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Uncertainty Analysis of Geothermal Development Projects Using Exploratory System Dynamics Modelling and Analysis Method

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Abstract. This study aimed to analyze uncertainty factors to provide knowledge and information regarding significant obstacles in developing geothermal energy in Indonesia. To achieve this, Exploratory System Dynamics Modelling and Analysis method was adopted. The results showed that four uncertainty factors have significant influence on the achievement of geothermal development in terms of total installed capacity, total revenue, and profit. Delay due to bureaucracy, social acceptance, exploration duration, and exploration permit processing time had 68% influence on total installed capacity and profit. Meanwhile, electricity price had 44% impact on total revenue. In conclusion, focus should be given to policy interventions such as streamlining bureaucratic processes, reducing delays, and shortening processing times, to enhance installed capacity and profit growth in the future.

Keywords: Exploratory modelling and analysis; Geothermal; Power plants development; System dynamics; Uncertainty analysis

1. Introduction

Indonesia is blessed with over 28.910 MW (40%) of geothermal energy reserve worldwide (Pambudi, 2018). The country intends to utilise this abundant resource for substantial carbon emission reduction. This was stated in the Energy Sector Commitment of reducing greenhouse gas emissions by 314–398-million-tons of CO2 by 2030. Additionally, Indonesia is dedicated to meeting the target of the Paris Agreement, aiming to maintain the global temperature increase above 2°C, preferably at 1,5°C. Despite the abundant potential of geothermal energy, the total installed capacity of power plants at over 70 sites across the country only reaches approximately 2.356 MW, according to ThinkGeoenergy study in 2022. Furthermore, the advancement of renewable energy, particularly in the geothermal sector, requires significant improvement, especially when compared with the National Energy Policy targets of approximately 4,417.5 MW in 2022 and 7,241.5 MW in 2025 (Saroji *et al.*, 2022).

Geothermal projects are usually divided into complex development phases before reaching the operational and maintenance stage. The phases comprise the geological and

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geophysical survey, exploration, exploitation, feed, EPCC, and production. These can be categorized into 3 main stages, namely exploration, exploitation, and operation. Based on Figure 1, there is a high chance of unsuccessful exploration due to the increased risk and uncertainty during the process. A significant obstacle to geothermal energy development in Indonesia is the high upfront investment cost and associated uncertainty (Compernolle *et al.*, 2019). Studies showed that geothermal projects are capital-intensive, complex, and sensitive to uncertainty and risks (Dewi *et al.*, 2022; Dewi, Setiawan, and Latief, 2020). For instance, development of a 30 MW condensing type of power capacity could require 7-12 years, with an investment ranging from USD 65-80 million (Monterrosa, 2009). The exploration phase, in particular, entails substantial upfront capital investment, often exceeding USD 5.2 million for a 1 MW geothermal power plant (Dewi *et al.*, 2022).

A key contributor to hindrances in geothermal energy development in Indonesia is the prevalence of uncertainty factors, including drilling success ratio, delay due to bureaucracy or social factors, electricity pricing, and other non-technical variables. Recent studies have explored aspects of geothermal development, such as investment cost and risk (Dewi *et al.*, 2022), the impact of feed-in tariff on installed capacity (Setiawan *et al.*, 2022), geothermal exergy analysis (Qurrahman *et al.*, 2021), and the risk allocation scheme (Nur, Burton, and Bergmann, 2023). However, there remains a gap in reports addressing the identification and analysis of uncertainty and their significance in achieving the objective of geothermal development.

This study aims to analyze uncertainty within geothermal energy development. From system perspective, geothermal projects are viewed as a complex system consisting of various elements, such as actors, institutions, and technologies, which are interrelated and changed over time. Factors contributing to the complexity of these projects include projects size, variety, interdependence, and context. To capture this complexity and address uncertainty, this study combines system dynamics (SD) method with exploratory modeling and analysis (EMA) framework. This innovative method facilitates the generation and execution of a series of computational experiments, providing valuable insights into the complexities of geothermal projects under uncertain conditions.

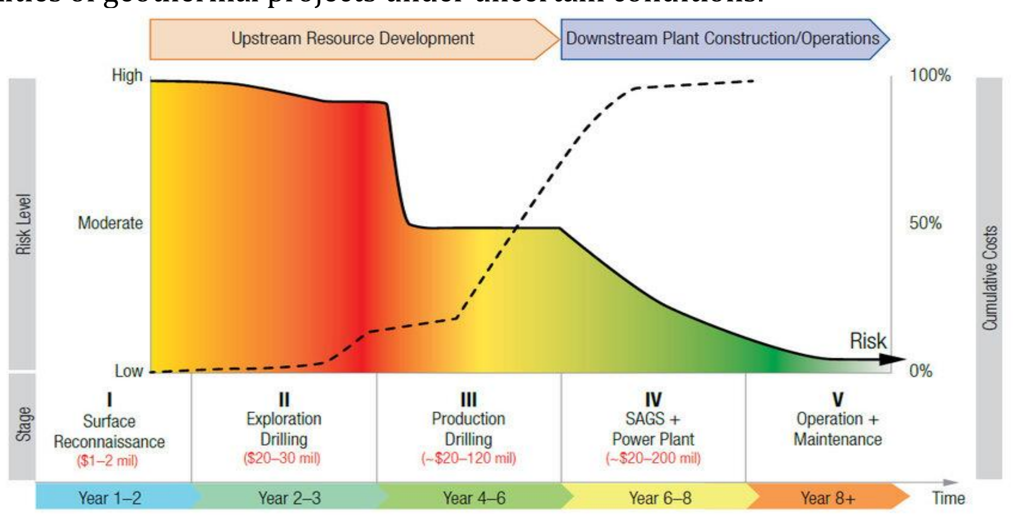


Figure 1 Risks and costs at different phases of geothermal projects (Fan and Nam, 2018)

2. Methods

2.1. ESDMA as a Method to Analyze Uncertainty in Geothermal Projects

Geothermal energy development is a complex system comprising dynamics interaction among variables, including uncertainty factors (Dewi, Setiawan, and Latief, 2020).

Uncertainty of geothermal projects was centralised on exploration and the production of natural resources, particularly due to the subsurface location. Furthermore, it covered geological, geophysical, temperature, and initial drilling data, which were used to model the potential geothermal reservoir.

SD method was implemented to understand the complexity of the end-to-end development process. This comprises model conceptualisation, formulation, verification and validation, as well as scenario analysis. However, in this study, the scenario analysis was different from the conventional method by incorporating EMA.

Previous study has shown that SD modelling and EMA are complementary (Kwakkel and Pruyt, 2013), culminating in development of ESDMA. In this method, SD was focused on the use of models to explore the interrelation link between system structure and its evolutionary behaviour over time. The objective is to explain this behaviour through causal 'theory' or dynamics hypothesis (Lane, 2017; Sterman, 2000). Unlike study forecasting method (Cendrawati *et al.*, 2023), EMA operates under the premise of not knowing enough to make predictions, recognizing the wealth of information available to support decision-making (Moallemi *et al.*, 2020; Bankes, Walker, and Kwakkel, 2013). Model development for EMA aimed to explicitly represent a set of plausible models by articulating alternative hypotheses about parameter values, mathematical relations between variables, and nonlinear relations in table functions. The integration of both methods to analyze uncertainty in geothermal projects is suitable. This is because SD provides qualitative insights into the structure-behavior relationship and identifies effective leverage points. On the other hand, EMA analyzes combinations of these leverage points to discern their impact on the behaviour of interest.

This study comprises a series of methodological steps, including model conceptualisation, model formulation, verification and validation, as well as scenario analysis. The scenario analysis was conducted using EMA, as detailed in Figure 2.

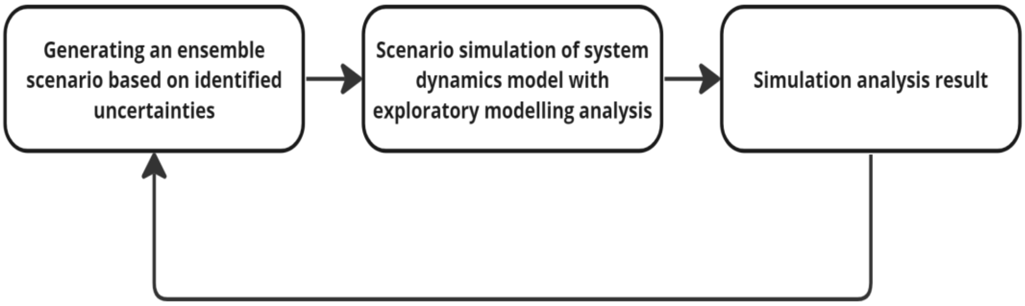


Figure 2 The Steps of Exploratory Modelling and Analysis Method

2.2. Model Conceptualisation

Model conceptualisation identifies and maps variables that build geothermal development performed by the National Geothermal Company (NGC). Currently, the company manages 13 sites scattered across Indonesia, with a total installed capacity of 1.877 MW consisting of 672 and 1.205 MW through standalone and joint operations, respectively. This study build upon previous investigation on geothermal development by (Setiawan *et al.*, 2022), with modifications to the conceptual model.

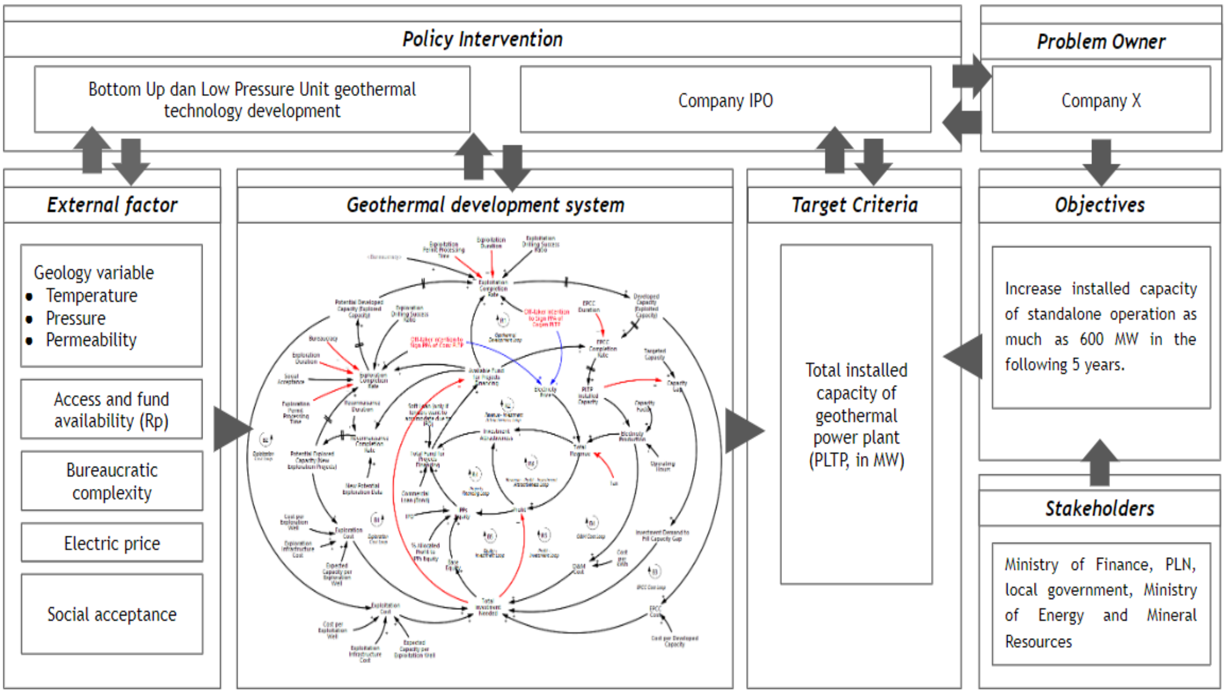


Figure 3 System diagram of geothermal development of the NGC (adapted from Setiawan *et al*. (2022), the enlarged picture of geothermal development system is shown in Figure 4)

2.3. Model Formulation

Model formulation includes the transformation of CLD into SFD and subsequent model testing. The CLD in Figure 4 was transformed into 3 SFD modules, namely main geothermal development, detailed costing of geothermal development and investment, as well as financing of geothermal projects. This study uses Vensim DSS software to develop and simulate the constructed SFD constructed. Figure 5 shows the SFD of geothermal development module. In this module, the outcome indicator of system was the total installed capacity of power generations, which consists of conventional and non-conventional technologies (binary unit and low pressure).

Figure 5 shows the main activities in geothermal development, indicating the variables contributing to the resultant total installed capacity. For the conventional technology stream, Installed Capacity Conv is the result of Developed Capacity Conv, which is determined by EPCC Completion Rate Conv and influenced by EPCC Duration Conv. Developed Capacity Conv is a factor of Potential Developed Capacity Conv and Exploitation Completion Rate Conv. Several variables that affect Exploitation Completion Rate Conv include Exploitation Duration Conv, Exploitation Drilling Success Ratio Conv, and Exploitation Starting Delay Conv. However, the Exploitation Starting Delay Conv is influenced by Exploitation Duration Conv, Delay due to Social Acceptance Conv, Exploration Permit Processing Time Conv, and Delay due to Bureaucracy Conv. Potential Developed Capacity Conv results from Potential Explored Capacity Conv and is determined by Exploration Completion Rate Conv. Exploration Drilling Success Ratio Conv influences this variable, along side Off-taker intention to sign PPA Conv, Parent Support for Exploration Conv, Exploration Duration Conv, and Exploration Starting Delay Conv. The Exploration Starting Delay Conv was influenced by the same delaying variables. Finally, the Potential Explored Capacity Conv was determined by the Reconnaissance Completion Rate Conv.

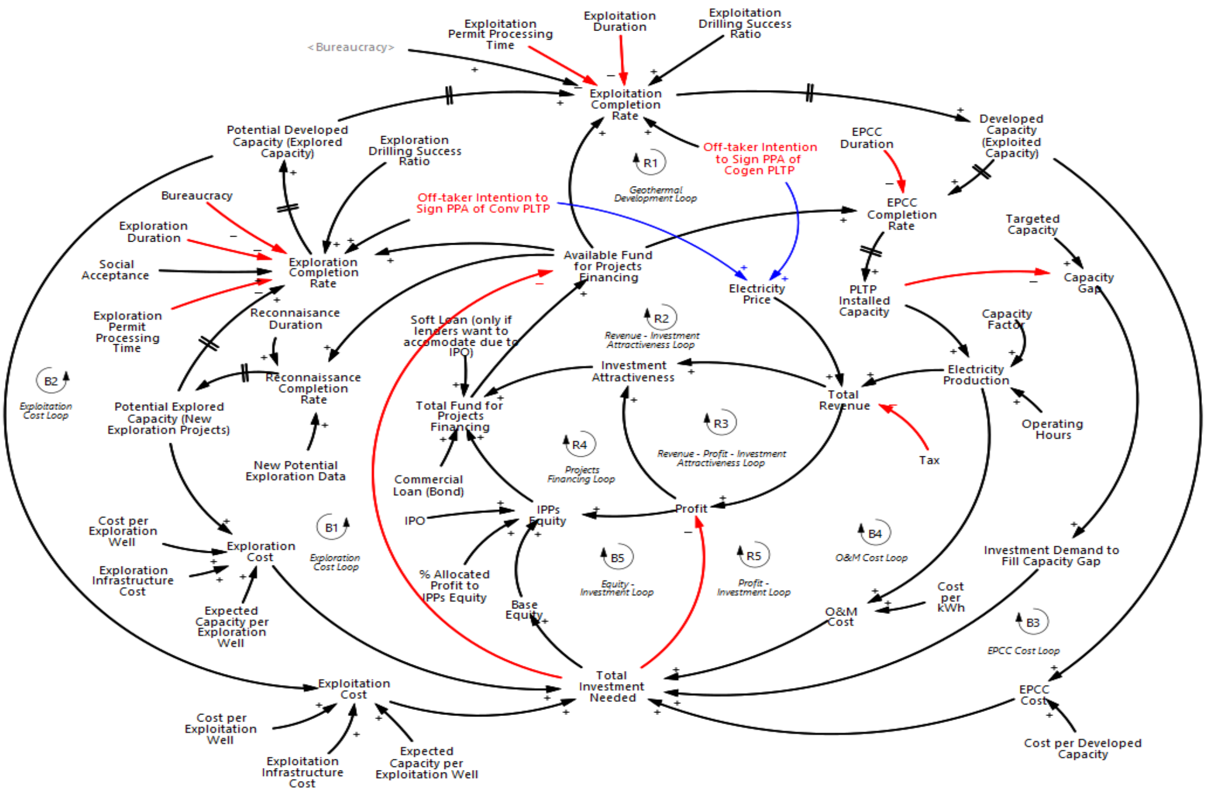


Figure 4 CLD of geothermal development system (adapted from Setiawan *et al.* (2022))

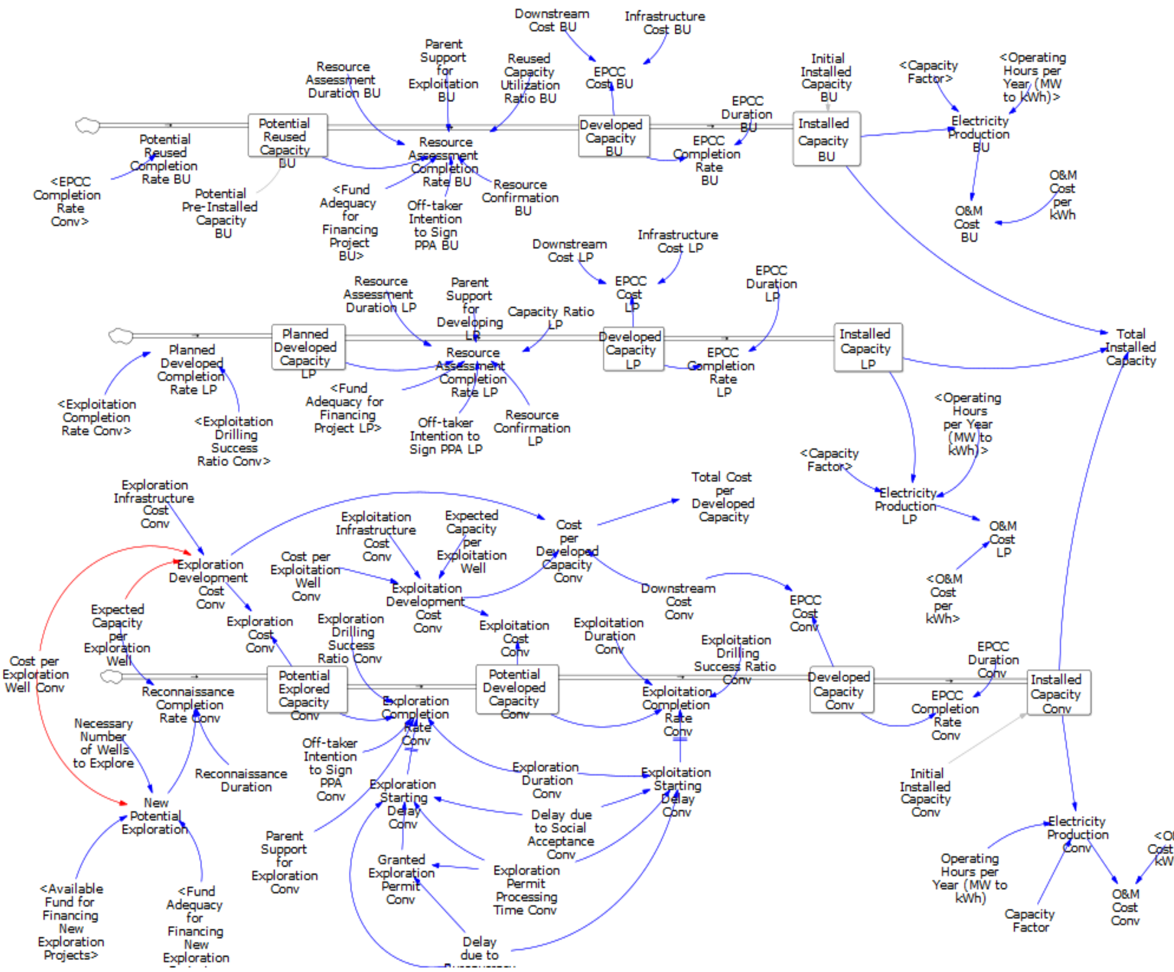


Figure 5 SFD of geothermal development of the NGC (adapted from Setiawan *et al.* (2022))

Before using the quantitative SFD in exploratory modelling analysis, this study conducted validation and verification tests for SD modelling based on Sterman (2000). These include tests for dimensional consistency, integration error, structure assessment, boundary adequacy, behaviour analysis, and extreme condition.

2.4. Exploratory Modelling and Analysis for Uncertainty Analysis of Geothermal Development

Exploratory modelling and analysis were implemented as scenario analysis by replicating simulations with various parameters of uncertainty variables that have been set before. This study used Jupyter Notebook to establish the Python script for running the simulation provided by EMA Workbench. Parameters with a varying range are outlined in Table 1.

Table 1 Parameter value ranges for the input of the simulation

Parameters	Range Value	Parameters	Range Value
Electricity Price Conv	0.0753–0.114	Off-taker Intention to Sign PPA Conv	0/1
Electricity Price LP	0.0886–0.13	Lender Approval on Soft Loan	0/1
Electricity Price BU	0.0766–0.2027	Delay due to Bureaucracy Conv	0-2
Exploration Permit Processing Time Conv	0-1	Delay due to Social Acceptance Conv	0-2
Cost per Exploration Well Conv	8.000.000-11.000.000	Exploration Duration Conv	1-3
Cost per Exploitation Well Conv	6.000.000-8.000.000	Exploitation Duration Conv	1-5
Exploration Infrastructure Cost Conv	2.00000-300.000	EPCC Duration BU	1-4
Exploitation Infrastructure Cost Conv	250.000-500.000	EPCC Duration LP	1-4
Resource Confirmation BU	0 or 1	EPCC Duration Conv	1-4
Resource Confirmation LP	0 or 1	Exploration Drilling Success Ratio Conv	0.5–0.58
Off-taker Intention to Sign PPA BU	0 or 1	Exploitation Drilling Success Ratio Conv	0.8–0.85
Off-taker Intention to Sign PPA LP	0 or 1		

The EMA Workbench runs 10.000 replications with different combinations of range value parameters. Subsequently, this study incorporates global sensitivity analysis in Feature Scoring which is a set of methods often applied in machine learning to identify the contributions of each feature to the outcome of interest in a model (Chen, Calabrese, and Martin-Barragan, 2024). The method offers advantage of convenience by eliminating the need to impose specific constraints on experimental design while accommodating real value, integer value, and categorical value parameters (Kwakkel, 2017). Feature scoring was applied to the outcomes of interest in geothermal development, specifically Total Installed Capacity, Total Revenue, and Profit. This method is only applicable to a single outcome of interest, with the default algorithm being Extra Trees feature scoring.

This study also implements scenario discovery, which produces insights into influential combinations of variables highly affecting the outcome of interest. Scenario discovery was presented using a more visual method in the form of a dimensional stacking diagram.

3. Results and Discussion

3.1. Results

Figure 6 shows the results of 10.000 replications executed using EMA Workbench with a range of value parameters. The results were presented as time-graphs for the 3 outcomes of interest. Boxplot on the side of the graph shows the data distribution of the replications for each outcome. The simulation results showed that majority of data generated by the replications were concentrated at 1.650 MW, USD 850 million, and USD 400 million for Total Installed Capacity, Total Revenue, and Profit, respectively.

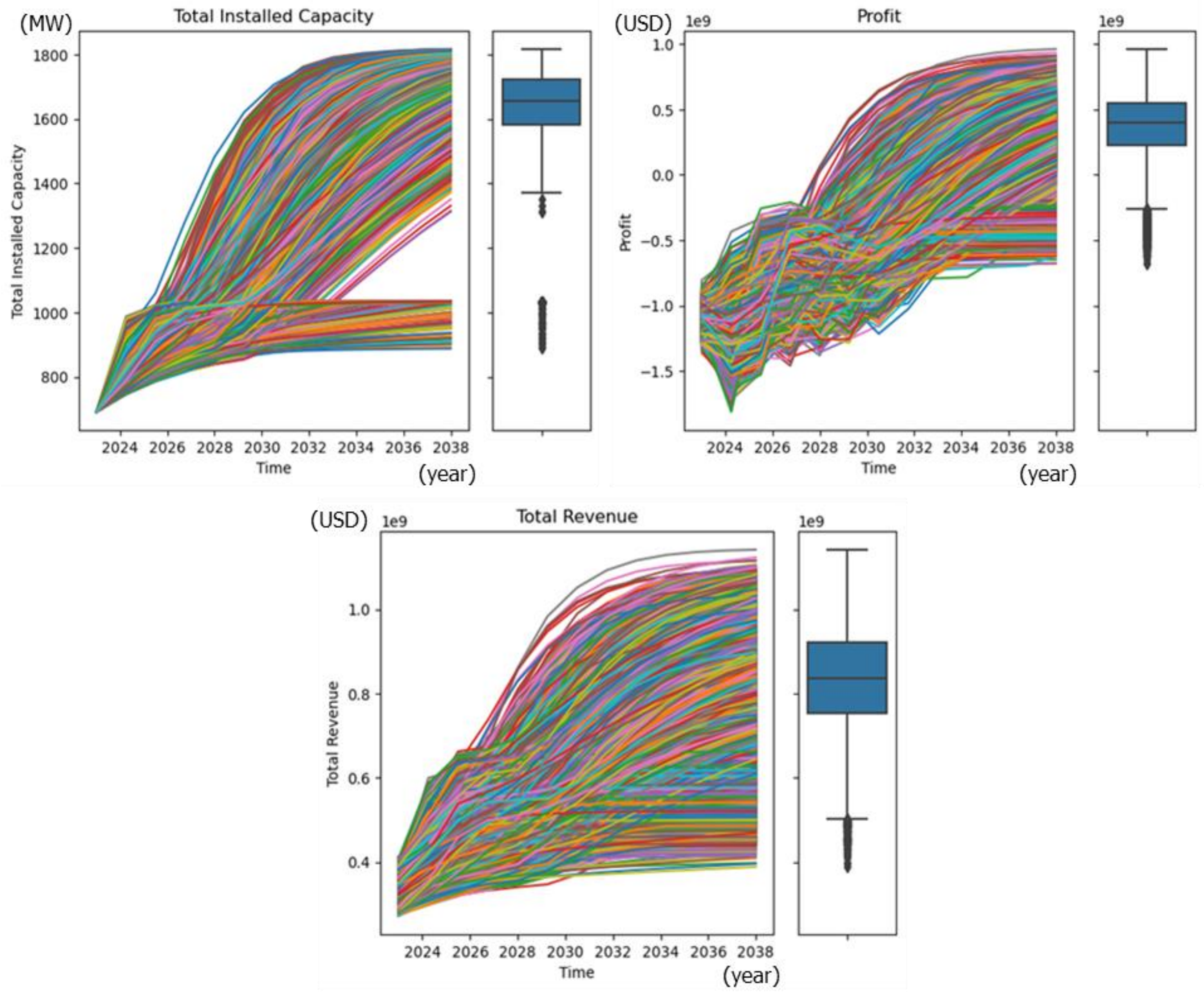


Figure 6 ESDMA simulation results as a graph of Total Installed Capacity, Total Revenue, and Profit over time.

The feature scoring result in Figure 7 shows that a few variables have significant value for outcomes of interest. These variables reflected uncertainty factors significantly influencing achievement of geothermal development in terms of total installed capacity, total revenue, and profit. Furthermore, they are regarded as deeply uncertain since the values cannot be easily predicted nor measured beforehand. For Total Installed Capacity, the 4 considerable features were Delay due to Bureaucracy Conv, Social Acceptance Conv, Exploration Duration Conv, and Exploration Permit Processing Time Conv. These factors had 68% influence on total installed capacity and profit. Meanwhile, electricity price had 44% impact on total revenue.

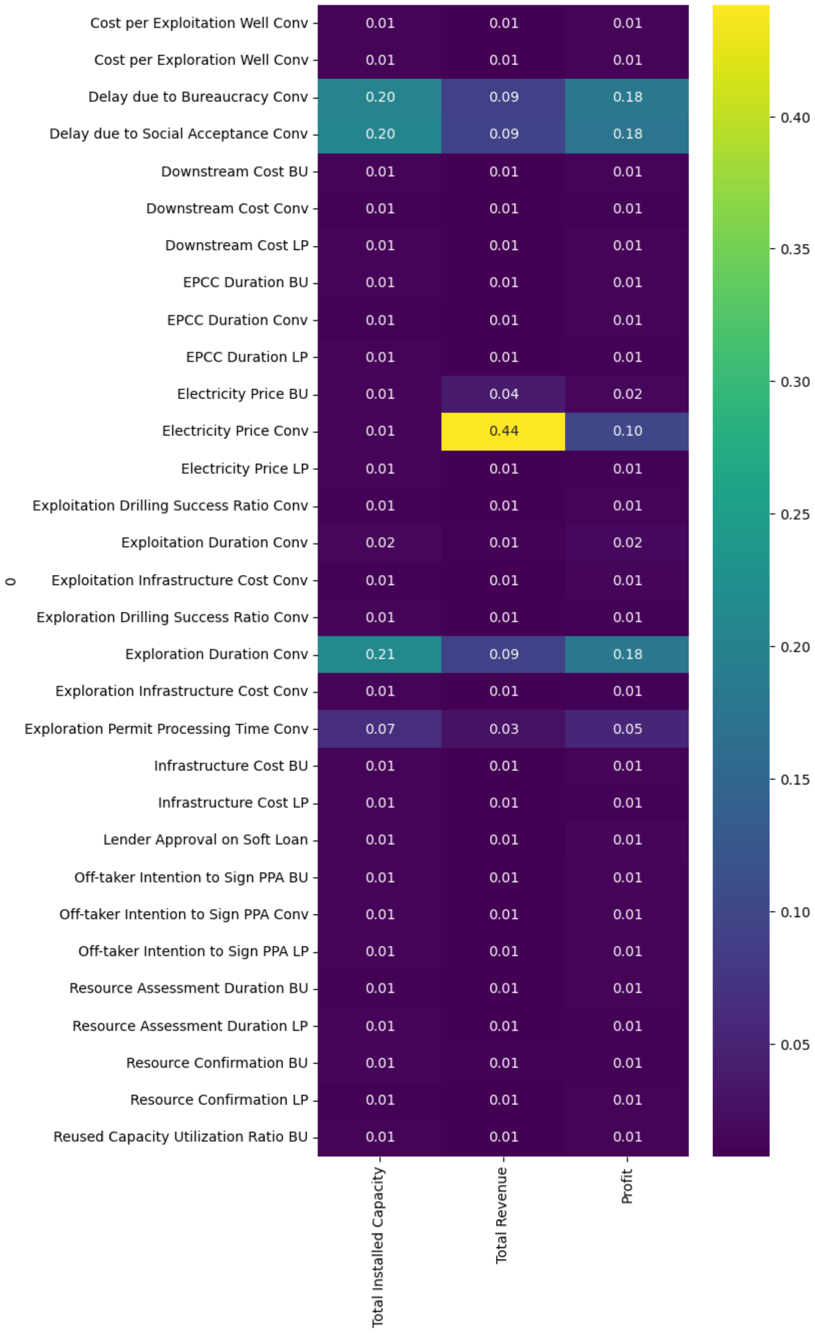
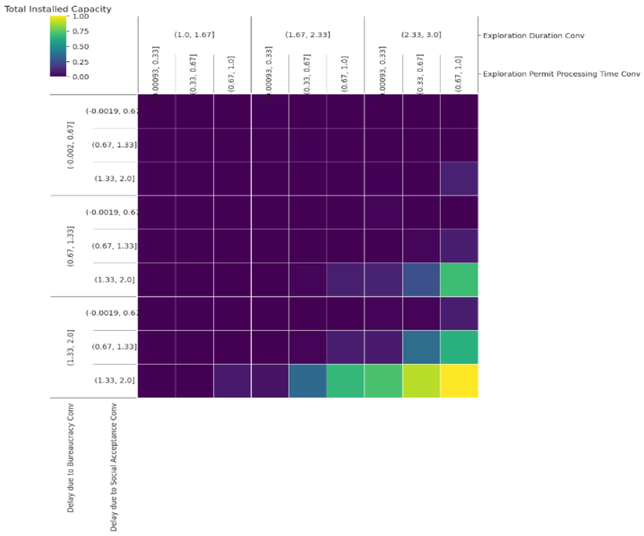
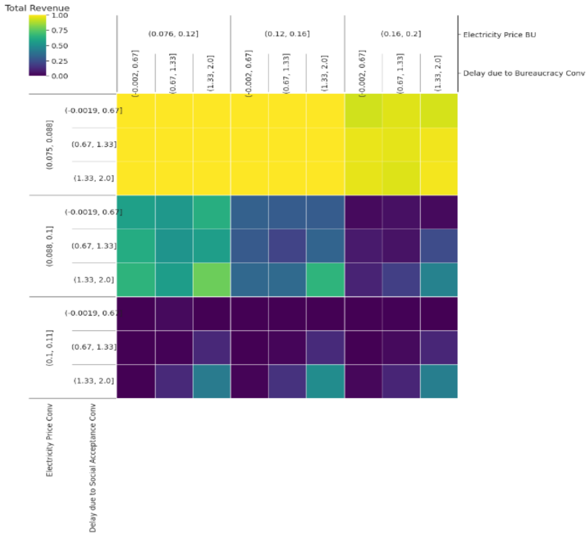


Figure 7 Feature scoring result using extra trees algorithm

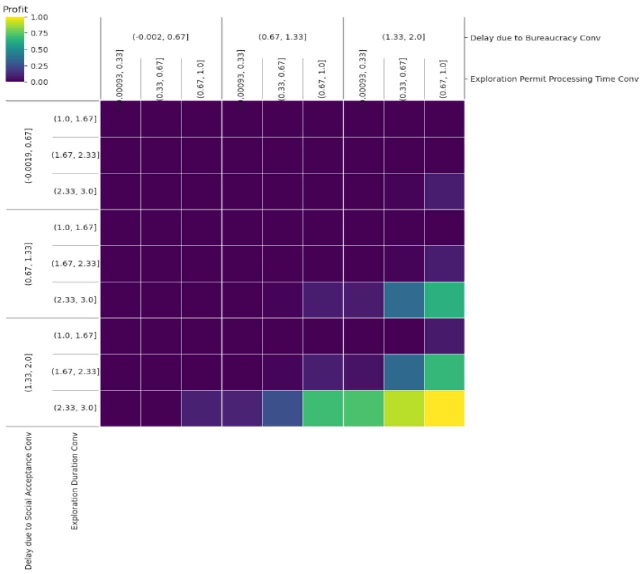
Scenario discovery results in dimensional stacking showed various combinations of variables that were highly impactful to the outcomes of interest. Each square represents a few simulations from the model, with brighter showing a higher concentration of simulations compared to darker colours. For the scenario discovery purpose, the target values for Total Installed Capacity, Total Revenue, and Profit were based on the results in Figure 6. According to Figure 8, the longer processing time led to more simulations with a Total Installed Capacity value lower than 1.650 MW. In terms of Total Revenue, lower Electricity Price Conv and Electricity Price BU (binary unit) results in more simulations with Total Revenue value below the value target. In terms of Profit, the result showed similarity with Total Installed Capacity, indicating that a more prolonged duration of processing time led to more simulations failing to achieve the value target.



Total Installed Capacity



Total Revenue



Profit

Figure 8 Scenario discovery results of Total Installed Capacity, Total Revenue, and Profit

3.2. Discussion

The results of the simulations using the EMA Workbench (Kwakkel, 2017) showed that a few variables significantly impact the outcomes of interest. The feature scoring in Figure 7, showed the impact of a few variables on Total Installed Capacity, Total Revenue, and Profit. For Total Installed Capacity, the four significant variables with the most influential uncertainty factors were Delay due to Bureaucracy Conv, Social Acceptance Conv, Exploration Duration Conv, and Exploration Permit Processing Time Conv. All the variables are associated with temporal processes, including delay, duration, and processing time. In the case of Total Revenue, Electricity Price Conv, Exploration Duration Conv, Delay due to Bureaucracy Conv, and Delay due to Social Acceptance Conv had individual impacts. The most prominent was Electricity Price Conv, which means the price fluctuation significantly affected the Total Revenue of this projects. Lastly, Profit was also impacted by Delay due to Bureaucracy Conv, Delay due to Social Acceptance Conv, Exploration Duration Conv, and Electricity Price Conv. These variables were related to conventional technology which has a significant effect on geothermal development projects. The scenario discovery method in dimensional stacking produced the value combinations based on significant variables from each outcome of interest.

Figure 8 shows a slight tendency for Total Installed Capacity and Profit, suggesting that a higher concentration of replications failing to achieve the median target are those with longer or higher values of the 4 significant variables. Therefore, the company can focus on making policy interventions that lead to faster duration and processing time while reducing delays, specifically for conventional technology, thereby increasing the possibility of achieving the total installed capacity target. In the case of Total Revenue, the dimensional stacking clearly showed that low Electricity Price Conv significantly caused the replication results not to achieve the median target. The graph also showed that the low Electricity Price BU could impede achieving the median target. This situation is quite challenging to solve as the Electricity Prices were usually discussed and set by the off-taker and cannot be independently developed by the company. A feed-in tariff policy from the government can help the company generate sustainable revenue and profit. This study shows the advantages of the ESDMA method. Compared to a recent reports by Setiawan *et al*. (2022) and (Dewi, Setiawan, and Latief, 2020), which only used SD method to evaluate geothermal development target achievement and offered a conceptual model to analyze uncertainty factors, respectively, ESDMA proved more useful. Projects developer was more anticipative to the identified uncertainty factors. In the long run, such action can be taken beforehand with sufficient understanding on uncertainty factors in geothermal development, thereby increasing the possibility of higher achievement.

4. Conclusions

In conclusion, after analyzing various uncertainty factors, it was discovered that the focus should be on policy interventions aimed at reducing both the duration and processing time to mitigate delays effectively. This strategic focus was essential for enhancing installed capacity and fostering profit growth in the future. Additionally, collaboration with the Indonesian government was recommended to enforce feed-in tariff policies, ensuring a sustainable revenue stream and supporting the long-term development of geothermal power plants in Indonesia. It is important to note that this study was confined to an aggregate level analysis of geothermal power plants. However, extrapolating these results to individual power plants holds the potential to yield a more nuanced understanding of the distinctive patterns and trends of each plant. This tailored method enabled the identification of specific factors influencing individual power plants within geothermal projects. Future investigations on this subject can benefit from adopting an optimization method, particularly using the EMA-directed search method. This method facilitated the identification and analysis of precise measures needed to achieve the specific installed capacity targets of geothermal development projects.

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References

Bankes, S., Walker, W. E., Kwakkel, J.H. 2013. Exploratory Modeling and Analysis. *In:* GASS, S.I. & FU, M. C. (eds.) *Encyclopedia of Operations Research and Management Science.* Boston, MA: Springer US

Cendrawati, D. G., Hesty, N. W., Pranoto, B., Aminuddin, Kuncoro, A. H. & Fudholi, A. 2023. Short-Term Wind Energy Resource Prediction Using Weather Research Forecasting Model for a Location in Indonesia. *International Journal of Technology,* 14**,** 291–319

Chen, Y., Calabrese, R., Martin-Barragan, B. 2024. Interpretable Machine Learning for Imbalanced Credit Scoring Datasets. *European Journal of Operational Research,* Volume 312**,** pp. 357–372

Compernolle, T., Welkenhuysen, K., Petitclerc, E., Maes, D., Piessens, K. 2019. The Impact of Policy Measures on Profitability and Risk in Geothermal Energy Investments. *Energy Economics,* Volume 84, p. 104524

Dewi, M.P., Setiawan, A.D., Latief, Y. 2020. Developing a Sustainable Financing Model for Geothermal Projects: A Conceptual Framework. *In:* Proceedings of the 3rd Asia Pacific Conference on Research in Industrial and Systems Engineering, Depok, Indonesia: Association for Computing Machinery

Dewi, M.P., Setiawan, A.D., Latief, Y., Purwanto, W.W. 2022. Investment Decisions Under Uncertainties In Geothermal Power Generation. *AIMS Energy,* Volume 10**,** pp. 844–857

Fan, K., Nam, S., 2018. Accelerating Geothermal Development in Indonesia: A Case Study in the Underuse of Geothermal Energy. *Consilience***,** Volume 19, pp. 103–129

Kwakkel, J.H. 2017. The Exploratory Modeling Workbench: An open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making. *Environmental Modelling & Software,* Volume 96**,** pp. 239–250.

Kwakkel, J.H. Pruyt, E. 2013. Exploratory Modeling and Analysis, an approach for model-based foresight under deep uncertainty. *Technological Forecasting and Social Change,* Volume 80**,** pp. 419–431

Lane, D.C. 2017. Diagramming Conventions in System Dynamics. *Journal of the Operational Research Society,* Volume 51(2)**,** pp. 241–245

Moallemi, E.A., Kwakkel, J., de Haan, F.J., Bryan, B.A., 2020. Exploratory Modeling for Analyzing Coupled Human-Natural Systems Under Uncertainty. *Global Environmental Change,* Volume 65**,** 102186

Monterrosa, M. 2009. Planning of Geothermal Projects: A Case Study on Central America. Presented at "Short Course on Surface Exploration for Geothermal Resources", organized by UNU-GTP and LaGeo, in Ahuachapan and Santa Tecla, El Salvador

Nur, S., Burton, B., Bergmann, A. 2023. Evidence on Optimal Risk Allocation Models for Indonesian Geothermal Projects Under PPP Contracts. *Utilities Policy,* Volume 81**,** p. 101511

Pambudi, N.A. 2018. Geothermal Power Generation in Indonesia, a Country Within the Ring of Fire: Current Status, Future Development and Policy. *Renewable and Sustainable Energy Reviews,* Volume 81**,** pp. 2893–2901

Qurrahman, A.H., Wilopo, W., Susanto, S.P., Petrus, H.T.B.M., 2021. Energy and Exergy Analysis of Dieng Geothermal Power Plant. *International Journal of Technology,* Volume 12(1)**,** pp. 175–185

Saroji, G., Berawi, M.A., Nunik, M.S., Joanna, M., Socaningrum, F., Susantono, B.S., Woodhead, R., 2022. Optimizing the Development of Power Generation to Increase the Use of Renewable Energy Sources. *International Journal of Technology,* 13(7)**,** pp. 1422–1431

Setiawan, A.D., Dewi, M.P., Jafino, B.A., Hidayatno, A., 2022. Evaluating Feed-In Tariff Policies on Enhancing Geothermal Development in Indonesia. *Energy Policy,* Volume 168**,** 113164

Sterman, J.D. 2000. *Business Dynamics. Systems Thinking and Modeling for a Complex World.,* Boston, McGraw Hill Higher Education.