIALS AND METHODS

This study explores the optimal choice of geothermal power plant technology, taking into account resource characteristics, operational risks associated with equipment and resource management, opportunities, and electricity generation efficiency. The SWOT analysis method involves using information from an environmental analysis to categorize it into two groups:

- Internal issues: strengths (e.g., plant adaptability, proven technology) and weaknesses (e.g., scaling susceptibility, efficiency limitations)
- External Issues: opportunities (e.g., policy incentives, new markets) and threats (e.g., resource depletion, regulatory constraints).

The goal of a SWOT analysis is to leverage an organization's knowledge of its internal and external environments to develop its strategy (Sammut-Bonnici & Galea, 2015).

David (2006) proposed four types of strategies: SO (strengths-opportunities), WO (weaknesses-opportunities), ST (strengths-threats), and WT (weaknesses-threats). SO Strategies use a company's internal strengths to take advantage of external opportunities. When an organization faces significant threats, it tries to avoid them by focusing on opportunities. WO Strategies aim to improve internal weaknesses by leveraging external opportunities. ST Strategies use a company's strengths to reduce or prevent the impact of external threats. WT Strategies are defensive tactics designed to minimize internal weaknesses and prevent external threats.

SWOT analyses for binary plants, flashing-type plants, and combined power plants are presented in Tables 1, 2, and 3, respectively. As seen, each of them has unique sets of opportunities, threats, strengths, and weaknesses. Considering these characteristics, SWOT strategies should be developed to proactively minimize potential risks while maximizing profit from a given geothermal resource with appropriate power plant technologies.

Table 1: SWOT Analysis for Binary Cycle Geothermal Power Plants (ORC)

Strengths	It can use low to medium temperature resources (>85°C) Environmentally safer (closed-loop system, reduced emissions and fluid loss) More reliable performance during reservoir decline Modular and more adaptable for scaling or relocating Operates efficiently at lower reinjection temperatures without scaling
Weaknesses	Lower thermodynamic efficiency (5–10%) compared to flash plants. Heavily influenced by ambient temperature – up to 40% reduction in summer with dry cooling. Complex heat exchangers and scaling risk when using brine directly. Safety concerns related to using flammable or explosive working fluids like n-butane and pentane. High cost per megawatt in certain low-temperature fields
Opportunities	Growing interest in low-enthalpy geothermal reservoirs and district heating. Integration with waste heat recovery or solar-thermal hybrid systems Improvements in ORC technology and supercritical CO_2 cycles Carbon-neutral potential with brine CO_2 reinjection
Threats	Competitive technologies, such as solar PV and batteries, might replace it in small-scale grid applications. Poor maintenance can cause organic fluid leaks. Climate-related cooling inefficiencies decrease performance

Table 2: SWOT Analysis for Flashing-Type Geothermal Power Plants (Single/Double Flash/Triple Flash)

Strengths	High efficiency (up to 17–21%) with high-temperature resources Simple and robust for vapor-dominated or two-phase systems Well-developed and widely used globally Suitable for large-scale power generation
Weaknesses	Requires high-temperature resources (>200°C) to be feasible. It is sensitive to declines in reservoir pressure and temperature. Once designed, it offers limited flexibility and retrofitting can be costly. There is a higher potential for scaling in separators and reinjection lines.
Opportunities	Applicable in volcanic zones with high enthalpy fields Can be upgraded to combined systems if brine quality allows
Threats	Resource depletion leads to rapid efficiency loss Regulatory risk from high NCG emissions

Table 3: SWOT Analysis for Combined (Flash + Binary) Geothermal Power Plants

Strengths	Maximizes energy recovery from both steam and brine Higher overall efficiency compared to single system types Once designed, it offers limited flexibility, and retrofitting can be costly. Can use waste brine that would otherwise be reinjected
Weaknesses	Very complex design and integration challenges High CAPEX and OPEX – not suitable for small projects Specialized equipment makes sourcing and maintenance difficult Vulnerable to performance drops if one system fails
Opportunities	Ideal for fields with both steam and hot brine Hybridization with other renewables or energy storage
Threats	High technical risk in operation; failure in one loop affects the whole system More extended payback periods, sensitive to market electricity prices and subsidy policy changes

3. CASE STUDY: ALAŞEHİR GEOTHERMAL FIELD

The Alaşehir geothermal field, with an installed capacity of 322 MW, is among Türkiye's most active geothermal areas. It is situated on the Gediz graben, where intersecting high-angle normal faults and strike-slip faults control the fluid flow within the reservoir. Metamorphic rocks, including marble, quartz, and schist, host liquid-dominated geothermal fluids with a significant amount of non-condensable gases, primarily carbon dioxide (comprising more than 99% by volume of the gases). Reservoir temperature ranges from 150 to 250°C, depending on different regions in the field. Connectivity between highly conductive faults forms an extensive network among geothermal wells. The interference between wells has been documented using various reservoir monitoring methods, including tracer tests (Aydin & Akin, 2020), geochemical monitoring (Aydin et al., 2018), pressure transient tests (Aydin et al., 2024), and production capacity of power plants (Aydin et al., 2020).

3.1 Reservoir Dynamics and Production Challenges:

Due to significant hydraulic connectivity between production and re-injection wells, a rapid decline of NCG and early thermal breakthrough have been reported in various studies. Aydin et al. (2020) employed decline curve analysis to model the decline of NCG in the Alaşehir field. The hyperbolic decline provided a better match with the measured data from production wells. It was reported that NCG content decreased from 3% to less than 0.5% over three years of production. Similar results are discussed in Akin et al. 2020, noting that the decline in NCG is mainly caused by the dilution of reservoir fluid with gas-free injection brine. Concurrently, Aydin & Akin (2021) reported a decline in reservoir temperature of 1 to 3°C per year of production.

Due to the decline in NCG and temperature, the wells' production performance decreased significantly. In the early years of production, makeup production wells were completed but found to be ineffective due to high level of interference between production wells. Artificial lifting methods such as Electrical Submersible Pumps (ESPs) and gas lifting have been implemented to compensate for the reduced fluid production. Aydin et al. (2021) reported the first ESP applications in the Alaşehir field, with an average run life of 6 months. However, the latest ESP run life records have exceeded 24 months, primarily due to declining temperatures and improvements in ESP technology, especially in electrical components. Aydin & Merey (2024) proposed gas lift as an alternative to ESPs in the Alaşehir field. Aydin et al. (2025) reported the first nitrogen lift application in the Alaşehir field, which increased the production rate by 50 tons per hour.

3.2 Power Plant Configuration and Process Flow

A simplified flow diagram of the double flash and binary unit in the Alaşehir field is shown in Fig. 2. The steam turbine processes high-pressure (HP) and low-pressure (LP) steam. Waste steam from the HP blades is recovered in the binary unit's steam heat exchanger. A brine vaporizer, installed downstream of the brine injection pump, allows for additional heat extraction prior to reinjection, optimising thermal recovery. A wet-type cooling tower is used to mitigate the detrimental effects of high ambient temperatures on power output.

Critical components of the NCG removal system include a vacuum pump, ejectors with HP motive steam, and an after-ejector serving as redundancy for the vacuum pump.

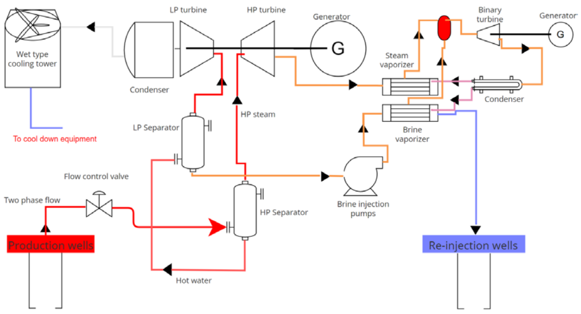

Figure 2: Flow diagram of a combined geothermal power plant in Alaşehir field.

4. RESULTS AND DISCUSSIONS

From a resource temperature perspective, the Alaşehir geothermal field is a hot water resource suitable for binary, flashing, and combined cycle power plants. Multiple independent operators are exploiting the basin with aggressive and rapid production strategies without coordinated reservoir management or data sharing among them. The lack of cooperation has resulted a high interference between geothermal wells, and has led to unwanted outcomes like significant performance drops and temperature decreases.

4.1 Operational challanges

Operating a double-flash combined system in such a geologically complex and dynamically managed setting can be challenging. Some of the important revisions in the power plant are presented at Aydin et al. 2025.

NCG Decline and Turbine Performance:

A high NCG decline has caused the plant to operate outside its designed parameters. Both turbine inlet pressure and HP steam flow rates have decreased. To compensate for the enthalpy reduction, high-temperature wells were drilled. Although pure steam production partially compensated for enthalpy loss, the absence of NCG reduced the partial pressure in the turbine, limiting steam throughput and efficiency.

NCG Removal System Oversizing:
The original NCG removal system was designed for 67 tons of NCG per hour. However, the NCG rate was reduced to 7 tons per hour after the sharp decline. As a result, the NCG removal system became oversized under the new conditions. One of the critical components of the NCG removal system, the vacuum pump, was replaced with a smaller-capacity one to operate more efficiently.

Artificial Lift and Reinjection Upgrades:
To reduce the effects of early temperature decline, more fluid extraction was necessary. ESPs and nitrogen lifting were effectively employed to increase the performance of the wells. Additional injection pumps were added in parallel to the existing ones and new reinjection wells were drilled to increase the reinjection capacity.

Solids Production and Surface Infrastructure:
Producing high flow rates from the reservoir has sped up the movement of fine particles from the unconsolidated formation. This led to increased abrasiveness at the pumps and accumulation of particles on surface infrastructure such as separators, valves, and production lines.

Cooling system expansion:
The increased LP steam rate at the main condenser has increased the need for additional cooling tower capacity. Therefore, a new cooling tower unit was added to the wet-type cooling tower to meet this requirement.

4.2. Resource Management Recommendations

A common practice in western Türkiye is that each operator evaluates the resource without considering the effects of other producers from the same basin. This approach typically results in oversized power plants, leading to low operational capacity in the long term. Therefore, developing a unified numerical reservoir simulation that integrates all data into a single model can enable unitized reservoir management. As a result, potential risks can be proactively identified before long-term production and each operator can benefit from more accurate predictions of reservoir behaviour under various production scenarios. Conducting sensitivity analyses of reservoir parameters would enhance understanding of the impact of future production on the performance of the power plants.

We propose SO/WO/ST/WT strategies to mitigate potential risks associated with developing geothermal projects (Table 4).

Table 4: SO/WO/ST/WT strategies for the safe operation of geothermal power plants

	Strengths (Internal)	Weaknesses (Internal)
Opportunities (External)	Utilize the high efficiency of combined systems in high-enthalpy fields. Employ binary systems in low- to medium-enthalpy fields for safer and more feasible operations.	Utilize simulation-based forecasting to align power plant types and equipment with future reservoir conditions, thereby reducing design errors and revision costs.
Threats (External)	Design backup systems in combined plants to maintain efficiency during seasonal cooling losses. Leverage the operational simplicity of binary plants in regions with limited technical support.	Deploy modular binary units in low-resource fields to reduce CAPEX/OPEX risk. Avoid over-reliance on high-spec equipment by designing flexibility and redundancy. Use artificial lifting methods (like ESP, gas lift) in low-pressure or marginal wells to prevent production losses and reduce the risks of investment failure in resource-challenged fields.

4. CONCLUSION

This study offers a comparative evaluation of binary, flashing-type, and combined geothermal power plants through a structured SWOT analysis framework. Each plant type has distinct strengths and vulnerabilities influenced by resource traits, operational needs, and economic viability. Binary power plants provide operational flexibility and environmental benefits for low-to-medium enthalpy fields but are constrained by lower efficiencies and seasonal cooling challenges. Flashing-type plants achieve high efficiency from high-temperature resources but are vulnerable to drops in reservoir pressure and temperature. Combined plants show the highest energy recovery potential by using both steam and brine, but they involve significant design and control system complexity and higher capital and operational costs and careful coordination between different subsystems for smooth and efficient operation.

The Alaşehir geothermal field case study illustrates the real-world effects of these configurations. Especially resource decline, significant well interference and equipment oversizing caused by uncoordinated production and changing reservoir conditions emphasize the requirement of for adaptive and resilient plant designs. Operational interventions, including artificial lifting, equipment replacement, and capacity upgrades, highlight the need for flexible engineering solutions informed by robust forecasting and monitoring. The findings emphasize the importance of integrated field-wide reservoir simulation and unitized resource management in maintaining long-term sustainability and economic viability.

Future geothermal development should tailor plant design to both existing and anticipated reservoir conditions, include redundancy to reduce operational risks, and focus on modular and flexible technologies. The suggested SO/WO/ST/WT strategies serve as a guideline for proactive decision-making in geothermal project planning and management.

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