U.S. Department of Energy
Advanced Research Projects Agency – Energy (ARPA-E)

Request for Information
DE-FOA-0003448 on
Enabling and Transformative Technologies for Superhot Geothermal Power

Introduction:

The purpose of this Request for Information (RFI) is to seek input from researchers and technologists of various backgrounds, representing a broad range of fields and disciplines, with the goal of evaluating novel approaches to develop superhot (defined as greater than or equal to 375°C and associated pressures of roughly 22 megapascals (MPa)) enhanced geothermal power for generating electricity and other uses. These approaches should accelerate the construction of high-temperature geothermal wells that may include water in a supercritical state, or "superhot". The information you provide may be used by ARPA-E in support of program planning.

Areas Not of Interest for Responses to this RFI: Technologies solely relevant to geothermal environments with temperatures less than 375°C and pressures less than 22 MPa.

RFI Guidelines:

CAREFULLY REVIEW ALL RFI GUIDELINES BELOW.

Note that the information you provide will be used by ARPA-E solely for program planning, without attribution. **THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME.**

The purpose of this RFI is solely to solicit input for ARPA-E's consideration to inform the possible formulation of future research programs. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use information submitted to this RFI without any attribution to the source. This RFI provides the broad research community with an opportunity to contribute views and opinions.

No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E may contact respondents to request clarification or seek additional information relevant to this RFI. All responses provided will be considered, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses. **Respondents shall not include any information in the response to this RFI that could be considered proprietary or confidential**.

Responses to this RFI should be submitted in PDF format to the email address **ARPA-E-RFI@hq.doe.gov** by **5:00 PM Eastern Time on September 30th, 2024.** Emails should conform to the following guidelines:

- Insert "<your organization name> - Response to Enabling and Transformative Technologies for Superhot Geothermal Power" in the email subject line.
- In the body of your email, include your name, title, organization, type of organization (e.g., university, non-governmental organization, small business, large business, federally funded

research and development center [FFRDC], government-owned/government-operated [GOGO]), email address, telephone number, and area of expertise.
- Responses to this RFI are limited to no more than 10 pages in length (12-point font size).
- Responders are strongly encouraged to include preliminary results, data, and figures that describe their potential materials, designs, or processes.

Technical Background:

Geothermal systems have been a reliable source of baseload electrical power and direct use for decades, but in recent years growth has lagged behind that of other renewables, such as solar and wind power, in part due to the geographically limited number of natural hydrothermal systems suitable for power production. The total contribution of geothermal systems to the United States (U.S.) utility-scale electricity production is presently less than 1%.[1] This contribution could be significantly increased by broadening the geographical range of viable sites and improving the power production per field. Estimates indicate that the extractable energy within the upper 3–10 kilometers (km) of the subsurface is 2,000 times the annual consumption of primary energy in the U.S.[2]

Enhanced (or engineered) geothermal systems (EGS) may be able to expand the geographic range of geothermal power, but current EGS efforts are focused on temperatures at roughly 200°C due to equipment constraints.[3] Higher temperature systems (especially "superhot" systems that reach supercritical temperatures and pressures) provide much higher power per well due to the higher enthalpy fluid and increased efficiencies in energy generation at higher temperatures. Superhot is defined as geothermal wells with formation temperatures of 375°C and above, with associated high enthalpy fluids (greater than 2100 kJ/kg). [4] Depending on pressure and fluid chemistry, these wells may also host supercritical water. The capability to reliably extract power from superhot systems could increase average baseload production to 20 megawatts (MW) per well as compared to the present average of approximately 7 MW per well.[4] Successful development of superhot geothermal systems could position baseload geothermal power as a significant provider of U.S. electricity by 2050 at a levelized cost of energy (LCOE) comparable with other dispatchable baseload power technology while expanding the energy source's viability to a wider geographical range in the U.S.

This RFI seeks information about key enabling technologies for development of high-temperature geothermal resources. Equivalent, well-tested, and mature equipment, developed by the petroleum industry, exists for lower temperatures (roughly 200°C) but will fail rapidly at the higher temperatures and corrosive conditions of high-temperature geothermal wells. This RFI focuses on addressing basic technological needs for superhot geothermal energy generation without prescribing a specific approach (e.g., stimulation versus closed loop).

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[1] U.S. National Renewable Energy Laboratory, "2021 U.S. Geothermal Power Production and District Heating Market Report." (2021). https://www.nrel.gov/docs/fy21osti/78291.pdf

[2] J.W. Tester, B.J. Anderson, A.S. Batchelor, D.D. Blackwell, R. DiPippo, E.M. Drake, J. Garnish, B. Livesay, M.C. Moore, K. Nichols, S. Petty, M.N. Toksöz, J.R.W. Veatch, R. Baria, C. Augustine, E. Murphy, P. Negraru, and M. Richards, "The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century." (2006):372.

[3] J. Norbeck, T. Latimer, C. Gradl, S. Agarwal, S. Dadi, E. Eddy, S. Fercho, C. Lang, E. McConville, A. Titov, K. Voller, and M. Woitt, "A Review of Drilling, Completion, and Stimulation of a Horizontal Geothermal Well System in North-Central Nevada". Proceedings, 48th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 6-8. (2023): SGP-TR-224.

[4] T.T. Cladouhos and O.A. Callahan, "Heat Extraction from SuperHot Rock – Technology Development". Proceedings, 49th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 12-14, (2024): SGP-TR-227.

While high-temperature resources occur at shallow depths (less than 3 km) in a few isolated areas, most high-temperature resources will require drilling up to approximately 10 km of vertical depth or more to enable access over a wider geographical range.[5] Wells have been previously drilled to these depths and temperatures, but the equipment and sensors necessary for modern directional drilling cannot handle elevated temperatures. Bottom-hole temperatures can be extremely high and can adversely affect the drill pipe, bit, and associated equipment, including sensors and electronics. This can be mitigated by using drilling fluids to reduce the high temperatures or by insulating the drill pipe.[4]

Well construction presents a more difficult challenge, as it requires cost-effective materials that last 10 to 20 years for casing, joints, and cements. It also requires designs that are resistant to high temperatures and pressures, corrosion, and thermal shock. For stimulated wells requiring fracture creation, techniques and components needed for high temperatures present an additional challenge. These include initiation and control of fracture development, proppants, and characterization of the fracture networks and temperature distributions after creation via tracers.

Efficient operations require an understanding of the borehole and reservoir environment, but few sensing tools can survive at temperatures greater than or equal to 375°C. High-temperature acoustic and temperature sensors are needed. Tools such as imaging logs would be useful and may require high-temperature electronics and batteries (or alternate sources of power), or novel encapsulation methods for optical fibers.

New cost-effective materials will play a key role, but validation of these materials is essential to avoid costly failures after deployment. Simultaneously matching well temperatures, pressures, and chemistry in a test environment is challenging, especially for materials that must survive the length of production. For example, present elastomers are largely inadequate at high temperatures.[6] Validation of alternatives may require a combination of laboratory and in situ tests combined with numerical modeling.

Surface facilities for power production also represent a large portion of the initial capital investment and ongoing operational costs due to corrosion and scaling. While the basic technology is relatively mature, innovative approaches, such as alternate working fluids, could reduce costs. Optimized and constrained borehole flow rates and pressures enabled by specifically designed subsurface components could allow standardized surface facilities. Innovative ancillary revenue streams are also of interest.

RFI Questions:

ARPA-E encourages responses that address any subset of the following topics. The questions present a variety of topics as examples, but do not restrict responses to these topics and may encourage innovative ideas. Information and suggestions from experts outside the geothermal and petroleum industries are especially encouraged. Respondents may provide responses and information about any of the following questions. **ARPA-E does not expect any one respondent to answer all, or even many, of the questions in this RFI.** In your response, indicate the question number(s) (e.g., Response to RFI Section 1. II. a.) you are responding to. Appropriate citations are highly encouraged. Respondents are

[5] D. Blackwell, M. Richards, Z. Frone, J. Batir, A. Ruzo, R. Dingwall, and M. Williams, “Temperature at depth maps for the conterminous US and geothermal resource estimates”. *GRC Transactions*. (2011):35.
[6] T. Sugama, T. Pyatina, E. Redline, J. McElhanon, and D. Blankenship, “Degradation of different elastomeric polymers in simulated geothermal environments at 300 C”. *Polymer Degradation and Stability*”. Volume 120. (2015):328-339.

also welcome to address other relevant avenues or technologies that are not outlined below, except for those that fall under the “Areas Not of Interest for Responses to this RFI” described above.

Section 1: Transformational Technologies for Superhot Geothermal Systems

I. What are the key technological needs to implement superhot geothermal systems?
II. What are state-of-the-art technologies and improvements required to produce superhot geothermal systems (at greater than or equal to 375°C and associated pressures of roughly 22 MPa) for the following topics (and what topics are missing)?
    a. Drilling (e.g., rock reduction, borehole diameter, directional drilling, measurement while drilling, lost circulation, cooling, insulation of drill pipe, advanced mechanical or non-mechanical drilling);
    b. Well construction (e.g., casing, cement, elastomers, cementing, cement evaluation);
    c. Well stimulation (e.g., fracturing fluids, plugs, sleeves, proppants) and understanding of geo-mechanical properties at high temperatures;
    d. Closed loop systems (e.g., U-tube, co-axial, conductive materials); and
    e. Reservoir or borehole characterization (e.g., acoustic logs, resistivity logs, borehole imaging, stress and pressure measurements, fluid composition, logging-while-drilling, tracers, downhole electronics, batteries).

Section 2: New Materials for High-Temperature, High-Pressure, Corrosive Environments

I. What are examples of innovative materials that may be useful but are not commonly used in present geothermal wells (e.g., ceramics, composites, additive-manufactured components)?
II. What methods exist to rapidly accelerate identification of new materials for geothermal wells (e.g., artificial intelligence, machine learning)?
III. What methods (e.g., laboratory, in situ, computational) and facilities are available for testing and validation of high-temperature materials and tools?

Section 3: Operational Needs and Supporting Technologies

I. What are state-of-the-art technologies and possible improvements in power generation?
    a. What conditions are expected for the surface output (e.g., temperature, pressure, fluid composition) of high-temperature geothermal wells, and what challenges are expected in the generation of electricity, either initially or over time?
    b. What are possible alternative working fluids for power generation (e.g., supercritical carbon dioxide)?
    c. What are possible alternative methods of power production (e.g., thermoelectric)?
    d. What are possible direct uses for output from high-temperature geothermal wells?
II. What ancillary revenue streams might exist for superhot geothermal development (e.g., energy storage, critical minerals, hydrogen generation)?
III. What other constraints exist for expanding geothermal production, and how might these be addressed (e.g., availability of water supply, grid connectivity, permitting)?
IV. How does the workforce need to adapt to a dramatic increase in geothermal energy development?
V. What other areas/fields may benefit from technologies developed for superhot geothermal systems?
VI. What experts from outside the geothermal community would be useful to consult?

VII. What are possible metrics to evaluate technologies and materials developed for use in superhot geothermal and related systems?

Section 4: Other

I. Elaborate on any additional technological needs you feel are not covered in the above sections.