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IDA SCIENCE AND TECHNOLOGY POLICY INSTITUTE

FORGE

FRONTIER OBSERVATORY FOR RESEARCH IN GEOTHERMAL ENERGY: A ROADMAP

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Critical Research Areas

	Stimulation Planning and Design	Fracture Control	Reservoir Management
Definition	Research that supports efforts to design and optimally stimulate a well in accordance with natural subsurface characteristics	Research that supports efforts to develop an optimal fracture network as well as increase understanding of the resulting fracture system	Research that supports efforts to sustain long-term heat exchange in the system
Core R&D Actions	• Develop new **well configurations and well field designs** for optimal reservoir stimulation and operation • Develop **new and adapt existing fracturing technologies** and **procedures** for EGS	• **Optimize design of fracture procedures** to reservoir conditions • Develop **alternative injection practices and procedures** • Understand the effect of different **stimulation types** on the resulting fracture system • Develop methods for successful **zonal isolation** during stimulation at high temperatures and pressures	• **Predict and monitor changes** in the fractures system over time • Engineer **solutions to compromised or other unwanted changes** in reservoir permeability that can disrupt operation
Supporting R&D Actions	• Quantify **vertical and horizontal stress** at higher resolution • Correlate **wellbore stress measurements** beyond the wellbore • Correlate **in situ elastic rock property measurements** beyond the wellbore • **Reduce uncertainty** of optimized residence times and reservoir volumes	• **Predict induced seismicity** with higher reliability and accuracy • **Predict changes** in permeability, volume, conductivity, and other factors impacting heat exchange during fracture creation • Conduct **real time in situ monitoring** of key variables to track stimulation and heat exchange potential	• Incorporate in situ, **permanently installed monitoring instrumentation** in wellbore • Develop **active reservoir management** processes, procedures, and tools, including zonal isolation, to avoid thermal breakthrough and optimize flow rate • Resolve **fracture connectivity** and estimate reservoir volume

Enabling R&D

Subsurface Characterization	Drilling	Well Completions	Induced Seismicity Management

Implementation Principles

Cross-Cutting Research Principles	Operational Considerations

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Executive Summary

The Department of Energy (DOE) Geothermal Technologies Office (GTO) tasked the IDA Science and Technology Policy Institute (STPI) to research, design, and develop a roadmap for the Frontier Observatory for Research in Geothermal Energy (FORGE) initiative. The objective of this roadmap is to provide technical research recommendations to DOE GTO, FORGE's Science and Technology Analysis Team (STAT), and the broader research community for the 5 years of FORGE's operation as an enhanced geothermal systems (EGS) research site operated by the Utah FORGE team at the Milford, Utah site. While the roadmap's components are focused primarily on FORGE's 5-year timeline and are appropriate for the geology of the FORGE test site, these activities will also contribute to the knowledge and understanding of how to build future large-scale, economically sustainable EGS systems beyond the FORGE site.

This roadmap is intended for an audience knowledgeable about geothermal technology and research, and EGS topics specifically. The roadmap focuses on describing high-priority research that can advance EGS technology development at FORGE. Non-technical challenges related to EGS commercialization, such as economic, social, and regulatory barriers are not included in the scope of the roadmap.

STPI used several methods to generate the data and information needed as input to the roadmap content. These methods included an August 2018 facilitated workshop designed to elicit input from the EGS research community, a series of interviews held in early 2018 with EGS experts in academia, industry, and the Federal Government, and a review of relevant, recent literature. Once these inputs were synthesized, DOE assessed the relative contribution of each research activity to the overarching goals of FORGE. This assessment then informed the structure and research prioritization included in this roadmap.

The FORGE Roadmap describes discrete actions that could be carried out at FORGE to overcome key technical challenges necessary for EGS to be reliable and reproducible. These actions are organized in the roadmap in three sections: critical research areas, enabling research and development (R&D), and implementation principles. Each section supports the research described in the previous section(s). A visual representation of this approach is shown in Figure 1.

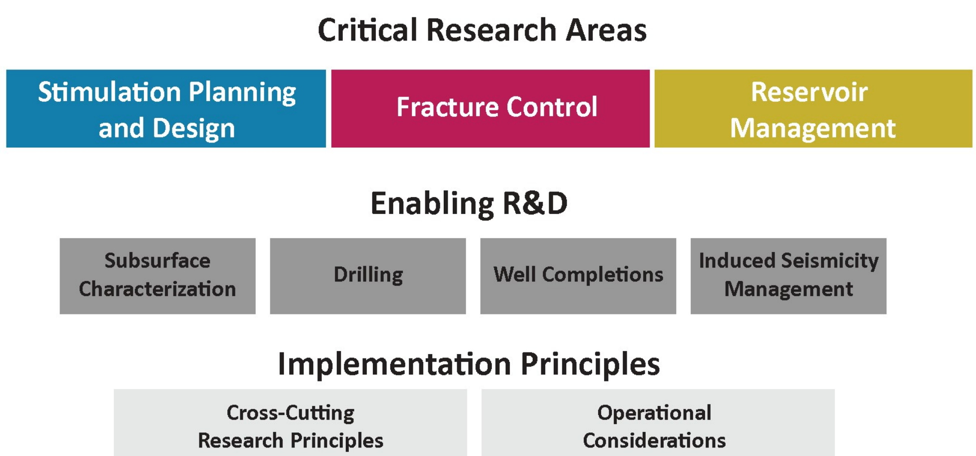

Figure 1: Visual representation of the structure of the FORGE Roadmap

The critical research areas represent the recommended primary foci of research in the FORGE Roadmap. They are:

- **Stimulation planning and design**: research that supports efforts to design and optimally stimulate a well in accordance with natural subsurface characteristics
- **Fracture control:** research that supports efforts to develop an optimal fracture network as well as increase understanding of the resulting fracture systems
- **Reservoir management**: research that supports efforts to sustain the long-term heat exchange in the system

Within each of these critical research areas, the roadmap describes 1) core research actions that are essential in furthering EGS development and 2) additional research that could play a supportive role in furthering EGS development. Core research actions aim to address ongoing technical challenges where there is no known technical solution in the current EGS research landscape or research that must be successfully addressed for FORGE to show progress towards a set of technical solutions that will enable a rigorous and reproducible EGS methodology (Figure 2). Core R&D actions are considered the highest priority research actions within this roadmap and are emphasized over the supporting R&D actions and other roadmap components.

	Stimulation Planning and Design	Fracture Control	Reservoir Management
Core R&D Actions	• Develop new **well configurations and well field designs** for optimal reservoir stimulation and operation • Develop **new and adapt existing fracturing technologies** and **procedures** for EGS	• **Optimize design of fracture procedures** to reservoir conditions • Develop **alternative injection practices and procedures** • Understand the effect of different **stimulation types** on the resulting fracture system • Develop methods for successful **zonal isolation** during stimulation at high temperatures and pressures	• **Predict and monitor changes** in the fractures system over time • Engineer **solutions to compromised or other unwanted changes** in reservoir permeability that can disrupt operation

Figure 2: The three critical research areas of the FORGE Roadmap with their associated core R&D actions

In addition to the three critical research areas that are the central objective of this FORGE Roadmap, the roadmap contains a section titled "Enabling R&D," which describes additional research areas that would facilitate the translation of FORGE's research and results to other sites and contribute to increased EGS efficiency. While these areas are high impact research needs, the underlying tools and techniques are already more technologically advanced than those of the critical research areas and are therefore not central to this roadmap's research priorities for FORGE. The Enabling R&D areas include subsurface characterization, drilling, well completions, and induced seismicity management.

While this roadmap focuses on recommending specific research actions that could be conducted at FORGE, it also recommends implementation principles that were emphasized by the research community as critical to the success of FORGE research endeavors. These principles provide an implementation framework for conducting and managing research at FORGE to facilitate advancement in the critical research areas. They include cross-cutting research recommendations that should underlie the technical foundations of all research conducted at FORGE as well as broad operational considerations for the management of the FORGE facility that are born from lessons learned in previous EGS research efforts.

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INTRODUCTION

The U.S. Department of Energy (DOE) Geothermal Technologies Office (GTO) tasked the IDA Science and Technology Policy Institute (STPI) to research, design, and develop a roadmap for the Frontier Observatory for Research in Geothermal Energy (FORGE) initiative that provides research recommendations for the 5 years of FORGE's operation as an enhanced geothermal systems (EGS) research site. GTO has identified the desired outcome of FORGE as the development of technical solutions that result in a rigorous and reproducible EGS methodology that will enable development of domestic, cost-competitive EGS energy. This roadmap identifies the research activities that, if successfully executed, can help FORGE achieve this goal. It aims to provide strategic guidance for all stakeholders involved in the planning, operation, and funding of technical research taking place at FORGE, including DOE GTO, FORGE's Science and Technology Analysis Team (STAT), and the larger EGS research community.

Geothermal Energy and Enhanced Geothermal Systems

Geothermal energy is a renewable energy source that is derived from heat naturally occurring below the surface of the Earth. In some locations, this geothermal heat is easily accessible and can be used to heat residential and commercial buildings or, in select cases, to generate electricity. Geothermal energy production and consumption (electricity generation and direct-use) currently represents ~2% of the U.S. renewable energy mix (equivalent to ~62,000 GWh/yr).[1] DOE GTO "researches, develops, and validates innovative and cost-competitive technologies and tools to locate, access, and develop geothermal resources in the United States" and is part of DOE's Office of Energy Efficiency and Renewable Energy (EERE).[2]

Some geothermal reservoirs are more difficult to exploit and require subsurface engineering. These reservoir designs are called enhanced geothermal systems or engineered geothermal systems. While technically challenging, successful development of a methodology to generate energy from EGS reservoirs could drastically expand the overall potential energy generation from geothermal resources. Widespread deployment of EGS could enable production of 500 GWe from geothermal energy across the U.S., an order of magnitude more potential than that of conventional geothermal resources.[3] Research and development (R&D) advances in a wide range of geothermal technologies and methodologies, especially those focused on creating and managing engineered reservoirs, are needed for commercially viable EGS.

DOE GTO's current and past research portfolio consists of numerous EGS R&D projects that focus on specific technical issues related to EGS development. These projects have enabled industry to improve EGS capabilities in the near-term. However, DOE identified a need to promote transformative, high-risk R&D beyond the scale of previous DOE-funded demonstration projects or projects the private sector is capable of funding, through a concentrated science and engineering R&D effort to reduce the technical risk associated with developing a full-scale EGS reservoir. In 2014, DOE released a Funding Opportunity Announcement (FOA) for the FORGE initiative as this critical next step towards commercial EGS deployment.

FORGE Background

FORGE is a DOE effort to accelerate R&D in EGS over the next 5 years at a field site near Milford, Utah, operated by a team led by the University of Utah. FORGE's mission is to enable cutting-edge research, drilling, and technology testing, underpinned by a comprehensive instrumentation and characterization effort and open data policy. Through this project, DOE endeavors to facilitate and spur transformative EGS research across the domestic and international geothermal community, with FORGE at

1 EIA Monthly Energy Review. "Table 10.1 Renewable Energy Production and Consumption by Sources." 2018. https://www.eia.gov/totalenergy/data/monthly/pdf/sec10_3.pdf

2 DOE Geothermal Technologies Office website. Accessed January 28, 2019. https://www.energy.gov/eere/geothermal/about

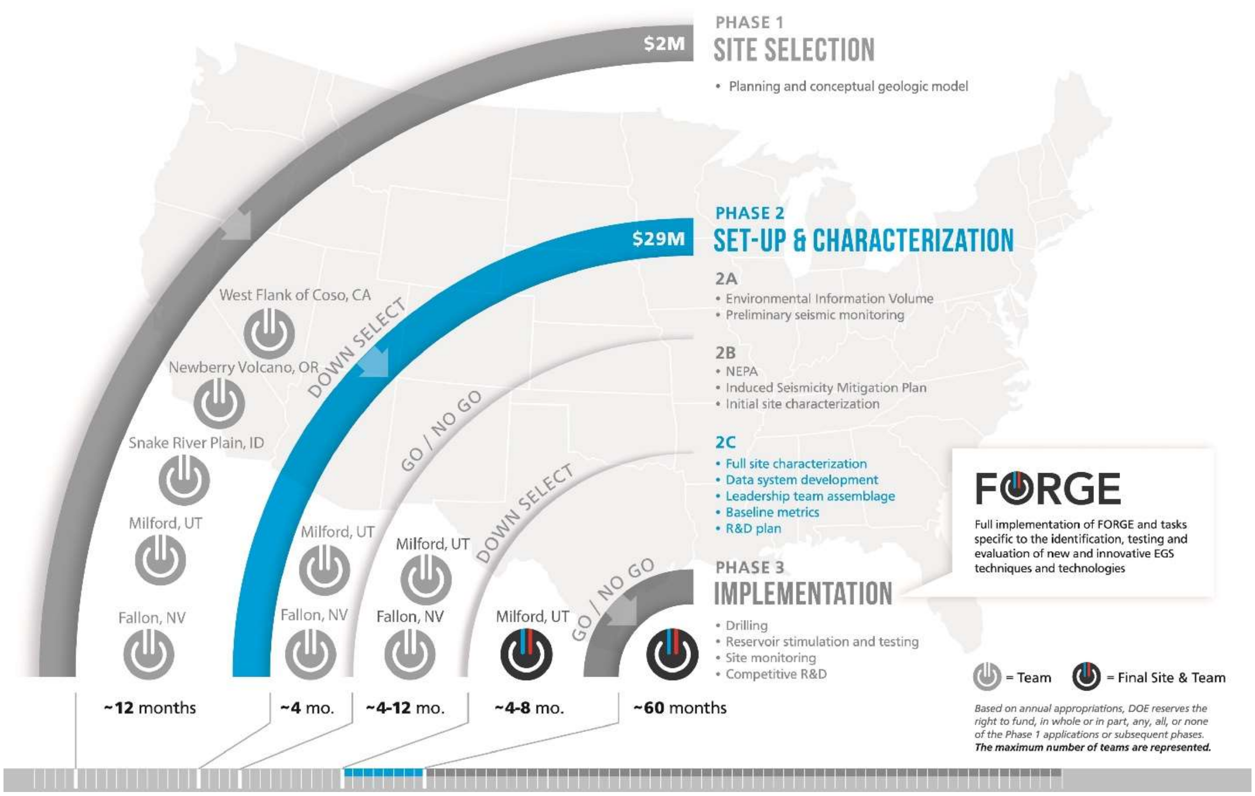
3 USGS (2008), "Assessment of Moderate- and High-Temperature Geothermal Resources of the United States," USGS Fact Sheet, 2008-3082, U.S. Geological Survey.

the center, culminating in a set of rigorous and reproducible EGS technical solutions and a commercial pathway to successful EGS development.

The desired outcomes of the FORGE initiative are to:

- Allow the subsurface research community to develop, test, and improve new EGS technologies
- Gain fundamental understanding of key mechanisms controlling fracture generation, fluid flow, heat transfer, and sustainability of EGS reservoirs
- Enable rapid dissemination of technical data to the research community, developers, and other stakeholders
- Enable a pathway towards a rigorous and reproducible EGS development approach
- Reduce uncertainty and risk for industry

To determine the appropriate site for FORGE's implementation, DOE GTO conducted a competitive, phased site-selection process, initiated with an FOA in 2014. GTO selected five teams who responded to the FOA to develop conceptual geological models and plans for implementing the FORGE initiative at their proposed sites. In 2016 DOE GTO, with recommendations from an independent panel of experts, selected two sites to continue the site development process by undergoing environmental reviews, characterizing their EGS reservoir and site, and conducting preliminary seismic monitoring. These two remaining sites at Fallon, Nevada and Milford, Utah submitted final materials to DOE in March 2018 to inform the final FORGE site selection. Figure 3 shows the basics of the FORGE timeline and down-select process.

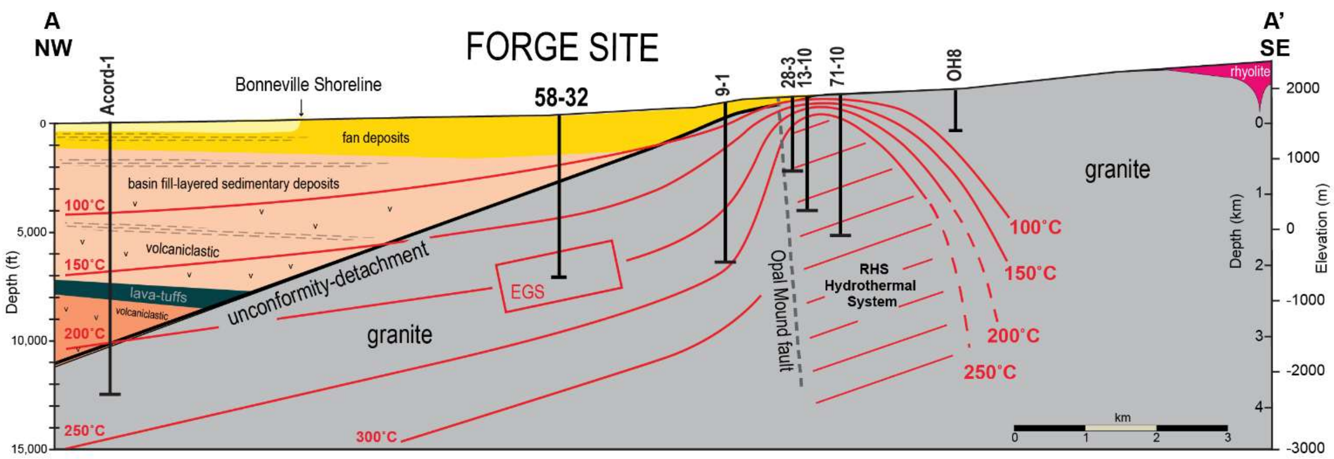


Courtesy of the Department of Energy, https://www.energy.gov/eere/forge/timeline/forge-timeline.

Figure 3: FORGE phases and approximate schedule. FORGE is currently in Phase 2C.

On June 14, 2018, GTO selected the site in Milford, Utah as the final location for the FORGE initiative,[4] beginning the final stage of site set-up and characterization (Phase 2C, shown in Figure 3), which is scheduled to conclude in mid-2019. This stage is followed by the implementation phase (Phase 3) of the FORGE initiative after a final site review is conducted. Phase 3 will be 5 years in duration and will run from approximately mid-2019 to mid-2024. The research recommendations in this roadmap cover this 5-year implementation phase of FORGE at the Utah site.

The Utah FORGE site (see Figure 4) is within a deep, asymmetrical basin. The granite basement is closer to the surface in the eastern part of the site and represents the FORGE test bed. This site has already undergone significant characterization and testing as part of the FORGE initiative, and data have been collected on site subsurface stress and fracture orientations, stress gradients, subsurface permeabilities, temperatures, rock type, and fracture distribution. In addition, a test well has been drilled on the Utah FORGE site to a depth of 7536 feet (2297 meters), in which a maximum bottom-hole temperature of almost 200˚C was measured.[5] Utah FORGE will begin the 5-year implementation period for FORGE that is covered by this roadmap in mid-2019.



Courtesy of Utah FORGE.

Figure 4: Utah FORGE site subsurface mapping of temperature and geologic characteristics

Other DOE EGS Efforts

While FORGE stands alone as a research and development testbed for EGS technology, tools, and methods, DOE GTO is also supporting other targeted efforts to advance EGS research:

- *EGS Collab*: This is an in situ field laboratory where a large collaborative team is performing experimental testing focused on intermediate-scale EGS reservoir creation and related model validation. DOE established this program with its national laboratories in early 2017. Elements of the Collab experiments requiring additional field testing at commercial scale may ultimately be tested at FORGE.
- *EGS Funding Opportunities*: DOE GTO is supporting the targeted development of new tools and techniques that address specific technical challenges. These projects are considered separate from FORGE, but the resulting technology and knowledge may be used as an input to FORGE research and operations, as applicable. A few examples of these types of efforts include:

[4] Department of Energy. "Department of Energy Selects University of Utah Site for $140 Million Geothermal Research and Development." 2018. https://www.energy.gov/articles/department-energy-selects-university-utah-site-140-million-geothermal-research-and

[5] Moore, J., McLennan, J., Allis, R., et al. "The Utah Frontier Observatory for Geothermal Research (FORGE): Results of recent drilling and geoscientific surveys." *Transactions, Geothermal Resources Council*, 42 (2018).

- Zonal Isolation for Manmade Geothermal Reservoirs: In June 2018, DOE announced a funding opportunity of $4.45 million for researchers to develop zonal isolation technologies that allow for the command and control of fractures during EGS stimulation activities, improving the economics and performance of stimulated geothermal reservoirs.
- Machine Learning for Geothermal Energy: In July 2018, DOE announced a funding opportunity of $3.6 million for four to six projects focused on using machine learning to improve exploration and operation processes for geothermal energy.
- Waterless Stimulation: In July 2018, DOE awarded three projects for National Laboratory-led research into advancing the state of the art of waterless stimulation methods for creating and sustaining fracture networks in geothermal environments.
- Efficient Drilling for Geothermal Energy (EDGE): In October 2018, DOE awarded seven projects for researchers to develop and adapt technologies for drilling geothermal wells in less time and with greater efficiency and to accelerate the migration of drilling technologies from the laboratory-scale to the commercial-scale through modeling or other approaches.

In addition to FORGE and the DOE GTO programs listed above, other parts of DOE, such as the Office of Fossil Energy and the Advanced Research Projects Agency - Energy (ARPA-E), are pursuing research to address EGS's toughest challenges. These include topics such as exploring migration of high speed/efficient drilling methods developed as part of the unconventional oil and gas revolution and examination of how changes in tools and methods might impact the cost of successful EGS reservoir operation.

Roadmap Purpose & Scope

This FORGE Roadmap describes critical research areas for FORGE to address key technical challenges facing EGS energy development and strengthen the understanding of the mechanisms controlling EGS success. For each critical research area, the roadmap highlights discrete, core research activities and supporting research activities that could be carried out at FORGE, including how to identify whether progress is being made for each research activity.

The roadmap reflects the input of members of the EGS research community and aims to provide strategic guidance for all stakeholders involved in the planning, operation, and funding of technical research taking place at FORGE. Specifically, it provides recommendations that DOE GTO, the Utah FORGE team, and the FORGE STAT may use as a guide for research solicitations throughout the implementation phase of this initiative. While the roadmap's components are focused primarily on FORGE's 5-year timeline and are appropriate for the geology of the FORGE test site, these activities will also broadly contribute to the knowledge of how to build large-scale, economically sustainable EGS systems that will ultimately facilitate EGS commercialization elsewhere.

This roadmap is intended for an audience knowledgeable about geothermal technology and research, and EGS topics specifically. It is not intended to be a project-level review of research that will be conducted at FORGE—it is an overview of the research areas that, if successfully executed at FORGE, would significantly advance the goal of developing a set of rigorous and reproducible EGS technical solutions. Accordingly, this roadmap does not identify or prioritize individual technologies or potential organizations best suited to address the identified technical challenges.

The methodology used to develop this roadmap focused on technologies, tools, and processes that would advance EGS research, but experts in this area acknowledge that a number of challenges for EGS exist in addition to technical research and development, such as the economic, social, and regulatory barriers. Given the scope and mission of FORGE, this roadmap focuses on the technical challenges associated with commercial EGS development. The non-technical challenges are considered out of scope for the purposes of this document.

ROADMAP DEVELOPMENT METHODOLOGY

STPI used several methods to generate the data and information needed to inform the FORGE Roadmap. This information collection focused on the following:

- The current state of EGS research, including recent successes, failures, and developments;
- The remaining technical challenges and research needs of the field, including unmet needs related to tools, data collection methods, specific data or information, modeling and predictive algorithms, and techniques for drilling and measurement; and
- How these needs and challenges could be addressed by research at the FORGE site, including furthering research in specific areas of EGS and special considerations for the FORGE site in Milford, Utah.

To ensure meaningful and relevant information was gathered on the topics above, STPI created an elicitation strategy that included stakeholder groups with subject matter expertise. This strategy was executed in stages (shown in Figure 5) that built off each other, so outputs from one stage could be used to inform the next stage. There were also reflective processing steps in between each stage to ensure the strategy was on-track towards procuring the data and information needed for roadmap development. The elicitation steps included:

1. Conducting a literature review of relevant EGS strategic planning documents and EGS technology review documents;
2. Holding a series of semi-structured, topical interviews with staff from DOE GTO;
3. Holding a series of semi-structured, topical interviews with a diverse selection of members of the EGS research community; and
4. Organizing and convening a facilitated workshop hosted by STPI in August 2018 that included EGS subject-matter experts from the research community.

The technical information derived from the elicitation process was provided to DOE GTO, which reviewed the research activities and identified those that represented core research to accomplish the objectives of FORGE. DOE GTO also determined which activities represented other supporting or enabling research. Clear focus areas emerged from DOE's review of the research activities generated by the elicitation process, and those critical research areas are used to frame the FORGE research recommendations included in this roadmap. STPI then drafted the roadmap and conducted a peer review of this document prior to publication.

Figure 5: STPI's step-by-step methodology for developing this roadmap

Literature Review

STPI conducted a review of the relevant literature and programs to identify ongoing EGS technical challenges and research needs. This review included U.S. and foreign EGS reviews, roadmaps, and vision studies from the past two decades,[6,7,8,9] as well as the current DOE GTO program portfolio. A number of documents provided information concerning the technical development of EGS that were significant in understanding the context for the FORGE Roadmap. A 2006 MIT report[10] identified the outcomes of important EGS R&D projects dating back to the 1970s, while the 2013 EGS Roadmap[11] provided a framework for conceptualizing major research areas and future research efforts through 2030. Pertinent information from this review was consolidated in a database broadly including overarching goals, technical challenges, research needs, and project examples presented in literature and reports. This knowledge base was used as an input to determine the topics and desired outputs for the interview phase of this development process.

Interviews

STPI conducted face-to-face and phone interviews with representatives from DOE, DOE National Laboratories, industry, and academia to inform the development of the FORGE Roadmap and workshop content. Twenty-four stakeholders were interviewed in two phases: a first set of interviews with officials within the DOE GTO office, and a second with the broader research community, including representatives from the FORGE Phase 3 candidate teams. These semi-structured interviews were intended to gain insight into the technical barriers associated with EGS commercialization. The results of the interviews served as initial input on the roadmap structure and content and directly informed the framework and topics covered in the August 2018 workshop.

STPI developed a generalized interview protocol that focused on, for a given area of EGS research, identifying recent achievements, ongoing technical challenges, which of these challenges are the most important and/or most feasible to address at FORGE, and how to measure progress related to these challenges. The interview protocols were individualized to tailor the areas of research under discussion to the interviewee's area of expertise. In the first phase of interviews, STPI researchers conducted interviews with 14 DOE GTO staff. In the second interview phase, STPI interviewed 10 members of the EGS research community, including representatives from university research groups, DOE National Laboratories, and private industry.

After each interview phase, interview notes were synthesized to identify common themes, specific technical challenges, technical constraints, and input on important milestones and logistical considerations at the FORGE site. All interviews were non-attributional. These synthesized findings were reviewed with DOE GTO staff and their feedback was considered and incorporated when translating the interview findings into the approach, topics, and agenda for the FORGE Roadmap Development Workshop.

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6 Huddlestone-Holmes, C., Hayward, J. "The Potential of Geothermal Energy." Commonwealth Scientific and Industrial Research Organisation (2011).

7 Commonwealth of Australia Department of Resources, Energy and Tourism. "Australian Geothermal Industry Technology Roadmap." (2008).

8 Jeanloz, R., Stone, H., et al., "Enhanced Geothermal Systems." The MITRE Corporation (2013).

9 Olasolo, P., Juarez, M.C., Morales, M.P., D'Amico, S., Liarte, I.A. "Enhanced Geothermal Systems (EGS): A Review." *Renewable and Sustainable Energy Reviews* (2016).

10 Tester, J. W., et al. "The Future of Geothermal Energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century," Massachusetts Institute of Technology and U.S. Department of Energy Report, Idaho National Laboratory, INL/EXT-06-11746. (2006).

11 Ziagos, J., Phillips, B.R., Boyd, L., et al. "A Technology Roadmap for Strategic Development of Enhanced Geothermal Systems." *Proceedings of Thirty-Eighth Workshop on Geothermal Reservoir Engineering* (2013).

Workshop

STPI hosted a FORGE Roadmap Development Workshop on August 9–10, 2018 in Golden, Colorado that was attended by approximately 30 EGS subject matter experts from across academia, DOE National Laboratories, industry, and government. The objective of this workshop was to elicit input from experts across the EGS community to inform the technical foundation of the FORGE Roadmap through facilitated discussions. Workshop participants were provided an overview of STPI's findings-to-date ahead of the workshop, which were based on the outputs of the interviews and literature review. This material included a list of identified technical challenges in EGS as well as suggested "R&D actions" that represented potential FORGE research activities that could address those challenges. These were broken out by the EGS topic areas of Site Planning, Well Development, Reservoir Stimulation, and Fracture Management—the definitions of which are shown in Table 1.

Table 1: Definitions of the four EGS topic areas used to structure the workshop

EGS Workshop Topic	Explanation
Site Planning	Effectively utilizing a chosen site for EGS development, including characterizing the subsurface and selecting wellbore locations
Well Development	Drilling the wells and executing completions
Reservoir Stimulation	Engineering the subsurface to create complex interconnected fracture networks
Fracture Management	Maintaining effective fracture networks and facilitating optimal fluid flow throughout the reservoir

The STPI workshop discussions investigated R&D actions pertinent to the goals and mission of FORGE that are most feasible to accomplish at the FORGE site. The workshop's discussions built off technical input provided to STPI throughout the interview process. In particular, the workshop participants were asked to provide technical input on the following:

- R&D actions that are well-suited to the FORGE timeline, scope, and site geology and address key EGS technical challenges
- Technical milestones for FORGE's 5 years of operation
- Criteria to measure technical progress relative to each R&D action

Workshop participants approached these topics in three separate discussion groups, where each focused on one or two of the EGS topic areas shown in Table 1. Throughout the workshop, STPI facilitators and analysts helped to guide discussions and process participants' input. The workshop sessions were organized such that the technical content that the group generated or validated would inform subsequent discussions. The full workshop agenda can be found in Appendix A.

Processing of Subject Matter Expert Input

The steps in this elicitation process—a literature review of existing EGS technical challenges and research previously performed, semi-structured interviews with subject-matter experts, and the stakeholder workshop—represent a progression of inputs that identified current technical challenges to commercial EGS development and which R&D actions would be applicable to solving those challenges and were within the scope of FORGE. In between each step, with input from the DOE GTO staff, STPI researchers iteratively revised the inputs received into distinct and unique technical challenges and associated R&D actions that are considered feasible for completion at the FORGE site during the 5 years of operation.

After the stakeholder workshop was completed, STPI researchers reviewed all inputs received and developed a revised set of R&D actions to recommend for FORGE. R&D actions that persisted through this final processing step had to meet five qualifications:

1. Addresses a barrier that currently limits reproducibility and reliability of EGS;
2. Has the potential to result in significant advancement of EGS knowledge, tools, or technical capabilities;
3. Builds on an existing proof of concept (e.g., lab scale experiment results, modeling results, results from other EGS field sites, empirical data from other sectors);
4. Relates to performance criteria to evaluate progress; and
5. Is appropriate for the scale of FORGE, the FORGE site, and the scope and timeline of FORGE.

The revised set of technical challenges and associated R&D actions that emerged from the processing of subject matter expert input meet these criteria. These R&D actions and technical challenges were then presented to DOE GTO for a review discussed in the Development of Critical Research Areas section.

Development of Critical Research Areas

Following the development of the revised list of technical challenges, R&D actions, and progress indicators from the roadmap elicitation process, this information was reviewed by DOE GTO. DOE prioritized specific R&D actions that will more directly contribute to the goal of FORGE to develop a set of rigorous and reproducible EGS technical solutions. This prioritization resulted in two categories of R&D actions for inclusion in the FORGE roadmap:

- **Core R&D actions:** areas for which there is no known technical solution in the current EGS research landscape or research that must be successfully addressed for FORGE to show progress towards productive and reproducible EGS.
- **Supporting R&D actions:** research that currently has technical solutions but requires additional basic research and development for these solutions to be used in a robust methodology across the varying characteristics of EGS reservoirs.

Once DOE prioritized the R&D actions developed from the elicitation process, clear focus areas emerged centered around specific technical challenges. These are the roadmap's critical research areas for FORGE and include:

- **Stimulation planning and design**: research that supports efforts to design and optimally stimulate a well in accordance with natural subsurface characteristics
- **Fracture control**: research that supports efforts to develop an optimal fracture network as well as increase understanding of the resulting fracture systems
- **Reservoir management**: research that supports efforts to sustain long-term heat exchange in the system

Outside of the critical research areas described above, this process also yielded supportive research topics that will be important for interpreting and translating FORGE research to other EGS sites and enabling future success in EGS reservoir development. These are included as "enabling R&D" in this roadmap.

Each step of the elicitation process added to the technical foundation of the roadmap and provided a better understanding of how best to represent the technical content. As an example, while the potential FORGE milestones developed in the workshop represented an assessment of the different steps and phases to successful EGS reservoir development, it was ultimately determined that the milestones did not contribute to the R&D actions or technical challenges in a way that was new or different than the currently well-understood EGS reservoir development process. The milestones are therefore not included here. In consultation with DOE, the information derived from the elicitation process was consolidated in the roadmap to provide greatest utility to the managers and operators of FORGE and the greater EGS community.

Subject Matter Expert Peer Review

Prior to the publication of the roadmap, STPI requested the document be subject to a peer review. DOE GTO selected a small group of subject matter experts for the peer review that included representatives from industry, DOE National Laboratories, and academia. Peer reviewers focused primarily on assessing the technical content of the roadmap for accuracy, clarity, and relevancy to the advancement of EGS at FORGE. STPI adjudicated and incorporated input from their review in coordination with DOE.

RESEARCH AT FORGE

Field-scale research and development into EGS technologies, drilling processes, and modeling have taken place since the 1970s. Previous field studies supported by the U.S. and international groups have made significant advances that demonstrate EGS as a technically feasible option for producing net thermal energy.[12] These advances have come through field study investments such as the U.S. field sites at Fenton Hill, Coso, Desert Peak, Glass Mountain, Brady's, Newberry, Raft River, and The Geysers, and international field sites at Rosemanowes (UK), Soultz (France), Cooper Basin (Australia), and Hijiori and Ogachi (Japan).[13,14,15] Additionally, more recently DOE has funded the creation of the EGS Collab,[16] which is designed to be a meso-scale field site to validate modeling output with in situ experiments.[17] These investments have demonstrated current technical capabilities to drill wells, stimulate wells to increase transmissivity, target sites, demonstrate long durations of fluid circulation at rates of 10–30 kg/s, and demonstrate fracture monitoring capabilities.

Technical challenges remain for EGS technologies to develop to the point where commercial viability can be demonstrated—both long-term commercial viability as well as commercial viability in the U.S., specifically. In Europe, EGS development is increasing due to financial incentives and incentives related to European Union commitments under the Paris agreement.[18] These technical challenges span across the life-cycle of an EGS project, but focus on activities involving advancing economically-feasible drilling technologies and approaches, identifying suitable formation characteristics a priori (e.g., porosity, permeability, fracture distribution density, stress state), developing approaches to fracturing and stimulating the reservoir to maintain sufficient permeability, and maintaining a productive reservoir over the life of a commercial project.

Critical Areas of FORGE Research

The ultimate goal of FORGE is to make progress towards furnishing the geothermal energy industry with a set of rigorous and reproducible EGS technical solutions and a commercial pathway to EGS. These research areas will be advanced both through targeted research efforts and through supporting research outlined as "enabling R&D." The roadmap's highest priority research recommendations, the core R&D actions,[19] are shown in Table 2 below.

12 Tester, 2006.

13 Ibid.

14 Ziagos, J., Phillips, B.R., Boyd, L., et al. "A Technology Roadmap for Strategic Development of Enhanced Geothermal Systems." *Proceedings of Thirty-Eighth Workshop on Geothermal Reservoir Engineering* (2013).

15 Tester, 2006.

16 Department of Energy. "EGS Collab." Accessed October 11, 2018. https://www.energy.gov/eere/geothermal/egs-collab

17 Kneafsey, T.J., Dobson, P.F., Blankenship, D., Dobson, P.F., et al. "EGS Collab Experiment 1 overview and progress." *Geothermal Resources Council Transactions* 42 (2018): 735–755.

18 United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement, signed December 12, 2015, https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

19 As previously defined, core R&D actions are areas for which there is no known technical solution in the current EGS research landscape or research that must be successfully addressed for FORGE to show progress towards rigorous and reproducible EGS.

Table 2: FORGE critical research areas and their associated core R&D actions

Critical Research Areas	Core R&D Actions
Stimulation Planning and Design	Develop new well configurations and well field designs for optimal reservoir stimulation and operation
	Develop new and adapt existing fracturing technologies and procedures for EGS
Fracture Control	Optimize design of fracture procedures to reservoir conditions
	Develop alternative injection practices and procedures
	Understand the effect of different stimulation types on the resulting fracture system
	Develop methods for successful zonal isolation during stimulation at high temperatures and pressures
Reservoir Management	Predict and monitor changes in the fracture system over time
	Engineer solutions to compromised networks or other unwanted changes in reservoir permeability that can disrupt operation

Stimulation Planning and Design

State of the Art and Current Challenges

Successful stimulation must be reliable and reproducible to create productive, adaptable, and sustainable reservoirs. The oil and gas industry has significant experience with fracture stimulation; however, research is needed to determine if and how their techniques (based on softer, sedimentary rock) might be effectively adapted to EGS conditions (harder, igneous and metamorphic rocks). Characterizing rock formation and variation, local stress conditions, geochemical interactions, and potential stimulated reservoir volume and connectivity are critical factors in reservoir planning that require new tools and technologies to successfully meet the diversity of reservoir design criteria.

Developing technical capabilities to better understand a site's natural subsurface properties would enhance the ability of site operators to select and optimize well placement for optimal reservoir stimulation. To date, many EGS test wells have been failed hydrothermal wells—i.e., wells of opportunity that were not designed, drilled, and completed with EGS in mind. The preexisting subsurface stress environment and rock mechanical properties dictate natural and manmade fracture shape, extent, and direction. Estimating these factors is key to understanding how they might constrain EGS site development and long-term energy production. Obtaining reliable stress measurements at depth, at EGS temperatures, and beyond the wellbore is an ongoing challenge. Mechanical and chemical properties also influence the behavior of natural fractures under stress; however, predicting the relationship between rock properties and fracture behavior remains a challenge.[20]

Reservoir planning also requires insight into subsurface properties that indicate heat transfer processes and inform optimized residence times and reservoir volumes. Thermophysical properties, such as thermal diffusivity and flow distribution, govern heat transfer processes; however, challenges remain in determining which subsurface properties are critical to measure prior to drilling to predict an EGS reservoir's heat transfer behavior. Furthermore, advanced models that translate these parameters into heat exchange predictions have not been validated. Another pervasive challenge is the development of methods to assess the extent of formations and to correlate rock properties with a high degree of certainty beyond the borehole. Knowledge gaps persist in estimating a site's potential fracture surface area, fracture spacing, fracture size and length, and in modeling and predicting heat transfer even when fractured rock mass properties and well configurations are known.

Desired FORGE Outcome

Research activities at FORGE should aim to advance knowledge, methods, and techniques associated with reliable stimulation planning, design, and execution. At the end of the FORGE timeline, new knowledge that supports modeling efforts to better

[20] Tester, 2006.

characterize the subsurface environment should allow operators the ability to improve stimulation plans and provide added tools and capabilities that facilitate informed, real-time stimulation operations to develop ideal fracture networks.

Core R&D Actions

- **Develop new well configurations and well field designs for optimal reservoir stimulation and operation.** Existing EGS research indicates that there is a key relationship between successful well completions and successful reservoir stimulation. However, further research is needed to better pair casing and completion techniques to specific stimulation techniques for optimal outcomes. Research in this area might explore how completion techniques may facilitate zonal isolation during stimulation and production or the potential to deploy alternative completion techniques, or to adopt unconventional oil and gas stimulation methods. Apart from optimized well completions, understanding the relationship between well design and configurations and reservoir stimulation and operations is a multiple step process that will likely require modeling to couple optimal well design and reservoir operations. Improvements in this area could be determined by examining the heat extraction per unit subsurface volume and extraction rates in wells engineered with R&D-informed orientations, configurations, and completions versus those designed using standard operating procedures.
- **Develop new and adapt existing fracturing technologies and procedures for EGS.** Low volume, high pressure hydraulic fracturing has proven successful in the oil and gas industry to facilitate extraction out of a single well. While EGS differs in that it requires stimulation to connect an inlet and an outlet well, oil and gas stimulation practices may inform EGS stimulation efforts if the appropriate technology can be successfully adapted. Alternatively, other stimulation technologies, such as those associated with thermal, chemical, or energetic processes, may ultimately prove to be more effective for EGS reservoir creation. Progress in this R&D action will require 1) development of generally accepted characterization criteria for asserting that selected stimulation methods may be well-suited to the EGS environment, and 2) demonstration of their effectiveness in creating new pathways or contacting sufficient pre-existing pathways to enable economic recovery of heat. Stimulation experiments at the scale of the FORGE site will contribute to understanding in this area of technology development, and lessons learned from these tests can better inform further experimentation in fracturing technologies.

Supporting R&D Actions

- ***Quantify vertical and horizontal stress at higher resolution.*** Optimized well siting and stimulation planning requires improvements in the accuracy and precision of stress state magnitude and direction measurements. In particular, while using measurements to estimate minimum principal stress is currently achievable, quantifying maximum principal stress at depth and temperature relevant to EGS remains a challenge. Research in this area includes technological advancements to infer in situ stress via indirect or remote methods. Reduced uncertainty in the relative magnitude of maximum and minimum stress and subsequent enhanced resolution of subsurface stress state mapping would facilitate optimal well siting and stimulation planning.
- ***Correlate wellbore stress measurements beyond the wellbore.*** This goal relies upon improving modeling to extend estimated vertical and horizontal stresses beyond the wellbore, including stress magnitude and orientation, as well as other related parameters, such as fracture propagation direction and distance. These models will require higher resolution data from improved surface or downhole sensors and a better understanding of the relationship between fracture slippage, fracture creation, and fracture extension in rock masses. This data can be used to predict or correlate fracture behavior of the rock masses further away from the well. Additionally, it is important to understand how near-wellbore and far-field stress states are altered by the stimulation itself.
- ***Correlate in situ elastic rock property measurements beyond the wellbore.*** Similar to stress measurements, developing new models for understanding how rock properties influence subsurface behavior would provide site operators with more accurate understanding of the subsurface on which to base decisions. One promising approach used today is extending 2D fracture models of the borehole to accurate 3D models of the rock mass. Additionally, coupling models with observations could lead to a better understanding of elastic and inelastic rock properties beyond the wellbore. This knowledge would improve stimulation modeling and thereby inform the success and reproducibility of an EGS methodology.
- ***Reduce uncertainty in estimates of fluid residence times and reservoir volumes.*** Improving the accuracy of estimations of the EGS system variables controlling heat transfer would improve the projection of requisite residence

times and reservoir volumes, thereby aiding in the design of drilling and stimulation plans and increasing the likelihood of long-term sustainable EGS operations. These variables include rock mass properties such as permeability, fracture toughness, pore and fracture volumes, heat capacity, and thermal conductivity and their temperature dependences. This R&D action includes both estimating what residence time will likely result from a given stimulation scenario and projecting desired residence time for the system.

Fracture Control

State of the Art and Current and Current Challenges

Prior field studies have demonstrated to varying degrees technical capabilities to augment natural fracture networks and create manmade fractures that allow for fluid flow and heat exchange. Modeling studies have demonstrated that a distributed fracture network is required for effective heat transfer—a few fractures with high flow rates can lead to early thermal breakthrough.[21] Recovery factors from EGS resources developed to date are typically more than an order of magnitude lower than those corresponding to conventional hydrothermal systems, suggesting that multizonal stimulation is critical for sustained EGS reservoir performance.[22] Additionally, the oil and gas sector has existing injection practices that could be leveraged towards improved selection of fracturing fluid properties once stimulation has been initiated in the desired wellbore interval. Challenges remain in advancing these capabilities and technologies to improve the initiation and control of fractures in order to optimize the resulting network and enhance heat exchange to a degree that can facilitate commercial-scale heat extraction.

An important research area in fracture control is the development of zonal isolation technologies that provide an EGS operator the ability to reliably fracture or access different portions of the reservoir rock. Conventional packer technologies, proppants, and other techniques for temporary or permanent installation commonly used in the oil and gas industry cannot currently operate within the high-temperature EGS environment. Once stimulation is initiated in the desired wellbore interval, measurement and analysis techniques need to be applied to enable intelligent, real-time modification of fracturing fluids and pumping schedules as the stimulation progresses if the job is not going according to plan.

Desired FORGE Outcome

Continuing research needs, both for informed real-time stimulation modification and to guide simulation of long-term EGS reservoirs, include improving the ability to use microseismic events, tomography, and other remote data/observations to advance understanding of rock-fluid interactions and predict reservoir permeability enhancement and fracture propagation through stimulation and fracture modeling.

Research at FORGE in this area should leverage the outcomes of the DOE FY 2018 Zonal Isolation Funding Opportunity Announcement[23] and test full-scale zonal isolation tools that can control and direct where and how fluid interacts with rock. The ultimate objective of this research is to enable permeability enhancement to occur in an orderly, strategic way throughout the wellbore, thereby controlling fracture location and increasing the effectiveness of the stimulation process. If a stimulated fracture or fracture zone's location, size, and shape are controllable, fracture networks are more easily predicted and optimized. An optimized fracture network will establish a productive reservoir, producing more energy from fewer wells.[24] Additionally, increased predictability and control of stimulated fracture networks reduces the risks associated with induced seismicity during stimulation activities.[25]

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21 Doe, T., McLaren, R., and Dershowitz, W. "Discrete fracture network simulations of enhanced geothermal systems." *Proceedings, 39th Workshop on Geothermal Reservoir Engineering*, (2014).

22 Grant, M.A. "Physical performance indicators for HDR/EGS projects." *Geothermics*, 63 (2016), 2-4.

23 DE-FOA-0001945: ZONAL ISOLATION FOR MANMADE GEOTHERMAL RESERVOIRS available on the DOE Energy Efficiency and Renewable Energy (EERE) Funding Opportunity Exchange (https://eere-exchange.energy.gov/)

24 Ibid.

25 Meier, P.M., Rodríguez, A.A., Bethmann, F. "Lessons learned from Basel: new EGS projects in Switzerland using multistage stimulation and a probabilistic traffic light system for the reduction of seismic risk." *Proceedings of World Geothermal Congress* (2015).

Core R&D Actions

- **Optimize design of fracture procedures to reservoir conditions.** Certain fracturing procedures and injection practices are better suited for different reservoir conditions. Understanding how fracture networks form as a result of specific fracture stimulation procedures is critical to creating effective interconnected systems for maximal energy recovery across varied EGS environments. Furthermore, a possible need in this area is to develop and test robust proppants that will not degrade under elevated temperatures; this is critical to effectively sustain open fractures in EGS reservoirs. In addition to developing successful stimulation methods that are broadly applicable to EGS, research at FORGE might elucidate the relationships between various fracturing procedures and geologic reservoir conditions. In developing the fracture network at FORGE, the stimulation design should be optimized based on in situ data on the specific features of the reservoir, including stress fields and pre-existing fractures. Research in this area will inform the development of well-specific stimulation plans; knowledge in this area is especially critical for successful engineering in the subsurface across lithological boundaries, where varying geological units may respond differently to stimulation. Comprehensive coupled modeling tools could be effective in optimizing stimulation strategies.[26,27] Advancing this research area will require improved characterization of thermal-hydraulic-mechanical-chemical processes to better model the response of fractures to stimulation. When combined with improvements in monitoring changes in the fracture network, this research has the potential to track reservoir permeability changes before, during, and after stimulation, which may assist with both informing and verifying expected stimulation outcomes.
- **Develop alternative injection practices and procedures.** Modifying existing stimulation practices, through operations such as sequencing and cycling, has the potential to enhance reservoir creation while minimizing downhole corrosion. Such processes may also impact the frequency and magnitude of associated induced seismic events.[28,29] As an example, sequencing of thermal, hydraulic fracturing, and chemical stimulation at various pressures and volumes could result in more interconnected, complex fracture networks conducive to sustainable heat exchange. Understanding the interactions among multiple stimulation practices might optimize permeability creation and enhancement. Developing a suite of injection practices and procedures will allow operators to adapt operations to unique reservoir conditions to generate sustainable EGS reservoirs in varying geological environments.
- **Understand the effect of different stimulation types on the resulting fracture system.** A better understanding of the relationship between fracturing techniques and the resulting fracture network is essential to creating successful fracture networks. It can also help inform real-time stimulation management and future stimulation planning and design. Characterizing a fracture system during and after stimulation, both in the short-term and the long-term, may elucidate the relationships between fracture techniques and the resulting fracture networks, enabling better understanding of how to control fractures in different scenarios. Progress in this area might include the short-term goal of identifying the effects of different stimulation types on the subsurface with respect to one another, in terms of observables such as seismic, flow, and temperature data, and a long-term goal of predicting these parameters more effectively. A particular challenge in this area, as well as in EGS broadly, is characterizing fluid flow networks resulting from aseismic fracturing.
- **Develop methods for successful zonal isolation during stimulation at high temperatures and pressures.** Zonal isolation is a critical tool in successful reservoir stimulation and management because geological features and associated subsurface parameters can vary with temperature, depth, rock type, and rock structure. These parameters include permeability, in situ stress, fracture density and orientations, and rock mechanical properties. Zonal isolation will enable stimulation techniques and processes to be tailored to specific geologic features at various depths. This control would help ensure the resulting fracture network is appropriately distributed in a manner optimized for heat exchange, rather than containing non-isolated, dominant fractures that have the potential to short circuit the heat exchanger and contribute to accelerated thermal drawdown along these flow paths, resulting in decreased production

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26 Pettitt, W.S., Hazzard, J., Riahi, A., et al. "Simulated microseismicity in geomechanical models with natural and induced fractures." *SEG Technical Program Expanded Abstracts* (2018): 2992-2996.

27 Li, T., Shiozawa, S., and McClure, M.W. "Thermal breakthrough calculations to optimize design of a multiple-stage Enhanced Geothermal System." *Geothermics* 64 (2016): 455-465.

28 Zang, A., Stephansson, O., Stenberg, L., et al. "Hydraulic fracture monitoring in hard rock at 410 m depth with an advanced fluid-injection protocol and extensive sensor array." *Geophysical Journal International*, v. 208 (2017): 790-813.

29 Hoffman, H., Zimmermann, G., Zang, A., and Min, K.B. "Cyclic soft stimulation (CSS): a new fluid injection protocol and traffic light system to mitigate seismic risks of hydraulic stimulation treatments." *Geothermal Energy*, 6:27 (2018).

temperatures over time. There are numerous promising approaches to zonal isolation that are worthy of exploration. One opportunity is to diversify and enhance traditional packers to withstand EGS subsurface conditions by changing materials. Alternatively, packer designs or innovative chemical diverters or thermal materials could be developed that degrade over time as replacements for traditional physical packers. Whether traditional mechanical packers or more innovative diverter designs are explored, successful zonal isolation tools for FORGE would need to be operational at 200°C. In addition to packers, zonal isolation could also be executed through wellbore design improvements, such as permanent control valves. Success in this research area is critical for successful creation and management of an active reservoir over time.

Supporting R&D Actions

- ***Predict induced seismicity with higher reliability and accuracy.*** Researchers continue to advance understanding of the relationship between stimulation, in situ stress state, permeability, and induced seismicity. Ultimately, operators should have forecasting tools to predict the magnitude and distribution of induced seismicity prior to stimulation, within an order of magnitude. Improving the ability to monitor and locate seismic events may provide additional information on the induced fracture system resulting from stimulation efforts.[30] Research in this area might include the application of machine learning or other advanced prediction capabilities to these relationships and work focused on quantifying the relationship between operational parameters, such as cumulative injection volume and injection flow rate, on associated seismic activity. Demonstrating the ability to correlate seismicity with flow rates and injection from the time of the first stimulation to the time of the second stimulation would represent incremental progress towards this goal. Development of improved conceptual and geomechanical models that can be constrained and tested using field data is an important part of this effort. For example, uncertainties remain regarding what specific mechanisms and fluid/reservoir interactions contribute to seismic events.
- ***Predict changes in permeability, volume, conductivity, and other factors impacting heat exchange during fracture creation.*** Subsurface chemical, biological, and physical properties interact to augment or restrict fracture formation that supports sustained heat exchange. These interactions ultimately affect the development of a site's stimulation plan. Research is needed to understand these interactions and provide predictive capabilities to tailor stimulation plans to site-specific conditions. Comparing baseline pre-stimulation parameters such as flow rate, temperature, fracture length, and surface area—or estimating these parameters using advanced methods, if they cannot be measured accurately—with those measured following fracturing is one method for measuring progress in this area. However, quantifying fracture length and surface area remains a challenge, and requires the development of new techniques to measure these critical parameters. Related research efforts might identify what level of uncertainty is tolerable in such prediction capabilities to effectively manage risk in stimulation planning and design.
- ***Conduct real time in situ monitoring of key variables to track stimulation and heat exchange potential.*** Downhole sensors in the injection well and monitoring wells can measure real-time strain rates, pore pressure, and other variables to help inform how changes occur in the subsurface before, during, and after stimulation. In particular, R&D needs include faster data processing and the ability to automate data processing in order to more effectively utilize existing monitoring tools, as well as the development and deployment of new downhole sensors and other monitoring techniques. The information provided by downhole sensors will supply operators with actionable information to adjust operations. Tracking variables such as permeability, volume, and conductivity can contribute to assessments of heat exchange potential. Employing downhole sensors, and translating the real-time data into actionable operational outcomes, is critical to developing a reliable and consistent method for reservoir stimulation. Smart tracers may provide another means of identifying fluid flow paths and effective fracture surface areas, key factors in evaluating heat exchange in a reservoir. Progress in this R&D action can be demonstrated by collecting and processing data more effectively in real time, to provide actionable information for operators. This may involve computational approaches such as machine learning methods for dealing with processing and interpreting extremely large data sets.

[30] Warpinski, N. "Microseismic monitoring: Inside and out." *Journal of Petroleum Technology* 61, no. 11 (2009): 80-85.

Reservoir Management

State of the Art and Current Challenges

Commercially viable EGS will require long-term, sustainable reservoir operations providing continuous, reliable, and sufficient geothermal energy. While EGS research has demonstrated increased transmissivity and long-duration fluid rates (10–30 kg/s range), the EGS community has limited experience in long-term operation and management of an EGS reservoir.[31,32] As a result, activities associated with maintaining and operating the reservoir during its operational phase constitute ongoing technical challenges for EGS development. Long-term operational factors that must be addressed include managing the impacts of changing reservoir geochemistry and geomechanics on the temperature profile and developing techniques to control fluid flow across fractures. These advancements would allow for maintaining effective fracture networks and facilitating optimal fluid flow throughout the reservoir.

Two key aspects of reservoir management include monitoring and managing fluid flow throughout the reservoir to achieve optimal heat transfer performance. Monitoring reservoir conditions will provide operational information on how much and where fluid is maintained within the reservoir system, and if and where it is lost. Advancements in intermittent to continuous monitoring and subsequent mapping of the fracture network, paired with predictive analytics, will be needed to sufficiently track fluid flow and heat transport to facilitate effective reservoir management.

If fluid flow issues are identified, operators require tools and methods to manage and repair the “heat exchanger.” This includes altering the subsurface network to restore the fracture network to its optimal conditions to meet generation requirements. Active reservoir management will require operators to successfully isolate portions of the fracture network to repair fractures and optimize flow and heat transfer throughout the reservoir over time.

Desired FORGE Outcome

FORGE provides a unique opportunity to design an ideal field-scale reservoir and then validate how specific field-scale methods perform in real-world conditions. Through the operation of the FORGE reservoir, significant experience should be gained in developing real-time monitoring of reservoir conditions (e.g., fracture lengths and surface area) and collecting empirical data on interventions, such as zonal isolation and targeted workovers. By the end of FORGE, researchers should have validation of methods, tools, and information needs to successfully isolate a reservoir zone, the ability to reestablish flow through a zone, and demonstrate that a reservoir’s fracture network has not experienced unintended alterations, such as the development of unwanted fast flow pathways that could lead to thermal short circuiting or fluid losses to the surrounding subsurface environment.

Core R&D Actions

- **Predict and monitor changes in the fracture system over time.** Demonstrating sustained flow through a fracture network requires understanding the structural, geomechanical, and geochemical constraints on sustained permeability and predicting and monitoring changes over time. Research is needed to relate changes in reservoir productivity to observed changes in the fracture network from activities such as tracer testing, seismic monitoring, and geochemical monitoring, among others. These activities would provide EGS operators with important information for developing reservoir operation plans and manipulating operations for sustainability. Progress in this area may be demonstrated through comparing modeling results and observational data, as well as the demonstration of new tools to collect and model these measurements.
- **Engineer solutions to compromised networks or other unwanted changes in reservoir permeability that can disrupt operation.** There is a need to develop technical approaches and engineering solutions that maintain long-term reservoir sustainability, whether through reduction or improvements in fracture conductivity, and allow system operators to quickly address and manage compromised fracture network sections. As an example, there are R&D

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31 Tester, 2006.

32 Baria, R., Mortimer, L., and Beardsmore, G. "Development and Sustainability of Engineered Geothermal Systems." *Power Stations Using Locally Available Energy Sources: A Volume in the Encyclopedia of Sustainability Science and Technology Series, Second Edition* (2018): 281-295.

opportunities in exploring the use of additives in injection fluid to address challenges arising due to geochemical reservoir properties and smart valve technologies to facilitate precise control of reservoir fluid flow. Progress in this R&D action can be achieved through demonstration of the ability to eliminate short circuits, quickly and efficiently conduct successful re-stimulations, and to verify these achievements through measurement of variables such as flow rate, temperature, geochemistry, seismicity, tracer return curves, or pressure drop through the fracture system.

Supporting R&D Actions

- ***Incorporate in situ, permanently installed monitoring instrumentation in wellbore.*** Research advancing wellbore instrumentation via an extensive network of downhole sensors can facilitate the collection of rich data sets that will allow high-resolution, in situ monitoring of the subsurface prior to and during stimulations. Successful deployment of robust (i.e., high temperature) and sensitive monitoring instrumentation would facilitate long-term monitoring, which informs assessments of reservoir conditions and experiments, such as in situ stress states, induced seismicity, strain, and permeability. Instrumentation considered for this research should be capable of functioning in an open hole without being disruptive to wellbore operations. Potential research might include chemical and acoustic sensors, fiber optic monitors, nanosensors, smart tracers, and other promising technologies that can sustain data telemetry while operating under high temperature conditions, and examine new tools for monitoring cement integrity that can establish performance baselines and aid long-term monitoring (e.g., electromagnetic, ultrasonic). Regardless of the technology, these tools should be able to operate for long durations within expected ranges of latency (e.g., real time or near-real time data feeds).
- ***Develop active reservoir management processes, procedures, and tools, including zonal isolation, to avoid thermal breakthrough and optimize flow rate.*** Reservoir management processes, procedures, and tools support the development of a reservoir operation plan and the demonstration of sustained flow through the fracture network. Research in this area includes proactive management of the reservoir, as opposed to reactive management of short circuits and other unwanted changes. In particular, zonal isolation techniques, including innovative chemical or physical diverters, may help optimally distribute fluid flow across the fracture network during reservoir operations to avoid thermal breakthrough. With regard to modeling, more robust field-scale fracture models may help operators manage fluid injection and understand water loss in the system. Measuring progress in this area will include manipulating and predicting flow changes in the reservoir through the application of the tools and techniques described. Numerous physical parameters might serve as indicators of these desired changes, as well as additional parameters such as expected versus predicted flow rate, temperature, fracture lengths, and surface area. Zonal isolation might be measured through monitoring flow rates and temperature to ensure manipulations have successfully redistributed flow and not damaged the fracture network.
- ***Resolve fracture connectivity and estimate reservoir volume.*** Fracture surface area contributes to the overall heat transfer between rock and injected fluid. Thus, accurate assessments of fracture connectivity and reservoir volume are critical to determining reservoir performance. The process of identifying active, open, and permeable network components may benefit from increasing the resolution of subsurface fracture network imaging and experimenting with tools such as acoustic emissions, advanced tracers, resistivity tomography, and micro-seismic monitoring. Comparing modeling results and observational data gathered with these new or more innovatively applied tools might demonstrate progress. Tools not traditionally used to measure fracture connectivity that may be more accurate than current methods are of particular interest. This research will support the demonstration of a sustained fracture network connection between wells at FORGE.

Enabling R&D

In addition to the specific research needs outlined in the previous sections of this report, FORGE will serve as an opportunity to continue to enhance knowledge, capabilities, and operational expertise around other aspects of EGS development. This research will facilitate more efficient and sustainable well development by improving current practices. Efforts to address many of the ongoing challenges might benefit from transferring technologies from the oil and gas and mining sectors, such as hardening existing casing materials and existing drilling components for long-duration high temperature and pressure environments. The research described below does not fall into the three critical research areas that emerged from DOE's prioritized research activities; while the following are recognized as high impact research needs, the underlying tools and techniques are already more technologically advanced than those of the critical research areas and are therefore not central to this roadmap's research priorities for FORGE.

- **Subsurface Characterization:** Characterizing critical subsurface mechanical, chemical, and hydrological parameters informs well placement and improves the likelihood of successful stimulation. Additionally, characterizing rock heterogeneity and imaging existing fault and fracture zones not intersected by boreholes would aid in reservoir stimulation efforts. Success in this area would facilitate the identification of critical and sensitive variables to monitor, and ultimately lead to reduced uncertainty in estimating fracture properties, including length, orientation, and density. These improvements in natural fracture characterization will be used to populate discrete and continuum fracture network models and ultimately guide well layout design. Research on reservoir geology could also inform well location and design, as well as the choice of wellbore material. Managing fluid chemistry requires an understanding of acidity, corrosion potential, and reservoir reactivity. Understanding potential chemical impacts of short-term and prolonged subsurface equipment exposure to reservoir conditions may require gas chemistry analysis on mud samples using well-established measurement techniques for gases such as methane, hydrogen sulfide, and carbon dioxide. These analyses would allow operators to choose equipment and wellbore materials suitable to site conditions.
- **Drilling:** Advances and best practices to reduce non-drilling time and improve control of well trajectory will lead to improved methods, processes, and ultimately faster drilling speeds and lower costs. Research to improve drilling speed could include process improvements, such as developing risk registers to optimize drilling processes and development of best practices and protocols, and research into operational improvements, such as using downhole feedback to adjust drilling operations in real time and identifying relevant alternative drilling methods appropriate for testing at the FORGE site. Drilling speed is an area that would likely benefit from leveraging lessons and process improvements from oil and gas operations. Determining the well trajectory in real time and controlling the well profile with more responsive and precise tools will also increase effectiveness of EGS well development. Operators need capabilities to collect and assimilate real-time downhole monitoring data, analyze the data stream, and provide informative input to streamline and expedite drilling operations. Research could explore improvements in drill logging, including effectively using existing oil and gas operator techniques in geothermal drilling, to facilitate the incorporation of real time measurement into drilling operations to enhance operators' responses and improve well profile control.
- **Well Completions:** Developing new casing materials, cementing methods, and essential well-bore completions that can withstand the high temperature and potentially corrosive nature of the reservoir fluids and formations is essential to the long-term sustainability of an EGS well. Development and deployment of innovative, strong, corrosion-resistant well construction materials (facilitated by adapted drilling equipment to accommodate these new materials as needed) would reduce the risk of well degradation, thereby minimizing the frequency of well workovers and re-drills. Research into these issues could involve developing or exploring alternative casing connections and new or adapted materials to improve well integrity, such as advanced concretes or steel. Characterizing how the extreme temperature, pressure, and chemical conditions test materials to their mechanical strength limits would help prioritize research in this area and better understand limitations of current options and technology for EGS.
- **Induced Seismicity Management:** Mitigating induced seismicity through operational best practices has been a central component of EGS site characterization and reservoir development. Practicing and continuing to improve the best available protocols is essential to mitigating the risk of induced seismicity. FORGE will present an opportunity to test and revise this protocol as needed. Success in this area would be represented by the ability to conduct operations in such a way as to avoid unexpected induced seismicity.

FORGE IMPLEMENTATION PRINCIPLES

As the FORGE initiative embarks on the implementation phase (Phase 3) of the research facility, the EGS research community identified cross-cutting principles of research and operational considerations that are imperative to the success of FORGE. These principles provide an implementation framework for conducting and managing research at FORGE to facilitate advancement in the critical research areas. They are not intended to target any one specific research action or technical challenge, but rather to underlie and streamline all research at FORGE.

Cross-Cutting Principles for Conducting Research at FORGE

Robust data management, modeling, and benchmarking principles should underpin research at FORGE to ensure that data are high quality and usable beyond the operational lifetime of FORGE. This effort can ensure progress towards a set of technical solutions that will enable a reliable and reproducible EGS methodology and provide a strong foundation for future work. The following principles support this endeavor and are cross-cutting with respect to the technical content; they should therefore be considered by FORGE participants and incorporated into all relevant research activities.

- **Incorporate uncertainty into geological and geomechanical models.** Physical measurements carry an inherent uncertainty associated with instrumentation and environmental conditions. This systematic uncertainty is often not incorporated and propagated in the creation of predictive models. Conceptual models form the underpinnings for developing robust numerical models of the EGS reservoir, and incorporation of measurement characteristics such as accuracy and precision, as well as the frequency of tool calibration and calibration methodology, should be considered in model creation as well. The incorporation of uncertainty and these other factors would contribute to the identification of the most critical and sensitive parameters in various reservoir models and would provide operators and researchers with more holistic and statistically robust model results to inform decision making.
- **Improve ability to update models in near real-time to guide decision-making.** As new data are collected at the FORGE site, existing conceptual models for the site should be updated and revised accordingly. The models should be based on a synthesis of all available information (geologic, geophysical, geochemical, hydrological, geomechanical, etc.). Also, it is critical that alternative models be evaluated and considered when there are contradictions between field observations and model predictions. For example, having the ability to update models on short timeframes and incorporate newly available data would provide drilling and reservoir operators with information to assess unexpected circumstances encountered in real time. The traditional paradigm of collecting data and then modeling does not encourage feedback in such living models. Furthermore, these complex models are difficult to update and currently do not provide updated insights on a timescale that would assist real-time decision making. Research should identify opportunities where considering timeliness as a design parameter would benefit EGS operations and develop models that provide this functionality.
- **Develop methods for addressing issues with scaling datasets (small-scale models, etc.).** Researchers struggle to scale existing datasets for use in a larger-scale environment, including extrapolating from localized or small-scale measurements to reservoir or regional-scale estimates. Developing methods to evaluate the representativeness of datasets and reduce uncertainty in scalability would improve overall site characterization and inform well location and orientation.
- **Develop a comprehensive baseline for existing equipment used in EGS research and development to set benchmarks for what technologies need to be advanced at FORGE.** While previous experiences provide potential baselines for a subset of equipment used in EGS development, FORGE provides an opportunity to update and create a more comprehensive baseline for current technologies as well as technical and performance criteria for improvements in these technologies. This work would provide information to measure progress at FORGE, compare progress and advancement in technologies pre and post FORGE, and establish baselines for future research efforts.

Operational Considerations for FORGE

The elicitation process yielded a number of ideas from the EGS research community that could inform the operation of the FORGE site but did not fit within the structure or scope of the roadmap's R&D actions presented in the "Research at FORGE" chapter. These are largely observations associated with lessons learned in previous EGS research that subject matter experts thought should be provided as guidance for the implementation phase of FORGE. While they are presented at a higher level than other recommendations throughout the roadmap, these considerations can prompt FORGE operators to prioritize research that incorporates collaborations and considers the broader context for data collection efforts. In no specific order, the considerations for operating the FORGE site noted by the research community include:

- **R&D collaboration:** There are important elements of research that are critical to the advancement of EGS across multiple topics, such as model development and validation, tool development, instrumentation planning, and data utilization for decision making. Collaboration across these research elements will be critical to maintaining consistency and continuously utilizing the best available data. Furthermore, FORGE research has a clear relationship to (and dependence on) lab work, such as that conducted via the EGS Collab project. Ongoing communication and collaboration with laboratory researchers and computational modelers throughout the EGS research community will provide key insights and help understand observations made at the FORGE site. Finally, collaboration with industry will complement FORGE research efforts; for example, some EGS advancements can be achieved through learning processes and adapting technologies employed in the oil and gas industry. Collaboration with international EGS research efforts can help leverage new findings from other EGS field sites.
- **Data collection and dissemination:** Instrumentation is a key consideration in the planning and implementation of many areas of research at FORGE. Extensive instrumentation and long-term monitoring of key parameters (e.g., flow testing, downhole seismicity) will ensure data collection is meaningful. Accurate and thorough collection of data that can be shared with the broader research community is a key objective of FORGE. High quality data is desired more than a high quantity of data.
- **Framing success:** R&D conducted at FORGE should have clear, actionable objectives and desired outcomes. Metrics that track progress in advancing knowledge or technical capabilities need to be identified and baselined prior to the implementation of each research effort. Documenting incremental advancements stemming from R&D efforts is critical to prioritizing subsequent research projects and to measuring the overall success of FORGE.
- **Quantifying and managing risks:** FORGE has the dual purpose of taking risks to push the boundaries of EGS scientific understanding while also mitigating risk by vetting technologies before deploying them in EGS fields. These concerns were especially prevalent for high-risk, high-reward technologies, such as those that enable zonal isolation. Potential methods for mitigating risk might include graduating technologies from laboratory settings to field testing in empty wells before deploying in the full-scale wellbore.
- **Communicating with the public:** Successful EGS reservoir development and operations require that accurate technical information be communicated to public stakeholders who have an interest in the project's operations. Important work remains in continually updating existing best practices and guidance to facilitate public communications about induced seismicity risks and other issues related to EGS development such as water usage and noise.

CONCLUSION: A PATHWAY FORWARD FOR EGS

Widespread deployment of EGS could enable production of 500 GWe from geothermal energy across the U.S., an order of magnitude more potential than conventional geothermal resources.[33] FORGE has the opportunity to fill critical scientific knowledge gaps that exist today in EGS and develop techniques to overcome challenges that have consistently constrained commercial EGS development. The FORGE Roadmap seeks to point research at FORGE towards a longer-term pathway to success for EGS. While technically challenging, successful development of a methodology to generate energy from EGS reservoirs could drastically expand the overall potential energy generation from geothermal resources.

FORGE's mission is to enable cutting-edge research, drilling, and technology testing, underpinned by a comprehensive instrumentation and characterization effort and open data policy. More specifically, the desired outcomes of the FORGE initiative are to:

- Allow the subsurface research community to develop, test, and improve new EGS technologies
- Gain fundamental understanding of key mechanisms controlling fracture generation, fluid flow, heat transfer, and sustainability of EGS reservoirs
- Enable rapid dissemination of technical data to the research community, developers, and other stakeholders
- Enable a pathway towards a rigorous and reproducible EGS development approach
- Reduce uncertainty, risk, and cost for industry

This roadmap provides a framework for achieving these outcomes by describing three critical research areas, enabling R&D, and supporting cross-cutting research principles and operational considerations. Research conducted at FORGE will address critical EGS challenges, while maintaining operational discipline and scientific rigor with respect to data collection and implementation of research. The three research areas identified as being most critical for FORGE to enable future EGS success are stimulation planning and design, fracture control, and reservoir management.

DOE's concept of a transformative, high-risk R&D field laboratory for EGS development beyond the scale of previous demonstration projects has become a reality. The next 5 years will determine how the FORGE initiative contributes to EGS technology and research. If FORGE can successfully execute the core research actions and research implementation principles discussed in this roadmap, then it can chart a pathway to success for developing a rigorous and reproducible EGS methodology and move our Nation closer to the vision of a future with 500 GWe of renewable, geothermal energy.

[33] USGS (2008), "Assessment of Moderate- and High-Temperature Geothermal Resources of the United States," USGS Fact Sheet, 2008-3082, U.S. Geological Survey.

APPENDIX A: FORGE ROADMAP DEVELOPMENT WORKSHOP AGENDA

STPI hosted the FORGE Roadmap Development Workshop on August 9–10, 2018 at the DOE and National Renewable Energy Laboratory (NREL) offices in Golden, CO. The workshop was attended by approximately 30 subject matter experts and stakeholders from across academia, the DOE National Laboratories, industry, and government. The agenda for the workshop is presented below.

Thursday, August 9, 2018	
Time	**Title**
8:00 – 8:30	REGISTRATION & REFRESHMENTS
8:30 – 8:50	Welcoming Remarks
8:50 – 9:10	Workshop Opening & Scope
9:10 – 9:30	Introduction to Breakout Session 1
9:30 – 9:50	BREAK
9:50 – 11:20	Breakout Session 1: *R&D Actions at FORGE*
11:20 – 12:00	Breakout Session 1 Report Outs
12:00 – 1:00	LUNCH - State of the FORGE Site
1:00 – 1:20	Introduction to Breakout Session 2
1:20 – 2:20	Breakout Session 2: *FORGE Timeline & Milestones*
2:20 – 3:00	Breakout Session 2 Report Outs
3:00 – 3:15	BREAK
3:15 – 3:35	Introduction to Breakout Session 3
3:35 – 4:45	Breakout Session 3: *FORGE R&D Action Dependencies*
4:45 – 5:15	Breakout Session 3 Report Outs
5:15 – 5:30	Day 1 Wrap Up
Friday, August 10, 2018	
Time	**Title**
8:00 – 8:15	MORNING REFRESHMENTS
8:15 – 8:45	Opening and Framing Remarks
8:45 – 9:05	Introduction to Breakout Session 4
9:05 – 10:35	Breakout Session 4: *Criteria for Technical Progress*
10:35 – 10:50	BREAK
10:50 – 11:30	Breakout Session 4 Report Outs
11:30 – 12:15	Closing Group Discussion
12:15 – 12:30	Wrap-Up and Closing Remarks

APPENDIX B: ORGANIZATIONS REPRESENTED IN THE ELICITATION PROCESS

STPI worked with subject matter experts and stakeholders from 17 organizations across government, academia, and industry throughout the interview process and workshop. The organizations listed here are those that were represented in one or both of these key roadmap development steps.

1. AltaRock Energy
2. EGS Energy Limited
3. Fervo Energy
4. Great Basin Center for Geothermal Energy
5. Idaho National Laboratory
6. Lawrence Berkeley National Laboratory
7. Lawrence Livermore National Laboratory
8. National Renewable Energy Laboratory
9. Navy Geothermal Program Office
10. Ormat Technologies
11. Sandia National Laboratories
12. Stanford University
13. U.S. Department of Energy
14. U.S. Geological Survey
15. University of Oklahoma
16. University of Strasbourg
17. University of Utah

APPENDIX C: WORKS CITED

Baria, R., Mortimer, L., and Beardsmore, G. "Development and Sustainability of Engineered Geothermal Systems." *Power Stations Using Locally Available Energy Sources: A Volume in the Encyclopedia of Sustainability Science and Technology Series, Second Edition* (2018): 281-295.

Commonwealth of Australia Department of Resources, Energy and Tourism. “Australian Geothermal Industry Technology Roadmap.” (2008).

DE-FOA-0001945: ZONAL ISOLATION FOR MANMADE GEOTHERMAL RESERVOIRS available on the DOE Energy Efficiency and Renewable Energy (EERE) Funding Opportunity Exchange (https://eere-exchange.energy.gov/)

Department of Energy. “Department of Energy Selects University of Utah Site for $140 Million Geothermal Research and Development.” https://www.energy.gov/articles/department-energy-selects-university-utah-site-140-million-geothermal-research-and

Department of Energy. “EGS Collab.” Accessed October 11, 2018. https://www.energy.gov/eere/geothermal/egs-collab

Doe, T., McLaren, R., and Dershowitz, W. “Discrete fracture network simulations of enhanced geothermal systems.” *Proceedings, 39th Workshop on Geothermal Reservoir Engineering*, (2014).

EIA Monthly Energy Review. “Table 10.1 Renewable Energy Production and Consumption by Sources.” 2018. https://www.eia.gov/totalenergy/data/monthly/pdf/sec10_3.pdf

Huddlestone-Holmes, C., Hayward, J. “The Potential of Geothermal Energy.” Commonwealth Scientific and Industrial Research Organisation (2011).

Jeanloz, R., Stone, H., et al., “Enhanced Geothermal Systems.” The MITRE Corporation (2013).

Kneafsey, T.J., Blankenship, D., Dobson, P.F., et al., “EGS Collab Experiment 1 overview and progress.” *Geothermal Resources Council Transactions* 42 (2018): 735–755.

Grant, M.A. “Physical performance indicators for HDR/EGS projects.” *Geothermics*, 63 (2016), 2-4.

Hoffman, H., Zimmermann, G., Zang, A., and Min, K.B. “Cyclic soft stimulation (CSS): a new fluid injection protocol and traffic light system to mitigate seismic risks of hydraulic stimulation treatments.” *Geothermal Energy*, 6:27 (2018).

Li, T., Shiozawa, S., and McClure, M.W. "Thermal breakthrough calculations to optimize design of a multiple-stage Enhanced Geothermal System." *Geothermics* 64 (2016): 455-465.

Lu, S.M. “A global review of enhanced geothermal system (EGS).” *Renewable and Sustainable Energy Reviews*, 81 (2018): 2902-2921.

Moore, J., McLennan, J., Allis, R., et al. “The Utah Frontier Observatory for Geothermal Research (FORGE): Results of recent drilling and geoscientific surveys.” *Transactions, Geothermal Resources Council*, 42 (2018).

Olasolo, P., Juarez, M.C., Morales, M.P., D’Amico, S., Liarte, I.A. “Enhanced Geothermal Systems (EGS): A Review.” *Renewable and Sustainable Energy Reviews* (2016).

Meier, P.M., Rodríguez, A.A., Bethmann, F. “Lessons learned from Basel: new EGS projects in Switzerland using multistage stimulation and a probabilistic traffic light system for the reduction of seismic risk.” *Proceedings of World Geothermal Congress* (2015).

Tester, J. W., et al. "The Future of Geothermal Energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century," Massachusetts Institute of Technology and U.S. Department of Energy Report, Idaho National Laboratory, INL/EXT-06-11746. (2006).

United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement, signed December 12, 2015, https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

USGS “Assessment of Moderate- and High-Temperature Geothermal Resources of the United States,” USGS Fact Sheet, 2008-3082, U.S. Geological Survey (2008).

Warpinski, N. "Microseismic monitoring: Inside and out." *Journal of Petroleum Technology* 61, no. 11 (2009): 80-85.

Pettitt, W.S., Hazzard, J., Riahi, A., et al. “Simulated microseismicity in geomechanical models with natural and induced fractures.” *SEG Technical Program Expanded Abstracts* (2018): 2992-2996.

Zang, A., Stephansson, O., Stenberg, L., et al. “Hydraulic fracture monitoring in hard rock at 410 m depth with an advanced fluid-injection protocol and extensive sensor array.” *Geophysical Journal International*, v. 208 (2017): 790-813.

Ziagos, J., Phillips, B.R., Boyd, L., et al. “A Technology Roadmap for Strategic Development of Enhanced Geothermal Systems.” *Proceedings of Thirty-Eighth Workshop on Geothermal Reservoir Engineering* (2013).