PROCEEDINGS, 50th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2025
SGP-TR-229

Drilling for Superhot Geothermal Energy: A Technology Gap Analysis

Rebecca Pearce[1], Tony Pink[2]

Cascade Institute, Royal Roads University, 2005 Sooke Road, Victoria, BC, Canada, V9B 5Y2[1], Pink Granite Consulting, 42 Sherborne St, Cheltenham, UK, GL52 2JU[2]

pearce@cascadeinstitute.org, tonypink1@gmail.com

Keywords: Superhot rock, drilling, temperature management, downhole tools, high-enthalpy geothermal, next-generation geothermal

ABSTRACT

The research frontier of drilling and well construction for superhot rock (SHR) geothermal energy systems — the production of renewable, baseload electricity by circulating water in deep (greater than 5 km), hot (greater than 374˚C) rock — is steadily advancing. Recent achievements in polycrystalline diamond compact (PDC) drill bit design, improved rates of penetration (ROP) into hard rock, and the development of insulated drill pipe show that deep drilling for SHR geothermal projects is within reach. However, several key technology gaps stand in the way of drilling in hostile subsurface domains. Specialized drilling rigs, bit technology, high-temperature downhole tools, and temperature management equipment must achieve further engineering feats to successfully access and develop SHR resources. This study reviews state-of-the-art geothermal drilling and well-construction technologies, identifies existing technology gaps for SHR drilling, and suggests strategies to overcome these gaps. Specific technologies covered in this report include conventional (rotary) drilling, hybrid-conventional (percussive, waterjet, and particle) drilling, and direct energy (plasma and millimeter wave) drilling methods, as well as high-temperature downhole tools (measurement-while-drilling tools, magnetic ranging instruments, and downhole motors), temperature management equipment (insulated drill pipe, drilling fluids, and mud coolers), and corrosion inhibition technologies. Overall, we find that SHR geothermal wells can be drilled by deploying a combination of existing technologies and that the technological challenges to SHR drilling are surmountable. A first-order gap these technologies share is the lack of access to SHR conditions, both in-field and in controlled laboratory settings. Without open-access experimental facilities and pilot sites, these technologies cannot undergo iterative improvements necessary to de-risk SHR drilling and propel the industry forward.

1. INTRODUCTION

To successfully construct a Superhot Rock (SHR) geothermal well (>374˚C temperatures and >22 MPa pressures in pure water), a SHR drilling program must drill deep wells in crystalline basement, into progressively hotter and higher-pressure conditions. All components of a drilling system must have the capacity for these conditions, including rock-destroying equipment, high-temperature downhole tools, temperature management equipment, and topside equipment. Industry, along with university and government research labs, are building upon the decades of research conducted by the oil and gas (O&G) industry on the construction of complex, high-temperature, high-pressure wells. While some of these technologies are transferrable to SHR drilling today, others require further research and investment (Petty et al., 2020; Thorsteinsson et al., 2008; van Oort et al., 2021). This paper investigates state-of-the-art drilling technologies capable of reaching SHR temperatures by drilling ultradeep (>5 km) wells through hard rock lithologies. The sections cover rock-destroying technologies, high-temperature electronic tools, and temperature management equipment. These findings are the results of an extensive technology gap analysis by Pearce & Pink (2024) as part of the five-part series *Bridging the Gaps for Superhot Rock Geothermal Energy* facilitated by the Clean Air Task Force (https://www.catf.us/superhot-rock/bridging-gaps/).

2. ROCK-DESTROYING EQUIPMENT

To reach SHR, we must drill exceedingly deep wells into hard rock, which would incur prohibitively high costs with existing drilling technologies. Improving bit performance and maximizing bit longevity to reduce trip times are equally important for increasing the rate of penetration (ROP). In this section, we assess three categories of drilling techniques: conventional rotary drilling (polycrystalline diamond cutter [PDC], roller cones, and hybrid PDC/Roller cone systems), hybrid conventional drilling (percussive, waterjet, and particle impact), and direct energy (plasma and millimeter-wave).

2.1 Conventional Rotary Drilling Technologies

The majority of conventional and next-generation geothermal projects have been drilled with conventional rotary drilling systems. Major advancements in rate of penetration (ROP) have been demonstrated in recent EGS-type projects in hard rock (Dupriest & Noynaert, 2022a; El-Sadi et al., 2024). Rotary methods, however, are originally designed to cut through soft lithologies and must be further adapted for geothermal projects in hot, hard rock. This section explores four sub-categories of rotary drilling innovation:

1. Efficiency (the optimization of bit and cutter design for hard rock drilling, control of downhole drilling parameters and bit dysfunction mitigation to improve productive drilling time and reduce drilling costs),
2. High temperatures (specialized drill bits for SHR temperatures),
3. Directional drilling (methods and equipment for drilling deviated wells in SHR), and
4. Performance in interbedded formations (bit designs and methods to overcome bit wear from heterogeneous formations that can be encountered in basement volcanic sequences).

2.1.1 Efficiency through ROP Generation and Bit Dysfunction Mitigation

The optimization of cutter shape and bit design for hard rock drilling is well-documented. While roller cones are typically used for conventional geothermal projects, the rotating components of these bits are prone to failure due to high frictional heating and high weight on bit (WOB), and are limited by the temperature ratings of elastomer seals and bearing assemblies (approx. 130°C) (Petty et al., 2020). Fixed cutter bit performance has been significantly improved in recent decades by advancements in cutter grade and shape, such as PDC bits, with materials resistant to thermal abrasive wear enabling their use in hard rock formations, including those expected at deep geothermal sites.

PDC bits have been further engineered to cope with supercritical geothermal settings, where elevated risks of thermal wear, mechanical damage, lateral vibration, and excessive torque are expected (Roberts et al., 2022). However, the designs have not yet been run in SHR conditions, and further bit and cutter engineering may be needed to cope with the plastic behavior of rock at the brittle-ductile transition. Pathways for further research and experimentation to improve bit efficiency are finite element analysis of cutter and bit performance at super-critical depths and temperatures, laboratory experiments in brittle-ductile conditions (e.g., Rahmani et al., 2021; Rasyid et al., 2021; Roberts et al., 2022), and field experiments in brittle-ductile conditions with state-of-the-art robust drill bits, such as the Steam-Trooper (NOV) or Vulcanix^{TM} Kymera (Baker Hughes).

Standard drilling optimization methods improve ROP and bit life using techniques such as real-time surface mechanical specific energy (MSE) surveillance, testing bit/borehole assembly (BHA) design, drill bit forensics, and parameter mapping (Sugiura et al., 2021). At Utah FORGE, mitigation against drilling dysfunctions, such as stick-slip and bit-balling, was achieved by improving monitoring systems and topside communications, as well as deploying the automated REVit$^{®}$ ZT stick-slip management system from Nabors. Facilitating specialized training programs for drilling operators also improved dysfunction management (Dupriest & Noynaert, 2022b). To further improve WOB and MSE management, automated or assisted drilling rigs should be deployed at ongoing geothermal sites, such as Utah FORGE, or future SHR experimental sites. Comparing MSE management and ROP between automated systems such as the Nabors SmartSuite^{TM} and traditional manual drilling rigs will highlight further strengths and limitations of automated drilling.

2.1.2 High Temperatures

For deep geothermal drilling, conventional drill bits must be adapted to cope with exceedingly high temperatures (>374°C). Thermal damage is typically exhibited at the cutter shoulders, where cutter shear length and sliding distance are highest. NOV has engineered various round and V-shaped cutters with denser diamond grades that are resistant to abrasive wear. These cutters also achieve greater durability against thermal wear by removing cobalt catalysts within the diamond at the cutting edges, increasing the diamond temperature rating from 700°C to 1,200°C (Roberts et al., 2021; Self et al., 2021). The dynamics of the fluid channeled through the top of the bit also play a critical role in regulating bit temperature, minimizing thermal abrasion, and cleaning the cutters. The main parameters affecting hydraulics include cooling fluid flow rate, nozzle configuration, mud weight, total flow area, and mud type. These parameters can be optimized to distribute the correct amount of cooling to the most vulnerable cutters (Roberts et al., 2021).

The study by Vetsak et al. (2024) demonstrates that a temperature difference of 100°C to 300°C between hot, dry rock and drilling fluid can lead to an increase in drilling performance from 69 to 197 percent for PDC bits, and 59 to 108 percent for roller cone bits, with improved performance correlated to WOB. This encouraging result suggests that implementing thermal shock with cold drilling fluid will greatly enhance the viability of SHR development with correctly rated drill bits. Several drill bit technologies can withstand 300°C; however, the remaining 75-100°C expected at supercritical temperatures must still be “unlocked.” It should be noted that drilling through 400°C rock does not mean that the bits will encounter 400°C, due to significant cooling from the drilling fluid. Lack of access to these extreme temperature conditions remains a major challenge for experimentation.

2.1.3 Directional Drilling

Precise directional drilling tools that can operate above 374°C and at great depths are required to deploy lateral well sections for well-to-well intersections or to optimize lateral borehole separation for reservoir stimulation. Directional drilling requires a drive system that can be steered in three dimensions. Using traditional technology, three-directional steering is performed with a mud motor and/or a rotary steerable tool. Both these drive systems have temperature limitations of between 175°C and 200°C, thus the drilling system will need to be cooled below these temperatures.

Directional drilling of a SHR well above 374°C is possible today. However, depending on the efficiency of the temperature management system, it may be necessary to complete all the directional work with electronic tools before the highest temperatures are encountered. The modelling work done on insulated drill pipe suggests that directional work can be done at depths of 8,000 m and with formation temperatures above 374°C. A set of full-scale test joints must first be produced and tested, followed by the development of a complete string to validate that the bottom hole circulating temperature can be maintained below the operating temperature maximum of the tools.

2.1.4 Performance in Interbedded Formations

SHR conditions are generally found in basement rock at depths greater than 5 km. When PDC cutters transition from soft to hard formations in heterogenous domains, the drill string rotation is slowed, yet the force on the bit remains the same (Graham et al., 2017). The excess force dissipates through the cutters, causing breakage or chipping if the force exceeds their fracture strength. Tricone bits may be better suited for these conditions, as they penetrate the rock with the weight of the drill string rather than the rotational force applied by fixed cutters (Graham et al., 2017; Rahmani et al., 2021).

Engineers at Fervo Energy have stated that lithological hardness becomes more uniform with increasing depth, and current drill bit technology will not be at risk of premature bit-wear from drilling through heterogeneous formations, such as sediments, interbedded tufts, calcites, and granite. In heterogeneous media, one ReedHycalog bit managed to drill through sediment, interbedded tuffs, calcites, and granite, demonstrating that conventional bits are sufficient in interbedded domains (interview with experts at Fervo, 2024). Conversely, experts at Utah FORGE consider interbedded formations to be a first-order innovation gap for hard rock drilling, and the Stn-1 project in Finland encountered complex geology in the Fenno-Scandinavian shield, a geological regime with presumably uniform rock hardness.

One approach to overcoming interfacial severity includes adaptive drilling methodologies that can detect fractured lithology before interception, potentially through acoustic and sonic techniques that can be incorporated into automated drilling methods (interview with J. Moore and J. McClennan at Utah FORGE, 2024). Other recommendations include deploying conical diamond element bits or geothermal-specific bits such as the Vulcanix$^{\text{TM}}$ Kymera (Baker Hughes) in deep, cold, heterogeneous geologies (e.g., Stn-1) to compare performance to conventional PDC cutter shapes. A Utah FORGE-equivalent test site located in a volcanic geological environment featuring igneous rock with a high variability of hardness would provide an optimal environment to conduct these experiments.

2.2 Hybrid Conventional Drilling Technologies

Hybrid conventional BHA's are grouped as rotary drill bits with the percussive/waterjet/particle impact modifications designed to target the brittle state of hard rock formations to improve drilling performance and increase ROP. For example, waterjet methods alter the stress state at the bottom of the hole to improve its failure, and percussive and particle impact fracture the brittle hard rock. The same core challenges facing conventional drilling apply to hybrid conventional drilling methods, namely: efficient drilling through deep, hard rock formations under exceedingly high temperatures and pressures. The advantages of hybrid conventional drilling may prove superior to purely rotary techniques in the pursuit of SHR, although further experimentation in SHR conditions is required for all methods.

2.2.1 Percussive Drilling

An air or fluid hammer percussive BHA operates by pneumatically impacting the bit repeatedly into the rock, with rock cuttings cleared away by the rotary component of the drill bit (Depouhon et al., 2015; H. Song et al., 2022). Percussive drilling systems have been used in several hard rock drilling geothermal programs, notably Stn-1, Fervo, and IDDP-2. Percussion drilling has produced improved hole geometry, reduced stress on the drill string, improved bit longevity due to reduced contact time with the rock, and better cutting shape and size for transport. In Perth, Australia, Strada's fluid hammer was used to reach depths of over 6,000 m and achieved 20 m/hr ROP in 200 MPa hard rock, including granite and basalt, reducing drilling costs by 70 percent (Olijnyk, 2024).

Percussive drilling can, however, lead to wellbore instability due to excess energy transfer in soft formations, poor performance in soft rocks, and vibrational dysfunction (Bruno, 2005). Air hammer drilling will not perform efficiently at great depths due to well instability and loss of force to the drill bit, nor in wells with incoming water. Mud hammer drilling may incur substantial water loss if operating in porous or fractured media. A collaborative research project between Mines ParisTech and Drillstar Industries has identified four focus areas for how to adapt percussive drilling for deep geothermal projects (Gerbaud et al., 2022): 1) theoretical development, computational analysis, and experimentation on the stress regime at the drilling front in a deep borehole to optimize bit and cutter design, 2) cutting element optimization at the rock-bit interface under specific drilling conditions, 3) design of a hydraulic hammer for 8 ½" boreholes, and 4) in field testing. The Department of CNPC Engineering Technology in Beijing has also conducted extensive modelling and laboratory experiments on stress wave propagation mechanisms and rock fragmentation up to 300°C (H. Song et al., 2022). Collaborations between these groups could advance percussive drilling performance in deep, high-temperature, high-pressure conditions.

2.2.2 Waterjet Drilling

Waterjet drilling uses high-pressure water to weaken the rock formation and borehole, reducing the strain on the drill bit as it progresses downhole. The EU Horizon 2020-funded Orchyd Project, in collaboration with Drillstar Industries, has developed a hybrid high-pressure waterjet and mud hammer. This hydro-mechanical drilling system operates to reduce the confining stresses of the rock at the drilling front, improve drilling efficiency and reduce the impact of hard, abrasive formations on bit-life (Wang et al., 2021). With these designs, current system testing at the ARMINES laboratory facility in Pau, France demonstrated an 80 percent increase in ROP with the combined system, a rate of 4-10 m/hr (Jahangir et al., 2022). Further design improvements are expected, with the target of the fully completed system to have an ROP of roughly 20-25 m/h in hard rock.

Water-jet drilling has not been extensively tested in supercritical temperature and pressure conditions. Top-side equipment must be designed to support the extreme volumes of fluid delivered downhole (600 L/m in the case of the Orchyd Project), especially at extreme depths. Maintaining that pressure to depths of up to 10 km will be critical for the success of waterjet designs. Some key areas of design improvement are their application in high compressive strength formations, directional control systems design within the jetting system, and performance modelling in hard rock formations (Ahmed & Teodoriu, 2023). The reduction of downhole stresses is one of waterjet drilling's biggest advantages. However, the technology requires more validation based on the standoff distance to the rock surface to maximize stress reduction. Surface systems must be evaluated to ensure consistency with significantly increased flow rates at long distances through the drill string.

2.2.3 Particle Drilling

Particle drilling involves the injection of steel shots of various sizes into the drilling fluid through the drill bit. The impact of accelerated drilling fluid bearing the steel shots weakens the formation to improve the efficiency of the PDC drill bit. The company Particle Drilling (PD) and NOV partnered to design a hybrid particle impact and PDC bit and conduct lab and field testing in hard igneous rock in central Texas. PD's hardware is not affected by the temperature and pressure of drilling through SHR; however, the injection process must be closely monitored when making drill pipe connections. A significant technology gap is compatibility with measurement-while-drilling (MWD) tools. To drill directional wells efficiently, particle drilling requires an MWD telemetry system that can send signals uphole without a pulser or modulator (T. Pink et al., 2022).

Canopus Drilling Solutions (CDS) in the Netherlands is also developing a hybrid particle impact and PDC system (Interview with Jan Jette Blangé, Feb. 2024). Additionally, they are designing and testing a complete MWD package and steering unit. The Canopus system's basic principles are the same as PD. The technologies differ in that Canopus uses the shots to steer the well and uses a PDC bit to remove the weakened rock, whereas PD solely reams a small section of destressed rock on the outside of the hole. Canopus is pushing towards market readiness in 2024 but must perform a full-scale drilling test with a vertical-mounted conventional rig. Tests thus far have been in soft rock, and must be demonstrated in hard rock formations.

2.3 Direct Energy Drilling Technologies

As well depths increase, both rotary and hybrid conventional drilling methods will increasingly face challenges from excessive string weight, high frictional resistance, and exceedingly long trip times, possibly negating advancements in ROP generation. Direct energy drilling involves the destruction of rock by exposing it to high-powered energy sources, such as plasma or millimeter-wave (MMW) energy. Cuttings are cleared by a circulating purge gas or drilling fluid, exposing the next segment of rock to further direct energy, deepening the well.

Direct energy drilling systems have several advantages over conventional drilling, including no anticipated complications from supercritical conditions, minimal downhole tools and equipment, no/reduced tripping times as there is no/reduced contact of the rock to the drill bit, capacity to transmit energy to depths required of SHR (>5 km), and relatively minimal energy requirements to operate the direct energy system. However, direct energy methods are highly novel, and require substantial innovation before commercialization. Direct energy methods are designed for hard rock conditions; as such, conventional drilling methods are still required to drill through the top 2-3 km of sedimentary overburden to reach the basement. Direct energy drilling methods for deviated well sections are still under development, thus conventional drilling techniques will also be required in tangential well sections.

2.3.1 Plasma Drilling

Plasma drilling is the application of electrical currents to create a plasma pulse through the grain boundaries of the rock formation, to vaporize the rock. This can be achieved by direct contact with the rock interface or while maintaining a stand-off distance (Q. Zhang et al., 2023). With a projected consumed energy of 100-200 J/m^3, plasma technology requires roughly 3-5x less energy than conventional drilling systems. The low energy requirements reduce costs by an estimated 17 percent, with the possibility of up to 90 percent reductions with future improvements. Slovakia's GA Drilling is at the forefront of innovating plasma systems for geothermal drilling. They have designed a system that can be integrated with existing conventional drilling methods (Anchorbit®), as well as a standalone design for ultra-deep depths (Plasmabit®). Testing of Anchorbit® was completed by ETH Zurich and demonstrated a high ROP of 7.2 m/hr in granite samples.

While plasma drilling technologies show promise for reaching SHR, technology gaps remain. For plasma drilling of hard rock formations (especially granite), the breakdown of the rock formation plays just as critical a role as the technology used to remove the material. Heterogeneous composition within different granite formations plays a significant role in the amount of energy consumed by the drill system and the amount of material removed during each pulse. A recent study by Walsh & Vogler (2020) shows a significant relationship between the pore size and the amount of total energy consumed during the operation, with implications for ROP and the total required energy to complete the borehole.

Another key factor in the success of plasma drilling is the drilling fluid. Most geological-based laboratory tests use water as the dielectric fluid within the system, but engineers must better understand how to maintain clean drilling fluid downhole in field conditions. GA's hybrid conventional plasma technology shows the most promise but must overcome the challenge of maintaining clean dielectric fluid and standard drilling fluids. Engineers from Nabors acknowledge that further work must be focused on how cuttings are removed and the challenges of switching between fluids.

2.3.2 Millimeter Wave Drilling

Millimeter wave (MMW) drilling vaporizes rock by applying intense electromagnetic energy to the rock surface, powered by a gyrotron at the surface and transmitted downhole by a metal waveguide. Vaporized debris is excavated from the well by a circulating purge gas, and the borehole wall is automatically reinforced by rock vitrification (Houde, Woskov, et al., 2021). The companies spearheading MMW are Quaise Energy (based out of the MIT Plasma Science and Fusion Centre), AltaRock, Advanced Research Projects Agency-Energy (ARPA-E), Oak Ridge National Laboratory (ORNL), and Nabors Industries. Quaise estimates that MMW could achieve an ROP of 3-5 m/hr with a 1 MW gyrotron for an 8-10" borehole diameter, reaching 10 km in 100 days or less. Monitoring downhole conditions may be communicated through remote diagnostic signals transmitted down the waveguide; for example, the depth to the ablation front is monitored using radar/reflectometry. This information may provide real-time recordings of ROP, downhole dysfunction, plume depth, temperature, waveguide bends, lithology, fluids, and MWW wave mode changes (Oglesby et al., 2014). Information may also be collected through the deployment of downhole sensors (Houde, Araque, et al., 2021).

Experimental scale-up and ruggedization of the gyrotron instruments are both an immediate focus for MMW-drilling R&D. Acquiring a high-powered MMW gyrotron to scale-up experiments, as well as a research stand capable of confining rock samples at supercritical conditions, are first-order tasks to conduct further testing. Along with bench tests, Quaise, with engineering support from Nabors and

ORNL, is designing a drilling rig that can accommodate the complex gyrotron system to conduct in-situ field tests. This rig will be deployed at a field location in Texas in 2025, aiming to penetrate 100-1,000 m. The rig will be designed to ensure that it can withstand field conditions, namely rough roads to remote areas, and be operated by drilling personnel.

Similar to plasma drilling, the dielectric absorptive properties of rock in the context of MMW drilling require further analysis through modelling and experimentation. Different rock types will evaporate at different rates depending on their electrical conductivity and absorptive properties (Woskov, 2017; Woskov & Cohn, 2009; A. Zhang et al., 2023). Even within granite, variations in quartz content with low-absorptivity properties can induce heterogeneous vaporization. This may lead to an asymmetrical borehole and compromise the deployment of the metal waveguide. A greater understanding of these complex processes through numerical and laboratory experimentation is required.

The deployment and retrieval of the downhole waveguide remains a challenge. The waveguide must retain a near-perfect vertical orientation to avoid rapid overheating from the MMW encountering the waveguide. For example, a 30 m bent section of the waveguide can heat to over 200°C in 8 minutes from a 2 MW beam, leading to 10 percent energy losses, damaging the waveguide (steel starts to degrade at 316°C), and potentially preventing its further deployment downhole (Oglesby et al., 2014). Tortuous or "corkscrew" trajectories commonly seen in conventionally drilled wells may lead to this problem, as conventional drilling methods will be required to through the 2-5 km of sedimentary overburden. The expansion/contraction of the waveguide under different temperatures and pressures, and preventing cementation of the waveguide to the borehole wall due to liquefaction and solidification processes from rock vitrification require further investigation.

3. HIGH-TEMPERATURE DOWNHOLE TOOLS

In geothermal drilling, "downhole tools" refer to the instruments and devices used in the wellbore to perform operations, gather data, and manage the drilling process. Key components of downhole tools include the components of the BHA, which comprises stabilizers, reamers, shock tools, mud motors, rotary steerable systems (RSS), Measurement While Drilling (MWD) tools, and Logging While Drilling (LWD) tools. Additionally, downhole sensors are essential for monitoring and gathering data during the drilling process. The ability of these tools to operate in high-temperature, high-pressure environments is vital to the success of a drilling project. Manufacturers working on HTHP tools and their respective temperature ratings are Hephae (210°C), NOV (175°C), Weatherford (200°C), Gunnar Energy Services (370°C), Baker Hughes (175°C), MB Century (350°C) and Schlumberger (200°C) (refer to Pearce & Pink (2024) for details).

3.1 Organic sealants and insulators

Pressure limitations of most high-temperature tools are in the range of 25,000-30,000 psi, which is within the range of SHR wells. High-temperature tool limitations are currently around 175°C to 200°C. The main limitation of these tools is the maximum temperature rating of the elastomers in the pressure seals. Viton rubber seals have a max temperature of 300°C and Tetrafluoroethylene O-Rings 232°C.

3.2 Metal-to-Metal Motors

A major challenge for high-temperature downhole tools is power supply. The maximum operating temperature of downhole battery packs is 200°C. This limitation can be overcome with a downhole turbine that provides power to the tool. High-temperature electric motors for downhole turbines with non-organic insulation are achieving higher temperature ratings (demonstrated at the Lincoln Laboratory). A turbine can be problematic for measurements that require a continuous supply of power.

Baker Hughes has implemented full metal stators in their high-temperature drilling system, referred to as the metal-to-metal (M2M) motors, that are composed solely of steel alloys with a mud-lubricated assembly and are rated up to 300°C. The rotor and stator are elastomer-free with a wear-protection coating that protects the metal-to-metal contact points. One drawback is the potential for fluid leakage between the rotor and stator without the elastomer sealing; however, a fully sealed chamber could be engineered with further R&D. In-field and laboratory experiments proved that high torque outputs can be maintained at temperatures over 250°C for over 50 hours, with an anticipated drop in rotational speed from 80-50 RPM throughout the drilling run (Epplin, 2015; Stefánsson et al., 2018). An outstanding challenge is in machining the steel parts within the required tight tolerances—and, even when those tolerances are met, the motors can be susceptible to erosion by particles in the drilling fluid.

3.3 High-temperature rated electronics

Downhole MWD and LWD instruments contain electronics that cannot withstand SHR temperatures. The practicality of building tools to survive in borehole temperatures of >374°C without the use of any temperature management systems would require significant scientific breakthroughs. The National Renewable Energy Lab and NOV spent a year investigating 374°C-rated electronics to determine if it was possible to design tool components using packaged aluminum gallium nitride/gallium nitride (high electron mobility transistors are used in high-frequency and high-power switching applications). This study showed that even if chipsets could be built with this compound, the batteries and other components remained a limitation (based on the experience of the author Tony Pink at NOV).

Rather than developing costly electronic tools with higher temperature ratings, Baker Hughes developed a cooling system for their BHA to maintain internal temperatures at 175°C, even under 300°C conditions. According to John Macpherson (Interview, 2024), Baker Hughes' cooling system capitalizes on the evaporative properties of water, and isolates the temperature of the thermos flask containing the electronics through a control valve. The consensus of equipment manufacturers is that electronics will only withstand SHR conditions with a combination of the highest-temperature-rated tools and a cost-effective temperature management system. As described in section 4, managing the temperature of the borehole to below 175°C is achievable today, but temperature management equipment requires further testing and validation in SHR conditions. If manufacturers can increase the temperature rating of the tools it will improve reliability and increase safety margins to prevent tool damage. Hepahae's electronics have been tested in ovens above 225°C in the last 3 months.

4. TEMPERATURE MANAGEMENT EQUIPMENT

When drilling fluid gets too hot, its ability to carry the drilled cuttings deteriorates, bit wear increases, downhole tools are destroyed, and the risk of drill pipe and casing corrosion increases by orders of magnitude. Overheated drilling fluids also prevent the use of downhole motors and electronic instrumentation, and can affect borehole stability and well control. Each of these consequences can be countered by individual technology developments, but all can be solved (or greatly mitigated) by simply cooling the downhole environment. Temperature management can be achieved with a combination of equipment, including low-heat coefficient coatings, mud coolers, and (most significantly) insulated drill pipe (IDP). Current drilling technologies can be used in 400°C rock; however, to do this economically, a combination of technologies must be deployed. For example, the combination of high-temperature tools with low-heat coefficient coatings and mud coolers decreases the amount of IDP needed, lowering daily operating costs.

4.1 Insulated Drill Pipe

There are three basic approaches to IDP. The advantages and disadvantages of these approaches were defined well by the Sandia team in 2000 and are summarized in Table 1 below.

Fabrication Method	Advantages	Disadvantages
Single-wall, insulation inside	Lightweight; insulation, protected from abrasion wear and impact with casing or wellbore; minimum erosion from cuttings, could insulate tool joints.	Failed insulation could plug bit or downhole motor; difficult to install, repair, or replace insulation; requires tough, strong insulation.
Single-wall, insulation outside	Lightweight; insulation easy to apply; insulation failure would not have a serious effect on circulation.	Insulation is vulnerable to erosion and impact; probably could not insulate tool joints or pipe handling areas of pipe body; requires tough, strong insulation.
Double-wall	Excellent insulation properties; a rugged design that could handle tough drilling conditions. Reliable protection for insulation; no strength (except compressive) or toughness requirement on insulation. Insulation material development is not required.	The pipe is heavy: fabrication is complex and expensive. The reduced inside diameter affects hydraulics.

Table 1 Fabrication methods for IDP (adapted from (Champness et al., 2008)).

Several recent studies have investigated the effectiveness and potential of IDP in SHR applications (Ajima & Nagananwa, 2022; A. Pink et al., 2023; Vetsak et al., 2024). The study by Ajima and Naganawa modelled the use of IDP in a 4,000 m well with a max temperature of 600°C. They used the base pipe design from Sandia and Drill Cool and GEOTEMP2 software. The model showed that a full string of IDP could deliver sub-175°C fluid at 4,000 m under supercritical conditions.

For the drill string (not including mud coolers and mud properties), the currently available IDP technology combined with coated regular drill pipe can deliver sub-175°C fluid to the bottom of a 7,000-8,000 m well in SHR conditions. Operators should look for the lowest-cost, highest-value combination of coated pipe, IDP, and high-temperature downhole tools (along with a surface rig that delivers the optimum flow rate with sufficient hoisting capacity). If the IDP drill string is too heavy, higher temperature-rated tools could be run and/or surface mud coolers could be added to the system.

Recent modelling shows that there are no major technology gaps for managing the temperature of a 400°C SHR well below 175°C while drilling (A. Pink et al., 2023). However, the technology must be manufactured, and a full-scale pilot project must be drilled at SHR conditions to validate the technology and ensure that it is field hardened for the downhole conditions. The complete drilling system must be modelled prior to in-field testing to ensure the most cost-effective solution is selected.

4.1.1 Titanium Drill Pipe

Titanium is well-established in aerospace, marine, and defense industries for its outstanding performance in environments above 500°C. The metal's low thermal conductivity insulates drilling fluids within the pipe from extreme external heat to maintain lower temperatures within the pipe and increase drilling efficiency. When paired with low heat coefficient coatings, titanium drill pipe can further reduce thermal transfer, boosting drilling rates by promoting temperature-induced fracturing at the bit face. Titanium also exhibits superior fatigue resistance and dimensional stability, crucial for maintaining structural integrity during severe thermal cycling. This property makes it particularly suitable for scenarios with frequent temperature fluctuations, effectively preventing fatigue cracks and deformations that could lead to system failures.

Titanium’s excellent strength-to-weight ratio enables the production of lighter yet stronger drill pipe and well tubulars. This weight reduction improves the depth capabilities of drilling rigs, broadens rig selection and options to control rig move costs, and reduces the footprint of drilling pads. Further, titanium's superb corrosion resistance and thermal stability at temperatures up to 500°C ensures the long-term durability of tubulars and downhole equipment in harsh conditions with far longer life cycles than stainless chrome and nickel alloys. These longer life cycles significantly decrease the need for maintenance and replacement in severe downhole conditions.

ALTISS Technologies is at the forefront of titanium drill pipe designed for hostile geothermal conditions, including SHR conditions. Their patented titanium drill pipe dampens vibrations to enhance mechanical energy efficiency, leading to higher penetration rates and extending the life of the BHA and drill string. In addition to drill pipe, ALTISS is applying titanium to other components, including drilling and completion systems components, casing, and tubing. This underscores titanium’s growing importance and ongoing improvements in high-performance applications.

4.2 Drilling Fluid

4.2.1 Water-based Fluid

Drilling fluid maintains downhole drilling temperatures and mud stability, suspends cuttings, and protects the wellbore. These functions are essential in geothermal domains where the borehole is at risk of thermal and structural instability, circulation losses, and high frictional resistance (Petty et al., 2020; X. Song et al., 2023). Drilling muds may be susceptible to degraded mud chemistry in high-temperature boreholes, and the inclination and depths of geothermal wells may increase frictional resistance, further compromising cutting transport (X. Song et al., 2023). Innovative drilling fluids may overcome these risks.

From a purely temperature management point of view, running mud with a higher specific heat capacity than water would be beneficial; however, data from FORGE has shown that drilling with water with little or no additives has a significantly positive effect on ROP. Synthetic polymers <204˚C can be added to the drilling mud, as well as clay-based drilling fluids such as Halliburton’s ilmenite-based Microdense^{TM} mud system used at Larderello for the project DESCRAMBLE. The mud for the IDDP-2 well was rated up to 300°C and remained stable after 50 hours of use. This mud was water-based, with a bentonite stabilizer and low molecular weight copolymer additives and vinyl-sulfonated copolymers. Additional lubricants were required to maintain the elastomer-free MWD deployed at this site (Petty et al., 2020; Stefánsson et al., 2018). Finally, Baker Hughes has developed 260°C rated viscosifiers, thinners, deflocculants, and filtration reducers that can be added to bentonite slurries (X. Song et al., 2023).

Water, at the correct fluid velocity, is sufficient to clean the hole if developers maintain the borehole inclination below 20 degrees. Above a 20 degree inclination, research is needed in high-temperature additives that would provide adequate rheology to clean the hole, especially if operators begin drilling horizontal SHR wells. R&D in high-temperature fluids could be conducted by national labs and universities in partnership with a commercial entity that can test the technology. Advanced testing equipment that can perform a full set of mud tests at 400°C does not exist.

4.2.2 CO_2-based fluid

The primary benefits of using sCO_2 as a drilling fluid – distinct from using sCO2 as a working fluid – are: the ability to cool the drilling system so conventional or high-temperature rated tools could be run in combination with the sCO_2 system, the lower annular pressures which significantly reduce the risk of lost circulation in naturally fractured formations, and potential increases in ROP from the thermal impact of hitting SHR with sCO_2. The primary disadvantages and complications of running a sCO_2 system are: sourcing a sufficient amount of sCO_2, the environmental impact of potential leaks, and the need for crewmembers with experience drilling with sCO_2 (Phuoc et al., 2020).

All the components of a sCO_2 system exist, but the complete system needs to be engineered and fully integrated into a package that includes all the mechanical hardware, a control system, a model, and trained experts to run it—and then tested in the field. With the right level of investment, this package could be realistically developed and tested in 2-3 years. However, CO_2 production must increase to scale up this technology.

4.2.3 Low heat coefficient coatings

Low heat coefficient coatings can be used independently to moderately reduce borehole temperature or used with insulated drill pipe and mud coolers to deliver much larger temperature reductions. Through iterative formulation adjustments, NOV, in collaboration with Eavor Technologies, has developed and commercialized a coating formulation called Drakon with an average conductivity of just 0.16 W/mK, well below the conventional coating value and the operator’s target. Another company, Tuboscope, is also developing low heat coefficient coatings with even lower thermal conductivities to help future geothermal operators drill into deeper reservoirs with temperatures exceeding 300°C. Such innovations will also help operators in shallower, lower-temperature reservoirs minimize heat losses in the pipe to support applications such as district heating, low-enthalpy electricity generation, greenhouses, and hydroponics farms. Models have demonstrated that the temperature could be maintained below 150°C (A. Pink et al., 2023).

Low heat coefficient coatings are used commercially in geothermal wells and other deep hot wells. SHR well temperatures will be best managed by combining mud coolers, insulated drill pipe, and other temperature management equipment, rather than relying on low heat coefficient coatings alone. Continued research into low heat coefficient coatings and the potential use of nanoparticles and other insulative materials may further lower the conductivity. This research would be carried out most effectively through collaborations between national labs and commercial test partners. The low heat coefficient coatings may also be considered for insulative purposes on other tubulars in the wellbore.

4.2.2 Mud Coolers

As the well gets deeper (with a constant circulation rate), the total travelling time and distance of the drilling fluid to reach the bottom hole increases. Surface mud coolers are a relatively cheap solution to reducing borehole circulating temperatures. Mud coolers are effective in relatively shallow superhot geothermal wells, but if used with conventional drill pipe, the effectiveness diminishes with depth (Khaled et al., 2023).

Although results show that mud coolers are not an effective heat management strategy for SHR wells, they still offer benefits when used during drilling by maintaining low surface mud temperature. Lower surface mud temperatures increase crew safety and help avoid mud pump failure caused by high-temperature mud. In addition, the effectiveness of mud coolers is increased when combined with IDP. Mud coolers that can be deployed for SHR projects exist today.

5. ADDITIONAL CONSIDERATIONS

5.1 Corrosion Inhibition

Corrosion inhibition is largely beyond the scope of this paper as this concern is primarily for production companies rather than drilling operators. The drillers must, however, consider the impact of corrosion on drilling equipment, downhole tools, casing metallurgy, and the design of the cement. All the corrosive processes associated with drilling geothermal wells would be exaggerated under SHR conditions.

The chemistry of the formation fluids and the presence of chlorides, carbon dioxide, and hydrogen sulphide will impact the well design. Hydrogen sulphide is commonly present in O&G drilling and steel pipe, and casings are available in grades resistant to hydrogen sulphide embrittlement. Otherwise, corrosion-resistant coatings can be incorporated into low heat coefficient coatings produced by NOV. Titanium drill pipe is very resistant to corrosion but is expensive compared to steel pipe.

To mitigate corrosion, the casing material must be selected based on the project life span, the temperature of the well, and the produced fluid chemistry. Depending on the conditions, casing corrosion can be managed by selecting materials that withstand elevated temperatures, such as high-chromium, nickel-based alloys which can fortify casing integrity in geothermal environments. In lower-temperature but corrosive environments, non-metallic liners can be run inside the casing; these provide excellent corrosion inhibition at a much lower cost compared to advanced steel alloys. One example is NOV’s fiberglass TK Liner. However, this has a maximum temperature of only 121°C, thus can only be used in shallower well sections or surface piping on a SHR project.

5.2 Topside Equipment

Drilling SHR wells will require a fit-for-purpose drilling rig and topside equipment to power and integrate all the considerations discussed in this paper (ROP, high-temperature downhole tools, temperature management equipment, drill string, casing and cement). For example, a MMW rig must have sufficient capacity to withstand 900 tons of force for the weight rating of the rig, and a 5,300-horsepower drawworks to raise or lower the metal waveguide to depths >7 km. Rigs with these capabilities do exist today but are rare and difficult to source (Houde, Araque, et al., 2021). In another case, if a full string of IDP is needed to maintain borehole temperatures below the temperature ratings of downhole tools (Section 3), a significantly larger rig, a higher-pressure surface system, and greater hoisting capacity are required to support the IDP. The increase in rig size and the additional cost of the IDP may incur costs that make the SHR project uneconomic.

Reaching SHR requires wells with very deep true vertical depths, which must be considered before other drilling factors such as rock hardness, high friction coefficients, and elevated temperatures. The rig must be sized to lower, pull, and potentially rotate the heaviest string going into the hole. The substructure and derrick must be strong enough to lower and pull the deep 9 5/8” (or equivalent) casing. For example, the weight of a 9 5/8”, 58.4 lb/ft, P110 casing at 20,000 ft is over a million pounds. The rig derrick and top drive must turn the whole drill string in a high-friction environment and provide adequate torque at the bit to fail the rock efficiently. Developers will need a rig with some of the highest specifications available today (e.g., the Doyon Rig 26 in Alaska, which is drilling exceptionally long O&G wells on the North Slope). We estimate the number of rigs with these specifications to be less than 50 worldwide.

6. CONCLUSIONS

SHR geothermal systems have the potential to provide long-term, scalable, renewable baseload power. Unlocking this potential requires significant innovation in drilling and well-construction technologies to improve ROP and develop high-temperature electronic downhole tools for MWD, logging-while-drilling LWD, and directional drilling in SHR conditions

Currently, rock-destroying equipment, high-temperature downhole tools, temperature management equipment, and corrosion inhibition share three overarching challenges:

1. Lack of access to SHR in controlled, laboratory settings,
2. Lack of access to SHR in in-field settings, and
3. Lack of incentives for collaboration between major drilling firms.

Collaboration between the public and private research community can help create these R&D conditions by first identifying all facilities around the world capable of SHR experimentation (e.g., Newberry, IDDP, GEODE). This must be followed by incentivizing the cooperation between major drilling companies and research groups, and finally ramping up experimentation and R&D in SHR conditions.

One theme is clear across all well-construction technology domains: the technology to complete superhot and ultradeep geothermal boreholes and wells exists—but we must reduce the overall cost and time required to drill a deep, superhot geothermal well. With continued support and development, the future of geothermal energy is extraordinarily bright.

ACKNOWLEDGEMENTS

We would like to thank Chris Rush for key contributions to the literature review and writing process; Jenna Hill, Terra Rogers, Jordan Bendall, and Scott Janzwood for reviewing and editing the report; and our network of experts from the international geothermal and drilling communities for reviewing the report and providing helpful feedback. These findings are the results of an extensive technology gap analysis by Pearce & Pink, (2024) as part of the five-part series *Bridging the Gaps for Superhot Rock Geothermal Energy* facilitated by the Clean Air Task Force.

REFERENCES

Ahmed, R. M., & Teodoriu, C. (2023). *Applications of Radial Jet Drilling Techniques in Geothermal Wells*. Proceedings: 48th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA.

Ajima, K., & Nagananwa, S. (2022). *Evaluatingwellbore cooling effect with insulated drill pipes in supercritical geothermal well drilling*. *46*, 28–31.

Champness, T., Worthen, T., & Finger, J. (2008). *Development and Application of Insulated Drill Pipe for High Temperature, High Pressure Drilling*. Drill Cool Systems Incorporated.

Depouhon, A., Denoël, V., & Detournay, E. (2015). Numerical simulation of percussive drilling. *International Journal for Numerical and Analytical Methods in Geomechanics*, *39*(8), 889–912.

Dupriest, F., & Noynaert, S. (2022a). *Drilling practices and workflows for geothermal operations*. IADC/SPE International Drilling Conference and Exhibition.

Dupriest, F., & Noynaert, S. (2022b). *Drilling practices and workflows for geothermal operations*. IADC/SPE International Drilling Conference and Exhibition.

El-Sadi, K., Gierke, B., Howard, E., & Gradl, C. (2024). *Review Of Drilling Performance In A Horizontal EGS Development*.

Epplin, D. (2015). *Drilling Motors for 300oC Geothermal Wells*. IADC Extreme Drilling Technology Forum. https://iadc.org/wp-content/uploads/2015/11/Dave-Epplin-DEC-Presentation.pdf

Gerbaud, L., Pubill, A., Adannawy, H., Rouabhi, A., Lamazouade, M., Souchal, R., & Cuillier, B. (2022). *Mud Hammer Drilling in Deep Hard Geothermal formation, from the single impact to the directional and vibration characterization*. European Geothermal Congress 2022.

Graham, P., Krough, B., Nelson, T., White, A., & Self, J. (2017). *Innovative Conical Diamond Element Bit in Conjunction With Novel Drilling Practices Increases Performance in Hard-Rock Geothermal Applications, California [C]*. 223–227.

Houde, M., Araque, C., Oglesby, K., & Woskov, P. (2021). *Rewriting the Limits for Deep Geothermal Drilling: Direct Energy Drilling Using Millimeter Wave Technology*. Proceedings World Geothermal Congress 2020+1, Reykjavik, Iceland.

Houde, M., Woskov, P., Lee, J., Oglesby, K., Bigelow, T., Garrison, G., Uddenberg, M., & Araque, C. (2021). Unlocking Deep SuperHot Rock Resources Through Millimeter Wave Drilling Technology. *GRC Transactions*, *45*.

Jahangir, E., Sellami, H., & Gerbaud, L. (2022). *Improvement of drilling performances in deep geothermal drilling in hard rocks, by using a novel Hydro-Mechanical Drilling*. European Geothermal Congress 22.

Khaled, M. S., Wang, N., Ashok, P., & van Oort, E. (2023). Downhole heat management for drilling shallow and ultra-deep high enthalpy geothermal wells. *Geothermics*, *107*, 102604.

Oglesby, K., Woskov, P., Einstein, H., & Livesay, B. (2014). *Deep geothermal drilling using millimeter wave technology (final technical research report)*. Impact Technologies LLC, Tulsa, OK (United States).

Olijnyk, T. (2024, February 20). Strada Water Hammer shipped for Geothermal Projects. *LinkedIn*. https://www.linkedin.com/feed/update/urn:li:activity:7159030855720390656/

Pearce, R., & Pink, T. (2024). *Drilling for Superhot Geothermal Energy A Technology Gap Analysis* (Bridging the Gaps to Super Hot Rock). Granite Consulting, Cascade Institute, Clean Air Task Force. https://cascadeinstitute.org/technical-paper/drillingreport/

Petty, S., Uddenberg, M., Garrison, G. H., Watz, J., & Hill, B. (2020). *Path to Superhot Geothermal Energy Development*.

Phuoc, T. X., Massoudi, M., Wang, P., & McKoy, M. L. (2020). A study of temperature distribution and thermal stresses in a hot rock due to rapid cooling. *Journal of Heat Transfer*, *142*(4), 042302.

Pink, A., Patterson, A., & Thoresen, K. E. (2023). *Building a System to Solve the Challenges of Drilling Hot Hard Rock for Geothermal and Oil and Gas*. SPE/IADC International Drilling Conference and Exhibition.

Pink, T., Shiller, J., Pink, S., & Carlson, A. (2022). *The success of world's first Hybrid PDC and Particle Drilling bit for Geothermal Applications*.

Rahmani, R., Pastusek, P., Yun, G., & Roberts, T. (2021). Investigation of PDC cutter structural integrity in hard rocks. *SPE Drilling & Completion*, *36*(01), 11–28.

Rasyid, A., Mardiana, R. Y., Budiono, K., & Noviasta, B. (2021). *Drilling optimization in geothermal exploration wells using enhanced design of conical diamond element bit*. 1795–1808.

Roberts, S. L., Bailey, M. J., Babaie Aghdam, A., Suleiman, A., & Fathy, A. (2021). *Novel Drill Bit Analysis to Delay and Mitigate Fixed Cutter Thermal Damage*. D021S017R002.

Roberts, S. L., Bailey, M. J., Victor, P., Sutan, M., Prasetia, B., & Lock, E. (2022). *Building up steam, a progressive approach to drilling volcanic geothermal formations*. D021S035R006.

Self, J., Stevenson, M., Roberts, T., Rivera, R., & Onderko, L. (2021). Fixed cutter bit & cutter technology set new performance standards for geothermal drilling. *GRC Transactions*, *45*, 826–846.

Song, H., Shi, H., Yuan, G., Xia, Y., Li, J., & Liu, T. (2022). Experimental study of the energy transfer efficiency and rock fragmentation characteristics in percussive drilling. *Geothermics*, *105*, 102497.

Song, X., Li, G., Huang, Z., Shi, Y., Wang, G., Song, G., & Xu, F. (2023). Review of high-temperature geothermal drilling and exploitation technologies. *Gondwana Research*, *122*, 315–330.

Stefánsson, A., Duerholt, R., Schroder, J., Macpherson, J., Hohl, C., Kruspe, T., & Eriksen, T.-J. (2018). *A 300 degree celsius directional drilling system*. IADC/SPE Drilling Conference and Exhibition.

Sugiura, J., Lopez, R., Borjas, F., Jones, S., McLennan, J., Winkler, D., Stevenson, M., & Self, J. (2021). *Oil and Gas Drilling Optimization Technologies Applied Successfully to Unconventional Geothermal Well Drilling*. SPE Annual Technical Conference and Exhibition.

Thorsteinsson, H., Augustine, C., Anderson, B., Moore, M., & Tester, J. (2008). *The impacts of drilling and reservoir technology advances on EGS exploitation*. 1–14.

van Oort, E., Chen, D., Ashok, P., & Fallah, A. (2021). *Constructing deep closed-loop geothermal wells for globally scalable energy production by leveraging oil and gas ERD and HPHT well construction expertise*. D021S002R001.

Vetsak, A., Besoiu, C., Zatonski, V., Torre, A., Hodder, M., & Toews, M. (2024). *The Insulated Drill Pipe-Field Experience and Thermal Model Validation*. D031S021R001.

Vetsak, A., Gerbaud, L., Shor, R., Rogers, A., Jordaan, W., & Toews, M. (2024). *Thermal Effects on Drilling Performance in Hot Dry Rock*. D031S021R004.

Walsh, S. D., & Vogler, D. (2020). Simulating electropulse fracture of granitic rock. *International Journal of Rock Mechanics and Mining Sciences*, *128*, 104238.

Wang, H., Liao, H., Wei, J., Liu, Y., & Chen, J. (2021). *Downhole Stress Release Effect of Grooving by Means of Ultra-high Pressure Water Jet in Deep Geothermal Drilling*.

Woskov, P. (2017). *Millimeter-Wave Directed Energy Deep Boreholes*. AIG DRILLING FOR GEOLOGY II CONFERENCE Brisbane, Australia.

Woskov, P., & Cohn, D. (2009). *Annual report 2009: Millimeter wave deep drilling for geothermal energy, natural gas and oil MITEI seed fund program*.

Zhang, A., Millmore, S., & Nikiforakis, N. (2023). Thermal simulation of millimetre wave ablation of geological materials. *Computers and Geotechnics*, *161*, 105571.

Zhang, Q., Wang, G., Pan, X., Li, Y., He, J., Qi, Y., & Yang, J. (2023). High Voltage Electric Pulse Drilling: A Study of Variables through Simulation and Experimental Tests. *Energies*, *16*(3), 1174.