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Generative AI: Prospects and Applications in Geothermal Energy

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ABSTRACT

Generative AI, a specialized branch of artificial intelligence, focuses on creating fresh and significant content like text, images, or audio from unstructured data. Its popularity has surged across diverse sectors recently due to its expanding range of applications. Notable examples encompass resilient conversational agents enhancing customer satisfaction in business domains, code synthesis aiding software developers, and the generation of audio and video content for the advertising and entertainment sectors. These fast-improving applications show huge prospects for the application of generative AI in various fields. Hence, this study presents achievable and innovative applications of generative artificial intelligence in the geothermal energy. To showcase the prospects and feasibility of this technology, three case studies were considered in this work, namely; geothermal drilling operation, seismic imaging and interpretation, and well management. By clearly leveraging instances of technology in various fields, the case studies were properly discussed. Consequently, this research seeks to inspire and provide valuable insights into the potential domains where this technology can be applied. With efficient and ethical implementation, it holds the promise of streamlining processes, reducing costs, enhancing safety, and allowing researchers and the industry to capitalize on the value it offers.

1. INTRODUCTION

Humans have been known to possess the ability to innovate and express creativity in various areas examples, artistic designs, creative tasks such as writing poems, creating software, designing fashion, and composing songs. However, the advent of artificial intelligence has rapidly revolutionized this assumption as smart technological systems can generate new content in ways that cannot be distinguished anymore from human craftsmanship (Hartmann et al., 2023). The branch of artificial intelligence responsible for this technological advancement is the generative artificial intelligence or generative AI. Generative AI refers to computational techniques that leverage massive datasets to produce new and meaningful content, including text, images, or audio, in response to user prompts or commands. With great dependence on its varieties of algorithms such as Generative Adversarial Networks (GANs), Variational Autoencoders (VAEs), Autoregressive Models, Transformer-based Models etc. this technology can generate contents cutting across text, audio, and images based on user-prompts (van der Zant et al., 2013). More interestingly, individuals, companies of all sizes and institutions are leveraging on this technology to drive production, reduce operational costs and enhance efficiency. For example, nTop company, leverages generative AI design approach in optimizing their topology designs thereby exploring large design space, perhaps cycling through different materials, manufacturing processes, functional requirements, or even the basic assumptions built into the process by the engineer (nTop, 2024). This can be appreciated in Fig.1 below, as it showcases a structural bracket design alongside raw topology optimization results tailored to different specifications.

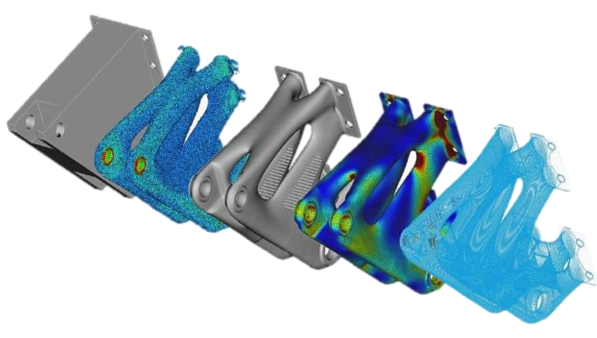

Figure 1: A structural bracket design and new generated raw topology optimization results (modified from (nTop, 2024))

Hence, owing to the multifaceted nature and inherent advantages of this technological domain, its potential applicability in the field of geothermal energy is evident. As such, this study endeavors to explore the prospects and feasibility of integrating this technology by conducting a comprehensive analysis of three distinct case studies: geothermal drilling operations, seismic imaging and interpretation, and well management.

2. WORKFLOW OF A GENERATIVE AI SOLUTION

This section delineates the systematic steps and methodologies commonly employed in constructing a generative AI solution. Although specific approaches may vary, a typical generative AI solution is illustrated in Figure 2, which encompasses a series of stages, beginning with problem scoping and extending to deployment and post-deployment activities.

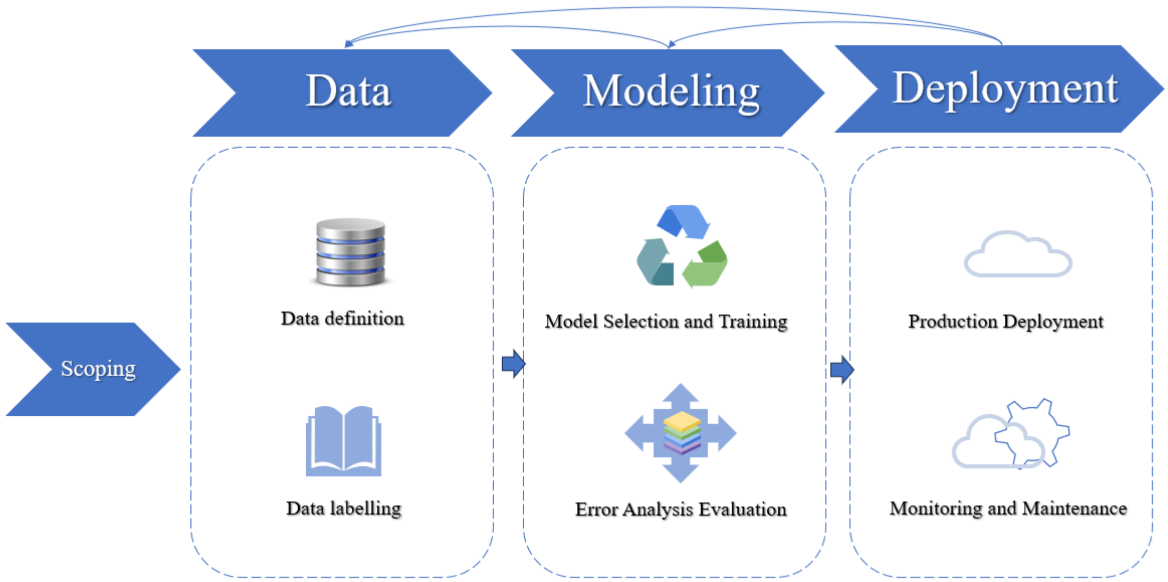

Figure 2: Typical Generative AI Solution Workflow

2.1 Project Scoping

In the project scoping stage of developing a Generative AI solution, it's essential to define the project's objectives, scope, stakeholders, data requirements, technology stack, evaluation metrics, timeline and resources, as well as risks and mitigation strategies. This involves clearly articulating the purpose of the solution, specifying the types of inputs and outputs, identifying all involved stakeholders, determining the necessary data sources and any privacy considerations, selecting appropriate technologies for development and deployment, establishing criteria for evaluating performance, outlining a timeline with milestones, allocating resources effectively, and identifying potential risks along with strategies to address them (Gozalo-Brizuela & Garrido-Merchán, 2023; Weisz et al., 2023). By thoroughly addressing these aspects, the project can proceed with a clear understanding of its goals, constraints, and the steps needed for successful implementation of the Generative AI solution.

2.2 Data Acquisition

In this stage, two crucial sub-stages are data definition and data labeling. Firstly, in data definition, it's imperative to precisely outline the characteristics, formats, and sources of the data required for training the generative AI model. This involves identifying relevant datasets that align with the project objectives and scope, understanding the structure and quality of the data, and ensuring its compatibility with the chosen technology stack and modeling approach. Additionally, data definition includes establishing procedures for data collection, preprocessing, and storage to maintain consistency and accessibility throughout the project lifecycle. Secondly, in data labeling, the focus shifts to annotating the dataset with appropriate labels or tags that provide context and meaning to the data samples. This process often involves human annotators who assign labels based on predefined criteria or guidelines, ensuring that the data is structured and labeled accurately to facilitate supervised learning or other training paradigms (Desmond et al., 2021). Data labeling is critical for training the generative AI model effectively, enabling it to learn patterns and generate meaningful outputs based on the labeled examples. Both data definition and data labeling stages are foundational in ensuring the quality, relevance, and usability of the dataset for training the Generative AI solution, ultimately contributing to the success of the project.

2.3 Modeling

Two key sub-stages are must be captured in the modeling stage, namely; Model Selection and Training, as well as Error Analysis Evaluation. Firstly, in Model Selection and Training, the idea is to choose the appropriate architecture, algorithms, and hyperparameters for the Generative AI model based on the defined objectives, data characteristics, and available resources. This involves experimenting with various model architectures and configurations, fine-tuning parameters, and training the model using the labeled dataset acquired in earlier stages. The focus is on optimizing model performance, generalization, and computational efficiency to achieve the desired outcomes effectively (Morande, 2023). Secondly, in Error Analysis Evaluation, the emphasis shifts to assessing the model's performance, identifying potential sources of errors or biases, and refining the model based on feedback and insights gained from the evaluation process. This involves analyzing metrics such as accuracy, precision, recall, and F1-score, as well as conducting qualitative assessments to understand the model's behavior and limitations. Error analysis also entails exploring techniques for mitigating errors, improving model robustness, and enhancing overall performance to meet the project objectives and stakeholder requirements (J. Huang et al., 2022). By iteratively refining the model through Model Selection and Training and conducting rigorous Error Analysis Evaluation, the Generative AI solution can evolve and adapt to produce high-quality outputs that effectively address the targeted problem or task.

2.4 Deployment

In the Deployment stage of a Generative AI solution, the process consists of two critical sub-stages: Production deployment and Maintenance and Monitoring. Firstly, Production deployment involves transitioning the trained model from the development environment to a production environment where it can be used to generate outputs in real-world scenarios. This entails configuring the necessary infrastructure, integrating the model with existing systems or applications, and ensuring scalability, reliability, and security of the deployed solution. Additionally, thorough testing and validation procedures are conducted to verify the functionality and performance of the deployed model under various conditions. Secondly, Maintenance and Monitoring focus on ongoing management and optimization of the deployed Generative AI solution. This involves monitoring model performance, identifying and addressing potential issues or drifts in data distribution, updating the model to incorporate new data or adapt to changing requirements, and implementing measures to ensure continuous availability and efficiency of the solution (Zhai et al., 2022). Furthermore, proactive maintenance and monitoring practices help in detecting anomalies, improving model accuracy, and enhancing user experience over time, thereby maximizing the value and impact of the Generative AI solution in practical applications.

3. APPLICATION OF GENERATIVE AI - CASE STUDIES

3.1 *Case Study One: Optimized Geothermal Drilling Operation*

Geothermal reservoirs pose unique challenges, including high temperatures and unstable, hard rock formations, which can degrade drilling fluid rheology and cause downhole tool failures (Purba et al., 2022). Drill bits operating in such conditions face significant hurdles: reduced rock breaking efficiency and shortened service life due to extreme temperatures up to 288°C. To endure thermal degradation and maintain wear and impact resistance, drill bits require ultra-hard, thermally stable materials. Continuous cooling by drilling fluid systems is crucial to prevent overheating, with drill bits sometimes needing retrieval to cooler intervals during circulation pauses. Overcoming these challenges necessitates innovative engineering solutions to enhance temperature and wear resistance, ensuring optimal p erformance in demanding geothermal environments (Weili & Kai, 2017). Hence, generative AI can be integrated in the design of drill bits which can meet up with these requirements as can be described in Figure 3.

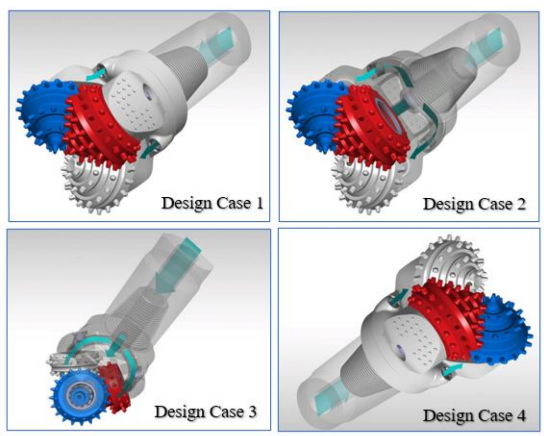

Figure 3: Generative AI Design for a Tricone drill bit (Modified from (Adobe, 2023))

3.2 *Case Study Two: Geothermal Seismic Imaging and Interpretation*

Seismic imaging and interpretation play a pivotal role in geothermal prospecting by providing valuable insights into the subsurface structure and identifying potential reservoirs for geothermal energy extraction. In geothermal exploration, seismic techniques enable geoscientists to image and characterize subsurface fracture/fault zones, which serve as conduits for hydrothermal fluid flow. By accurately delineating these fracture networks, seismic data help in identifying favorable zones for geothermal reservoirs and optimizing well placement within these structures (Y. Huang et al., 2021; Louie et al., 2011). However, seismic imaging and interpretation in geothermal exploration face challenges from complex geological structures, including numerous faults and noisy surface seismic data with strong ground-roll noise. Additionally, the presence of fracture zones and anisotropic properties in geological formations further complicates accurate subsurface imaging, hence, the need for noise suppression and proper consideration of anisotropic effects to enhance resolution and interpretation capabilities. Generative AI algorithms, when trained with well-labeled data, excel in distinguishing noise from relevant features within seismic images. By leveraging this capability, they can generate refined seismic images that preserve essential geological information while eliminating noise and emphasizing critical areas of interest. This facilitates geoscientists in exploring diverse subsurface models and gaining deeper insights into geological complexities, thereby enhancing the effectiveness of exploration strategies in geothermal prospecting. A pictorial description can be seen in Figure 4.

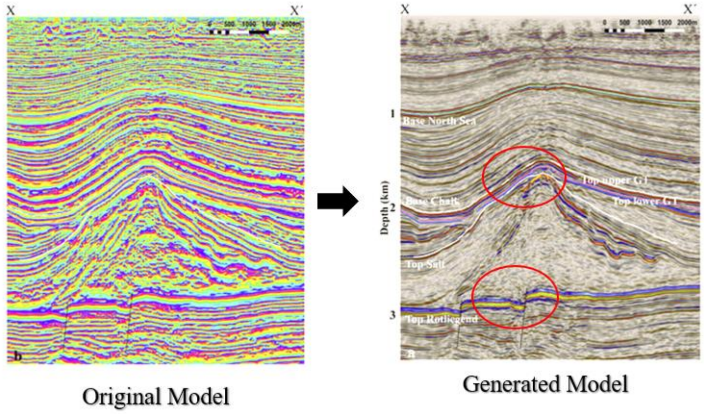

Figure 4: Generated Seismic from the original model (modified from (Daniilidis & Herber, 2017))

3.3 *Case Study Three: Geothermal Well Management*

Generative AI solutions can revolutionize geothermal well management in two critical ways. Firstly, by monitoring well and behavior, Generative AI algorithms can continuously analyze data streams from geothermal wells, detecting anomalies, predicting potential failures, and optimizing operational parameters in real-time. These algorithms can identify patterns in temperature, pressure, and flow rates, alerting operators to potential issues before they escalate, thus ensuring proactive maintenance and minimizing downtime (Tut Haklıdır, 2020). Secondly, Generative AI can suggest areas of improvement by leveraging historical data to simulate various scenarios and predict the effects of different operational adjustments. By generating virtual models of geothermal reservoirs and well systems, AI can recommend optimized drilling strategies, reservoir management techniques, and injection practices to enhance efficiency, increase energy extraction, and mitigate risks. Moreover, Generative AI can explore unconventional approaches, such as utilizing machine learning-generated seismic imaging for enhanced reservoir characterization, leading to more precise drilling and resource utilization (Allahvirdizadeh, 2020). Ultimately, these innovative applications of Generative AI can drive cost savings, maximize energy production, and foster sustainable geothermal energy development.

4. CONCLUSION

Generative artificial intelligence (AI) presents a transformative opportunity in the field of geothermal energy, offering innovative solutions to overcome challenges and optimize operations across various domains. Through the exploration of three distinct case studies encompassing geothermal drilling operations, seismic imaging and interpretation, and field management, this research underscores the vast potential of integrating generative AI technologies. In geothermal drilling operations, where extreme temperatures and challenging rock formations pose formidable obstacles, generative AI facilitates the design of drill bits with enhanced temperature resistance and wear durability. This enables improved drilling efficiency and prolonged tool longevity, crucial for successful geothermal exploration and production. Seismic imaging and interpretation, vital components of geothermal prospecting, benefit significantly from generative AI algorithms capable of distinguishing relevant geological features from noise in seismic data. By generating refined images and facilitating accurate subsurface characterization, generative AI enhances the identification and optimization of geothermal reservoirs. Furthermore, in geothermal well management, generative AI enables real-time monitoring of well behavior, anomaly detection, and predictive maintenance, leading to increased operational efficiency and reduced downtime. Additionally, AI-driven simulations and optimization strategies empower operators to make informed decisions, optimize resource utilization, and mitigate risks, thereby fostering sustainable geothermal energy development

5. RECOMMENDATION

To capitalize on the potential of generative AI in the geothermal energy sector, it is recommended that:

- Continued research and development efforts should focus on refining generative AI algorithms tailored specifically to the unique challenges and requirements of geothermal exploration and production. Collaboration between AI specialists, geoscientists, and engineers can drive innovation and yield more effective solutions.
- Access to high-quality, well-labeled data sets is paramount for training generative AI models effectively. Efforts should be made to collect comprehensive data sets encompassing diverse geological formations and operational scenarios to improve model accuracy and robustness.
- As with any emerging technology, ethical and regulatory frameworks must be established to govern the ethical use and deployment of generative AI in the geothermal energy industry. Transparency, accountability, and responsible AI practices should be prioritized to ensure trust and mitigate potential risks.
- Industry stakeholders, including geothermal energy companies, government agencies, and research institutions, should actively explore opportunities for integrating generative AI technologies into existing workflows and operational processes. Pilot projects and collaborative initiatives can help demonstrate the tangible benefits and feasibility of AI-driven solutions.

By embracing generative AI and leveraging its capabilities to address key challenges and optimize operations, the geothermal energy sector stands to benefit from enhanced efficiency, reduced costs, and sustainable resource development in the pursuit of a cleaner and more renewable energy future

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