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Exploring the Synergy: Leveraging Oil and Gas Drilling Solutions for Enhanced Geothermal Drilling

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ABSTRACT

Geothermal energy has immense potential as a green, sustainable, and weather-independent source of power, offering a pathway to reduce greenhouse gas emissions and mitigate climate change. While the geothermal resource is abundant in its potential, its successful extraction comes with substantial challenges, with drilling operations, specifically, emerging as a critical bottleneck. This paper delves into the promising synergy between the oil and gas drilling industry and geothermal drilling, aiming to enhance the efficiency and viability of geothermal energy extraction.

The paper begins by elaborating on the fundamental differences between oil and gas drilling and geothermal drilling processes, highlighting the unique challenges geothermal well construction faces, and summarizing existing knowledge gaps. It then reviews recent advancements in drilling technologies within the oil and gas sector, emphasizing innovations such as advanced modeling, digital twins, and AI/ML applications, which have the potential to be adapted for geothermal applications. The solutions are illustrated for various phases of drilling, from planning, real-time execution, replay, and training. Furthermore, two case studies related to geothermal drilling challenges are presented, i.e., identification and prevention of loss circulation and improvement of drilling efficiency within safeguards.

In summary, this paper explores the emerging collaborative initiatives and partnerships to facilitate knowledge transfer and promote cross-industry innovation between geothermal and oil and gas industries. It underscores the immense potential of leveraging oil and gas drilling solutions to enhance geothermal drilling performance and reduce costs, ultimately fostering the growth of geothermal energy as a reliable and sustainable power source. By embracing this synergy, we can pave the way for accelerated geothermal energy development, contributing significantly to the global transition to cleaner and more sustainable energy systems.

1. INTRODUCTION

The role of energy companies as drivers of R&I to accomplish the transition from fossil fuels' dependency to the predominance of clean and renewable energy sources is of key relevance in the global efforts to mitigate climate change. In terms of the technologies that have aided in the continuous optimization of the drilling process for O&G (oil and gas) with the use of AI, ML and predictive analytical technologies, this paper approaches the current challenges and knowledge gaps of drilling for geothermal energy as an opportunity to bring together our expertise to contribute to the energy transition at the global and our company level. The synergy between geothermal and hydrocarbon energy production is not new, for many decades the technical expertise from O&G has been transferred and adapted to support geothermal drilling and its completion methods, due to the similarities that both energy resources present when it comes to resource location, matter constitution, and the ways to reach and exploit them.

Unlike fossil fuels, geothermal energy is a heat-based natural resource that is continually generated within the earth´s crust, and it can be classified as a renewable source of energy with the right practices and techniques. In addition to having several other environmental benefits such as extremely low carbon emissions from its productive processes. Geothermal energy resources have been classified into distinct categories according to "geologic settings, intrinsic properties, and viability for commercial utilization" (Williams, Reed, et al, 2011). For this paper's purpose, we focus our analysis on the resources suitable for electricity generation -medium to high-temperature reservoirs- that exist at a technically viable drilling reach. Furthermore, our study covers current hydrothermal resources, but highlights the great potential of hot rock resources, also known as Enhanced Geothermal Systems (EGS) to make geothermal energy widely available on a global scale.

As opposed to hydrothermal resources in which it is possible to extract heat in the form of water and steam, EGS refers to artificially made systems that extract the heat stored in either completely dry, to relatively dry and low-permeability rock "by pumping a transfer medium, typically water, down a borehole into the hot fractured rock and then pumping the heated fluid up another borehole to a power plant, from where it is pumped back down (recirculated) to repeat the cycle" (IEA, 2011). According to the International Energy Agency (IEA) and the renewables platform REN 21, one of the biggest challenges for the expansion and growth of geothermal energy is its high overall project costs (IEA, 2011 and REN 21, 2022). Therefore, the existing installed power capacity and market for geothermal energy is concentrated in the countries where hydrothermal resources are not only abundant, but more easily accessible; USA, Indonesia, Philippines, Turkey, New Zealand, Mexico, Kenya, Italy, Iceland, Japan, Chile and Costa Rica (REN 21, 2022).

Because of its independence from seasonal factors, geothermal energy is one of the most efficient baseload power sources that can operate continuously to meet the minimum level of power demand 24/7. Given this proven ability to provide constant energy, its widespread production has been limited by various factors such as lack of access to thermal supplies, high capital cost, and operating risk during geothermal well drilling.

Currently, geothermal corresponds to around 1% of the global energy mix (Standford Energy, 2023). In 2021 electricity generation totalled an estimated 99 TWh (REN 21, 2022). To put this into perspective, total electricity consumption in Denmark, Ireland and Island reached 90 TWh that same year (EIA, 2023). Despite the relatively small contribution of this energy source compared to other renewable sources, its global demand has been increasing at a rate of 29% since 2016 (Standford Energy, 2023), and according to IEAs predictions; "by 2050 geothermal electricity generation could reach 1,400 TWh per year, around 3,5% of global electricity production, avoiding almost 800 *Mt of CO2 emissions per year (IEA, 2011)." IEA also sustains in their analysis that: "By 2050, more than half of the projected increase comes from exploitation of ubiquitously available hot rock resources, mainly via enhanced geothermal systems (EGS)" (IEA, 2011).

Aghahosseini and Breyer's s study from 2020 analyzed and visualized the energy potential of EGS across the world (see Figure 1). In their visualization, it is possible to observe a meaningful global expansion of geothermal resources compared to current hydrothermal resources. The study also elaborates on the global energy potential of EGS by 2050 using different parameters; their results showed that EGS alone can contribute from up to 200 TWe to as little as 256 GWe when applying sustainability constraints, especially when it comes to water stress and how fast heat can regenerate within the EGS reservoirs (Aghahosseini and Breyer, 2020).

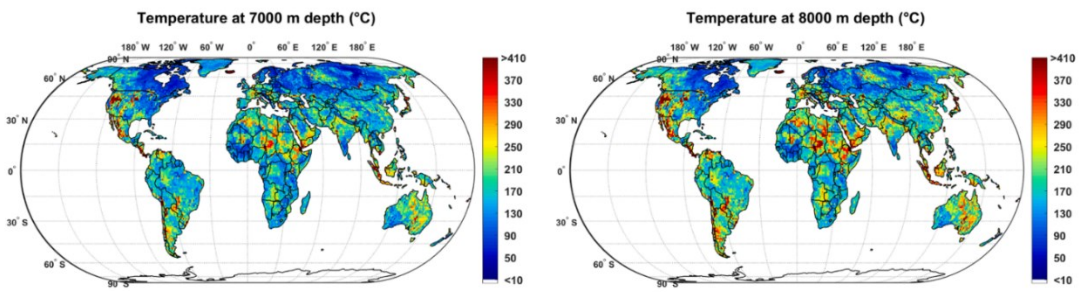

Figure 1: Visualization of ESG resources by depth and temperature (Aghahosseini and Breyer, 2020)

However, the geothermal market is developing at an unprecedented scale due to the global commitments made to increase the share of renewable and clean energies. Technological advancements that make both conventional hydrothermal and EGS systems more economically and sustainably viable are also predicted to happen by 2030 and onwards (IEA, 2011 and REN 21, 2022). From our part, we wish to build the foundations to accomplish our goal of developing a software solution, through making synergy from our background within O&G, to accelerate the development and growth of geothermal energy by understanding its current drilling challenges, so we can strategically address and overcome them, thereby enhancing the efficiency of geothermal operations. This will in turn optimize processes, reduce costs, and boost its competitiveness in the renewables market, ultimately contributing to the energy transition.

2. CHALLENGES IN GEOTHERMAL DRILLING

Geothermal drilling is a critical process in unlocking Earth's thermal energy, with complex challenges requiring advanced engineering solutions. This overview zooms into the nuanced complexities of geothermal drilling, spotlighting the critical challenges that must be addressed to enhance the efficiency and viability of sustainable geothermal energy extraction, elaborating on four key challenges selected and combined from the broader spectrum of issues in geothermal drilling. Table 1 below outlines ten common issues in geothermal drilling, derived from studies spanning from 2000 to recent years. It provides insights into recurring challenges, offering valuable information for current and future exploration and drilling practices.

2.1 Drilling Fluids/ Tool Limitations due to Temperature and Pressure

Common challenges associated with high-temperature geothermal fluids include the corrosive nature of the fluids and issue of precipitation, often referred to as 'scaling'. The presence of hydrogen sulphide (H2S) poses a requirement to use heavier drill pipes and drillstring, as lighter grades are susceptible to sulphide stress cracking. One expert has compared the challenging conditions of geothermal drilling to those of 20,000-foot oil and gas wells, highlighting that certain geothermal environments can be even more extreme. Geothermal environments characterized by high temperatures and the abrasiveness of drilling with air or aerated systems frequently result in significant wear and tear. This wear and tear affect almost all components in geothermal drilling operation, including pump components, shaker screens, drill pipes, which then require costly tungsten hardbands, and drill collars. "The cost of expendables on geothermal wells is four times that of an oil and gas well," said one expert. The same expert estimated that drill collar and drill pipe life in geothermal wells is a fifth of oil and gas wells. The heat limitation of directional drilling tools is a major challenge. Geothermal exploration and development clearly could benefit from horizontal drilling to better intersect non-vertical fractures but high-temperature electronics and MWD systems will be required. (Denninger, et al., 2015)

No	Subsurface hazard	Explanation	Petroleum well (likelihood)	Geothermal well (likelihood)	References
1	Loss circulation	The phenomenon where large amount of drilling fluids flow into the formation under the effect of pressure difference	2	4	(Guan, Chen, & Liao, 2021)
2	Swelling clay	Clay swelling occurs when the clay is exposed to aqueous solutions having a brine concentration below the critical salt concentration. Clay swelling can cause reduction of hole diameter, resulting in stuck drill pipe or failure in running the casing.	2	4	(Khilar & Fogler, 1983; Finger & Blankenship, 2010)
3	Acidic environment	An immediate area or enclosure with pH below 7.0 can precipitate premature cement degradation or corrosion to equipment.	1	3	(Corrosionpedia, 2018)
4	Paleosol	Paleosol is ancient soil that formed in the past landscapes. Flood debris, landslides, volcanic ash, and lava have buried most paleosol in the sedimentary record. Paleosol in some cases contain a large proportion of smectite clay. Smectite is inert, but when disturbed by drilling especially with freshwater, it will become physically unstable.	2	2	(Gunderson et al., 2000; Retallack, 2014)
5	Steam cap	A vapor-dominated zone overlying a liquid-dominated zone. The steam cap presents hazardous high temperatures if not anticipated by early detection.	1	2	(Grant & Bixley, 2011)
6	Unstable formation	Sediment that is loosely arranged or unstratified (not in layers) or where particles are not cemented together (soft rock) and unstable rock layers formed by hydrothermal alteration are prone to sloughing. Sloughing can create significant washout which complicate drilling and cementing.	3	4	(OWP, 2019; Meller & Kohl, 2014)
7	Gas trap	Natural gas accumulation at abnormal pressure which exists in shallow burial depth under the seabed and does not have the value for industrial exploitation. Trapped gas is often flammable.	4	2	(Ren, Liu, Huang, & Zhang, 2019)
8	Abrasive formation	The cuttings from the rock formation, produced by the action of a drill bit, are hard, sharp-cornered, angular grains, which grind away or abrade the metal on bits and drill-stem equipment at rapid rates. The abrasiveness of formation is usually measured by quartz content. Higher quartz content represents higher abrasion risk.	2	4	(Mindat, 2021; Wheeler, 2018)
9	H_2S	Hydrogen sulfide is colorless, flammable, and extremely hazardous gas, found in both petroleum and geothermal wells. In a petroleum reservoir, H_2S is formed as a natural by-product of organic material decomposition while it is sometimes found in gas zones above a geothermal reservoir. This gas can cause corrosion and safety risks.	3	4	(OSHA, 2005; Finger & Blankenship, 2010)
10	High temperatures	High temperatures can alter drilling fluid properties and its additives.	1	4	(Finger & Blankenship, 2010)
1: less likely, 5: most likely					

Figure 2: 10 common issues in geothermal drilling gathered from studies from 2000 to recent years. (Purba, D. et. al, 2022).

2.2 Loss Circulation

An optimal geothermal production site typically features highly fractured formations, which usually comes with high possibility of lost circulation. Effectively addressing this issue requires proactive anticipation and preparation, involving the careful formulation of drilling mud with suitable properties and sufficient volume preparation. Despite proactive measures, unforeseen changes in the formation can lead to more significant losses during drilling, needing to incorporate specific lost circulation materials in response to unexpected challenges. Failing to address the loss promptly can result in the creation of larger and longer fractures. Notably, the pressure required to propagate a fracture is usually lower than initiation. It is crucial to recognize that both original and induced porosities contribute to the occurrence of losses. In geothermal wells, cooling of the well during drilling. Complete loss of drilling fluid, exceeding 16 m^3/hr, can occur due to various factors such as inadequate filter cake formation and high-pressure disparities. While total losses in geothermal wells indicate positive production potential, they pose drilling complications. Consequences include increased non-productive time, insufficient well hydrostatic pressure, mud and material loss, expensive drilling methods, well instability, and poor cuttings information.

2.3 Stuck Pipe – Differential Sticking

Since geothermal drilling targets lost circulation zones at reservoir depth, the chance of getting stuck pipe events becomes higher. Numerous publications underscore that events leading to stuck pipe have emerged as a major contributor to non-productive time (NPT) and associated costs in geothermal drilling projects. Lost circulation causes a decline in wellbore hydrostatic pressure, with the differential pressure—defined as the gap between wellbore hydrostatic and formation pressure—the primary driver for differential sticking. Substantial differential pressure forces the drill string, be it drill pipe or drill collars, against the wellbore wall due to the ensuing pressure gradient, as explained by Makuk (2013). Given the significant impact of these dynamics on operational efficiency, especially in the context of stuck pipe scenarios, careful management of differential pressure is thus essential in mitigating the risks associated with stuck pipe during geothermal drilling.

2.4 Enhancing Drilling Efficiency

The process of drilling geothermal wells can be both costly and timely, highlighting the significance of optimizing and closely monitoring the drilling procedures to improve well performance and profitability. Drilling optimization includes the utilization and incorporation of advanced software and modelling techniques throughout well construction process; from planning and detailed design to execution of drilling by defining the well's path, casing, and drilling parameters. It also involves simulating and assessing various scenarios and potential risks, coupled by the deployment of sensors and instruments to gather and analyze real-time data pertaining to drilling conditions, including factors such as temperature, pressure, depth, rate of penetration, torque, and vibration. The integration of drilling optimization and monitoring serves to enhance drilling precision, safety, dependability, and efficiency while facilitating the prompt identification and resolution of any challenges or deviations that may arise.

In analyzing the operational time versus depth, Denninger et al. (2015), highlighted the differences in depth versus days between the best geothermal well compared to the best oil well. In order to close the gap, rate of penetration (ROP), bit life, and mud losses are important factors to consider. In this case, drilling dynamics and proper roadmap drilling parameters could enhance the ROP, directing more energy towards rock destruction rather than having this energy dissipated in the form of undesired vibrations and high torque.

3. KNOWLEDGEG GAPS PRESENT WITHIN ABNORMAL DRILLING REALM

The exploration and development of geothermal energy resources play a critical role in the global demand for sustainable and clean energy alternatives. It is inevitable that there are challenges and knowledge gaps distinguishing geothermal drilling from conventional oil and gas drilling. This section will outline and elaborate the current knowledge gaps existing between geothermal and oil and gas drilling, outlining known gaps from aspects of geological, technical, technology and digitalization, with a specific focus on the challenges and opportunities presented by the integration of digitalization into these drilling practices.

- Reservoir Characterization: Understanding and characterizing geothermal reservoirs present unique challenges compared to oil and gas reservoirs. Geothermal reservoirs involve complex geological formations with different heat transfer mechanisms, making accurate reservoir characterization and modelling crucial but remain challenging.
- Drilling Fluids and Mud Chemistry: The development of drilling fluids customized for geothermal conditions and needs, considering the specific geochemistry of the formations, remains ongoing research. Unlike oil and gas drilling, where standard mud formulations are well-established, geothermal drilling requires fluids that can withstand high temperatures and corrosive conditions, while remain handleable during scenarios like loss circulation.
- Digital Twin Technology for Geothermal Wells: Digital twin technology, extensively utilized in oil and gas, is an area where geothermal drilling can benefit. Developing accurate digital representations of geothermal wells can enhance monitoring, operational, and optimization efforts, further optimizing drilling performance and reducing downtime, hence reducing costs.
- Machine Learning and Predictive Analytics: The oil and gas industry has made significant advances in utilizing machine learning and predictive analytics for reservoir management, drilling optimization and power plant management. Applying these technologies to geothermal reservoirs can enhance forecasting accuracy, optimize drilling parameters, and improve overall project performance.
- Advanced Drilling Technologies: Geothermal drilling often faces challenges in high-temperature environments, requiring specialized drilling technologies. Adapting and developing advanced drilling technologies, such as high-temperature drill bits and sensors, is essential to improve drilling efficiency and reduce costs.
- Knowledge Management Systems: These systems facilitate knowledge transfer and lessons learned from previous drilling operations, helping teams make informed decisions and avoid repeating mistakes.

The integration of advanced technologies in geothermal well construction presents a wide range of benefits. Real-time data analysis and optimization will enhance efficiency, facilitating faster drilling and reducing downtime. The early detection of issues would prevent accidents and mitigate risks. More importantly, the efficient drilling, decreased downtime, and improved planning translate into substantial cost savings. Knowledge management systems play a crucial role in sharing and replicating best practices and lessons learned across diverse teams and projects, fostering knowledge sharing and best practices. The integration of digital twin technology and advanced planning software holds the potential to optimize well designs. Additionally, these technologies offer the opportunity to minimize environmental impacts and reduce the overall footprint of geothermal facilities through optimized drilling practices. In short, the application of these technologies has the capacity to make drilling more efficient, safer, and cost-effective while fully capitalizing on the vast potential of geothermal resources.

4. STATE-OF-THE-ART DRILLING SOLUTIONS

In the forefront of advanced drilling solutions, technologies such as drilling with digital twins, thermal dynamic modelling, and AI solutions are revolutionizing well construction. Digital twins create virtual representations of the physical drilling environment, enhancing real-time monitoring, optimization, and training. Thermal dynamic modelling integrates a comprehensive wellbore model that dynamically solves conservation equations, considering factors like dynamic mass transport and temperature effects. AI solutions from eDrilling include an integrated drilling simulator, data quality module, real-time supervision, diagnosis methodology, advisory technology, and 3D visualization, enhancing real-time drilling analysis. The implementation of these advanced solutions promises to elevate and modernize decision-making, minimize non-productive time, and optimize drilling operations for better efficiency and safety throughout the well construction process.

4.1 Drilling with Digital Twins

Drilling with digital twins leverages advanced technology and software tools to optimize drilling operations. Introduced by Dr. Michael Grieves, the digital twin concept involves creating a virtual representation of physical assets, widely adopted in various industries, including oil and gas, for performance optimization and operational cost reduction. In the oil and gas sector, a digital twin can represent assets from individual equipment to entire oilfields, serving purposes such as improving efficiency in commissioning, operating, planning, and designing assets. This approach enhances performance through data-driven operations, minimizing the need for equipment services and upgrades, thus improving reliability (Endress A., 2017; Grieves M., 2006; Grieves M., 2016; eDrilling AS, 2010).

Within drilling operations, a digital twin is a sophisticated virtual well based on all the defining features of the well, and when we coupled that with complex hydraulic and mechanical models, real-time 3D visualization. This integration provides a comprehensive and real-time overview, offering a clear comparison between what is going on and what is supposed to be going on—all on a single screen. These drilling models can be applied throughout the drilling lifecycle, encompassing planning, real-time monitoring, optimization, post-analysis, and even crew training. The system generates diagnostic messages during operations to alert the crew to deteriorating drilling conditions, enabling timely actions and informed decisions. The use of digital twins in drilling can lead to cost savings, enhanced safety, increased efficiency, reduced non-productive time, and avoidance of unplanned maintenance (Mayani et al., 2019; Mayani et al., 2018).

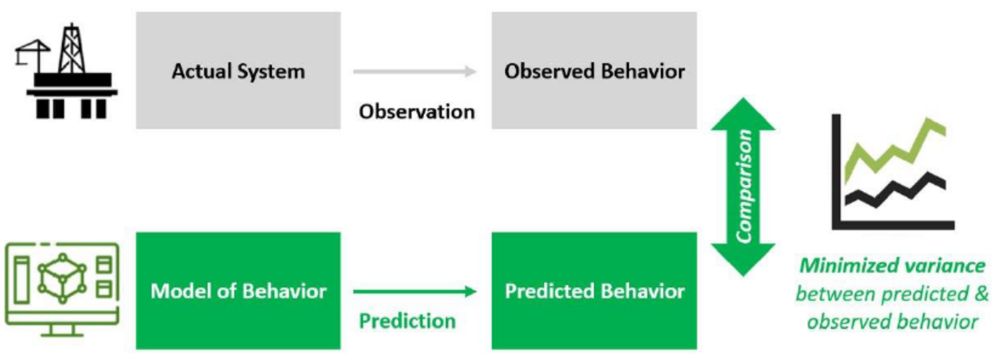

Figure 3: Discrepancy between observed and modelled parameters trigger automated diagnostics.

A digital twin of a well brings opportunities for operational optimization and improved performance, representing dynamic software models mirroring various assets, systems, and processes. Sensors collect data, making it accessible across organizational departments. The digital drilling twin allows forecasting, parameter adjustments and simulations for optimizing drilling efficiency without disrupting ongoing well operations. It facilitates quicker and more informed decision-making by predicting and preventing non-productive time while enhancing drilling operations. Implementing digital twins in drilling is a modern, cost-effective approach for planning, monitoring, and operating well construction compared to traditional methods. It involves advanced downhole data utilization and sophisticated modelling based on thermo-hydraulic and mechanical models throughout the well construction lifecycle, providing benefits such as early anomaly detection, preventive diagnostic messages, reduced non-productive time, and improved safety.

In summary, drilling with digital twins is an innovative approach that leverages advanced modelling, real-time data integration, and visualization to optimize drilling operations, enhance efficiency, and improve safety in the oil and gas industry.

4.2 Thermal Dynamic Modelling/ Thermohydraulic Wellbore Model

The core model discussed here is an integrated thermohydraulic wellbore model designed to solve the mass, momentum, and energy conservation equations within the drilling system (Petersen et al., 2008). This comprehensive model consists of two main components: a 1D flow model and a 2D thermal model. It has found applications in various contexts, as referenced in the literature (Barr Aas et al., 2016; Blikra et al., 2014, and related works).

One of the key features of this model is its incorporation of dynamic mass transport in hydraulic calculations. This implies that changes in boundary conditions and temperature profiles are not instantaneously reflected; rather, they propagate gradually through the system. The density of the fluids involved (drilling mud, spacer, pill, cement, etc.) is influenced by pressure and temperature, and if available, laboratory measurements can inform these calculations. Rheological properties and density, both pressure and temperature-dependent, are central to the model. Real-time data collected from the well are incorporated into the calculations. These data are then interpolated along the flow path to determine pressure and temperature profiles over time and position.

Frictional pressure loss is assessed by fitting rheological data to a three-parameter model. Established methods for handling laminar, transitional, and turbulent flows are applied, considering factors such as rotation and cuttings load and transport in the annulus. The model accommodates multiple fluids and multiphase flows, including the influx and transport of gases and other hydrocarbons within the well, as well as phase transitions within the complex mixture of oil-based mud and influx.

The temperature model considers the geological structure of the well and the properties of concentric layers, including casing/liner layers with cement and other materials. It also factors in fluid properties, thermophysical characteristics, and operational parameters, such as rotation. The dynamic temperature model (2D) is seamlessly integrated with the dynamic mass transport model (1D), with inputs including formation temperature gradients and mud temperature.

Dynamic modelling offers multiple advantages in optimizing the drilling process:

- Interpretation and Training: It enables the simulation of fingerprinting and flowback effects, aiding in the interpretation of conditions, including distinguishing between influx and no influx.
- Surge and Swab Effects: The model allows for the simulation of dynamic surge and swab effects during pipe and completion running, supporting the development of safe procedures for tripping and connections.
- Dynamic Kick Development: It addresses dynamic kick development, considering factors such as dissolution in oil-based mud, providing a realistic alternative to static models for assessing gas effects in wells and risers.
- Pressure Losses: The model simulates pressure losses in choke and kill lines, facilitating training for well control procedures.
- Temperature Effects: Dynamic modeling encompasses the simulation of temperature changes on mud properties and cuttings transport, enabling assessments of low mud temperatures at the mudline and optimizing cuttings transport in cold risers.
- High Temperature Electronics: Most of the downhole sensing and ranging tools are limited to 175 C, but to access deep and hot formations, extended exposure to + 200 C formation is needed. The development of cooling methodologies using drilling fluids, active cooling, insulation and isolation, new materials and fabrication technologies can enable closed loop system in hot and dry formation.
- High Temperature Elastomers: present day mud motor and RSS tools are unable to withstand temperatures up to 165°C but must be adapted to higher temperatures. Metal to metal mud motors have been prototyped and tested, high temperature composite materials. This will enable directional drilling in got formations.
- Drilling Rate in Igneous Rock: igneous and metamorphic rocks are significantly stronger than sedimentary rocks. Current drilling speeds range between 7 and 15m/hr and bit life are between 100 and 500m. This can be resolve through new and improved but designs, Hammer, jetting and plasma arc technologies, real-time but life monitoring and drilling energy optimisation. This technology will help reduce CAPEX through shorter drilling time.

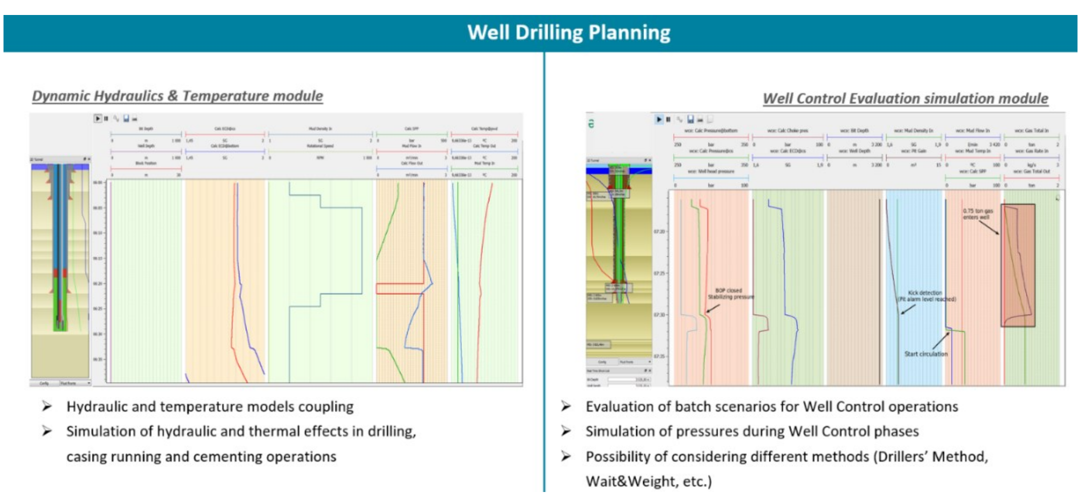

Figure 4: Various modules utilizing advanced modelling, implemented throughout well construction process.

The model is linked directly to operational parameters real-time, including pump rate, rate of penetration, weight on bit, revolutions per minute, connection practices, and tripping velocities, enabling real-time evaluation. It calculates well pressures versus position and other parameters, with results compared to measured data when available. In cases where measured data is lacking, the computed equivalent circulating density/equivalent static density serves as a reference for well pressure. This integration ensures an accurate representation of drilling conditions, supporting effective decision-making and procedure optimization.

4.3 AI Solutions

The technology provided by eDrilling enables real-time modelling, supervision, optimization, diagnostics, visualization, and control of the drilling process, allowing remote drilling experts to monitor and enhance drilling operations. The key technology elements include:

- Integrated Drilling Simulator: This advanced and high-speed simulator dynamically models various drilling subprocesses and their interactions in real-time. It can be used for on-the-fly re-planning (what-if scenarios).
- Data Quality Module (DQM): This module focuses on ensuring the correct processing and interpretation of data acquired during drilling. It systematically models physical effects that can influence measured values, correcting errors and improving the quality of drilling data.
- Real-Time Supervision Methodology: Real-time supervision of the drilling process utilizes time-based drilling data and drilling models (integrated drilling simulator) to monitor and analyze drilling operations in real-time.
- Diagnosis Methodology: Various process and operational modules built on top of the basic process models aid in interpretation and diagnosis, helping identify potential issues early in the drilling process.
- Advisory Technology: This technology offers advisory support for optimizing drilling operations by providing recommendations and solutions for achieving optimal drilling efficiency.
- Virtual Wellbore (3D Visualization): The Virtual Wellbore is a 3D visualization tool that provides a real-time, detailed insight into ongoing drilling operations. It offers a user-friendly interface and allows operators, support personnel, and management to visualize the entire drilling process in three dimensions.
- Data Flow and Computer Infrastructure: The infrastructure supports the flow of data and computing resources required for the operation of the digital twin.
- In summary, eDrilling's technology provides a comprehensive solution for real-time drilling analysis, from data quality improvement to advanced modelling, supervision, diagnosis, advisory support, and immersive 3D visualization, all contributing to safer, more efficient drilling operations.

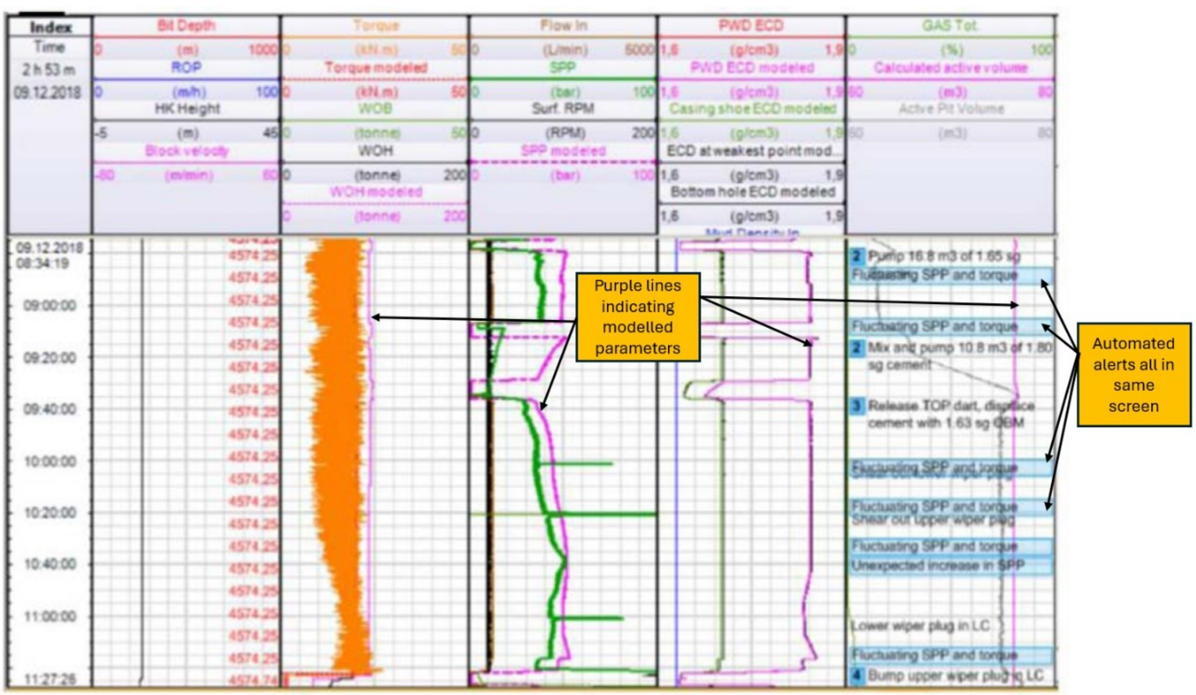

Figure 5: Measured RT data and modelled data displayed in same screen, alongside ML comments and automated diagnostics.

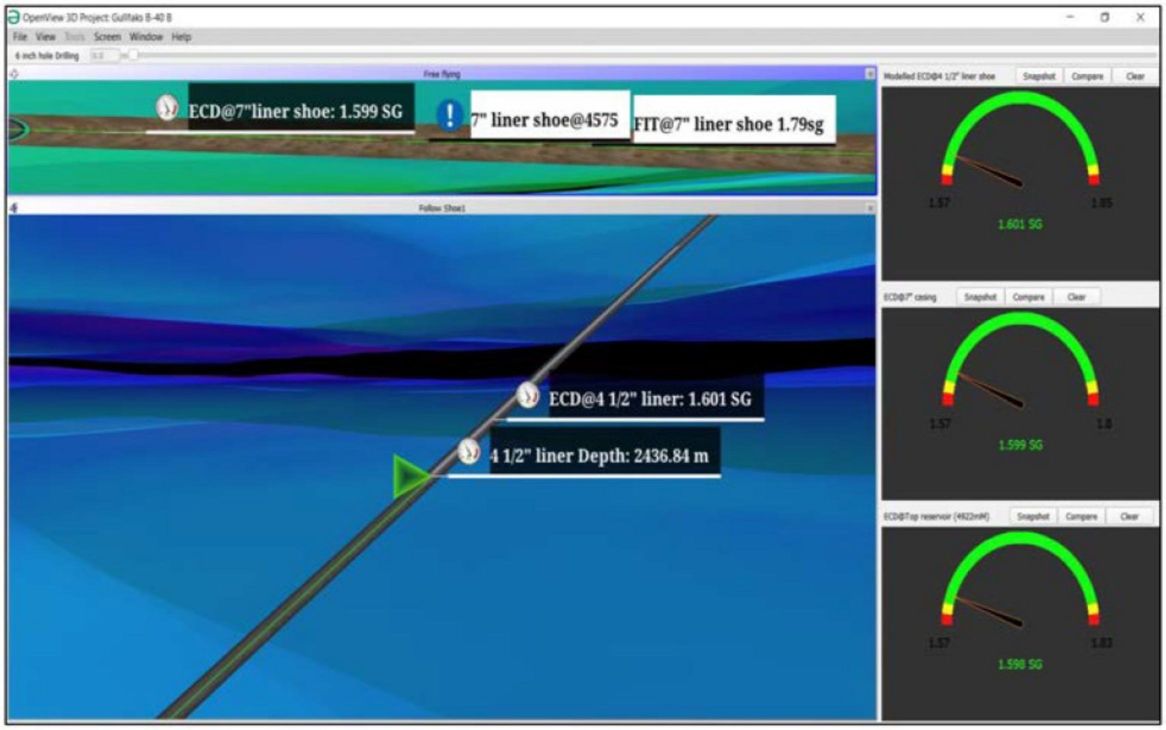

Figure 6: 3D visualization enabling clear view of what's ahead.

5. FUTURE WORK

In terms of future work and developments in geothermal drilling and digital twin technology, several areas can be explored:

1) Machine Learning and AI: Further exploration of machine learning and artificial intelligence can enhance the predictive capabilities of digital twins in geothermal drilling. These technologies can identify patterns, anomalies, and optimization opportunities more effectively.
2) New Data and Models for Geothermal Drilling Downhole Tools and Sensors: Geothermal drilling has specific challenges and requirements that require the development of specialized data and models for downhole tools and sensors. These tools can help capture relevant geothermal data and improve the accuracy of the digital twin for geothermal drilling applications.
3) Limits of Pressure and Temperature (P/T) in Dynamic Modeling: Geothermal drilling often involves extreme pressure and temperature conditions. Future work may focus on expanding the capabilities of dynamic modeling to handle a wider range of P/T conditions, ensuring accurate simulations and predictions in geothermal wells.
4) Customization for Geothermal Drilling Process: Geothermal drilling has unique characteristics compared to conventional drilling, such as high-temperature environments and specific geological challenges. To optimize drilling operations in geothermal fields, digital twin technology should be customized to address these specific requirements and challenges.
5) Integration of Environmental Factors: Geothermal drilling may also benefit from incorporating environmental factors, such as the potential impact on local ecosystems and groundwater. Future developments may include environmental modeling within the digital twin to ensure sustainable geothermal drilling practices.
6) Data Integration and Standardization: Standardizing data formats and integration methods across the geothermal industry can facilitate the seamless exchange of information between different stakeholders and systems, enhancing the effectiveness of digital twin technology.

In summary, future developments in geothermal drilling and digital twin technology should aim to address the specific challenges and requirements of geothermal wells while also exploring advanced capabilities such as AI, environmental considerations, and collaborative decision support to further optimize drilling operations in this unique and valuable energy sector.

- New data and model for geothermal drilling downhole tools and sensors
- Limits of P/T of dynamic modeling
- New features needed to customize for geothermal drilling process

6. SUMMARY

This paper investigates how the integration of oil and gas drilling technologies can significantly enhance geothermal drilling safety and efficiency. It delves into the challenges faced in geothermal drilling, particularly the high costs and technical complexities. By adopting advanced technologies and practices from oil and gas drilling, such as AI and digital twin technologies, the paper suggests that geothermal drilling can achieve greater cost-effectiveness and operational efficiency. The study includes case studies and emphasizes the importance of cross-industry collaboration, aiming to bolster the development of sustainable geothermal energy as a viable alternative energy source. While the paper outlines promising strategies for integrating oil and gas drilling technologies into geothermal drilling, it acknowledges that further research and development are needed. Bringing geothermal energy to the forefront as a cost-effective and sustainable energy source requires ongoing innovation and a deeper understanding of geothermal-specific challenges. This involves addressing technical limitations, optimizing resource utilization, and fostering industry collaborations to accelerate advancements in geothermal drilling technology.

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