

## Utilization of Superhot Geothermal Fluids from the Krafla Magma Testbed Project

María Sigríður Guðjónsdóttir<sup>1\*</sup>, Agata Rostran Largaespada<sup>1</sup>, Samuel Scott<sup>2</sup>, Gioia Falcone<sup>3</sup>, Nursanty Elisabeth Banjarnahor<sup>1,4</sup>

Reykjavík University<sup>1\*</sup>, University of Iceland<sup>2</sup>, University of Glasgow<sup>3</sup>, GRÓ Geothermal Training Programme<sup>4</sup>  
msg@ru.is

**Keywords:** Krafla Magma Testbed, superhot geothermal, thermodynamic power cycles, steam scrubbing

### ABSTRACT

Superhot geothermal resources present a promising next-generation energy source with significant potential to enhance geothermal energy output and efficiency. Projects worldwide, including FORGE and Newberry EGS in the United States, the Japan Beyond-Brittle Project (JBBP), Geothermal: The Next Generation in New Zealand, the Krafla Magma Testbed (KMT), and the Iceland Deep Drilling Project (IDDP) in Iceland, are actively exploring deeper and higher temperature geothermal resources. Resources with temperature  $>375^{\circ}\text{C}$  are usually referred to as superhot geothermal resources, and they present unique challenges due to their extreme temperature and pressure conditions. Their development and utilization require novel engineering approaches to ensure safe and efficient operation. One of the aims of the KMT project is to drill a production well into the magma body previously encountered by the IDDP-1 well. In this study, we model production characteristics given anticipated downhole conditions of approximately 160 bar(a) and  $500^{\circ}\text{C}$  for the KMT project. Further, we evaluate proposed open-loop methods for utilization and power generation under the anticipated flow conditions, examining reservoir characteristics, downhole conditions, wellbore behavior, wellhead dynamics, and potential power generation cycles. The analysis highlights key challenges while quantifying the potential of harnessing superhot geothermal resources, offering insights that could significantly enhance geothermal energy production capabilities. Corrosion mitigation needs to be considered using either dry or wet scrubbing. In this study, six power cycles are evaluated: a dry steam cycle without mitigation, a dry steam cycle with dry scrubbing, a single-flash power cycle with wet scrubbing and an additional turbine, a single-flash cycle with wet scrubbing, a single-flash cycle with wet scrubbing and heat recovery, and a binary cycle. Power output increases with wellhead pressure up to an optimal range of 30–50 bar(a). Considering the silica scaling challenges in the well and wellhead equipment, the utilization of wells with wellhead pressures in the range of 100–120 bar(a) is recommended by previous studies. At a wellhead pressure of 100 bar(a), the estimated power outputs from the KMT well are 19–28 MWe, with the dry steam without mitigation, giving the highest power, while the single flash cycle with wet scrubbing gives the lowest. With the existing Krafla power plant conditions also taken into account and a separation pressure of 8.8 bar(a), the power output is approximately 12.7–14.3 MWe, which is nearly 40% of the installed capacity of a single Krafla power-plant unit. Based on these results, the utilization of KMT wells clearly presents an interesting and promising energy source.

### 1 INTRODUCTION

Superhot geothermal systems, with superheated or supercritical steam temperatures exceeding  $375^{\circ}\text{C}$ , offer a major opportunity to expand renewable energy generation. However, they also introduce significant technical challenges due to extreme pressure and temperature conditions involved. Understanding how to effectively utilize these deep resources requires both geoscientific insight and robust engineering design. Optimizing power cycles is essential to convert the available heat into electricity efficiently. The utilization of superhot resources offers several advantages: (i) improved drilling cost-to-power output ratio, (ii) increased power output without increasing the environmental footprint, (iii) extended resource lifetime through enhanced reservoir thickness or volume, (iv) access to deeper and hotter reinjection zones, and also (v) improved economic performance due to higher thermal efficiency (DiPippo et al., 2025). The following sections outline global superhot geothermal initiatives and give an overview of the power cycle analysis for this research, including the operational challenges.

#### 1.1 Worldwide Projects

Iceland has led superhot geothermal development through the Iceland Deep Drilling Project (IDDP) and the Krafla Magma Testbed (KMT). The IDDP-1, drilled in 2009 in the Krafla Caldera, unexpectedly encountered rhyolitic magma at 2.1 km depth, with surrounding temperatures above  $900^{\circ}\text{C}$ . The well produced  $\sim 450^{\circ}\text{C}$  superheated steam at up to 50 kg/s and a wellhead pressure ranging from 40 to 140 bar(a) during flow tests,

suggesting a power potential of ~36 MWe, seven times greater than typical wells in the same field (Mortensen et al., 2014; Ingason et al., 2014; Scott, 2023). These shallow, high-enthalpy conditions demonstrated the potential of near-magma reservoirs. Building on this, KMT proposes the world's first long-term magma observatory. KMT targets zones where reservoir pressure remains below the critical point (<220 bar), but temperatures exceed 500°C offering favorable conditions for superhot geothermal energy production (Lavallée et al., 2024). Power modeling indicates that a 5 km deep well at 550 °C could yield 50–60 MWe for electricity production (Albertsson et al., 2003).

In contrast, the Newberry EGS Demonstration in Oregon targets ~4.5 km deep, low permeability volcanic reservoir with temperatures ranging from ~320 to 500 °C. The project builds on a 3 km well drilled in 2008 and plans to deepen it to access superhot rock and demonstrate enhanced geothermal recovery at these conditions. Despite challenges such as casing failure, the project successfully demonstrated fracture stimulation and fluid flow, with future plans including restimulation and production testing (Cladouhos et al., 2018). These conditions reflect deeper, higher-pressure environments with engineered permeability more suitable for EGS-type development. Utah FORGE, established in 2015, tests stimulation in crystalline basement rocks at >2 km depth and >175 °C. While temperatures are below superhot thresholds, the project provides valuable data on reservoir stimulation, circulation, and fracture behavior in low-permeability systems (Jones et al., 2024).

In Japan, The Japan Beyond-Brittle Project (JBBP) focuses on developing reservoirs in the brittle–ductile transition (BDT) zone at 3–5 km depth and 350–500 °C. It explores two types of reservoirs: those at the BDT's top (potentially connected to hydrothermal systems) and deeper isolated zones entirely below it. These systems may be hydraulically closed, with better control over stimulation and reduced induced seismicity risks. Saline fluids and high pressures (30–50 MPa) present additional thermodynamic and chemical complexity (Muraoka et al., 2014).

In New Zealand, The Next Generation initiative, led by GNS Science, investigates supercritical resources (>400 °C) in the Taupō Volcanic Zone at 4–10 km depth. The project integrates geoscientific modeling and laboratory simulations to understand magmatic heat transport, fluid-rock interaction, and the feasibility of accessing deep, high-energy zones. CO<sub>2</sub> reinjection is also being considered for zero-emission operation (Chambefort et al., 2019).

To date, there are no commercial power plants operating using supercritical or superhot geothermal resources. Together, this research initiatives described here are shaping the future of superhot geothermal development, offering key insights into reservoir creation, drilling technologies, and power cycle optimization under extreme subsurface conditions.

## 1.2 Power Cycles, Technical Challenges, and Mitigation

In addition to extreme thermodynamic conditions, such as temperature and pressure, the technical challenges of superhot geothermal systems also depend on the chemical composition of the fluids and site-specific characteristics. This paper uses data from previous study (Scott, 2025) regarding fluid parameters (mass flow, surface temperature and wellhead pressure) from simulated superhot conditions for KMT. This section elaborates on the technical challenges that must be reconsidered compared to the utilization of conventional geothermal field used to date.

The design and operation of geothermal power cycles must be adapted to the unique properties of the fluid. Utilizing a superhot geothermal system for power production requires a specialized combination of technologies to address thermal, chemical, and mechanical challenges. The geothermal power cycles considered in this study include dry steam, flash, and binary systems. As of 2022, the global geothermal power plant inventory indicated that binary Organic Rankine Cycle (ORC) units accounted for the largest share of installed power plants, representing 42.8% of all units. However, flash steam plants dominated in terms of installed capacity, contributing 52.7% of the global geothermal generation capacity (Gutiérrez-Negrín, 2024). The dry, or direct-steam, cycle is the simplest, but it requires that the geothermal fluids from the wells are in vapor form only. Several aspects will be investigated in this study to determine the most suitable power cycle (see Section 2).

### 1.2.1 Silica Scaling

Silica is one of the most abundant components of the Earth's crust and a critical chemical species in geothermal systems. In geothermal systems, quartz (SiO<sub>2</sub>) is the primary source of dissolved silica, and its solubility behaviour directly influences key processes such as mineral scaling, permeability evolution, and energy conversion efficiency. While silica solubility in liquid-dominated geothermal systems has been extensively studied, significantly less is known about its behaviour in the vapor phase under high-temperature, with variable-

pressure conditions typical of volcanic and superheated geothermal reservoirs. Quartz solubility in water vapour at 400–800 °C and pressures 50–270 bar(a) has been studied showing that quartz dissolves via formation of hydrated gaseous silica species such as  $\text{Si(OH)}_4(\text{g})$ ,  $\text{Si(OH)}_4 \cdot (\text{H}_2\text{O})_2(\text{g})$ , and  $\text{Si(OH)}_4 \cdot (\text{H}_2\text{O})_4(\text{g})$  with strong dependence on temperature and pressure (Stefánsson et al., 2024)). These species can rapidly precipitate during cooling or phase change, resulting in silica fouling of pipelines, turbines, and reinjection infrastructure. Accurate prediction of quartz solubility and silica transport in water vapor is therefore essential for the sustainable exploitation of high-enthalpy geothermal resources. Based on reservoir–wellbore simulations for Krafla-like superhot systems, wellhead pressures of approximately 100–120 bar(a) have been suggested as operationally desirable to suppress silica precipitation during ascent, supported by the silica solubility behavior constrained by Stefánsson et al. (2024) (Scott, 2025).

As one of the alternative mitigation methods, research on silica scaling in superhot geothermal resources has found that scrubbing tests using a  $\text{K}_2\text{CO}_3$  solution to remove silica from superheated steam show improved scrubbing efficiency at higher salt concentrations. In a thermodynamic simulation based on the IDDP-1 well fluid, replacing traditional wet scrubbing with  $\text{K}_2\text{CO}_3$  to preserve the superheat conditions suggested increased utilization efficiency by up to 7% and work output by up to 12% (Chauhan et al., 2020).

### 1.2.2 Corrosion

Geothermal steam containing volatile chloride (mainly HCl) has been documented in several steam-dominated or superheated geothermal fields (Truesdell et al., 1989; Hjartarson et al., 2012). When steam bearing HCl cools to its acid dew point, droplets form, and the HCl dissolves, producing a strongly acidic condensate (hydrochloric acid) that can lead to rapid pitting corrosion and stress-corrosion cracking in components like turbines and heat exchangers (Hjartarson et al., 2012). Mitigation methods such as wet scrubbing with NaOH or dry scrubbing by absorbents/adsorbents have been proposed (Fisher & Jung, 1996; EPRI, 2016).

Mitigation of corrosion for geothermal fluids which contain volatile chloride typically involves two methods: wet and dry scrubbing. For wet scrubbing, condensate, which may be drawn from the condenser, especially a surface type for cleaner condensate, containing dissolved sodium hydroxide (NaOH), is sprayed into the steam line, cooling and desuperheating the fluid to saturation. HCl dissolves in the liquid, where it reacts with NaOH, resulting in mixture of NaCl and  $\text{H}_2\text{O}$ , and thereby neutralizing the HCl acid. The brine is removed in a high-efficiency separator or scrubber to prevent liquid carry-over to the turbine. For dry scrubbing, a solid or atomised reagent is injected into the steam line or into a dedicated reactor. The reagent can be either an absorbent or an adsorbent. Absorbents with chemical reaction consist of  $\text{CaCO}_3$ ,  $\text{Ca(OH)}_2$ ,  $\text{Na}_2\text{CO}_3$ , ZnO,  $\text{NaNO}_3$ , triazoles and amines. Adsorbents, surface capture, uses activated carbon, activated alumina, silica gel, zeolites (Fisher & Jung, 1996). The waste material is collected downstream in a bag-house filter or electrostatic precipitator and can often be recycled, preserving almost all the superheat in the steam. Although still under development for geothermal applications, dry scrubbing shows promise for mitigating corrosion while maintaining superheated conditions (Hirtz, 2002).

### 1.2.3 Erosion

Erosion caused by solid particles that are entrapped in the geothermal reservoir fluid (Eliasson et al., 2011) can result in serious damage to surface facilities, particularly wellhead valves, fittings, and pipe bends, due to the high velocity and momentum of the fluid. To mitigate this, a cyclone-type separator can be used to remove solid particles from the steam gathering system. It utilizes centrifugal force to separate solids, which are then collected at the bottom of the unit.

## 2 METHODOLOGY

This paper elaborates on the technical feasibility of power cycles to generate electrical power from superhot fluids from a notional KMT wellbore. The analysis of power output and utilization efficiency is intended to support the selection of appropriate technologies for harnessing superhot geothermal resources. Results from previous research, which used reservoir wellbore simulations of Krafla-like systems under a base transmissivity scenario and simplified binary power cycle modelling, are used as baseline data in this study. The baseline data, consisting of wellhead pressure, mass flow rate, and power output, are shown in Figure 1, with enthalpy values ranging from 3,100 to 3,300 kJ/kg (Scott, 2025). Even though it is recommended to limit the wellhead pressure to 100–120 bar(a) (Scott, 2025) when utilizing this fluid, this study models the power output for the wellhead pressure range of 10–140 bar(a).

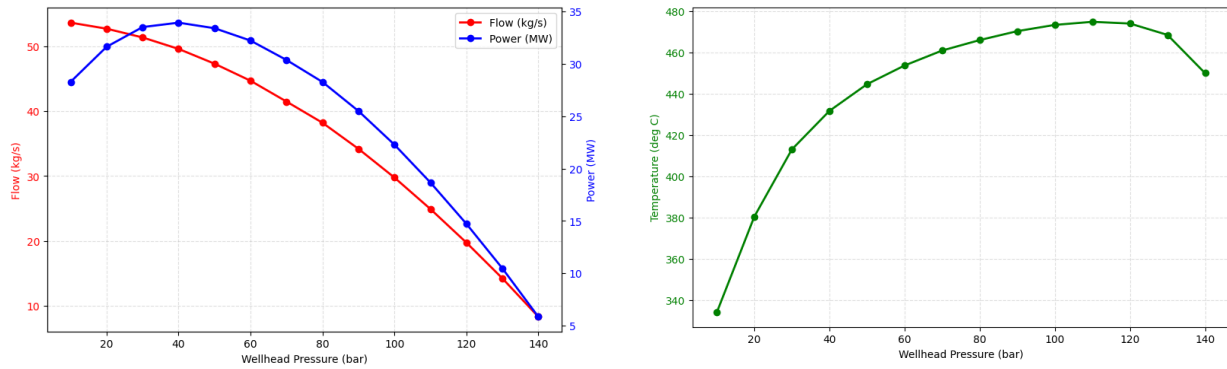


**Figure 1. Modelled parameters as a function of wellhead pressure: mass flow rate and corresponding power output (left), and temperature (right) for the base transmissivity case under calibrated Krafla-like conditions, based on a previous simulation by Scott (2025).**

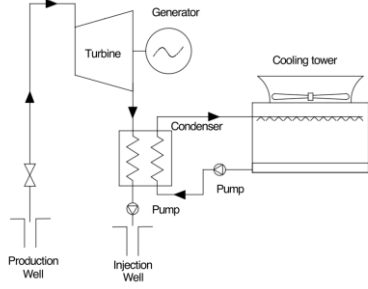
## 2.1 Power Cycle Parameters

The list of power cycles in this research refers to the cycle selection presented by Hjartarson (2012) and Hjartarson et al. (2014), which evaluated six different power cycles for the superhot IDDP-1 fluid. In this study, the fluid properties used for the power cycle calculations are modelled for the KMT conditions from Scott (2025) and are slightly different from the IDDP-1 conditions. Thermodynamic modeling is developed for several power cycle configurations: (i) dry steam, (ii) single flash, and (iii) binary cycle. To address the technical challenges associated with silica scaling, corrosion, and erosion, selected cycles incorporate dry and wet scrubbing. The following section provides a detailed explanation of the modelling approach and calculation methods applied for each of these configurations with different fluid characteristics. Equations used in the power cycle are primarily drawn from (DiPippo et al., 2025). The following conceptual power cycles are implemented to explore utilization scenarios for superhot geothermal fluids, as shown in Figure 2.

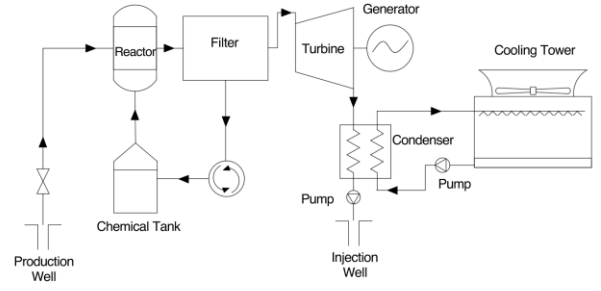
The six power cycles presented in this paper are adapted from Hjartarson (2012) and Hjartarson et al. (2014). Figure 2a illustrates a dry steam cycle without mitigation, in which superheated steam is directly expanded in a turbine without chemical treatment or separation, representing the ideal and simplified case. Figure 2b shows the same cycle but incorporates a dry scrubbing system upstream of the turbine to remove corrosive components, such as HCl. This configuration reflects a more realistic approach for long-term operation under aggressive fluid conditions. In this cycle, the reaction vessel and filter cause a small pressure loss (assumed to be 0.14 bar) and heat loss (assumed to be 0.5% of the enthalpy), while the mass change is assumed to be negligible. Figure 2c shows a process of single flash wet scrubbing by using only a single turbine stage, with the assumptions of 98% steam quality after wet scrubbing. After the fluid from the well first expands through a back-pressure turbine, as shown in Figure 2d, it undergoes wet scrubbing before being expanded in a second turbine stage to produce additional work. In this configuration, the wet scrubbing process assumes a steam quality of approximately 98% prior to the separator. The flashed and scrubbed steam is expanded through the second turbine. Figure 2e represents a single-flash system with wet scrubbing and additional heat recovery. After the flashed steam expands through the turbine, the remaining heat in the brine is recovered using a heat exchanger to enhance total energy extraction. At the heat exchanger outlet, the fluid retains 20 °C of superheat. Finally, Figure 2f represents a standalone binary cycle in which the geothermal fluid transfers heat to binary fluid (in this case water), used as the secondary working fluid, through a heat exchanger and the turbine pressure remains 10 bar(a).

For all power cycle calculations, assumptions are also adapted from Hjartarson (2014) and DiPippo (2025). The turbine exhaust (condenser) pressure is assumed to be 0.1 bar(a), the dry-steam turbine isentropic efficiency is taken as 85%, a conservative value typical for geothermal turbines, and the generator efficiency is 95% (DiPippo et al., 2025). The geothermal fluid outlet temperature in the binary cycle is fixed at 60 °C, which is relatively low and may pose a risk of silica precipitation in the brine if not properly controlled. The turbine inlet pressure is assumed to remain equal to the wellhead pressure, unless stated otherwise in the previous paragraph.

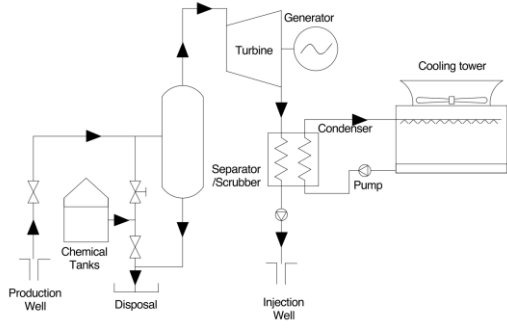
a.



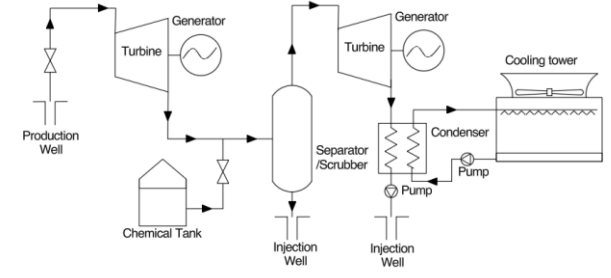
b.



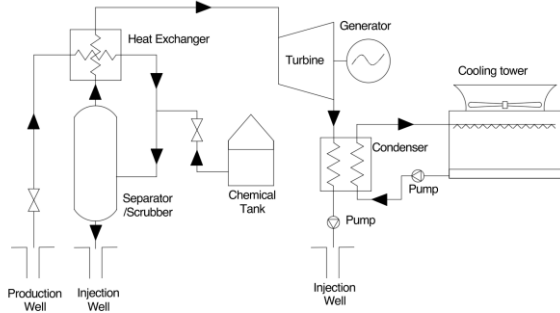
c.



d.



e.



f.

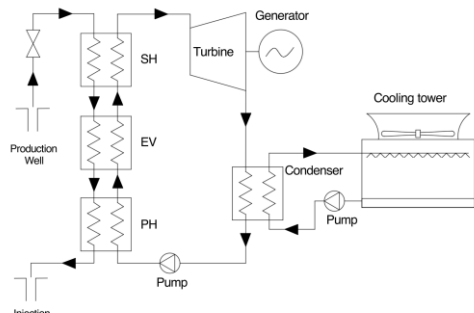


**Figure 2. Schematic design of: (a) dry steam cycle without mitigation; (b) dry steam cycle with dry scrubbing; (c) single-flash cycle with wet scrubbing; (d) single-flash power cycle with wet scrubbing and an additional turbine; (e) single-flash cycle with wet scrubbing and heat recovery; and (f) binary cycle.**

## 2.2 Energy Conversion

For cycle configurations involving steam separation, the separator is assumed to operate isobarically, meaning the pressure remains constant across the unit. The steam mass flow rate is calculated as the product of the total well flow rate ( $\dot{m}_{gf}$ ) and the steam quality ( $x$ ) and is a function of fluid pressure and enthalpy at wellhead conditions derived from simulations from Scott (2025).

For all configurations that include turbine expansion, the specific mechanical power output ( $\dot{W}_t$ ) is calculated as the product of the mass flow rate ( $\dot{m}$ , in kg/s) and the specific enthalpy drop across the turbine, where  $h_{in}$  and  $h_{out}$  are the specific enthalpies (in kJ/kg) at the turbine inlet and outlet, respectively:

$$\dot{W}_t = \dot{m}(h_{in} - h_{out}) \quad (1)$$

In dry steam cycles, expansion inside the turbine is modeled as isentropic expansion of superheated steam, where the outlet thermodynamic state is determined using the CoolProp thermophysical property library (Bell et al., 2014), assuming that the steam remains fully superheated throughout the process. For flash cycles, where

the steam becomes saturated during expansion, wet expansion is considered. In such cases, efficiency losses due to moisture are accounted for using the Baumann rule (DiPippo et al., 2025), which defines the wet turbine isentropic efficiency  $\eta_{tw}$  as:

$$\eta_{tw} = \frac{\eta_{td}(1 + x_{outlet})}{2} \quad (2)$$

where  $\eta_{td}$  is the dry turbine isentropic efficiency and  $x_{outlet}$  is the steam quality (vapor fraction) at the turbine outlet.

To assess the thermodynamic performance, the second law utilization efficiency ( $\eta_u$ ) is calculated as:

$$\eta_u = \frac{\dot{W}_{t,net}}{\dot{m}_{gf}e} \quad (3)$$

where  $\dot{W}_{t,net}$  is the net power output (in MWe),  $\dot{m}_{gf}$  is the geothermal fluid mass flow rate (in kg/s), and  $e$  is the specific exergy of the fluid (in kg/kJ). Specific exergy is computed relative to ambient (dead state) conditions as:

$$e = h_1 - h_0 - T_0(s_1 - s_0) \quad (4)$$

where  $h_1$  is the specific enthalpy at the wellhead (kJ/kg),  $h_0$  is the specific enthalpy at ambient or dead-state conditions (kJ/kg),  $s_1$  is the specific entropy at the wellhead (kJ/kg·K),  $s_0$  is the specific entropy at dead-state conditions (kJ/kg·K), and  $T_0$  is the ambient temperature, typically 25 °C.

In the single flash power cycle with wet scrubbing and heat recovery configuration, the thermodynamic state of the fluid after separation and scrubbing was evaluated following the approach of Hjartarson (2012). Before the superheated geothermal steam undergoes wet scrubbing, it first passes through a heat exchanger where it cools isobarically. At the outlet of the heat exchanger, the fluid retains approximately 20 °C of superheat, sufficient to prevent condensation during expansion. Subsequently, controlled water injection is applied to achieve the desired steam conditions before expansion. After separation, the steam is reheated in the heat exchanger and then expanded in the turbine.

The corresponding energy balance for this process, used to determine the post-scrubbing enthalpy and mass flow conditions at the turbine inlet, is expressed as:

$$\dot{m}_{brine}(h_{in,brine} - h_{out,brine}) = \dot{m}_{steam}(h_{out,steam} - h_{in,steam}) \quad (5)$$

where  $\dot{m}_{brine}$  and  $\dot{m}_{steam}$  are the mass flow rates of the brine and steam, respectively, and  $h_{in,brine}$  and  $h_{out,brine}$  are the specific enthalpies of the brine at the inlet and outlet of the heat exchanger;  $h_{in,steam}$  and  $h_{out,steam}$  are corresponding enthalpies of the steam before and after superheating.

In binary cycle configurations, where heat is transferred from the geothermal fluid to a secondary working fluid, a lumped heat exchanger energy balance is used. Although the preheater, evaporator, and superheater are not modeled as separate units, the total heat exchange is approximated by:

$$\dot{m}_{gf}(h_1 - h_4) = \dot{m}_{wf}(h_e - h_b) \quad (6)$$

where  $\dot{m}_{gf}$  and  $\dot{m}_{wf}$  are the geothermal and working fluid mass flow rates (in kg/s), respectively, and  $h_1$  is the enthalpy of the geothermal fluid at the heat exchanger inlet (in kJ/kg),  $h_4$  is the enthalpy of the geothermal fluid at the outlet (after heat exchange) (in kJ/kg),  $h_e$  is the enthalpy of the working fluid at the evaporator outlet (turbine inlet) (in kJ/kg),  $h_b$  is the enthalpy of the working fluid at the heat exchanger inlet (pump outlet). In this study the working fluid (wf) is water. A minimum pinch point temperature difference of 5 °C is assumed between the geothermal and working fluid to ensure effective heat exchange.

### 3 RESULTS AND DISCUSSIONS

#### 3.1 Power Cycles Calculation Results

Using the baseline well data presented in Section 2, Figure 1, and the equations in Section 2.2, the power output and utilization efficiency were calculated for all modeled power cycle configurations. The power output increases with wellhead pressure up to an optimal range of 30–40 bar(a), then decreases as the mass flow rate

decreases. It should be noted that all power values mentioned in this section represent gross power. The net power generated by a geothermal power plant will be lower due to parasitic loads, such as pumps and cooling towers, and efficiencies related to equipment such as separators. Consequently, the overall power output typically decreases depending on the power cycle type and ambient conditions.

The gross power outputs for all modelled cycles are shown in Figure 3. Among the evaluated cycles, the direct dry steam configuration provides the highest output, peaking at approximately 43 MWe at 30–40 bar(a), consistent with the maximum values in the plot refer to Figure 3. The lowest-performing configuration is the single-flash wet-scrubbing (NaOH) without heat recovery, at approximately 32 MWe. This lower performance is due to chemical mixing prior to the separator, which reduces the extractable superheat and lowers the mixture enthalpy. Although the dry steam cycle yields the highest power, it also presents the greatest challenges under superhot conditions. Across all cycles, the difference in gross power output at optimal pressures is approximately 10–12 MWe, corresponding to a variation of 25–30%, depending on the fluid parameters.

The utilization efficiency results, calculated using Equation 3 and 4, exhibit similar trends. The dry steam cycle achieves the highest efficiency (~72–73%), reflecting minimal thermal losses and maximum use of superheat. Incorporating dry scrubbing slightly reduces efficiency to around 70%. Wet scrubbing (NaOH) introduces substantial loss of superheat through chemical quenching, lowering the utilization efficiency to approximately 63–66%. The binary cycle demonstrates the lowest efficiency (~50–53%), due to significant heat-exchange irreversibilities and relatively high auxiliary loads.

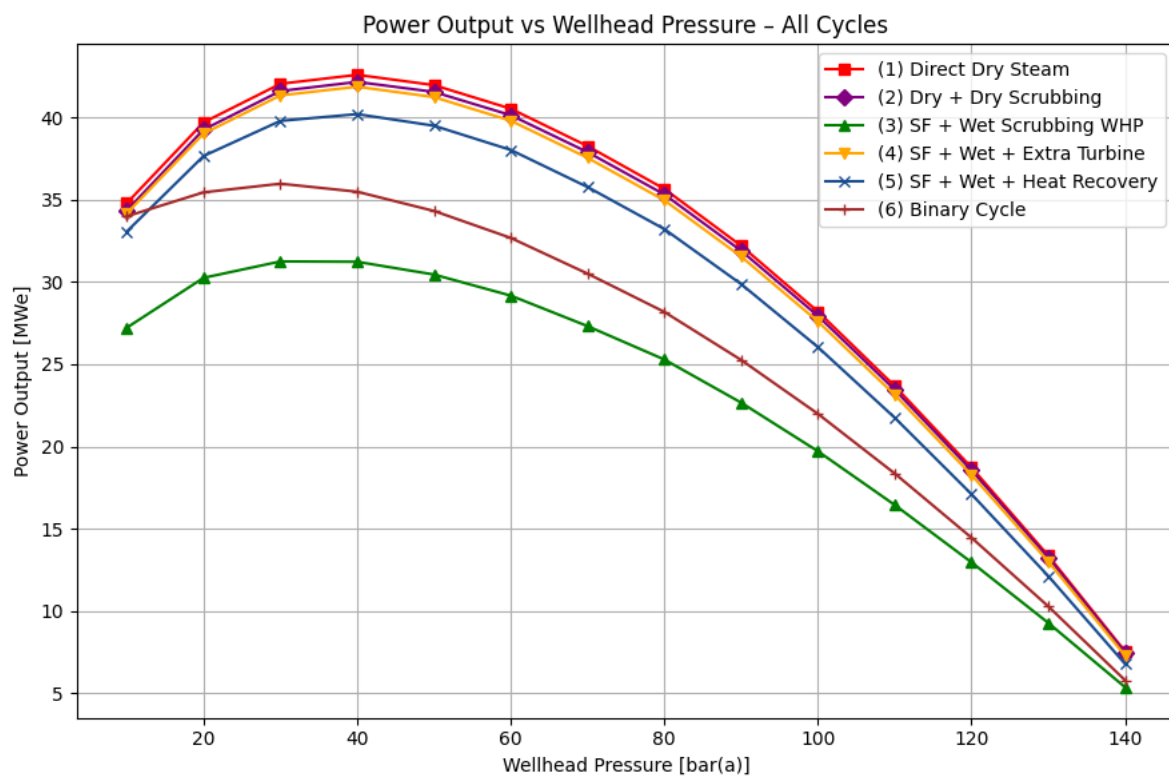


**Figure 3** Gross power output as a function of wellhead pressure for all modelled power cycle configurations: (1) dry steam without mitigation, (2) dry steam with dry scrubbing, (3) single-flash with wet scrubbing, (4) single-flash with wet scrubbing and an additional turbine, (5) single-flash with wet scrubbing and heat recovery, and (6) binary cycle. Calculations are based on the mass flow rate and wellhead pressure data shown in Figure 1.

At elevated pressures around 100 bar(a), representative of conditions such as those at KMT to reduce silica scaling, the expected gross power output ranges from ~19–28 MWe, depending on cycle configuration. Comparison of power output and utilization efficiency for the recommended wellhead pressure of at least 100–120 bar(a) based on the silica scaling limitation given in Table 1.

**Table 1 Power Output and Utilization Efficiency with Wellhead Pressure 100 bar(a).**

| No | Power Cycle                                               | Power Output (MWe) | Utilization Efficiency (%) |
|----|-----------------------------------------------------------|--------------------|----------------------------|
| 1  | Dry steam without mitigation                              | 28.2               | 69.2                       |
| 2  | Dry steam with dry scrubbing                              | 27.9               | 68.5                       |
| 3  | Single-flash with wet scrubbing                           | 19.7               | 48.3                       |
| 4  | Single-flash with wet scrubbing and an additional turbine | 27.6               | 67.7                       |
| 5  | Single-flash with wet scrubbing and heat recovery         | 26.0               | 63.9                       |
| 6  | Binary with water                                         | 21.9               | 53.9                       |

Although the comparison with IDDP-1 is not strictly comparable, because the well flowed under different mass-flow conditions, chloride-rich chemistry, and wellbore behaviour, the overall thermodynamic characteristics align closely with the trends modelled in this study. During its brief superheated discharge, IDDP-1 was estimated to be capable of producing approximately ~36 MWe of gross power, stated in Section 1. The wellhead enthalpy reported for IDDP-1 was approximately 3100 kJ/kg (Hjartarson, 2012), only slightly lower than the enthalpy range applied in the present simulations (3109–3310 kJ/kg) (Scott, 2025).

According to the study of Hjartarson (2012) and Hjartarson et al. (2014), the expected power output of IDDP-1 varied significantly with wellhead pressure. At elevated wellhead pressures around 100 bar(a), the predicted gross power ranged from ~18–23 MWe. As the wellhead pressure decreases toward the optimal expansion range of 30–40 bar(a), the power output increases substantially, reaching ~28–36 MWe for a dry-steam configuration (Hjartarson, 2014). This pressure–power relationship follows the same trend observed in the present study, power increases toward an optimum pressure, then declines at higher pressures due to reduced mass flow. Overall, both studies show strong agreement in terms of thermodynamic behaviour. The IDDP-1 results validate the trends found here, namely, that moderate wellhead pressures yield the highest power output and utilization efficiency, while high-pressure conditions (e.g., ~100 bar(a)) still provide significant but reduced power.

Such high-pressure conditions of the steam are rare for operations of geothermal power plants, and these limitations will need to be addressed and updated in future calculations. Adapting such designs for superhot geothermal service requires consideration of geothermal-specific fluid characteristics, resource conditions, steam quality (including moisture and non-condensable gases), material compatibility, corrosion and scaling risks, and overall cost.

### 3.2 Connecting to the Existing Krafla Power Plant

Based on six schematic designs (Figure 2) and the corresponding power cycle calculations, utilizing the fluids either through a flash process or with turbines operating isobarically at wellhead pressure is one of the proposed system configurations. In addition, the option of using the existing Krafla power plant is also worth further investigation. The Krafla geothermal power plant consists of two dual-pressure 30 MWe turbine–generator units with similar design characteristics. Unit 1, commissioned in 1978, employs a single-cylinder, double-flow turbine operating with high-pressure steam at 7.55 bar(a) and 168 °C, and low-pressure steam at 1.86 bar(a) and 118 °C. The unit receives approximately 52.5 kg/s of high-pressure steam and 17.9 kg/s of low-pressure steam, and uses a direct-contact tray-type condenser supported by two vertical centrifugal hot-well pumps. Unit 2, commissioned in 1997, is effectively identical in nominal capacity and configuration, operating as a dual-pressure system supplied by updated high-pressure (~8.8 bar(a)) and low-pressure (~2.5 bar(a)) separators and associated moisture-removal equipment. In the current plant configuration (as of 2016), both units operate within a double-flash cycle using a horizontal gravity-type high-pressure separator and a vertical cyclone-type low-pressure separator, delivering a combined installed capacity of approximately 60 MWe (Langella et al., 2017).

Using the existing power plant data, the total steam flow of 70.4 kg/s produces 30 MWe net, giving a Specific Steam Consumption (SSC) of 2.35 kg/s per MWe. Therefore, for the KMT mass flow at 100 bar(a) wellhead pressure and estimated mass flow of 29.8 kg/s of steam (see Figure 1), applying the same SSC indicates that the KMT production well could contribute 12.7 MWe. Another approach to calculating the power output is to operate at a wellhead pressure of 100 bar(a), followed by wet scrubbing, targeting a steam quality of 98% after chemical injection, as shown in Figure 2(c). In this scenario, the available steam is reduced to 29.2 kg/s. Instead of using a separator pressure equal to the wellhead pressure, a separator pressure of 8.8 bar(a) and a turbine inlet pressure of 7.55 bar(a) are used, resulting in a power output of 14.3 MWe with a utilization efficiency of 35%. With both approaches, almost 40% of the power produced by one Krafla power plant unit could come from the KMT well.

However, using a 100 bar(a) wellhead pressure with an 8.8 bar(a) separation pressure would require a let-down valve or pressure-reducing valve, along with engineered pipelines, which would result in significant energy losses and additional costs. Furthermore, scrubbing mitigation also needs to be investigated, and the potential increase in superheated conditions must be assessed. A possible mitigation strategy would be to include an intermediate turbine stage that expands the steam to near-saturation conditions before wet scrubbing at the turbine inlet, allowing part of the excess energy to be recovered while maintaining corrosion control.

#### 4 CONCLUSION

Superhot geothermal resources represent a promising next-generation energy source with significant potential to enhance geothermal power output and efficiency. The Krafla Magma Project (KMT) is a research project where one of the aims is to drill into the magma body, where the anticipated downhole conditions may reach up to 160 bar(a) and temperatures of up to 500°C (Scott, 2025). Calculations using six different power cycles were conducted to evaluate the proposed methods for power generation. Overall, power output increases with wellhead pressure up to an optimal range of 30–50 bar(a). The results show that the dry steam cycle without mitigation yields the highest power output. Among the evaluated systems, the dry steam cycle achieved approximately 45 MWe at a wellhead pressure of around 40 bar(a). The dry steam cycle with dry scrubbing produced approximately 7% lower output, while the binary and single-flash systems delivered roughly 20–27% less power, corresponding to a difference of 10–12 MWe. Despite the calculation result showing the lowest, the binary cycle still demonstrates a considerable power output, reaching approximately 35 MWe within the optimum wellhead pressure range. In terms of utilization efficiency, the dry steam cycle achieved the highest value of approximately 73%, reflecting minimal cooling and maximum exergy conservation. The dry steam cycle with dry scrubbing showed a slightly lower efficiency of 70% due to minor thermal and mechanical losses introduced by the scrubbing process.

In terms of the highest power output and efficiency, these do not necessarily represent the best overall solution at present. There are still many factors to consider in mitigating the associated technical challenges. The binary cycle offers the advantage of preventing direct contact between geothermal fluids and the turbine, which minimizes corrosion and scaling issues. However, it is also logically more expensive due to the additional equipment required. Meanwhile, the dry steam cycle with dry scrubbing is also an interesting option, as it combines high power output and efficiency with potential strategies to manage technical challenges. However, despite its favorable performance, the dry steam configuration may be limited in practice by corrosion, scaling, and material degradation risks, especially in untreated superhot environments. The addition of a dry scrubbing system helps mitigate these issues but introduces additional system complexity and may reduce efficiency. Considering the silica scaling challenges, the utilization of wells with wellhead pressures in the range of 100–120 bar(a) is recommended by previous studies. At a wellhead pressure of 100 bar(a), the estimated power outputs are 19–28 MWe, with the dry steam without mitigation giving the highest power and the single flash cycle with wet scrubbing giving the lowest. The existing Krafla power plant is also considered: with a separation pressure of 8.8 bar(a), the power output is approximately 12.7–14.3 MWe, approximately 40% of the installed capacity of a single Krafla power-plant unit. Based on these results, the utilization of KMT like wells is clearly an impressive and promising energy source.

#### 5 FURTHER STEPS

This research is limited to a single scenario based on a preliminary deliverability curve predicted for Krafla-like, low-pressure, high-enthalpy systems (as reported in previous studies) as the base case. Further investigations are required to include expanded sensitivity analyses on overall reservoir and wellbore performance, including deeper and higher-pressure reservoirs, additional transmissivity scenarios, and high-salinity two-phase systems. Exploring alternative secondary working fluids beyond water for the binary cycle would also be valuable. A more detailed assessment either for a new power plant or a connection to an existing power plant, such as that at Krafla, is encouraged with respect to a comprehensive evaluation of various scrubbing methods.

#### Acknowledgements

This research was supported by 187172-0611 Rannis Technology Development Fund. The authors also appreciate the collaboration of members of the Steering Committee and Working Groups of the KMT project.

#### REFERENCES

Albertsson, A., Bjarnason, J.Ö., and Gunnarsson, T.: IDDP Feasibility Report Part 3: Fluid Handling and Evaluation. (*Report*) (2003).

- Bell, I.H., and Wronski, J.: CoolProp: An Open-Source Thermophysical Property Library, *Industrial & Engineering Chemistry Research*, 53, (2014), 2498–2508
- Chambefort, I., Mountain, B., Blair, A., and Bignall, G.: Geothermal: The Next Generation. In *Proceedings of the 41st New Zealand Geothermal Workshop*, Auckland, New Zealand (2019).
- Chauhan, V., Gudjonsdottir, M., and Saevarsdottir, G.: Silica particle deposition in superheated steam in an annular flow: Computational modeling and experimental investigation. *Geothermics*, 86, (2020).
- Cladouhos, T.T., Petty, S., Bonneville, A., Schultz, A., and Sørlie, C.F.: Super Hot EGS and the Newberry Deep Drilling Project (SGP-TR-213). In *Proceedings of the 43rd Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, USA (2018).
- DiPippo, R., Gutiérrez-Negrín, L., and Chiasson, A.: Geothermal Power Generation Development and Innovation. *Woodhead Publishing Series in Energy, Elsevier* (2025).
- Eliasson, E.T., Thórhallsson, S., Steingrímsson, B.: Geothermal Power Plants, *Short Course on Geothermal Drilling, Resource Development and Power Plants*, Santa Tecla, El Salvador, (2011).
- Gutiérrez-Negrín, L.C.A.: Evolution of worldwide geothermal power 2020–2023, *Geothermal Energy*, 12, (2024).
- Hirtz, P., Broaddus, M. L., Gallup, D. L.: Dry Steam Scrubbing for Impurity Removal from Superheated Geothermal Steam. *Geothermal Resources Council Transactions*, vol. 26, (2002), 751-754.
- Hjartarson, S.: Utilization of Superheated Geothermal Fluid. *MSc Thesis, Reykjavik University, Iceland* (2012).
- Hjartarson, S., Sævarsdóttir, G., Ingason, K., Pálsson, B., and Harvey, W.S.: Utilization of the chloride-bearing, superheated steam from IDDP-1. *Geothermics*, 49, (2014), 83–89.
- Ingason, K., Kristjánsson, V., and Einarsson, K.: Design and development of the discharge system of IDDP-1. *Geothermics*, 49, (2014), 58–65.
- Jones, C., Simmons, S., and Moore, J.: Geology of the Utah Frontier Observatory for Research in Geothermal Energy (FORGE) Enhanced Geothermal System (EGS) Site. *Geothermics*, 122, (2024), 103054.
- Langella, G., Paoletti, V., DiPippo, R., Amoresano, A., Steinunnardóttir, K., and Milano, M.: Krafla geothermal system, northeastern Iceland: Performance assessment of alternative plant configurations. *Geothermics*, 69, (2017), 74–92.
- Lavallée, Y., Kendrick, J.E., Eichelberger, J.C., Papale, P., Sigmundsson, F., and Dingwell, D.B.: Accessing Magma: A Necessary Revolution in Earth Sciences and Renewable Energy. *European Review*, 32(4), (2024), 412–434.
- Mortensen, A.K., Egilson, B., Gautason, B., Árnadóttir, S., and Guðmundsson, Á.: Stratigraphy, alteration mineralogy, permeability and temperature conditions of well IDDP-1, Krafla, NE-Iceland. *Geothermics*, 49, (2014), 31–41.
- Muraoka, H., Asanuma, H., Tsuchiya, N., Ito, T., Mogi, T., Ito, H., and ICDP/JBBP Workshop Participants: The Japan Beyond-Brittle Project. *Scientific Drilling*, 17, (2014), 51–59.
- Scott, S.: Production Characteristics of Superhot Resources: Role of Permeability, Reservoir Pressure and Fluid Salinity. (*Unpublished*) (n.d.).
- Stefánsson, A., Scott, S.W., Bjarkadóttir, A.B., Bravo, A.M., Aðalsteinsdóttir, S.M., Straume, E., and Lemke, K.H.: Silica solubility and molecular speciation in water vapor at 400–800 °C. *Geochimica et Cosmochimica Acta* (2024).