CHAPTER FIVE

The *GeoVision* Roadmap: A Pathway Forward

Monitoring geothermal fumarolic activity on Akutan Island, Alaska.
Photo credit: Nick Hinz

5 The *GeoVision* Roadmap: A Pathway Forward

The *GeoVision* analysis supports the conclusions that extensive geothermal energy deployment by 2050 is feasible and that increased deployment of geothermal energy could provide broad, direct benefits to the United States. These benefits include reliable and renewable "always-on" power generation with load-following capabilities; cost-effective, energy-efficient heating and cooling solutions for residential and commercial buildings; economic benefits to the geothermal industry; and environmental benefits for the nation. As discussed in Chapter 2, however, realizing the opportunities offered by geothermal resources will require overcoming a range of technical and non-technical barriers aimed at reducing the risks and costs of geothermal development.

This chapter presents the *GeoVision* Roadmap: a compilation of technical, economic, and institutional actions across the geothermal community—including the U.S. Department of Energy (DOE), industry, academia, and other stakeholder groups—that can help address barriers and ensure the continued contribution of geothermal energy as a renewable and diverse energy solution for the United States. The Roadmap is not intended to be an exhaustive list; it is instead meant to serve as a guide that the collective geothermal community can use to meet those key objectives and allow the nation to harness the potential offered by geothermal resources.

The Roadmap actions in this chapter aim to achieve the possible and potential deployment levels indicated by the *GeoVision* analysis. The actions address steps to advance both proven and unproven technologies. For *proven* technologies, technical advancements will help, but the most vital steps needed are to overcome barriers related to project financing, regulatory timelines, outreach and education, and market structures. For *unproven* and developing technologies, the most crucial steps are research and development (R&D) and technology advancement.

The *GeoVision* Roadmap is a compilation of technical, economic, and institutional actions across the geothermal community that can help address barriers and ensure the continued contribution of geothermal energy as a renewable, reliable, and diverse energy solution for the United States.

The Roadmap actions also address the three key principles or foundational objectives of the *GeoVision* analysis, as introduced in Section 1.2. This relationship is discussed in more detail in Section 5.2.

5.1 Risks of Inaction

Geothermal energy provides reliable electricity generation, with capabilities to meet grid flexibility and load-following requirements, and it serves heating and cooling needs. This energy underlies the entire country, is "always-on," and represents vast domestic potential. The *GeoVision* analysis outlines the potential for geothermal energy through 2050 and identifies economic benefits to the geothermal industry and environmental benefits to the United States that can result from increased geothermal deployment (Chapter 4). However, only a fraction of the nation's geothermal energy potential has been realized, due to a combination of technical and non-technical barriers that constrain the use of this abundant, domestic energy resource.

An important question is: What are the repercussions for the nation if challenges to increased geothermal deployment are not addressed?

Electric Sector:
The *GeoVision* analysis confirms the potential for geothermal deployment of more than 60 gigawatts-electric (GW_e) in the electric sector. Getting

to even modest levels of deployment, however, depends on reducing geothermal development timelines by optimizing regulatory processes and improving the discovery of undiscovered hydrothermal resources through better resource assessment and exploration technologies. The explosive growth potential to 60 GW_e indicated by the Technology Improvement scenario in the *GeoVision* analysis is also contingent on developing innovative technologies to create reliable, sustainable, and cost-effective enhanced geothermal systems (EGS). Without the expanded and accelerated exploration and innovative technologies supported by actions in this *GeoVision* Roadmap, the geothermal electric sector is likely to continue to grow at a rate of only ~2% per year (Augustine et al. 2019), resulting in deployment of about 6 GW_e by 2050 (Business-as-Usual scenario). This limited deployment would prevent the United States from realizing the contributions that geothermal energy can make to the nation's electricity sector, including efficiency, reliability, and resiliency.

Non-Electric Sector:
As a cost-effective and efficient source of reliable heating and cooling, geothermal heat pumps (GHPs) can play a major role in the residential and commercial sectors. Growth in the GHP market, however, will require better consumer awareness and improved financing options, as well as technology advances that can lower the costs and improve the efficiencies of heat pumps and ground heat-exchange loops. EGS technology advancements will also be essential to lower costs and facilitate expansive increases in deployment potential for district-heating systems and other direct-use applications. Failure to overcome these challenges would mean missed opportunities to supply the country with renewable heating and cooling of residential and commercial buildings, in addition to missed opportunities for meeting the heat energy demands of a wide variety of industries and commercial enterprises.

5.2 The Roadmap Approach

The *GeoVision* Roadmap builds on the findings of the *GeoVision* analysis, which examines the potential of geothermal energy across multiple market sectors. The actions discussed in the Roadmap are intended to stimulate broadly inclusive, multistakeholder engagement to advance geothermal energy. The potential pathways resulted from a collaborative effort led by DOE, with contributions from national laboratories, a set of 20 industry peers known as "Visionaries," and a diverse group of 34 expert reviewers representing a range of geothermal stakeholders (Appendix D).

> The Roadmap is not intended to be prescriptive; it does not specify how or by whom suggested actions should be accomplished. The intent is to begin an evolving, collaborative, and necessarily dynamic process to inform future action across industry, government, academia, and other geothermal stakeholders.

As explained in Chapter 3 and Appendix C, geothermal development potential is highly sensitive to cost, and advancing the industry depends on the extent to which costs can be lowered through collective stakeholder engagement and efforts. For this reason, many of the Roadmap actions focus on areas related to cost: reduced development timelines, which can improve project economics; improved technologies that can more reliably explore for and target wells; and improved technologies that can reduce well-drilling costs and improve well productivity through novel stimulation techniques.

The Roadmap is not intended to be prescriptive; it does not specify how or by whom suggested actions should be accomplished. Furthermore, it is beyond the scope of the *GeoVision* analysis to propose unintroduced policies or policy changes, and the analysis does not do so. The analysis considers only policies that are in force or that have been introduced but not enacted. The intent is to begin an evolving, collaborative, and dynamic process to inform future action across industry, government, academia, and other geothermal stakeholders. Several action areas will include collaboration among federal, state, and local agencies, particularly where land-management negotiations are essential to a successful outcome.

As noted, the *GeoVision* analysis was based on three key objectives: 1) to increase access to geothermal resources, 2) to reduce costs and improve economics for geothermal projects, and 3) to improve education and outreach about geothermal energy through stakeholder collaboration. The three objectives align with the overarching goal of harnessing the potential of geothermal energy to increase value for the nation. The Roadmap targets these three key objectives through four major Action Areas, each with several key actions and sub-actions in which geothermal stakeholders can engage:

Action Area 1: Research Related to Resource Assessments, Improved Site Characterization, and Key Technology Advancements

Action Area 2: Regulatory Process Optimization

Action Area 3: Maximizing the Full Value of Geothermal Energy

Action Area 4: Improved Stakeholder Collaboration

The complex, many-to-many relationships between the key objectives and the Action Areas are reflected in the interrelated nature of the Roadmap. For example, technology advances discussed in Action Area 1 and regulatory process optimizations from Action Area 2 will impact access to resources and reductions in cost, whereas improved valuation for geothermal energy in Action Area 3 affects costs as well as education and outreach. Domestic and international collaboration (Action Area 4), especially on unproven and developing technologies, will impact the speed with which those technologies advance, thus driving resource access, costs, and global interest in geothermal energy. The interrelationships across the three key objectives and four Action Areas are the foundational framework of the Roadmap.

The Roadmap is intended to be a living document that will be modified using an evolving and collaborative process; it thus includes an action suggesting periodic reviews of progress toward the objectives. The reviews will allow stakeholders to assess the impacts of the Roadmap and suggest adjustments as necessary and appropriate through 2050. Regular reviews will allow for optimal adaptation to changing technologies, markets, public priorities, and policy factors. They will also support the ongoing prioritization of potential pathways to attain shared objectives across stakeholder groups.

5.3 The *GeoVision* Roadmap

Table 5-1 summarizes the *GeoVision* Roadmap, including the Action Areas and related primary suggested actions. The subsequent sections include a broad explanation for each Action Area and its related key actions and sub-actions. The order of the Roadmap actions is not intended to imply priority or relative importance. As previously noted, the Roadmap is meant to be a living document that will rely on stakeholder input to evolve and accommodate continued growth in geothermal deployment.

Autumn colors at Pilgrim Hot Springs on the Seward Peninsula in Alaska. *Photo credit: Dick Benoit*

Action Area 1:	**Research Related to Resource Assessments, Improved Site Characterization, and Key Technology Advancements**
Key Action 1.1 – Conduct national- and local-scale resolution resource assessments across the geothermal resource spectrum	
Key Action 1.2 – Improve detection of subsurface signals	
Key Action 1.3 – Improve geothermal drilling and wellbore integrity	
Key Action 1.4 – Improve geothermal energy resource recovery	
Key Action 1.5 – Improve geothermal resource and asset monitoring, modeling, and management	
Action Area 2:	**Regulatory Process Optimization**
Key Action 2.1 – Improve land access	
Key Action 2.2 – Improve the ability to develop geothermal energy in accessible lands	
Key Action 2.3 – Evaluate geothermal heat-pump regulatory processes	
Action Area 3:	**Maximizing the Full Value of Geothermal Energy**
Key Action 3.1 – Improve valuation of and compensation for geothermal energy	
Key Action 3.2 – Investigate geothermal hybrid opportunities	
Key Action 3.3 – Quantify additional geothermal value streams	
Key Action 3.4 – Assess the economic barriers and solutions pertaining to direct-use applications and geothermal heat pumps	
Key Action 3.5 – Identify opportunities to improve standards, business models, and economics for direct-use applications and geothermal heat pumps	
Action Area 4:	**Improved Stakeholder Collaboration**
Key Action 4.1 – Maintain the Roadmap as a vibrant, active process	
Key Action 4.2 – Improve public education and outreach about geothermal energy	
Key Action 4.3 – Increase awareness of employment and training opportunities across all geothermal energy technologies	

Table 5-1. *GeoVision* Roadmap Summary

Action Area 1: Research Related to Resource Assessments, Improved Site Characterization, and Key Technology Advancements

The actions outlined in Action Area 1 aim at understanding where geothermal resources exist as well as increasing access to and optimizing use of those resources. These objectives will be achieved by improving resource assessments, advancing technology, and improving efficiency. Results of these actions include better and more widespread opportunities for domestic geothermal resource use as well as reduced development cost through improved technologies and lower risk. Success will require increased collaboration among the global geothermal industry and its stakeholders. Outreach to other energy sectors will also contribute to achieving these actions.

Geothermal resources are unique among renewable energy technologies in that significant exploration and capital expenditure are required to locate, characterize, and prove a resource. Wind, solar, and hydropower resources are already well characterized, whereas the majority of hydrothermal resources are still undiscovered and—as such—uncharacterized. National assessments are available for EGS resources, but not at a resolution that can support practical investments in development. Similarly, GHP resources lack a central database of properties that indicate GHP suitability, such as a national map of soil thermal conductivity at the appropriate resolution. Improved resource and site characterization are key for increasing geothermal deployment in both the electric and non-electric sectors.

Harnessing geothermal resources at the scale envisioned by the *GeoVision* analysis will require improving and advancing technology. Progress is needed in detecting subsurface signals to remotely identify and characterize underground attributes. Similar to the way the medical field uses radiology to assess the need for and improve the success rates of more costly and invasive procedures, the geothermal industry would benefit from technology breakthroughs in non-invasive, lower-cost geophysical and remote-sensing technologies. Once geothermal resources are identified and characterized at a level that justifies a more capital-intensive investment toward development, technology advances in drilling and wellbore integrity will play a critical role in lowering the costs of development. Major advances in reservoir and subsurface engineering will be required to enable the cost-effective creation of EGS reservoirs and sustain their productivity once they are created.

Old Faithful Geyser in Yellowstone National Park, Wyoming.
Photo credit: Jim Stimac

Enhanced and innovative tools and techniques can also ensure optimal resource use, improve well life cycles, and enhance overall performance of geothermal wells. These results can, in turn, reduce risk and costs for geothermal developers and minimize adverse environmental impacts. Technology advances are crucial for developing commercially competitive EGS projects and unlocking the full potential of U.S. geothermal resources in the electricity and district heating and cooling sectors. New geothermal technologies should also leverage existing innovations from other U.S.

industries, including oil and gas. At the same time, investments in geothermal technology advancements are likely to yield benefit back to the oil and gas industry—e.g., the geothermal industry's DOE-supported development of polycrystalline drill bits and the subsequent adoption of this technology across the global oil and gas industry (Text Box 1-1).

Once geothermal resources are located, characterized, and harnessed, long-term production of geothermal energy will rely on improved resource monitoring, modeling, and management. Achieving these objectives can improve decision making and ensure longer life and better management of reservoirs and resources.

The DOE's 2019 Frontier Observatory for Research in Geothermal Energy (FORGE) Roadmap (McKittrick et al. 2019) includes activities that are synergistic with and cross-cut several key actions and sub-actions in Action Area 1. The FORGE Roadmap focuses on critical research areas in fracture control, reservoir management, and stimulation. These activities are applied specifically to technology advancements for EGS and are intended to be implemented at the DOE FORGE site in Milford, Utah. The *GeoVision* Roadmap highlights other activities that can be implemented by various stakeholder groups to address additional research areas and opportunities.

Drilling a geothermal well at twilight at McGuinness Hills, Nevada.
Photo credit: Piyush Bakane

KEY ACTION 1.1 – Conduct national- and local-scale resolution resource assessments across the geothermal resource spectrum		
Improving, expanding, and building on past assessments of geothermal resources by state and federal agencies and expanding assessments to include resources for GHP applications can help identify market opportunities.		
DELIVERABLE(S): Geothermal resource assessments that quantify electric and non-electric opportunities at the national and local scales.		
IMPACT(S): Better understanding of the location and diversity of geothermal resources, resulting in increased developer interest and reduced development costs and risk.		
SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 1.1.1: Conduct assessments of U.S. geothermal resource potential.	High-resolution maps at various scales indicating key subsurface parameters for both electric and non-electric sector resources.	Reduced exploration risk and costs. Additional identified and developable resources.

Rationale for Actions

SUB-ACTION 1.1.1: Conduct assessments of U.S. geothermal resource potential.

The economic viability of developing a geothermal resource is a complex function of geological and subsurface characteristics, combined with surface and subsurface access to those resources, market and transmission constraints, and wider stakeholder support. Variables such as market, transmission, and stakeholder support for a project cannot be determined without first understanding the resource potential—that is, where is the resource and what is its grade or quality? As such, the resulting economic determinations are only as accurate as the quality of the resource assessment data on which they are based. Mitigating uncertainty in resource assessments lowers the risk of unproductive exploration, thus reducing development costs.

The U.S. Geological Survey and the National Renewable Energy Laboratory developed national-scale assessments of conventional hydrothermal resources and EGS resources. The U.S. Geological Survey estimates more than 30 GW_e of undiscovered conventional hydrothermal resource potential in the United States (Williams et al. 2008), and the National Renewable Energy Laboratory (Augustine 2016) estimates more than 5,000 GW_e of EGS potential at depths between 3 and 7 kilometers (about 2 to 4 miles) across the country. Improving the quantity and spatial resolution of national-scale assessment data will reduce uncertainty and can potentially identify more resources (in terms of quantity and geographic distribution) than estimated as of 2017. As an example, the *GeoVision* analysis considered sensitivity runs comparing regional, high-resolution EGS resource assessments with broader national-scale data assessments based on EGS resource data from Southern Methodist University. The result was the identification of more than 84 GW_e of additional resources in the Great Basin area alone (Augustine et al. 2019).

High-resolution data on key soil properties for sizing ground heat exchangers and evaluating GHP economics (thermal conductivity and heat capacity) have not been compiled with sufficient resolution at a national scale. Improving the collection, availability, and integration of such data at the national and regional levels will improve economic and market-potential assessments for GHPs. Doing so will also improve the ability of developers to appropriately size and engineer GHP systems to improve efficiency and to reduce system and installation costs.

KEY ACTION 1.2 – Improve detection of subsurface signals		
Enhancing exploration tools for more reliable and accurate detection of geothermal reservoirs at depth can reduce development costs and create additional geothermal development opportunities.		
DELIVERABLE(S): Tools and technologies that provide greater understanding of subsurface characteristics vital to geothermal development, including temperature, permeability, and chemistry.		
IMPACT(S): Reduced uncertainty and development costs. Improved discovery of geothermal resources.		
SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 1.2.1: Develop exploration tools that identify undiscovered resources and improve the ability to identify prospective enhanced geothermal system resources.	Innovative exploration tools and methods. Big-data integration of multidisciplinary technical information.	Improved identification, increased rate of discovery, and increased deployment of undiscovered and deep enhanced geothermal system resources. Improved project economics and reduced exploration and development costs.
SUB-ACTION 1.2.2: Improve resolution of existing geophysical methods.	Improved resource characterization through geophysical tools, techniques, and methodologies. Improved data collection and evaluation methods.	Reduced exploration cost and risk. Increased geothermal deployment.

Rationale for Actions

SUB-ACTION 1.2.1: Develop exploration tools that identify undiscovered resources and improve the ability to identify prospective enhanced geothermal system resources.

New exploration tools are needed to find additional geothermal resources. Most of the identified hydrothermal systems in the United States are associated with surface expressions of thermal features (e.g., geysers, hot springs, fumaroles) that indicate a potential geothermal resource at depth. In contrast, most undiscovered resources do not display these physical manifestations and are therefore difficult to identify using existing industry exploration techniques. Expensive and invasive drilling is the only way to confirm the existence of a geothermal resource. One of the most effective ways to reduce geothermal development costs is to avoid drilling non-productive wells. Improving the ability to identify prospective geothermal resources and target wells into those resources will lower the risk of drilling unnecessary wells. Improving drilling success rates will also impact overall investor confidence in geothermal developments, which will, in turn, reduce project financing costs.

The development and availability of improved exploration tools that can reliably identify geothermal resources in part underpin the *GeoVision* analysis Technology Improvement (TI) scenario (Chapter 3). Technology improvements can reduce the costs of exploration drilling and full-size confirmation wells, and can improve drilling success rates. In the TI scenario, the effects of such improvements on both conventional hydrothermal and EGS are lower capital costs of development and improved favorability for geothermal project economics.

New and innovative exploration technologies and capabilities are needed to characterize subsurface permeability, temperature, and chemistry, along with major geologic structures and stress states in areas where no surface expression exists. Innovative technologies will be the primary means by which additional conventional and EGS resource potential can be identified and captured. Existing exploration tools would benefit from improvements in geophysical, geochemical, and geological sampling, modeling, analysis, and remote sensing. The geothermal industry would also benefit from the ability to integrate multidisciplinary datasets and new methodologies for capturing value from such data. In particular, advances in the field of machine learning could produce new capabilities for characterizing the subsurface through automated pattern identification and data interpretation tasks. Many of these technologies and capabilities are in early stages of research and development.

SUB-ACTION 1.2.2: Improve resolution of existing geophysical methods.

Improving existing geophysical methods and resolution will increase resource discovery and well targeting for both conventional hydrothermal and EGS resources. Seismic-reflection techniques and data-reduction algorithms used by other industries have not been as effective in the hard-rock environments where permeability is fracture-dominated—environments commonly encountered in geothermal energy systems. The most successful geophysical tools to date for imaging geothermal reservoirs in hydrothermal settings use geophysical resistivity methods; however, resolution of these imaging techniques is currently insufficient to identify and target discrete, fracture-hosted permeability. Effort should be directed toward improving existing resistivity-based geophysical methods; enhancing application of seismic reflection to geothermal environments; and developing innovative geophysical technologies and methods that show promise for identifying, imaging, and targeting permeability in geothermal settings. For EGS, geophysical advances in areas such as passive seismic monitoring, gravity and magnetic analysis, and joint inversion of datasets will improve real-time understanding of stimulations and reservoir evolution, allowing developers to create larger, more productive reservoirs.

Setting up field equipment to acquire audio magnetotelluric geophysics data. *Photo credit: Glenn Melosh*

KEY ACTION 1.3 – Improve geothermal drilling and wellbore integrity Integrating improved drilling and well-completion technology, better well design and construction materials, improved decision making, and innovative drilling financing can help industry realize better drilling efficiencies and effectiveness.		
DELIVERABLE(S): New designs and approaches that enhance drilling efficiency and reduce well costs.		
IMPACT(S): Reduced costs and risks, and improved reliability.		
SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 1.3.1: Develop drilling data repository.	A centralized, industry-wide repository of drilling information. A published set of standardized industry data-collection practices.	Improved overall drilling processes and better probability of drilling success.
SUB-ACTION 1.3.2: Increase technology and tool transfer from the oil and gas industry.	Catalog of existing oil and gas technologies that could improve geothermal drilling and lower cost barriers. Creative financing and incentive structures to facilitate technology transfer.	Improved drilling success rates and reduced costs. Improved geothermal project financing.
SUB-ACTION 1.3.3: Develop new drilling technologies, methods, and tools specific to geothermal environments.	New and improved drilling tools, technologies, and techniques, accompanied by standardized operating procedures for geothermal environments.	Better drilling success rates and reduced costs. Improved geothermal project financing. Faster construction timelines and increased development.
SUB-ACTION 1.3.4: Improve drilling decision making, operational culture, and efficiency.	Industry-wide studies of organizational and management culture impacts on effective team decision making. Guidance for implementing culture changes and disseminating industry best practices.	Reduced learning curves for drilling. Improved probability of success and lower drilling costs. Better organizational decisions and improved health and safety across geothermal projects.
SUB-ACTION 1.3.5: Improve well life cycles.	New and improved well design and engineering approaches. New monitoring and assessment capabilities and techniques.	Increased well life cycles. Improved project financing and operational economics.

Rationale for Actions

SUB-ACTION 1.3.1: Develop drilling data repository. The global oil and gas and mining industries drill tens of thousands of wells per year, in environments with relatively distinct and consistent classes of geological conditions. Collecting and analyzing large sets of drilling data has allowed these industries to optimize drilling approaches for specific conditions and subsurface environments, which has resulted in faster, lower-cost, and lower-risk drilling.

By comparison, the geothermal industry drills far fewer wells and does so through more variable rock types; as such, data on geothermal drilling are scarce by comparison. Drilling costs can account for 50% or more of the total capital costs for a geothermal energy project, which makes reducing drilling costs one of the most important factors for geothermal energy production to become economically viable across a range of subsurface environments (Lowry et al. 2017). The geothermal industry could benefit from using approaches similar to those used in mining and oil and gas to compile a critical mass of information and data to optimize drilling. Step-change improvements in geothermal drilling could be supported by two key activities: 1) a collaborative international effort to share data and knowledge through a well-managed drilling data repository, potentially integrated with the National Geothermal Data System; and 2) early-stage R&D activities that apply machine learning to data, with the goal of reducing non-productive drilling time and lowering drilling costs. As explained in Chapter 3 and Appendix C, lowering drilling costs and reducing overall development costs are essential to geothermal deployment.

SUB-ACTION 1.3.2: Increase technology and tool transfer from the oil and gas industry.
Many existing tools and technologies from the oil and gas industry could be leveraged for deployment in the geothermal industry, resulting in significant improvements in exploration and drilling success rates—and, in turn, reducing development costs. In some cases, barriers to this implementation are technical; for example, many potentially useful downhole tools cannot be deployed in geothermal wells due to temperature limitations of the electronics and hardware. As explained in Lowry et al. 2017, the main failure points within downhole components are the electronics, elastomers, and organic materials. Modifications using existing technologies can help accommodate the higher temperatures and often corrosive environments found in geothermal drilling.

Other areas of potential improvements to facilitate technology transfer include reducing polycrystalline drill-bit cutter wear and failure in hard-rock environments. Logging and measurement while drilling are also common technologies in the oil and gas industry that can reduce drilling costs by providing real-time information to optimize a drilling operation (Lowry et al. 2017). Research, development, and industry collaboration will be essential to addressing barriers that limit the transfer of these types of tools and technologies to the geothermal industry.

A related non-technical barrier is that drilling and wellfield service providers tend to focus on the existing, larger oil and gas markets, perceiving the geothermal market and growth potential to be too small to warrant the investments needed to port technologies across the two industries. Many providers may be unaware of the potential for geothermal market growth and the fact that—with relatively limited additional investment—

Experimental testing of a prototype polycrystalline diamond compact drill bit at Sandia National Laboratories' Hard-Rock Drilling Lab. *Photo credit: Randy Montoya/Sandia National Laboratories*

the geothermal industry could readily adapt oil and gas tools for geothermal applications. The *GeoVision* analysis helps illuminate geothermal industry potential. As explained in Chapter 4, if the TI scenario of the *GeoVision* analysis is achieved through stakeholder collaboration and the actions in this Roadmap, the geothermal industry would likely need to drill hundreds to thousands of additional wells per year. While not a direct comparison, in 2016, the domestic oil and gas industry drilled about 1,000 wells per month in the United States (EIA 2018). The potential impact on the U.S. drilling industry is apparent when considering the number of additional wells needing to be drilled and serviced. Such market growth is likely to draw attention from existing oil and gas service providers. This action is also related to Action Area 4, Improved Stakeholder Collaboration.

SUB-ACTION 1.3.3: Develop new drilling technologies, methods, and tools specific to geothermal environments.
Leveraging tools from the petroleum industry is one option to advance technology for geothermal environments (Sub-Action 1.3.2); however, transfer of existing technology from other industries alone is not adequate. The geothermal industry encounters high-

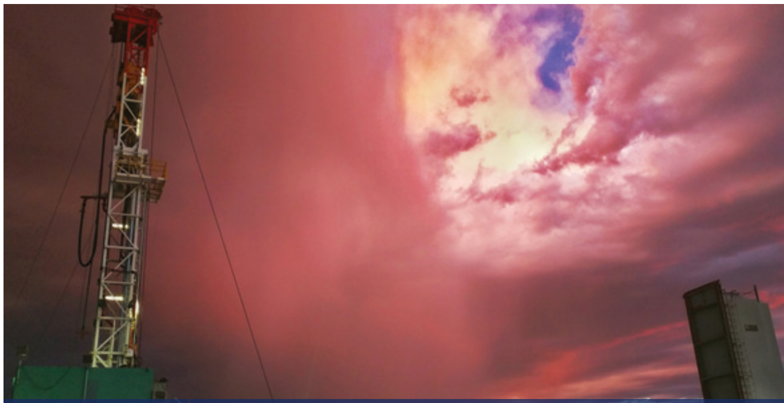
strength, hard-rock environments with distributed fracture permeability and extremely high temperatures, in some cases combined with high-gas, corrosive, and acidic environments. R&D on technologies that improve drilling processes and efficiencies in geothermal-specific environments can fill gaps that existing technology transfer cannot.

Technology advancements are needed in drilling hardware (e.g., drill bits, drill strings, mud motors), well construction materials (e.g., casing, cements), and drilling systems and methodologies (e.g., mud programs, advancing and cementing casing, innovative drilling approaches). As discussed in Lowry et al. 2017, key areas for improvement are likely to be early-stage research activities that reduce tangible costs, such as casing and cementing, as well as intangible costs, such as drilling time and non-drilling time.

Tangible drilling costs can be reduced through novel well designs and casing and cementing techniques that decrease the number of casing strings required. Non-tangible costs, especially non-drilling time, can result from issues such as difficulty cementing, wellbore instability, and equipment failures, but are caused most often by lost circulation and stuck pipes. Lost circulation occurs when drilling fluid flows into the geologic formation instead of returning to the surface; such losses are estimated to cost the oil and gas drilling industry $1 billion per year in rig time, materials, and other financial resources and to add an estimated average of $185,000 per well to geothermal rig costs (Lowry et al. 2017). Additional opportunities exist in technologies that can alter the rock ahead of the drill bit to make drilling easier and increase the rate of penetration while drilling. This will require research into geothermal applications of chemical-enhanced drilling, jet-assisted drilling, and laser-enhanced drilling. Developments and innovations will improve geothermal drilling success rates and drilling efficiency while reducing drilling times and development costs.

SUB-ACTION 1.3.4: Improve drilling decision making, operational culture, and efficiency.
Although many technology improvements are necessary to realize the deployment potential of geothermal energy projected in the *GeoVision* analysis, humans are ultimately required to make the critical decisions in geothermal developments and drilling operations. Human interactions and team dynamics are critical to leveraging data and information in the most impactful and beneficial way, and good decision making drives efficient and low-cost drilling (Melosh 2017). Effective geothermal drilling decisions in uncertain conditions rely on accurate and reliable forecasting. Team-thinking and collaborative decision-making processes have been proven to reduce drilling costs (Melosh 2017). Even in the absence of innovative technology or hardware (tool) development, further research on and implementation of decision processes and organizational and management cultures that streamline approaches in geothermal drilling are expected to yield cost and efficiency improvements.

SUB-ACTION 1.3.5: Improve well life cycles.
Geothermal wells and wellbores are subjected to extreme temperature, pressure, and chemical conditions that can push well-construction materials to their limits—and, often, into modes of failure that result in significant repair costs for geothermal operators. Prolonging the life cycles of geothermal wells can reduce costs and significantly improve geothermal project economics because fewer make-up wells will be required over a project lifetime. Achieving this goal will require understanding root-cause failure modes, improving well engineering design and construction, and early-stage R&D to develop new and hardened construction materials that can withstand higher temperatures and corrosive environments. Tools and systems to monitor wellbore integrity once a well is completed and in service also need to be developed to establish a baseline condition against which an asset's performance and health can be measured over time. This will allow geothermal operators to make proactive management decisions that reduce development and operational costs.



Drilling at Don A. Campbell Geothermal Project in Mineral County, Nevada. *Photo credit: Piyush Bakane*

KEY ACTION 1.4 – Improve geothermal energy resource recovery		
Technology advances could enhance rock-formation permeability and enable improved energy recovery across the geothermal spectrum.		
DELIVERABLE(S): Methods that allow developers to better access geothermal heat and efficiently bring that heat to the surface for use in energy production and heating and cooling.		
IMPACT(S): Increased well productivity and reduced risk of non-productive or sub-commercial wells. Increased development of hydrothermal resources through stimulation of non-productive wells. More efficient and cost-effective use of all geothermal resources, including low-temperature resources.		
SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 1.4.1: Develop existing and innovative stimulation methods for improved geothermal resource recovery.	Improved methods for existing stimulation technologies. Innovative technologies and approaches to well and reservoir stimulation.	Higher probability of successful stimulation. Substantially reduced costs in conventional hydrothermal and enhanced geothermal system deployment for electric and non-electric applications. Improved well productivity and flow rates.
SUB-ACTION 1.4.2: Improve zonal-isolation techniques.	Technologies, methodologies, and best practices that ensure reliable zonal isolation in geothermal environments.	Reduced costs and operational risks. Improved economics for enhanced geothermal system projects.
SUB-ACTION 1.4.3: Develop advanced real-time fracture modeling and mapping.	Advanced real-time, integrated fracture mapping that enables operators to monitor progress in reservoir stimulation.	Actively managed stimulation operations, resulting in improved success rates, lower costs, and lower risk of induced seismicity.
SUB-ACTION 1.4.4: Quantify the relationship among *in-situ* state of stress, induced seismicity, and permeability.	Quantified relationship among relevant subsurface parameters.	Optimized reservoir permeability. Minimized hazards from induced seismicity.
SUB-ACTION 1.4.5: Improve heat-exchange mechanisms and system design for geothermal heat pumps.	Advanced ground heat exchangers for residential and commercial uses.	Reduced cost and land use for geothermal heat pumps and direct-use systems. Improved efficiency of geothermal heat pump systems.

Rationale for Actions

SUB-ACTION 1.4.1: Develop existing and innovative stimulation technologies for improved geothermal resource recovery.

The potential widespread geothermal deployment outlined in the *GeoVision* analysis—supported in great part by EGS resources—will require developing cost-competitive, effective, and reliable stimulation methods. The success of EGS is contingent on the ability of the industry to predictably and reliably stimulate economic reservoir volumes from downhole points of access. Achieving this will require overcoming large gaps in existing knowledge of the mechanism by which stimulation occurs; that is, whether is it from creating new fractures, shearing existing fractures, or a combination of both. Without this understanding, stimulation is a hit-or-miss activity with little or no guarantee of success (Lowry et al. 2017).

Stimulation is used to enhance the natural permeability of a reservoir so that fluids can flow and heat extraction can be achieved in a more cost-effective manner. The goal is to establish an efficient and cost-effective fracture network in hot rock with an initial low permeability. Developing existing and innovative stimulation technologies will have a direct and critical impact on improving well flow rates and, thus, rates of geothermal energy recovery. Achieving this will mean overcoming a fundamental economic limitation for EGS development, where capital costs are not yet commercially competitive. As illustrated in Table 3-3 and Appendix C, a doubling of well flow rates and a 10-fold increase in well productivity are necessary to reduce capital costs of EGS development to the point that wells can support commercial rates of energy extraction and achieve the 60-GW_e EGS deployment levels indicated in the *GeoVision* TI scenario.

Stimulation is also used in maintaining and managing conventional hydrothermal systems to rejuvenate underperforming systems or extend them to increase overall capacity. This activity could include the conversion of non-productive wells to productive assets that can support economic power production on conventional hydrothermal systems, thus reducing project capital costs.

Stimulation falls into two broad categories, with significantly different methods of implementation and results: 1) high-pressure, low-volume stimulation techniques commonly applied in the tight oil industry, and 2) low-pressure, high-volume stimulation that can be a byproduct of injection commonly performed in most existing geothermal fields. These two stimulation approaches may ultimately be applied in concert to create economic EGS reservoirs—starting in the in-field EGS environment and progressing outward toward deep-EGS resources. Geothermal fracture networks are distinct from those created for hydrocarbon recovery, and opportunity exists to continue to adapt oil and gas stimulation methods to conventional geothermal uses. However, it is likely that early-stage R&D will be required to develop an entirely new class of stimulation technologies and approaches that can make EGS economically viable.

On the R&D pathway to this ultimate goal of economic EGS, the geothermal industry generally recognizes that low-pressure, high-volume stimulation has produced notable successes where it has been applied to in-field EGS environments. It is not clear, however, why this has been successful; i.e., what are the underlying subsurface processes that drive stimulation, and how do they interact to create sustainable permeability? EGS reservoir conditions, production flow rates, temperatures, pressures, and fluid chemistries are unique, and the coupled thermal-hydraulic-mechanical-chemical processes that control these geothermal conditions are not well understood. Research into these processes, as well as influence and constraints placed on them by the local and regional stress states, will be critical to improving success rates of existing stimulation methods and laying the knowledge base necessary for innovative stimulation methods for deep, high-temperature, high-pressure EGS environments.

Raft River geothermal power plant in Idaho.
Photo credit: Roxie Crouch

SUB-ACTION 1.4.2: Improve zonal-isolation techniques.

The ability to successfully isolate zones within a borehole for stimulation purposes is critical for EGS success. Zonal-isolation technologies adapted from the oil and gas industry—such as those used in unconventional shale plays—as well as new zonal-isolation technologies developed specifically for geothermal applications will play an integral part in the ability to control fracture location and initiation. Designing zonal-isolation strategies requires fully understanding the local and regional states of geological stress through improved collection of geomechanical data and understanding the impacts of pumping rates and fluid chemistries on stimulation. This sub-action is a critical companion to Sub-Action 1.4.1 and will support the objective to improve geothermal stimulation. The ultimate impact will be reducing capital costs to the point that EGS developments can be commercially competitive.

SUB-ACTION 1.4.3: Develop advanced real-time fracture modeling and mapping.

The ability to reliably predict permeability changes during stimulation in both conventional hydrothermal and EGS reservoirs will require improved models. These models should incorporate real-time changes in well pressure, temperature, and chemistry to understand dynamic reservoir processes and their impacts on reservoir sustainability and opportunities for optimization.

Robust field-scale fracture models that can help predict system performance are essential for creating and managing EGS reservoirs. Developing such models requires a fundamental understanding of the fracturing process and advanced real-time fracture mapping that enables operators to monitor the progress and success of a well-stimulation operation. Improved fracture models that are fully integrated with thermal-hydraulic-mechanical-chemical controls and real-time, georeferenced micro-earthquake data will advance this area of research.

The National Renewable Energy Laboratory's EAGLE high-performance computing system. Such computing will be essential for advanced numerical modeling and machine-learning analysis of geothermal systems. *Photo credit: National Renewable Energy Laboratory*

SUB-ACTION 1.4.4: Quantify the relationship between *in-situ* state of stress, induced seismicity, and permeability.

Understanding the complex relationships among stress state, seismicity, and permeability is critical to creating functional and economic EGS reservoirs and managing their long-term sustainability. Predicting long-term permeability behavior is complex and requires an understanding of the interrelated effects of pressure, fluid chemistry, temperature, stress, and flow-rate variability. To date, industry has only been able to identify empirical links among these phenomena, and experimental results are often independent from one another. Coupled thermal-hydraulic-mechanical-chemical models that provide response feedback information will constrain the most critical parameters impacting permeability. Identifying and coupling these mechanisms in robust models could allow operators to adjust field strategies quickly, optimizing manipulation of permeability while minimizing induced-seismicity hazards.

SUB-ACTION 1.4.5: Improve heat-exchange mechanisms and system design for geothermal heat pumps.

Additional R&D in heat-exchange mechanisms and improved software tools can significantly reduce costs and improve performance of ground heat exchangers used in GHP systems. Innovation and technology advancements are needed to develop new ground heat exchangers. Ground heat exchangers using deep boreholes can be less expensive in some subsurface systems and are needed for applications where available land is limited. Alternative heat-exchanger designs—such as developing helical heat-exchange loops and using foundation piles as heat exchangers as elaborated in Liu et al. 2019—show promise in lowering costs and increasing performance. In addition, large GHP systems for commercial applications could be made more energy efficient through optimized system design using advanced software and other design tools. Improvements and technology breakthroughs could reduce heat-exchange loop costs by as much as 30%. Enhancing heat-pump efficiencies by as much as 50% by 2030 is also achievable through technology breakthroughs that include developing and implementing variable-speed compressors and dual-stage heat pumps dual-stage heat pumps (Liu et al. 2019).

KEY ACTION 1.5 – Improve geothermal resource and asset monitoring, modeling, and management Accurate forecasting of fluid flow through geothermal reservoirs can allow better management of production from associated resources.		
DELIVERABLE(S): Improved methods and tools that allow developers to monitor and model geothermal resources.		
IMPACT(S): Improved sustainability and more efficient and cost-effective management of geothermal resources.		
SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 1.5.1: Improve monitoring, modeling, and forecasting of reservoir performance.	Improved, integrated, and coupled full-field (reservoir-steamfield-power plant) models and forecasting.	Improved resource sustainability and project economics. Reduced costs and improved geothermal economics.
SUB-ACTION 1.5.2: Develop advanced reservoir tracers and tracer-deployment techniques.	Innovative tracers and tracer-deployment methods and monitoring tools that allow for continuous monitoring for tracer returns.	Improved monitoring, management, and characterization of geothermal resources. Reduced costs and improved geothermal economics.

Rationale for Actions

SUB-ACTION 1.5.1: Improve monitoring, modeling, and forecasting of reservoir performance.
Resource monitoring serves two primary purposes in reservoir management: 1) establishing the baseline status of the system and 2) creating a record of reservoir responses and performance over time that can be assessed to continually optimize the system. Cost restrictions often limit the amount of monitoring data collected at geothermal operations. Adequate monitoring data are needed for developing and integrating models of geothermal reservoirs, steamfields, power stations, and other infrastructure. If integrated appropriately, these data could be used to forecast system performance and plan major capital expenditures. The quality, resolution, and predictive ability of the models on which these data are built is critical. Improved monitoring, modeling, and forecasting tools—including applications of machine learning technologies—could support better and more timely decision making and resource management, which can reduce the number of make-up wells that need to be drilled on an operating field. The ultimate impact would be reduced geothermal development costs and improved project economics.

SUB-ACTION 1.5.2: Develop advanced reservoir tracers and tracer-deployment techniques.
Effective geothermal field management requires identifying and understanding the dynamic response and evolution of reservoir heat flow, permeability, pressure, and fluid chemistry to changes in field operations. Reservoir tracer tests facilitate understanding of these critical relationships at depth and over relatively large distances. Tracer tests also provide an understanding of changes in reservoir hydrology in response to production and injection activities.

Existing tracers and tracer test data and interpretation techniques provide only limited spatial resolution of the reservoir characteristics (Hawkins et al. 2017). Innovative tracers, tracer test methodologies, and interpretation techniques can maximize the value of test data and improve reservoir management in conventional hydrothermal and EGS reservoirs. Improved knowledge of subsurface fluid flow and temperature distributions and their changes in response to operational activities (production and injection) will support improved field management and sustainable geothermal generation. The overall impact will be to reduce operational costs and improve the economics of geothermal energy.

Action Area 2: Regulatory Process Optimization

Regulatory processes are essential in helping to ensure that geothermal development is carried out responsibly and consistently. However, geothermal regulations have evolved over time in separate instances, resulting in processes that are often inefficient and complex. In addition, regulatory processes do not always account for advances in technology, changes in the energy market, or other factors.

Overcoming complexity and uncertainty in costs and development timelines resulting from regulatory processes can support increased geothermal deployment. The *GeoVision* analysis confirmed that shortening permitting and regulatory process times alone can result in increased exploration and a higher rate of geothermal project development over the status quo; increased deployment projected to occur through improved regulatory timelines would occur even in the absence of technology improvements. Because 90% of conventional geothermal resources in the United States are located on federally managed lands (Young et al. 2014), collaboration among agencies with land-management responsibilities will be essential to optimizing regulatory processes. Action Area 2 includes activities for stakeholders to evaluate and navigate regulatory processes, not to propose requirements or modifications to regulations. These actions rely on collaborative processes, careful and objective analysis, and consideration for a range of stakeholder needs.

It was beyond the scope of the *GeoVision* analysis to identify or propose policy changes, and no attempt is being made to do so in this section. The activities in Action Area 2 focus on reviewing and researching the effects of regulation on the geothermal industry to help inform decisions and provide understanding for the industry.

KEY ACTION 2.1 – Improve land access		
Streamlined processes for leasing lands with prospective or known geothermal resources could expedite development of those resources.		
DELIVERABLE(S): Optimized and standardized leasing and land-access processes.		
IMPACT(S): Increased discovery of geothermal resources. Reduced construction timelines, risk, and costs for development.		
SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 2.1.1: Evaluate geothermal leasing processes for federal lands and examine potential opportunities to improve such processes.	Optimized and consistent leasing processes for geothermal development on federal lands.	Potential for increased discovery rate of geothermal resources. Potential to shorten project timelines and improve project economics.
SUB-ACTION 2.1.2: Improve ability to deploy geothermal energy for electricity and direct use on U.S. military bases.	Collaborative and comprehensive report on the potential for geothermal energy applications on military bases.	Improved national security through reliability and resiliency provided by geothermal electricity generation and heating and cooling on military bases.
SUB-ACTION 2.1.3: Examine opportunities for standardized permitting processes.	Standardized and coordinated processes across federal and state organizations.	Shortened review time and consistent requirements. Shorter project timelines. Improved project economics.

View to the northwest of Navy I geothermal power plants at Coso geothermal field in California. *Photo credit: Andy Sabin*

Rationale for Actions

SUB-ACTION 2.1.1: Evaluate geothermal leasing processes for federal lands and examine potential opportunities to improve such processes.

The length of time from the start of exploration to the day on which a geothermal operation produces power and begins generating revenue is generally 8–10 years (Young et al. 2019). The overall development timeline may be even longer than that as a result of requirements associated with processing a lease nomination, and some lease stipulations may prevent development entirely (Young et al. 2014, Young et al. 2019). Although a federal or state land-management agency can nominate lands for leasing (i.e., request that those lands be made available for development), nominations typically come from prospective developers—especially at the federal level.[101] Before the responsible land-management agency (e.g., the Bureau of Land Management) can lease federal or state lands, the agency typically must complete a pre-leasing analysis and post the land for lease sale.[102] This process results in a Lease Sale Queue that has historically taken as long as five years on federally managed land (Bureau of Land Management and U.S. Forest Service 2008). Examining opportunities to streamline lease processing and requirements can simplify the leasing process for both agencies and developers. Streamlining could allow stakeholders to address leasing issues in a consistent and collaborative manner, potentially mitigating impediments to project development and enhancing opportunities for responsible geothermal development on public lands. Collaboration among agencies with land-management jurisdiction will be vital in examining lease process improvements that account for all stakeholder needs.

SUB-ACTION 2.1.2: Improve ability to deploy geothermal energy for electricity and direct use on U.S. military bases.

Military installations have a demand for power and are motivated to be energy independent to help ensure security of operations. Geothermal development could help military bases meet mission requirements and prevent grid encroachment through extended transmission and distribution power lines. The Department of Defense's Geothermal Program Office has the authority to explore, develop, and sell geothermal resources on military installations, as defined in 10 USC 2916 and 2917 (Levine and Young 2017); however, potentially developable resources on military installations are not yet developed (Meade et al. 2011, Alm et al. 2012). A collaborative effort to evaluate the potential for geothermal installations on military bases and to clarify appropriate land-management authorities could open military sites for geothermal development—in turn, potentially helping to provide energy security for military operations.

SUB-ACTION 2.1.3: Examine opportunities for standardized permitting processes.

As discussed in Section 2.4, developing a geothermal project requires a variety of permits, and—although federal permits are the same nationwide—state permits can vary widely. Administrative procedures to obtain permits involve several federal, regional, and local authorities, and the complex and sometimes time-consuming procedures can impact the investment potential of a geothermal project because of extensive delays and varied requirements (Young et al. 2019).

Coordinated federal and state permit offices are in place to manage the required permit applications and environmental reviews of permits for projects involving oil and gas, mining, solar energy, wind power, and other large infrastructure projects (Young et al.

101 In a geothermal lease nomination, an entity (e.g., developer) requests to lease a parcel to develop geothermal resources, at which point a federal—or, in some cases, state—agency reviews the nomination. In some cases, a federal or state agency may not receive a lease nomination, but may determine on its own that it wants to lease the parcel.

102 Where another federal agency manages the surface estate above the geothermal resources managed by the Bureau of Land Management, such as the Forest Service, the surface manager only conducts the pre-leasing analysis (including compliance with the National Environmental Policy Act of 1969) and provides the Bureau of Land Management with a "concurrence" to lease the underlying mineral rights. The Forest Service does not nominate lands or post them for lease sale.

KEY ACTION 2.2 – Improve the ability to develop geothermal energy in accessible lands A new model for permitting lands for geothermal energy use could enable market forces to drive future development through improved regulatory processes.		
DELIVERABLE(S): Tools and strategies that simplify market access while mitigating environmental impacts.		
IMPACT(S): More efficient, cost-effective, and environmentally sound access to geothermal resources.		
SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 2.2.1: Study the potential for streamlining environmental review and permitting of geothermal development activities.	A report of the potential for and benefits of streamlining reviews of geothermal activities on federally managed lands.	Understanding of how streamlined reviews could reduce exploration costs and risks for developers.
SUB-ACTION 2.2.2: Develop innovative strategies to minimize and mitigate environmental impacts during geothermal siting and development.	Mitigation measures that facilitate geothermal development while reducing environmental impacts.	Ensured protection of environmental, biological, cultural, tribal, and archeological resources while allowing geothermal development.
SUB-ACTION 2.2.3: Collaborate among local, state, and federal stakeholders to examine strategies to improve market access.	Strategies to address financial and market barriers to geothermal power development.	Better access to power purchase agreements for new geothermal developments.

2019). The *GeoVision* analysis confirms that permitting improvements and efficiencies could be realized through a number of mechanisms and could lead to expanded geothermal deployment. Collaborative efforts to examine these mechanisms and their impacts could identify opportunities to improve geothermal permitting.

Rationale for Actions

SUB-ACTION 2.2.1: Study the potential for streamlining environmental review and permitting of geothermal development activities.
Many permitting reviews for federal land use are based on important considerations for preserving the environmental quality, ecological health, and overall aesthetics of public lands. Accommodating those requirements is essential to ensuring long-term protection for and quality of such locations.

Geothermal projects that are on federally managed land and/or receiving federal funding may be subject to an environmental review process under the National Environmental Policy Act (NEPA) as many as six times—from the land-use planning phase through use of the geothermal resource (as determined through analysis of the geothermal NEPA review process in Young et al. 2014).

As described in Section 2.4, the type of NEPA review process required (i.e., categorical exclusion, Environmental Assessment, Environmental Impact Statement) depends on the complexity of the activity being permitted; decisions about how the process is conducted can impact overall geothermal development timelines. Identifying opportunities for streamlining permitting processes for geothermal development could decrease the cost and time associated with geothermal exploration and resource confirmation. These findings can be used to advance discussions and motivate further investigation of tools such as programmatic analyses, categorical exclusions, and/or streamlining of other environmental reviews as a means to help accelerate geothermal project development while accommodating and respecting crucial protections.

SUB-ACTION 2.2.2: Develop innovative strategies to minimize and mitigate environmental impacts during geothermal siting and development.
As noted in Sub-Action 2.2.1, responsible energy development requires accounting for considerations that preserve the environmental quality, ecological health, and overall aesthetics of U.S. lands. To further enable geothermal development, the industry can develop new—and improve on existing—strategies to minimize impacts during the early stages of geothermal development. In addition, mitigation techniques used by other industries (e.g., using temporary roads) can allow development with minimal surface impact. Applying similar measures to geothermal energy projects could potentially allow geothermal development to proceed more efficiently and in more areas.

SUB-ACTION 2.2.3: Collaborate among local, state, and federal stakeholders to examine strategies to improve market access.
Difficulty in financing geothermal projects—accessing capital and acquiring power purchase agreements—is the greatest non-technical barrier to geothermal projects being developed in the United States (Wall and Young 2016). Removing hurdles to obtaining power purchase agreements and capital could significantly increase geothermal development. In addition, state-level renewable portfolio standards are often not applied evenly among technologies and—as currently implemented—tend to hinder geothermal energy. Collaboration among stakeholders can help support strategies to address financial and market barriers such as disparities in incentive programs. Strategies could include: 1) support for increased deployment of renewable technologies that exhibit flexible-generation characteristics and can operate in either a traditional "baseload" configuration or as load-following generation, 2) programs that support increased geothermal deployment, and 3) changes in market-pricing structures to address asymmetries across energy technologies.

KEY ACTION 2.3 – Evaluate geothermal heat-pump regulatory processes

Standardized local permitting and building codes, based on statewide policies, can improve acceptance of GHPs in heating, ventilation, and air-conditioning markets.

DELIVERABLE(S): Analyses that can identify optimized policies and benefits for GHP applications.

IMPACT(S): Increased consumer interest and improved economics for GHP applications.

SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 2.3.1: Analyze the impacts of policies related to geothermal heat pumps.	Study of the potential for and impacts of state-level policies to improve geothermal heat-pump access and deployment.	Increased understanding of geothermal heat-pump policy impacts.
SUB-ACTION 2.3.2: Collaborate to evaluate tax credits and other programs for geothermal heat pumps that are similar to those for other technologies.	Study of tax credits and other programs for installation of geothermal heat pumps.	Increased deployment of geothermal heat pumps through reduced upfront installation costs.

Rationale for Actions

SUB-ACTION 2.3.1: Analyze the impacts of policies related to geothermal heat pumps.
The use of GHPs for heating and cooling can provide societal and environmental benefits, but the initial installation costs of such systems are usually more costly than conventional systems. In addition, state-level policies that mandate the adoption of renewable energy have not included GHPs as an eligible resource because heat pumps do not produce electricity that can be metered. Some states, however, have started to recognize GHP as a renewable technology and are allowing utilities to consider GHP systems to meet goals. Deploying GHP systems increases energy efficiency and can result in demand-side management improvements; however, the full impact of policies on the GHP market is not yet well understood. Analyzing these impacts is essential for informing policymakers and the GHP industry on where resources can be best leveraged. Policy analysis can also help identify opportunities to reduce cost, improve installation quality, increase public awareness, and encourage investments in GHP technology.

SUB-ACTION 2.3.2: Collaborate to evaluate tax credits and other programs for geothermal heat pumps that are similar to those for other technologies.
Tax credits, rebates, and other incentive programs have been proven to encourage consumer acceptance of GHP technology by partially defraying installation costs for investment and production (Hughes and Pratsch 2002, Liu et al. 2019). Further examining the efficacy of federal, state, and local benefits and incentives on GHP deployment can help policymakers, industry, and consumers evaluate opportunities for cost-effective GHP use. This understanding could help the nation employ appropriate incentives to realize benefits from increased use of GHPs.

High-voltage power lines transmit reliable and renewable geothermal electricity to American consumers.
Photo credit: National Renewable Energy Laboratory

Action Area 3: Maximizing the Full Value of Geothermal Energy

Geothermal energy is a renewable and diverse domestic energy solution for the United States—delivering reliable and flexible electricity generation as well as serving heating and cooling needs. Leveraging “always-on” and broadly available geothermal resources can provide a range of benefits, including grid stability, reliability, and resiliency; efficient residential and commercial heating and cooling; environmental improvements; and geothermal industry growth. However, the benefits that geothermal brings are not always valued fully in the marketplace.

Action Area 3 presents actions that can help the United States realize these benefits by encouraging geothermal development and improving geothermal project economics for both the electric and non-electric sectors. These actions are intended to address improvements in economic and revenue structures that extend beyond levelized cost of electricity or levelized cost of heat. Activities in this area focus on assessing economic barriers; creating new geothermal business models; investigating geothermal-hybrid applications; and assessing value-added markets for geothermal, such as desalination and mineral recovery.

KEY ACTION 3.1 – Improve valuation of and compensation for geothermal energy Accurately capturing the value of geothermal resources across electric and non-electric uses can help support a viable, cost-effective alternative to other power sources.		
DELIVERABLE(S): Analyses and understanding of and opportunities for geothermal energy.		
IMPACT(S): Increased opportunities to realize additional value from geothermal technologies.		
SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 3.1.1: Quantify the value that geothermal resources can provide to stakeholders.	Identification and quantification of the value that geothermal energy provides.	Defined areas in which the value of geothermal energy can be leveraged and improved.
SUB-ACTION 3.1.2: Improve data and education to financial institutions for geothermal power, direct-use applications, and geothermal heat pumps.	Comprehensive fact sheets and other educational tools for lenders.	Better lender understanding of geothermal projects, leading to increased availability of geothermal financing programs.
SUB-ACTION 3.1.3: Determine the impacts of financing structures on geothermal drilling.	Identification of existing and new financing structures that could be applied to the geothermal industry. Techno-economic analysis on the impact of financing structures on drilling.	Improved geothermal project financing and reduced financing costs. Shortened construction timelines. Increased exploration and capture of undiscovered resources.

Rationale for Actions

SUB-ACTION 3.1.1: Quantify the value that geothermal resources can provide to stakeholders. Success in geothermal project development depends partly on awareness of the complete set of benefits that geothermal energy can provide. As discussed in previous chapters, benefits of increased geothermal deployment could include geothermal industry growth, improved air quality, and grid stability and resilience provided through load-following (dispatchable) capabilities and ancillary services. These impacts can be complex to quantify and are often not included in analyses of electricity markets that only focus on levelized costs of electricity or valued in traditional power purchase agreements for geothermal energy. Stakeholders must be able to quantify the value of the resource in order for geothermal energy to be valued accurately in the market. Some recent power purchase agreements have included valuation of services such as regulation and ramping (Edmunds et al. 2014), but further analysis is warranted to better understand all values provided by electricity-generation sources. Analyses that determine values for capacity, ancillary services, storage, and transmission can help provide a more complete picture of the value of geothermal energy and allow the United States to realize the full benefits of geothermal deployment.

SUB-ACTION 3.1.2: Improve data and education to financial institutions for geothermal power, direct-use applications, and geothermal heat pumps. Geothermal technologies are not widely known or understood in the United States. This lack of understanding and knowledge can lead commercial banks and lenders to mischaracterize the risk of geothermal projects. This concern spans the geothermal energy spectrum, affecting both electric and non-electric applications.

For conventional hydrothermal and EGS power and direct-use applications, the amount of data needed to prove an economic resource can be overwhelming, even to investors with geothermal knowledge. The need for large volumes of data can lead to miscommunication in project risk, which can ultimately drive higher financing rates. Standard data reporting and information can improve communication and education, thus helping to improve investor confidence and reduce the cost of financing.

For GHPs, investors need a standardized and reliable way of quantifying benefits. Educational programs and case studies of installed GHPs could provide investors with detailed and potentially quantified comparisons between GHPs and conventional heating and cooling (Liu et al. 2019). Blockchain technology—which would provide a decentralized, autonomous ledger of transactions that cannot be corrupted or hacked—may also factor into future deployment of GHP and direct-use systems.

SUB-ACTION 3.1.3: Determine the impacts of financing structures on geothermal drilling.
Geothermal drilling is an inherently risky proposition—an issue that is highly integrated with development costs and resource uncertainties. Increased resource risk also presents challenges in obtaining project financing. Identifying mechanisms that could help shift risk from developers, reduce upfront exploration costs, and improve access to financing could impact geothermal drilling and help reduce development costs through improved financing. This action focuses on identifying existing and new financing structures that could be applied to geothermal and includes a techno-economic analysis of the effect of these structures on geothermal drilling activities.

KEY ACTION 3.2 – Investigate geothermal hybrid opportunities

Integrating geothermal energy with other energy sources can enhance the production of reliable, flexible power.

DELIVERABLE(S): Analyses and understanding of opportunities for geothermal hybrid (multifuel and multiapplication) technologies.

IMPACT(S): Increased opportunities to realize additional value from geothermal technologies.

SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 3.2.1: Develop commercially viable applications of geothermal paired with solar, coal, natural gas, and energy storage.	Identification of opportunities to develop and deploy technologies that allow for geothermal to be paired with other energy sources.	Improved efficiency of geothermal generation. Increased reliability of variable energy sources. Efficient energy-storage applications.
SUB-ACTION 3.2.2: Improve hybrid power-plant configurations to increase efficiency at various operating conditions.	Analysis of geothermal-hybrid configurations that can improve power-plant efficiency.	Improved power-plant configurations that facilitate or aid in flexible geothermal power-plant operations.
SUB-ACTION 3.2.3: Analyze the thermal management of geothermal reservoirs for various hybrid power-plant configurations.	Analysis that investigates the potential for subsurface thermal energy storage and its impact on lifetime reservoir thermal management.	Potential to maintain or increase output, even in the event of a decrease in geothermal resource productivity. Extended life of geothermal resources.
SUB-ACTION 3.2.4: Develop modeling tools to evaluate multisource power generation for geothermal-hybrid systems.	A flexible model that can be used to evaluate and optimize multisource power-generation output.	Optimized power generation from multisource hybrid systems without a lag in power output. Reduced fuel costs at fossil fuel power plants and lower levelized cost of electricity than stand-alone power plants.

Rationale for Actions

SUB-ACTION 3.2.1: Develop commercially viable applications of geothermal paired with solar, coal, natural gas, and energy storage.
Due to its versatility, geothermal energy can be matched and integrated with many other energy sources to produce reliable, flexible power production. Deploying geothermal energy in tandem with another technology can have benefits over both technologies being deployed alone. Some technologies and configurations of hybrid energy systems were explored in the *GeoVision* analysis, but there are others that were beyond the scope of the analysis. The explored hybrid systems can be improved on by reducing costs, scaling up, and increasing efficiencies to support commercial deployment. In turn, hybrid systems can lower the risks and costs of geothermal deployment by using existing infrastructure or improving an under-producing or declining geothermal resource.

The use of hybrid technologies can assist in making flexible operation of geothermal plants commercially viable and could help stabilize the electric grid. Geothermal power plants can operate in a load-following configuration; however, the curtailment of geothermal generation during periods of over-generation or off-peak demand can lead to revenue loss and impacts on the plant infrastructure, reservoir permeability, and long-term thermal management of the reservoir. Hybridization may be able to mitigate these impacts; for example, incorporating solar with thermal energy storage may allow for time-shifting of both the solar and geothermal generation. Onsite thermal uses (e.g., hydrogen production, mineral recovery, thermal desalination) can provide thermal demand response while geothermal electricity generation is being curtailed. Additional research is needed across these areas.

SUB-ACTION 3.2.2: Improve hybrid power-plant configurations to increase efficiency at various operating conditions.
Many configurations of geothermal-hybrid power plants include operating the plant at variable or off-design conditions. For instance, in certain hybrid configurations, the operating conditions may cycle daily, or it might benefit grid operations to operate hybrid plants in a flexible mode, where they can run in a load-following setting. Analytical tools that help achieve the highest efficiencies and identify the ancillary grid services that maximize the value of geothermal hybrid plants can improve performance of hybrid power plants that operate in such conditions. In addition to analytical tools, entirely new power-plant designs could be developed to maximize efficiency at partial-load conditions.

The Stillwater hybrid geothermal/solar photovoltaic power plant in Nevada. *Photo credit: Ronald DiPippo*

SUB-ACTION 3.2.3: Analyze the thermal management of geothermal reservoirs for various hybrid power-plant configurations.
Pairing geothermal energy with a variable thermal resource, such as concentrated solar power, opens the opportunity for subsurface thermal energy storage. This use could be examined in applications such as borehole thermal energy storage or aquifer thermal energy storage. Hybrid approaches could also directly impact the life-cycle thermal management of the geothermal reservoir itself, and each configuration of a hybrid plant will have differing impacts on the thermal management of the system. Analyzing the various attributes and opportunities of hybrid systems can help identify new options for managing geothermal reservoirs. In addition to site-specific considerations, pertinent variables for analysis include greenfield versus brownfield designs, whether or not the system includes surface thermal energy storage, considerations of how to incorporate disparate heat sources into the thermodynamic cycle, and the long-term effects of reservoir thermal management.

SUB-ACTION 3.2.4: Develop modeling tools to evaluate multisource power generation for geothermal-hybrid systems.
Modeling advancements were discussed with respect to geothermal energy systems in various actions under Action Area 1: Research Related to Resource Assessments, Improved Site Characterization, and Key Technology Advancements. Advanced modeling is also required to optimize the impact of geothermal-hybrid systems. Exploring the technical potential and economic viability of geothermal hybrid power plants with new modeling tools will help to identify commercial opportunities to demonstrate and deploy hybrid systems. Enhanced modeling can include improving the assessment of pairing geothermal with coal or natural-gas combined-cycle plants as described in the *GeoVision* analysis or going beyond to assess hybrid plants that integrate geothermal with multiple fuel sources.

KEY ACTION 3.3 – Quantify additional geothermal value streams

Additional geothermal value streams, such as tapping the desalination potential of geothermal energy and recovering dissolved solids from geothermal fluids, can help address the country's water and critical materials issues and create added revenue opportunities for geothermal operations.

DELIVERABLE(S): Analyses of additional geothermal value streams, including new potential value streams.

IMPACT(S): Increased opportunities to realize additional revenue and value from geothermal technologies.

SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 3.3.1: Conduct techno-economic feasibility analysis of developing and commercializing thermal-desalination technologies.	Cost-effective thermal-desalination methods and processes.	Establishment of economic viability of using geothermal heat to desalinate non-freshwater sources.
SUB-ACTION 3.3.2: Analyze potential and develop advanced technologies for cost-effective and commercial-scale mineral recovery.	Economically feasible methods and processes to recover minerals from geothermal fluids at the commercial scale.	Ability to economically extract valuable and strategic materials from geothermal fluids. Cost-effective extraction of strategically important resources from geothermal brines.
SUB-ACTION 3.3.3: Develop and evaluate other innovative value streams for geothermal technologies.	Discovery and evaluation of additional value streams to pair with geothermal systems.	Increased value and potential revenue for existing and new geothermal projects.

Rationale for Actions

SUB-ACTION 3.3.1: Conduct techno-economic feasibility analysis of developing and commercializing thermal-desalination technologies.
The process of desalination removes salts from brines, brackish water, or saltwater to create freshwater. The use of geothermal power in desalination applications is promising because geothermal brine can provide both an energy source and a potential feedstock for such an application. In addition, geothermal resources frequently occur where water is scarce, such as in the arid western United States. Investigating the market opportunities for thermal desalination will help developers and stakeholders understand how to best develop and integrate desalination into geothermal development.

This action requires a geographic confluence of a non-freshwater water source, available geothermal heat, and a market for the treated water. The opportunity is that the heat requirements for thermal-desalination processes are often available from geothermal sources that are not being used. This means that, although there may be substantial capital costs to deploy a geothermal desalination system, the operating cost for the energy to drive the process would be lower than other desalination systems. Validating pilot-scale demonstrations can support scale-up of existing systems.

Initial niche uses for geothermal desalination, such as treating waters from oil and gas production, could help scale technologies and reduce system costs. Deployment opportunities could potentially be increased by pairing desalination with EGS resources. Such resources have the advantage of being deployable to supply the thermal-energy demand for desalination at locations where hydrothermal resources do not exist but brackish or saline aquifers are present for use as feedstock to the desalination process. This would offer needed flexibility toward meeting desalination co-location requirements. Ultimately, co-location issues—rather than cost targets—are likely to provide the greatest barriers to widespread deployment of geothermal-based desalination projects. The use of widespread EGS resources in combination with lower-cost desalination technologies is likely to help address these barriers.

In applications where the primary driver for installation of a desalination plant is the demand for purified water, geothermal desalination is expected to be more cost competitive when using higher-temperature geothermal resources. The economics of geothermal desalination are likely to continue to improve with better plant performance and lower costs, especially as freshwater scarcity impacts water-stressed regions of the country.

Sapphire Pool in Biscuit Basin at Yellowstone National Park, Wyoming. *Photo credit: Jim Stimac*

SUB-ACTION 3.3.2: Analyze potential and develop advanced technologies for cost-effective and commercial-scale mineral recovery.
Geothermal brines often contain dissolved solids that include valuable and strategic minerals. Findings in Neupane and Wendt 2017 indicate that, for geothermal brines with high mineral potential, mineral-extraction plants co-located with power plants could help make geothermal power more cost effective. However, extracting these minerals can be cost prohibitive. Establishing mineral-extraction facilities at any candidate sites will first require characterizing the most valuable minerals and evaluating extraction technology, capital/operating costs, and market forces. Essential steps to the viability of mineral recovery from geothermal brines include developing methods to recover dissolved minerals and ways to process high volumes of fluids with relatively low concentrations of target minerals and a range of fluid qualities. Realizing this additional value stream will require research to continue to evaluate methodologies and test innovative approaches at pilot scale.

Exploring extraction technologies at locations with the largest concentrations of minerals with commercial potential may provide the greatest initial impact. Experience by an early adopter could help scale up many components of the technology to become commercially viable for other locations. In the longer term, market segments of interest include: 1) extractions of critical minerals that address national security concerns and strategic demands, 2) recovery of high-value minerals that can provide additional revenue streams to improve economics of geothermal power production, and 3) minerals of high abundance (e.g., silica) whose removal can improve geothermal plant performance with some potential added revenue.

Additional steps in combining mineral extraction with geothermal power generation may include identifying opportunities for power production to be sited alongside existing mining operations and to use the associated fluids, establishing an industry consortium to scale up and commercially deploy geothermal mineral-extraction technologies, and publishing parameters and goals on the economic viability of geothermal brines for strategic and critical materials.

SUB-ACTION 3.3.3: Develop and evaluate other innovative value streams for geothermal technologies. The *GeoVision* analysis included a broad but not exhaustive look at numerous potential value streams to improve the economics of geothermal development (Wendt et al. 2018). As innovations continue across the geothermal industry and related sectors, additional opportunities may become available. The technical and economic potential of each new opportunity will need to be evaluated with quantitative modeling tools. This will enable stakeholders to accurately assess the prospects and incorporate the most promising options into existing operations and new developments.

KEY ACTION 3.4 – Assess the economic barriers and solutions pertaining to direct-use applications and geothermal heat pumps

Better understanding of markets suitable for geothermal heat pumps and direct-use systems could promote greater penetration of geothermal applications into those markets.

DELIVERABLE(S): Studies and models that facilitate understanding of the economic conditions for and value of geothermal heat pumps and direct-use systems.

IMPACT(S): Increased industry and consumer interest in geothermal heat pumps.

SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 3.4.1: Perform in-depth studies of economic barriers for geothermal heat pumps and direct-use applications.	Studies that identify underlying economic and market conditions and barriers as well as the most viable future deployments of geothermal heat pumps and direct-use systems.	Established record of the state of geothermal heat pump and direct-use economic conditions.
SUB-ACTION 3.4.2: Improve techno-economic modeling for geothermal heat pumps and direct-use systems.	Publicly accessible techno-economic models for project assessment.	Optimized use of geothermal heat pump and direct-use systems to meet cost-saving and energy-performance goals.
SUB-ACTION 3.4.3: Engage realtor and appraiser industries to develop a better understanding of the value of geothermal heat pumps in home appraisals and sales.	Understanding of and models for the value of geothermal heat pumps in the appraisal of real-estate property market value.	Full accounting of the effects of geothermal heat pumps on market value in new and resale homes.

Rationale for Actions

SUB-ACTION 3.4.1: Perform in-depth studies of economic barriers for geothermal heat pumps and direct-use applications.

Market studies for GHPs have been ongoing since the 1990s. As market conditions change over time, so does the ability of GHPs to capture market share. Tracking GHP installation and shipment data will help provide a complete dataset for domestic use of such technologies and can facilitate extended studies and analysis. Periodic GHP market studies should be performed to capture trends and identify possible remedies for declining or stalled market share, as well as to identify areas that are most viable for future deployment. Studies can be used to update the GHP industry and related stakeholders on the installation base (capacity, characteristics, and geographical distribution of GHP projects), field performance, growth rate, barriers, and R&D needs. Direct-use market studies for applications such as district heating should also be performed on a periodic basis, starting with a baseline analysis.

Any future market studies should include actual field performance of GHPs and direct-use systems, which is important to enable third-party financing and other policies related to financial incentives. Data on performance could also provide important insights to evaluate the impact of state policies on GHPs and direct-use systems.

SUB-ACTION 3.4.2: Improve techno-economic modeling for geothermal heat pumps and direct-use systems.

Improved techno-economic modeling for both GHPs and direct-use applications will allow stakeholders to evaluate various options (technical and financial) in a timely, efficient manner. Models can simulate GHP and direct-use energy utilization in individual, clustered, and large buildings, and can be structured to support urban-energy planning. Models could also be developed to assess technical and financial options for energy retrofits and new construction. A web-based tool could allow home owners, developers, and financiers to easily and quickly identify the best and most financially sound solutions to meet cost-saving and energy-performance goals. Modeling tools can be made broadly available on websites and in consumer-friendly modeling platforms.

SUB-ACTION 3.4.3: Engage realtor and appraiser industries to develop a better understanding of the value of geothermal heat pumps in home appraisals and sales.

Despite the acknowledged high efficiencies and long-term energy cost savings offered by GHPs, including ENERGY STAR® certification,[103] there is no generally accepted or standardized means of determining the value of GHPs in real-estate markets. A coordinated effort among geothermal stakeholders and the realtor and appraiser industries could help establish a mechanism to determine GHP value in real estate. This could provide a way for real-estate listings to reflect the value of GHPs accurately and help consumers better understand and potentially adopt GHPs.

Drilling and installation of a vertical closed-loop ground heat exchanger for a geothermal heat pump system. *Photo credit: Ed Lohrenz/International Ground Source Heat Pump Association*

103 See the ENERGY STAR® website at https://www.energystar.gov/products/heating_cooling/heat_pumps_geothermal.

KEY ACTION 3.5 – Identify opportunities to improve standards, business models, and economics for direct-use applications and geothermal heat pumps		
Integrating geothermal heat pumps and direct-use systems into commercial/industrial designs for large installations can lead to greater use of these geothermal technologies at all consumer levels.		
DELIVERABLE(S): Analyses of consumer adoption rates for geothermal heat pumps and direct-use systems; standards and best practices related to system design.		
IMPACT(S): Increased consumer adoption rates of geothermal heat pumps and direct-use systems.		
SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 3.5.1: Standardize geothermal heat-pump system designs and installations.	Improved standards and a handbook of best practices for geothermal heat-pump system design and installations.	More accessible geothermal heat-pump financing. Wider industry compliance with state and local permitting requirements.
SUB-ACTION 3.5.2: Determine market-adoption rates for geothermal district-heating and cooling systems.	Market adoption and impact analysis for domestic geothermal district heating.	Potential for increased deployment of geothermal direct-use district heating and cooling.
SUB-ACTION 3.5.3: Identify opportunities to develop integrated business models for geothermal heat pumps and direct-use systems.	Business models that overcome high initial cost barriers.	Wider adoption of GHP and direct-use technologies.

Rationale for Actions

SUB-ACTION 3.5.1: Standardize geothermal heat-pump system designs and installations.
Case studies about GHPs have determined that more benefits can be achieved if the design and controls for GHP systems are standardized, including optimal system integration to maximize heat recovery and smarter control to avoid excessive pumping power (Liu et al. 2019). The GHP industry can benefit from established standards for design and installation of GHPs, along with a handbook of best practices, reviewed and possibly endorsed by professional organizations. Improved standardization of GHP systems and tools to communicate practices could help increase acceptance of the technology by builders, investors, and other related stakeholders.

SUB-ACTION 3.5.2: Determine market-adoption rates for geothermal district-heating and cooling systems.
Although geothermal district cooling is not a widely adopted technology—and, thus, not assessed in the *GeoVision* analysis—future technologies could increase opportunities for district cooling as well as district heating (which is assessed in the analysis). The information available for conducting market-potential-based assessments of heating and cooling applications has historically been restricted to general behavior of individual consumers, e.g., those who might install rooftop solar. However, district-heating and cooling technologies tend to be deployed at the community level. The adoption behaviors of district versus individual groups differ, and community decision-making behavior related to heating and cooling technology adoption at a market level is not

well understood. Nevertheless, deployment projections on the basis of economic potential are significant for the United States and demonstrate that this could be an area of industry growth. District heating and cooling systems are more widely adopted in Europe, where associated consumer behaviors have been studied and may serve as a general guide for understanding U.S. market potential. Quantifying the market potential and related benefits of geothermal direct-use applications can raise awareness of the potential and encourage use of renewable, geothermal direct-use heating and cooling solutions in U.S. communities.

SUB-ACTION 3.5.3: Identify opportunities to develop integrated business models for geothermal heat pumps and direct-use systems.
Several barriers prevent rapid adoption of GHPs in the United States, including high upfront costs, poor public awareness, and lack of government support (Hughes 2008, New York State Energy Research and Development Authority 2017). Geothermal district heating and cooling systems also have high upfront costs and suffer from a lack of public awareness. Alternative business concepts, such as third-party ownership and associated business models, could help reduce barriers related to high initial cost for GHPs and direct-use applications. New business structures could also monetize energy savings and environmental benefits over the life span of the systems.

Other business- and market-related developments could reduce the cost of GHPs, including mass production of GHP equipment, large-scale GHP applications (e.g., GHP systems for campuses or large commercial buildings and building complexes) that take advantage of economies of scale, and vertically integrated business models (design, build, operate) to improve the efficacy and quality of GHP installations. Thorough analysis of business models and validation with pilot programs could help establish strategies to overcome high initial-cost barriers and raise awareness among stakeholders.

McGinness geothermal power plant in Nevada.
Photo credit: Haim Shoshan

Action Area 4: Improved Stakeholder Collaboration

Helping consumers, businesses, investors, and the prospective workforce to better understand the benefits and impacts of geothermal energy will require stakeholder collaboration and enhanced outreach. This work should include an ongoing effort to revise and update this Roadmap. Maintaining the Roadmap can help in overcoming economic, technical, and regulatory barriers to geothermal deployment as the industry evolves. In addition, expanded education and communication can raise public awareness of the benefits of geothermal energy and how challenges such as induced seismicity are addressed. This could improve public acceptance and help increase deployment and market penetration. In addition, growing the geothermal industry to the deployment levels identified in the *GeoVision* analysis will require developing and sustaining a qualified, well-trained workforce.

KEY ACTION 4.1 – Maintain the Roadmap as a vibrant, active process Regularly updating the *GeoVision* Roadmap by tracking technology advancement and deployment progress can help engage stakeholders and identify priority geothermal R&D activities. DELIVERABLE(S): Periodic reports on progress and updated Roadmap actions in response to technology advancements, deployment, and economic conditions. IMPACT(S): Ongoing availability of up-to-date information and recommendations that inform and guide geothermal stakeholders in planning and decision making.		
SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 4.1.1: Periodically update Roadmap progress and actions.	Updated Roadmap actions that account for geothermal technology advancements and changes in economic conditions.	Informed and up-to-date planning and decision making for the geothermal industry.

Rationale for Actions

SUB-ACTION 4.1.1: Periodically update Roadmap progress and actions.
This Roadmap is intended to be a living document that is regularly revised by a collaborative group of stakeholders. Using an evolving process of periodic reviews, informed by analysis, updates can be used as a means to discuss and reflect on progress toward the objectives and opportunities identified in the *GeoVision* analysis. Periodic reviews will allow stakeholders to assess effects and revise activities, as necessary and appropriate, in response to changes in geothermal technologies, energy markets, industry and consumer needs, and other factors. Consistent review of the pathways identified in the *GeoVision* analysis will allow the Roadmap to reflect changing circumstances and maintain momentum toward increased geothermal deployment.

KEY ACTION 4.2 – Improve public education and outreach about geothermal energy Effective public education and outreach strategies can inform the public about geothermal technologies and applications, leading to engagement and interest in the geothermal industry. DELIVERABLE(S): Public awareness and outreach programs. IMPACT(S): Increased public acceptance and awareness of geothermal technologies.		
SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 4.2.1: Improve public education and outreach about geothermal power, geothermal heat pumps, and geothermal direct-use applications.	An actionable strategy for education and outreach across the geothermal spectrum.	Public engagement and interest in continuing the growth of the geothermal industry.

Rationale for Actions

SUB-ACTION 4.2.1: Improve public education and outreach about geothermal power, geothermal heat pumps, and geothermal direct-use applications. Geothermal energy has a unique value proposition, providing electricity as well as non-electric applications for heating and cooling. A key factor for geothermal energy is perceived value in the eyes of the public, policymakers, and other stakeholders (Hanson and Richter 2017). For the non-electric sector, where geothermal resources are distributed and available nationwide, deployment tends to be hindered by a lack of education, outreach, and basic awareness of this cost-effective technology. In particular, GHPs lack appropriate business and financing models to incentivize consumers in selecting the technology for new construction and as retrofits on existing buildings.

The geothermal industry can benefit from a strategy for public outreach and education as well as a clear branding message that describes what geothermal energy is and what it can provide to the public. Collaboration across geothermal stakeholders can help develop and establish a consistent, credible, and compelling message. Stakeholders can leverage this message to create outreach tools, including effective use of social media. This effort can ultimately result in increased public awareness and interest in geothermal resources as an energy solution.

KEY ACTION 4.3 – Increase awareness of employment and training opportunities across all geothermal energy technologies

Evaluating and developing comprehensive employment and training programs can help attract and train the workforce required to meet the geothermal industry's long-term needs, ultimately providing long-term geothermal jobs.

DELIVERABLE(S): Training and educational resources intended to attract and inform a skilled geothermal workforce.

IMPACT(S): A workforce that is prepared to support growth and technological change in the geothermal industry.

SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 4.3.1: Develop comprehensive training, workforce, apprenticeship, and educational programs in geothermal energy.	Geothermal education and certification programs at demonstration centers and other centers of higher learning.	Creation and maintenance of a trained and experienced workforce in geothermal development, deployment, and safety.
SUB-ACTION 4.3.2: Expand and foster international exchange and collaboration in geothermal energy.	Working international partnerships that benefit all stakeholders for sharing best practices, knowledge, and innovation.	Increased domestic and global engagement, communication, knowledge sharing, and collaboration.

Rationale for Actions

SUB-ACTION 4.3.1: Develop comprehensive training, workforce, apprenticeship, and educational programs in geothermal energy.
Workforce skills and practices are vital to growing the geothermal industry and helping support safety and efficiency. With increased geothermal deployment, greater numbers of trained professionals will be needed across the geothermal spectrum to satisfy demands for installation, construction, financing, regulation, operations, and maintenance across the geothermal spectrum. Additionally, trained salespeople and marketing experts will be essential to convey the technology's benefits to the public, policymakers, and other stakeholders. The geothermal industry can benefit from approaches similar to those of other renewable technology industries, such as wind power and solar energy, which have established training and licensing programs to develop robust and sustainable workforces experienced in installing and maintaining those systems.

Expanding effective geothermal training, education, and apprenticeship programs will help ensure availability of well-trained workers. Professional development of potential workforce members can be supported by geothermal-specific learning opportunities at multiple levels—from pre-college to trade—to ensure and maintain a high-quality workforce. Educational programs can be customized to meet the particular needs of a given region (e.g., regional differences in regulations, business opportunities, and public acceptance, as well as technical factors such as climate and geologic conditions). Educational and outreach programs can be modeled after similar successful initiatives, such as outreach efforts of the Geothermal Heat Pump Consortium, the DOE's Solar Decathlon, and others. Additional approaches, including apprenticeship programs, have been demonstrated as effective in other industries and could be implemented for geothermal technologies. Hands-on learning programs can foster interest in geothermal energy technologies and help both the workforce and the public understand associated benefits and opportunities.

SUB-ACTION 4.3.2: Expand and foster international exchange and collaboration in geothermal energy.
The U.S. geothermal industry does not exist in a vacuum—although the United States leads in many areas of geothermal deployment, other countries demonstrate leadership in various aspects of geothermal technologies. The action areas and sub-actions in the Roadmap can be supported through knowledge-sharing across the international and domestic industry.

The United States participates in a number of key international geothermal partnerships and associations. Engagement has historically been limited due to resource constraints and low participation. As a result, the domestic industry has not been able to realize the full benefit of associations, working groups, and partnerships. The *GeoVision* analysis highlights the opportunity and need for U.S. representatives to expand engagement in a way that positions the nation as a visionary leader in geothermal energy. Engaging more actively in international collaborations and investing in the international participation of key U.S. geothermal stakeholders can propel the industry forward across all geothermal energy sectors and technology applications.

Giraffes amidst Olkaria III geothermal piping at Hell's Gate National Park. *Photo credit: Ormat Technologies, Inc.*