A Technology Road Map for Next-Generation Geothermal

Unlocking Superhot Rock Innovation through Strategic Collaboration

CLEAN AIR
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Executive Summary

Superhot rock (SHR) geothermal is a high-potential clean energy source that, with innovation, could provide large-scale, reliable electricity and heat nearly anywhere on Earth. Unlike conventional geothermal, which is limited to geologically specific areas, enhanced and closed-loop geothermal techniques, paired with deep drilling, could make geothermal possible in almost every part of the world. Accessing SHR—rock hotter than 400 °C—using these techniques could produce five to ten times more energy per well. If successfully developed and deployed, SHR geothermal could support global decarbonization while using a fraction of the land required for other sources of energy.

While the potential of this energy source is clear, the technologies required to reach commercial viability remain under development. Research and pilot efforts are dispersed across institutions and countries, so a shared framework will help to align priorities, avoid duplication, and accelerate collective progress toward commercial viability. This road map presents a practical strategy for this collective process of SHR technology readiness and deployment. It breaks down the path into six coordinated phases that guide investment, collaboration, and technical progress.

Phase 1: Establish a Coordination Structure and Governance calls for the creation of a coordinated international Steering Committee to guide the effort. This group will bring together project developers, research institutions, governments, standards bodies, and data specialists. It will coordinate working groups, manage communication across projects, and define shared goals. This phase also includes launching a formal standards body to start documenting best practices and building qualification frameworks. Multisource funding must be assembled from public, private, and philanthropic partners to support not only technology development but also coordination, data systems, and infrastructure.

Phase 2: Identify Resources focuses on identifying and organizing the technology, materials, and facilities that already exist. A portfolio of existing technologies and materials will help project teams begin testing without starting from scratch. A global inventory of lab and testbed facilities will clarify where upgrades are needed. These shared resources will reduce redundancy, inform future investments, and create a baseline for collaboration.

Phase 3: Fill Technical Gaps targets the tools, materials, and infrastructure that are missing or underperforming. For example, project teams and research institutions will work on high-temperature and high-pressure drilling tools, advanced well materials, corrosion resistance, sensors, and zonal isolation systems. Modeling tools will also be extended to simulate SHR-specific conditions, guiding both lab tests and field deployments.

Phase 4: Iterate, Refine, and Reexamine centers on a structured cycle of modeling, lab testing, and field validation. Each cycle generates data that feeds back into the design process. Teams will use shared testing protocols and data reporting formats to ensure consistency and comparability across projects. A global information-sharing platform, established in Phase 1, will serve as the hub for publishing findings, coordinating technical analysis, and de-risking future work.

Phase 5: Deploy transitions the work from lab and field iterations to end-to-end projects. Pilot-scale projects will test full-system performance in relevant geologic and operational conditions. Lessons from these pilot projects will inform commercial deployment, which will require scaling up manufacturing, addressing interconnection needs, and coordinating across supply chains. To support these efforts, new financing models will be needed to reduce risk and support early investment.

Phase 6: Facilitate Continual Improvement Life Cycle ensures that the field continues to grow and mature over time. Standards will be formalized, qualification systems will be launched, and training programs will be built to prepare the workforce. Findings from projects will be incorporated into updated models and design practices, and data sharing will continue through regular meetings and reporting.

Across every phase, coordinated action is required from a wide range of stakeholders. Project developers should lead on-the-ground work. Research institutions should support modeling, validation, and training. Industry contributors, including equipment suppliers and energy developers, should drive prototyping, facility upgrades, and commercial deployment. Governments should help align funding, support risk-sharing mechanisms, improve permitting processes, and provide incentives for innovation. The Steering Committee should partner with standards bodies to collect and formalize best practices developed during this process. Data specialists should manage knowledge sharing platforms. Training providers should prepare a skilled workforce, and multilateral institutions together with philanthropies should work to align international efforts and support early-stage funding.

Each step in the Road Map defines where these different actors are best positioned to contribute. The organizational diagrams included in the report provide clear examples of how governance, standards development, infrastructure evaluation, modeling, deployment, and workforce development rely on distinct but interconnected roles. This shared structure is intended to clarify responsibilities and encourage effective collaboration across sectors and regions.

Much of the foundational work is already underway. Clean Air Task Force (CATF), which authored this report, has helped launch a task group under International Energy Agency (IEA) Geothermal to build momentum for collaboration between projects. Organizations in several countries are actively pursuing SHR projects, including Japan, New Zealand, Iceland, and the United States. Technical reports, facility surveys, and gap assessments have already been published, and R&D and demonstration projects are in motion.

This road map connects and strengthens those efforts. It provides a common reference for funders, project teams, policymakers, and researchers to align their actions and accelerate progress. The steps are designed to move in parallel, not strictly in order. Taken together, they chart a path to faster technology validation, lower development costs, and a clear line of sight to commercial-scale deployment. Superhot rock geothermal is already being pursued around the world. This road map illustrates how those efforts can become a global solution for climate change.

SECTION 1

Introduction

The International Energy Agency (IEA) projects that geothermal energy could supply up to 15% of additional global electricity demand growth by 2050, even though it provides less than 1% today[1]. Next-generation geothermal is needed to make this possible. Extending next-generation geothermal into reservoir temperatures of 400˚C and above (i.e. superhot rock [SHR]) will further maximize this potential. With innovation, and by following the collaborative road map laid out in this report, commercialization of SHR at scale will become possible. SHR could play an important role in meeting the world's rising energy demands in the coming decades.

Conventional geothermal relies on rare sites where naturally occurring hot water sources (hydrothermal systems) are close to the surface. SHR geothermal, in contrast, targets deeper zones where rock temperatures exceed 400°C. While a few shallow hydrothermal systems exist at 400˚C, most SHR development will depend on next-generation approaches such as enhanced geothermal systems (EGS) and advanced closed-loop systems (AGS). These systems introduce fluid into hot underground rock and return it for power generation, direct heat, or industrial decarbonization.

A handful of wells worldwide have reached SHR conditions[2], but none have yet produced sustained energy. At lower temperatures, EGS and AGS are already proving their ability to expand geothermal beyond traditional geographies. Expanding these technologies into SHR conditions would take this further by delivering abundant, affordable, and widely available clean energy with higher well output and greater plant efficiency.

The urgency for clean energy solutions like SHR is growing. Global electricity demand is rising quickly due to economic growth, increasing industrialization, rising living standards, electrification of major systems like home heating and transportation, population growth, and the growing demand from data centers. At the same time, the world must cut greenhouse gas emissions dramatically to avoid the worst impacts of climate change. Clean, firm power sources are important to enabling a fully decarbonized grid and displacing fossil fuel dependence. SHR geothermal is promising on both counts: It has the potential to meet growing energy demand while also playing a meaningful role in climate mitigation.

A soon-to-be-published analysis by Jason Lipton, commissioned by Clean Air Task Force, shows that EGS production temperatures have trended upwards over the past five decades, with a ~50˚ increase per 25 years.[3] Without an intentional effort, it is reasonable to assume that the geothermal industry could maintain its current trajectory, and continue to increase by 50˚C per 25 years. However, SHR needs to be developed faster in order to be a meaningful climate solution. A key way to accelerate the development timeline for SHR is to coordinate collaboration among distinct projects and contributing stakeholder groups, share learnings and resources, develop a coordinated approach to technology development, and coordinate goals. This kind of coordination would help to ensure that projects are building off one another and learning from the mistakes of other projects. However, the form and process of collaboration remain undefined.

1 IEA. 2024. "The Future of Geothermal" https://iea.blob.core.windows.net/assets/b5b73936-ee21-4e38-843b-8ba7430fbe92/TheFutureofGeothermal.pdf

2 Clean Air Task Force. 2025. "Superhot Rock Heat Endowment and Project Map": https://www.catf.us/shr-map/

3 Jason Lipton & Angela Seligman for Clean Air Task Force. 2025. "Powering the Future: What 50 Years of Enhanced Geothermal Teaches Us Today": https://www.superhotrock.org/library/

Thus far, most SHR pilot projects have existed in isolation, without much sharing of technologies. Clean Air Task Force (CATF) and its partners have worked with technology leaders across the sector to determine the technology readiness levels of each aspect of SHR geothermal energy recovery. The resulting report series—*Bridging the Gaps: Advancing Superhot Rock Geothermal*—is a collection of five flagship reports that evaluate the state of SHR geothermal, pinpoint the remaining technological gaps, and identify where future R&D and testing should concentrate.[4]

Bridging the Gaps explored the readiness levels for the technologies needed for Siting and Characterization, Drilling, Well Construction, Heat Extraction, and Power Production for SHR geothermal conditions globally. This follow-up report is intended to be a living document, creating a structured approach for government agencies, research institutions, industry, hyperscalers, standards organizations, and sector leaders to collaborate on actions to address the technological gaps previously identified.

The ultimate goal is to commercialize SHR geothermal, scaling it to a degree that it can make a meaningful impact on climate change.

Scope and Focus

The focus of this road map is on technical readiness and infrastructure development across the five technology verticals explored in the gap analyses—Well Construction, Drilling, Siting and Characterization, Power Production, and Heat Extraction—as well as the Geoscience and Geochemistry aspects of SHR geothermal. See **Figure 1** for a breakout of these verticals. Global technology leaders, industry consortia, policymakers, and research institutions will need to work together across borders to accelerate the timeline for commercial SHR geothermal. Work on SHR geothermal is already underway in several countries—Iceland, Japan, New Zealand, Norway, Switzerland, and the United States—but without collaboration, these efforts risk being siloed, slowing progress and raising risks and costs for each project team. Thus, the scope of this road map is to provide a structured, global plan for collaborative innovation throughout the technology maturity process.

Figure 1: The technology categories ("technology verticals") broken out for analysis of technology advancement needs within an end-to-end superhot rock geothermal project

[4] Clean Air Task Force. 2024. "Bridging the Gaps": https://www.catf.us/superhot-rock/bridging-gaps/.

Methodology

Creating this road map involved a collaborative effort to ensure both technical depth and broad stakeholder alignment. Input was first gathered from subject matter experts across each technology vertical through research report development, structured interviews with public laboratories and industry leaders, and discussion sessions held both in the United States and Europe.

This information was organized into a detailed table that ranked the technology gaps identified based on criticality, cost, and the availability of potential contributing stakeholder groups to address these issues. These gaps were originally identified in CATF's Bridging the Gaps report series, which outlined technology needs for each technology vertical: Well Construction, Drilling, Siting and Characterization, Power Production, and Heat Extraction. More than 80 experts worked together to prioritize key technology gaps and to shape a road map outlining the path from current capabilities to viable solutions. These results then informed the development of an integrated road map.

Organically, through a series of strategy sessions, Geoscience and Geochemistry was added as a sixth technology vertical with its own needs, challenges, and stakeholders. All categories are overlapping, but separating these categories allowed Bridging the Gaps report writers to be comprehensive in reviewing the full suite of technologies required for SHR geothermal to become commercially viable, cost-competitive, and scalable.

To validate the findings, technology leaders were interviewed to review and confirm the accuracy and relevance of the information within their areas of expertise. Individualized road maps were built out through these strategy sessions, discussed in distinct interviews, and then integrated into the technology development road map that is discussed in this report.

SECTION 2

Key Participant Groups

While the Road Map outlines a phased approach to advancing SHR geothermal—from coordination and resource mapping to pilot deployment and commercialization—this section focuses on *who* is positioned to carry out the work. **Figures 2** and **3** work together to demonstrate how various organizations and stakeholder groups contribute distinct capabilities that align with the Road Map's process steps.

Key participant categories identified in Section 4 *(The Full Road Map)* include:

- industry contributors (vertically integrated energy companies, upstream service providers, equipment manufacturers, project developers, and asset owners),
- research institutions (both national laboratories and universities),
- government bodies,
- multilateral organizations,
- data specialists,
- testbed operators,
- training organizations,
- offtakers,
- philanthropies,
- Investors, and
- communities.

Each step of the Road Map identifies a "lead participant" and "contributing participants" from among this list of participant groups. These roles align with broader participant categories represented in Figure 2. The figure's purpose is to illustrate the types of organizations that typically fall into each category, providing concrete examples of who might lead or support various activities outlined in the Road Map. The organizations listed in Figure 2 are well-positioned to engage in the work described in the Road Map; they are not necessarily actively doing SHR work at this time, nor have they necessarily agreed to pursue such work. **Figure 3** is designed to help clarify how different stakeholders throughout the ecosystem can engage in and contribute to advancing SHR geothermal development. In the full road map (Section 4), when "lead" and "contributing" participants are referenced, it means these institutions.

Active participation in road map activities from multiple roles and functions brings together complementary abilities important to advancing the technology from early-stage R&D to full-scale deployment.

- **Research institutions and national laboratories** are well positioned to support testing, validation, early-stage deployment and data sharing. They can contribute important R&D by developing and testing high-temperature materials, reservoir modeling, and energy conversion systems.
- **Industry contributors**, including vertically integrated energy companies, are well-positioned to drive project financing, provide operational expertise, and define viable commercialization pathways. Their equipment and infrastructure expertise, technical knowledge, and investment capacity make them useful for deploying SHR geothermal systems at scale.
- **Project developers and asset owners** are well-positioned to identify and prepare viable sites, manage permitting and stakeholder engagement, and integrate new technologies into real-world projects. There is overlap here with **testbed operators**, especially in piloting new approaches, validating full-system integration, and generating operational data that can inform broader deployment strategies.
- **Upstream service providers and equipment manufacturers**, such as drilling technology firms and well construction companies, play an important role in developing and supplying high-temperature tools and equipment such as drill tools and well casing. Their involvement in testbeds and prototyping supports rapid iteration and practical validation of technologies under real-world conditions.

Figure 2: Example organizations well-positioned to contribute to superhot rock geothermal development, categorized by role and function

Category	Institutions		
Industry Contributors	**Vertically Integrated Energy Companies** • Chevron • Contact Energy Ltd. • ENI • Equinor • OMV • Oxy • Repsol • Totalenergies	**Upstream Service Providers and Equipment Manufacturers** • 8Sigma Energy Services • ALTISS Technologies • Baker Hughes • Blade Energy Partners • Curistec • Drill Cool • Enthalpion Energy LLC • Gerosion • Halliburton • Hephae • Iceland Drilling • MicroSeismic • Nabors • NOV • SLB • Vallourec • Weatherford	**Project Developers & Asset Operators** • 400C Energy • ARAMCO (nationalized) • ConocoPhillips • Eavor • Energy Development Corporation • HS Orka • Landsvirkjun • Mazama Energy • Orkuveitan (Reykjavík Energy) • PETROBRAS (nationalized) • Quaise Energy • Starr Energy • XGS Energy
Research Institutions	• Brookhaven National Laboratory • CanmetENERGY • Curistec • ETH Zurich • Geothermal Consortium and Wells for the Future Consortium at Texas A&M • Gerosion • Iceland GeoSurvey (ÍSOR) • Idaho National Laboratory • Lawrence Berkeley National Laboratory • National Renewable Energy Laboratory • National Taiwan University • New England Research Lab • New Zealand Institute for Earth Sciences (formerly GNS Science) • Norwegian Research Centre (N ORCE) • Oak Ridge National Lab • Oregon State University • Sandia National Laboratories • Stanford Geothermal Program • University of Iceland • University of Oklahoma		
Government Agencies	• European Commission Energy Union • Icelandic National Environment and Energy Authority • Italian Ministry of Environment and Energy Security • Japanese Ministry of Economy, • Natural Resources Canada (NRCan) • New Zealand Ministry of Business, Innovation & Employment • Trade and Industry (METI) • U.S. Department of Energy		

Category	Institutions
Testbed Operators & Facilities	• Aksaray, Turkiye (GMK Energi) • Acoculco (UNAM) and Los Humeros geothermal fields (CFE) • Bedretto Underground Research Laboratory (ETH Zurich) • Confidential New Zealand site (disclosure pending) • Coso Geothermal Field (U.S. Navy) • Hengill Geothermal Field (Reykjavik Energy) • Kakkonda, Kuju, Yuzawa, Appi Geothermal Fields (various Japanese utilities & JOGMEC) • Krafla Magma Testbed (Landsvirkjun) • Larderello (ENEL) • Newberry Volcano (various) • Ullrigg Test Centre (NORCE)
Multilateral Organizations & Standard Bodies	• American Petroleum Institute (API) • European Investment Bank • International Energy Agency • International Organization for Standardization (ISO) • International Renewable Energy Agency • New Zealand Standards (NZS) • World Bank
Data & Reporting Specialists	• Geoscience Australia • Geothermal Technologies Office (GTO) • International Energy Authority (IEA)
Offtakers & Demand Partners	• Utilities • Data centers or other corporate buyers • Military bases • Energy buyer coalitions
Philanthropic & Impact Funders	• Strategic grantmakers • Venture-style philanthropies
Investors	• Impact investors • Venture capital and private equity firms
Communities	• Varies by project location

- **Government bodies and multilateral institutions** are important for developing policy frameworks, formalizing standards, enabling international partnerships, and creating financial backstops and/or incentives to reduce investment risks for the private sector. In many cases, the degree of government willingness to collaborate, particularly across borders, can shape the pace and scale of progress. Motivations for engagement differ by country, and international cooperation remains a key enabler for reducing risk, sharing innovation, and moving more quickly toward commercial viability.
- **Philanthropic bodies and impact funders** can play a catalytic role in funding early-stage efforts that are too risky for traditional investors. Their support can help launch collaborative platforms, underwrite testbed programs, and ensure global equity and access as the technology matures.
- **Offtakers** are an important piece of the puzzle. This may include utilities, hyperscalers and other corporate buyers, military bases, and energy buyer coalitions. Long-term procurement commitments and willingness to support early projects can help de-risk investments and drive demand.
- **Training organizations** are essential for developing a specialized workforce capable of supporting high-temperature geothermal projects, including with drilling, well operations, and plant construction. Workforce readiness is a key enabler of both pilot projects and broader deployment.
- With local **communities** near projects, early communication and awareness-raising is important. Inclusive engagement helps build trust, align projects with community priorities, and ensure benefits are shared equitably. It also reduces the risk of permitting delays or opposition.

Collaboration across the participant groups defined in **Figure 2** can also reduce investment risks and speed up the time to commercial viability. The activities tied to each participant group in the Road Map are laid out in **Figure 3**.

Figure 3 outlines the participant groups assigned to activities defined in the Road Map. The Road Map is framed into five distinct phases: Governance & Coordination; Identify Resources; Fill Technical Gaps; Iterate, Refine, and Reexamine; Deploy; and Facilitate Continual Improvement Lifecycle. Each Phase category includes specific tasks or deliverables—such as forming a Steering Committee, developing standards or protocols, creating a global database for information sharing, and conducting pilot projects—supported by various types of contributors with an emphasis on collaboration across sectors.

Figure 3 translates organizational categories from **Figure 2** into functional roles within each phase of the Road Map.

- Under the “**Governance & Coordination**” category, government agencies, multilateral institutions, NGOs, and research institutions are well-suited to establish a Steering Committee, define shared protocols, coordinate funding, and oversee standards development.
- In the “**Identify Resources**” phase, research institutions and manufacturers contribute to global assessments of available technology and testing facilities, coordinated through the Steering Committee and supported by NGOs.
- For “**Filling Technical Gaps**”, research institutions and testbed operators lead upgrades to testing facilities, refinement of models, and field testing of advanced materials and systems. Equipment manufacturers and service providers play a role in iterative prototyping and validation.
- **Deployment** activities span both pilot projects and commercial-scale rollout. Project developers, vertically integrated energy firms, and service providers drive project implementation. Offtakers and utilities provide market pull through procurement agreements, while funders and financing institutions reduce risk through capital mobilization.
- In the final category, “**Facilitate Continual Improvement Cycle**”, institutions, training organizations, and industry partners collaborate to define workforce standards and deliver training programs aligned with the needs of SHR project development and operations.

Some stakeholder groups, such as philanthropic funders and data specialists, cut across multiple phases of the Road Map. Philanthropic organizations may underwrite collaborative governance, support early testbed operations, or invest in training infrastructure. Data specialists play an essential role in ensuring that field results are captured, analyzed, and shared across the ecosystem to support continuous improvement. Communities remain central throughout—from early project siting and permitting to employment and long-term partnership.

Taken together, **Figures 2** and **3** demonstrate that no single actor or institution can deliver superhot rock geothermal alone. Success will depend on deliberate coordination, clear role delineation, and sustained collaboration. This road map is designed to support that coordination by clarifying not only the steps required for SHR development, but also the types of organizations best positioned to lead or support them.

Figure 3: Organizational Structure and Engagement of Key Participant Groups

KEY RESOURCES

Governance & Coordination

Est. Steering Committee
- Director
- Project developers
- Research institutions
- Industry contributors
- Government bodies & NGOs

Assemble Funding
- Steering Committee
- Government bodies & NGOs
- Multilateral organizations
- Philanthropies
- O&G companies
- VC and impact investors

Develop Standards Body
- Steering Committee
- Standards organization
- Project developers
- Industry contributors
- Research institutions

Develop Protocol
- Steering Committee
- Research institutions
- Project developers
- Data scientists
- Standards organizations

IP Model
- Legal teams
- Project developers
- Industry contributors
- Data mgmt team

Establish an Information-sharing Platform
- Data mgmt team
- It Consultants
- Project Developers

Identify Resources

Landscape Technology Options
- Steering Committee
- Materials manufacturers
- Research institutions
- Industry contributors

Landscape Facilities
- Steering Committee
- Research institutions
- Upstream and vertically integrated industry
- Government bodies & NGOs

Fill Technical Gaps

Upgrade Facilities
- Steering Committee
- Industry contributors
- Government bodies & NGOs

Extend and Update Models
- Project developers
- Research institutions

Develop New Materials, Methods, Equipment
- Project developers
- Industry (upstream)
- Testing facilities
- Research institutions
- Standards organizations
- Steering committee

Iterate, Refine, Reexamine

Conduct Lab Tests
- Research institutions
- Project developers
- Test site operators

Update Models
- Research institutions
- Project sevelopers
- Test site operators
- Equipment manufacturors

Field Testing
- Testbed operators
- Research organizations
- Upstream service providers & equipment manufacturers
- Project developers
- Steering committee

Share Learnings
- Project developers
- Data mgmt team
- Research institutions
- Steering committee
- Standards bodies
- Equipment manufacturers
- Service provider
- Test site operators

Deploy

Develop Pilot-scale Projects
- Project developers
- Asset operators

Address Supply Chain and infrastructure needs
- Steering committee
- Equipment manufacturers
- Logistics providers
- Transmission operators
- Govt bodies

Develop Financing Strategies
- Steering Committee
- Public finance institutions
- Investors
- Offtakers

Deploy Commercial-scale Projects
- Project developers & asset operators
- Private ecosystem partners (e.g. service providers, equipment manufacturers).

Facilitate Continual Improvement Cycle

Qualification Standards & Best Practices
- Industry contributors
- Standards organizations

Training Programs
- Research institutions
- Training organizations
- Industry contributors

Incentives for Various Stakeholder Groups

Industry

Vertically integrated energy producers may want to pursue collaborative innovation to reduce exploration and development risk, influence permitting and standards, and access new sources of high-temperature heat. Early involvement in testing, deployment, and standards development supports internal capital allocation decisions across low-carbon energy strategies. These firms benefit from helping shape data protocols, infrastructure plans, and intellectual property (IP)-sharing frameworks, enabling large-scale deployment with greater confidence and lower costs. This only works if collaborative efforts are structured so that a company is the technology leader in a given area, the benefits of collaboration outweighed by the risk to their lead in IP over competitors. Some large oil and gas companies have shown a willingness to invest in technologies that help reduce their emissions, particularly when they can be integrated into existing operations. Targeted incentives like tax credits would further encourage their participation in SHR development.

Upstream service providers and equipment manufacturers have strong incentives to collaborate in order to gain early insight into tool specifications, design constraints, and performance requirements. Participating in SHR development efforts allows them to prototype and test tools, materials, and well designs under realistic conditions, validate performance through shared infrastructure, and refine models with deployment data. This participation helps ensure their products meet evolving standards and increases the likelihood of adoption by operators. Early engagement also positions these firms to shape market expectations and establish themselves as preferred vendors.

Downstream energy producers may be interested in collaborating to accelerate project timelines, share development costs, and boost investor confidence. By aligning with partners on a shared vision, co-developing facilities, and contributing to testing protocols, these companies can reduce the burden of independently de-risking projects. Participation also helps build technical and commercial credibility across the sector.

Lastly, for industry as a whole, the success of this work, ending in SHR as a viable commercial resource, would enhance the ability of companies to access reliable, 24/7 clean power and high-density industrial heat, SHR as a resource would allow some of these industry players strengthen their ability to meet decarbonization targets while maintaining competitiveness in global energy markets. This ensures long-term resilience as demand for low-carbon energy intensifies.

Training and Workforce Development Organizations

Training and workforce development organizations would benefit from engaging in SHR collaboration by aligning curricula with emerging industry needs. Participation in model and standards development ensures that workforce training reflects current technical and operational practices. Collaboration with technology developers, field operators, and research bodies also provides access to real-world case studies and facilities, supporting experiential and competency-based learning. Hands-on involvement in emerging geothermal technologies allows universities to expand into adjacent fields and prepare students for careers in a growing sector.

Research Institutions

Research institutions are incentivized to collaborate to advance their missions in applied science and innovation. Participation in joint lab and field testing boosts the visibility and impact of their work while improving access to funding and shared infrastructure. Institutions benefit directly from participating in efforts to address technical gaps (Phase 3), whereas research partnerships can unlock new high-temperature/high-pressure testing environments and shared data platforms. By aligning with facility upgrade priorities and joining coordinated pilot deployments, institutions help shape emerging technology standards and gain early insight into industry-relevant performance thresholds.

Government Bodies

Government bodies, such as the New Zealand's Ministry of Business, Innovation & Employment and the U.S. Department of Energy, are incentivized to support collaborative innovation to stay ahead of the curve and anticipate supply chain needs, technical barriers, and funding gaps that inform program design. Collaboration also fosters best practices and offers exposure to international approaches in supporting innovation, whether through public-private funding, de-risking mechanisms, or other tools. This helps agencies adapt and target interventions where public investment has the greatest impact in advancing technology readiness and market development. For example, the U.S. Department of Energy's involvement aligns with its priorities to accelerate energy innovation, expand and diversify energy sources, enhance energy security, and strengthen domestic supply chains. Regulators and permitting bodies also play a role here. Staying engaged allows permitting and regulatory bodies to anticipate regulatory needs and shape permitting processes in ways that reduce barriers, support early deployment, and maximize the return on public investment.

Additionally, supporting SHR development advances national energy security and competitiveness, reducing dependence on imported fuels while positioning their economies at the forefront of clean firm power innovation. This proactive engagement helps countries safeguard affordable, reliable energy systems in a decarbonizing world.

Standards Organizations

Standards bodies like API are incentivized to collaborate to develop technical expertise and information to create effective, consensus-based best practices and standards that support safe and scalable deployment. Early engagement with the proposed Steering Committee, stakeholders, and technology leaders across the SHR geothermal sector gives them more time, resources, and expert input to inform well-founded best practices and standards.

Multilateral Organizations

Multilateral organizations like the IEA are specifically designed to support the kind of cross-border collaborative innovation outlined in this report. They can coordinate member country efforts, track deployment progress, and identify shared infrastructure or R&D needs—core functions aligned with their mission. These organizations also offer neutral platforms for information sharing, coordinate joint funding across national agencies, and establish governance structures like action committees or task groups. For example, the IEA Geothermal platform can convene technology developers, governments, and researchers to align timelines, share pilot outcomes, and formalize best practices. Their involvement adds legitimacy and ensures continuity in long-term coordination beyond any single funder or national agenda.

Data and Reporting Specialists

Data management and reporting specialists should collaborate to ensure emerging data flows are standardized, transparent, and actionable. These groups help define lab and field data protocols, metadata requirements, and information-sharing platforms — reducing downstream interoperability costs, improving research quality, and enabling cross-project comparison and modeling.

Participation also allows these groups to shape standards, position their tools as defaults in a growing field, and build relationships with early government and industry adopters. As structured data becomes essential to funding decisions, performance tracking, and policy design, these organizations are well positioned to anchor core elements of the infrastructure that others will rely on.

Test Site Operators and Facilities

Owners and operators of sites suited for SHR field testing and pilots have clear incentives to collaborate. Hosting joint R&D and testing efforts strengthens an operator's influence in shaping standards and attracts startups and industrial developers seeking qualified test environments. For publicly funded facilities like FORGE or BedrettoLab, collaboration supports national energy goals and enhances international standing. For private operators, it positions their site as a hub for high-profile demonstrations, generating revenue and long-term partnerships. For site owners and operators engaging in pilots, engagement in this effort will allow them to avoid repeating mistakes previously, ultimately reducing technology risk, resulting in a reduced overall cost of the pilot. For operators and owners engaging in testing operations, collaboration will allow more confidence that decisions made in their testing is based on all available information, and will allow them to avoid duplicating efforts, and thus be more impactful in the long run.

Offtakers

Offtakers—including utilities, corporate energy buyers, and governments—may support collaborative innovation to advance a technology that can provide them with high-density baseload heat and power, diversify assets, enhance resilience, and meet decarbonization goals. Involvement in road map efforts also offers insight into technical progress and developer credibility. Recent interest in geothermal startups like XGS, Eavor, and Fervo from companies like Meta and Google highlights this early engagement trend. SHR, as a resource, offers offtakers a pathway to reliable, around-the-clock clean power that diversifies their energy portfolios and reduces exposure to fuel price volatility. Access to firm geothermal heat and electricity could enhance the resilience of their resources while advancing their ability to meet decarbonization commitments.

Philanthropies

Philanthropies can incentivize collaborative innovation to amplify the impact of their climate portfolios via their unique access to capital in the form of grants and, in some cases, impact investments. Early road map steps, such as forming a Steering Committee to convene stakeholders, design governance, and create shared information platforms, are high-leverage interventions with lasting effects on accelerating SHR geothermal to commercial scale.

Philanthropies can also expand the SHR geothermal space by funding technology development and facility upgrades that serve multiple stakeholders. Shared assets require flexible, risk-tolerant capital that is designed to move quickly and inclusively, enabling broad participation in testing and validation. By supporting both early coordination mechanisms and technical infrastructure, philanthropies can help unlock additional public and private investment, thereby increasing the chances that early adopters survive the gap between R&D and commercial deployment.

Investors

Investors—ranging from venture capital and private equity to institutional and impact funds—are searching for the next wave of scalable clean energy. Engaging in collaborative innovation on SHR geothermal offers them a chance to gain a strategic advantage. First, it gives them early visibility into technology readiness, project pipelines, and risk management needs, enabling more informed capital deployment. It also positions them to influence industry norms, performance benchmarks, and financing structures suited to SHR's long timelines and infrastructure needs. Coordinated road mapping adds market transparency, speeds de-risking, and opens co-investment opportunities. For firms with energy or climate mandates, SHR geothermal stands out as one of the few technologies that could be capable of delivering round-the-clock, low-carbon power at scale—an asset class that could define the next decade of clean energy investment. Early participation in technology development not only strengthens the investment landscape but also allows investors to secure a leadership position as the sector advances. Insurance and risk underwriters may also be considered part of this stakeholder category.

SECTION 3

Technology Road Map Overview

Introduction

The road map presents a phased, time-bound strategy for advancing all key technologies required for SHR geothermal development. It outlines six phases—from Establish Governance to Facilitate Continual Improvement Life Cycle—and illustrates how they interact. An overview of the Road Map's phases, steps, and iterative cycles, and a generalized timeline can be found in **Figure 4**.

Figure 4 breaks down the Road Map into key steps that are plotted in horizontal bars on a timeline spanning quarterly intervals (Q1 to Q16). The horizontal bars indicate each step's estimated duration and phase of implementation. There are six independent implementation phases: (1) Establish Coordination Structure and Governance; (2) Identify Resources; (3) Fill Technical Gaps; (4) Iterate, Refine, and Reexamine; (5) Deploy; and (6) Facilitate Continual Improvement Life Cycle. This structure is intended to balance sequential

Figure 4: Technology Road Map Steps and Iterative Cycles: A Generalized Timeline

The Road Map shows an ideal sequence for coordination, but it is not strictly linear. Work on later-phase activities—such as pilots, laboratory testing, and materials development—should not wait for earlier steps to finish.

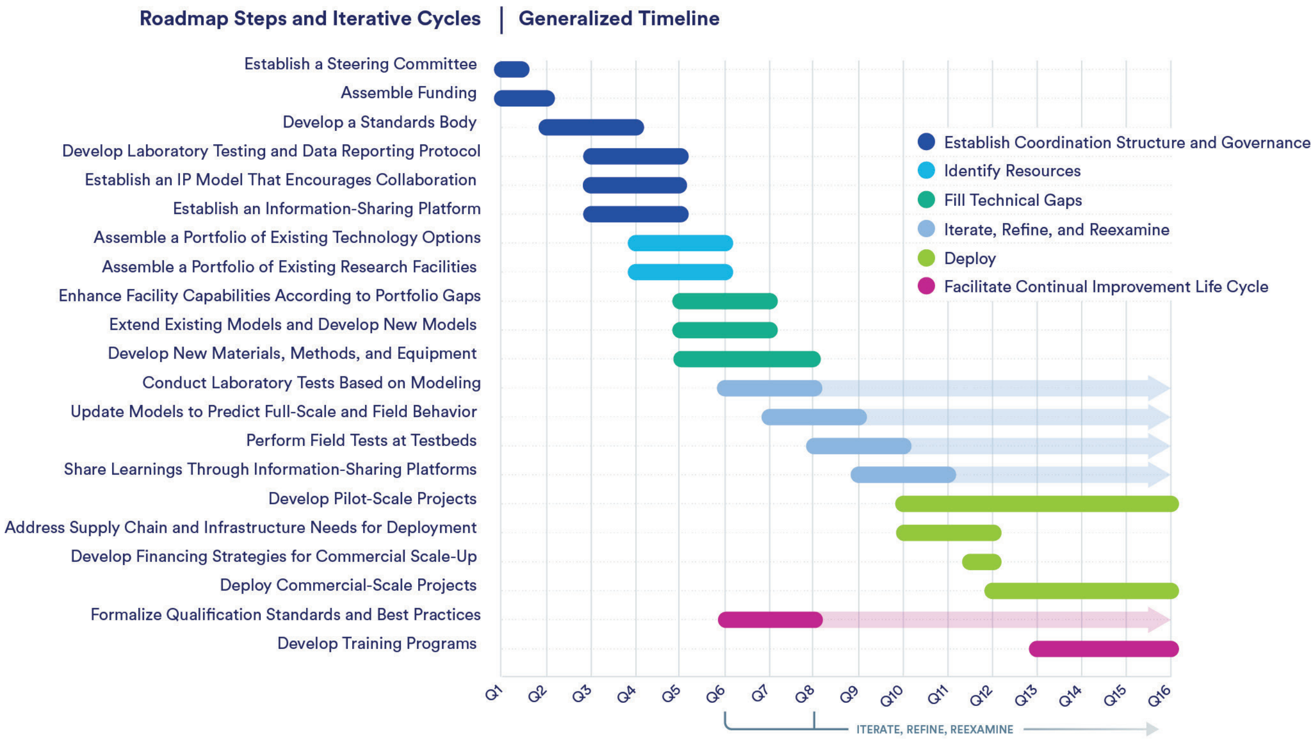


Figure 5: Road Map Steps and Iterative Cycles: Flow Diagram

technological development with ongoing iterative testing cycles, so that insights from each phase inform and improve the next.

Steps like “update models,” “perform field tests,” and “share learnings through informationsharing platforms” span Q6 through Q16 because they require ongoing processes rather than a single short-term task. These steps, in the “iterate, Refine, and Reexamine” phase, will need to be repeated for continuous improvement and adaptability throughout the project's life cycle, so that lessons learned at each phase are incorporated into future efforts.

Steps can be separated into six overlapping phases, shown at the top of **Figure 5**. Each step prior to deployment will be carried out based on the specific requirements and needs of the technology and is well suited for coalitional support and collaboration. The final steps, categorized under “Facilitate Continual Improvement Life Cycle,” focus on establishing a framework to sustain progress by sharing learnings, developing qualification standards and best practices, and developing training programs. These are complemented by the continued “iterate, refine, and reexamine” steps that begin earlier in the process and continue for ongoing technology optimization, even after SHR has reached commercial viability.

How to Use the Road Map

The Road Map is broken down into 21 steps across six phases, each ending with a conclusion/recommendation. Further details about each technology can be found in the *“Applying the Road Map”* section (Section V), the “*Gap Assessment and Prioritization*” section (Section VI), and in Appendix A.

While the Road Map follows an idealized sequence to promote streamlined progress and effective coordination, it is not strictly linear. Many activities, such as laboratory testing or materials development, can and should begin in parallel with infrastructure and planning work, before all infrastructure gaps are fully addressed. Considering opportunities for strategic sequencing, however, is useful. For instance, mapping existing facilities before upgrading facilities, or establishing mechanisms to maintain standards before defining qualification benchmarks helps minimize inefficiencies and overlaps. Every step outlined here is an important piece of the puzzle.

The Road Map helps clarify who should be involved at different phases of SHR development and what types of support might be needed to build momentum. To be effective, SHR development must be led by a clearly defined Steering Committee and stakeholders who commit to accountability. Sustained progress will also require joint funding or dedicated financial commitments from participating organizations to ensure that those leading this work have the resources and incentives to drive this work. Regular reporting and updates will be essential to maintaining traction and ensuring this road map drives real-world impact.

For convening parties such as IEA Geothermal, the Road Map offers a practical playbook for structuring collaboration. By outlining sequenced actions for innovation and deployment, it provides a shared reference that can be used to align efforts across countries and sectors.

For funding agencies, it offers a framework to help identify where support might have the greatest impact. Rather than distributing resources across disconnected efforts, funders may find this document useful in targeting specific technical gaps, replicable projects, or system enablers that may be most impactful in accelerating SHR readiness.

For ministries, national energy offices, and private-sector actors who are interested in SHR but unsure where to begin, the Road Map suggests a range of entry points. It outlines practical ways these stakeholders might contribute—whether through permitting, infrastructure, data sharing, or policy—and highlights areas where their involvement could be most valuable.

Overall, the goal of this road map is to offer a shared point of reference that can help partners align strategy, investment, and technical priorities, while leaving room for adaptation based on local context and stakeholder goals.

SECTION 4

The Full Road Map

Phase 1: Establish Coordination Structure and Governance	
Step 1: Establish a Steering Committee	
Purpose	Coordinate efforts between international technology leaders and project leaders to ensure project developers work toward common goals.
Actions	→ Identify and invite participants with necessary expertise → Secure funding and administrative support for committee meetings and operations → Agree on common goals and divide responsibilities → Set up regular meetings and communication channels between project teams and technical experts → Set up technology interest groups to act as resources for project developers → Oversee data management team → Create working groups for specific technical or operational tasks as new needs aris
Lead Participant	→ Director, assigned by multilateral organization (IEA or similar)
Contributing Participants	→ Project developers → Research institutions and industry contributors with technical expertise that aligns with major technology gaps for SHR geothermal, as identified in the *Bridging the Gaps* synthesis report → Government bodies and NGOs (for country-level engagement, funding, and representation of external stakeholder needs)

Step 2: Assemble Funding	
Purpose	Secure multiphase, multisource funding to support the Steering Committee, data sharing, R&D, field testing, demonstrations, and early commercial-scale deployment of SHR geothermal worldwide.
Actions	→ Identify target funding levels for each stage (R&D, pilot, demonstration, commercial deployment) based on expected liftoff and scale-up costs → Engage national governments and multilateral climate finance institutions for early-stage capital to de-risk SHR geothermal → Coordinate with philanthropic funders and development banks on risk-sharing instruments → Encourage joint funding calls from public and philanthropic funding bodies → Approach tangential industries such as oil and gas and mining firms, clean technology financers including venture and institutional funds, large scale buyers such as data centers and industrial electricity patrons, and utilities with strategic interest in SHR technologies → Set up a standing mechanism for funding coordination through a Steering Committee
Lead Participant	→ Steering Committee (with representation from both governmental and technical bodies)
Contributing Participants	→ Government agencies (e.g., New Zealand Ministry of Business, Innovation & Employment, U.S. DOE, European Commission, METI Japan, etc.)[5] → Multilateral organizations (e.g., IEA) → Philanthropic foundations (e.g., those aligned with climate innovation or clean firm power goals) → Oil and gas companies and geothermal developers (for strategic equity or in-kind support) → Venture capital and impact investors (for pilot projects or early commercial phases)

5 See Appendix B for Acronyms and Abbreviations used throughout this report.

Step 3: Develop a Standards Body	
Purpose	The standards body is a dedicated group responsible for identifying, organizing, and refining best practices as they emerge. This group will also create a framework for formalizing these practices into technical standards as the technology matures.
Actions	→ Identify a standards organization to partner with for developing best practices and standards. This standards organization will house the subsequent actions listed. → Establish a subgroup within the identified standards organization, focused on SHR, so that findings can be wrapped into a globally recognized formal ANSI-certified standards-setting system. → Create expert working groups for each major technical topic, led by subject matter experts and supported by a staff facilitator from the standards body (e.g., API) → Identify and invite participants that have a direct and material interest in the practices and standards determined → Compile and review existing standards applicable to geothermal (e.g., NZS, ISO, API) as a starting point → Use collaborative tools (e.g., shared literature spreadsheets) to crowdsource relevant technical references and best practices → Allocate resources for regular updates and revisions
Lead Participant	→ SHR geothermal subgroup within a standards-setting organization (e.g., ISO,[6] NZS,[7] API[8])
Contributing Participants	→ Steering Committee (to establish partnership with standards body and recruit subgroup participants) → Project developers → Industry contributors (upstream, downstream, and vertically integrated companies) → Research institutions → Any group that has a direct and material interest in the outcome of standards set for the technology

6 International Standards Organization is a globally oriented standards body.

7 Standards New Zealand (also referred to as New Zealand Standards) developed NZS 2403:2015, which defines well construction standards for geothermal wells up to 350°C and thus has become the standard for high-temperature geothermal wells globally.

8 American Petroleum Institute is the standards body typically referenced in the U.S. for drilling and well construction.

Step 4: Develop Laboratory Testing and Data Reporting Protocol	
Purpose	Standardize testing and data sharing to ensure reliable and comparable results while avoiding unnecessary duplication of testing.
Actions	→ Review protocols from industries with similar testing environments (e.g., oil and gas, aerospace, nuclear) → Organize discussions among research institutions → Define a shared data format and reporting standard to support testing later in Phases 3 and 4 → Develop templates and guidelines for data reporting → Specify required file types (e.g., CSV, JSON, Shapefile) and submission procedures for lab and field datasets to the information-sharing platform established in Step 6 → Communicate standards to the standards body established in Step 3
Lead Participant	→ Laboratory Coordination Team (appointed by the Steering Committee, composed of cross-institutional technical experts)
Contributing Participants	→ Project developers (to pilot and refine protocols) → Data scientists (to design reporting frameworks and testing standards) → Standards body (developed in prior step, to review existing protocols, receive, and record information as standards and best practices emerge)

Step 5: Establish an IP Model That Encourages Collaboration	
Purpose	Create a structured framework that enables multiple companies, research institutions, and governments to engage in shared testing, data analysis, infrastructure use, and technology development that reduces IP conflicts and administrative overhead.
Action	→ Define baseline rules of engagement for IP ownership, licensing, patents, and use. For example: • All background IP remains the property of contributing parties • IP generated through joint work is owned by the coordinating research host (e.g., university or consortium) and licensed to all participants • Provide academic-use licenses for institutions and commercial-use licenses for companies • Include opt-out clauses for participants who cannot share certain results due to existing obligations → Develop a simple participation and contribution model: • Establish a flat membership model with flexibility for both public and private participants • Allow voluntary in-kind contributions (e.g., equipment, data, testbed access) to satisfy participation requirements but avoid complex valuation schemes • Enable participants to join specific R&D campaigns with targeted IP terms and use rights, rather than requiring full program commitment • Draft an IP agreement template based on best practices from public-private research consortia (e.g., RAPID, KTB, Innovation Norway). Project teams will have to vet their agreement based on their location and public funding requirements • Offer supporting tools such as nondisclosure agreements, joint work agreements, and data-sharing agreements that can be adapted based on the level of openness → Support data sharing with clear boundaries: • Establish a semiprivate data repository that provides value through data access for participants. This may look like a fixed-timeline data embargo, for example. This may build from an existing data repository to avoid duplication • Coordinate regular sharing of nonconfidential findings via quarterly convenings, webinars, and a central platform
Lead Participant	→ Legal Chair (appointed by Steering Committee, housed at a host institution such as a university)
Contributing Participants	→ Legal teams from research institutions or national labs (template development) → Project leads and industry representatives (define acceptable terms) → Data management team (support tiered data sharing)
Relevant Precedents or Models	→ RAPID (U.S.) – Flat-fee, multi-institution IP framework → KTB (Germany) – Public/private data collaboration → Innovation Norway/NORCE – 80% public funding that brings in private capital → Alberta Drilling Accelerator – Effective joint industry project (JIP) for advanced drilling

Step 6: Establish an Information-Sharing Platform	
Purpose	To facilitate global collaboration and knowledge exchange for advancements for all stakeholders. This should include both a central data repository and regular meetings between global project teams.
Actions	→ Secure software licensing and funding to continually support a shared data platform → Build an online platform with data storage, visualization, and collaboration tools. The platform should be designed to receive structured contributions from lab, field, and pilot projects across phases → Establish governance rules for data sharing and privacy → Host regular global meetings or webinars
Lead Participant	→ Data Platform Oversight Team (appointed by Steering Committee, with technical and data governance representation)
Contributing Participants	→ IT consultants or staff (develop and maintain the platform) • This should include a database designer, a database architect, and a database manager → Project developers (to contribute data and attend information-sharing meetings) • Project developers would represent a specific project (for example, the Iceland Deep Drilling Project) • Project developers may be public institutions or private industry though likely made up of a mix of both • Projects may be at any level of maturity (preliminary modeling, research, testing, pilot, commercial-scale project, or anywhere in between)

Phase 1 Recap: Establish Coordination Structure and Governance

The Road Map begins with establishing global alignment across funding, governance, and collaboration systems. First, a cross-sector Steering Committee must be formalized to set global goals, ensure project interoperability, and oversee early infrastructure, including data systems and the creation of a standards body. Further key actions include assembling a multisource funding coalition—national governments, climate finance institutions, oil and gas companies, utilities, and philanthropic foundations—to support not just technical R&D, but also global coordination, standards development, data infrastructure, and setting up a standards body. The standards body should compile best practices as they emerge, so they are ready for use in Phase 6, which includes compiling and formalizing these best practices into formal standards. Once this foundation is in place, common lab testing and data protocols must be developed, piloted, and integrated into the standards framework. An open IP model would allow joint work on infrastructure and shared R&D while protecting proprietary technologies. A centralized information-sharing platform would facilitate global data access, coordination, and knowledge exchange. A steering committee, as structured in this phase, is hugely beneficial to coordination in the beginning of this effort. However, as the technology and process matures, more bodies will enter the space, and this committee may ultimately evolve from a leading role into a resource from which projects can draw upon. Finally, this phase includes the establishment of an information-sharing platform. Given how few SHR wells have been drilled globally, each dataset from a real-world project is disproportionately valuable. Empirical observations—however imperfect—are the only way to constrain and validate models in these extreme environments. Without broad international data sharing, developers risk repeating avoidable mistakes and missing rare but critical insights hidden in early project anomalies. A coordinated, global data platform will accelerate technical learning curves and de-risk future investments more effectively than any single project operating in isolation.

Milestones for this phase include establishment of the Steering Committee, adoption of a standardized IP agreement, and launch of the shared data platform.

Phase 2: Identify Resources	
Step 7: Assemble a Portfolio of Existing Technology Options (Materials, Equipment, Design)	
Purpose	To provide a starting place for technology leaders to start their R&D and testing and to reduce technology risk across projects. The aim is that this would create a foundation that raises all ships and enables more successful, differentiated solutions to emerge.
Actions	→ Conduct an industry survey and literature review → Survey materials suppliers for specifications of materials options that would be recommended for each component of a SHR system → Consider materials, equipment, and design options from other industries (e.g., aerospace, nuclear) → Compile and administer a "state-of-technology" portfolio portal that is updated on a biannual basis
Lead Participant	→ Steering Committee
Contributing Participants	→ Materials manufacturers (provide technical details) → Research institutions (evaluate materials) → Industry contributors (upstream manufacturers, service companies, and vertically integrated companies, to provide non-proprietary information, and use the results to make plans for their own technology development)
Step 8: Assemble a Portfolio of Existing Research Facilities	
Purpose	Identify existing facility capabilities and gaps.
Actions	→ Survey and document capabilities and gaps in current testing facilities. Prioritize needs for the technology gaps identified as most 'critical' in figures 8 and 9, and in Appendix A, particularly items related to corrosion testing, materials testing, material bonding, reservoir lifetime, and thermal cycling. → Compile a "state-of-facilities" resource guide
Lead Participant	→ Steering Committee
Contributing Participants	→ Research institutions (to report facility capabilities and expand scope to other research institutions) → Upstream and vertically integrated industry (to report facility capabilities, expand scope to research institutions not previously considered, and to take on facility upgrades) → Government bodies (to consider public funding, incentives) and NGOs (to advocate for funding to expand laboratory capabilities)

Phase 2 Recap: Identify Resources

The second phase establishes a complete picture of the technologies and infrastructure available for SHR geothermal development. This begins with a comprehensive survey of existing high-temperature materials, tools, and design methods across geothermal and oil and gas sectors, with some consideration of overlap in nuclear and aerospace sectors. In parallel, research facility mapping efforts must identify testing capabilities. Data collected during this phase must be shared in a common location to inform future funding, partnership, and testing decisions. By the end of this phase, project teams should have a vetted catalog of equipment options and lab capabilities to support design and avoid duplication.

Key milestones include completing a global state-of-technology portfolio and a companion state-of-facilities portfolio.

Phase 3: Fill Technical Gaps

Step 9: Enhance Facility Capabilities According to Portfolio Gaps

Purpose	Enhance testing and development facilities based on the specific technology and equipment needs, and associated facility gaps, identified in Phase 2. Ensure these facilities can support the next phase of tool development, prototyping, and validation work.
Actions	→ Reference facility capability gaps identified under portfolio of existing facilities step (Step 8) to ensure facility capability enhancements are needed and only redundant when necessary → Secure funding for new capabilities → Develop detailed requirements for each facility → Partner with existing labs to minimize costs and avoid unnecessary duplications
Lead Participant	→ Research institutions (to communicate facility capabilities and needs)
Contributing Participants	→ Steering Committee (to coordinate) → Industry (including service companies, vertically integrated energy producers, and equipment manufacturers to report facility capabilities, expand scope to other research institutions, and to take on facility capability enhancements) → Government bodies (to consider incentives and public funding) and NGOs (to advocate for funding for facility upgrades)

Step 10: Extend Existing Models and Develop New Models	
Purpose	To reduce technology risk and help inform future research, development, testing, and demonstration decisions. This is the initial model development and simulation setup step—full integration of testbed/lab data into model updates occurs in Phase 4.
Actions	→ Model the use of conventional geothermal materials and design approaches as well as alternative approaches for use in SHR. Build on existing conventional geothermal and oil and gas models (e.g., TOUGH2, PetraSim, GeoTherm) → Include, at a minimum, temperature, geochemical, and mechanical factors. Although not an exhaustive list, additional important parameters include heat gradient, stress regime, seismic anelasticity, electrical conductivity, stress states, permeability measures, rock physics behavior, and a way to track and predict permeability evolution as well as heat and fluid sustainability over a long term. → Consider using machine learning to integrate and interpret large, multi-modal subsurface datasets (e.g., geophysical, geochemical, and drilling data). Prioritize applications that improve uncertainty quantification, automate anomaly detection, and support real-time decision-making during siting, drilling, and reservoir stimulation.
Lead Participant	→ Research institutions (to develop, refine, and publish models)
Contributing Participants	→ Project developers (e.g., Earth Sciences New Zealand, Mazama – to share operational data)

Step 11: Develop New Materials, Methods, and Equipment	
Purpose	Accelerate performance improvements and reduce technology risk across the SHR geothermal system by designing novel materials, methods, and equipment suitable for extreme temperatures, pressures, and geochemical conditions.
Actions	→ Identify materials, methods, and equipment gaps across each technology vertical (Heat Extraction, Power Production, Drilling, Well Construction, Siting and Characterization, Geoscience and Geochemistry) → Prioritize development in areas with high risk of project failure or uncertainty, such as: • Zonal isolation and packers rated for >400°C • Non-steel and non-metallic casing materials • Downhole sensors, fiber optics, and electronics for long-term operation in extreme conditions • Materials or coatings for corrosion and scaling resistance in supercritical environments → Consider the use of AI tools and machine learning to: • Efficiently screen large sets of existing and potential materials from existing materials databases for desirable bulk properties (beginning with materials used in adjacent industries such as aerospace, advanced manufacturing) • Rapidly predict the behavior of components under combined thermal, chemical, and mechanical stress • Use test and field performance data to narrow down viable material candidates for high-priority components → Design replicable test protocols for SHR-relevant conditions, such as thermal cycling with temperature swings with temperature differences of up to 450°C

Step 11: Develop New Materials, Methods, and Equipment	
Actions	→ Coordinate component testing across participating labs to ensure cross-comparability → Build modular test setups that simulate multiple SHR conditions simultaneously → Share findings with modeling teams and standards bodies to close data gaps and inform integrated system design
Lead Participant	→ Project developers (e.g., Earth Sciences New Zealand, Mazama), with input from technology interest groups, convened by the Steering Committee
Contributing Participants	→ Upstream industry contributors (service providers, equipment manufacturers) → Materials science and engineering teams (design and test components) → Research institutions (AI and data science experts to support materials discovery and performance prediction) → Standards organizations (track best practices and integrate learnings into guidance) → Steering Committee (ensure alignment and collaboration across verticals)

Note: This step is highly variable depending on the technology vertical. Variability for each technology vertical will be discussed in Section VII: Applying the Road Map: Detailed Strategies for Each Technology Vertical.

Phase 3 Recap: Fill Technical Gaps

Phase 3 targets the most critical infrastructure and knowledge gaps that slow technology development. First, lab capability upgrades are prioritized based on the facility survey, with funding packages assembled and improvements initiated at high-priority sites. In parallel, model development accelerates to simulate material and system behavior under SHR conditions—including pressure, temperature, chemical reactivity, and mechanical stress—drawing from geothermal, oil and gas, and materials science, and validated using real-world test data. Development of new materials and tools, such as high-temperature packers, sensors, corrosion-resistant alloys, and novel cements and casing materials, must be prioritized based on risk and importance to system integration. Although novel materials may not be required for first-of-a-kind projects, finding materials that are optimized for the specific needs of SHR systems would help to improve the cost and lifetime of SHR systems in the long term. AI tools could be used to screen underutilized materials and predict material performance. Test setups should replicate field conditions and be coordinated across labs.

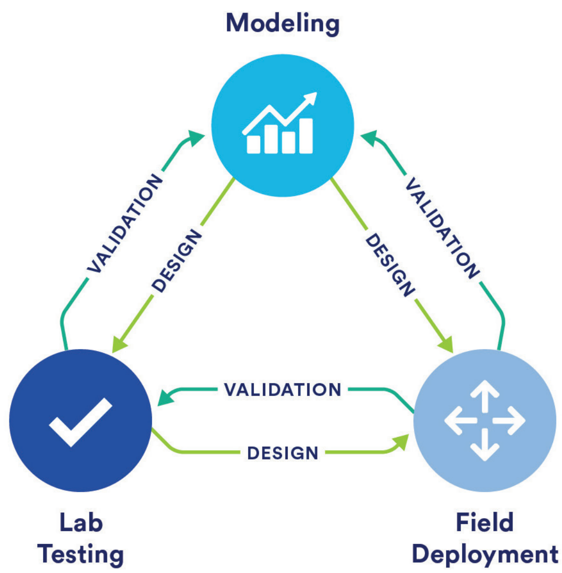
Key milestones include commissioning upgraded facilities, validating material-behavior models, and sharing initial test results from high-priority components via the central platform.

Phase 4: Iterate, Refine, and Reexamine

Technology development depends on a continuous, iterative cycle linking modeling, lab testing, and field validation (**Figure 6**). Each step builds on the last: models inform lab work, lab results guide field tests, and field insights flow back to refine designs. Validation is very important at every stage—models must be tested against lab results, and lab results must hold up in the field. Steps in this phase are labeled "cycled" to reflect their non-linear structure; rather than following a strict sequence, they operate in an ongoing loop that enables continuous improvement as the technology matures. Fast, deliberate, and data-driven iteration reduces risk and supports testing at multiple scales before full deployment. Shared information across phases ensures global alignment, avoids duplication, and strengthens the path to commercialization.

Figure 6: Overview of the Iterative Process

Lab testing represents Step 12, Modeling represents Step 13, and Field Deployment represents Step 14. Step 15 is represented by the Design and Validation arrows feeding between each step.



The iterative process starts with existing knowledge. Beyond that, modeling, lab testing, and field deployment exist in a continuous loop. Computational models, in tandem with existing knowledge from past projects, help to shape the design of laboratory experiments and field trials by predicting material behavior, thermal cycling, and mechanical stresses under the high pressures and high temperatures of SHR conditions. Lab experiments will then validate (or invalidate) model predictions and refine the parameters for field deployment. Results from lab experiments will inform updates to material qualification criteria and support the optimization of drilling and power production systems. Finally, data from field trials will feed back into both modeling and lab testing for continuous improvement. Real-world failures and successes will inform new designs, standards, and technology improvements. The coordinated approach, which will continue throughout the development of the Road Map, is intended to minimize unexpected failures by validating technology in controlled environments before full-scale use, so long as global technology leaders commit to continuous data sharing and iterative improvements. Data sharing will accelerate commercialization.

Step 12: Conduct Laboratory Experiments to Test Existing Modeling Results (Cycled)	
Purpose	Validate (or invalidate) models to assess and improve materials and equipment performance in controlled environments.
Actions	→ Design tests based on model predictions → Coordinate testing campaigns across multiple projects and stakeholders → Test individual components, subsystems, and full integrated systems under simulated SHR conditions (e.g., >400°C, pressure cycling, corrosive fluids) → Cycle between lab testing, field deployment, and modeling. See Figure 6.
Lead Participant	→ Research Institutions (design and run tests)
Contributing Participants	→ Equipment manufacturers and service providers (advise and supply equipment) → Project developers (support the research institutions in their understanding of needs, and to take in learnings and update project plans accordingly) → Test site operators (stay informed)

Step 13: Update Models to Predict Full-Scale and Field Behavior (Cycled)	
Purpose	Validate (or invalidate) models to assess and improve materials and equipment performance in controlled environments.
Actions	→ Collect laboratory and field data to update and validate (or invalidate) models. → Incorporate updated lab and field data to refine assumptions and predict longterm performance under probable conditions
Lead Participant	→ Research institutions (take in data, update models, and refine assumptions)
Contributing Participants	→ Project developers (e.g., Earth Sciences New Zealand, Mazama, to collect and relay learnings) → Equipment manufacturers and service providers (support project developers during testing, to better understand learnings to help understand what model refinements may be needed) → Test site operators (stay informed)

Step 14: Perform Field Tests at Testbeds (Cycled)	
Purpose	Test materials and systems in real-world conditions to validate their effectiveness.
Actions	→ Identify and establish testbed locations. Consider coordinating with existing testbeds, or locations well positioned to be testbeds, identified in Figure 2 → Design monitoring and data collection systems → Deploy components or subsystems in real-world SHR environments and collect long-duration performance data
Lead Participant	→ Test site operators (host tests)
Contributing Participants	→ Research organizations (collect, analyze, and relay data) → Equipment manufacturers and service companies (provide equipment and expertise) → Project developers (execute the projects) → Steering Committee (provide information on compatibility with other global projects) → Steering Committee (to use learnings to guide future decision-making)

Step 15: Share Learnings Through Information-Sharing Platforms (Cycled)	
Purpose	Disseminate findings to ensure transparency and collaboration across projects. This should occur throughout the full road map process. In Figure 6, this is represented by the arrows connecting modeling, lab testing, and field deployment.
Actions	→ Use the established data platform for updates and tag data by component and testing environment to enable comparison across projects → Host webinars and conferences
Lead Participant	→ Project developers (data providers), coordinated by the Steering Committee
Contributing Participants	→ Data management team (collect project data and ensure it is usable for future projects and meta-analysis) → Research institutions (curate findings) → Steering Committee (convene members and make plan for socializing findings) → Standards Bodies, equipment manufacturers, service providers, test site operators (stay informed)

Phase 4 Recap: Iterate, Refine, and Reexamine

This phase supports continuous improvement through tightly linked modeling, lab testing, and field trials. Key actions include incorporating existing knowledge to design assumptions used in models, laboratory tests, and field tests, collected during the Phase 3. Then, launching test campaigns at lab scale based on model outputs, validating component behavior, and adjusting models based on empirical results. These updated models and lab-scale testing results then inform the design of field trials, which are conducted at dedicated testbeds. Field data must be collected under controlled conditions, with sensors in place to track equipment and integrated system performance over time. After each cycle, findings flow back into models and standards. Data must be shared through the information platform, regular webinars, and reports to keep all stakeholders aligned.

Major milestones include model and laboratory testing, deployment of at least one major testbed, and at least one full validation cycle completed for a high-priority component (e.g., zonal isolation system or sensor package). Iteration should be treated as a requirement for progress, not a byproduct of it.

Phase 5: Deploy

Step 16: Develop Pilot-Scale Projects

Purpose	Implement findings at a pilot scale to demonstrate feasibility, system integration, and scalability.
Actions	→ Secure funding and permits → Execute pilot projects in the field → Where project developers opt in, findings from pilot-scale projects should be shared through the established information-sharing platform established in Phase 1, especially where public funding or shared infrastructure was used.
Lead Participant	→ Project developers (e.g., Earth Sciences New Zealand, Mazama, Reykjavik Energy)
Contributing Participants	→ Asset operators (led independently)

Step 17: Address Supply Chain and Infrastructure Needs	
Purpose	Enable a globally coordinated supply chain and supporting infrastructure capable of delivering commercial SHR projects. Ensure materials, equipment, transport, workforce, and grid access are ready to support sustained, multinational deployment. Engage manufacturers across multiple countries to scale up production of qualified materials and components. Move from custom-built tools to standardized, factory-produced components that can be easily replicated and scaled.
Actions	→ Identify component and service constraints that emerged during field testing across regions. Prioritize equipment with long lead times or low manufacturing volume (e.g., high-temperature drilling tools, sensors, packers, and heat exchangers). → Forecast component demand and service needs based on national and multinational deployment targets for 2030–2040 → Coordinate with transport and rig service providers to ensure international movement of components and field services → Assess grid interconnection constraints and prepare for regional build-out of substations and transmission capacity → Share nonproprietary component specifications and test results to enable manufacturers across regions to produce compatible systems
Lead Participant	→ Steering Committee subcommittee: supply chain group
Contributing Participants	→ Equipment and materials manufacturers (scale production and establish regional supply hubs) → Developers and utilities (define deployment timelines and aggregate procurement) → EPC firms and logistics providers (to manage transport and on-site deployment) → Transmission operators (coordinate interconnection needs) → National and regional governments (incentivize manufacturing and training, remove trade and customs bottlenecks)

Step 18: Develop Financing Strategies for Commercial Scale-Up	
Purpose	Enable sustained capital formation for commercial-scale SHR geothermal deployment by developing financing strategies that reduce risk, attract a broader set of investors, and support early projects becoming bankable and repeatable models.
Actions	→ Define capital needs across key stages of commercial deployment (e.g., exploration, drilling, plant construction, and long-term operations) → Identify where financing risks are concentrated (e.g., early drilling and reservoirperformance) and align financing instruments to mitigate them → Deploy risk guarantees and insurance products for early commercial-scaleprojects to bridge high-risk phases with focus on technology demonstration andprojects that characterize unexplored regions → Support offtake agreements that reflect the system value of SHR (e.g., clean firm PPAs and heat purchase contracts) → Create a common checklist and reporting format for early project financial models to help investors compare opportunities → Share early project economics and performance data transparently through the Steering Committee to inform market benchmarks. Sharing of this information would either happen informally through regular project developer calls or more formally through the shared database established in Phase I.
Lead Participant	→ Finance Working Group (formed by Steering Committee)
Contributing Participants	→ Public finance institutions (e.g., U.S.DOE Loan Programs Office, European Investment Bank, EU Innovation Fund) → Investors (commercial banks and project financiers) → Offtakers (utilities, buyers alliances, and industrial offtakers)

Step 19: Deploy Commercial-Scale Projects	
Purpose	Deploy pilot systems at a commercial scale to validate real-world performance and readiness.
Actions	→ Scale solutions for commercial applications → Focus on cost-effectiveness and reliability → Monitor for long-term performance → Learn from and contribute to established information-sharing platform(s)
Lead Participant	→ Project Developers (including vertically integrated companies)
Contributing Participants	→ Private ecosystem partners (service providers, equipment manufacturers, government institutions, etc.)

Phase 5 Recap: Deploy

Deployment begins with pilot projects designed to test full-system integration in relevant geologic and thermal environments. These projects must reflect real-world constraints in permitting, interconnection, and workforce mobilization and will serve as testbeds for cost, performance, and operational integration. Another step is addressing potential supply chain and infrastructure needs. Pilot outcomes will then guide early commercial deployment planning, especially for infrastructure and across the supply chain. Securing innovative financing structures, including public-private partnerships, and risk mitigation tools, will be useful to enable early deployments and attract follow-on investment. Project developers may wait to ensure pilot-stage results meet defined cost, performance, and durability benchmarks before moving to commercial-scale projects. Commercial-scale projects supported by public or multilateral funding should contribute structured, nonconfidential data to the shared system to inform future work. Consistently formatted data (i.e., structured data) is important for ensuring that learnings can be analyzed and compared across projects. Technology Readiness Level (TRL) thresholds, including TRL benchmarks, operational metrics, and economic indicators, should be clearly defined and used to determine when technologies are eligible for commercial deployment.

Milestones include securing at least three funded pilot projects across diverse geographies and subsurface heat regimes. Major supply chain milestones include the standardization of core components, joint purchasing agreements, launch of high-temperature drilling training programs, and identification of transmission and interconnection needs for target regions.

Phase 6: Facilitate Continual Improvement Life Cycle

Step 20: Formalize Qualification Standards and Best Practices

Purpose	Translate emerging best practices and operational learnings into technical documents that define qualification, safety, and performance expectations for SHR geothermal wells. This step will build on the standards body created in Phase 1 and begin producing structured standards documents.
Actions	→ Continue the standards body work initiated in Phase 1 to draft technical content → Compile lessons and recommendations from Phase 2–5 into technical reports and bulletins. These documents will serve as a starting point to capture what is currently known. → As consensus builds and data accumulates, begin drafting performance-based equipment or process guidance → When industry practices mature and show consistency, elevate content to formal, codifiable standards that can be referenced in procurement specifications, regulations, or safety protocols → Allocate resources for ongoing revision cycles, tied to milestones in this road map and feedback from field deployment
Lead Participant	→ Standards body established in Phase 1
Contributing Participants	→ Steering Committee (establish partnership with standards body and recruit participants) → Government Agencies (provide funding, and consider codifying best practices once developed) → Project developers (e.g., Earth Sciences New Zealand, Mazama, provide expertise) → Industry (upstream, downstream, and vertically integrated companies, provide expertise) → Research institutions (provide expertise) → Any group that has a direct and material interest in the outcome of standards set for the technology (provide input)

Step 21: Develop Training Programs	
Purpose	Ensure workforce readiness and knowledge transfer for SHR geothermal. This includes educating an emerging workforce on design, construction, and operation.
Actions	→ Develop curricula and training materials → Partner with universities and training providers that are already anchored in geothermal or oil and gas training programs → Host workshops and online courses → Maintain continual updates to materials based on continually updating standards
Lead Participant	→ Training organizations (design and conduct programs)
Contributing Participants	→ Industry contributors (share expertise)

Phase 6 Recap: Facilitate Continual Improvement Life Cycle

The final phase ensures long-term system integrity and workforce readiness. The body of standards created in Phase 1 must now evolve to include operational qualification benchmarks for wells, materials, and power systems under superhot conditions. Workforce readiness programs must launch in tandem. Training curricula must address SHR-specific needs—extreme temperature design, thermal cycling impacts, high-temperature rig operations, and heat-to-power systems. Existing oil and gas workers should be targeted for reskilling through direct training partnerships based on their existing expertise. Workshops, online courses, and field-based certifications must be rolled out globally. Together, these actions would help ensure future generations are prepared to sustain the technology at scale.

Milestones include publication of qualification standards and their validation by industry through deployed projects. Training milestones could include the launch of at least two university-certified programs, creation of an international training consortium, and onboarding of the first SHR-trained technician cohort.

SECTION 5

Applying the Road Map: Detailed Strategies

Applying the Road Map: Detailed Strategies

There are useful additional details to keep in mind for each technology vertical. This section expands some of the specific strategies that might be considered for each technology vertical considered in the *Bridging the Gaps* report series.

Road Map Breakout: Siting and Characterization[9]

Accurate siting underpins the success of any in-field geothermal project. Without subsurface models that cover stress, temperature, permeability, and structure, efforts in drilling, reservoir creation, and production optimization risk failure. Steps 4, 5, 6, and 14 all require more detail in this topic.

Develop Laboratory Testing and Data Reporting Protocols (Step 4): Teams must develop consistent methods for measuring temperature, pressure, stress, and permeability in highgradient environments. Protocols should include processes for sidewall coring, stress logging in deviated and horizontal wells, and wireline production logging in complex boreholes. Tools must be tested for accuracy and repeatability under relevant field conditions, including real-time instrumentation for long-term monitoring in the brittle-ductile transition zone (BDTZ).

Establish an IP Model That Encourages Collaboration (Step 5): An IP framework developed for a joint SHR project should support shared access to nonproprietary site-specific characterization data critical for collective progress. Data such as temperature logs, seismic reflection profiles, and stress field estimates, often generated through public or co-funded exploration, should be treated as shared infrastructure and made available to the community. The Road Map must also clearly define which data types are public, and which may remain confidential. IP agreements should prevent commercial developers in public-private partnerships from restricting access to generalized findings or methods. Shared repositories should tag and protect location-specific data while ensuring broader models are transparent and reproducible.

Establish an Information-Sharing Platform (Step 6): An important part of the roadmap, particularly relevant to Siting and Characterization, is open access, among participants, to highresolution subsurface data, including thermal gradients, pressure logs, stress maps, core analyses, geologic structure interpretations, and permeability data. Induced seismicity mitigation plans, thermal breakthrough tracking, and long-term reservoir response data must also be standardized and shared. Models and results must be archived with metadata detailing collection methods, uncertainty, and resolution.

Extend Existing Models and Develop New Models (Step 10): Multiscale models for thermal gradient, deformation regime, and reservoir geometry, should compare tradeoffs between drilling depth and surface infrastructure (e.g., power plant siting and transmission distance) to inform

9 Chhun, C., Pearce, R., Caraccioli Salinas, P., Saltiel, S., and Munoz Saez, C. 2024. "Bridging the Gaps: A Survey of Methods, Challenges, and Pathways Forward for Superhot Rock Siting and Characterization." https://cdn.catf.us/wp-content/uploads/2025/01/11102623/shr-bridging-gaps-siting.pdf?

project design. Standardized play fairway analysis with transparent input assumptions is essential. While machine learning can assist in screening regional datasets, models must remain interpretable and validated.

During Step 14, *Perform Field Tests at Test Sites*, key Siting and Characterization technologies to include are joint inversion workflows and coupled thermal, hydraulic, mechanical, and chemical (THMC) models. Field testing should generate the empirical data needed to calibrate and validate these tools. Reliable, integrated workflows will improve understanding of subsurface conditions, reduce uncertainty, and de-risk SHR projects, which in turn, support better design decisions and provide long-term optimization.

Machine learning (ML) may be able to accelerate Siting and Characterization capabilities by rapidly integrating heterogeneous datasets, such as seismic, geochemical, geomechanical, and thermal gradient measurements, into predictive, multiscale models. In early phases (*Steps 4 and 6*), ML could support quality control and anomaly detection in field data, improving the accuracy and completeness of shared datasets. In modeling-focused steps (*Step 10*), ML algorithms might be applied to joint inversion workflows and coupled THMC models to identify key subsurface parameters, optimize play fairway analysis, and refine uncertainty estimates. If utilized correctly, ML could be used to accelerate the *Iterate-Refine-Reexamine* feedback loop (*Phase 4*).

Road Map Breakout: Geoscience and Geochemistry

SHR Geoscience and Geochemistry work must address mechanical and chemical behavior of rock under extreme high-pressure, high-temperature (HPHT) conditions. Labs should handle large rock samples, replicate realistic pressure–temperature cycles, and simulate dynamic fracture growth and closure in supercritical environments.

Develop Laboratory Testing and Data Reporting Protocols (Step 4): Laboratories should be equipped to handle large rock samples and replicate realistic high-pressure, high-temperature (HPHT) conditions, including the ability to control pressure and temperature variations. They should simulate dynamic fracture behavior and measure fracture growth, closure, and permeability changes in real time under supercritical conditions. Testing protocols should cover key parameters: thermal cycling, creep, fracture propagation, permeability loss, and scaling. Measurements should track changes in permeability, mechanical strength, porosity, and surface chemistry after repeated exposure to superhot fluids of varying chemistry. Geochemical tests (and models) should simulate both reservoir and surface conditions, measuring corrosion rates, mineral precipitation, and changes in brine composition over time. Data from these tests should be reported consistently to ensure comparability across projects.

Establish an IP Model That Encourages Collaboration (Step 5): Collaboration is strengthened when participants share core datasets that affect system-wide performance—such as creep behavior, fracture toughness, brine evolution, and reaction kinetics—through an open repository. Proprietary process controls or site-specific treatment methods can be protected, but generalized model inputs and validated protocols should be openly shared to improve replication and system design.

Establish an Information-Sharing Platform (Step 6): Data on rock mechanical behavior, fluid–rock interaction, scaling, corrosion, and thermal stress should be organized with standardized input conditions (fluid type, pressure, temperature, rock type), output metrics (e.g., permeability change over time), and metadata. Geochemical and THMC (thermal–hydrological–mechanical– chemical) model outputs should link directly to test results. Operational challenges such as fouling, pH shifts, and trace metal content must also be reported.

Extend Existing Models and Develop New Models (Step 10): THMC models are essential for simulating time-varying stress, fluid behavior, mineral reactions, and flow changes. Shared modeling assumptions, geomechanical inputs, and predictive outputs can help identify degradation pathways such as fracture sealing, chemical clogging, and structural fatigue.

Develop New Materials, Methods, and Equipment (Step 11): Materials screening should focus on chemical compatibility, including corrosion-resistant materials, coatings, scaling mitigation (e.g., pH control, brine blending), and fluid injection strategies that reduce precipitation. AI can aid geochemical screening and THMC calibration, but results must be grounded in empirical test data.

[10] Pink, Tony and Rebecca Pearce. 2024. “Bridging the Gaps: A Survey of Methods, Challenges, and Pathways Forward for Superhot Rock Drilling.” https://cdn.catf.us/wp-content/uploads/2024/05/10102719/shr-bridginggaps-drilling.pdf?.

[11] CATF. 2025. “SHR Map” https://www.catf.us/shr-map/

Road Map Breakout: Drilling Specifics[10]

SHR drilling faces extreme downhole conditions, long durations, and tight cost constraints. Conventional geothermal methods do not meet the required depth, temperature, or precision, with common challenges including tool degradation above 400°C, incomplete hardware solutions for these environments, and weak feedback loops between field tests and redesign.

Both incremental mechanical drilling improvements and energy-drilling approaches are relevant:

- Mechanical drilling could reach 10-15 km, opening access to SHR resources in a significant portion of the world—though still less than half (by land), according to currently available data[11]. It remains important even if energy-based drilling emerges, as upper, more permeable formations will still require mechanical methods.
- Energy drilling methods, such as plasma and millimeter-wave (MMW), could unlock the deeper half of the global 400°C+ resource. They are most effective below water-rich layers, where mechanical drilling would first be used.
- The two approaches are likely to be complementary, with mechanical methods drilling upper sections and energy systems taking over at depth.

Develop Laboratory Testing and Data Reporting Protocols (Step 4): Individual tools like hightemperature magnetic ranging devices, cryogenic shielding, and coated drill pipes should undergo thermal cycling and erosion testing in integrated products. For novel systems such as casing-while-drilling, dynamic testing in controlled environments is critical before field deployment. Testing must simulate mechanical stress, bit wear, vibration, and fluid chemistry under representative superhot conditions. Additive packages in drilling fluids must also be tested in tandem with pipe coatings, bit materials, and fluid circulation regimes to track compound effects. Additionally, full-string systems, not just components, should be tested under representative conditions.

Establish an Information-Sharing Platform (Step 6): Real-time drilling data—ROP, bit life, torque, drag, mud return temperature, tool failures, circulation losses—should be shared alongside drilling optimization models and cost predictions. Standardize post-run tool failure analyses and capture non-viable configurations to prevent repetition of failures.

Develop New Materials, Methods, and Equipment (Step 11): This should include a consideration of how to optimize existing materials and equipment while not leaving behind possible step changes in technology that will improve the long-term economics and scalability of the technology. Considerations for this step should include a focus on novel drill bits, advanced coatings, and fluid compatible materials. Components like insulated drill pipe and tool temperature shielding require further optimization to withstand prolonged exposure above 400°C, including long hold times, thermal expansion, and chemical corrosion. AI-driven tools could support material screening and optimize component geometry based on real-world thermal and mechanical loads.

Step 14 (Perform Field Tests at Test Sites) is another place in the road map where ML could play a role. As field testing progresses (Step 14), ML could use real-time monitoring data to improve decision-making during drilling and reservoir stimulation. There has also been some discussion within industry of ML being used to predict bit wear or downhole tool failures before they occur by analyzing historical performance data and drilling conditions.

Reaching depths >15 km will require high-capacity rigs. Current innovation focuses on adapting tools to oil and gas rigs, but rig design innovation will be necessary for ultra-deep wells. Systems integration—hardware, fluids, sensors, and automation—should be developed and tested as complete packages to ensure multi-run reliability and commercial feasibility.

Road Map Breakout: Heat Extraction Specifics[12]

Two main SHR methods are in focus: EGS (fractured systems) and AGS (closed loop). EGS demands precise control of fracture geometry, zonal isolation, and fluid chemistry under extreme conditions, with iterative lab–field cycles to refine designs. AGS shares fewer of these subsurface challenges but faces materials and well design requirements detailed under Well Construction and Design. Thus, AGS needs are detailed in the following 'Well Construction and Design" Road Map Breakout.

Develop Laboratory Testing and Data Reporting Protocols (Step 4): For EGS, testing should validate stimulation and flow monitoring tools under superhot conditions. Many key technologies—zonal isolation devices, thermofracturing methods, proppants, cement alternatives—are at TRL 4–6 and require testing across varied temperature and stress regimes. Facilities should enable full-system observation to prevent fracture channelization and validate zone-specific flow monitoring.

[12] Cladouhos, Trenton T. and Owen A. Callahan. 2024. "Bridging the Gaps: A Survey of Methods, Challenges, and Pathways Forward for Superhot Rock Heat Extraction." https://cdn.catf.us/wpcontent/uploads/2024/05/23155355/shr-bridging-gaps-heat-extraction.pdf?.

Establish an Information-Sharing Platform (Step 6): An information-sharing platform that supports advancements in Heat Extraction methods should have the capacity for detailed, highresolution data on subsurface flow behavior and stimulation effectiveness. Key datasets to share include flowrate and pressure histories by zones, tracer return patterns, seismicity logs linked to stimulation stages, and degradation patterns of packers and proppants in superhot and corrosive environments. Because fracture behavior in superhot and supercritical conditions differs from conventional or even enhanced geothermal systems, transparent sharing of failures, anomalies, and unintended outcomes (e.g., short-circuiting, proppant washout, reactions and deposits that occur in the subsurface) is crucial for learning across sites. The platform should also facilitate structured comparisons between modeling predictions and observed behavior, especially for reservoir response, fracture models, and heat drawdown profiles over time.

Develop New Materials, Methods, and Equipment (Step 11): R&D should focus on materials durability above 400˚C and at high pressures—particularly zonal isolation equipment, stimulation fluids, and proppants. Research institutions that have the ability to screen material degradation in lab-scale autoclaves and validate them in multistage stimulation sequences will be important to incorporate into this process. Innovation is also needed in low-permeability perforation tools, such as next-generation perforating guns or nonexplosive alternatives – see Appendix A for more technology development needs in this category.

Road Map Breakout: Well Construction and Design Specifics[13]

High-temperature durability, thermal cycling tolerance, long-term integrity under extreme stress, and a consideration of how casing and cement interact under all of these conditions, is an important consideration for technology development. Conventional casing and cement systems degrade quickly above 374°C and at high pressures, especially when exposed to supercritical fluids, pressure and temperature cycling, and stimulation events. Technology development plans should consider the refinement of existing systems and testing of new well architectures capable of handling these conditions reliably. Lastly, design must combine mechanical strength to resist deformation with flexibility to handle thermal expansion and pressure cycling. See more specific information in the related report, *Bridging the Gaps: A Survey of Methods, Challenges, and Pathways Forward for Superhot Rock Well Design and Construction*.

Develop Laboratory Testing and Data Reporting Protocols (Step 4): Thermal fatigue testing of full casing-cement-connection systems should be the center of the focus of these protocols. Protocols should simulate pressure and temperature ramp cycles, high-stress stimulation events, and long hold times. Testing should cover novel casing geometries, hybrid support systems, and alternative cement emplacement methods like reverse circulation. Testing should also be undertaken to determine the minimum acceptable standards required for success in such things as cement and cement placement.

Establish an Information-Sharing Platform (Step 6): Collect and share data on casing deformation, cement bond strength over time, cycling durability, and connection failure modes, noting materials, bonding methods, and conditions. Compare outcomes to model predictions to refine design standards. Results shared should specify which casing materials or bonding strategies failed, under what conditions, and how outcomes compared to model predictions. Such information is key for modeling teams to refine predictions of deformation, stress accumulation, and bond degradation under thermal cycling.

Develop New Materials, Methods, and Equipment (Step 11):

R&D should focus on materials and designs that can maintain integrity under the extreme thermal cycling, pressure changes, and corrosive environments expected in SHR wells over decades of operation. Near-term priorities include incremental improvements to today's casing and cement systems to extend life and reliability under >400°C conditions. In parallel, research should evaluate more advanced options—such as nonmetallic casings, ductile composites, thermally stable cements, and alternative solutions for cement–casing bond issues—that could provide step-changes in performance over the long term. AI tools can support this work by screening under-characterized materials and modeling stress responses.

[13] Suryanarayana, P.V., Krishnamurthy, R.M., and Bour, D. 2024. "Bridging the Gaps: A Survey of Methods, Challenges, and Pathways Forward for Superhot Rock Well Design and Construction." https://cdn.catf.us/wpcontent/uploads/2024/10/01162900/shr-well-design-construction.pdf?.

Wellhead valves are another important technological focus for advancing Well Construction and Design, as wellhead valves have historically failed in SHR demonstration projects. Improvements can be both incremental—such as higher-grade alloys, better seal materials, and optimized valve designs—and innovative, with room to rethink wellhead architecture entirely.

Because material volumes are small (e.g. there is often only one wellhead associated with thousands of meters of subsurface equipment), it creates a practical opportunity to prototype and test new designs without the cost barriers seen in subsurface hardware.

Lastly, research institutions, developers, and other industry stakeholders exploring AGS heat extraction methods will also want to explore high-conductivity cement alternatives for well completions and insulated return pipe for companies piloting the closed-loop tube-in-shell well design as a part of this process. Well design must align with reservoir and heat extraction strategies—two-well, direct reservoir flow, closed-loop, or fracture-enhanced circulation. Without integrated design and validation, even the best materials will not ensure long-term reliability in superhot systems.

Road Map Breakout: Power Production Specifics[14]

The Power Production vertical for SHR is the most mature part of the SHR system, but still would benefit from targeted technology improvements. Power conversion above 400°C lacks commercial precedent for geothermal systems, and design must account for site-specific thermodynamic and geochemical conditions. For advancing the Power Production technology vertical, activities should aim to address gaps in turbine performance, material compatibility, and plant configuration under SHR conditions, and additionally assess for relevant learnings from what is capable in adjacent sectors, like coal and nuclear power production.

Develop Laboratory Testing and Data Reporting Protocols (Step 4): Controlled testing should assess steam systems, thermoelectric alternatives, and high-temperature heat exchangers under thermal cycling, scaling-prone fluids, and off-design load following (operating above or below optimal steady-state output). Evaluate surface piping and HP/HT components for stress and corrosion. Consider an exploration of topping cycles and cascading uses—which use highest-temperature steam in a primary stage before feeding remaining heat to a secondary process—to improve efficiency and economics.

Establish an Information-Sharing Platform (Step 6): Share plant-level data: cycle efficiency by configuration, turbine degradation, heat exchanger fouling, startup/shutdown response, and cost-performance benchmarks. Provide site-specific performance models and grid-integration studies. This could work to help build out a tool for SHR projects to model power plant design to help with early project planning, financing, and de-risking, which would in turn bring SHR closer to commercial viability.

Develop New Materials, Methods, and Equipment (Step 11):

Standardizing turbines for SHR is a high priority. Although custom-build turbines for SHR plants are possible at high costs14, off-the-shelf models that can operate in SHR conditions would reduce costs, improve planning, and enhance predictability. Custom-built steam turbines are predicted to represent among the highest equipment costs in a SHR power plant, and a major opportunity for cost reduction. Developing standardized turbine designs for SHR is a modest step with significant benefits. Modeling tools that optimize power plant layout based on well locations and site-specific conditions would improve early-stage financing, planning, and risk management. A set of industry-standard optimized plant designs would also reduce the need for custom solutions on every project.

While these are incremental steps—refinements of existing approaches that can streamline early-stage development—no end-to-end SHR power plant has yet been built. Connecting a SHR demonstration well to a working power plant would represent a more significant leap— validating full-system integration and generating the performance data needed to improve design tools, modeling accuracy, and industry standards.

14 Brown, D., Roy, C., Hill, J., and Rogers, T. 2024. "Bridging the Gaps: A Survey of Methods, Challenges, and Pathways Forward for Superhot Rock Power Production." https://cdn.catf.us/wpcontent/uploads/2024/05/07160524/shr-bridging-gaps-power-production.pdf.

SECTION 6

Gap Assessment and Prioritization

To assist in determining priorities for the more than 80 technology gaps identified in the *Bridging the Gaps* reports, the CATF team created a bubble plot (**Figure 7**) to showcase the most immediate and strategically-important needs and improvement areas in SHR geothermal development. The complete gap list, along with rankings used for creating the bubble plot (**Figure 7**) is included in Appendix A.

The prioritization framework visualized in the bubble plot provides a comparative assessment of the key technology gaps that need to be addressed to advance SHR geothermal systems. It organizes challenges across the six core technology verticals: Siting and Characterization, Drilling, Well Construction, Geoscience and Geochemistry, Heat Extraction, and Power Production.

Each bubble in the plot represents a distinct technology gap, plotted according to two key metrics: criticality, or how much the gap limits system viability and scalability, is on the X axis; and level-of-effort (LoE) index, required to advance the technology, is on the Y axis.

Criticality rankings were weighted numerically based on three factors: (1) whether advancement is required for a first-of-a-kind (FOAK) SHR plant to be possible (Yes = 15, Maybe = 7.5, No = 0), (2) whether advancement is required to reduce risk of technical failure (Yes = 10, Maybe = 5, No = 0), and (3) whether advancement is required to reduce cost or increase scalability (Yes = 5, Maybe = 2.5, No = 0). A "Yes" in FOAK automatically cascades to the other two categories, since enabling a FOAK plant inherently reduces risk and supports scalability.

LoE index is calculated by determining which stages of development remain for a given technology gap under SHR-relevant conditions. These stages include data collection, modeling, development or design, laboratory testing and upgrades, integrated field validation, deployment, and development and sharing of best practices. Each stage is assigned a point value, with higher-cost or more resource-intensive activities (such as field validation and deployment) weighted more heavily than lower-cost activities (such as additional modeling). The values are then summed to create the final LoE index displayed on the figures below.

Finally, the size of each bubble represents the number of active or potential contributors (examples identified in **Figure 2**)—such as industry leaders, researchers, and project developers—who could contribute to addressing each gap. This measure is weighted to reflect the relative influence of each stakeholder, giving larger contributing participants (e.g., major energy firms or national labs) a greater numerical impact. Bubble color corresponds to the technology vertical, enabling clear distinction among the six main categories.

If a gap appears in the chart, it indicates that its criticality score is greater than zero—meaning that at least some improvement would be required, even if only to reduce cost or increase scalability. If a gap is not included in the appendix, experts determined that no additional technology improvement is necessarily required at this point. For all of the gaps shown, the underlying technology pieces are likely already commercially viable and operable under some conditions, but would need further development to perform reliably in SHR projects, particularly when coming into contact with potentially corrosive, ~400°C geofluid.

This format allows users to easily identify both quick wins and major undertakings for maturing the technology. Because there are overlapping bubbles and this figure is not complex enough to incorporate all gaps, you can see the full corresponding table in *Appendix A*.

Applications for Road Map Execution

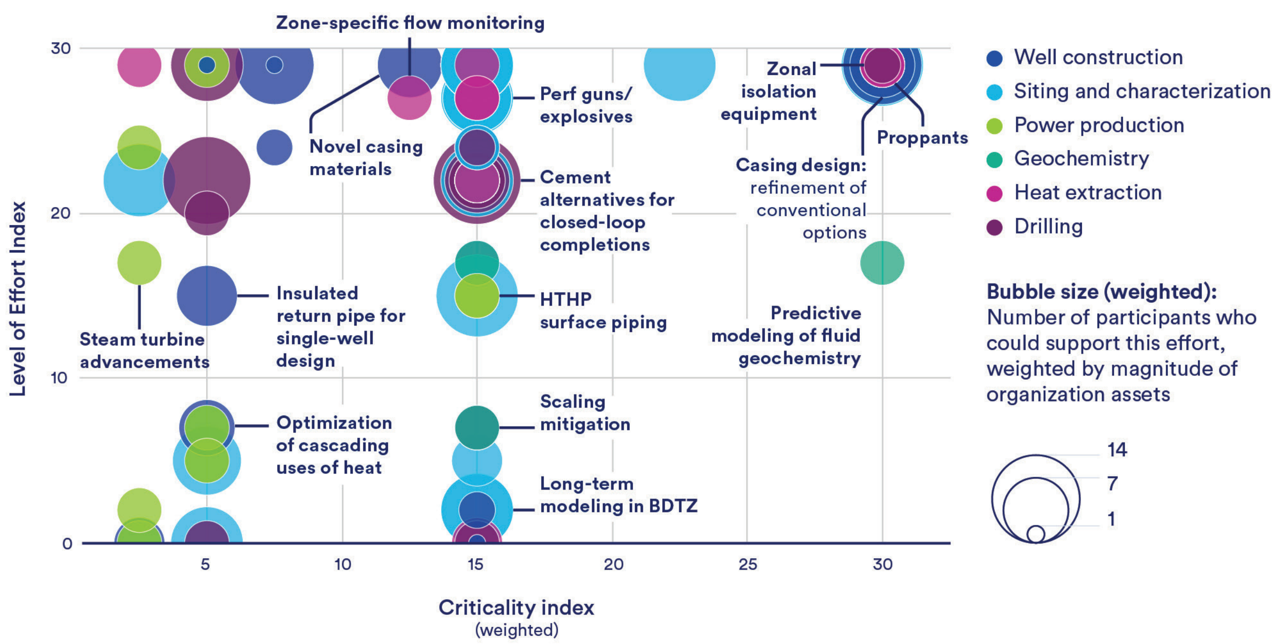
By scanning the bubble plot, stakeholders can target their most suitable role such as: governments de-risking high-cost, high-risk projects and targeting funds toward technologies that unlock broader deployment potential; investors capturing fast wins and finding investment-worthy projects with short commercialization timelines; researchers and national labs identifying underdeveloped areas that align with their expertise; and multilateral institutions identifying areas where collaboration is sparse but needed. Each bubble also signals where new actors could fill gaps or where existing strengths could be better coordinated.

Example: Proppants

Proppants are shown in the upper right corner of **Figure 7**, with both high criticality and a high level of effort. Proppants are used to hold fractures open in the EGS-style heat extraction approach for SHR projects. They are already commercially viable at low to moderate temperatures and pressures, but no proppant has yet been demonstrated to withstand superhot conditions (≥400°C with harsh fluids) over a 25-year production life.

Proppants received a criticality ranking of 30. This is because their advancement is required for a FOAK SHR power plant that uses fracture-based extraction, and therefore also necessary to reduce technical risk and improve scalability. They received an LoE index of 29. This reflects the fact that all activities in the LoE framework remain necessary, from lab testing through field integration and best-practice development. The bubble size was rated seven. Three companies were identified as well-positioned to advance proppants for SHR, two of which have larger balance sheets. This gave them higher weighting in the size calculation. This example illustrates how a technology gap can be both critical and resource-intensive to address. Proppants would be a good example of a top strategic priority for public funding support.

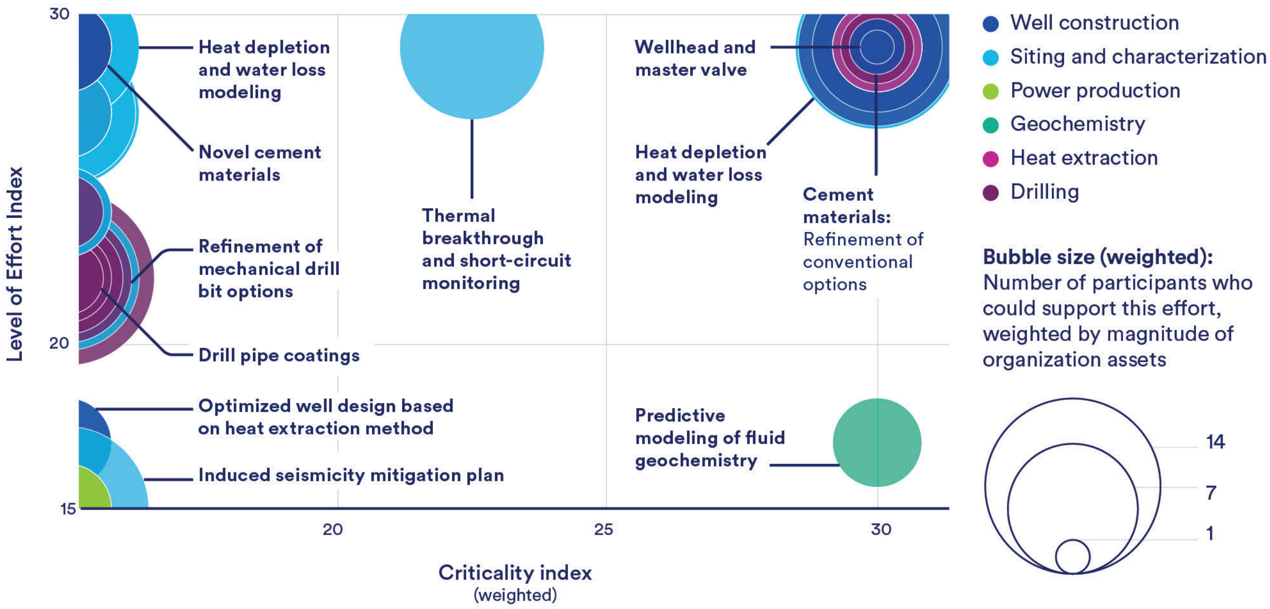
Figure 7: Gap Prioritization Bubble Plot: Full Distribution



Interpreting the Prioritization Landscape

Upper-right quadrant of the bubble plot (**Figure 8**): Identifies high-criticality, high-effort items (e.g., the exploration of novel materials to make breakthrough improvements in the robustness and lifetime of a well)—technology gaps that are essential to system success but also require substantial investment and collaboration. These are the top strategic priorities for public-private partnerships and government R&D support. These areas—such as high-temperature sensors, zonal isolation systems, and advanced drilling tools—require early investment and coordination to overcome technical and financial risk.

Figure 8: Gap Prioritization Bubble Plot – Upper-Right Quadrant: High Level of Effort, High Criticality



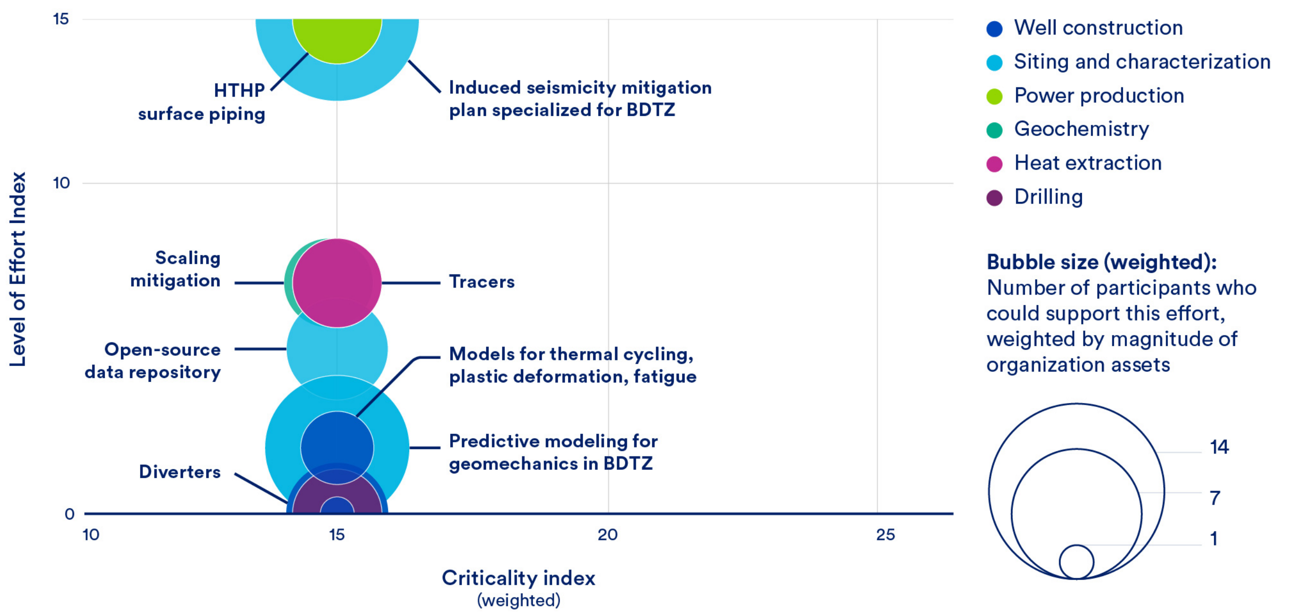
Example: Cement materials (refinement of conventional options)

Cement materials received a criticality ranking of 30. Their advancement is required for a FOAK SHR project, since conventional cement systems are not proven to withstand the temperature swings required for a SHR well, and maintain operation in >400˚C conditions over decades of operation. As with other FOAK-enabling technologies, this makes them inherently necessary to reduce technical risk and ensure long-term scalability. They received an LoE index of 17, reflecting that some—but not all—stages of the LoE framework remain necessary, including laboratory testing, design refinement, and validation under SHR conditions. The bubble size is determined by the number of industry and research groups positioned to contribute improvements to high-temperature cements, with weighting given to those with larger technical and financial capacity. The U.S. Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E), for example, has a history of engaging in high-criticality, high-effort topics, and has chosen well construction, with cement as a sub-topic, as an area of focus for its future "SUPERHOT" program[15].

[15] Advanced Research Projects Agency-Energy. 2025. "SUPERHOT: Stimulate Utilization of Plentiful Energy in Rocks Through High-Temperature Original Technologies". https://arpa-e.energy.gov/programs-and-initiatives/view-all-programs/superhot

Lower-right quadrant of the bubble plot (**Figure 9**): Shows high-criticality, low-effort items with near-term opportunities for deployment-focused investors and developers. These gaps, like refinement of conventional casing design and improvements to conventional cementing systems, are important and affordable to address, with fast feedback loops and short commercialization pathways. Investors and developers can engage quickly and generate early value here.

Figure 9: Gap Prioritization Bubble Plot – Lower-Right Quadrant: Low Level of Effort, High Criticality



Example: Scaling mitigation

Scaling mitigation received a criticality ranking of 15. It was identified as important primarily for reducing technical risk and ensuring reliability, though not as a FOAK-enabling technology. Its advancement is necessary to prevent mineral buildup and performance decline in both surface and subsurface systems, which directly affects long-term plant efficiency and cost. The LoE index was 7, reflecting that only a few stages of the LoE framework remain, primarily data compilation, modeling, and upgrades in the field. Because scaling mitigation already exists and is widely applied in conventional geothermal and other energy systems, the level of effort is relatively low compared to other SHR gaps. The bubble size corresponds to the number of chemical and service companies with expertise in scale inhibitors, surface treatment, and monitoring tools. This example illustrates how a relatively lower-effort, non-FOAK technology gap can still play an important role in improving system reliability and cost-effectiveness.

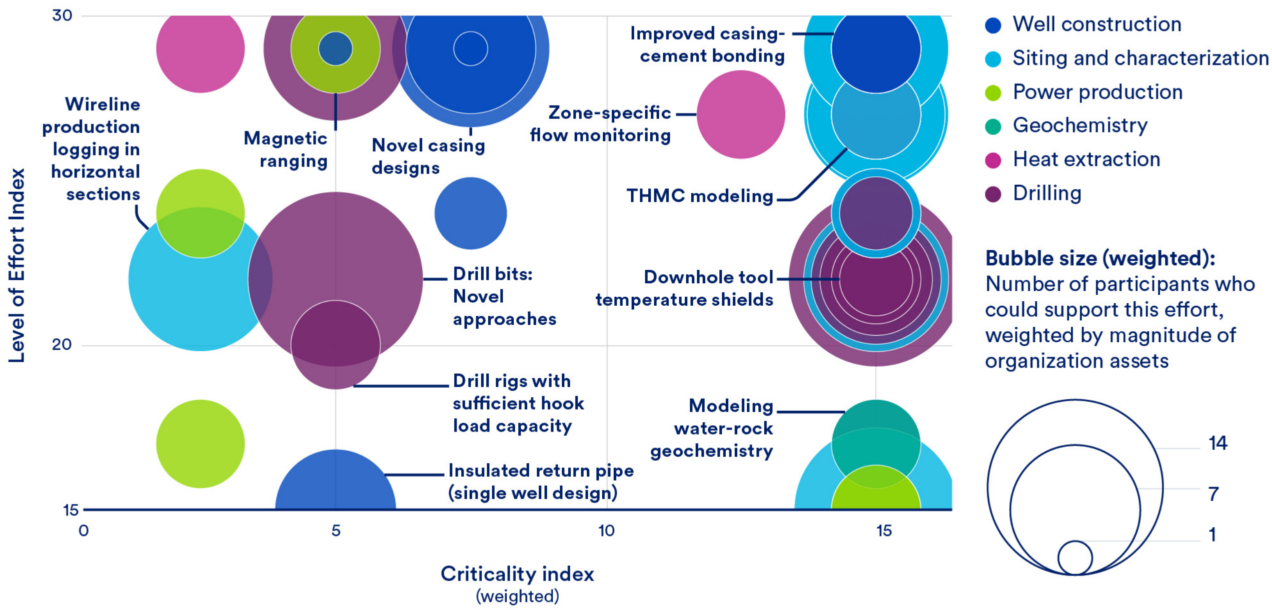
Upper-left quadrant of the bubble plot (**Figure 10**): These low-criticality, high-effort items include optional technologies, like the optimization of power plants for complementary uses of heat. These are innovation plays with a vision toward needs that will emerge once the technology is commercially viable, often useful for advanced optimization, lowering operation costs, or enhancing performance in specific settings. SHR geothermal will still be possible without these advancements. Labs or funders exploring next-generation concepts may choose to invest here.

Example: Temperature shields for downhole tools

Temperature shields for downhole tools received a criticality ranking of 15. An improvement of current technologies is important to reduce technical failure risk and extend tool lifetimes in SHR environments, though not required for a FOAK SHR project to be possible. Without improvements, downhole electronics and mechanical systems are at more risk to extreme thermal degradation, reducing reliability and driving up operating costs. They received an LoE index of 22, due to their need for significant development and validation, including development or design (materials selection), laboratory testing at SHR conditions, and integrated field trials. The bubble size accounts for the number of estimated companies with capability in advanced materials, electronics packaging, and high-temperature shielding with an interest in engaging in geothermal work. This example illustrates a gap that is not FOAK-critical but still requires substantial investment and engineering effort to ensure long-term tool survivability and operational success.

Lower-left quadrant of the bubble plot (**Figure 11**): Low-criticality, low-effort items where modest resources may yield incremental improvements or resilience benefits. This includes developing standard reservoir protocols and an SHR power plant design model to guide optimized configurations. In many cases, these are the technology gaps that will lower costs. Governments, utilities, and early-stage developers with limited budgets can contribute here without duplicating high-cost efforts.

Figure 10: Gap Prioritization Bubble Plot – Upper-Left Quadrant: High Level of Effort, Low Criticality

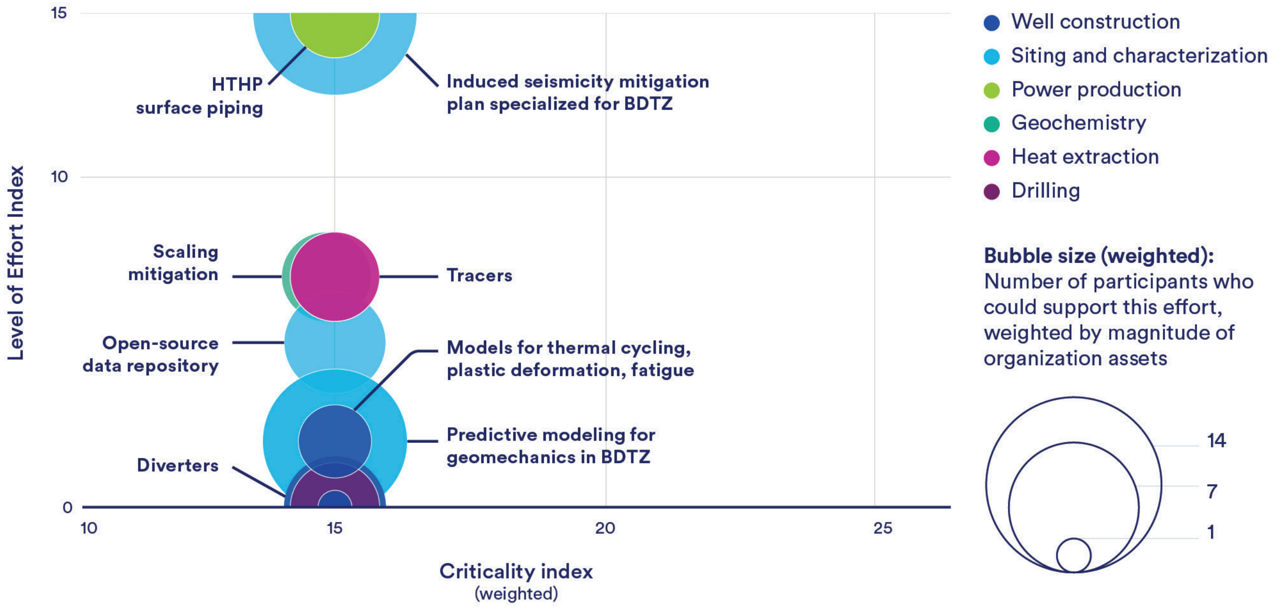


Example: Smart power plant configuration tool

The development of a smart power plant configuration tool received a criticality ranking of 5. Its advancement would primarily help reduce cost and improve scalability of SHR power production, rather than being necessary for FOAK demonstration. Such tools would optimize plant design and operations by integrating reservoir and surface facility data into real-time planning models. The LoE index was 5, reflecting that only limited development steps remain, such as model integration and software validation. This is a relatively low-effort gap compared to hardware-intensive needs. The bubble size corresponds to the estimated number of software and engineering groups positioned to contribute, with weighting given to those with proven experience in geothermal and power plant design optimization. This example illustrates a lower-criticality, lower-effort opportunity where relatively modest investment could yield efficiency improvements at the system level.

The bubble plot should act as a guide to highlight the most strategic and immediate SHR geothermal technology gaps to be addressed, guiding stakeholder investment, innovation, and collaboration. Readers can target their most suitable role: governments reducing the burden of high-cost, high-risk projects, investors capturing fast wins, and conveners identifying areas where interested parties are sparse but needed. The full technology gap list that includes the rankings used for this diagram are included in Appendix A.

Figure 11: Gap Prioritization Bubble Plot – Lower-Left Quadrant: Low Level of Effort, Low Criticality



SECTION 7

Current Status

Phase 1, "Establish Governance," includes steps now being implemented through a Task Group under IEA Geothermal. This Task Group includes both a Steering Committee (Step 1) and establishing an information-sharing platform (Step 6). The platform is supported in two ways: (1) a quarterly Developers' Roundtable for project teams advancing in-ground SHR geothermal, and (2) the development of a structure—pending sufficient resources—to oversee data collection, standardization, and meta-analysis of project progress.

IEA Geothermal's convening power is also being used to support the collection and development of best practices. These practices may form the foundation for future standards. API has launched a geothermal-specific workstream within its low-carbon standardization program, and best practices gathered by the IEA Geothermal Task Group will be shared with API and other relevant entities, including the New Zealand Standards system.

CATF has also advanced work under Steps 7 and 8—developing a shared understanding of prior work and assembling a portfolio of existing technologies and lab capabilities. The *Bridging the Gaps* series published in 2024 identifies the current state of the art, the technical targets needed for commercial viability, and the necessary actions to close the gaps. These findings are available on the Bridging the Gaps website and summarized in the gap table in Appendix A. CATF has also begun compiling a global database of laboratory capabilities relevant to SHR development. This involved surveying laboratories worldwide to document available infrastructure, tools, and technical readiness. You can add your research capabilities to the database by filling out our survey.

Pilot-scale project deployment (Step 16) is underway through efforts led by global site-specific project teams, including the Japan Supercritical Project, New Zealand's Supercritical Geothermal initiative, Quaise Energy, Mazama Energy, and the Iceland Deep Drilling Project. To support these pilots, these teams have already completed—or are in the process of completing—parts of Phase 5: planning for validation, preparing for operations, and securing sites and permits, which are all part of deployment. CATF is working to create opportunities for these teams to share learnings and coordinate, with the goal of enabling more rapid progress through shared insights. Each of these project teams has been invited to participate in IEA Geothermal convenings.

If the collaborative innovation structure outlined in this road map functions effectively, it will accelerate progress for SHR geothermal energy.

SECTION 8

KPIs for Implementation of the Road Map

As recommended in this road map, CATF suggests that collaborative innovation, executed through the recommendations in this road map, be tracked through measurable key performance indicators (KPIs). To support this effort, CATF recommends that the Steering Committee produce a biannual KPI report. The next section outlines potential KPIs.

Short-Term KPIs (0–2 years)

Over the next two years, KPIs focus on foundational research, early-stage collaboration, testing, and standards development. Together, these metrics will reflect the growth, coordination, and momentum of SHR geothermal.

Industry coordination and global implementation: A useful KPI for this topic would be measured by the number of countries with valuable resources engaged in international collaboration and substantially contributing to a shared geothermal data repository. An appropriate goal would be to bring five countries into the shared collaboration within the first year. While country engagement is useful, a key part of this KPI should be *which* countries join into the collaboration. A group of countries with no industry or resources would not be very effective – thus, resources for a country to qualify for helping meet this KPI would include countries that hold existing industry, financial support, or potential test sites. New Zealand, Iceland, Japan, Italy, the United States, Turkiye, Indonesia and Germany, are all examples of countries who would bring unique value into this space. Other than country count, success could also be measured by tracking the total investment from both private and public sectors in SHR projects, including in-kind contribution, and tracking the number of new companies entering the SHR technology space.

KPIs across the road map (short-term):

- 30 monthly users of shared data repository
- Five countries actively participating in collaboration within year one.
- Funding from 3+ countries committed to SHR collaboration, or a set amount of combined public-private investment.

Technology-specific KPIs (short-term):

- For Geoscience and Geochemistry, field trials showing corrosion and scaling control at >400˚C.
- For Well Construction, success should be measured by the number of SHR wells that maintained casing integrity for over a year.
- For Drilling, key metrics might include a reduction in nonproductive time (NPT) caused by high-temperature challenges and a measurable improvement in rate of penetration (ROP) in SHR formations. A composite KPI that accounts for both NPT and ROP may be most useful for measuring improvements in drilling.
- For Siting and Characterization, progress could be reflected in the number of wells drilled based on predictive models that successfully confirm SHR conditions and how well the models predicted the geology and geochemistry of the reservoir.
- For Power Production, the development of a planning model that guides early topside design, planning, and financing decisions will signal readiness for project execution.
- For Heat Extraction and reservoir management, the number of field trials demonstrating effective scaling and corrosion control at temperatures exceeding 400°C is an indicator of technological maturity.

Long-Term KPIs (3–10 years)

These KPIs measure commercialization and sustained performance of SHR systems.

Industry coordination and global implementation:
Over years three to ten, it will be important to track the number of SHR projects being developed worldwide and the existence and consistent use of a broadly accepted set of global standards. These standards should offer decision-making guidance tailored to specific geological conditions, ensuring alignment across international efforts.

KPIs across the road map (long-term)

- A 3x increase in global SHR projects, as tracked by a shared project map.
- In Power Production, a major milestone goal could be three SHR power plants achieving commercial output above 30 megawatts in the next five years.

Technology-specific KPIs (long-term):

- For Well Construction, success will be measured by the formalization of early best practices in commercial SHR wells.
- For Drilling, key metrics will include a percentage reduction in overall drilling cost per meter and an increase in the depth of the deepest geothermal well achieved globally.
- For Heat Extraction and reservoir management, a useful KPI could be measured by the number of SHR reservoirs with sustained output for more than five years.
- For Siting and Characterization, progress can be tracked by the successful siting and drilling of SHR wells in at least three new geologic regions within the next five years.
- For Geoscience and Geochemistry, KPIs could include the inclusion of long-term geomechanical data of BDTZ in a shared data repository.

KPIs should be tracked in a publicly available location to allow for media, investors, policymakers, and other ecosystem partners to track global progress. Tracking KPIs publicly is useful for maintaining excitement and momentum for the work, and will provide ecosystem partners, who are not engaged in day-to-day projects, with metrics they can use to message outwardly about work and progress in the space.

Clean Air Task Force tracks progress and aligns its work to a technology development S-curve that is based on the technology development trajectory of other past technologies. The figure below shows an ideal scenario of growth over time. The position of longer-term KPIs along the S-curve helps stakeholders evaluate whether progress is on track, ahead, or falling behind relative to the overall SHR development trajectory. This approach helps identify bottlenecks and prioritize intervention where acceleration is needed most--especially in drilling, reservoir management, and full-system integration.

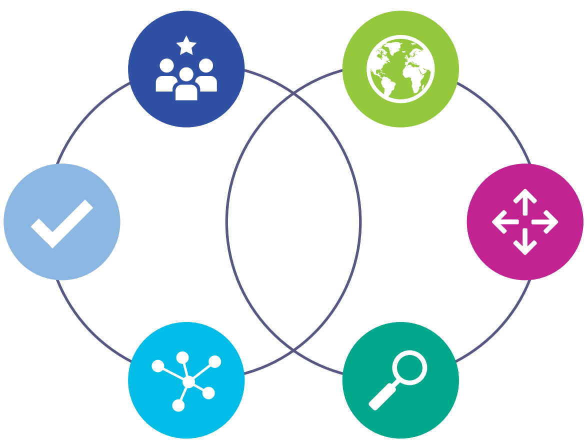
Figure 12: Key Performance Indicators for tracking progress on the Road Map laid out in the report

SHORT-TERM KPIS (0–2 YEARS)

Industry Coordination
30 monthly users of shared data repository; 5 countries actively participating in collaboration within year one.

Joint Funding Commitments
Funding from 3+ countries committed to SHR collaboration; track combined public-private investment.

Field Testing
Field trials showing corrosion and scaling control at >400°C; improved ROP and reduced nonproductive time.



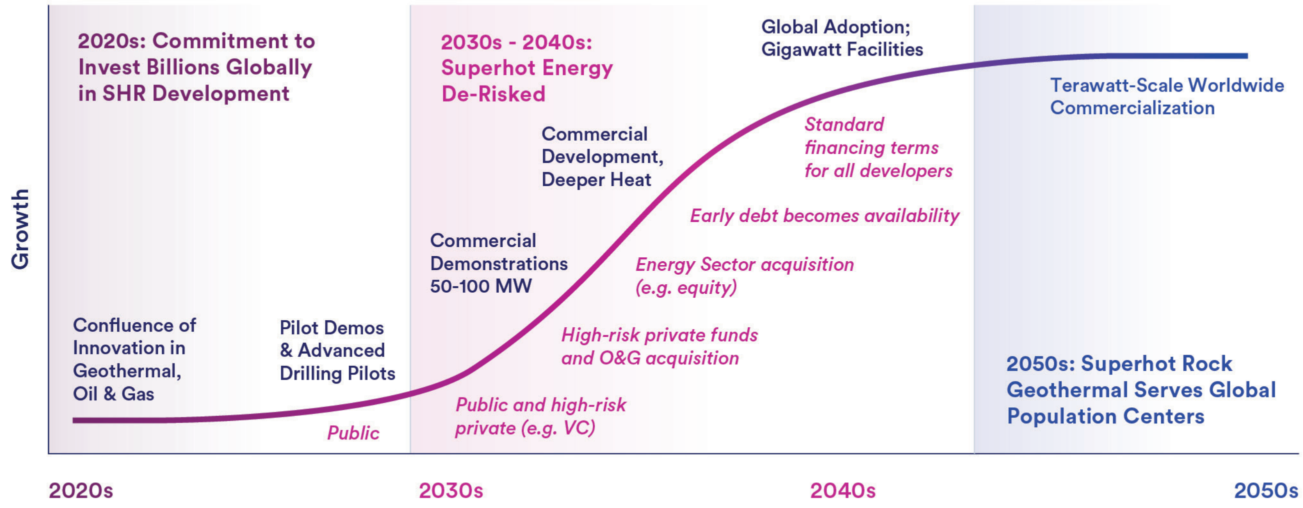
LONG-TERM KPIS (3–10 YEARS)

Project Growth
3x increase in global SHR projects; new entrants tracked via survey and project map.

Technology Readiness and Standards
Shared standards for SHR wells; off-the-shelf equipment adoption; early model-based siting validated by drilling.

Commercial Deployment
Three SHR plants >30 MW online within 5–10 years; deep wells exceeding past depth benchmarks.

Figure 13: S-curve showing predicted SHR technology development timeline given adequate policy and funding support



Many elements could impact this timeline, including funding and cost barriers. Maturing and de-risking SHR is expensive, which makes collaboration across road map steps an important part of the process. Addressing the technology gaps identified in Appendix A is estimated to cost $1.4 billion (USD) if pursued through separate, standalone projects. However, *this cost could be cut significantly* through shared facilities, joint infrastructure, and coordinated investment—as reflected in the level-of-effort estimates in Appendix A—highlighting how collaboration can reduce costs and accelerate progress.

Drilling is the primary cost driver for SHR technology innovation; drilling innovation will be required to get projects from the lab into the field. In conventional geothermal, drilling can account for up to 50% of capital costs for a typical 50 MW plant; in enhanced geothermal projects, drilling and subsurface engineering can exceed 75% of total project costs.[16] For SHR, where subsurface uncertainty is high, these costs will likely dominate. Advancing technologies from TRL 6 to TRL 7 requires subsurface testing, which remains a hurdle. However, once validated, de-risking the subsurface environment through the steps laid out in this road map could significantly reduce overall project costs.

A major technical barrier is integrating system components into a full-system test and optimizing them for higher-temperature, high-stress environments. Prior to full system integration, the biggest technical challenges are in the Heat Extraction and Well Construction technology verticals. Heat Extraction remains untested in the field because it is the final subsurface stage. Well Construction faces high failure rates, primarily due to drastic thermal expansion mismatches between cements and casing steels. Other technological gaps remain, but these two verticals demand the most urgent R&D, testing, and demonstration. For more information on technology gaps, see *Appendix A* of this report and the full *Bridging the Gaps* report series released by CATF in 2024.[17]

16 Robins, J.C., Kesseli, D., Witter, E., and Rhodes, G. 2022. "2022 GETEM Geothermal Drilling Cost Curve Update." National Renewable Energy Laboratory. https://docs.nrel.gov/docs/fy23osti/82771.pdf.

17 Clean Air Task Force. 2024. "Bridging the Gaps" series of five reports: https://www.catf.us/superhot-rock/bridging-gaps/.

Engaging key stakeholder groups in collaborative innovation is challenging, especially when it involves information sharing, standards alignment, or cross-boundary coordination. Private companies may hesitate due to concerns around intellectual property, data confidentiality, or competitive disadvantage. These concerns are valid and need to be addressed through clear frameworks for rights management, IP protection, and role clarity. Still, the benefits of coordinated action—particularly cost reduction, faster validation, and expanded market access—provide strong incentives to engage. The incentives outlined in Section IV: *Incentives* reflect why diverse stakeholders, including private firms, have a strategic interest in collaboration and how well-structured efforts can support both individual and collective goals.

While government funding and support for multilateral collaboration can unlock significant private investment, these efforts are often limited by geopolitical complexities and slow multilevel approval processes. Public-sector involvement can be a catalyst, but it can also introduce delays or obstacles. Knowing when and how to leverage public-sector engagement is critical to advancing these technologies.

SECTION 9

Conclusion

Superhot rock geothermal is a promising but largely overlooked energy source with the potential to deliver scalable, around-the-clock clean power with a small surface footprint. But realizing that potential depends on more than technical promise: it requires deliberate collaboration.

This road map lays out six phases that build toward commercialization: 1) establish coordination and governance; 2) identify resources; 3) fill technical gaps; 4) iterate, refine, and reexamine; 5) deploy; and 6) support long-term improvement. These phases are not strictly linear, but they build momentum when aligned. When combined, these phases in the road map should build the global foundation needed to launch SHR geothermal at commercial scale.

The first steps are clear.

1. Establish a Steering Committee made up of international technology leaders, site-specific project teams, and policy experts that can coordinate global goals and communication across distinct SHR projects, organize working groups, identify when shared learnings and resources will accelerate progress, and act as a central point of contact, aligning efforts across sectors and geographies.
2. Assemble a diverse funding base to support early R&D, field testing, and eventual commercial projects.
3. Launch a standards body that captures best practices as they emerge and supports the development of qualification benchmarks.

These three actions lay the foundation.

Much of this work is already underway. Countries including Japan, New Zealand, Iceland, and the United States have active SHR projects. A dedicated initiative is already being developed through the IEA Geothermal Task Group and administered by CATF. Several later steps are also underway: CATF has begun assembling global portfolios of technology and lab capabilities, and pilot projects around the world are beginning to explore opportunities to collaborate.

The steps in this road map do not need to move in lockstep—many can and should happen in parallel—but their combined effect can be enhanced by a coordinated structure. Forming a central body to codify best practices, facilitate real-time information exchange, and coordinate targeted cross-border working groups would help accelerate development and reduce risk. Done together, they could help ensure that critical components are not left behind and that commercial-scale deployment comes within reach.

SHR geothermal is no longer a distant possibility, it's a near-term opportunity. With the right coordination, investment, and urgency, SHR can become a cornerstone of the global, clean energy systems, offering always-on power with a small land footprint and global reach. The building blocks are in place. What's needed now is collective will to move faster and act together.

APPENDIX A

Complete Gap List

Technology category	Technology gap (Equipment, method, material, or design) [1]	TRL [6]	Needed: Compilation of existing data and/or options [2]	Needed: Modeling [4]	Needed: Development or design	Needed: Testing and upgrades (Lab and field iteration)	Needed: Demonstration and/or integrated field validation
Well construction	Casing materials: Refinement of conventional options	5	X	X	X	X	X
Well construction	Novel casing materials (for example, ceramics, or other composite or non-metallic material, including ductile material)	2	X	X	X	X	X
Well construction	Casing design: Refinement of conventional design	8	X	X	X	X	X
Well construction	Novel casing designs	1	X	X	X	X	X
Well construction	Insulated return pipe (for single-well closed-loop design)	7	X				X
Well construction	Casing connections for extreme temperature variations	6	X				
Well construction	Improved casing-cement bonding	2	X	X	X	X	X
Well construction	Robust and consistently followed cement emplacement procedures	9	X				
Well construction	Alternative cement emplacement procedures (e.g. reverse circulation with vacuum)	6	X	X		X	X
Well construction	Cement materials: Refinement of conventional options	5	X	X	X	X	X

Needed: Deployment	Needed: Development and sharing of best practices	Is an advancement in this category needed to make a FOAK SHR plant possible? (Y=15, M= 7.5, N=0) [5]	Is an advancement in this category needed to reduce cost or increase scalability? (Y=5, M= 2.5, N=0)	Is an advancement in this category needed to reduce cost or increase scalability? (Y=5, M= 2.5, N=0)	X Value (criticality index) [7]	Y Value (level of effort index) [7]	Z value (estimated # of champions - weighted)
X	X	15	10	5	30	29	11
X	X	0	5	2.5	7.5	29	11
X	X	15	10	5	30	29	7
X	X	0	5	2.5	7.5	29	7
X	X	0	0	5	5	15	6
	X	0	5	0	5	0	4
X	X	0	5	5	10	29	3
X	X	0	10	5	15	0	1
X	X	0	10	2.5	12.5	24	2
X	X	15	10	5	30	29	3

Technology category	Technology gap (Equipment, method, material, or design) [1]	TRL [6]	Needed: Compilation of existing data and/or options [2]	Needed: Modeling [4]	Needed: Development or design	Needed: Testing and upgrades (Lab and field iteration)	Needed: Demonstration and/or integrated field validation
Well construction	Cement materials: Use of new materials	1	X	X	X	X	X
Well construction	Systematic approach to use of cement additives for customized to site conditions	9	X	X		X	X
Well construction	Non-cement casing support designs (e.g. All-metal packers or other swellables, hybrid cement/ packer systems, strongbacks)	2-4 swellables and other centralizers 9 (packer stage collars)	X	X	X	X	X
Well construction	Optimized well design based on heat extraction method	9	X	X			X
Well construction	Models for thermal cycling, plastic deformation, fatigue.	9	X	X			
Well construction	Wellhead and master valve design and materials improvements	6	X	X	X	X	X
Well construction	Well design for high pressure variation during fracture stimulation	9	X	X	X	X	X
Well construction	Improved conduction on inlet and insulation on outlet wellhead valves	9	X	X	X	X	X
Well construction	Low-cost monitoring wells and instrumentation	9		X	X		
Siting and Characterization	In-well status monitoring capabilities (pressure, temperature, fatigue)	6	X			X	X
Siting and characterization	Improved methods for measuring electrical conductivity	8	X	X	X	X	X

Needed: Deployment	Needed: Development and sharing of best practices	Is an advancement in this category needed to make a FOAK SHR plant possible? (Y=15, M= 7.5, N=0) [5]	Is an advancement in this category needed to reduce cost or increase scalability? (Y=5, M= 2.5, N=0)	Is an advancement in this category needed to reduce cost or increase scalability? (Y=5, M= 2.5, N=0)	X Value (criticality index) [7]	Y Value (level of effort index) [7]	Z value (estimated # of champions - weighted)
X	X	0	5	5	10	29	3
X	X	0	10	5	15	24	3
X	X	0	5	2.5	7.5	29	1
X	X	0	0	5	5	17	3
X	X	0	10	5	15	2	2
X	X	15	10	5	30	29	1
X	X	0	10	5	15	29	3
X	X	0	0	5	5	29	1
X	X	0	0	5	5	7	5
X	X	0	10	5	15	22	9
X	X	0	10	5	15	29	9

Technology category	Technology gap (Equipment, method, material, or design) [1]	TRL [6]	Needed: Compilation of existing data and/or options [2]	Needed: Modeling [4]	Needed: Development or design	Needed: Testing and upgrades (Lab and field iteration)	Needed: Demonstration and/or integrated field validation
Siting and characterization	Logging temperature and pressure in borehole	9	X	X	X	X	X
Siting and characterization	Logging stress in borehole	7	X	X	X	X	X
Siting and characterization	Logging permeability in borehole	6	X	X	X	X	X
Siting and characterization	Understanding of rock physics and core analysis	7	X	X	X	X	X
Siting and characterization	Sidewall coring	7	X			X	X
Siting and characterization	Wireline production logging in horizontal sections	6				X	X
Siting and characterization	Global open-source repository and universal data sharing methods	9	X		X		
Siting and characterization	Exploration-scale models: geothermal gradient	7	X		X	X	X
Siting and characterization	Exploration-scale models of stress state, deformation regime, understanding geologic structures.	9	X		X	X	X
Siting and characterization	Standard play fairway analysis approach to target SHR plays (machine learning)	6	X		X	X	X
Siting and characterization	A model that weighs drilling deeper vs. transmitting further for supporting project siting decisions.	2	X		X		
Siting and characterization	Induced seismicity mitigation plan specialized for BDTZ	9					X
Siting and characterization	Permeability enhancement monitoring	2	X	X	X	X	X

Needed: Deployment	Needed: Development and sharing of best practices	Is an advancement in this category needed to make a FOAK SHR plant possible? (Y=15, M= 7.5, N=0) [5]	Is an advancement in this category needed to reduce cost or increase scalability? (Y=5, M= 2.5, N=0)	Is an advancement in this category needed to reduce cost or increase scalability? (Y=5, M= 2.5, N=0)	X Value (criticality index) [7]	Y Value (level of effort index) [7]	Z value (estimated # of champions - weighted)
X	X	0	10	5	15	29	9
X	X	0	10	5	15	29	9
X	X	0	10	5	15	29	9
X	X	0	10	5	15	29	9
X	X	7.5	10	5	22.5	22	9
X	X	0	0	2.5	2.5	22	9
X	X	0	10	5	15	5	4
X	X	0	10	5	15	27	8
X	X	0	10	5	15	27	8
X	X	0	10	5	15	27	8
X	X	0	0	5	5	5	8
X	X	0	10	5	15	15	12
X	X	15	10	5	30	29	12

Technology category	Technology gap (Equipment, method, material, or design) [1]	TRL [6]	Needed: Compilation of existing data and/or options [2]	Needed: Modeling [4]	Needed: Development or design	Needed: Testing and upgrades (Lab and field iteration)	Needed: Demonstration and/or integrated field validation
Siting and characterization	Heat depletion and water loss modeling (thermal breakthrough/short-circuit modeling)	2	X	X	X	X	X
Siting and characterization	Long-term monitoring in the BDTZ	-	X	X			
Siting and characterization	Understanding seismic anelasticity	9	X	X	X	X	X
Siting and characterization	Effective methods of joint inversion interpretation for SHR	7	X		X	X	X
Siting and characterization	THMC modeling	6-7	X		X	X	X
Siting and characterization	Predictive modeling of geomechanics in BDTZ in a range of SHR conditions and lithologies.	1	X	X			
Siting and characterization	Standard reservoir characterization protocols	9	X				
Siting and characterization	Real-time THMC model updates and production rate tracking for real-time optimization of operations.	2	X		X	X	X
Siting and characterization	Real-time decisions on production rate for optimized approach	3		X		X	X
Power production	Steam turbine generator	9					X
Power production	Lower cost surface condenser	9	X	X	X	X	X
Geochemistry	Ability to consistently predict, manage, and treat geochemistry at the surface.	9	X	X	X	X	X

Needed: Deployment	Needed: Development and sharing of best practices	Is an advancement in this category needed to make a FOAK SHR plant possible? (Y=15, M= 7.5, N=0) [5]	Is an advancement in this category needed to reduce cost or increase scalability? (Y=5, M= 2.5, N=0)	Is an advancement in this category needed to reduce cost or increase scalability? (Y=5, M= 2.5, N=0)	X Value (criticality index) [7]	Y Value (level of effort index) [7]	Z value (estimated # of champions - weighted)
X	X	7.5	10	5	22.5	29	12
X		0	10	5	15	2	9
X	X	0	10	5	15	29	9
X	X	0	10	5	15	27	9
X	X	0	10	5	15	27	9
	X	0	10	5	15	2	9
X	X	0	0	5	5	0	9
X	X	0	10	5	15	27	3
X	X	0	10	5	15	24	3
X	X	0	10	5	15	15	3
X	X	0	0	5	5	29	3
X	X	15	10	5	30	29	3

Technology category	Technology gap (Equipment, method, material, or design) [1]	TRL [6]	Needed: Compilation of existing data and/or options [2]	Needed: Modeling [4]	Needed: Development or design	Needed: Testing and upgrades (Lab and field iteration)	Needed: Demonstration and/or integrated field validation
Power production	Consideration of other working fluids (.e.g. CO2)	9	X	X		X	X
Power production	Modularity	9					
Power production	Thermoelectric/ steam turbine alternatives	9	X	X			X
Power production	Options for increasing conversion efficiency (e.g. topping heat)	9		X			
Power production	Optimization with cascading uses of heat (i.e. thermal recycling)	9	X	X	X		
Power production	Smart power plant configuration tool	9	X		X		
Power production	HTHP surface piping	9	X				X
Heat extraction	Zonal isolation equipment, including sliding sleeves, packers, and plugs	4-6	X	X	X	X	X
Heat extraction	Perf guns/explosives	4-6			X	X	X
Heat extraction	Stimulation fluid	6	X			X	
Heat extraction	Proppants	4-6	X	X	X	X	X
Heat extraction	Tracers	4-6	X			X	
Heat extraction	Improved perforation approach	9	X	X	X	X	X
Heat extraction	Robust methodology for thermofracturing	6	X	X	X	X	X
Heat extraction	Understanding of and consistent approach to avoiding channelization	1	X	X	X	X	X
Heat extraction	Zone-specific flow monitoring	6	X		X	X	X

Needed: Deployment	Needed: Development and sharing of best practices	Is an advancement in this category needed to make a FOAK SHR plant possible? (Y=15, M= 7.5, N=0) [5]	Is an advancement in this category needed to reduce cost or increase scalability? (Y=5, M= 2.5, N=0)	Is an advancement in this category needed to reduce cost or increase scalability? (Y=5, M= 2.5, N=0)	X Value (criticality index) [7]	Y Value (level of effort index) [7]	Z value (estimated # of champions - weighted)
X	X	0	0	2.5	2.5	24	3
X	X	0	0	2.5	2.5	0	3
X	X	0	0	2.5	2.5	17	3
X	X	0	0	2.5	2.5	2	3
X	X	0	0	5	5	7	3
X	X	0	0	5	5	5	3
X	X	0	10	5	15	15	3
X	X	15	10	5	30	29	3
X	X	0	10	5	15	27	3
X	X	0	10	5	15	7	3
X	X	15	10	5	30	29	3
X	X	0	10	5	15	7	3
X	X	0	10	5	15	29	3
X	X	0	0	2.5	2.5	29	3
X	X	0	10	5	15	29	3
X	X	0	10	2.5	12.5	27	3

Technology category	Technology gap (Equipment, method, material, or design) [1]	TRL [6]	Needed: Compilation of existing data and/or options [2]	Needed: Modeling [4]	Needed: Development or design	Needed: Testing and upgrades (Lab and field iteration)	Needed: Demonstration and/or integrated field validation
Heat extraction	Improved reservoir and fracture models that include temporal predictions and have an increased accuracy and speed.	6-8	X		X	X	X
Heat extraction	Cement alternatives for closed-loop completions	4-6				X	X
Geochemistry	Scaling mitigation	9	X			X	
Geochemistry	Modeling water-rock geochemistry	9	X	X			X
Geochemistry	Predictive modeling of fluid geochemistry	-	X	X			X
Geochemistry	Flow assurance modeling	9	X		X	X	X
Geochemistry	Comprehensive understanding of water-rock interaction in various SHR conditions	9	X	X	X		X
Drilling	Magnetic ranging tools	9	X	X	X	X	X
Well construction	Diverters	5					
Drilling	Drill bits: Refinement of mechanical options	9				X	X
Drilling	Drill bits: Novel approaches	3				X	X
Drilling	Drill pipe coatings	6				X	X
Drilling	Insulated drill pipe	7				X	X
Drilling	Improved or robust approach to drilling fluid and drill fluid additive use	8-9 (4-5 for horizontal wells)	X	X	X	X	X
Drilling	Downhole tool temperature shields (e.g. cryoflask, thermos) [3]	7				X	X

Needed: Deployment	Needed: Development and sharing of best practices	Is an advancement in this category needed to make a FOAK SHR plant possible? (Y=15, M= 7.5, N=0) [5]	Is an advancement in this category needed to reduce cost or increase scalability? (Y=5, M= 2.5, N=0)	Is an advancement in this category needed to reduce cost or increase scalability? (Y=5, M= 2.5, N=0)	X Value (criticality index) [7]	Y Value (level of effort index) [7]	Z value (estimated # of champions - weighted)
X	X	0	10	5	15	27	3
X	X	0	10	5	15	22	3
X	X	0	10	5	15	7	3
X		0	10	5	15	17	3
	X	15	10	5	30	17	3
X	X	0	10	5	15	27	3
X	X	0	10	5	15	22	3
X	X	0	0	5	5	29	9
X	X	0	10	5	15	0	4
X	X	0	10	5	15	22	14
X	X	0	0	5	5	22	14
X	X	0	10	5	15	22	5
X	X	0	10	5	15	22	7
X	X	15	10	5	30	29	2
X	X	0	10	5	15	22	2

Technology category	Technology gap (Equipment, method, material, or design) [1]	TRL [6]	Needed: Compilation of existing data and/or options [2]	Needed: Modeling [4]	Needed: Development or design	Needed: Testing and upgrades (Lab and field iteration)	Needed: Demonstration and/or integrated field validation
Drilling	Drill rigs	"9 for < 15km 7 for > 15km"			X		X
Drilling	Blowout preventors (BOPs)	9				X	X
Drilling	Mud motors	9				X	X
Drilling	Logging while drilling (LWD)	9				X	X
Drilling	Drilling cost prediction decision models	9	X				
Drilling	Casing-while-drilling	6				X	X
Drilling	Improved drill string dynamic efficiency	9		X		X	X
Drilling	Drilling automation, and optimization with machine learning	9	X			X	X

[1] All technology gaps listed are gaps for SHR conditions, not necessarily remaining gaps for use in oil and gas or geothermal at lower temperature and pressure conditions. Instead of saying "proppants that can operate in SHR conditions" for example, the table says "proppants".

[2] This is not selected when it is clear what the technology approaches are and they just need to be tested, demonstrated, or published in best practices. This is only selected if there is a heavy disbursement of data that needs to be collected in order to fill this gap.

[3] Need identified: Tools that can operate in cases where downhole cooling fails or is insufficient

[4] For rows where modeling itself is the gap, the action of modeling is not selected for that gap, because modeling of the modeling is not needed. If a model needs to be developed, "development" may be selected as the needed action instead.

[5] The 'Maybe' option is chosen when the gap is not the only possible approach, and it is not yet known if this approach is the most effective approach available.

[6] TRL = Technology Readiness Level. If something is TRL9, but still included in this table, it means that the item is ready for a FOAK project but could use improvement.

[7] See Part VI in the report for information on how the criticality and Level of Effort index is calculated.

[8] If no advancement is needed, the technology was not included on this table.

Needed: Deployment	Needed: Development and sharing of best practices	Is an advancement in this category needed to make a FOAK SHR plant possible? (Y=15, M= 7.5, N=0) [5]	Is an advancement in this category needed to reduce cost or increase scalability? (Y=5, M= 2.5, N=0)	Is an advancement in this category needed to reduce cost or increase scalability? (Y=5, M= 2.5, N=0)	X Value (criticality index) [7]	Y Value (level of effort index) [7]	Z value (estimated # of champions - weighted)
X	X	0	0	5	5	20	3
X	X	0	10	5	15	22	3
X	X	0	10	5	15	22	3
X	X	0	5	5	10	22	3
	X	0	0	5	5	0	3
X	X	0	0	5	5	22	3
X	X	0	10	5	15	24	2
X	X	0	5	5	10	22	3

APPENDIX B

Acronyms and Abbreviations

AGS	Advanced Geothermal Systems/closed loop geothermal systems
API	American Petroleum Institute
ARPA-E	Advanced Research Projects Agency - Energy
BDTZ	Brittle-ductile transition zone
CEN	European Committee for Standardization
U.S. DOE	United States Department of Energy
GDR	United States DOE Geothermal Data Repository
LPO	United States Loan Programs Office
EGS	Enhanced Geothermal Systems
EIB	European Investment Bank
EPC	Engineering, procurement, and construction firms
EU	European Union
FOAK	First-of-a-kind
FORGE	United States DOE Frontier Observatory for Research in Geothermal Energy
HP/HT	High pressure, high temperature
IDDP	Iceland Deep Drilling Project
IEA	International Energy Agency
IEA TCP	International Energy Agency Technology Collaboration Programme
IRENA	International Renewable Energy Agency
ISO	International Organization for Standards
ISMP	Induced seismicity mitigation plan
JIP	Joint industry project
KfW	Kreditanstalt für Wiederaufbau - German state-owned investment and development bank
KPI	Key Performance Indicator
KTB	German Continental Deep Drilling Programme

LoE	Level of Effort
METI	Japan Ministry of Economy, Trade and Industry
MW	Megawatt
NGO	nongovernmental organization
NOAK	Nth-of-a-kind
NORCE	Norwegian Independent Research Institute
NPT	Nonproductive time (drilling)
NZS	New Zealand Standards
PPA	power purchase agreement
R&D	research and development
RAPID	Rig Automation and Performance Improvement in Drilling Group at the University of Texas at Austin
ROP	Rate of penetration
SHR	Superhot rock geothermal
THMC	Thermo-Hydro-Mechanical-Chemical (modeling)
TRL	Technology Readiness Level
U.S. DFC	U.S. International Development Finance Corporation

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