CLEAN AIR TASK FORCE

Induced Seismicity and Next-Generation Geothermal

May 2026

Key takeaways and recommendations

- We have safeguards in place to minimize risk from induced seismicity, which are informed by scientific and technical best practices developed by leading independent experts.
- Early geologic mapping can help avoid siting a project in a location that would create a high risk of felt induced seismicity.
- Additional research can aid in the development of improved safe practices such as improving the accuracy of Adaptive Traffic Light Systems, which could help forecast the likelihood of future induced seismicity magnitudes over the lifetime of an enhanced geothermal system (EGS) project.
- Mitigation protocols, such as the U.S. DOE's Induced Seismicity Protocol or Switzerland's Good-Practice Guide, should be included as a regulatory requirement for all next-generation geothermal projects. Closed-loop geothermal projects may benefit more from the hazard-based approach of Switzerland's Good-Practice Guide, given their lower risk, relative to EGS.
- Engagement with communities, early and often, as part of an induced seismicity protocol, is an important aspect of developing a successful next-generation geothermal project.

Why next-generation geothermal?

Next-generation geothermal technologies, including superhot rock (SHR) geothermal, are poised to play a transformative role in the global energy mix. This technology, in particular, stands out for its potential to deliver cost-competitive, continuous clean power at a scale capable of meeting rising global electricity demand. Next-generation geothermal offers the promise of low-emission, firm electricity that reinforces grid reliability and reduces long-term energy costs. Like any emerging energy technology, next-generation geothermal must address potential challenges – one of which is induced seismicity.

Mitigating potentially damaging induced seismic events is possible – and an essential aspect of successful next-generation geothermal projects. This fact sheet provides clear answers to common questions on this topic.

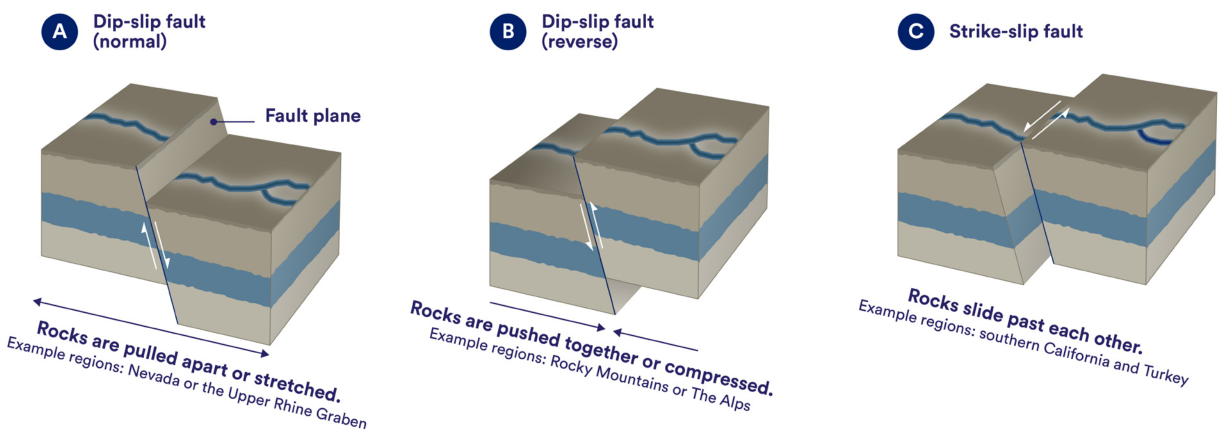
How does next-generation geothermal work?

Next-generation geothermal works like an underground radiator. Water or another type of fluid (e.g., CO_2) is injected deep into the earth's subsurface, where it absorbs the earth's heat and is returned to the surface to produce clean electricity and heat for existing and novel industrial applications, ranging from metal processing to desalination.

What is induced seismicity?

Earthquakes, or seismic events, happen when rocks slip past each other along a fault (Figure 1). Induced seismic events are seismic events that are caused by human activities, such as the injection of fluids underground.

Figure 1. Illustrative examples of different types of faults. Faults come in many sizes, ranging from smaller than a millimeter to tens of kilometers. Seismicity happens when rocks slip past each other along a fault. Thorough geologic mapping of a region before project development is important to avoid developing a new project in a region with larger faults.



Why does seismicity occur in next-generation geothermal systems?

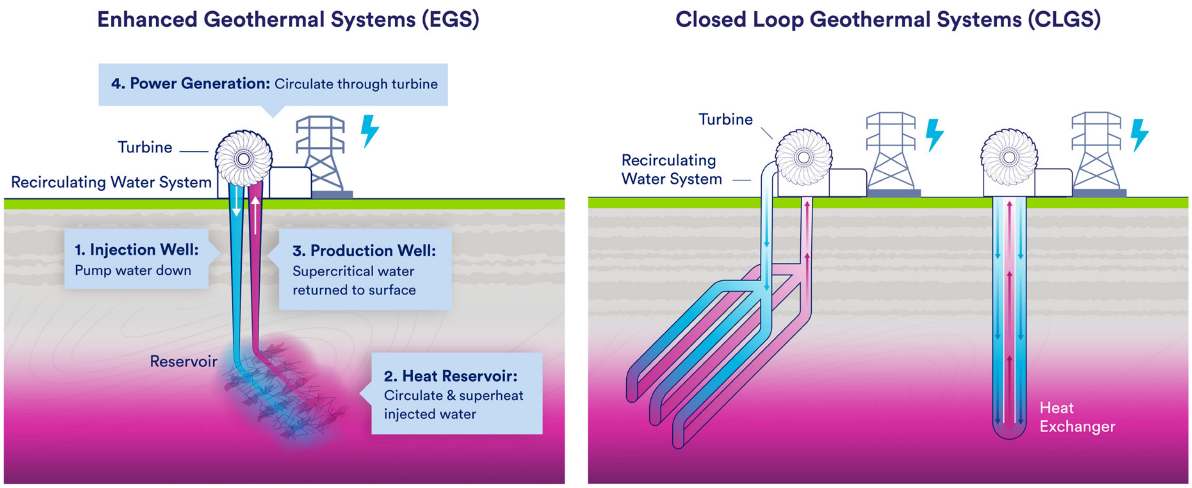
Not all geothermal systems start with sufficient fluid and pathways within the rock (i.e., sufficient permeability). Permeability is necessary for fluid to travel from the injection well, through the reservoir of hot rock, and up through the production well. In these situations, pathways need to be created to develop a geothermal system. In closed-loop geothermal systems, pathways are created by drilling and installing a network of pipes through the rock beneath Earth's surface (Figure 2). In enhanced geothermal systems (EGS), permeability may need to be created by injecting fluid underground to either "enhance" an existing reservoir or create a new one (Figure 2).

The magnitude and intensity of shaking on the Earth's surface, is directly related to the impact of the seismic event. While the felt impacts also depend on the depth of the earthquake, the distance to the Earth's surface, and the local site conditions, Table 1 shows an illustrative example of potential impacts in relation to earthquake magnitude.

Table 1: An illustrative example of potential impacts associated with different magnitudes of earthquakes. Modified from USGS resource.

Earthquake Magnitude	Potential Impacts
1.0-3.0	Typically not felt. This is the magnitude range typical of induced seismicity associated with enhanced geothermal systems.
3.0-3.9	Potentially felt by people at rest or indoors. Vibrations similar to the passing of a truck.
4.0-4.9	Felt by many. Dishes and windows may be broken, and unstable objects may fall.
5.0-5.9	Felt by all. Buildings damaged.
6.0 and higher	Considerable damage, increasing with magnitude.

Figure 2. Illustration showing the two primary types of heat extraction in next-generation geothermal systems, with enhanced geothermal systems shown on the left and closed-loop geothermal systems shown on the right.



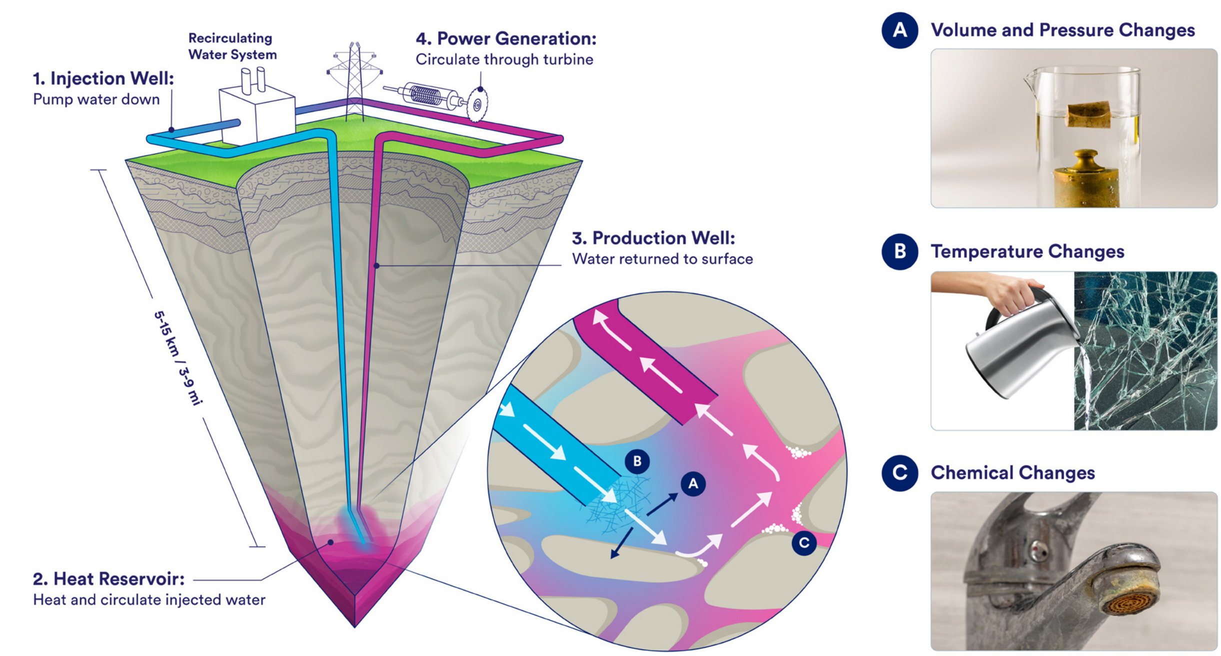
Enhanced geothermal systems (EGS)

Some induced seismicity, such as microseismicity (small earthquakes not felt by humans), is a beneficial part of reservoir development in EGS, because it can help developers identify ideal locations for injection and production wells. However, larger induced seismicity that is felt in populated regions can harm local communities and project success. Early and thorough geologic mapping can help avoid siting a project in a location that would create a high risk of felt induced seismicity. Thorough geologic mapping is essential to identifying large faults in the region that could contribute to larger induced seismic events.

There are three main processes in EGS that can trigger induced seismicity:

- **Volume and Pressure Change:** Relative changes in volume (and therefore pressure) due to an increase in water in the reservoir closer to the injection well or a decrease in water in the reservoir closer to the production well. Local volume changes due to injection or removal of fluids underground change the pressure of the rocks near the reservoir, which causes rocks to shift. Smaller shifts aren't felt at the surface, but larger shifts can result in induced seismicity that is felt at the Earth's surface (see Figure 3A).
- **Temperature Change:** Decrease in temperature due to injection of water that is cooler than the surrounding rock. This can cause the rock to contract, shift, and fracture (see Figure 3B).
- **Chemical Change:** Injection of new fluids can cause chemical alterations at the fracture surfaces. This process is somewhat similar to the buildup that forms around faucets and showerheads. The chemical alterations can change the stickiness of the surface of a fault and cause earthquakes to be more likely (less sticky) or less likely (stickier) (see Figure 3C).

Figure 3. Illustration of how an enhanced geothermal system works and the main ways that induced seismicity can be triggered. A-C graphics showing how (A) volume and pressure change (e.g., adding fluid into a container, causing a floating object to rise), (B) temperature change (e.g., hot water poured on cold glass, causing it to crack), and (C) chemical change (e.g., removal of buildup on a faucet, causing connections to be easier to unscrew) can cause induced seismicity.



Closed-loop geothermal systems

Closed-loop geothermal systems have a smaller risk of induced seismicity relative to EGS, since their development doesn't involve creating a reservoir in the surrounding rocks and the injected fluid never comes into direct contact with the surrounding rocks. Therefore, these systems aren't likely to demonstrate volume or chemical change. However, since closed-loop geothermal systems are drawing heat from surrounding rocks, they may induce seismicity from temperature changes, which can cause the surrounding rock to cool and contract.

Superhot rock geothermal

The likelihood that any of the above-mentioned processes result in a felt induced seismic event is dependent on the local geologic conditions. It is expected that some superhot rock (SHR) EGS reservoirs will be developed at depths beyond the extent of large-scale faults and where the geology is less variable, which may reduce the risk of induced seismicity. However, further research into SHR reservoir development is needed to better understand the induced seismicity risk in any potential SHR system.

Induced seismicity from oil and gas

Induced seismicity in the oil and gas industry often comes from wastewater disposal, which has caused multiple large induced seismic events. These earthquakes are caused by volume (and pressure) change: wastewater disposal involves the injection of large amounts of water belowground without also removing a similar amount of water. This causes a buildup of pressure that can result in induced earthquakes. By contrast, geothermal energy generally cycles water through the underground, removing water as other water is injected. This allows the risk of induced seismicity based on volume (and pressure) change to be much lower, but does not eliminate the risk, since the local pressures are still impacted. As such, controlling the rate at which fluid is injected below ground for next-generation geothermal systems is important for controling volume and pressure changes and mitigating the risk of induced seismicity.

Why is it important to mitigate induced seismic events?

Mitigating induced seismic events felt by communities is important for maintaining the safety and livelihood of nearby communities as well as the long-term success of the geothermal industry. This is important for avoiding a repeat of earlier incidents of induced seismicity that have led to project cancellations and negative impacts to local communities. In 2006, reservoir stimulation of a project in Basel, Switzerland led to a magnitude 3.4 event that caused non-structural damage. To date, the worst incidence of induced seismicity occurred at a 2017 project in Pohang, South Korea, where a magnitude 5.4 event caused structural damage and injured 90 people. As of the release of this fact sheet, the Pohang incident is the only known incident of geothermal induced seismicity causing human harm. See Table 1 for reference of earthquake magnitude and potential impacts. Importantly, neither of these projects used the current leading practice protocols to mitigate induced seismicity, since mitigation methods have improved since the development of these projects.

How can induced seismicity in next-generation geothermal systems be managed?

The risk of induced seismicity felt by communities can be minimized using best practice protocols that are informed by scientific and technical knowledge from independent experts. Governments should require the use of such protocols for next-generation geothermal projects. This fact sheet highlights two first in class protocols below.

The U.S. DOE's Induced Seismicity Protocol is focused on enhanced geothermal systems and emphasizes the need for: 1) an early understanding of local geology and seismic history, 2) strong community engagement, and 3) real-time seismic monitoring. Developers must assess both natural and induced seismic hazards and create a risk-based mitigation plan based on a thorough understanding of the local geology and seismic risks. A key feature of this plan is a traffic light system that guides operations. During project activities, developers track seismic activity in real time. If seismicity exceeds pre-set thresholds, project activities are changed or paused to reduce the risk of felt induced seismicity (Figure 4). This approach supports safer development and builds community trust.

Figure 4. Visualization of the traffic light protocol.

RED – the lower bound of the red zone is the level of the ground shaking at which damage to buildings in the area is expected to set in. *Pumping suspended immediately.*

AMBER – the amber zone is defined by ground-motion levels at which people would be aware of the seismic activity associated with geothermal activity, but damage would be unlikely. *Pumping proceeds with caution, possibly at reduced flow rates, and observations are intensified.*

GREEN– the green zone is defined by levels of ground motion that are either below the threshold of general detectability or at ground-motion lower than the already-established background activity level in the area. *Pumping operations proceed as planned.*

Adapted from the U.S. DOE's Induced Seismicity Protocol.

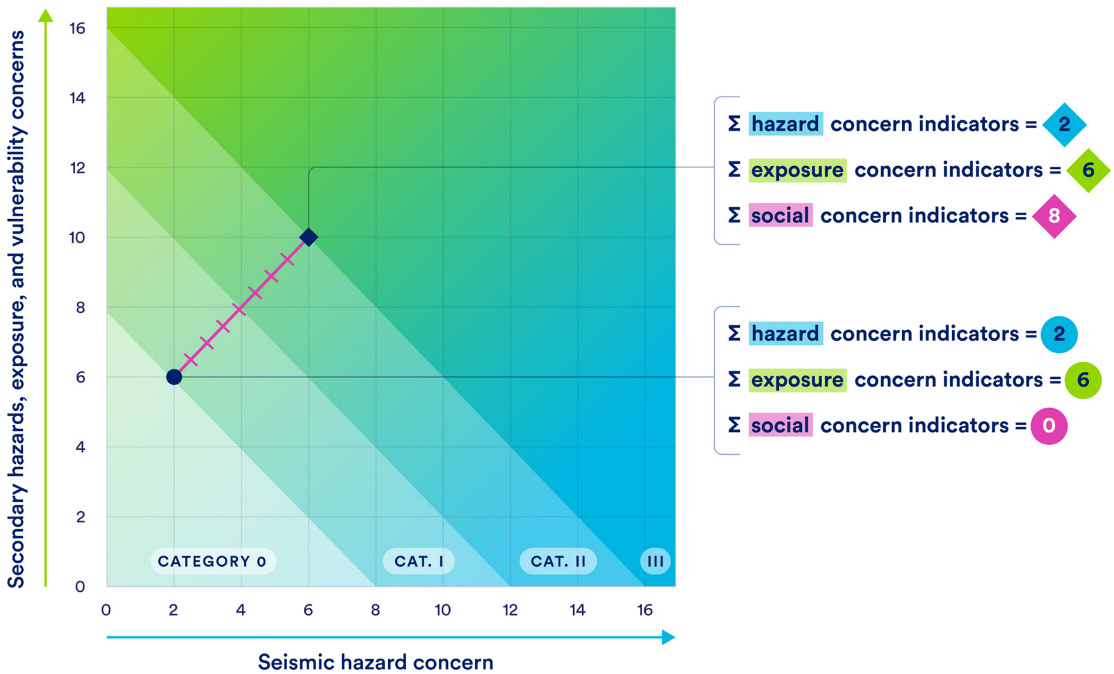
In the U.S., Department of Energy (U.S. DOE)-funded EGS projects are required to use the U.S. DOE's Induced Seismicity Protocol.

As of the release of this fact sheet, none of these projects have created felt induced seismicity.

Researchers with the Swiss Seismological Service have also developed a [best practice guide for managing induced seismicity](), which applies to all next-generation geothermal projects. In addition to the steps included in the U.S. DOE's Induced Seismicity Protocol, the Swiss Seismological Service's best practices include a Geothermal Risk of Induced seismicity Diagnosis (GRID) score, which accounts for both technical risk and public concern (Figure 5). GRID scores are jointly developed and evaluated by at least three groups: 1) the project operator, 2) the regulatory agency, and 3) independent experts such as geothermal academic experts. Projects with higher GRID scores – reflecting greater potential for seismicity or social sensitivity – must undergo more rigorous risk assessments and mitigation.

Projects with a higher GRID score are also required to operate an Adaptive Traffic Light System. These systems have been developed over the last decade and are meant to improve the forecasting of the near-term seismic response during operations at a given EGS project based on the local geology. More research and development are needed to ensure the accuracy of these systems in more regions and for longer time spans (e.g., the lifetime of an EGS project).

Figure 5. Visualization of the Swiss Seismological Service's GRID score. Category 0 indicates a lower concern (e.g., closed-loop projects) while a Category III indicates the highest concern (e.g., EGS projects).



Adapted from the Swiss Seismological Service's [Good-Practice Guide for Managing Induced Seismicity in Deep Geothermal Energy Projects in Switzerland.]()

For more information, please contact:

Angela Seligman at aseligman@catf.us