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Research article

Risk of temperature differences in geothermal wells and generation strategies of geothermal power

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Abstract: The objective of this paper is to discuss the impacts of the uncertainties of temperature differences between production and injection wells on geothermal power generation strategies using real option valuation. Contrary to previous studies, this study focuses on volumetric risk from the wells' temperature differences which produce both the power generation revenue and the scale-driven maintenance cost. We propose a new model of the temperature difference in a geothermal power plant and evaluate two newly designed American-type real options of a geothermal power plant with uncertainties in the temperature differences by incorporating twofold power generation strategies with temperature difference boundaries. In the first strategy, if the difference exceeds an upper threshold, the power generation ceases due to the increase of the maintenance cost from scale formation; in the second, if the difference is greater than an upper threshold or is less than a lower threshold, the power generation ceases due to the increase of the maintenance cost from scale formation or due to a shortage of calories, respectively. Results show that the net present value of a geothermal project is greater than the real option value with both the maintenance cost uncertainty and power generation uncertainty due to the negative and positive impacts of the temperature on the generation, while the net present value is less than the real option value which only reflects the maintenance cost uncertainty. It implies that the appropriate inclusion of the temperature difference risk is essential to evaluating the project value of geothermal power generation.

Keywords: geothermal power generation; temperature differences in geothermal wells; scaling; maintenance cost; real option

JEL Codes: G12, G42

1. Introduction

Countless geothermal resources are latent in the world. A lot of geothermal projects around the world have been running, and geothermal power development has been successfully carried out in many countries. For example, exploration is also underway in African countries such as Tanzania, and Uganda. Since 2015, five countries, including Latin American countries of Chile and Honduras, have recently installed geothermal power plants for the first time. Globally, installed geothermal capacity has increased from 12.3 GW in 2015 to 15.9 GW in 2020, an estimated growth of 3.6 GW (about 27% of 2015 capacity) over the past five years (Huttrer, 2020). Thus far, companies, governments, and research organizations in various countries have operated geothermal power generation. In order to choose appropriate geothermal projects, it is important to take into account uncertainties when creating the evaluation framework of the projects. There are various hurdles to creating geothermal projects and operating the plants, including the following obstacles: i) A geothermal reservoir is designated as a national park and legal matters delays development; ii) Lack of cooperation with locals and with local coordination; iii) Uncertain maintenance cost; iv) Excavation success rates are low due to unclear elucidation of underground structures; v) Potential for negative impacts on hot spring resources adjacent to geothermal resources; vi) High construction cost; vii) Long lead time and development span when the feed-in tariff price is not guaranteed at the start of operation; viii) Uncertainty of the geothermal resource itself. Due to the hurdles even Japan, which has a large number of geothermal resources, has yet to see the widespread introduction and diffusion of geothermal power generation. While Japan alone has the potential for 23.47 GW in geothermal production, the third largest in the world (Shiozaki, 2019), the installed capacity is as low as 550 MW, or only 2.4% of the resource potential (Huttrer, 2020). The reason behind this reluctance to adopt geothermal power generation lies in the fact that investors have not begun investment in renewable energy. It is because geothermal power generation has high levels of uncertainties due to the above hurdles. In particular, scaling from geothermal fluids, which causes uncertainties in the maintenance cost of geothermal energy, has been recognized as a major obstacle in the generation of geothermal energy. For example, geothermal plants in Turkey have shown that silica scaling has caused a decline in power plant performance over time; in 2009, 270 kW was recorded, and by 2012, a decline of 760 kW was recorded (Karadas et al., 2015).[1] In addition, the uncertainty of the geothermal resource's structure itself also has a significant impact on investor's confidence. Both of these two uncertainties are due to the uncertainty of geothermal well temperature differences. We focus on the evaluation of geothermal energy projects by considering the uncertainties.

To account for uncertainty and irreversibility, the real option method has been widely applied to renewable energy investment decisions (e.g., Ritzenhofen and Spinler, 2016; Loncar et al., 2017; Kitzing et al., 2017; Mo et al., 2018; Gazheli and van den Bergh, 2018; Zhang et al., 2020). However, the application of real options to geothermal energy investment valuation is limited. Chen et al. (2019) conducted a study of investment strategies for shallow geothermal resources with uncertainty in marginal revenues, which are linked to prices. The paper shows that the maximum profit was obtained when the investment scale was 1,280,000 m^2 and the investment timing was 1.05 years after the plant begins operation. Yu et al. (2019) set fossil fuel, carbon emission trading price and subsidies

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[1] There is a need not only for a scientific literature review on geothermal power projects but also for a follow-up study of recent trends and technological advances in the geothermal industry through contacts with companies and practitioners.

methods as uncertainty and considered two real options simultaneously: deferral and abandonment. They conclude that the value of the option to defer has a negative effect on the initial fossil fuel price, while the value of the option to abandon has a positive effect on the volatility of the carbon price. Bilqist et al. (2018) evaluate and analyze the present value of the geothermal power plant projects in Indonesia using net present value and real options valuation approach with uncertainties of discount rate, production volume, and operation and maintenance (O&M) cost. They found that the project value evaluated using the real option was higher than the project value evaluated using net present value (NPV). These studies are quite valuable when considering the impacts of various kinds of uncertainties, including price risk, on the project evaluations. However, they do not focus on geothermal wells' temperature difference risk, which is the key element of the power generation. Knaut et al. (2012) compared the project value from NPV to that from the real option evaluation with temperature uncertainties based on the data acquired in the Hague, the Netherlands. Their results show that negative project values are obtained from the NPV, while positive project values are obtained from the real option analysis. Compernolle et al. (2019) recently conducted a geological economic Monte Carlo simulation to evaluate a firm's option to abandon the geothermal project development after the initial drilling under both market and geological uncertainty, including reservoir temperature, in a geothermal well in Belgium. Introduction of temperature uncertainty may be important to evaluate a geothermal project value. However, the studies do not model scale formulation-related maintenance cost, which is the bottleneck of the power generation, using the uncertainties in temperature differences of production wells and injection wells.

This paper discusses how the uncertainties of power generation and maintenance cost from the wells' temperature difference affect geothermal power generation strategies by using real option valuation. We propose a new model of the temperature difference in a geothermal power plant and evaluate two newly designed real options of the project based on power generation strategies with temperature difference boundaries: 1) If the difference exceeds an upper threshold, the power generation ceases due to the increase of the maintenance cost from scale formation; 2) If the temperature is over an upper threshold or is less than a lower threshold, the power generation ceases due to the increase of the maintenance cost from scaling or due to shortage of calories, respectively. Our results show that the net present valuation of a geothermal project overestimates the project value from the real option valuation, which reflects the reality of geothermal power generation with the negative and positive impacts of the temperature differences on the generation, while the net present value is less than the real option value which only reflects the maintenance cost uncertainty.

The structure of this paper is as follows. Section 2 proposes a new model for temperature differences in a geothermal power plant and shows the evaluation framework of two newly designed options value of the project by considering the strategies of the operations under the uncertainties of maintenance costs and power generation. Section 3 conducts a real option evaluation of geothermal power plants and compares the results with a conventional valuation method by conjecturing the model parameters based on the empirical evidence. Section 4 concludes and suggests avenues for future research.

2. Model

Silica is the main cause of adhesion in scale generation[2] depending on temperature and pH. In their study, Hosoi and Imai (1982) show that scale occurred at pH 6.9–8.3 in geothermal water, which is hot liquid from geothermal reservoir, through the production well in 92–95°C to injection well in 55–75°C of the plant under test. According to Alexander et al. (1954) and Goto (1955), the silica solubility is constant under range of pH 6.9–8.3 and temperature range of 50–90°C settings. Therefore, referring these literatures, we make the following assumptions: 1) The silica concentration at pH 6.9–8.3 is constant regardless of the pH value and adhesion is independent of pH; 2) Scale generation rate is not affected by differences in absolute temperature. In contrast, the temperature difference between the production well and the injection well has strong impacts on the scaling, and we have focused on this aspect. Geothermal power creates energy through the temperature difference between the production well and the injection well, but simultaneously the geothermal water loses heat, resulting in low-temperature geothermal water. Due to the difference in solubility caused by differing temperatures, the geothermal water exceeds the threshold for unsaturated state, and the remaining silicon becomes solid silica and adheres to the well pipe and devices in the plant, which is referred to as the scale. Based on the backgrounds, we show the relationship between temperature difference and generated scale size in Figure 1 from the sample in Hosoi and Imai (1982), excluding a zero scale data point.[3] The corresponding regression Equation is shown in Equation (1).

$$\ln(Sc(t)) = \alpha T_{dw}(t) + \beta + \epsilon_t \tag{1}$$

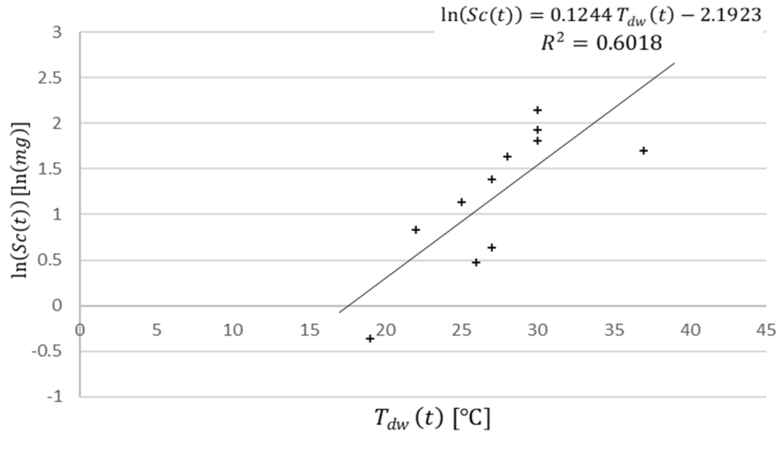

Figure 1. Temperature Difference and Scale Size: According to data in Hosoi and Imai (1982), it can be inferred that natural log of scale sizes due to temperature differences are in a proportional relationship.

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[2] This is also referred to as adhesion. The scale problem is caused by various metallic substances such as calcium (Ca) and magnesium (Mg) that produce calcium carbonate ($CaCO_3$), and silicon (Si) that produces silica (SiO_2). In this study, it was assumed that the geothermal reservoir is also the same because the quality of Japanese springs is characterized by well-melted silicon.

[3] We recognize the differences of the impact of absolute temperature values on scaling, but we use the data with relatively constant temperature of production and injection wells in Hosoi and Imai (1982). Thus, we assume that the impact of absolute temperature is limited in this paper in the first order approximation.

We define $Sc(t)$ as scale size, $T_{dw}(t)$ as temperature difference between the production well and the injection well, and ϵ_t as error between the regression equation and the data. When the temperature difference between the production well and the injection well is high, a relatively large silica scale is generated. This phenomenon indicates that the larger the temperature difference, the larger the scale size that remains in the geothermal water transportation process and adheres to the well, i.e. the temperature difference affects the scale size and the generation rate, resulting in the maintenance cost of geothermal power. This paper assumes that the maintenance cost due to the scale, i.e. $MC(t)$, is a function of the temperature differences, given by Equation (2). Note that $MC(t)$ is positive and is not to take a negative value. The α and β are the slope and intercept respectively of a linear function of temperature which represents the natural log of scale size and that γ is a conversion parameter to obtain maintenance cost.

$$MC(t) = \max\left[\gamma e^{\alpha T_{dw}(t)+\beta}, 0\right] \tag{2}$$

Next, we model the changes in temperature differences. Snyder et al. (2017) show the graph of standardized temperature change over time of 196 out of 375 production wells installed in 19 geothermal plants (12 binary and 7 flash) in California and Nevada, USA. The temperatures of these production wells, which are both flash-type and binary-type geothermal plants, tend to drop constantly over the years. About 90 % of the wells follow a downward linear trend. In addition, data from Snyder et al. (2017) show that future production well temperatures will fluctuate uncertainly with the passage of time and geothermal storage from wells. The two factors shown in this previous study, the downward trend and the uncertainty of fluctuating temperature differences, were extracted to model the future temperature changes in production wells as shown in Equation (3). $\Delta T_{dw}(t)$ in the left-hand side of Equation (3) represents the temperature differences between at the time $t + \Delta t$ and t. The right-hand side represents the drift term ($\mu_T \Delta t$) and the fluctuation term ($\sigma_T \Delta\varepsilon_t$), representing the downward trend and the uncertainty. That is to say, μ_T and σ_T represent the mean and the standard deviation of the temperature differences during a unit time change, respectively. $\Delta\varepsilon_t$ represents an independent and identically distributed random variable with $N(0, \Delta t)$ where $\Delta t = 1$. This uncertainty affects the rate of scale generation and impacts geothermal cash flows as the scale generated requires maintenance costs to be removed.[4]

$$\Delta T_{dw}(t) = \mu_T \Delta t + \sigma_T \Delta\varepsilon_t \tag{3}$$

where $\Delta\varepsilon_t \simeq N(0, \Delta t)$, This is a new model of temperature differences in production and injection wells in geothermal power.

We assume that the cash flow $CF^j(t)$ from a geothermal power is calculated as constant revenues minus temperature-dependent maintenance costs. If the cash flow in each year is positive, the geothermal power plant continues to generate power. Otherwise, the plant takes the strategy not to generate power. This relationship is like a payoff of a call option. RE is denoted by revenue as a constant value. As the first real option (RO) of a geothermal power plant, Equation (4) represents a real option of strategic maintenance constraint denoted by RO (*sc*) when $j = sc$.

$$CF^{sc}(t) = \max\left[RE - MC(t), 0\right] \tag{4}$$

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[4] In addition to the uncertainty of future production well temperatures, as the actual phenomenon, the injection well also fluctuates uncertainly. Due to availability of the data, we have assumed a constant value in the first order approximation.

However, the option has an additional restriction on the temperature difference. According to the Current Status and Trends in Geothermal Power Generation 2017 (2018), the critical temperature for generating electricity in a geothermal power plant is 126.8°C[5], and a positive cash flow with a temperature in production wells below 126.8°C is not suitable for the power generation due to the low energy. In this study, the mean value of the injection wells was set at 76.0°C based on the findings in Snyder et al. (2017). Therefore, if the temperature difference between production and injection wells is less than 50.8°C, it is not suitable for power generation due to physical constraint denoted above. Equation (5) is the corresponding cash flow at time t. As the second real option of a geothermal power plant, Equation (5) represents a real option of strategic maintenance constraint and physical constraint denoted by RO (*sc*+*pc*) when $j = sc + pc$.

$$CF^{sc+pc}(t) = \max\,[\{RE - MC(t)\}1_A, 0\,] \tag{5}$$

$$\text{where } 1_A = \begin{cases} 1\ (T_{dw}(t) \geq 50.8) \\ 0\ (T_{dw}(t) < 50.8) \end{cases}$$

These two strategies are novel designs of American-type real options of a geothermal power plant with uncertainties in the temperature difference in a geothermal power plant.

Finally, the project value (V_0^j) of the maintenance cost sector in geothermal power generation is calculated as expectation of the summation of the cash flows in Equations (4) and (5) from present to maturity τ converted to present value, discounted at the risk-free rate r_f under the risk-neutral probability Q[6], and shown in Equation (6).

$$V_0^j = E^Q\left[\sum_{t=0}^{t=\tau}\left(\frac{1}{1+r_f}\right)^t CF^j(t)\right] \tag{6}$$

Note that $j = sc$ and $sc + pc$ represent real options of strategic maintenance constraint and real option of strategic maintenance constraint and physical constraint, respectively. The V_0^{NPV} represents project value which is calculated by net present value.

3. Real option valuation

To evaluate the option, we need to set the model parameters in advance. As shown in Figure 1, a linearly regressed line was drawn on the scatter plot with temperature difference on the horizontal axis and natural log of scale size on the vertical axis. From Table 1, the slope of this regression was $\alpha = 0.12437$, and the intercept when intersecting the *y*-axis was $\beta = -2.19229$. $e^{\alpha T_{dw}(t)+\beta}$ in Equation (2) represents the amount of scale generation depending on t.

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[5] As of 2016, the lowest production well temperature among the geothermal power plants operating in Japan above the approximately 30,000 kW class is 126.8°C.

[6] Originally, there is liquidity in the market, and it cannot be expressed as risk neutrality. In other words, the price is determined based on the strong assumption that the market risk is traded in the market, but the risk of temperature difference is not traded in the market.

Table 1. Estimate, Standard Error and P-value of α and β, and Correlation Coefficient (R): The data were given from Figure 1.

	Estimate	Standard Error	P-value	Correlation Coefficient (R)
Slope (α)	0.12437	0.03372	0.00501	0.77584
Intercept (β)	−2.19229	0.93502	0.04369	

Based on the p-values, α and β are statistically significant at a significance level of 0.05. Multiplying this by a coefficient $\gamma = 175.3420$ [in 10,000 JPY], which is converted into the cost required to remove a scale of a certain size, a time-dependent maintenance cost formula is derived. The calculation of γ is the cost of removing the 1 mg unit size of scale, as shown in Appendix A. We assume a geothermal power plant with the specifications shown in Table 2, based on the Sumikawa Power Plant in Japan, which has similar capacity to the geothermal power plant discussed in Snyder et al. (2017).

Table 2. Details of Geothermal Power Plant: The reason for mentioning the Sumikawa geothermal power plant in Japan is because it is similar to the plant in Snyder et al. (2017) due to factors such as 2000 m pipes and the temperature of the production wells at about 150°C. Specifically, based on the calculations in Appendix A, we have set an estimated initial maintenance cost is 12.8 million JPY.

Capacity [kW]	Number of Wells in Operation	Well Diameter [mm]	Average Temperature in the Wells [°C]	Annual Budget Allocated to Maintenance Costs (RE)[in million JPY]	Estimated Initial Maintenance Costs (MC) [in million JPY]
30,000	14	215.9	Production Well: 151.6 Injection Well: 76.0	17.0	12.8

Then we set the parameters of the temperature difference model in Equation (3). Since the coefficient μ_T represents a term that constantly decreases, the value -1.2128, i.e. the value obtained by multiplying the slope of the Flash Best-Fit in the data in Snyder et al. (2017) by the average temperature of the production well, was substituted. σ_T is a term in which the temperature of the well changes uncertainly over time. The frequency of normalized temperature that changed after $\Delta t = 1$ was plotted in Figure 2 to see the variation in the change. This distribution is assumed to be a normal distribution, and $\sigma_T = 0.0580$ is calculated as the standard deviation of temperature-time changes.

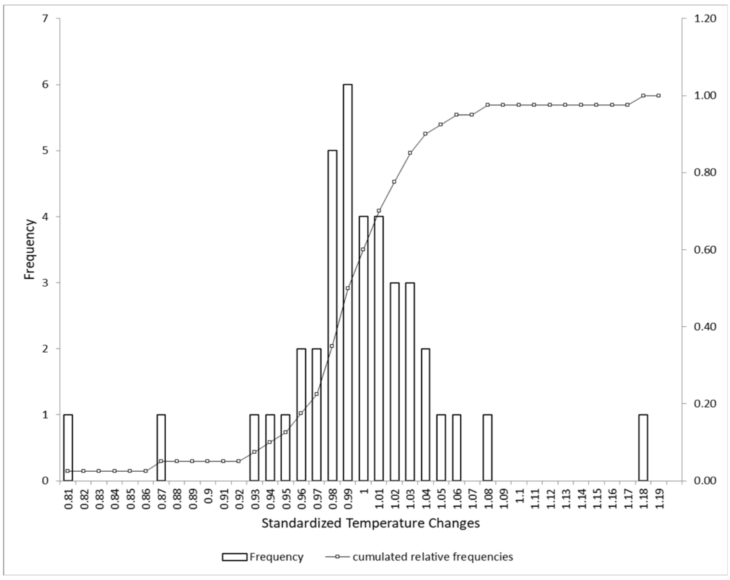


Figure 2. Standardized Temperature Difference Distribution after 1 Year: For the temperature differences of 40 production wells that can be extracted from the data in Snyder et al. (2017), the frequency changes after one year are shown in a histogram. Since the standard deviation σ_T is about 5.8%, the temperature change within plus and minus about 5.8% from the reference point is roughly distributed in 74% of the total cumulative relative frequencies.

For RE, we assume 17 million JPY per year from based on general maintenance costs of a 30,000 kW geothermal power plant. We evaluate the project value in Equation (6) using the lattice method with temperature uncertainty. We assume the maximum maturity of the project as eight years. Risk free rate is assumed as 0.1%. The results of cash flows at each node are shown in Figure 3.

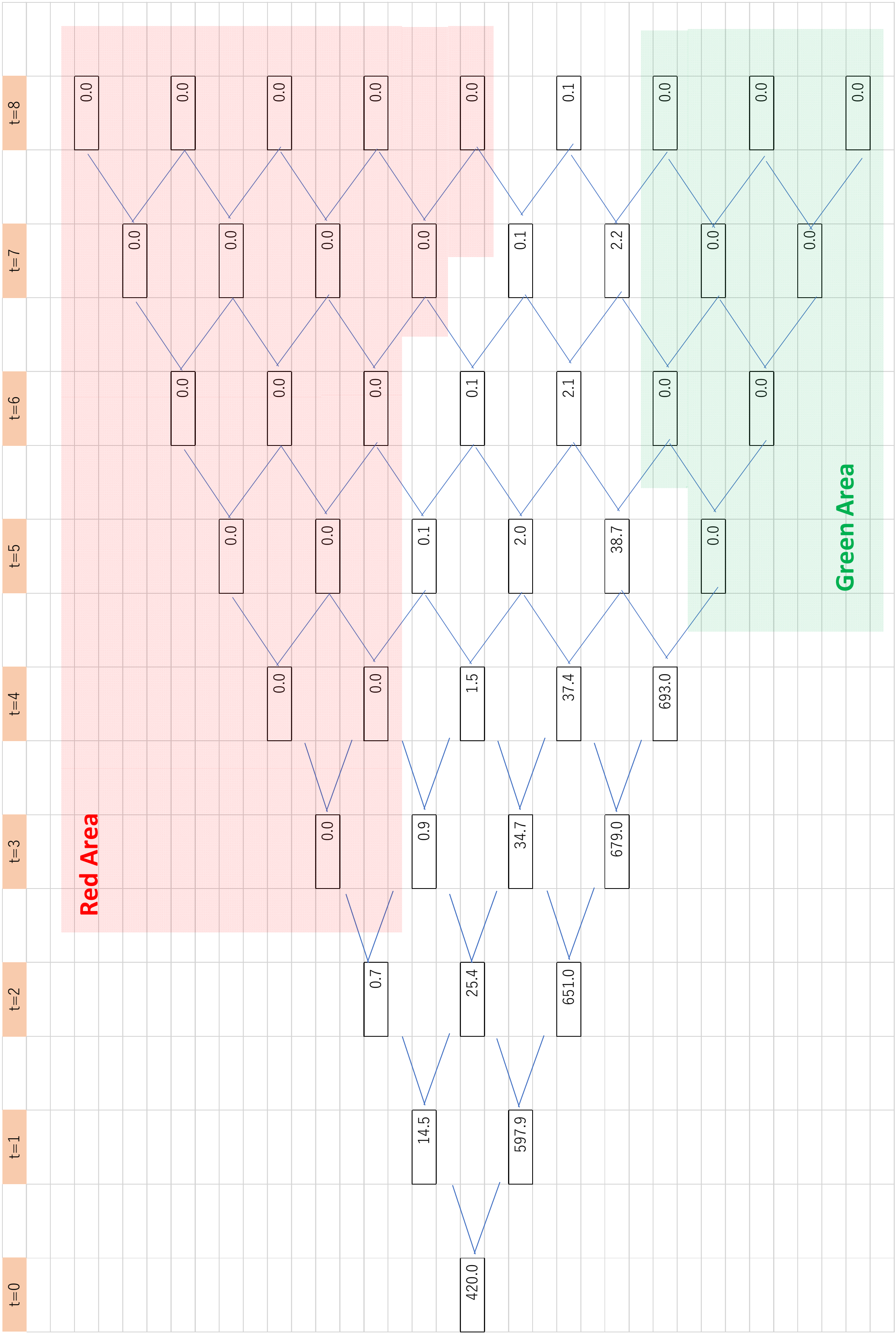
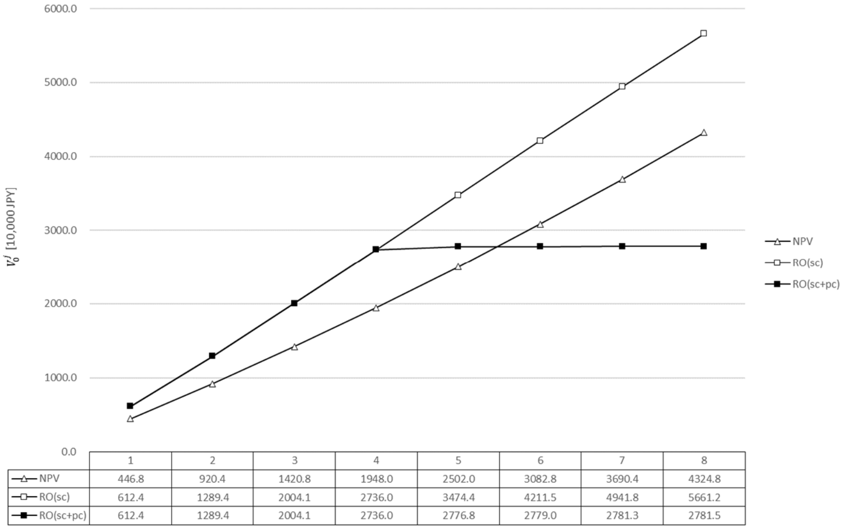


Figure 3. Lattice of Cash Flows from Geothermal Power Generation: The red area represents the strategy of stopping investment due to maintenance costs exceeding the budget, and the green area represents the strategy of reducing power generation.

Figure 4 compares the accumulated project values of real option (RO (*sc*) and RO (*sc*+*pc*) and net present value (NPV) each year. The cash flows on each year are converted to every current value and are cumulative values from year 0 to year t respectively. The project value of the real option under strategic maintenance conditions (RO (*sc*)) is larger compared to the NPV for any year when the project ends. While, considering in reality that evaluating both uncertainties of maintenance cost and power generation shortage imposed on real option under strategic maintenance constraint and physical constraint (RO ($sc + pc$)), the project value reverses between $t = 5$ and $t = 6$. As a result, RO ($sc + pc$) is less valuable than NPV when the project continues past year five.

Figure 4 illustrates the following findings. Suspension of power generation due to increased maintenance costs increase V_0^{sc}. However, as the years pass, V_0^{sc+pc}decreases due to the fact that less power will be generated due to small temperature difference with insufficient calorific value, rather than due to the effect of the power generation stoppage to prevent the decrease in income due to the increase in maintenance costs. In other words, immediately after start of the operations, the effect of stopping the power generation is large in consideration of the increase in the maintenance cost due to the increase in scale, but the effect of reducing the amount of power generation due to the temperature decrease exceeds the effect as the period becomes longer. It implies that the appropriate inclusion of the temperature difference risk is essential to evaluate the project value of geothermal power generation.



	1	2	3	4	5	6	7	8
△ NPV	446.8	920.4	1420.8	1948.0	2502.0	3082.8	3690.4	4324.8
□ RO(sc)	612.4	1289.4	2004.1	2736.0	3474.4	4211.5	4941.8	5661.2
■ RO(sc+pc)	612.4	1289.4	2004.1	2736.0	2776.8	2779.0	2781.3	2781.5

Figure 4. Comparison of V_0^{sc}, V_0^{sc+pc} and V_0^{NPV} in Geothermal Power Plant: The horizontal axis represents year t and the value on the vertical axis which represents the accumulated value of the plant in case it operates from year 0 to year t. Note that the case of RO (*sc*) takes account of only the maintenance cost increase (red area in Figure 3) and that the case of RO (sc + pc) takes account of both the maintenance cost increase power generation reduction due to temperature decrease (red and green area in Figure 3).

4. Conclusion and future research

In this paper, we examined the influence of the uncertainty from the temperature of the geothermal wells in geothermal power generation on the power generation strategy. Then we created a new model of the temperature differences in the production and injection wells of a geothermal power plant and evaluated the American-type real option of the geothermal power plant project value by incorporating the power generation strategy at the temperature boundary.

As a result, when considering only the uncertainty of maintenance cost, real option valuation produces more value than NPV, but considering both uncertainties of maintenance cost and power generation decrease due to lack of temperature resource, the real option is less valuable than NPV. In brief, NPV will be a misleading measure of evaluation if both the uncertainty of the maintenance cost and the uncertainty of the selling price of the electricity generated is not taken into consideration. By taking such uncertainties into consideration, it is possible to evaluate the project value of geothermal power generation more appropriately. Including the uncertainties of the geothermal power projects and the appropriate investment strategies can reduce the investment barriers in the valuation of the projects and promote the investment in geothermal power generation, leading to the further spread of renewable energy, which may be the social significance of this research.

The future directions of this research aim to refine the model and improve parameter accuracy. Specifically, we believe that the following approach can be used to improve parameter accuracy. In this paper, we adopt parameter estimation based on the existing literature referenced in Figures 1 and 2. However, the statistical data to set the parameters is somewhat scarce. In order to improve the accuracy of the parameters, we need to observe more data related to the scale problems recorded by geothermal plants. Furthermore, in the background of this paper's discussion, which focuses on the temperature difference in the geothermal water flowing between wells, we have assumed a setting of pH within a certain range and conditions that are not affected by absolute temperature. Therefore, from the point of improving parameter accuracy, future research would incorporate the influence of pH and absolute temperature into the model. Moreover, a continuous model should be adapted to replace the current discrete binomial lattice model. For example, the sampling of random variables obtained from Monte Carlo simulations should be used to evaluate project value. We leave these items for our future research.

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Conflict of interest

All authors declare no conflicts of interest in this paper.

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