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Siting deep geothermal energy: Acceptance of various risk and benefit scenarios in a Swiss-German cross-national study

Theresa A.K. Knoblauch[a,*], Evelina Trutnevyte[a,b], Michael Stauffacher[a]

[a] Swiss Competence Center for Energy Research-Supply of Electricity (SCCER-SoE) and Transdisciplinarity Lab, Department of Environmental Systems Science (D-USYS), ETH Zurich, Switzerland

[b] Renewable Energy Systems, Institute of Environmental Sciences (ISE), Section of Earth and Environmental Sciences, Faculty of Science, University of Geneva, Switzerland

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ABSTRACT

Deep geothermal energy projects offer low-carbon, renewable base-load resources for electricity and heat production. Siting such projects can be challenging because past projects have induced seismicity. This suggests siting projects in remote areas away from populated areas and infrastructure, with minimal seismic risks. However, deep geothermal projects are most viable when they use residual heat, which requires proximity to heat consumers and thus, ideally, a rather urban environment. Hence, siting options carry various risks and benefits. It is informative to see how the public responds to these risks and benefits. This study investigates how well the public accepts various heat benefits when induced seismic risks are comparatively high or low. Respondents rated their acceptance of four deep geothermal energy scenarios in an online survey ($N = 814$) conducted in Switzerland and Germany. Conjoint and mixed multivariate statistical analyses show that the public prefers projects sited in remote areas and using residual heat for industrial applications. The results in Switzerland and Germany were rather similar, but the Swiss public was generally more positive. Importantly, induced seismic risks affected acceptance ratings most strongly. Thus, policies to reduce the risk of induced seismicity must be given the highest priority to enable an open dialogue.

1. Introduction

Renewable energy resources are a promising way to address challenges such as climate change and nuclear energy phase-out, but acceptance is crucial in their development (Cohen et al., 2014; Huijts et al., 2012; Wüstenhagen et al., 2007). Despite generally positive public attitudes, the siting of renewable energy facilities has sometimes led to local opposition (Jones and Richard Eiser, 2010; Moore and Hackett, 2016). Research has extensively investigated the conditions under which the local public is likely to accept renewable energy facilities and how to respond to opposition, often with a focus on compensation or benefits for the local public (Botelho et al., 2017; Dreyer et al., 2017; García et al., 2016; Kerr et al., 2017; Tabi and Wüstenhagen, 2017). One case in point is deep geothermal energy (Kunze and Hertel, 2017), a renewable energy resource that can produce base-load energy from local resources that are available almost everywhere (Chamorro et al., 2014; van Wees et al., 2013). However, until now, research on the siting and acceptance of renewable energy has largely overlooked deep geothermal energy. For such projects, siting can be particularly sensitive because past deep geothermal energy projects have been associated with increased seismicity (Giardini, 2009).

As an emerging technology, deep geothermal energy can become increasingly relevant as a way of supplying future low-carbon energy when projects are sited successfully (Schilling and Esmundo, 2009; Tester et al., 2007): deep geothermal energy is expected to supply 3% of global electricity and 4 to 5% of global heat in 2050 (Beerepoot, 2011; Goldstein et al., 2011). Countries such as Switzerland and the US have made deep geothermal energy a pillar of their future energy supplies (Swiss Federal Office of Energy [SFOE], 2013; U.S. Senate Committee on Energy and Natural Resources, 2015), and many countries around the globe have already started to harness deep geothermal energy on various scales, including Australia, South Korea, Germany, and France (Agemar et al., 2014; Bertani, 2016, 2012; Lu, 2018; Purkus and Barth, 2011). Bertani estimates that worldwide, around 40 countries could be powered exclusively by geothermal resources (Bertani, 2016). Deep geothermal energy can be harnessed by circulating fluid through an underground heat exchanger. This heat exchanger can be natural (hydrothermal reservoirs) or artificially created through hydraulic fracturing (enhanced geothermal systems, or EGS). For viable electricity

* Correspondence to: Transdisciplinarity Lab, Department of Environmental Systems Science (D-USYS), ETH Zürich, Switzerland.
E-mail address: theresa.knoblauch@alumni.ethz.ch (T.A.K. Knoblauch).

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production, both methods of harnessing deep geothermal energy require well drilling to reservoir depths of at least 3 km, where temperatures reach above 100 °C. This is different from widespread shallow geothermal energy for heating applications, where depths reach, at maximum, 400 m.

The risk of induced seismicity represents a potential impediment to the realization of deep geothermal energy projects because it is very visible in the public discourse around it (Stauffacher et al., 2015), even if there are public deliberations on other environmental and economic impacts (Volken et al., 2017, 2018). Seismicity can be induced during both reservoir creation, when it can be technically helpful, as well as during operation (Gischig et al., 2014). Induced seismicity risk assessments involve uncertainties and potential expert disagreements (Trutnevyte and Azevedo, 2018). Consequently, risk of induced seismicity and the associated uncertainties can cause concern among affected residents, as well as the larger public. This may even be expressed in the form of public protest and opposition and can lead to the abandonment of deep geothermal energy projects. In Switzerland, two deep geothermal energy projects were abandoned after noticeable induced seismic events: an induced seismic event of magnitude 3.4 occurred in Basel and resulted in damage claims of 9 million USD, and an induced seismic event of magnitude 3.5 was recorded in St. Gallen (Edwards et al., 2015; Giardini, 2009). In Germany, induced seismic events associated with the deep geothermal energy project Landau reached a magnitude of 2.7 (Breede et al., 2013; Groos et al., 2012), which led to public protests and the formation of civil initiatives (Leucht, 2012). In the US, an induced seismic event of magnitude 4.6 was recorded in the Geysers (Majer et al., 2007), a remote area away from populated spaces. More examples of induced seismicity linked to deep geothermal energy activities can be found in (Breede et al., 2013; Evans et al., 2012; Hirschberg et al., 2015; Zang et al., 2014).

One strategy to reduce the risk of induced seismicity associated with deep geothermal energy projects is to site deep geothermal energy in remote areas thus away from populated spaces and infrastructure (Bommer et al., 2015; Majer et al., 2007; McGarr et al., 2015; Trutnevyte and Wiemer, 2017). Because of otherwise large uncertainties when predicting induced seismicity and the associated damage to buildings, this study focuses on the siting in order to reduce induced seismicity risks (i.e. building damage) rather than hazard (i.e. probability and magnitude of earthquakes). Given the identical induced seismic hazard, parameters that influence risk are the composition of the exposed building stock, vulnerability of these buildings, the economic value of these buildings and so on (Knoblauch and Trutnevyte, 2018; Trutnevyte and Azevedo, 2018; Trutnevyte and Wiemer, 2017). When siting deep geothermal energy projects in remote areas the number of buildings and people exposed to potential seismic events can be reduced (Trutnevyte and Wiemer, 2017; Wiemer et al., 2014). In case of an induced seismic event, damage in remote areas would be significantly less than damage in urban areas or cities. Assuming rational actors and constant benefits, the benefit-to-risk ratio would be improved, and thus, decision making would come to favor siting deep geothermal energy projects in remote areas. By placing fewer buildings and less infrastructure at stake, siting deep geothermal energy projects in remote areas may reduce public concerns and opposition. For the remainder of this paper, we distinguish between low and high levels of induced seismic risk: low-level induced seismicity risk describes deep geothermal energy siting in remote areas, where very few to no buildings and infrastructure are exposed to potential induced seismicity, whereas high-level induced seismic risk describes deep geothermal energy siting in urban areas, where many buildings, infrastructure, and people may be exposed to induced seismicity (Knoblauch and Trutnevyte, 2018). We intentionally distinguish between urban and remote in relative terms rather than absolute distances to keep the study more generic. Referring to specific distances would need complex geological models that can only be applied to very specific regions.

One drawback of siting in remote areas, however, is that there is little to no efficient use of residual heat from electricity production. Only the efficient use and sale of residual heat, e.g., for residential district heating (DHN) or industry, makes deep geothermal energy an economically viable energy resource and allows the further maximization of saved CO_2 emissions because this heat can replace, for instance, oil heating (Giardini, 2009; Knoblauch and Trutnevyte, 2018; Treyer et al., 2015). Thus, when siting deep geothermal energy projects, there is a trade-off to be made between reducing the risk of induced seismicity and maximizing the benefits of deep geothermal energy, such as price competitiveness and CO_2 savings (Kraft et al., 2009). For the remainder of this paper, we distinguish between deep geothermal energy scenarios with low-level and high-level benefits: the low-level benefits of deep geothermal energy include electricity production without the use of residual heat, whereas the high-level benefits of deep geothermal energy include the additional use and sale of residual heat. The revenues from heat sales decrease the price of electricity from deep geothermal energy, and through the use of the remaining heat, CO_2 emissions can be significantly decreased as compared to conventional heating, e.g., heating with oil.

How various deep geothermal energy siting scenarios and the corresponding induced seismic risks and benefits relate to the acceptance of deep geothermal energy remains to be studied systematically (Trutnevyte and Ejderyan, 2017). In this paper, we understand acceptance as a generally positive, tolerant attitude towards deep geothermal energy without active support (Batel et al., 2013). Elsewhere, this is termed public acceptance (Zoellner et al., 2008), social acceptance (Dermont et al., 2017), or socio-political acceptance (Wüstenhagen et al., 2007). In this sense, past quantitative and qualitative research indicates that deep geothermal energy is generally accepted in Australia, Italy, and Switzerland (Dowd et al., 2011; Knoblauch et al., 2017; Pellizzone et al., 2015). This research also indicates that the public generally prefers deep geothermal energy projects to be sited away from populated spaces (Carr-Cornish and Romanach, 2014; Hoşgör et al., 2013). However, the public does not consider the lost benefits from the remaining heat. Past studies in the energy field have shown that perceived benefits are the best predictor of acceptance (Bronfman et al., 2012; Visschers and Siegrist, 2014). Accordingly, studies have shown that when perceived benefits outweigh perceived risks, respondents accept carbon capture and storage (CCS) and nuclear energy projects (L'Orange Seigo et al., 2014; Visschers et al., 2011). Regarding geothermal energy, it is unknown how the public perceives the benefits of heat production and whether these benefits can compensate for perceived risks. This conceptualization of acceptance resonates with the compensatory approach to energy infrastructure in general and deep geothermal energy in particular (Cohen et al., 2014; Meller et al., 2017; Zoellner et al., 2008).

This compensatory logic, however, may not necessarily hold in the case of induced seismicity, as evidence from the literature suggests. A study by McComas et al. observed that respondents did not accept any level of induced seismicity, regardless of the benefits the associated activity would provide (McComas et al., 2016). The concepts of "tampering with nature" (Sjöberg, 2000, p. 353) or "messing with nature" (Corner et al., 2013, p.938) may apply to induced seismicity, meaning that induced seismicity and felt earthquakes are perceived as an unprecedented and morally sensitive form of interference with nature and are by no means justifiable, regardless of the benefits. As soon as the risks exceed a certain threshold, a suggested deep geothermal energy project will not be accepted regardless of the presented benefits. Thus, a non-compensatory weighting of risks and benefits takes place, which stands in contrast to the acceptance models discussed above. Presumably, this behavior is more pronounced when induced seismic risks are high. In the literature, this phenomenon has been previously observed regarding the acceptance of another underground technology, namely CCS (Wallquist et al., 2012), as well as geoengineering (Wibeck et al., 2015). Qualitative research on the perceptions of another emerging subsurface energy resource, shale gas, also found that the risk posed by the technology had a decisive impact on perceptions (Thomas et al., 2017). Along similar lines, Walter discusses the undesired transgression of acceptable limits from the perspective of "protected values" in the domain of wind energy (Walter, 2014).

The consideration of the risks and benefits of new technologies does not play out in a vacuum and the decisive factors might differ between regions (Chavot et al., 2018). These decisive factors can be influenced by existing socio-political contexts, such as, for instance, the debates on climate change and nuclear phase-out (Delina and Janetos, 2017; Spreng, 2014). Also, factors such as trust, the siting process, perceived impact by individuals, or place attachment, might influence the perception of risks and benefits (Bell et al., 2005; Devine-Wright, 2011; Greenberg, 2014; Gross, 2007; Pellizzone et al., 2017). Both Switzerland and Germany have been discussing and implementing deep geothermal energy projects within such a context. Hence, the public has been confronted with deep geothermal energy and the related induced seismic risk to a certain degree (Giardini, 2009; Kreuter, 2011; Swiss Federal Office of Energy, 2013). The national context of deep geothermal energy and its interaction with deep geothermal energy acceptance may, however, still differ between countries. In Switzerland, the public discourse reflects induced seismic risks but also emphasizes the benefits of deep geothermal energy (Stauffacher et al., 2015), whereas in Germany, local protests against deep geothermal energy paint a picture of a contested technology (Kunze and Hertel, 2017). Also, elsewhere, perceptions and acceptance of deep geothermal energy risks vary between countries (Reith et al., 2013). To date, how deep geothermal energy is perceived in Switzerland as compared with Germany and whether and how risk-benefit compensation is perceived in both countries remain unknown.

In this paper, we aim to investigate how the public accepts various deep geothermal energy siting scenarios, along with their corresponding induced seismic risks and heat benefits. We propose to explain the variation in the dependent variable, the acceptance of deep geothermal energy, via three guiding hypotheses which are based on the literature above:

1. In general, the public accepts siting deep geothermal energy projects in remote areas (low induced seismicity risks) more fully than siting such projects in urban areas (high induced seismicity risks).
2. In remote areas (low induced seismicity risk), the public accepts deep geothermal energy projects with high-level benefits more than deep geothermal energy projects with low-level benefits.
3. In urban areas, which face a high induced seismicity risk due to deep geothermal energy projects, there is no sensitivity to benefit perceptions, because the public perceives deep geothermal energy projects as "tampering or messing with nature."
   We further assume that context affects respondents' acceptance of deep geothermal energy projects as pointed out previously.
4. Although we expect that Hypotheses 1–3 will hold across countries, we expect that in general, the German public accepts all deep geothermal energy siting scenarios less fully than the Swiss public does.

We derive four realistic deep geothermal energy siting scenarios, each a combination of induced seismic risks (low or high) and heat benefits (low or high) and analyze the acceptance ratings of these deep geothermal energy scenarios via conjoint measurement. This conjoint measurement is part of an online survey of the general public in the German-speaking part of Switzerland and the German federal state of Rhineland-Palatinate (RP).

2. Method

2.1. Sample

Overall, 814 respondents who were recruited through an access panel completed the online survey in November 2017. Quotas were set for the sample in terms of region, age, and gender. The sample includes 404 respondents from the German-speaking part of Switzerland and 410 respondents from the German federal state of RP. Fig. 1 displays the sample's geographic information. The Swiss sample ranged in age from 15 to 69 years (M = 42.90, SD = 14.74), and n = 204 (50.5%) were male. Most of the Swiss respondents completed vocational school (n = 164, 40.6%), followed by a university degree (n = 108, 26.6%), with n = 25 respondents (6%) reporting compulsory education. The Swiss sample is representative in terms of age and gender ratio (Swiss Federal Office for Statistics, 2017a). It is also slightly more educated than the Swiss average (Swiss Federal Office for Statistics, 2017b). The German sample ranged in age from 15 to 69 years (M = 44.68, SD = 14.63), and n = 202 (49.3%) were male. The majority of German respondents had completed obligatory or secondary school without additional professional training (n = 177, 40.3%), followed by vocational school (n = 102, 24.9%), and a university degree (n = 100, 24%). The German sample is representative in terms of age and gender (Statistical Office Rhineland-Palatinate, 2016a), though it is slightly less educated than the state's overall population (Statistical Office Rhineland-Palatinate, 2016b).

Fig. 1. Map of sample regions.

2.2. Description of sample regions

Both sample regions, the German-speaking part of Switzerland and the German state of RP, have experienced induced seismicity associated with deep geothermal energy projects: induced seismic events above magnitude 3.4 were recorded in the Swiss cities of Basel (2009) and St. Gallen (2013) (Edwards et al., 2015; Giardini, 2009), while induced seismic events in Landau (RP) remained below magnitude 2.7 (Breede et al., 2013; Groos et al., 2012). There are two additional deep geothermal energy projects (Insheim and Bruchsal) in or bordering the federal state of PR. Previous literature shows, however, that public attitude towards deep geothermal energy seem to be quite different: in Switzerland, deep geothermal energy is currently rather accepted (Knoblauch et al., 2017), with a balanced public discourse including the risks and benefits of deep geothermal energy (Stauffacher et al., 2015). In contrast, some of the public in RP reacted very critically to induced seismicity events in 2007 and formed civil initiatives focused on induced seismicity (Leucht, 2012). An unprepared administration lost public trust, and the topic of induced seismicity was prominently featured in public discourse (Leucht, 2012). This led the Landau deep geothermal energy plant to begin running at reduced capacity (Stiftung Risiko-Dialog, 2012). Meanwhile, no additional induced seismicity has occurred, and the public may have developed more neutral perceptions of deep geothermal energy (Brian and Schneider, 2014).

2.3. Conjoint measurement of acceptance for various deep geothermal energy scenarios

In order to illustrate the trade-off between induced seismic risks and heat benefits, we assessed the acceptance of deep geothermal energy scenarios via a full-factorial conjoint measurement. Through conjoint measurement, a method of decomposing overall ratings into the causal effects of specific attributes (Alriksson and Öberg, 2008; Hainmueller et al., 2014), we can estimate the effects of induced seismic risks and heat benefits, as well as their interaction, on deep geothermal energy acceptance ratings. Technically, these effects are computed as the importance of attributes and the part worth of these attributes' levels. Conjoint measurement allows the respondents to rate complete scenarios and thus represents a more realistic setting than direct measurement of indivdual attributes separately. Respondents received four deep geothermal energy scenarios in two pairwise comparisons. Pairwise comparisons have shown the highest external validity among vignette and conjoint studies (Hainmueller et al., 2015). The order in which the scenarios appeared was randomly assigned. The respondents were asked to indicate the degree to which they would accept the various scenarios on a seven-point Likert scale (1: "don't accept at all" to 7: "totally accept").

2.4. Deep geothermal energy scenarios

The four deep geothermal energy scenarios are each a combination of the risk and benefit attributes (Table 1). Both attributes have two levels: high and low (Table 4). Scenario 1 (low benefit, low induced seismicity risks) is a deep geothermal energy plant with no use of residual heat that is sited in a remote area and thus poses a low risk of damage due to induced seismicity. This scenario involves the remote production of electricity from deep geothermal energy that is fed into the grid. Scenario 2 (low benefit, high induced seismicity risk) is a deep geothermal energy plant in which the residual heat is not being used, but the plant is sited in an urban environment, a rather unrealistic scenario. Scenario 3 (high benefit, low induced seismicity risk) is a remotely sited deep geothermal energy project in which residual heat is used for industrial or agricultural purposes. Lastly, Scenario 4 (high benefit, high induced seismicity risks) depicts a deep geothermal energy project sited in the middle of a city, with the residual heat being fed into a local DHN. The prices of electricity and induced seismicity damage in these deep geothermal energy scenarios are adapted from previous research (Knoblauch and Trutnevyte, 2018; Schenler, 2015), see Table 2.

Table 1
Deep geothermal energy scenarios.

Deep geothermal energy scenario	Scenario description		Conjoint attributes	
	Heat benefit	Siting	Benefit (low, high)	Induced seismic risk (low, high)
1	No	Remote	Low	Low
2	No	Urban	Low	High
3	Yes	Remote	High	Low
4	Yes	Urban	High	High

2.5. Procedure and further variables

The online survey consisted of eight sections and took the respondents an average of 8 min to complete. The survey was adapted to each country in terms of currency and, where necessary, terminology. Both regions use German as a language, but some political institutions are named differently. After the respondents were directed to their country's version of the survey, the respondents received a two-part introduction to deep geothermal energy. The first part of the introduction was adopted from Knoblauch et al. (2017) and informed the respondents about deep geothermal energy and the differences between it and shallow geothermal energy. The respondents were then asked about their general attitudes towards deep geothermal energy (7-point Likert scale from 1: "totally oppose" to 7: "totally in favor") and whether they knew anything about deep geothermal energy previously (7-point Likert scale from 1: "nothing at all" to 7: "a lot"). The second part of the introduction informed the respondents about the siting of deep geothermal energy in more detail, including induced seismicity risks, continuous and local electricity production, and various other benefits. The concept of exposure and the resulting induced seismic damage was introduced. Further, the introduction addressed the uncertainty regarding induced seismicity associated with deep geothermal energy, as well as with energy production. Both parts of the introduction can be found in Appendix A2. The next section was comprised of the conjoint measurement of acceptance. It presented the four deep geothermal energy scenarios and asked the respondents to indicate their acceptance of these scenarios, as described above.

In the final part of the survey, we asked respondents more generally about deep geothermal energy and related topics and provided answers on a 7-point Likert scale (1: "don't agree at all" to 7: "totally agree"). Where internal consistency was at least acceptable (Cronbach's alpha > 0.7), we combined several items into a single scale (Cronbach, 1951). Specifically, we asked respondents about their perceptions of the risk of induced seismicity due to deep geothermal energy (Cronbach's alpha $= 0.87$, $N = 3$); their support for building deep geothermal energy projects (Cronbach's alpha $= 0.81$, $N = 4$); their trust in the authorities, scientists, and deep geothermal energy operators involved (Cronbach's alpha $= 0.90$, $N = 3$), their agreement with the Swiss energy strategy or German energy turnaround; their willingness to accept induced seismicity in exchange for significantly lower electricity prices (Cronbach's alpha $= 0.90$, $N = 2$), their knowledge of their monthly energy costs, their willingness to pay a premium for electricity derived from deep geothermal energy projects, their attitude towards climate change (Cronbach's alpha $= 0.72$, $N = 4$); and socio-demographic variables. Items were, in part, adapted from (Dermont et al., 2017; Palmgren et al., 2004; Pidgeon and Spence, 2017).

Table 3 displays Swiss and German respondents' attitudes towards DGE and related topics. Accordingly, Swiss respondents rated their knowledge levels about deep geothermal energy as being significantly higher and indicated more positive attitudes toward and higher levels of support for deep geothermal energy as compared to German respondents. Swiss respondents perceived induced seismicity risks as being significantly lower and were also significantly more likely to accept them as compared to their German counterparts. Trust was significantly lower among German respondents than among Swiss respondents. Even though German respondents indicated a significantly higher knowledge of their energy costs, Swiss respondents were significantly more willing to pay a premium for electricity derived from deep geothermal energy.

Table 2
Deep geothermal energy scenarios presented to respondents based on Knoblauch and Trutnevyte (2018) and Schenler (2015). Our translation from the German original, which can be found in Appendix A1.

Deep geothermal energy plant 1	Deep geothermal energy plant 2	Deep geothermal energy plant 3	Deep geothermal energy plant 4
Electricity for 5000 households is continuously being produced. No heat will be provided or sold. The price of electricity is ca. 0.26 euro/kWh.	Electricity for 5000 households is continuously being produced. No heat will be provided or sold. The price of electricity is ca. 0.26 euro/kWh.	Electricity for 5000 households is continuously being produced. In addition, heat for 3000 households is provided and sold. Large amounts of carbon-dioxide (ca. 7 million tons/year) can be saved. Electricity can be sold at half price (price of electricity decreases from ca. 0.26 euro/kWh to 0.13 euro/ kWh).	Electricity for 5000 households is continuously being produced. In addition, heat for 3000 households is provided and sold. Large amounts of carbon-dioxide (ca. 7 million tons/year) can be saved. Electricity can be sold at half price (price of electricity decreases from ca. 0.26 euro/kWh to 0.13 euro/kWh).
The deep geothermal energy plant is planned for a remote area, with very few houses nearby. Thus, the induced seismic damage would be very small.	The deep geothermal energy plant is planned for an urban area, near many houses and flats. Thus, the annual induced seismicity damage could reach 4 million euro.	The deep geothermal energy plant is planned for a remote area, with very few houses nearby. Thus, the induced seismic damage would be very small.	The deep geothermal energy plant is planned for an urban area, near many houses and flats. Thus, the annual induced seismicity damage could reach 4 million euro.

2.6. Analysis

We conducted conjoint and mixed multivariate statistical analyses of deep geothermal energy acceptance ratings using SPSS Version 23.0. The conjoint analysis decomposed the acceptance ratings of the deep geothermal energy scenarios into the relative importance of the deep geothermal energy attributes, as well as the part worth of the attribute levels (Backhaus, 2016). The relative importance of deep geothermal energy attributes is calculated based on the attribute's range of part worth over the summed range of all attributes' part worth. For a more detailed description, see, e.g., (Rao, 2014). A three-way $2 \times 2 \times 2$ (induced seismicity risk $\times$ benefit $\times$ country) mixed ANOVA analysis of acceptance provided further insights.

3. Results

3.1. Acceptance of deep geothermal siting scenarios and related induced seismic risks and benefits

The results of the conjoint analysis are presented in Table 4. According to these results, the induced seismicity risks associated with a deep geothermal energy scenario have a decisive impact on its acceptance. The dichotomous attribute levels yield symmetrical part worth values, whereas both a low level of benefits and a high level of induced seismicity risk have negative signs. This means that refraining from using the heat from deep geothermal energy plants, as well as siting deep geothermal energy projects in urban areas, decreases the acceptance of deep geothermal energy projects. In contrast, using the heat from deep geothermal energy plants, as well as siting deep geothermal energy in remote areas, increases the acceptance of deep geothermal energy projects. The induced seismic risk and benefits affect acceptance to different degrees: in terms of impact on acceptance, the relative importance of induced seismicity risk is 2.6-fold higher than that of benefits (Table 4). This indicates that induced seismic risks outweigh the benefits of deep geothermal energy.

Table 4
Results of conjoint analysis.

Attribute	Relative importance	Level	Part worth
Benefit	28.21	High	0.303
		Low	− 0.303
Risk	71.77	High	− 1.036
		Low	1.036

Table 5 presents average acceptance ratings for the two sample regions (between-subjects measurement) and scenarios (within-subjects measurement). Across scenarios, the respondents expressed a rather neutral attitude in terms of their acceptance ratings ($M = 3.92$, $SD = 1.25$), which ranged, on average, from $M = 2.52$ ($SD = 1.48$) for Scenario 2 in the RP sample to $M = 5.26$ ($SD = 1.42$) for Scenario 3 in the Swiss sample.

A three-way $2 \times 2 \times 2$ mixed ANOVA revealed significant main effects on the part of induced seismic risk, heat benefits, and sample region on acceptance. Accordingly, respondents accepted deep geothermal energy projects sited in remote areas with low levels of induced seismic risk significantly more than they accepted deep geothermal

Table 3
Respondents' attitude towards DGE and related topics. Please refer to text for answer scales. $^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$; n.s. – not significant; one-way ANOVA used to control for respondents' residence country.

	Swiss sample	German sample	
Sample size	$N = 404$	$N = 410$	
Item/scale	***M (SD)***	***M (SD)***	***F* (1, 812)**
Self-reported knowledge of deep geothermal energy	3.60 (1.79)	3.20 (1.79)	10.12**
General attitude towards deep geothermal energy	4.78 (1.43)	4.50 (1.37)	8.08**
Risk perception regarding deep geothermal energy	4.40 (1.33)	4.82 (1.33)	20.82***
Willingness to accept certain risks for a sustainable energy mix	4.05 (1.60)	3.61 (1.62)	14.90***
Support for deep geothermal energy	4.77 (1.21)	4.55 (1.13)	6.89**
Trust in authorities, scientists, and operators that risks remain acceptable	4.58 (1.20)	4.24 (1.16)	16.70***
Agreement with energy strategy/energy turnaround	5.15 (1.77)	5.25 (1.72)	0.67 n.s.
Agreement with urban and remote regions sharing the consequences of the energy strategy/energy turnaround	5.16 (1.44)	5.28 (1.23)	1.50 n.s.
Willingness to accept perceivable induced seismicity in exchange for significantly cheaper electricity	3.27 (1.72)	2.95 (1.60)	8.00**
Knowledge of monthly spending on energy	4.41 (1.84)	5.54 (1.60)	88.93***
Willingness to pay a premium for electricity produced from deep geothermal energy	3.10 (1.49)	2.76 (1.49)	10.34***
Attitude toward climate change	5.35 (1.11)	5.26 (1.14)	1.30 n.s.

Table 5
Average deep geothermal energy acceptance for scenarios and sample regions.

Residence country[a]	Deep geothermal energy scenario[b]	Attribute levels (benefit, risk)	*M (SD)*	*95% CI*	*N*
Full sample	Across all scenarios		3.92 (1.25)	[3.84, 4.01]	814
Switzerland	1	Low, low	4.72 (1.48)	[4.57, 4.86]	404
	2	Low, high	3.05 (1.52)	[2.89, 3.19]	
	3	High, low	5.26 (1.42)	[5.12, 5.39]	
	4	High, high	3.54 (1.71)	[3.37, 3.70]	
Germany	1	Low, low	4.37 (1.63)	[4.21, 4.53]	410
	2	Low, high	2.52 (1.48)	[2.38, 2.67]	
	3	High, low	4.98 (1.56)	[4.82, 5.13]	
	4	High, high	2.99 (1.69)	[2.83, 3.16]	

[a] Between-subjects measurement.
[b] Within-subjects measurement.

energy projects sited in urban areas with high levels of induced seismic risk, $F(1, 812) = 1071.89$, $p < 0.001$, partial $\eta^2 = 0.57$. The significant main effect on the part of benefits on deep geothermal energy acceptance ratings shows that respondents accept deep geothermal energy projects with heat benefits significantly more than they accept those projects without heat benefits, $F(1, 812) = 264.25$, $p < 0.001$, partial $\eta^2 = 0.25$.

3.2. Comparing Swiss and German acceptance ratings

The sample region and thus respondents' countries of residence significantly affected deep geothermal energy acceptance, with Swiss respondents accepting all deep geothermal energy scenarios significantly more than their counterparts from RP, $F(1, 812) = 23.76$, $p < 0.001$, partial $\eta^2 = 0.03$. The difference in acceptance between countries is most pronounced when deep geothermal energy projects are sited in urban areas and thus carry high levels of induced seismic risk.

We observed two rather weak but significant two-way interaction effects: first, there was a significant interaction effect between risk and benefit, $F(1, 812) = 4.36$, $p < 0.05$, partial $\eta^2 = 0.005$, indicating that acceptance ratings increased significantly more due to low to high levels of benefits in the remote scenarios (low induced seismic risk) than in the urban scenarios (high induced seismic risk), as depicted in Fig. 2. A further sub-group analysis showed that this two-way interaction effect was only significantly pronounced for German women, $F(1, 207) = 11.44$, $p < 0.001$, partial $\eta^2 = 0.05$, while it was not significant for Swiss women and men or German men.

Second, there was a significant interaction effect between induced seismic risk and respondents' countries of residence, $F(1, 812) = 3.87$, $p < 0.05$, partial $\eta^2 = 0.005$. Acceptance ratings for the deep geothermal energy scenarios decreased significantly more from remote, as compared to urban, deep geothermal energy scenarios (low to high levels of induced seismicity risk) in the German sample than in the Swiss sample.

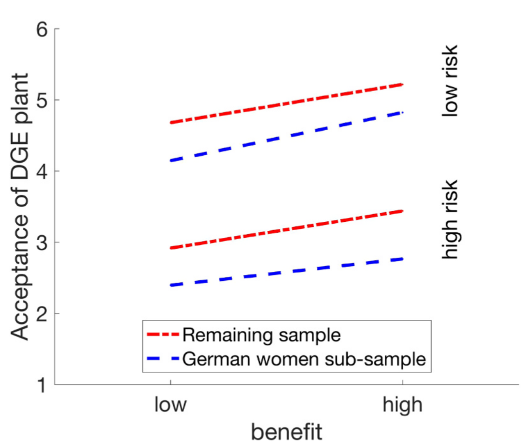

Fig. 2. Two-way interaction effect between risk and benefits for the entire sample (N = 814), most pronounced for German women (N = 208).

We controlled for respondents' residency in terms of remote or urban municipalities, which did not yield a significant effect on the acceptance ratings of the presented deep geothermal energy scenarios.

4. Discussion

Acceptance of renewable fuels is crucial in developing the future renewable energy supply. This may be especially true for deep geothermal energy because deep geothermal energy's prospects of providing low-carbon electricity and heat carry the risk of induced seismicity. Although, in theory, this resource is available almost everywhere, siting deep geothermal energy projects entails tradeoffs between induced seismic risk and heat benefits. In response to potential acceptance issues, this study investigated how the public views the tradeoff between induced seismic risks (low and high) and heat benefits (low and high) in various deep geothermal energy scenarios. We conducted a conjoint measurement in Switzerland and Germany, where the public has experience with deep geothermal energy and the governments plan to integrate deep geothermal energy into the future energy supply.

The results of the study support our first hypothesis: the public accepts siting deep geothermal energy projects in remote areas (low induced seismicity risk) more fully than siting them in urban areas (high induced seismicity risk), which is in line with the previous literature (Carr-Cornish and Romanach, 2014; Hoşgör et al., 2013). In addition, the conjoint analysis revealed that in terms of effects on acceptance, induced seismic risks have most importance among the tested attributes. This stands in contrast to previous models in which the benefits of renewable energy technologies were the best predictor of acceptance (Bronfman et al., 2012; Visschers and Siegrist, 2014). However, this result resonates with qualitative findings regarding shale gas, another subsurface energy resource (Thomas et al., 2017). Consequently, deep geothermal energy projects should be sited in remote areas, where induced seismicity risks are reduced, as highlighted in the previous literature (Bommer et al., 2015; Giardini, 2009; Majer et al., 2007; McGarr et al., 2015).

The study's second hypothesis more specifically considered siting deep geothermal energy projects in remote areas (low induced seismic risks) and how the public reacted to various levels of benefits. In line with the second hypothesis, the public accepted deep geothermal energy scenarios with high levels of benefits more fully than those with lows of benefits when the projects were sited in remote areas. According to a further comparison of means, the public is most accepting deep geothermal energy projects in remote areas with high levels of benefits. This finding refines existing research, which had previously only observed preference for siting deep geothermal energy in remote areas, without any consideration of the possible differences in benefits (Carr-Cornish and Romanach, 2014; Hoşgör et al., 2013). This finding further resonates with the observation that revenues from residual heat make deep geothermal energy economically viable and attractive (Giardini, 2009; Knoblauch and Trutnevyte, 2018; Kraft et al., 2009; Treyer et al., 2015). In practice, this means siting deep geothermal energy projects away from populated spaces or infrastructure while using residual heat. This can be realized by feeding residual heat through highly insulated pipes to industrial or agricultural applications.

This study's results do not completely support Hypothesis 3, which suggested that the public was indifferent to the various potential benefits due to siting deep geothermal energy projects in urban areas (high induced seismicity risks) because their views on “tampering with nature” (Sjöberg, 2000, p. 353) could suspend their compensatory thinking. Rather, the results suggest that the public is still responsive to various benefits when induced seismic risks are relatively high. Still, there was an interaction effect showing that sensitivity to benefits was lower in the face of high induced seismic risks. This interaction effect was especially distinct among German women. Thus, there is tentative evidence in support of Hypothesis 3. However, the specific formulation of Hypothesis 3 is not supported. The results thus indicate that when risk perceptions are especially high, such as among German women, the compensatory weighing of risks and benefits does not fully apply. Women have also previously shown higher risk perceptions than men (Gustafson, 1998). However, we are not aware of research that has further investigated gender differences in respect to phenomena such as “tampering with nature” with more detail.

Above results hold across the two sample regions, Switzerland and Germany. Thus, acceptance and the perception of induced seismic risks and benefits are stable across the two considered countries, which could be attributed to common contexts, such as nuclear phase-out and climate change discussions. However, as expected, the German public accepted all the deep geothermal scenarios less than the Swiss public. Thus, Hypothesis 4 is supported. Table 3 shows differences between the two countries that might, at least in part, explain why the public's overall acceptance of deep geothermal energy is divergent between countries. For instance, the willingness to take risks was higher among the Swiss public, which is in line with the previous literature (Volken et al., 2017). Consequently, the societal context of deep geothermal energy is crucial in its development.

This study's results have four primary limitations. First, we presented discrete deep geothermal energy scenarios to the public, which do not cover the entire range of possible deep geothermal implementations and impacts. Within the scope of the study, we could not consider all potentially crucial factors in acceptance, such as the siting process (Klain et al., 2017; Krütli et al., 2012, 2010), stakeholder engagement (Trutnevyte and Ejderyan, 2017), and the public's view of the high costs of geothermal energy and the associated noise (Volken et al., 2018). Also, the scenarios are relatively abstract and hypothetical. Thus, the public's response within the survey is indicative of, but probably different from, reality. The rather high acceptance for remote siting scenarios does not necessarily imply that such communities will automatically welcome deep geothermal energy projects. Furthermore, the survey results are a snapshot of the public's current attitudes and cannot necessarily be projected into the future (Renn, 2015). This should be kept in mind when interpreting the results. Second, the presentation and framing of induced seismicity risks and benefits could have influenced the public's perception of deep geothermal energy scenarios and, consequently, their acceptance, as observed elsewhere (Walker et al., 2014). Also, risk was only presented as a composite value in monetary units, which may have glossed over important details of risk communication, such as the probabilities and magnitudes of induced seismicity earthquakes (Knoblauch et al., 2017).

Third, our operationalization of induced seismic risks may not have triggered a feeling of “tampering with nature” and thus the strict non-acceptance of deep geothermal projects. Still, we cannot exclude the possibility that this phenomenon may apply in the case of deep geothermal energy, though perhaps to a slightly different degree than we expected. Fourth, we studied the acceptance of deep geothermal energy in isolation, whereas the ambitious energy strategies of today require a full portfolio of renewable energy technologies. Early evidence suggests that once the benefits and risks of deep geothermal energy are compared with those of other renewable technologies (Volken et al., 2018), the Swiss public will revise its technology preferences and rather rejects deep geothermal energy.

5. Conclusions and policy implications

This study investigates how well the public accepts various heat benefits when induced seismic risks are comparatively high or low. Respondents rated their acceptance of four deep geothermal energy scenarios in an online survey ($N = 814$) conducted in Switzerland and Germany. Conjoint and mixed multivariate statistical analyses show that the public prefers projects sited in remote areas and using residual heat for industrial applications. The results in Switzerland and Germany were rather similar, but the Swiss public was generally more positive. Importantly, induced seismic risks affected acceptance ratings most strongly.

Despite its limitations, this study's findings have implications for policy makers, as well as for further research. Because induced seismic risk is more important in the acceptance of deep geothermal energy than the associated benefits, efforts to reduce the risk of induced seismicity must be given the highest priority in the siting processes and participatory governance of geothermal energy. When the public perceives induced seismic risks to be high, it is less responsive to the increased benefits derived from deep geothermal energy, and this can be particularly pronounced for specific groups. Increases in compensation or community benefits will presumably not alleviate acceptance issues. The public must have a voice so that their concerns can be addressed and strategies for mutual and transparent communication can be developed (Klinke and Renn, 2010; Renn, 2008, 1999). Tailor-made risk governance can enhance the credibility and safety of such processes (Trutnevyte and Wiemer, 2017). Eventually, deep geothermal energy should also be embedded in the wider governance of the energy transition, where various energy supply alternatives need to be combined based on their pros and cons (Volken et al., 2018).

To what extent policy makers can rely on measures to mitigate induced seismicity remains to be discussed. Thus far, research on public perceptions of such mitigation measures, e. g. traffic-light systems (Bachmann et al., 2011) or the retrofitting of buildings (Bommer et al., 2015), is largely lacking (Perlaviciute et al., 2017). In addition, the context within which deep geothermal energy is implemented matters very much. Besides geological and technical aspects, policy makers should also keep in mind social site characterization (Chavot et al., 2018; Hoşgör et al., 2013; Trutnevyte and Ejderyan, 2017). If the public loses trust in policy makers and other responsible persons and deep geothermal energy becomes a contested technology, the realization and operation of deep geothermal projects will become more tedious and financially risky.

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Seigo. They also thank Sandro Bösch for helping design the figure 1.

Appendix A

A1 Original scenario description (German)

Szenario 1

Es wird kontinuierlich Strom für 5 Tausend Haushalte produziert.

Die Tiefengeothermie-Anlage wird für ein ländliches Umfeld mit wenigen umliegenden Gebäuden geplant. Dadurch wäre der Schaden durch ein Erdbeben sehr klein.

Szenario 2

Es wird kontinuierlich Strom für 5 Tausend Haushalte produziert.

Die Tiefengeothermie-Anlage wird für ein städtisches Umfeld mit vielen umliegenden Gebäuden und Wohnungen geplant. Dadurch könnte der Schaden durch ein Erdbeben jährlich bis zu 5 Millionen CHF betragen.

Szenario 3

Es wird kontinuierlich Strom für 5 Tausend Haushalte produziert.

Zusätzlich wird kontinuierlich Wärme für 3 Tausend Haushalte produziert und verkauft.

Es lassen sich so grosse Mengen Kohlenstoff-Dioxid einsparen (ca. 7 Tausend Tonnen).

Strom kann um die Hälfte günstiger verkauft werden (Strompreis sinkt von ca. 0.30 auf 0.15 CHF/kWh).

Die Tiefengeothermie-Anlage wird für ein ländliches Umfeld mit sehr wenigen umliegenden Gebäuden geplant. Dadurch wäre der Schaden durch ein Erdbeben sehr klein.

Szenario 4

Es wird kontinuierlich Strom für 5 Tausend Haushalte produziert.

Zusätzlich wird kontinuierlich Wärme für 3 Tausend Haushalte produziert und verkauft.

Es lassen sich so grosse Mengen Kohlenstoff-Dioxid einsparen (ca. 7 Tausend Tonnen).

Strom kann um die Hälfte günstiger verkauft werden (Strompreis sinkt von ca. 0.30 auf 0.15 CHF/kWh).

Die Tiefengeothermie-Anlage wird für ein städtisches Umfeld mit vielen umliegenden Gebäuden und Wohnungen geplant. Dadurch könnte der Schaden durch ein Erdbeben jährlich bis zu 5 Millionen CHF betragen.

A2 Introduction (German)

Part 1

Einleitung

Was ist Tiefengeothermie?

Geothermische Energie – auch Erdwärme genannt – ist die als Wärme gespeicherte Energie unterhalb der Erdoberfläche. Im Erdinneren sind grosse Mengen dieser Energie vorhanden. Grundsätzlich gilt: je tiefer man ins Erdinnere vordringt, desto wärmer wird es. Im Schnitt nimmt die Temperatur pro 100 Metern Tiefe um etwa drei Grad Celsius zu.

Je nach Tiefe gibt es zwei Formen der Geothermie: oberflächennahe Geothermie (Wärmepumpen, Abbildung, links) und Tiefengeothermie (Abbildung, rechts). Wir beschäftigen uns in dieser Umfrage ausschliesslich mit der Tiefengeothermie, d.h. der Wärmenutzung in einer Tiefe von mehr als 400 Metern (Abbildung, rechts).

[Abbildung]

Part 2

Bei der Tiefengeothermie wird bis in 5000 m Tiefe gebohrt. Durch die hohen Temperaturen in dieser Tiefe kann Strom produziert werden. Dabei bleibt immer etwas Wärme übrig. Wenn möglich, kann die restliche Wärme an ein Fernwärmenetz oder das Gewerbe verkauft werden. Wenn die Wärme verkauft wird, kann dafür der Strom günstiger verkauft werden. Durch Verwendung der Wärme lassen sich zudem grosse Mengen an Kohlen-Stoff-Dioxid einsparen.

Eine Tiefengeothermie-Anlage ist lokal und im Gegensatz zu anderen erneuerbaren Energien nicht von Sonne oder Wind abhängig.

Die Tiefengeothermie kann zu Erdbeben führen. Diese Erdbeben sind spürbar und können leichte Schäden an umliegenden Gebäude verursachen, z.B. feine Risse im Mauerwerk oder Verputz. Je nach Anzahl der betroffenen Gebäude fällt der Schaden grösser (viele umliegende Gebäude) oder kleiner aus (wenige umliegende Gebäude).

Bisher wurden erst wenige Erfahrungen mit dieser Art von Tiefengeothermie gemacht. Daher sind die Vorhersagen über Erdbeben, aber auch über die Energieproduktion etwas unsicher.

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