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ABSTRACT

Recent analysis has shown that by 2050, geothermal energy will be able to supply up to 90 GW of power to the US electrical grid. Reducing the life cycle cost of geothermal wells is critical to achieving this level of adoption. Although time-related costs of drilling remain an important issue, the costs associated with casing and cementing of geothermal wells also warrant attention. This report provides a road map of RD&D activities needed to reduce the life cycle cost of casing and cementing while improving life-of-well performance. The purpose of the road map is to develop priorities for RD&D in the areas of (1) high-performance and cost-effective materials for target geothermal well conditions, (2) well construction methods and techniques to reduce construction costs, and (3) methods and techniques to decrease long-term operating costs. The road map sets targets for the next 10 years and purposely excludes RD&D efforts to improve rock reduction. The road map was developed by a joint working group of experts from Oak Ridge National Laboratory, Brookhaven National Laboratory, and Sandia National Laboratories and 35 experts from industry and academia. Input from a series of information-gathering sessions with experts for industry and academia was used to inform and guide the development of the road map.

1. INTRODUCTION

Recent analyses performed by the National Renewable Energy Laboratory (NREL) in support of the US Department of Energy (DOE) Enhanced Geothermal Shot revealed that by 2050, geothermal energy will be able to supply 90 GW to the US electrical grid [1]. Achieving this level of geothermal electricity generation (nearly 25 times the current installed capacity) will require improvements to the many techno-economic factors that affect geothermal deployment. In particular, lifecycle cost reductions of construction and maintenance are an essential part of achieving the 90 GW target.

Geothermal energy can be used beneficially over a broad range of temperatures (see Figure 1), from low-temperature applications where the heat is used directly to super-hot resources exceeding 400°C used for power production. This road map addresses resource temperatures in the general range of 150°C to 300°C, which includes the bulk of the resources in the NREL analyses that will provide 90 GW to the grid by 2050 [1].

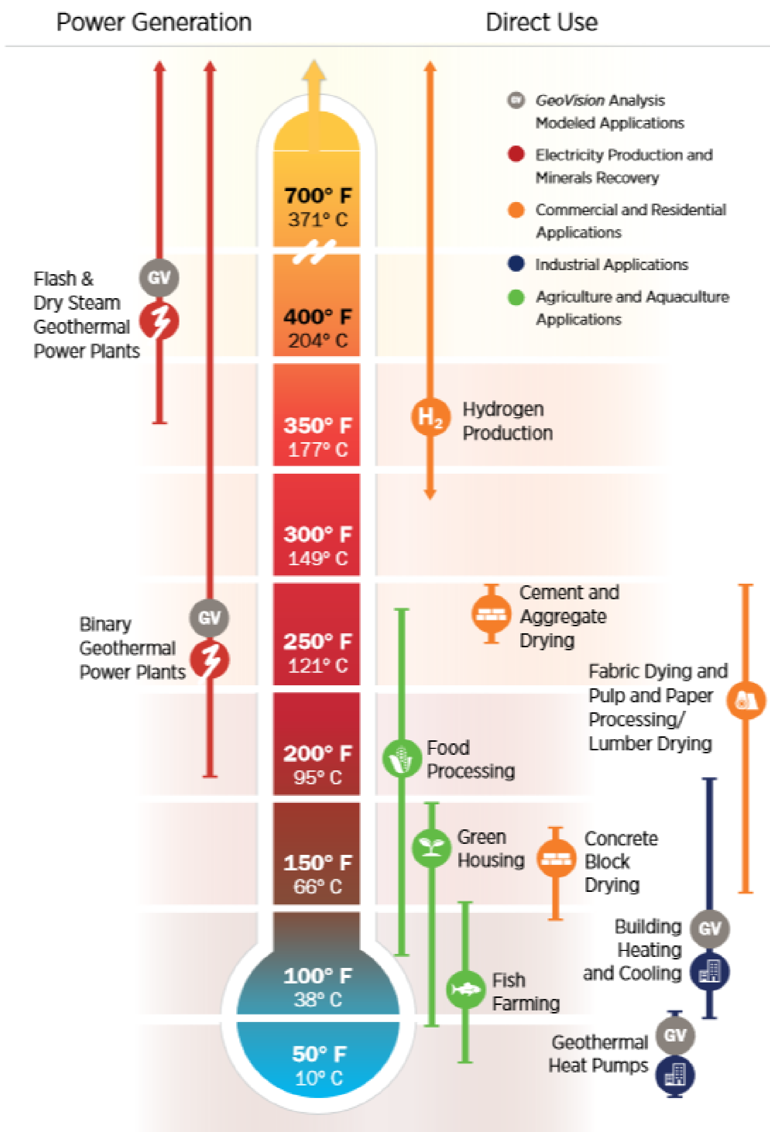


Figure 1. Geothermal applications over broad range of temperatures. Figure reproduced from *GeoVision* [2].

Geothermal electricity production requires subsurface access to thermal resources through drilled and completed wells. These wells, particularly production wells, are generally more expensive than onshore oil and gas wells because of slower drilling rates and larger wellbore diameters. Recent results at DOE's Frontier Observatory for Research in Geothermal Energy (FORGE) have shown dramatic increases in daily average geothermal drilling rates [3], but drilling speed is just one factor in the aggregate costs associated with well development. The costs of casing and cementing geothermal wells, including of the raw materials needed for larger-diameter wells and the time required to run and cement casing, are significant and can account for more than 50% of the cost of a geothermal well [4].

Reducing life cycle cost is essential to spurring the development of more geothermal wells. The DOE Geothermal Technologies Office (GTO) and others continue to direct significant RD&D funds toward reducing the time required for geothermal well drilling. Although the time-related costs of drilling geothermal wells remain an important issue, the costs associated with the casing and cementing of geothermal wells also warrant attention. The GTO's recently published *Fiscal Years 2022–2026 Multi-Year Program Plan* (MYPP) recognizes that well cost is driven by the time needed to drill the well and the materials used in the well construction [5]. The MYPP addresses both these factors and calls for the implementation of a program to reduce the cost of casing and cement required in geothermal well construction. This road map outlines research, development, and demonstration (RD&D) activities needed to the reduce life cycle cost of casing and cementing while improving life-of-well performance with a focus on enhanced geothermal systems. All activities and improvements are also applicable and beneficial to hydrothermal, direct-use, and closed-loop geothermal.

The recently announced Enhanced Geothermal Shot uses the Geothermal Electricity Technology Evaluation Model (GETEM) input parameters for the Technology Improvement (TI) scenario described in the *GeoVision* study [2] as its starting point. Key parameters were updated for the Geothermal Shot analysis based on recent and projected technology advances that are outlined in the GTO's MYPP [5]. For example, drilling costs were decreased to 80% of the ideal-case drilling costs found in the *GeoVision* study. This decrease from the *GeoVision* TI scenario reflects three important technological and engineering advances: an increase in the drilling rate of penetration (ROP) seen at FORGE wells [6, 7], an expected 10% decrease in casing and cementing costs, and the expected decrease in mobilization costs due to the introduction of pad drilling [8].

By focusing on life cycle costs, this road map recognizes that the costs associated with any well used for geothermal energy production includes both the capital costs associated with initial well development and the costs associated with the operation of a well over its useful life. When considering well costs, a balance between capital and recurring operational costs is needed. This road map uses an intentionally broad definition of casing and cement to include any approach or technology that replicates the intended purpose of establishing structural and hydraulic barriers required for well construction.

2. PURPOSE AND PROCESS OF THE ROAD MAP

In this road map, RD&D activities needed to reduce life cycle casing and cementing costs while improving life-of-well performance are divided into three categories: activities related to (1) high-performance and cost-effective materials for geothermal well conditions, (2) well construction methods and techniques that reduce well cost without increasing future operational and ownership costs, and (3) methods and techniques that decrease long-term operating costs without significantly increasing the cost of well construction. This road map purposefully excludes RD&D efforts to improve rock reduction (e.g., drilling ROP and bit life). The road map sets RD&D targets for the next 10 years.

As previously noted, the recently published GTO MYPP identifies a need to address materials costs in geothermal well development, namely casing and cement costs. In response to this plan, DOE initiated a road-mapping effort to guide future RD&D activities in this area. The effort was led jointly by Oak Ridge National Laboratory (ORNL) and DOE/GTO with support from Brookhaven National Laboratory (BNL) and Sandia National Laboratories (SNL). The road map was developed by convening a working group of experts from the geothermal industry, oil and gas industry, and academia with broad expertise in casing and cement materials development and manufacturing, well construction, and long-term well operations. Ultimately, 35 experts participated in a series of information gathering activities including surveys and teleconference meetings. The following charge questions were discussed in depth over the course of four working group meetings:

1. What are the major technology challenges that affect efforts to reduce well construction costs?

2. What are the major market challenges that affect efforts to reduce well construction costs?

3. What are the key performance targets that should be established to guide an RD&D program with the objective of reducing well construction costs?

4. What are the strategic areas of focus or interest that should be pursued as part of an RD&D program with the objective of reducing well construction costs?

These questions were discussed among the panel members, and the information gathered during the discussions guided the development of the road map. The boundaries of the discussions were intentionally broad given the focus on the casing and cementing of geothermal wells; as stated previously, only issues related to the rock reduction process were off-limits during the discussion of the industry experts. Materials, processes, and procedures that affect costs were all open for discussion.

3. CASING AND CEMENTING–RELATED CHALLENGES IN GEOTHERMAL WELL CONSTRUCTION

This section outlines the factors and challenges that affect the casing and cementing of geothermal wells and, where relevant, contrasts these issues with wells drilled by the oil and gas industry. Geothermal wells are drilled in hot lithologies that are commonly stronger and more abrasive than those in the oil and gas industry. Geothermal wells are also generally larger in diameter than land-based oil and gas wells, where the minimum production interval drilled diameter is approximately 8.5 inches but is commonly larger. Additionally, all casing strings for geothermal wells are commonly cemented to the surface to mitigate excess casing expansion during production, unlike general procedures for oil and gas. Formations are often fractured and underpressurized (i.e., in situ fluid pressure is less than that of a hydraulic column to the same depth) leading to issues of lost circulation. Encountered fluids are hot and often corrosive, and common high total dissolved solid (TDS) fluid chemistries can lead to scaling problems in the wells.

3.1 TEMPERATURE, WELL DIAMETER, AND CHEMISTRY

Temperature, well diameter, and fluid chemistry are the most obvious differences between oil and gas wells and geothermal wells. Higher geothermal temperatures create various challenges for materials and well construction technologies and often hinder direct technology transfer between the industries. Because geothermal wells generally have larger diameters, their material costs are higher than those of oil and gas wells at the same depth. Simply up-sizing oil and gas approaches to geothermal applications is often not feasible. The chemistry of geothermal fluids also varies widely but can be very high in TDS and corrosive to well cements and casing, often driving and limiting the selection of well materials.

3.2 LOST CIRCULATION

Geothermal wells are often constructed through poorly consolidated, regularly underpressurized formations and completed in zones of intense fracturing. As a result, a common problem affecting drilling, well casing, and cementing operations is lost circulation, a major cause of nonproductive time in geothermal well development [9]. Lost circulation during cementing and well completion results in major consequences including diminished well safety, reduced annular coverage and possible casing buckling, casing corrosion, poor zonal isolation, loss of completion fluid, down time, formation damage, and (in the worst-case scenario) complete loss of the well. DOE continues to support RD&D directed at drilling-related lost circulation, and although advances are being made in this area, curing lost circulation during drilling may not prevent potential lost circulation during cementing because static and circulating densities of cements are generally greater than the drilling muds used during drilling. An additional issue exacerbating lost circulation during cementing is that geothermal well casing strings are typically cemented to the surface, unlike in oil and gas wells. Fully cementing the entire annulus between the casing and the wall further increases wellbore pressure and can often lead to lost circulation during cementing, even if it was addressed during drilling. In some cases, using properly designed low-density cement slurries has a better chance of mitigating total losses to a vugular limestone than adding lost-circulation materials (LCMs) in the drilling mud [10]. To address lost-circulation problems with cementitious materials, DOE GTO has supported development of a cementitious sealer from industrial by-products. The formulated temporary sealing material was able to seal lost-circulation zones at lower bottom-hole circulating temperatures of 85°C–120°C and self-degrade when temperatures reached bottom-hole static temperatures of more than 200°C [11]. Loss of circulation, however, remains a concern with geothermal well cementing.

In addition to materials and time losses, lost-circulation problems may result in improper cement slurry design because of difficulties in determining cement placement temperature. Cement slurries designed for higher temperatures may take a long time to set in wells cooled down by the large volumes of circulating fluids and may not develop desirable properties, compromising well integrity. Lost circulation can not only result in higher costs and lower quality of a cemented section of casing but can also result in drilling difficulties that necessitate installation of a string of casing that would otherwise not be required, adding significant cost to a well.

To minimize lost-circulation problems during cementing, lightweight cement slurries are commonly used for cementing geothermal wells. For minor and partial losses during cementing of highly permeable formations (<100 barrels per hour), LCMs can be added to cement slurries. Thixotropic cement systems and foamed cement slurries are used to avoid lost circulation in formations with low fracture gradient. Many lost-circulation solutions have limited thermal stability and are costly. In general, lightweight slurries are required by most geothermal well operators. However, hostile underground environments and well operation conditions impose significant stresses on materials. The well fluids are often acidic from strong (hydrochloric, hydrogen sulfide gases) or mild (carbonic) acids, and TDS concentrations reach 200 g/L and higher. Additionally, the well materials may be subjected to thermomechanical-shock conditions during well operations when cold fluids are pumped down the casing and hot fluids are recovered from underground. Under such conditions, lightweight cements are more vulnerable to degradation than cements with regular densities.

3.3 INSPECTION AND CONFIRMATION LOGGING

As options to reduce the life cycle costs of wells (particularly those related to casing and cementing) are developed and deployed, methods for evaluating the efficacy of new technologies or approaches will be needed. Presently, few downhole logging and monitoring tools exist that are suitable for all but the coolest geothermal environments (i.e., less than 175°C). As a result of unique geothermal conditions, the suite of advanced tools and associated well integrity interpretation schemes available to the oil and gas industry (e.g., casing integrity and cement bond logs) are largely unavailable to the geothermal industry. Workarounds (e.g., vacuum flask housings and tubing-deployed logging that allow well cooling while logging) can be used for a select number of tools, but this adds significant costs to well interrogation efforts. In addition to the lack of high-temperature logging tools, multiconductor wireline cables suitable for higher-temperature operations are lacking and not commonly available.

3.4 CEMENT

In most cases, geothermal wells age more quickly than oil and gas wells, especially where cement and casing materials are exposed to highly aggressive and saline environments at high temperatures. Many cementing solutions developed for the oil and gas industry have limited use in geothermal environments or are considered too costly by geothermal operators.

Presently, only one non-Ordinary Portland Cement (non-OPC) cementing solution has been developed and commercialized with the support of DOE GTO specifically for applications in CO_2-rich geothermal wells [12]. Other cementing formulations developed with GTO support to withstand significant thermal shocks and improve heat recovery through well insulation are still undergoing industrial evaluation and optimization before field validation and deployment [13–15]. Many advanced cementitious materials targeting geothermal environments do not reach field trials in part because of the limited geothermal market compared with oil and gas production. Although geothermal wells are arguably the most difficult environments for cements to survive, cement performance requirements specific to geothermal wells are limited to recommendations of compressive strength of 1,000 psi and permeability of less than 0.1 mDa in the United States [16]. Despite performance limitations in harsh geothermal conditions, OPC and its modified formulations remain the material of choice for most wells because of its consistency, availability, and low cost.

A significant challenge in designing geothermal cementing programs is achieving multiple target properties of cementitious slurries for a successful cementing job. In addition to cement, common geothermal slurry designs contain lightweight components, dispersants, fluid loss control agents, free fluids controls, retarders, and antifoam additives. A full portfolio of such additives exists for OPC-based formulations but not for cementitious materials with alternative chemistries. Poor control of slurry properties and inconsistent performance have prevented some possible OPC alternatives (e.g., geopolymers, slag- and grade C fly ash–based formulations) from being utilized. Moreover, the major barriers to using these materials are the absence of information on their performance under the high-temperature, high-pressure, and thermal-shock conditions of enhanced geothermal system (EGS) wells and challenges in controlling their solidification kinetics for safe placement in deep wells [17, 18]. Previous thermal-shock tests with an alkali-activated slag composite, which can be considered an impure geopolymer material, demonstrated that samples of cement sheath around a metal tube may undergo catastrophic failure, breaking into small pieces from hot-to-cold water cycling [19].

The development of lower cost cements that address the demands of high-temperature geothermal wells remains challenging. Although attributing underground well failure to a single factor is generally difficult, the well failures in several geothermal fields have been directly attributed to cement failure caused by extreme well environments and high bottom-hole temperatures [20, 21]. The failure rates of geothermal cementing jobs are difficult to estimate because of the lack of open data and difficulties in attributing well failures to single causes. Based on the open data, the geothermal well maintenance cost was estimated to be approximately 1.2%–3.5% of the total estimated geothermal energy revenues in 2017 [22].

3.5 CASING

The challenging thermomechanical conditions in geothermal wells increase the risk of casing damage caused by heating from well fluids. The temperature transients increase the risk of casing damage from buckling and bending. To avoid casing damage and rapid corrosion, geothermal wells are usually cemented all the way to the surface, unlike oil and gas wells. Although this practice helps to support the tubular well structure, it results in increased volumes of cement, increasing material costs and limiting axial casing movement. Although fully cemented casing provides the benefit of limiting casing growth during well heating, the constraint can cause casing collapse if pockets of fluids remain between cement and casing during the production of hot fluids. Geothermal wells can also be subjected to extreme thermal cycles when wells are brought online and offline during plant maintenance and well workovers. The magnitude and frequency of thermal cycling in geothermal wells and resulting thermal stresses can result in casing failure.

Casing used in the US geothermal industry generally differs from casing used in the onshore and offshore oil and gas industry; the oil and gas industry has standardized size-grade combinations, many of which are applicable across multiple regions or plays. Casing manufacturers favor production for the oil and gas industry because the standardization and quantity of tubulars consumed by the oil and gas industry means mills can efficiently and continuously produce higher volumes of tubulars that are eventually sold. Because the tubulars used in the US geothermal industry are often different from the standardized oil and gas tubulars, mills face higher costs from adjusting equipment to produce geothermal-specific tubulars and lose efficiency because of short production runs. Although the geothermal industry may not be able to match or use oil and gas standardized items, standardization among geothermal operations may be a feasible opportunity and could decrease tubular prices for geothermal development.

When specialty alloys are required to address corrosion concerns, upfront casing costs may be significant. Coating and lining technology in the oil and gas industry has enabled projects to move forward at reduced costs. Although efforts have been made to develop coating and liners for the geothermal industry [23], robust options are not available for the full spectrum of geothermal environments. Coatings have also been shown to inhibit the formation of scale and reduce drag coefficients in oil and gas settings, but to date few materials are available for geothermal operations.

Although the geothermal industry has adapted to casing materials available through oil country tubular goods (OCTG) mills and suppliers, qualification testing of common alloys and connections for geothermal conditions is limited [24, 25]. This general lack of qualification testing requires that specification of materials and connections during well design be based largely on experience and can lead to underdesign or overdesign of a well, potentially affecting the short- and long-term well costs. Casing equipment such as liners, liner hangers, tiebacks, and staging tools are used in geothermal environments, but these systems suffer from reliability issues in geothermal environments and are often avoided.

3.6 WELL DESIGN AND PERFORMANCE DATA

As with casing, geothermal well design suffers from a lack of standardization across the industry. The diversity of geothermal formations, varying downhole conditions, and lower number of well completions all contribute to this issue. Improving the standardization of geothermal well designs may be an opportunity to reduce development costs, facilitate common cost saving measures across the industry, and lower barriers for investment and development.

The availability of detailed well design, construction, and operation data across the industry is limited, and data that are broadly available are generally sourced from DOE-funded drilling operations. This lack of data, particularly regarding problems that require interventions and failure mechanisms, hinders the ability to quantify the industry-wide magnitude of reported well-development and operational issues. The lack of data also inhibits the industry at large from comparing performance and identifying specific areas to improve.

4. MARKET CHALLENGES

The geothermal market lacks volume compared with oil and gas production. No dedicated geothermal industrial supply chain exists, and the geothermal sector must operate with the equipment and materials designed and principally supplied for the oil and gas industry. This results in difficulties in securing the necessary resources including drillers, materials, and contractors for geothermal well construction. Generally more significant well construction challenges, larger wells, higher material volumes per well, and increased sustainability demands all drive up the costs of geothermal well development compared with oil and gas wells.

The lack of geothermal industry–specific standards and criteria for well design, materials, methodologies, and facilities for characterizing performance capabilities with respect to pressure, temperature, and strength are all significant issues. These issues necessarily result in design compromises and limit the ability to develop and deploy well designs that could lower well construction costs. With the bottlenecks in the existing supply chain and long lead times, the oil and gas industry remains a priority for material and equipment suppliers. As a result, the inability to execute expedient deliveries (e.g., in the case of lost circulation) requires large inventories be kept on rigs. Because some materials are not widely available (e.g., calcium-aluminate cements), ensuring these products are available in quantities needed for contingency purposes during operations is costly and challenging. Long and complicated permitting processes further complicate geothermal development.

The small market, limited workforce, long lead times for products, and lack of rigorous standards, mean that the barrier to entry is higher for new geothermal developers, which disincentivizes the development of new geothermal projects. Unfortunately, the lack of new development then limits the number of exploration wells and hence available data and opportunities for the workforce and market to expand to support accelerated geothermal energy production. Breaking this negative feedback cycle is key to improving the market conditions for geothermal well development.

5. TECHNO-ECONOMIC ANALYSES

The following section outlines an economic analysis of geothermal well development with the purpose of helping to identify possible RD&D pathways that can most effectively reduce the cost of geothermal well construction. A time and cost estimation tool was developed based on previous software tools including Well Cost Simplified [26] and updated to include the cost of capital, overhead and labor costs, and greater per-interval parameter flexibility. Scenarios based on a base-case well design were used to outline a range of cost savings that might be achievable with changes in well design, material costs, and other optimizations. Cost comparisons are not intended to be accurate predictions of well costs but to provide guidance for where RD&D efforts would be most impactful.

5.1 WELL TIME AND COST ESTIMATION TOOL

The updated well time and cost analysis model developed and used in this road-mapping effort is based on the Well Cost Simplified tool, which allows cost comparisons between well construction scenarios. The new model is an Excel-based calculator that includes a convenient and flexible method to set parameters by interval, estimates labor/overhead costs, improves formulas, calculates the cost of capital, and generates detailed analysis charts and graphs. As discussed in the following sections, the additional flexibility in setting variables by interval allows for a wide range of scenarios to be explored in a straightforward manner. Example casing inputs are given in Figure 2 and similar tables for drilling, logging, cementing, and techno-economic analysis (TEA) parameters are included in the model.

CASING INPUTS	UNITS	0	1	2	3	4	5
Liner?	yes/no	no	no	no	no		
Tieback?	yes/no						
Casing - Outer Diameter	inches	24.00	16.00	11.75	7.00		
Casing - Weight	lbs/foot	128.00	84.00	60.00	38.00		
Casing - Mateiral Density	lbs/foot^3	500.00	500.00	500.00	500.00		
Casing - Length Shoe Track	feet		25	25	25		
Casing - Height Liner Hanger	feet						
Casing - Rate	feet/hour	100	100	100	100		
Casing - Time Standup + Laydown	hours	4.0	4.0	4.0	4.0		
Casing - Time Wellhead Pressure Test	hours	1.0	1.0	1.0	1.0		
Casing - Time Wellhead Operations	hours	12.0	12.0	24.0	24.0		
Casing - Time BOP Installation	hours	24.0	24.0	24.0	24.0		
Casing - Cost Casing	$/lb	$ 2.00	$ 2.00	$ 2.00	$ 2.00		
Casing - Cost BOP Rental	$/day	$ 2,000	$ 2,000	$ 2,000	$ 2,000		

Figure 2. Example casing input table for the geothermal well time and cost estimate model.

5.2 BASE CASE

The base-case well design was loosely modeled on the Utah FORGE 16B production well [27]. As depicted in Figure 3, the well design comprised a 24-inch conductor pipe set at 100 feet below the surface. Three casing intervals below the conductor pipe extended to 1,100 feet (16 in. casing with 22 in. hole), 4,960 feet (11.75 in. casing with 14.75 in. hole), and 10,197 feet (7 in. casing with 9.5 in. hole). Unlike the 16B well, the base case was assumed to be an entirely vertical well with no directional drilling.

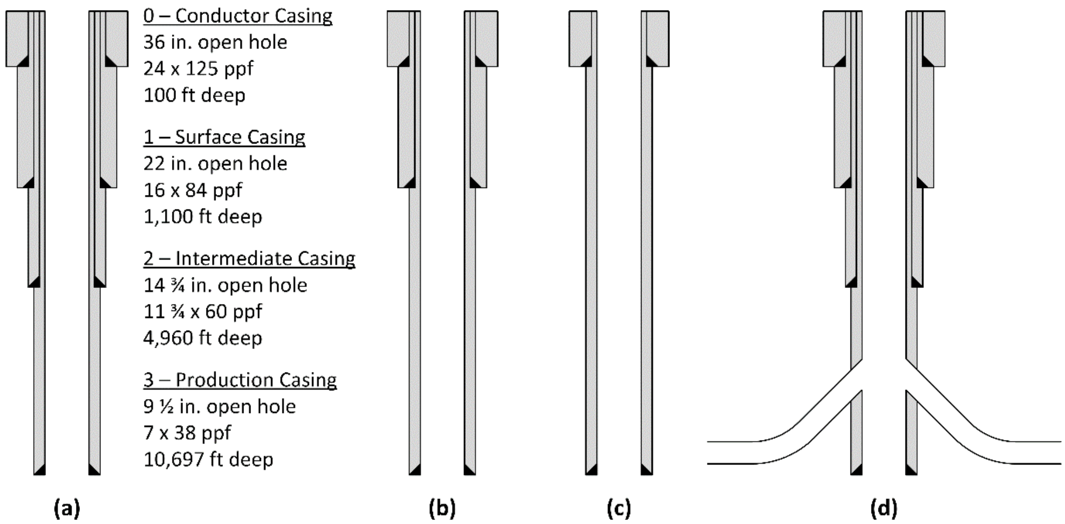


Figure 3. Well diagrams used for economic analysis of different construction scenarios: (a) base case, (b) consolidation of intervals 2 and 3, (c) monobore, and (d) branching below interval 2.

Drilling and casing parameters and costs were modeled on numbers provided in the 2008 *Enhanced Geothermal Systems (EGS) Well Construction Technology Evaluation Report* [28]. That report provided detailed cost, time, and construction summaries from which drilling rates, casing rates, rig costs, and other important parameters were based. These costs are obviously not current but are sufficient to illustrate the relative effects of changes to the well construction system. Breakdowns of interval costs and activities in the analysis were also based on results presented in that report.

The following figures provide an overview of the results for the base-case well design from the new Excel calculator. From Figure 4, drilling accounted for nearly 50% of well construction time and 25% of the overall cost. Casing and cementing activities accounted for approximately 20% of time and almost 30% of the overall cost. All other activities (circulating, bottom-hole assembly handling, blowout prevention, well head operations, logging, standup/laydown, and tripping) made up approximately 40% of the remaining time and 20% of cost. Labor (including overhead) and cost of capital made up the remaining 25% of the overall cost. Figure 5 gives a breakdown of activity time and cost by interval as percentages of the overall totals. These results indicate that improving casing and cementing activities in well construction can lead to significant savings.

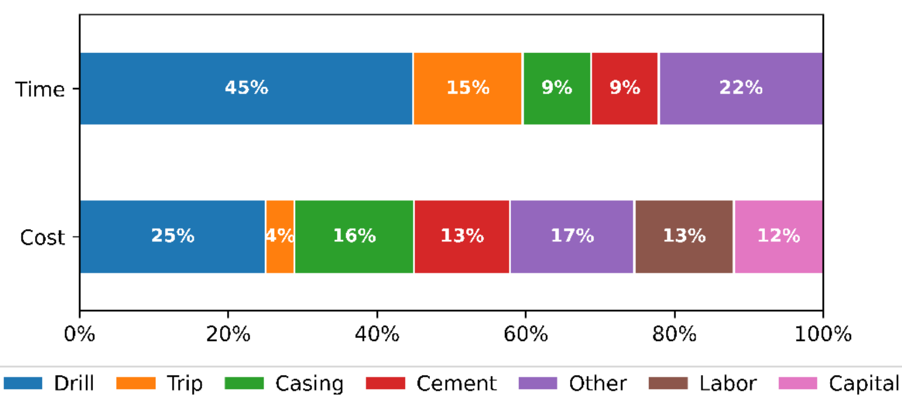


Figure 4. Breakdown of base-case well construction time and cost estimates from the developed model.

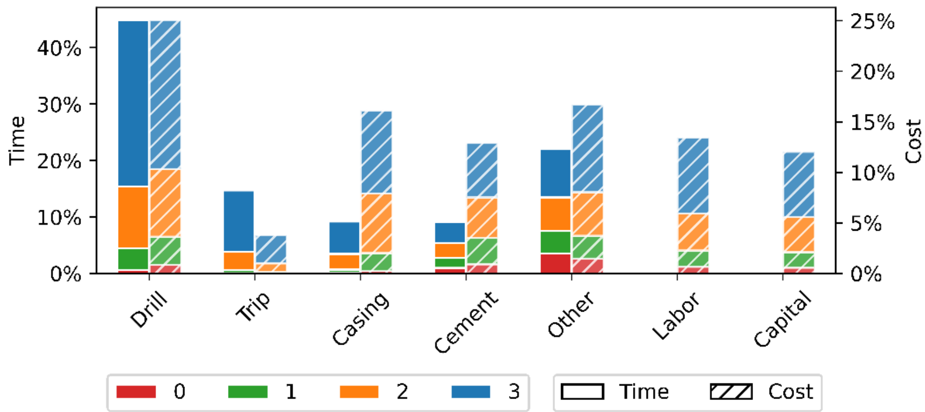


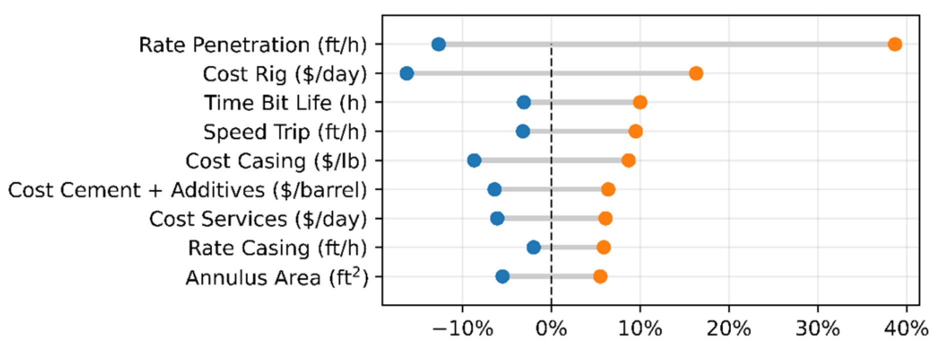
Figure 5. Breakdown of activity time and cost by base-case well design interval.

5.3 SENSITIVITY ANALYSIS

A simple sensitivity analysis was completed to determine which parameters in the well cost estimations had the greatest effect on final cost. Thirty-two parameters were identified for the analysis; each parameter was varied by ±50%, and the change in final cost was recorded. Care was taken to ensure that the varied parameter value still had a true physical meaning. For example, the effect of open-hole diameter was explored by reducing the area of the cementing annulus to ensure that the new open-hole diameter remained larger than the outer diameter of the casing string.

Nine of the parameters tested had an effect of 5% or more on the final total well cost (

Figure **6**). Daily rig cost, ROP, cost of services, bit life, and tripping speed are beyond the scope of this road map report. The asymmetry in ROP and bit life results was due to their assumed low values in the base case[1]. The remaining variables are the cost of casing, the cost of cement and additives, annulus area, and the casing running speed. Results reinforce the idea that RD&D into geothermal well construction that focuses the cost of casing and cementing activities can have a large effect on final well cost. Casing and cement are both large material costs and are affected by the hole size, casing running speed, and the cost of consumables like steel or cement. Reductions in the cost of casing and cement have direct effects on final cost of the well. Reductions in the annulus area mean less cement needs to be used to isolate and secure the well and faster casing running speeds reduce costs associated with rig and casing equipment although this may lead to adverse operational issues that would need to be considered.



[1]The effect on total well cost of time-based parameters such as ROP are geometric in nature. In the limit, reducing ROP to 0 ft/h would result in infinite well cost, whereas an infinite ROP would result in a finite well cost (e.g., cost of casing and cement).

Figure 6. Results of sensitivity analysis showing the effect on final cost of varying the 9 most important variables by ±50%.

5.4 SCENARIO ANALYSIS

Based on results from the sensitivity analysis, a collection of RD&D scenarios described below was identified for further investigation. The scenarios targeted reductions in the quantities of cement or casing steel that are required to be put in the ground. For each scenario, key parameters in the base-case model were adjusted to reflect changes in design or cost of materials for the modified well. Results are summarized in Figure 7, which shows the savings as percentages of the base-case estimated cost. Scenarios are presented to provide a range of cost savings achievable through the pursuit of different RD&D pathways. The current practicality of each scenarios is not considered.

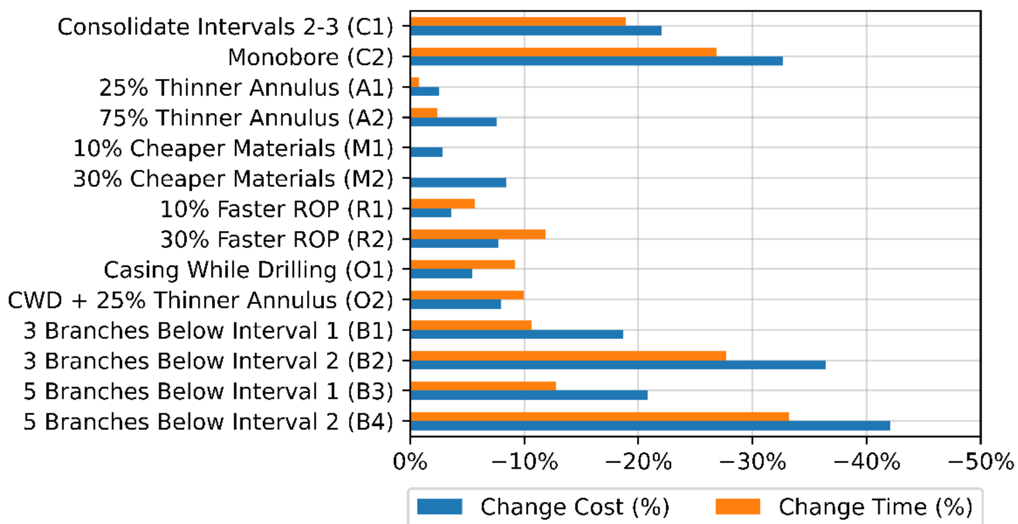


Figure 7. Reductions in base-case geothermal well cost for a selection of RD&D pathways.

The first set of scenarios investigated the effect of reducing the number of casing strings in the base-case design. In scenario C1, intervals 2 and 3 were consolidated, using the smaller casing size for both intervals (see Figure 3[b]). In Scenario C2, the effect of a monobore design was also estimated using the smallest casing size for the entire well below the conductor casing (see Figure 3[c]). Results showed a 22%–32% reduction in final well cost and an approximately 19%–26% reduction in total construction time. Cost savings were mainly the result of significant reductions in total steel and cement and of faster drilling times enabled by the smaller wellbore. Time savings were directly related to the faster ROPs achievable for the smaller diameters.

Reducing the area of the annulus between the open hole and casing outer diameter was also investigated (scenarios A1 and A2). For each interval, the area of the annulus was reduced by 25% and 75%, and the open-hole diameter required to achieve each reduction was calculated. Results showed a 2%–7.5% reduction in cost and a 1%–2.5% reduction in total time. Cost savings were mainly from reducing the total amount of cement required to isolate and secure the well and from small reductions in required pumping time. Along with the consolidated-interval scenarios, these results highlight the time and cost reductions possible from optimizing the base-case well design.

The next set of scenarios focused on well construction parameters. Reducing the cost of casing and cement by 10% and 30% in scenarios M1 and M2 resulted in a modest reduction in total cost (2.8%–

8.5%) and no effect on the total time. Material savings could come from the development of novel materials that can be produced at lower costs while still being suitable for geothermal well conditions. Standardization, particularly for the larger diameter sections, could also reduce material costs and allow economy of scale to further reduce costs. Improvements in ROP for each interval (scenarios R1 and R2) resulted in time savings (3.6%–7.7%) and cost savings (5.6%–11.9%) because of the reduced equipment time and labor time. Scenarios O1 and O2 investigated a casing-while-drilling (CWD) solution by eliminating casing running time, resulting in approximately 9%–10% time savings and 5.5%–8% lower total cost.

The final set of scenarios (B1 through B4) modeled branching of the main well into several child wells, see Figure 3(d) for diagram. Spreading the cost of the parent well across several branches can help to reduce the overall cost compared with the same number of separate well completions. The number of branches was varied and split below the first or second interval. As shown in Figure 7, more branches resulted in greater savings because time and cost were spread over a larger number of intervals. Similarly, savings were larger the deeper the branching occurred. Although technical challenges may be associated with branching wells in this manner (e.g., scaling in shared sections blocking flow), sharing cost over multiple intervals has clear and significant savings benefits.

5.5 KEY TAKEAWAYS

The economic analysis produced a few key takeaways. Reducing the amount of steel and cement required to complete a well can significantly reduce costs. This can be accomplished by changing the open-hole diameter (2%–7.5% cost reduction), consolidating intervals (22%–32% cost reduction), or branching a well to distribute costs across multiple well completions (19%–42% cost reduction). Cheaper materials including simplified material designs and logistics also reduce costs (2.8%–8.5%) and can be combined with other innovations such as casing while drilling to further increase savings. Although outside the scope of this report, improvements in drilling operations and other well construction practices can also reduce completion times and labor, overhead, and equipment costs.

6. PERFORMANCE TARGETS

To meet the goals of the Enhanced Geothermal Shot, well costs need to be reduced substantially. The Enhanced Geothermal Shot leverages the well cost scenarios described in the *GeoVision* study. Marked improvements in drilling rates were targeted in *GeoVision*, and based on the recent drilling performance at FORGE, the geothermal industry is on track to achieve the needed drilling rates. For material costs, namely casing and cement, *GeoVision* did not assume a reduction in the unit costs of materials but focused on the reduction of the amount of casing and cement that are deployed in well development—driving toward a monobore well design. Meeting the Enhanced Geothermal Shot goals will require a nominal decrease in materials costs (approximately 10%) in addition to the reduction of the amount of casing and cement used to construct EGS wells noted in the *GeoVision* study. Reductions in up-front capital costs must be weighed against the life cycle cost of the well.

7. AREAS OF FOCUS

Life cycle cost reduction for geothermal well development will require reductions in the volume of materials required, lower material costs, and reduced flat-time associated costs during construction. The following areas of focus are intended to address these issues. Examples of potential research given in the following subsections are intentionally broad and represent only a small number of relevant examples and concepts that can be considered. Note that although individual solutions may not decrease up-front costs, they may help decrease life cycle costs of the well systems or enable implementation of other solutions.

7.1 REDUCING MATERIAL COSTS

Lowering the unit life cycle costs of emplaced cements and casing materials is required. Measures to reduce these costs can include the development of fit-for-purpose materials or the qualification of existing materials to increase options for qualified cements and casing materials that can be used in the full range of geothermal conditions. The range of possible activities is broad and could include the following:

- Qualification of existing casing grades, casing connections, and cements for geothermal conditions such as temperatures, temperature cycling, and chemistry
- Development of new casing and cementing materials or modifications of existing materials (e.g., coatings in casing where applicable) for improved performance and economics
- Development of casing with reduced friction losses, allowing for smaller diameters
- Development of ancillary cementing materials (e.g., spacers)
- Development of ancillary cementing materials (e.g., spacers, additives) for geothermal conditions
- Development of new systems to convert drilling mud to cement in situ

7.2 MANAGING LOST CIRCULATION

Lost circulation has a direct and often dramatic effect on well-cementing activities, can be a significant factor in the total time associated with geothermal well development, can result in the need to set additional casing strings, and can affect the long-term integrity of the well. Lost circulation problems should be resolved or reduced during drilling with solutions generally dependent on the severity of losses and type of drilling mud used. If losses cannot be cured during drilling or are expected during cementing, a combination of solutions can be employed as discussed in Section 3.2. RD&D directed at mitigating lost circulation during drilling should continue or be expanded, and new programs building on past work in lost circulation during cementing should be initiated. Examples of potential subjects for future research include the following:

- Improved spacers and flushes designed for geothermal conditions that provide lost circulation control under geothermal conditions
- Improved diagnostics of lost-circulation potential prior to cementing operations
- Lost circulation mitigation approaches that eliminate the need to utilize additional casing strings to seal off trouble zones

- Continuation of RD&D into approaches for mitigating drilling-related lost circulation
- Development of alternative cementing systems and approaches
- Development of new cements to cure lost circulation during placement

7.3 WELL DESIGN IMPROVEMENTS

Alternatives to the way geothermal wells are designed and constructed merit investigation. Changes in well design can reduce the number of casing strings required to isolate all sections of the well or enable novel well construction approaches that utilize new or alternative materials and equipment. A common goal would be to develop robust well designs that reduce the volume of materials used along with life cycle cost reduction for well field development. Examples research subjects include the following:

- Alternatives to fully cemented casing where approaches to control casing growth and corrosion are developed
- Creation of leaner casing design approaches through the development of large-diameter casing-while-drilling technologies for deviated wells
- Development and deployment of cementless expandable casing systems
- New well control approaches during drilling to eliminate the need for intermediate casing strings
- Development of standard design approaches and best practices for the range of wells (from exploration to production wells) needed for geothermal development
- Exploration of multi-lateral well designs that reduce the number of large casing strings required for well completion

7.4 WELL INTEGRITY LOGGING AND MONITORING TOOLS

The lack of easily deployable tools suitable for geothermal conditions remains an issue and is particularly acute in well integrity monitoring. Cement and casing integrity can dramatically affect the life cycle costs of wells and is essential to maintaining the industry's social license to operate. RD&D of well integrity logging and monitoring tools should be pursued. Example research subjects include the following:

- Development of logging tools and approaches for evaluating post cementing and long-term well integrity for applications in geothermal conditions
- "Smart" casing and surface-based approaches to monitor long-term well integrity
- Component development to enable development of tools needed for operation in geothermal conditions

7.5 WELL PERFORMANCE ANALYSES

Workovers and interventions are thought to significantly add to the life cycle cost of a well. However, data supporting this assumption is sparse for geothermal applications. A program for reviewing and analyzing geothermal well performance that focuses on workovers and reasons for those workovers should be considered. Although data availability for this analysis may be an issue, if the causes of workovers can be better quantified, RD&D priorities can be more focused. Examples of potential research subjects include the following:

- Initiatives to search public data sources and publications across industry to develop a database of well performance

- Development of a public/private partnership to develop a structured platform for the sharing of well performance data not currently publicly available

8. CONCLUSIONS

A road-mapping effort to guide future RD&D efforts in geothermal well development was led jointly by a team from ORNL with support from BNL and SNL. The working group team organized data-gathering sessions, inviting experts and stakeholders from industry, national laboratories, and academia to help identify limitations of existing technology and processes that contribute to well construction costs. Four teleconference sessions were held focusing on different charge questions meant to seed conversation about different aspects of the problem. Sessions focused on major technology challenges, market challenges, key performance targets, and strategic areas of focus for future RD&D.

Information gathered from the discussion sessions identified several casing- and cementing-related challenges in geothermal well construction. The higher temperatures, larger diameters, and corrosive chemistries of geothermal wells often make using oil and gas solutions unsuitable for geothermal development, leading to higher costs because of custom components and lack of scale. Lost circulation is a major cause of nonproductive time during well construction and drives up completion costs. Lost circulation is common in geothermal wells because of construction in poorly consolidated formations, completion in intense fracturing zones, and often underpressurization of formations. A lack of downhole logging and monitoring tools suitable for geothermal well conditions was identified as a need that must be remedied to better characterize wells and avoid issues during construction. A need for a broader and more economic range of cement materials that can handle a wider range of conditions specific to geothermal wells was also identified. Several issues related to casing, including temperature transients, temperature cycles, corrosion, specialty alloys, coatings, and nonstandard sizes compared with the oil and gas industry, were also discussed. Finally, a lack of data regarding problems and interventions during geothermal well operations was identified as an issue.

Market challenges specific to the geothermal well industry were also identified. Low volume compared with oil and gas production means that no dedicated supply chain exists for the geothermal sector, increasing the time and cost to secure necessary equipment and resources to complete a well. Generally more significant well construction challenges, larger wells, higher material volumes per well, and increased sustainability demands all drive up the costs of geothermal well development compared with oil and gas wells. Scarcity of industry-specific standards for geothermal well design, a limited workforce, and long lead times all create a high barrier to entry for potential geothermal developers. Increasing the number of exploration wells is key to improving market conditions for geothermal development.

The information-gathering sessions were paired with a TEA to identify high-return investment areas for future RD&D activities. Building on past well construction models (i.e., Well Cost Simplified), a sensitivity analysis identified model parameters with the largest effects on overall well cost. Based on the identified parameters, several scenarios were explored to determine how changes to the well design or material costs would affect the cost of a base-case well and included interval consolidation, lower cost materials, and wellbore branching. Results showed that reducing the amount of steel and cement can significantly reduce costs. Branching of the wellbore reduced costs by spreading costs over the shared sections of the well, leading to large cost savings depending on the number of branches. Although outside the scope of this report, improvements in drilling operations and other well construction practices can also reduce completion times and lower labor, overhead, and equipment costs.

From the discussions and the TEA, several key areas of focus for future RD&D were identified to lower well construction costs. The costs of cement and casing materials may be reduced through development of geothermal-specific materials, qualification standards, and yet to be discovered innovative approaches. Cost effective cementing solutions should be prioritized. Lost-circulation management can reduce flat time, reduce the need for additional casing strings, and improve the long-term integrity of the well. Improvements in well design such as leaner casing designs, alternatives to fully cemented casings, or new drilling approaches to eliminate intermediate casing strings are all important areas of research. Finally, expanding the availability of well integrity–logging and –monitoring tools suitable for geothermal conditions can enable better characterization of wells and lower life cycle costs of well construction. These suggestions are meant to help guide RD&D efforts over the next 10 years to further the development and adoption of geothermal energy.

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