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ORIGINAL ARTICLE

How beliefs about tampering with nature influence support for enhanced geothermal systems: A cross-national study

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Abstract
Many believe that enhanced geothermal systems (EGS) can greatly increase the extraction of geothermal energy worldwide, helping to decarbonize heat and electricity production. Effective communication is key to realizing the potential of EGS, yet we currently know little about how the public perceives this emerging technology. This exploratory study contributes to the literature with a cross-national survey in the United States ($n = 1003$) and Switzerland ($n = 1028$), two countries with active EGS projects. Specifically, we explore how EGS support relates to beliefs about the deep underground and perceptions of EGS as tampering with nature. The results show that respondents tend to perceive the deep underground as part of nature, dangerous, and unpredictable. The majority are positive about using the deep underground as a resource, although there were variations regarding specific underground activities. In both countries, EGS support is greater for respondents who perceive the underground as something for human use, perceive more benefits than risks from EGS, and support their country's transition to renewable energy. In Switzerland, EGS support is positively related to trust in industry developers and negatively related to perceptions that EGS is tampering with nature. The results offer novel theoretical insights into perceptions of the deep underground in relation to energy development. From a practical standpoint, the results suggest that those seeking to develop EGS may want to consider how to familiarize individuals with current subsurface energy activities, including efforts to protect the underground from unwanted consequences of "tampering," alongside engaging in discussions about the risks and benefits of EGS.

KEYWORDS
Geothermal energy, risk communication, risk perception, tampering with nature, technology acceptance

1 | INTRODUCTION

Many energy experts believe that geothermal energy holds great potential as a renewable, carbon-neutral source for heating, cooling, and electricity production (DOE, 2016). Recent advances in enhanced geothermal systems (EGS), and other *deep* geothermal technologies, seek to extract geothermal energy at scale and overcome the geographical constraints associated with traditional, *shallow* geothermal technologies (Manzella et al., 2019). EGS (also called hot-dry rock systems) works by drilling wells 3–5 km deep into the Earth's crust to reach sufficiently hot rocks for producing electricity. Water is then injected to stimulate the rocks and to create a reservoir to allow water to flow between the wells. The heated water is finally extracted from the wells for generating heat and electricity at the surface (DOE, 2016). The US Department of Energy (2022) announced in 2022 a major "Energy Earthshot" goal to make EGS a widespread renewable energy technology option, noting that more than five terawatts of geothermal heat exist in the United States alone. Although the benefits are clear, EGS—as with any technology—can carry some risks. Notable ones include the potential for human-induced seismicity and the economic costs of drilling failures (Giardini, 2009).

Decades of research have shown that energy technologies are unlikely to reach their full potential if they are perceived as socially unacceptable (Kasperson & Ram, 2013; Wüstenhagen et al., 2007). Some deep geothermal projects have already been abandoned following public concerns over human-induced seismicity (Knoblauch et al., 2019). Therefore, understanding what influences public support for and opposition to EGS is essential so that development efforts can align with societal values and priorities. Despite the importance of understanding how the public perceives EGS, little empirical research exists on this topic, partly due to the newness of the technology. Researchers began investigating social aspects of shallow geothermal energy systems in the 1980s (Pasqualetti, 1980; Pasqualetti et al., 1979); however, most studies investigating social aspects of deep geothermal energy have been descriptive in nature and case specific (Manzella et al., 2019; Spijkerboer et al., 2022). Further, quantitative studies examining perceptions of deep geothermal energy and systems are limited (Cousse et al., 2021).

This study builds on earlier research using a comparative cross-national survey of two countries in similar phases of EGS exploration and development, the United States and Switzerland. Drawing on extant research examining how individuals evaluate risk, this study seeks to advance current knowledge of factors influencing public views of this emerging energy technology. Further, a two-country comparison allows us to explore patterns in the results and thus better inform nascent risk communication efforts.

2 | BACKGROUND

A large body of risk communication research shows that support for various technologies is influenced by factors such as risk perceptions, benefit perceptions, and trust (Balog-Way et al., 2020; Earle, 2010). Public perceptions often diverge markedly from scientific expert assessments (Siegrist & Árvai, 2020), and within communities, vocal minorities may lead to the rejection of potentially beneficial technologies (Cousse et al., 2020). Research has shown that engaging stakeholders early in the decision-making process can, inter alia, improve policymaker and project developer decisions (Trutnevyte & Wiemer, 2017), build trust, and increase acceptance of decisions (Balog-Way et al., 2020; Pidgeon, 2020).

On deep geothermal energy, some research has shown that perceptions of risks (e.g., earthquakes, water pollution) and benefits (e.g., low-carbon energy production) may be context-dependent (Cousse et al., 2021; Knoblauch et al., 2019; Lambert, 2022; Volken et al., 2019). McComas et al. (2016) showed that perceptions of induced seismicity related to technologies like EGS are highly dependent on procedural fairness and trust. Vargas-Payera et al. (2020) have further highlighted that concerns about seismic risk may not be prominent in all countries. Many studies have highlighted that the effectiveness of communication and public involvement processes positively influence the perception of the project or technology (Chavot et al., 2018; Ejderyan et al., 2019; Pellizzone et al., 2017; Ruef et al., 2020). Others have stressed, however, that focusing on risk too narrowly when communicating with the public inadequately responds to the range of concerns, social meanings, and incomplete knowledge the public may have (Chavot et al., 2018; Stauffacher et al., 2015).

Beyond risk and benefit perceptions, research suggests that potential underlying drivers of support for deep geothermal energy may include associations with extractive industries and perceptions of the deep underground, as well as beliefs about it being "local" or "natural." Studies on public concerns for deep geothermal technologies have noted that members of the public frequently associate the extraction process with fracking and other extractive industries (Cuppen et al., 2020), which can dampen enthusiasm, whereas perceiving deep geothermal energy as local and natural increases support (Blumer et al., 2018). Gross (2013) also suggested that while renewable energy is normally associated with aboveground activities, geothermal, as an underground energy resource, may be viewed in the same light as nonrenewable energy sources, which may in turn negatively influence the perception of the technology.

An additional concept not yet examined in relation to deep geothermal and EGS is the extent to which the public perceives the extraction process as "tampering with nature." Tampering with nature has been defined as the "belief that humans influence nature, by either the use of a specific technology or exhibiting certain behaviors, in a negative manner" (Hoogendoorn et al., 2021, p. 141). Researchers have explored whether resistance to scientific and technological developments—for example, geoengineering, genetically modified organisms, and pesticide use—may arise from discomfort with humans tampering with nature. In a systematic literature review, Hoogendoorn et al. (2021) found that tampering with nature is a strong predictor of public acceptance of certain behaviors and technologies and can influence risk perceptions (Visschers et al., 2017). Perceiving technologies as tampering with nature has even been found to have a stronger influence on acceptance than influential risk perception factors like dread and unknown risk (Corner et al., 2013; Fritz et al., 2004; Meisenberg, 2009; Sjöberg, 2000; Stewart & Lewis, 2017).

The extent to which individuals may view EGS as tampering with nature is currently unclear. The energy production process takes place deep underground in a widely unfamiliar location, which may or may not be viewed as part of nature. Further, there is limited empirical evidence documenting public beliefs about the underground. We do know that, generally speaking, the underground carries a range of cultural and religious connotations such as burial, storage, and discovery (Kearnes & Rickards, 2017). Historical and cultural meanings of the underground include depictions of it as an artificial, unnatural space, accessed and understood only through technological endeavors such as mining (Williams, 1990). Compared with more shallow subsurface activities, the "deep underground," which has no widely accepted scientific definition but has been described as greater than 500 meters below the Earth's surface (retrieved from the Swiss Federal Office of Topography, January 16, 2022), is even more remote from most people's daily lives. Some scholars have noted that deep subterranean spaces are widely considered mysterious, distant, and imperceptible (Kinchy et al., 2018; Stewart & Lewis, 2017). Further, heat from within the Earth can elicit primordial fears as well as fascination and curiosity (Gross, 2013). From this body of largely anecdotal evidence, it follows that beliefs about the underground may influence feelings about geothermal energy (Gross, 2013; Partridge et al., 2019).

In addition to people's perceptions of the underground and whether they perceive it as part of nature, there is also the question of whether the activities involved in EGS are themselves perceived as tampering with nature (Partridge et al., 2019). Drilling deep into the underground and potentially causing earthquakes may be perceived as tampering with nature, likely influencing public support for EGS (Giardini, 2009; Knoblauch et al., 2019). Technologies are also generally perceived as riskier the more they are perceived as unknown, unobservable, uncontrollable, or potentially catastrophic (Bassarak et al., 2017; Slovic, 1987). Along these lines, research has shown that the opacity of underground activities like hydraulic fracturing can increase concerns of uncontrollability and attitudes that humans should not interfere with the underground (Partridge et al., 2019). Given the associations of EGS with induced seismicity and fracking, it seems plausible that similar associations may occur; however, to our knowledge, no such examination has yet occurred.

To explore these questions, the current study explores how beliefs about the deep underground and perceptions of EGS as tampering with nature relate to EGS support. For a richer investigation, we compare the views of individuals living in Switzerland and the United States, two countries actively engaged in EGS development. In Switzerland, pilot projects are ongoing to demonstrate the technical feasibility of EGS after two failed projects in the country brought some skepticism about the feasibility of the technology (Delaye, 2022; ETH, n.d.; SFOE, 2020). In the United States, two EGS demonstration projects have been successful, and another demonstration site is currently further testing the technology (DOE, 2016). Although these two countries differ in terms of geographic size, the relative "newness" of the technology in both countries allows for some useful comparisons. If perceptions between the two countries vary, such as risks and benefits, it also offers some practical insight for risk communication to adapt to these differences. Currently, as no large-scale public opinion surveys on EGS exist, we know little about what factors may influence views beyond what prior research on other renewable energy technologies might suggest. Having a two-country comparison thus enables us to understand whether patterns in responses hold across contexts or differ in theoretically and practically meaningful ways.

In sum, our study addresses four research questions:

1. How do individuals perceive the deep underground with respect to EGS development?
2. To what extent do individuals consider EGS to be tampering with nature?
3. To what extent do beliefs about tampering with nature and perceptions of the underground relate to support for EGS development compared with risk perceptions, benefit perceptions, and trust?
4. How do the views of US and Swiss populations compare?

3 | METHOD

3.1 | Sample

We collected data using a survey conducted simultaneously in Switzerland and the United States in November 2021. The final sample had 2031 respondents, roughly divided between Switzerland (n = 1028) and the United States (n = 1003). The sample was nationally representative of age, gender, and education in both countries and by race in the United States, based on 2018 figures from the Swiss Federal Office of Statistics and the US Census Bureau. We collected additional demographic data in both countries on political orientation. Appendix A provides details on the demographics. Respondents were recruited by two market research agencies, Qualtrics (US) and Intervista AG (Switzerland), using online panels and quota sampling. The questionnaire was translated for Swiss respondents from English into German and French. The translation was conducted by trilingual experts experienced in both translations and survey research. High care was given to ensure that the meanings between languages were as close as possible. US respondents took an average of 17 minutes and Swiss respondents took an average of 19 minutes to complete the survey. Respondents who took less than the median time established in the prelaunch were automatically removed from the sample, as were those who failed the attention check question. We also removed 45 respondents (28 Swiss and 17 US) who provided "nonsense text" (e.g., random letters and numbers) in the open-ended associations or "straight lined" (e.g., selecting the first response to every question). Other respondents were subsequently removed from some analyses if they failed to answer questions only on specific occasions, and these numbers are reported in the text and tables.

3.2 | Measures and procedures

To answer our research questions and compare US and Swiss respondents, we primarily rely on means comparisons using t-tests. When comparing the two countries, if the differences between variables are not statistically significant, we generally only report the means and standard deviations for the combined sample rather than per country. Because of our large sample size, which may lead to a greater likelihood of statistical differences in our comparisons, we adopt a $p < 0.005$ level of significance and provide information on effect size using Cohen's d (small = 0.2, medium = 0.5, large = 0.8) (Cohen, 1988). We do not report effect sizes that are less than 0.2, adopting guidance that these differences are likely inconsequential or trivial (Cohen, 1988).

3.2.1 | EGS vignette

The questionnaire began by asking respondents to estimate their level of familiarity with geothermal energy. To measure familiarity, we asked how much, if anything, they knew about geothermal energy using the following 5-point scale: "I know a great deal about it," "I know a fair amount about it," "I know just a little about it," "I have heard of it but know almost nothing about it," and "I have not heard about it before today." Overall, about 40% of the sample indicated they knew almost nothing or nothing at all about geothermal, and another 40% said they knew just a little about it, with no significant differences between the two countries ($M_{US} = 3.22$, $SD_{US} = 1.12$, $M_{CH} = 3.27$, $SD_{CH} = 0.83$, n.s.). We then asked all respondents to read a one-page vignette with information on geothermal energy in general, how EGS works, and major EGS risks and benefits, as well as an illustrative graphic (see Appendix B). This process ensured respondents had a similar baseline knowledge of EGS based on previous work suggesting low familiarity with geothermal energy (Song et al., 2021). To ensure technical accuracy and balance, geothermal experts from the Swiss Seismological Service reviewed the vignette. Robustness checks were additionally conducted by asking, "To what extent do you agree or disagree with the following statements regarding the information we have provided you about EGS? The information provided was… (1) trustworthy, (2) balanced" on a 7-point Likert scale from strongly disagree to strongly agree. Respondents ($N = 2031$) evaluated the vignette as trustworthy (M = 5.06, SD = 1.45) and balanced (M = 4.99, SD = 1.45), with no significant differences between countries.

3.2.2 | Perceptions of the deep underground

To address RQ1, we measured how Swiss and US respondents perceived the underground (i) in general, (ii) as a place that should be left untouched by human activities or explored/exploited, and (iii) regarding its safety, controllability, and utility for storing. To link these items to the use of EGS and provide some boundaries in terms of thinking about the deep underground, questions were introduced with the statement: "As you read earlier, to produce electricity through EGS, we must drill wells deep underground (e.g., 5 km [3 miles]) to reach hot enough rocks. This section asks about your perception of the deep underground."

Respondents were asked to type the first thought, association, or image that came to their mind when they thought of the deep underground. They then ranked each association as positive or negative on a 7-point scale from "very negative" to "very positive."[1] We subsequently categorized this variable in the following categories: "Positive" corresponds to scores above 4, "negative" to scores below 4, and "neutral" to a score of 4.

Second, respondents indicated on a 5-point semantic differential scale which properties they associated with the deep underground. We developed these items from prior theoretical and qualitative work on perceptions of the deep underground (Gross, 2013; Kearnes & Rickards, 2017; Partridge et al., 2019; Williams, 1990). The word pairs were uncontrollable/controllable, unstable/stable, dangerous/safe, unpredictable/predictable, dirty/clean, unfamiliar/familiar, separate from nature/part of nature, and comprehensible/mysterious.

Third, we asked respondents to indicate their agreement with statements about human activity in the deep underground, using a 7-point scale ranging from "strongly disagree" to "strongly agree." We developed nine statements from prior theoretical and qualitative work on conceptions of the deep underground (Kearnes & Rickards, 2017; Partridge et al., 2019; Williams, 1990). We designed one set of statements to capture whether respondents believed that the deep underground should be left alone and another to measure whether respondents believed the deep underground was a place for human use. We used a factor analysis with a varimax rotation to see if the items loaded as we intended, and the rotation converged in three iterations with two factors, which reflected the intent of the measure (see Supplementary Table S1 for the factor loadings). We labeled these factors "Underground should be left alone" and "Underground as a resource for human use." We next examined the reliability of combining the items as scales and found that removing "the deep underground is a place to store things" increased the reliability (Cronbach's α) of the "Underground as a resource for human use" scale from 0.81 to 0.87, so we removed that item from the final scale. Cronbach's α for the "Underground should be left alone" scale was 0.81, with no benefit of removing any items. Table 2 lists the items that comprise each scale used in the regression model.

3.2.3 | EGS as tampering with nature

We followed Hoogendoorn et al. (2021) to address RQ2 and assess the extent to which respondents perceive EGS as tampering with nature.[2] Using a 7-point scale ranging from "not

[1] Studies have shown that this technique is a sensitive measure of the imagery and meaning associated with respondents' mental representations for a wide variety of technologies and behaviors (Balog-Way et al., 2020; Leiserowitz, 2006; Slovic et al., 2007).

[2] There is no widely agreed-upon or standardized scale for measuring whether individuals perceive a technology as tampering with nature (Hoogendoorn et al., 2021); some studies have used general measures to assess whether individuals hold the universal belief that humans should not tamper with nature (Raimi et al., 2020), while others connect tampering with nature to specific technologies (Hoogendoorn et al., 2021).

at all" to "very much," we measured whether respondents perceived EGS as (i) unnatural, (ii) disturbing the order of nature, and (iii) contrary to nature. Agreement with EGS as "unnatural" or "contrary to nature" measures whether the technology is perceived as not existing in nature or artificial. "Disturbing the order of nature," in comparison, measures whether respondents perceive EGS as negatively affecting the natural order of things.

For comparison purposes, we also measured technologies that previous research has shown are seen as tampering with nature: chemical pesticides and genetically modified organisms (GMOs) (Hoogendoorn et al., 2021). Lastly, we measured whether respondents perceive human-induced seismicity as tampering with nature, given that the EGS process can potentially cause earthquakes. For each technology, we averaged the three items to form scales labeled "EGS-as-tampering-with-nature" ($\alpha = 0.87$), "pesticides-as-tampering-with-nature" ($\alpha = 0.85$), "GMOs-as-tampering-with-nature"($\alpha = 0.87$), and "induced-seismicity-as-tampering-with-nature" ($\alpha = 0.83$).

3.2.4 | Support for EGS

Drawing on Brosch and Steg (2021), who highlighted that the affective responses people experience are strong predictors of policy support and technology acceptance, we measured support for EGS with an affective measure. Specifically, we asked respondents' general feelings about the implementation of an EGS project in the proximity of where they live on a 7-point Likert scale from "very negative" to "very positive." In terms of support, the results of the combined sample show that respondents were generally positive about EGS (M = 4.85, SD = 1.75), with no significant differences between the US and Swiss samples ($M_{US} = 4.90$, $SD_{US} = 1.71$, $M_{CH} = 4.79$, $SD_{CH} = 1.79$, n.s.).

3.2.5 | Factors relating to EGS support

In addition to tampering with nature and perceptions of the underground, we measured factors that previous research has shown as important predictors of technology support: perceived risks and benefits, trust, attitudes toward climate change and renewables, and demographics.

EGS risk–benefit perceptions

We measured EGS risk and benefit perceptions using a 5-point semantic differential scale. For risk perceptions, we measured whether respondents perceived EGS as dangerous/safe, unpredictable/predictable, unreliable/reliable, and unfamiliar/familiar. For benefit perceptions, we measured whether respondents believed EGS is a bad way/good way to address climate change, a bad way/good way to increase energy independence, a fossil fuel technology/renewable energy, and dirty/clean. A factor analysis using varimax rotation showed that the items loaded on a single component (see Supplementary Table S3 for factor loadings), and a reliability analysis showed a Cronbach's α of 0.90 for the nine items. The items were combined into one scale, "Risk–benefit perceptions" (M = 3.58, SD = 0.84), with no significant difference between US and Swiss respondents.

TABLE 1 Trust scale items.

I believe that… Private companies that would help develop and operate EGS plants would… [or] Government agencies that provide regulatory oversight would…

- Put the public's interests above their own
- Not allow the plant to put some people at greater risk than others
- Be willing to listen to public concerns
- Have respect for people like me
- Be quick to disclose potential risks
- Be accurate in what they tell the public
- Be fair in their dealings with the public
- Be honest in what they disclose to the public
- Ensure that the benefits are shared widely among the public

Note: Items were measured on a 7-point 1 = strongly disagree to 7 = strongly agree scale.

Trust

We measured trust in three entities: (1) private companies that develop and operate EGS projects, (2) federal agencies, and (3) local government agencies providing regulatory oversight of EGS projects using the same items having a 7-point "strongly disagree" to "strongly agree" scale (see Table 1). We used a factor analysis with a varimax rotation to determine whether the items loaded according to the entity. The rotated solution showed that the items for federal and local government loaded together, whereas the items for private industry loaded separately (see Supplementary Table S2). We combined the government items into one scale and industry items into the other, labeling the scales as "trust in the government" (M = 4.32, SD = 1.63; $\alpha = 0.99$) and "trust in industry" (M = 4.13, SD = 1.66; $\alpha = 0.97$). Although trust was generally above average for both private and government entities, US respondents were significantly more likely to trust industry than their Swiss counterparts ($M_{US} = 4.29$, $SD_{US} = 1.79$, $M_{CH} = 3.96$, $SD_{CH} = 1.51$, $p < 0.005$), with Cohen's d confirming a small but meaningful effect (0.20).

Views about renewable energy and climate change

We measured respondents' views about renewable energy by asking to what extent they agreed that moving to renewable energy is necessary for their country on a 7-point "strongly disagree" to "strongly agree" scale. Agreement was generally high (M = 5.71, SD = 1.47) without a meaningful significant difference between the two countries.

We measured views about climate change by asking respondents to indicate agreement with the following four statements using the same 7-point "strongly disagree" to "strongly agree" scale: "climate change is a serious problem that requires immediate action," "concern about climate change is overblown" (reverse coded), "I consider myself well-informed about climate change," and "climate change

TABLE 2 Perceptions of the underground: Semantic differential items.

	M (SD)		t (df = 2029)
	United States	Switzerland	
Separate from nature—Part of nature	3.79 (1.28)	4.09 (1.1)	−5.62[a]
Comprehensible—Mysterious	3.53 (1.26)	3.34 (1.16)	3.52
Dirty—Clean	3.20 (1.28)	3.40 (1.12)	−3.61
Unstable—Stable	2.92 (1.31)	3.00 (1.19)	−1.43
Uncontrollable—Controllable	2.94 (1.31)	2.61 (1.15)	5.92[a]
Dangerous—Safe	2.74 (1.34)	2.58 (1.1)	2.97
Unpredictable—Predictable	2.74 (1.35)	2.54 (1.16)	3.65
Unfamiliar—Familiar	2.72 (1.35)	2.52 (1.16)	3.61
Dynamic—Static	2.81 (1.21)	2.61 (1.13)	3.87
Grim—Bright	3.06 (1.26)	2.75 (1.08)	6.05[a]
Invisible—Tangible	3.34 (1.26)	2.77 (1.17)	10.51[a]

Note: We used a 1–5 scale, anchored at each end by the different items. All of the differences were significant at $p < 0.005$, with the exception of dynamic vs. static. We used Cohen's d to examine effect size: [a]Small effect size (0.20-0.45).

is mostly caused by humans." Reliability analysis indicated that removing the statement "I consider myself well-informed about climate change" improved the Cronbach α from 0.68 to 0.81, and we subsequently combined the three remaining items into "climate change concern" (M = 5.18, SD = 1.56). Overall, although concern was generally high, Swiss respondents were more concerned than their US counterparts ($M_{CH} = 5.33$, $SD_{CH} = 1.50$ versus $M_{US} = 5.02$, $SD_{US} = 1.61$, $p < 0.001$), with Cohen's d confirming a small but meaningful effect (−0.20).

4 | RESULTS

4.1 | General perceptions of the deep underground

To answer RQ1, we first explored how respondents viewed the deep underground. When asked to give their associations following the question prompt on the deep underground, respondents provided a total of 1923 spontaneous associations, which we next asked respondents to rate as negative or positive. Overall, 42% rated their associations as positive (greater than 4, the scale's midpoint), 28% were neutral (i.e., 4), and 30% were negative (i.e., 1–3). US respondents were more likely than Swiss respondents to rate their associations with the deep underground as positive ($M_{US} = 4.44$, $SD_{US} = 1.70$ versus $M_{CH} = 4.02$, $SD_{CH} = 1.74$, $p < 0.001$), with Cohen's d confirming a small but meaningful effect (0.24).

Table 2 reports the results of the semantic differential scale regarding perceived characteristics of the deep underground. Overall, respondents were more likely to consider the underground as part of nature, mysterious, and clean. In terms of country comparisons, although the means were generally significantly different between countries (except for dynamic versus static), Cohen's d suggests that most of the effect sizes were negligible, that is, less than 0.20, and therefore not meaningful. Among those with small effect sizes (i.e., 0.20–0.45), Swiss respondents tended to perceive the underground as more a part of nature and cleaner than their US counterparts. In comparison, US respondents perceived the underground as more controllable, tangible, and brighter than their Swiss counterparts.

4.2 | Human use of the deep underground

Table 3 offers additional insight into how respondents view human use of the deep underground. Overall, the results suggest that respondents tend to view the underground as a resource for humans to use. The exception is perceiving the deep underground as a "place to store things," which was rated lowest in terms of agreement. In general, US and Swiss respondents perceived human use of the underground similarly, with some exceptions: US respondents were significantly more likely to perceive the underground as "a sacred place," a "place to store things," and that "using resources from the deep underground can be done safely." When we compare the between-country results using the "underground as a resource for human use" and "underground should be left alone" scales, we find that US respondents were significantly more likely to give higher ratings to the items in the "underground for human use" scale at a meaningful level.

4.3 | EGS as tampering with nature

To examine RQ2, we explored whether respondents viewed EGS as tampering with nature. Overall, respondents rated the individual tampering-with-nature dimensions as slightly above the mean. Comparing the two countries, US respondents tended to consider EGS as more "contrary to nature" ($M_{US} = 4.14$, $SD_{US} = 1.85$, $M_{CH} = 3.77$, $SD_{CH} = 1.76$),

TABLE 3 Perceptions of human use of the underground: Scale items, means, standard deviations, and reliabilities.

	M (SD)		*t* (df = 2029)
	United States	Switzerland	
Underground: Leave alone (α = 0.81)			
Whatever is below us belongs to the Earth and should be left untouched	3.93 (1.85)	3.7 (1.81)	2.83
Humans should not interfere with Earth's fundamental processes (n.s.)	4.35 (1.78)	4.28 (1.73)	0.90
Because processes like EGS are hidden from sight, we won't know about problems until it's too late	4.60 (1.67)	4.33 (1.61)	3.74
The deep underground is a sacred place	4.06 (1.82)	3.25 (1.84)	9.96[a]
Drilling wells is an invasive way to take something from the Earth (n.s.)	4.38 (1.75)	4.22 (1.66)	2.11
We have no control over what happens in the deep underground (n.s.)	4.64 (1.77)	4.69 (1.65)	−0.68
Scale	4.38 (1.36)	4.25 (1.25)	2.36
Underground: Human use (α = 0.87)			
Exploring the underground is a pathway for new knowledge and discovery (n.s.)	5.27 (1.48)	5.19 (1.47)	1.09
The deep underground below us exists as a resource for humans to use	4.82 (1.63)	4.56 (1.65)	3.52
Using resources from the deep underground can be done safely	4.76 (1.59)	4.14 (1.57)	8.79[a]
The deep underground is a new frontier for humans to explore	5.05 (1.65)	4.77 (1.63)	1.09
Scale	4.97 (1.38)	4.67 (1.31)	5.15[a]
The deep underground is a place to store things.[b]	3.49 (1.83)	3.1 (1.83)	4.83[a]

Note: Scales ranged from 1 = strongly disagree to 7 = strongly agree. All items except those marked with n.s. are significantly different between countries at $p < 0.005$. We used Cohen's d to examine effect size: [a]Small effect size. [b]"The deep underground is a place to store things" did not load on either factor, reduced the Underground: Human Use scale reliability from 0.87 to 0.81, and was excluded from further analysis.

"unnatural" ($M_{US} = 3.98$, $SD_{US} = 1.91$, $M_{CH} = 3.77$, $SD_{CH} = 1.76$), and "disturbing the order of nature" ($M_{US} = 4.26$, $SD_{US} = 1.88$, $M_{CH} = 4.04$, $SD_{CH} = 1.77$) than their Swiss counterparts. Although the differences were significant, only "contrary to nature" had a small but meaningful effect size (d = 0.21).

When we compare these perceptions of EGS to views about pesticides, GMOs, and human-induced seismicity (see Figure 1), we find that respondents from both countries are more likely to perceive pesticides and GMOs as tampering with nature than EGS and induced seismicity. They also consider induced seismicity as tampering with nature more than EGS. Comparatively, although the differences between countries in views about tampering with nature were significant at $p < 0.005$, only perceptions of pesticides were meaningfully different (d = −0.34).

4.4 | Factors relating to EGS support

To examine RQ3, we used a linear regression to measure the relative influence of different sets of variables on respondents' general support for an EGS project near the proximity of their residence. We entered four different blocks, so we could examine the R square change, that is, the incremental change of the new addition. Tables 4 and 5 present the final block results for each country. No multicollinearity issues were observed as all VIFs were below 3. The bivariate correlations between all the variables are reported in Supplementary Tables S4 and S5. In the next few paragraphs, we describe the bivariate correlations between the variables and EGS support and the regression results, which control for the effects of all variables on EGS support.

In terms of demographics, there were significant correlations between EGS support and being male in both countries and leaning "left" politically in Switzerland. In the regression analyses, the results show that for both the Swiss and US sample, respondents who were younger were more supportive of EGS. For the US sample, respondents who self-identified as more "right" on the political spectrum were more supportive. Otherwise, demographics did not have a strong relationship with support for EGS projects in either country when controlling for other variables.

In both countries, perceptions of the underground and specifically whether respondents perceived the deep underground as a place for humans to use were positively associated with EGS support. Although believing that the underground should be left alone was negatively related to EGS support in the bivariate correlations in both countries, it did not have a statistically significant relationship with EGS support in the US or Switzerland regression analysis at $p < 0.005$.

The third block added risk–benefit perceptions, trust in government and private industry, climate change concerns, and support for moving to renewable energy. Each of these variables had a significant, positive relationship with EGS support in the bivariate correlations. In the regression analyses, risk–benefit perceptions and support for transitioning to renewable energy were significantly related to EGS support in both countries. For Swiss respondents, trust in private industry significantly related to EGS support, which was not the case for US respondents.

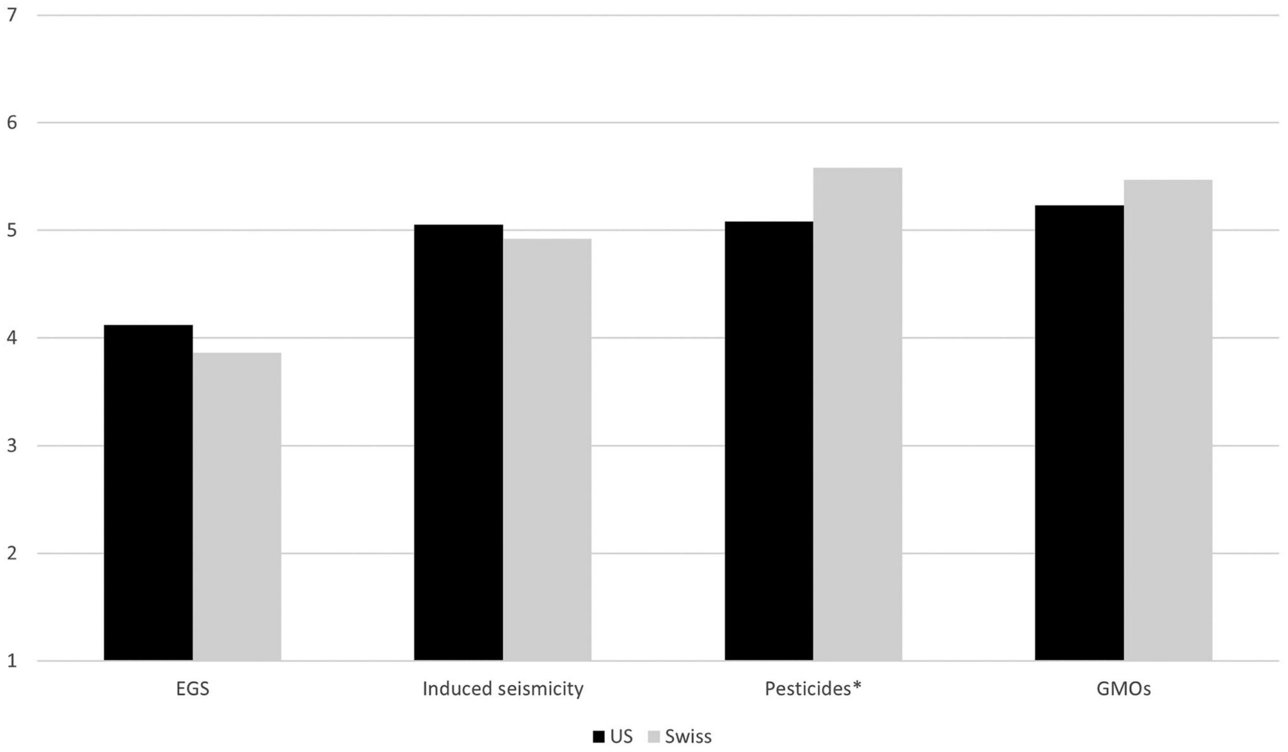

FIGURE 1 Bar chart showing perceptions of different technologies as "tampering with nature." Although there were significant differences between countries for each technology, an examination of effect size using Cohen's d suggests only the variable *pesticides* was meaningful (−0.34).

TABLE 4 Regression analysis for "What is your general feeling about the implementation of an EGS project in the proximity of where you live?" for the US sample ($N = 989$).

						95% Confidence interval for B	
Variables	***B***	**SE**	**Beta**	***t***	***P*-value**	**Lower bound**	**Upper bound**
(Constant)	−0.707	0.371		−1.905	0.057	−1.435	0.021
Education (low to high)	−0.078	0.072	−0.026	−1.078	0.281	−0.219	0.064
Gender (female = 1)	0.029	0.081	0.008	0.357	0.721	−0.131	0.189
Political leaning (Left/Right)	0.086	0.026	0.088	3.320	0.001	0.035	0.138
Age	−0.009	0.002	−0.094	−3.858	0.001	−0.014	−0.005
Location of residence (urban/rural)	0.020	0.039	0.012	0.524	0.601	−0.056	0.097
Adjusted R square 0.011	ANOVA F(5, 949) = 3.019), $p = 0.010$						
Underground: Human use	0.301	0.041	0.243	7.291	0.001	0.220	0.382
Underground: Leave alone	−0.049	0.039	−0.039	−1.264	0.207	−0.125	0.027
Cum. adjusted R square 0.364	ANOVA F(7, 942) = 78.602, $p < 0.001$						
Risk–benefit perceptions	0.676	0.062	0.356	10.822	0.001	0.553	0.798
Trust in government regulators	0.001	0.037	0.001	0.033	0.974	−0.071	0.074
Trust in private industry	0.087	0.035	0.090	2.452	0.014	0.017	0.156
Climate change concern	0.082	0.032	0.076	2.552	0.011	0.019	0.145
Support for moving to renewables	0.205	0.033	0.185	6.264	0.001	0.141	0.270
Cum. adjusted R square 0.514	ANOVA F(12, 937) = 84.760, $p < 0.001$						
EGS as tampering with nature	−0.023	0.031	−0.022	−0.758	0.449	−0.084	0.037
Induced seismicity as tampering with nature	0.052	0.031	0.044	1.683	0.093	−0.009	0.112
Cum. adjusted R square 0.515	ANOVA F(14, 935) = 72.962, $p < 0.001$						

Note: Listwise deletion of missing values.

TABLE 5 Regression analysis for "What is your general feeling about the implementation of an EGS project in the proximity of where you live?" for the Swiss sample ($N = 1027$).

						95% Confidence interval for B	
Variables	***B***	**SE**	**Beta**	***t***	***P*-value**	**Lower bound**	**Upper bound**
(Constant)	1.585	0.465		3.406	0.001	0.672	2.498
Education (low to high)	−0.117	0.073	−0.036	−1.601	0.110	−0.261	0.026
Gender (female = 1)	−0.059	0.083	−0.016	−0.707	0.480	−0.222	0.104
Political leaning (Left/Right)	−0.030	0.032	−0.023	−0.955	0.340	−0.092	0.032
Age	−0.013	0.003	−0.118	−5.297	0.001	−0.018	−0.008
Location of residence (urban/rural)	0.005	0.034	0.003	0.139	0.889	−0.061	0.071
Adjusted R square 0.024	ANOVA F(5, 1022) = 6.151, $p < 0.001$						
Underground: Human use	0.157	0.043	0.114	3.661	0.001	0.073	0.241
Underground: Leave alone	−0.110	0.041	−0.077	−2.690	0.007	−0.191	−0.030
Cum. adjusted R square 0.341	ANOVA F(7, 1020) = 76.844, $p < 0.001$						
Risk–benefit perceptions	0.803	0.074	0.346	10.860	0.001	0.658	0.948
Trust in government regulators	−0.002	0.042	−0.002	−0.054	0.957	−0.084	0.080
Trust in private industry	0.152	0.040	0.128	3.783	0.001	0.073	0.230
Climate change concern	−0.040	0.032	−0.033	−1.244	0.214	−0.103	0.023
Support for moving to renewables	0.232	0.037	0.175	6.250	0.001	0.159	0.305
Cum. adjusted R square 0.489	ANOVA F(12, 1015) = 83.009, $p < 0.001$						
EGS as tampering with nature	−0.139	0.031	−0.126	−4.449	0.001	−0.200	−0.077
Induced seismicity as tampering with nature	−0.017	0.016	−0.025	−1.079	0.281	−0.047	0.014
Cum. adjusted R square 0.499	ANOVA F(14, 1013) = 74.032, $p < 0.001$						

Note: Listwise deletion of missing values.

The fourth block examined the relationship between tampering with nature and EGS support. In both countries, respondents who perceived EGS as tampering with nature were more negative about EGS in the bivariate correlations. In the regression analysis, perceiving EGS as tampering with nature was significantly related to less support for EGS projects in the Swiss sample but not in the US sample.

5 | DISCUSSION

Energy experts believe that the widespread adoption of EGS and other deep geothermal systems can meaningfully reduce global greenhouse gas emissions and improve domestic energy independence. To better understand the factors underlying public support for EGS, our study addressed four research questions. We first examined how US and Swiss respondents perceive the deep underground, the place where EGS extraction takes place. We found that, among eight properties examined, respondents were most likely to perceive the deep underground as a "part of nature." The lack of surface disruption and low visual footprint relative to other technologies like wind and solar is often indicated as a key benefit of EGS (Stephens & Jiusto, 2010; Tester et al., 2007); however, given that people tend to view the underground as part of nature, the potential for disrupting the underground—and therefore nature—in people's minds should not be dismissed. Out of sight may not mean out of mind.

Other measures reveal notable differences between Swiss and US respondents. As described in Section 4.1, while respondents, on average, have a neutral to positive affective response to the deep underground in relation to the use of EGS, Swiss affective imagery was generally less positive than US imagery. This national variation may be linked to the two prior deep geothermal projects in Switzerland that caused felt earthquakes in the past and attracted attention nationwide (Stauffacher et al., 2015); similarly, it may also help to explain the stronger tendency of Swiss citizens to view the underground as uncontrollable, dangerous, unpredictable, and unfamiliar. Another potential explanation may lie in the US's greater familiarity with industries involving underground extraction, such as mining for coal, oil, and natural gas.

We found that respondents tend to perceive the underground as a resource for humans to use, though results are mixed regarding support for the specific activities, possibly due to the uncertainty and lack of knowledge around EGS. That the results showed low support for the use of the underground to store things is relevant both to EGS and other technologies, such as carbon capture and storage and nuclear waste storage, signaling that such technologies may face public resistance. US respondents are more likely than Swiss respondents to agree that the underground is a space for exploration and a resource for humans, but notably, they are also significantly more likely to view the underground as sacred, showing that one does not exclude the other. Future work may find different results in other countries where the underground may be viewed as more sacred or culturally significant.

Our second question examined EGS as tampering with nature. We found that while respondents viewed EGS as somewhat disturbing the order of nature, perceptions of EGS as tampering with nature were relatively neutral, especially when compared with GMOs and pesticides. Induced seismicity was more likely to be viewed as tampering with nature than EGS, even though it was presented as a consequence of EGS in the information vignette. Respondents' perceived benefits of EGS, such as its potential sustainability, reliability, and low environmental impact, may compensate for the perceived negative impacts of induced seismicity. Alternatively, the difference between EGS and induced seismicity perceptions may also be a further consequence of the complexity of "nature" as a construct. Tampering with nature can be seen as negative either because nature is vulnerable, and thus needs to be protected, or because nature is threatening, whereupon "tampering" leads to unintended consequences when nature "bites back." When assessing induced seismicity, it may suggest a sense of nature "biting back" after being disturbed, in a way that EGS alone does not. For risk communication, it may be important to differentiate between induced microseismicity, which is necessary to have the conditions for water to circulate and generate energy, versus unwanted induced seismicity which may result from EGS projects, consisting of earthquakes significant enough to be felt at the surface such as in Pohang, South Korea (Kim et al., 2018) and Basel, Switzerland (Deichmann & Giardini, 2009).

Our third research question investigated how beliefs about EGS as tampering with nature compared with other antecedents in explaining support for EGS development. Given the exploratory nature of our research, our analysis used bivariate correlations and regression analyses. Understandably, there were several significant bivariate correlations that were not significant in the regression analysis, which suggests that some variables were suppressing the effect of others. As examining all possible indirect effects of the variables on EGS support exceeds the scope of this exploratory research, we focus on the correlation analyses and regression results as the most parsimonious way to answer our research question. In our regression analysis, beliefs about tampering with nature were associated with EGS support in Switzerland but not in the United States. The same was true for trust in industry, which related to EGS support in Switzerland but not in the United States. The bivariate correlations showed significant relationships between EGS support and beliefs about tampering, trust in industry, and trust in government regulators; however, these effects were suppressed in the final regression model. In both countries, perceived risks and benefits and support for moving to renewable energy related to EGS support in the bivariate correlations and the regression analyses, demonstrating the overall weight of these relationships in the final model. The Swiss results align with past research on resistance to technological developments driven by discomfort with tampering with nature (Corner et al., 2013; Jobin & Siegrist, 2020; Wolske et al., 2019) and support findings from the risk perception literature for technologies such as geoengineering (Siegrist & Árvai, 2020). In addition, that beliefs about human use of the underground greatly matter in explaining support for EGS suggests that preexisting beliefs about the underground and with subterranean endeavors may be an important contextual factor in responses to deep geothermal development. Lastly, beliefs in the necessity of moving to renewable energy had one of the strongest associations with support for EGS. Further, in both countries, although there were some significant zero-order correlations in demographics, younger respondents were more supportive of EGS, a result consistent with research showing that age often relates to support for renewable energy (e.g., Hamilton et al., 2019).

In general, support for EGS development, measured by the affect elicited by having a project near one's home, was high in both countries, in contrast with case studies that have highlighted oppositional issues with deep geothermal projects (Chavot et al., 2018; Ejderyan et al., 2019). Respondents in both countries generally viewed EGS as a positive, renewable form of energy technology. Further, although there were notable differences between the US and Swiss samples, as noted above, the results also revealed many similarities between the two countries, also noted above, regarding factors relating to EGS support.

Future research should address some limitations of the present study. First, although our study represented populations from two countries, which are deploying deep geothermal technologies, it did not represent views from non-Western countries where relationships with nature in general may be different. The concept of "nature" is socially constructed and culturally interpreted (Corner et al., 2013; Demeritt, 2002); future studies should, therefore, investigate how perceptions of US and Swiss citizens compare with those from other countries. Second, having found that perceptions about EGS and induced seismicity as tampering with nature are distinct from each other, future research should investigate whether aspects of EGS are perceived to have a positive impact on nature and may thus compensate for negative impacts such as induced seismicity. Third, future studies should examine the tampering-with-nature concept in more depth and in different scenarios, including comparing different technologies, activities, and countries. This also includes investigating the term "nature" with greater nuance when considering different regions of nature, such as the deep underground or the deep sea, which are distant from individuals' personal realms of experience but increasingly critical to climate action (e.g., Jamieson et al., 2021). Finally, the data were collected using quota sampling, leading to some limitations in terms of the generalization of the results. By basing our sample on quotas for certain demographic variables, we may have missed other important sample attributes. Further, this type of sampling can lead to selection bias, in which respondents who are more interested in the topic may complete the survey.[3] It may be that a random, probability sample would have shown different results. That stated, our intent was not to generalize the results but to better represent patterns in public views across two countries. Future research may expand on these results with a probability sample.

6 | CONCLUSION

This study sought to augment the currently limited literature on the social acceptance of deep geothermal energy projects, especially EGS, by conducting a cross-national survey of US and Swiss respondents. The results suggest in both countries, perceptions of the underground relate to support for EGS development. That is, when individuals see the deep underground as a place for humans to use, they are also more supportive of EGS development. Swiss and US respondents overall tend to consider the deep underground as a resource to use, while respecting it as part of nature. Although respondents in both countries consider EGS as tampering with nature, only in Switzerland is this variable's relationship with EGS support significant in the regression analysis, meaning that those who perceive it more as tampering are also less supportive when controlling for other variables that related to EGS support. Different contexts between the United States and Switzerland with respect to histories with extractive industries and induced earthquakes may be an important determining factor in the relative effect of different factors on EGS support. In addition to these more novel variables, the results confirm that risk–benefit perceptions and support for moving to renewable energy relate to EGS support in both countries, whereas trust in industry developers relates to EGS support in Switzerland, when controlling for the effect of other variables.

The implications of this research for policymakers and for future research include the importance of supplementing qualitative research with quantitative research. Although some qualitative studies have defined deep geothermal systems as strongly opposed by the public (e.g., Boulouchos et al., 2022), our quantitative survey reveals overall positive attitudes toward the development of EGS in the United States and Switzerland. Further, our study shows that public perceptions have deeper roots than risk–benefit perceptions. Although past studies have investigated the role of trust, procedural justice, risks, and benefits, our research identified that other factors, such as how people think about human use of the underground, influence EGS support. Not understanding these factors will inhibit efforts to build constructive dialogue with members of the public. Our results further highlight that people view the deep underground, in and of itself, as more dangerous and unfamiliar than EGS. As such, risk communication about EGS projects could seek to familiarize individuals with current activities in the deep underground before trying to address fears around the use of EGS (e.g., induced seismicity). In addition, although the results found that the United States and Swiss public are largely in favor of the underground as a resource for humans to use, respondents also expressed concerns about exploitation (e.g., drilling and storage), suggesting that risk communication messages should convey what geothermal managers are doing to mitigate risks such as large earthquakes.

Although the study indicates that perceptions of EGS tend to be positive overall in both the United States and Switzerland, these perceptions will inevitably change as this emerging technology becomes more established. As opposed to the findings of Evensen and colleagues (2022) in the context of shale gas, communication may be effective in the case of EGS, as preferences are not yet fully formed. When people have low familiarity with a topic, as is the case with EGS, these perceptions will be more sensitive to the ways information is chosen and presented (Pidgeon et al., 2017). The way policymakers and project developers involve and communicate with the public in the near future may thus be decisive in terms of the acceptability of the technology. Rather than focusing only on mitigating fears of specific risks like induced seismicity, a focus on more affective aspects of EGS, such as perceptions of nature and the underground, may be equally important. For example, spending time on understanding what people feel when they think about machinery drilling into the Earth, and how it affects the Earth and nature more generally, from their point of view, may be a good starting point to subsequently discuss the risks and benefits of EGS.

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

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[3] To lessen this effect, we have indicated to potential respondents that the survey was about the energy transition in their country and did not specify that it was about geothermal energy.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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APPENDIX A: DEMOGRAPHICS AND DESCRIPTIVE STATISTICS

	Statistics	
Variable	**Switzerland (*N* = 1028)**	**United States (*N* = 1003)**
Age (years)	M = 47.49, SD = 15.96	M = 47.28, SD = 17.21
Gender	1: Male = 45.8%	1: Male = 49.7%
	2: Female = 53%	2: Female = 50.3%
	3: Not listed/nonbinary = 1.2%	3: Not listed/nonbinary = 0.0%
Education (highest level received)	1: No high school degree = 4.5%	1: No high school degree = 4.0%
	2: High school degree = 58.2%	2: High school degree = 51.5%
	3: Bachelor's degree or higher = 37.4%	3: Bachelor's degree or higher = 44.5%
Political orientation (1 = "left" to 7 = "right")	M = 4.05, SD = 1.34	M = 4.19, SD = 1.76
Place of residence (rural vs. urban) [a]	1: City = 23.1%	1: City = 29.0%
	2: Suburb = 17.6%	2: Suburb = 41.4%
	3: Small town = 20.3%	3: Small town = 11.4%
	4: Rural area = 39.0%	4: Rural area = 18.2%

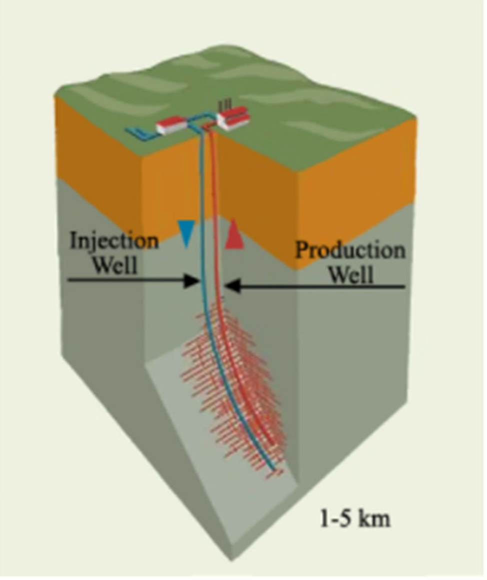
Note: [a]Differences between countries ($M_{US} = 2.19$, $SD_{US} = 1.05$ vs. $M_{CH} = 2.75$, $SD_{CH} = 1.20$) are significant at $p < 0.001$, Cohen's d = −0.50. All other between-country differences are not statistically significant.

APPENDIX B: EGS VIGNETTE

Geothermal energy is energy from heat inside the earth. The deeper we go into the earth's crust, the higher the temperature rises. Geothermal energy resources can be used in the form of heating, cooling, or electricity production. In this survey, we focus on electricity production.

To produce electricity from geothermal energy, the system needs water, heat and pathways for water to move through rocks. In a few select areas around the world (think of Iceland, New Zealand or California), conventional geothermal systems produce electricity by harnessing the heat from the tectonically active environment. They use steam from water naturally found in hot rocks generally near the surface to drive turbines to produce electricity. Conventional geothermal systems are limited to specialized areas where heat, water, and pathways for water to move through rocks already exist.

When these pathways for water do not exist, we can use Enhanced Geothermal Systems (EGS) to harness the heat stored in the earth. With EGS, we create our own reservoirs by drilling down deep enough (1-3 miles, depending on the region) to reach rock that is hot enough to use (see the image below). We then inject water into an injection well (Blue) at high pressure, which enlarges existing pathways in the rock, or creates new ones. The high pressure water causes the rock to slip slightly along existing fractures, enlarging pathways while also creating micro-earthquakes as part of the process. This allows the water to move through the hot rock to extract the stored heat. The hot water is then pumped up to the surface through a production well (red), where it can be used to generate electricity.



Risks linked to EGS include the risk of inducing earthquakes that can be felt by humans. However, research is ongoing to investigate techniques that can limit these risks. A risk of groundwater pollution can also occur but only if the well is not drilled according to best practices. Strict water and environmental protections regulations exist to avoid such pollution. Noise pollution may also occur; however, geothermal power plants will be subject to local regulations protecting against noise caused by industrial operations.

EGS also has several advantages. Making this technology commercially viable by 2030 is part of the Department of Energy's priorities for research and development. EGS can be used locally to provide heat and generate electricity for surrounding communities. The energy from EGS does not need to be imported; it is under our feet, increasing our energy independence. Also important, the energy supplied is continuous; the heat contained under the earth's crust is constant and not dependent on weather conditions, or the time of year or day. EGS also emits very little CO_2 into the atmosphere.