A Review on AI/ML applications in Geothermal systems

D. Uday Kiran[1], A. Gayathri[2], B. Rakesh[3], Kishore. T. S[4]

[1]UG Student, Dept. of EEE, GMR Institute of Technology
[2]UG Student, Dept. of EEE, GMR Institute of Technology
[3]UG Student, Dept. of EEE, GMR Institute of Technology
[4]Proffesor, Dept. of EEE, GMR Institute of Technology

---***---

Abstract - Artificial Intelligence (AI) and Machine Learning (ML) techniques have emerged as powerful tools to enhance the efficiency, reliability, and sustainability of geothermal energy systems. Traditional approaches to resource exploration, reservoir modeling, system optimization, and fault detection often face challenges due to the complex, nonlinear, and uncertain nature of geothermal environments. AI and ML algorithms, such as neural networks, support vector machines, decision trees, and deep learning architectures, offer data-driven solutions for handling these complexities. Recent studies demonstrate their effectiveness in geothermal resource identification, temperature and pressure prediction, energy production forecasting, and optimization of drilling and power plant operations. Additionally, hybrid approaches combining physics-based models with AI-driven methods are proving effective in improving accuracy and reducing computational costs.

Key Words: Geothermal energy, Artificial intelligence (AI), Machine learning (ML), Resource optimization, Fault detection

1.INTRODUCTION

Geothermal energy utilizes the heat found in the Earth's crust to produce electricity and for direct heating. It is one of the few renewable energy sources that can provide a steady baseload power supply without depending on weather conditions. Geothermal systems are attractive because of their low carbon emissions, highly reliable service, and long service life. Still, the adoption of geothermal energy has not advanced significantly since many geothermal energy projects have high capital costs and some uncertainty about geology.

Drilling costs account for nearly 60% of geothermal project costs, and there are risks associated with drilling operations such as lost circulation, fault structures, and damage from high temperatures. Additionally, challenges exist for reservoir characterization, predicting temperature, and maintaining geothermal production equipment, such as electrical submersible pumps (ESPs). If the drilling engineer does not detect faults or other issues with the reservoir early on, the company may engage in non-productive time, lose equipment or experience financial loss.

Geothermal power play a critical role in the global shift to a low-carbon and sustainable energy system. They offer clean, renewable and stable energy sources with the capacity to complement intermittent renewables, such as solar and wind. By utilizing resources available locally, they also promote energy security, reduce fossil fuel reliance, and support job growth in rural and developing regions. When smart control and predictive technologies are incorporated, these systems can operate more efficiently, reduce costs, and be more environmentally sustainable.

Intelligence (AI) and Machine Learning (ML) have emerged as valuable tools to overcome the constraints of geothermal energy system. In geothermal energy, AI/ML methods are being used to detect drilling faults in real-time, as well as to forecast reservoir properties, and generate power forecasts. Models such as Long Short-Term Memory (LSTM) Networks, and Federated Learning (FL), allow for accurate data transfer between geothermal plants without compromising privacy. These methods also yield improved accuracy of forecasting, along with improved safety and operational safety.

Through data-driven solutions integrated with physical knowledge, AI and ML are evolving into smart, adaptive, predictive control systems. In a fatigued workforce, these technologies enable substantial reductions in human error, enhanced efficiencies, and ultimately, sustainable and intelligent energy futures.

2. Working of Geothermal Energy Systems

2.1 Working of Geothermal Energy System

As indicated in the geothermal report, geothermal energy capitalizes on the natural heat that has risen to the surface of the Earth from within, allowing the conversion of heat to electricity and other direct use applications. The geothermal energy process involves extracting heat from geothermal reservoirs (most often hot water or steam trapped below the Earth's surface) and converting that process into mechanical energy using turbines.

2.2 Operational Frames of Reference:

2.2.1. Heat Source and Formation of Reservoirs

- Heat originates from radioactive decay of minerals and heat fro the Earth's core.

- Water migrates deep underground, becomes heated, and is close enough to the surface to form hot water or steam reservoirs.

2.2.2. Production Wells

- Production wells are drilled deep into the geothermal reservoirs to extract hot water or steam.
- Drilling is one of the most expensive phases of development (approximately 60% of total project costs).

2.2.3. Energy Conversion

- Steam is extracted and used to drive a turbine which drives a generator that produces electricity.
- In binary systems, heat is transferred from hot geothermal fluid to a secondary working fluid with a lower boiling point, causing the secondary fluid to vaporize and turn the turbine.

2.2.4. Reinjection Wells

- The cooled geothermal fluid is reinjected back into the Earth after the energy is extracted. This maintains pressure or sustains replenishment and can assure sustainability.

2.2.5. Monitoring and Control (with AI/ML)

- AI and ML models can monitor drilling conditions, fault detection for instance smelling pipes or loss of circulation, and even forecast power generation.

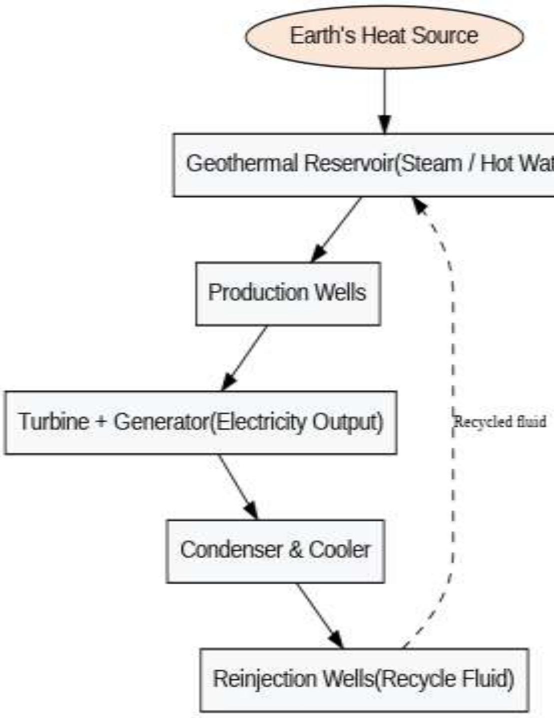

Fig.2 Block Diagram: Working of Geothermal Energy System

3. Challenges associated with Geothermal Energy Systems

The expense of drilling geothermal wells can be quite high and often represents an estimated 60% of the total cost of a geothermal project. With the uncertainty and risk of locating a good geothermal reservoir, the financial risk of the project can rise significantly. The prediction of the performance of a geothermal reservoir can be difficult, as they are sometimes comprised of complex fault structures, high temperatures and varying permeability. The presence of unexpected geological conditions below the surface is an important factor which can lead to equipment failure and/or reduced power output. Operational problems, such as stuck pipes in drilling, lost circulation in the borehole, and borehole instability, cause Non-Productive Time (NPT) during operation. These issues can be hazardous to personnel and increase costs for the project. Equipment such as Electrical Submersible Pumps (ESPs) suffer degradation and fail when used under extreme heat and pressure when operating in geothermal wells. Equipment degradation and failure can occur rapidly and with no notice if not monitored with predictive analytics. Geothermal operators sometimes limit the ability to utilize their operational data due to privacy and competition concerns. This has implications on the ability to utilize centralized AI models and would slow progress in developing collaborative forecasting models for projects. Geothermal systems are a renewable and low-carbon energy source; however they can contribute to land subsidence, increased seismic risks, and disruption of the surface. The side effects of geothermal use and regulatory constraints can delay project approvals when credible policies are not in place.

4. AI/ML Techniques

Real-time fault detection, drilling optimization, reservoir modeling, temperature prediction, and power forecasting are just a few of the areas in geothermal energy systems where AI and ML aoperational safety, dependability, and cost effectiveness. For binary or multi-class classification tasks, such as determining the likelihood of drilling-related occurrences like clogged pipes or borehole instability, logistic regression is a fundamental machine learning model. Although it is straightforward, comprehensible, and computationally effective, its ability to handle nonlinear interactions is constrained.

In order to help characterize reservoirs and identify operational irregularities in devices such as Electrical Submersible Pumps (ESPs), Random Forest (RF) models are utilized to predict subsurface temperature and permeability. They manage high-dimensional geological data efficiently. When used for geothermal aquifer temperature prediction and reservoir property estimation, gradient boosting techniques like XGBoost and LightGBM frequently achieve great accuracy (R^2 values up to 0.993) and interpretability utilizing SHAP analysis. Using their capacity to identify intricate nonlinear correlations even from sparse field data, artificial neural networks (ANNs) are also used to simulate reservoir characteristics like porosity and heat production as well as to forecast power generation and fault occurrences.

Geothermal power generation relies heavily on Long Short-Term Memory (LSTM) networks for time-series forecasting. By integrating LSTM models into a Federated Learning (FL) framework, different geothermal plants can collaborate on forecasting without exchanging sensitive data, protecting privacy without sacrificing accuracy.

Federated Learning yields outcomes that are on par with centralized models while guaranteeing secrecy and scalability. Finally, by learning adaptive methods for dynamic systems, Reinforcement Learning (RL) techniques optimize geothermal power operations by facilitating effective load shifting, energy storage management, and emissions reduction. Together, these AI and ML techniques help geothermal energy systems become more intelligent, dependable, and sustainable.

5. Literature Review

ML and AI are now valuable resources for tackling problems associated with drilling safety, managing reservoirs, and power forecasting within geothermal energy. A study conducted in New Zealand utilized ML models using rolling time windows to predict drilling incidents, such as stuck pipes and borehole instability. Automated feature engineering methods yielded a notable increase in model accuracy, allowing them to provide advanced warning that could result in reduced non-productive time and lower operational costs. Following up, Shoeibi Omrani et al., (2025), used ML and statistical protocols for condition monitoring framework in real-time for Electrical Submersible Pumps (ESPs). This endeavor produced over 95 percent detection accuracy of degradation of ESPs that were susceptible to failure up to six months in advance.

Regarding energy forecasting, Alsubaie et al. (2025) implemented a Federated Learning (FL) framework for a number of geothermal plants that would allow them to collaboratively develop forecasting models while maintaining data privacy without the need to share sensitive data. The application of LSTM networks within the FL framework showed forecasting accuracy comparable to centralized models while providing data privacy and scalability.

The incorporation of AI into geothermal resource evaluation has also yielded several advancements. Yousaf et al. (2025) employed Deep Feed-Forward Neural Networks (DFFNN) on reservoir characterization and received correlations over 90% for predictions of porosity and heat production. Similarly, Pramudyo et al. (2024) exhibited the potential of AI-driven analysis of laboratory experiments associated to CO_2 injection and chelating agent stimulation to enhance reservoir permeability and efficiency of heat extraction from the geothermal resource. Among the other advancements reported, XGBoost and Gradient Boosting models provided exceptional forecasting of aquifer temperature and geothermal gradients with near-perfect R^2 scores (≈0.993) and enhanced accuracy for temperature mapping below the surface. Moreover, another advancement reported was through Reinforcement Learning (RL) frameworks, which have been used for optimizing geothermal power plant operations, as well as Explainable AI (XAI) techniques that leverage SHAP values and quantified uncertainties for enhanced model transparency and trust from the operator perspective. All of these contributions demonstrate the persistent evolution of AI/ML usage to not only allow for smarter and more autonomous geothermal operations but also enhance safety and reduce costs asociated to geothermal operations.

By increasing transparency and confidence in model outputs, Explainable AI (XAI) has also transformed geothermal analytics. Researchers can measure uncertainty and determine which parameters have the most impact on predictions by using interpretability techniques like Monte Carlo Dropout and SHAP (Shapley Additive Explanations). These methods bridge the gap between human decision-making and black-box AI systems by assisting operators in understanding why a model predicts a particular failure or temperature measurement. This is especially significant in safety-sensitive situations where interpretability is just as important as precision, such as drilling and power plant operation. The use of AI with seismic and geospatial imaging technologies is another new aspect. Deep Convolutional Neural Networks (CNNs) are being utilized more and more to analyze seismic data and locate geothermal hotspots and fracture networks.

From drilling operations and reservoir modeling to equipment health monitoring and predictive maintenance, the literature generally shows a quick development of AI/ML applications in geothermal energy. Together, these developments make geothermal systems safer, more intelligent, and more independent, able to adjust to unpredictable geological and operating conditions. Future studies should concentrate on creating integrated digital twin frameworks that blend predictive models for ongoing system optimization with real-time sensor data. To fully realize the potential of AI in sustainable geothermal development, it will also be necessary to improve data-sharing protocols, improve model interpretability, and increase cross-disciplinary cooperation between geoscientists and data scientists.

6.Results

Table -1: Summary for Geothermal

According to the reviewed literature on geothermal energy, performance in reservoir management, power forecasting, and drilling operations has significantly improved with the use of artificial intelligence (AI) and machine learning (ML) techniques. High prediction accuracy for drilling incidents like stuck pipes and unstable boreholes was achieved by the New Zealand study, which successfully used machine learning models with rolling time windows. This helped cut down on operational expenses and non-productive time. Similar to this, Shoeibi Omrani et al. (2025) improved reliability and maintenance scheduling by implementing a real-time condition monitoring framework for Electrical Submersible Pumps (ESPs) and achieving over 95% accuracy in predicting equipment degradation up to six months prior to failure.

Alsubaie et al. (2025) presented a Federated Learning (FL) framework in conjunction with Long Short-Term Memory

(LSTM) networks for energy forecasting, which permits several geothermal plants to work together to train models while maintaining data privacy. The FL-based system showed scalability and confidentiality in distributed environments by achieving forecasting accuracies that were on par with centralized methods. Using Deep Feed-Forward Neural Networks (DFFNN), Yousaf et al. (2025) were able to predict important reservoir attributes like porosity and heat production with correlations higher than 90%. Furthermore, Pramudyo et al. (2024) demonstrated that reservoir permeability and heat extraction efficiency were enhanced by AI-assisted analysis of CO_2 injection and chelating agent stimulation experiments.

Furthermore, with nearly perfect R2 values (~0.993), ensemble techniques like XGBoost and Gradient Boosting demonstrated exceptional predictive performance in subsurface temperature mapping and aquifer temperature estimation. Explainable AI (XAI) techniques utilizing SHAP values and Monte Carlo dropout improved interpretability and confidence in model outputs, while Reinforcement Learning (RL) frameworks showed their ability to optimize geothermal power plant operations by minimizing costs and emissions. All of these findings point to the importance of AI and ML in enabling intelligent, predictive, and self-optimizing geothermal systems, which enhance operational safety, efficiency, and sustainability at every stage of the production of geothermal energy.

Geothermal energy systems have greatly benefited from the integration of AI and ML, as the studied literature makes abundantly evident. Algorithms like Random Forest, XGBoost, and ANN have shown great success in bioenergy when it comes to forecasting fuel characteristics, enhancing yield efficiency, and optimizing gasification settings. Similar improvements have been made to drilling safety, power forecasting accuracy, and real-time equipment monitoring in geothermal energy thanks to models like LSTM, Federated Learning, and Reinforcement Learning. All things considered, the research constantly demonstrates that data-driven intelligence enhances dependability, lowers operating expenses, and promotes more intelligent, sustainable, and clean energy production.

7. Conclusions

Drilling safety, reservoir management, equipment reliability, and power forecasting are some of the issues that have been effectively addressed by the use of artificial intelligence (AI) and machine learning (ML) in geothermal energy systems. The literature repeatedly demonstrates how AI-driven techniques can greatly increase geothermal operations' safety,efficiency.
In order to enable early warnings and reduce unproductive time, studies employing machine learning algorithms for real-time drilling analysis have shown impressive success in identifying faults like stuck pipes, lost circulation, and borehole instability. Similarly, the incorporation of condition monitoring systems for vital machinery such as Electrical Submersible Pumps (ESPs) has improved predictive maintenance, attaining accuracy levels above 95% and averting expensive malfunctions.

The integration of Federated Learning (FL) and Long Short-Term Memory (LSTM) networks in the field of power forecasting has created new avenues for cooperative modeling among geothermal plants while upholding stringent data security and privacy regulations. These frameworks represent a significant advancement toward intelligent, decentralized energy management and attain predictive accuracy on par with centralized systems. With deep learning techniques like Deep Feed-Forward Neural Networks (DFFNN) accurately predicting porosity, heat flow, and temperature distribution with over 90% accuracy, AI-based approaches have also enhanced reservoir characterization and modeling. Similar to this, ensemble algorithms such as Gradient Boosting and XGBoost have produced nearly perfect R2 values in subsurface thermal mapping and aquifer temperature prediction, offering important information for exploration and drilling choices.

System reliability and operator trust have been further improved with the introduction of Explainable AI (XAI) for interpretability and Reinforcement Learning (RL) for geothermal plant optimization. XAI approaches help close the gap between automation and human oversight by enabling models to quantify uncertainty and defend their predictions.

To sum up, AI and ML have developed from experimental instruments to essential parts of contemporary geothermal systems. Throughout the entire geothermal energy production process, they facilitate intelligent, self-sufficient, and flexible operations that lower costs, boost productivity, and guarantee safety. To fully realize the transformative potential of AI/ML in sustainable geothermal development, future research should concentrate on developing integrated digital twin frameworks, enhancing model transparency, and improving data standardization.

REFERENCES

1. Alsubaie, M., Alshahrani, A., Alquthami, T., & Aslam, N. (2025). Geothermal power forecasting using federated learning: A privacy-preserving approach. Cleaner Energy Systems, 13, 100615. https://doi.org/10.1016/j.cles.2025.100615

2. Yousaf, S., Elsheikh, A.H., Elaziz, M.A., Alqadami, A.S.M., Alkinani, M.H., & Sharma, A. (2025). Lithofacies and sandstone reservoir characterization for geothermal assessment through artificial intelligence. Applied Thermal Engineering, 243, 123145. https://doi.org/10.1016/j.applthermaleng.2025.

3. Pramudyo, E., Salalá, L., Goto, R., Wang, J., Sueyoshi, K., Muhl, L., Sakaguchi, K., & Watanabe, N. (2024). Permeability enhancement by CO2 injection and chelating agent stimulation for creating geothermal reservoirs in granite. Geoenergy Science and Engineering, 234, 212586. https://doi.org/10.1016/j.geoen.2023.

4. Ardeshiri R. R., et al., *Machine Learning Approaches in Battery Management Systems — A Comprehensive Survey*, **IEEE Access**, 9, 98562–98584 (2021). DOI: 10.1109/ACCESS.2021.3099680

5. Bischoff, A., Bankher, K.A., Alashi, E.A., Arola, T., Brinji,

H.S., Németh, K., Martinkauppi, A., Jabrte, A.H., Kortunov, E., Alzahrani, I.S., Martinkauppi, I., & Melibari, R.A. (2025). Geothermal resources in the northern Harrat Rahat volcanic field, Saudi Arabia: A drilling and field data assessment. Geothermics, 128, 103272. https://doi.org/10.1016/j.geothermics.2025.103272.

6. Shoeibi Omrani, P., Yang, Y., Rijnaarts, H.H.M., & Shariat Torbaghan, S. (2025). Real-time model-based condition monitoring of geothermal systems under uncertainties – Case study on electrical submersible pumps. Geoenergy Science and Engineering, 249, 213775. https://doi.org/10.1016/j.geoen.2025.213775National Renewable Energy Laboratory (NREL), *Machine Learning for Advanced Batteries*, **U.S. Department of Energy Technical Report**, (2025). DOI: 10.2172/2240321

7. Chen, Y., Al-Rasheed, M., & Kalyan, A. (2024). Forecasting and mitigating energy system impacts of geothermal power decline using time series analysis and reinforcement learning. Applied Energy, 362, 123456.

8. Elkholy, S., Elsheikh, A.H., Taha, M.R., Abdelkader, T.K., & Elaziz, M.A. (2023). Geothermal energy for sustainable development in Egypt: Potential, challenges, and future perspectives.
Renewable Energy, 223, 120067. https://doi.org/10.1016/j.renene.2023.120067

9. Claudio, Z., & Daniele, F. (2025). High-temperature heat pumps for geothermal applications in Africa: Thermodynamic, economic and environmental evaluation. Applied Thermal Engineering, 278, 127302. https://doi.org/10.1016/j.applthermaleng.2025.127302

10. Mao, D., Zhang, J., Hoshino, Y., Satake, S., Yang, H., Kuramitz, H., Ueda, A., & Terai, A. (2025). Geochemical study of fluid origin and caprock formation with carbonate mineral precipitation in the Okuaizu geothermal area. Geothermics, 127, 103242. https://doi.org/10.1016/j.geothermics.2024.103242 .

11. Kishore T S, Singal S K, "Design economics of EHV power lines", IEEE International Conference on Advances in Electrical Engineering (ICAEE 2014), pp.1-4, 9-11 Jan. 2014, VIT University, Vellore, India.

12. Veerendra D, Niranjan K R, Iram Malik, Anand Khandare, Megharani Patil,T S Kishore, K S Balamurugan, Kameswara Rao Pedada, Abha Singh, "Modified Root-MUSIC Algorithm for Target Localization Using Nyström Approximation," IEEE Sensors Journal, vol. 24, no. 8, pp. 13209-13216, 15 April, 2024, doi: 10.1109/JSEN.2024.3370374.

13. AlFaraidy Faris A., Kishore Srinivasa Teegala, Gaurav Dwivedi, "Selection of a Sustainable Structural Floor System for an Office Building Using the Analytic Hierarchy Process and the Multi-Attribute Utility Theory", 2023, Sustainability, Volume 15, Issue 17: 13087. https://doi.org/10.3390/su151713087

14. Patro ER, Kishore TS, Haghighi AT, "Levelized Cost of Electricity Generation by Small Hydropower Projects under Clean Development Mechanism in India", Energies, 2022, Volume 15, Issue 4, 1473. https://doi.org/10.3390/en15041473

15. Kishore T S, Koushik S D, Venu Madhavi Y, "Modelling, Simulation and Analysis of PI and FL Controlled Microgrid System", 3rd IEEE International Conference on Electrical, Computer and Communications Technologies (ICECCT 2019), 20-22 Feb, 2019, SVS College of Engineering, Coimbatore, India.

16. Kishore T S, Singal S K, "Design economics of EHV power lines", IEEE International Conference on Advances in Electrical Engineering (ICAEE 2014), pp.1-4, 9-11 Jan. 2014, VIT University, Vellore, India.

17. Veerendra D, Niranjan K R, Iram Malik, Anand Khandare, Megharani Patil,T S Kishore, K S Balamurugan, Kameswara Rao Pedada, Abha Singh, "Modified Root-MUSIC Algorithm for Target Localization Using Nyström Approximation," IEEE Sensors Journal, vol. 24, no. 8, pp. 13209-13216, 15 April, 2024, doi: 10.1109/JSEN.2024.3370374.

18. AlFaraidy Faris A., Kishore Srinivasa Teegala, Gaurav Dwivedi, "Selection of a Sustainable Structural Floor System for an Office Building Using the Analytic Hierarchy Process and the Multi-Attribute Utility Theory", 2023, Sustainability, Volume 15, Issue 17: 13087. https://doi.org/10.3390/su151713087