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Author(s):
Knoblauch, Theresa A.K.; Stauffacher, Michael; Trutnevyte, Evelina

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Communicating low-probability high-consequence risk, uncertainty and expert confidence: Induced seismicity of deep geothermal energy and shale gas

Theresa A. K. Knoblauch*, Michael Stauffacher, Evelina Trutnevyte

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

*corresponding author

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ABSTRACT

Sub-surface energy activities entail the risk of induced seismicity including low-probability high-consequence (LPHC) events. For designing respective risk communication, the scientific literature lacks empirical evidence of how the public reacts to different written risk communication formats about such LPHC events and to related uncertainty or expert confidence. This study presents findings from an online experiment (*N*=590) that empirically tested the public's responses to risk communication about induced seismicity and to different technology frames, namely deep geothermal energy (DGE) and shale gas (between-subject design). Three formats of written risk communication were tested: qualitative, quantitative and risk comparison (within-subject design). Respondents found the latter two the easiest to understand, the most exact, and liked them the most. Adding uncertainty and expert confidence statements made the risk communication less clear, less easy to understand and increased concern. Above all, the technology for which risks are communicated mattered strongly: respondents in the shale gas condition found the identical risk communication less trustworthy and more concerning than in the DGE conditions. They also liked the risk communication overall less. For practitioners in DGE or shale gas projects, the study shows that the public would appreciate efforts in describing LPHC risks with numbers and risk comparisons. However, there seems to be a trade-off between aiming for transparency by disclosing uncertainty and limited expert confidence, and thereby decreasing clarity and increasing concern in the view of the public.

KEY WORDS

low-probability high-consequence risk, induced seismicity, risk communication, geothermal, shale gas, energy

1. INTRODUCTION

Industrial activities to harness energy entail risks to human health, safety and the environment. Among these risks are low-probability high-consequence (LPHC) events (1). Once these LPHC events occur, they result in large damages and fatalities, as in the case of the Deepwater Horizon Oil Spill or the Fukushima Daiichi nuclear disaster. Sub-surface industrial activities for energy extraction, such as enhanced oil recovery, hydraulic fracturing, carbon capture and storage (CCS), deep geothermal reservoirs or wastewater injection from oil and gas operations are no exception (2). Such activities have recently led to an increase in induced (i.e. triggered or man-made) seismicity (3). A LPHC scenario for these sub-surface industrial activities would be to trigger seismicity on a previously unknown, tectonic fault (4,5). Some experts anticipate the most extreme consequences possible according to regional geophysics (4), e.g. an LPHC event of M7 with a probability of 10^{-7} (5,6). An M7 earthquake could cause severe damage, injuries and fatalities. However, there is no consensus on the likelihood and consequences of such LPHC events within the scientific community (5). Every sub-surface project is inherent to scientific unknowns and risks (6).

All energy decisions involve weighing benefits against tolerable risks (7,8). This is also the case for sub-surface energy activities. One such sub-surface activity is extracting deep geothermal energy (DGE). DGE is a local, environmentally friendly energy resource and is expected to contribute to energy transitions in Europe (9,10), the United States (US) (11) and elsewhere (12). Public discourse around DGE reflects these benefits, but also concerned with the risk of induced seismicity (13).

Another sub-surface activity is hydraulic fracturing for shale gas. Shale gas is a local, relatively inexpensive energy resource that can contribute to enhanced energy security and economic stability (14). It has revolutionized the energy landscape in the US and other countries might follow (15). However, shale gas production can lead to induced seismicity as well, although it is not as high as for enhanced oil recovery or injecting wastewater from oil or gas operations (16). Other concerns regarding shale gas are environmental impacts such as greenhouse gas emissions contributing to climate change (17), high water consumption, unintended emissions of substances harmful to human health and the ecosystem, and competition with renewable energy sources (14). Over 70% of respondents in a recent Eurobarometer survey would be concerned about a possible shale gas project in their vicinity (18). A large part of the US population seems to have no strong views about shale gas thus far (19), but controversies arise in affected regions (20). Concerns of US citizens include seismicity, health, environment, community issues and lack of trust towards operators (21).

When it comes to decisions concerning sub-surface activities such as DGE and shale gas, risk communication seems vital. Risk communication informs essential deliberations leading to these decisions (22) as it reveals what is at stake, who is responsible and what mitigation measures are taken. Risk communication is further a means to establish trust between affected parties (23). Ideally, risk communication also considers concerns and the risk understanding of affected parties and specifically addresses these (24). This is why US geothermal project developer guidelines (25) and a recent good-practice risk governance framework for geothermal-induced seismicity in Switzerland (26) both emphasize the need for transparent and clear communication on induced seismicity throughout projects. According to the Swiss framework, this communication should explicitly address LPHC events if planned projects are categorized as high induced seismicity risk projects, i.e. could lead to damaging events (26). Risk communication can serve as a source of information, unilaterally from project operator to the public. Preferably, it can also serve as an engagement process, multilaterally involving the operator, public and stakeholders to prevent and solve potential conflicts (26–28) .

However, until now there has been no research analyzing how the public responds to communication about induced seismicity LPHC events. It remains unclear how the public would perceive different risk communication formats for low probabilities, related uncertainty and expert confidence. Also, the ways in which public reactions might differ between sub-surface activities needs further investigation. Therefore, the present study conducts an online experiment in the German-speaking part of Switzerland with *N* = 590 respondents. It tests different written communication formats for induced LPHC earthquakes and observe how people react to information about uncertainty. The same risk communication formats were tested for both, DGE and shale gas. The next chapters outline the existing literature that led to the survey, its research questions, methods and findings.

2. LITERATURE REVIEW

2.1. Communicating LPHC events

Largely outside the field of induced seismicity, literature has reflected on the notion of LPHC events and to some extent their communication. Although no standard definition of LPHC events exists, literature suggests different, partially overlapping notions. These notions include industrial disasters (1), severe industrial accidents (29), interactions of several rare events (30), catastrophes (31), dragon kings (32) and black swans (33). Aven and Krohn (34) differentiate three types of black swans according to the level of knowledge: (i) unknown unknowns; (ii) unknown knowns; and (iii) events that have a negligible probability and are thus anticipated not to occur. The third type of black swan appropriately describes the notions of LPHC induced seismic events. Therefore, probabilistic prediction of LPHC induced seismic events, which lends itself to uncertainty, stands for subjective judgement. Further challenges of LPHC events are that low probabilities are often overestimated, their unbalanced distribution of risks and benefits among stakeholders, and their non-compliance with market-like solutions (35). For the remaining paper, LPHC events are considered corresponding to (34) as (i) being almost impossible to occur, (ii) having severely negative socio-economic consequences for health, safety and the environment, (iii) events whose assessment is fraught with uncertainty whereby experts potentially disagree.

The choice of format for communicating such LPHC events to the public seems not to be straightforward. Literature is equivocal about the ideal format to communicate low probabilities within the single-digit range or smaller, be it verbally (i.e. qualitatively) or probabilistically (i.e. quantitatively). On the one hand, qualitative statements seem intuitively applicable for the case of LPHC seismic events as Spiegelhalter and

Riesch (36) caution against quantifying risks without adequate evidence. Also, the public can have difficulties in understanding quantitative probabilities, especially when they are small (37). On the other hand, quantitative expressions are more effective than verbal ones (38) and people might assign quantitative probabilities by themselves if they are not presented(39). Further, studies have found different interpretation of qualitative statements as compared to quantitative ones because individuals interpret risk within the presented frame (40), context (41) and subjective experience. However, another study has found the variation in risk perception similarly large for qualitative and quantitative statements (42), which relativizes the effectiveness of quantitative statements over qualitative ones. Past studies have tested different risk communication formats, such as Bruine de Bruin et al. (43) and Gibson et al. (44). Findings led to recommendations such as to use both qualitative and quantitative statements to describe probabilities (45). Another recommendation is to provide an understandable reference class as it makes probability statements less ambiguous (46). Studies on interpreting qualitative versus quantitative probabilities have typically not extended to probabilities below 1 % (47). Past research found that people have difficulty in distinguishing between various extremely small probabilities and need relatively rich context information in order to grasp their actual dimension (48). Another study found that people might interpret extremely low probabilities as zero (49). In emotionally charged situations, however, the concept of “probability neglect” suggests low-probability events with significant outcomes, e.g. terrorism, are considered as disproportionally high (50). The findings of aforementioned empirical tests of risk communication formats remain to be extended to LPHC events where the need for further research is explicitly pronounced (51,52).

Another format for communicating LPHC events are risk comparisons. Risk comparisons are used to illustrate and enhance understanding of an unfamiliar risk, as they relate an unfamiliar risk to a better-known one with corresponding dimensions (53). For example, a risk comparison might relate the risk of fatalities from a chemical plant accident to the risk of dying in an automobile accident (48) or might relate induced to natural seismicity (25). Risk comparisons are rather controversial for communicating risk as they relate to subjective risk understanding and thus can cause a mismatch in the recipient's perception (54,55), limit risk to one dimension and potentially have a persuasive character (56). Putting unknown risk into context can however be helpful (57), especially if the probabilities are small (58). But the comparison's usefulness is susceptible to its framing (59) and context (48). Within their guideline for an DGE outreach program, Majer et al. (25) suggest using such risk comparisons for LPHC induced earthquakes. Yet, it has not been tested how the public responds to risk comparisons, or to qualitative/quantitative formats when communicating induced LPHC seismic events.

2.2. Communicating uncertainty and expert confidence

Uncertainty comes inherently with the assessment of LPHC induced seismicity (5,6). Literature commonly distinguishes between epistemic and aleatory uncertainty (23). Epistemic uncertainty is knowledge based and is reducible with gain of new knowledge. Aleatory uncertainty is stochastic and irreducible. This context-dependent distinction can help when interpreting and assessing risks (60). In an economic context, Knight (61) distinguishes between risk and uncertainty. According to this distinction, risk is quantifiable whereas uncertainty is not (61). There are, however, approaches to quantify uncertainty by means of probability, for instance the frequentist and the subjectivist or Bayesian approach (62). Within the frequentist approach, a probability is considered as the converging share of events when sampling would be infinitely repeated. The subjectivist approach refers to probability under consideration of the current state of knowledge and thus indicates a certain level of belief (62). In line with the subjectivist approach that is applicable to induced seismicity due to a limited number of comparable DGE and shale gas projects, the recommendations from climate change communication could be useful. The Intergovernmental Panel on Climate Change (IPCC) recommends to refer to probabilistically assessed outcomes and respective expert confidence in these outcomes in terms of level of evidence and agreement among experts (63). For the remaining paper, we follow the IPCC's recommendation and refer to uncertainty in general and, within uncertainty, to the degree of expert confidence more specifically. For induced seismicity, the limited degree of expert confidence means, for example, disagreement about the largest possible induced earthquake (64).

Whether the public benefits from knowing about uncertainties and whether this influences their perception of induced seismicity risks is important when designing risk communication material. Fischhoff and Davis (65) argue that communicating the uncertainty inherent in risk assessment leads to better decisions if the communication format has been edited for the respective audience (66). Communicating uncertainty can enhance the understanding of risk (67) as it makes numerical statements less irretrievable (36). A study on communicating uncertainty and environmental risks found that communicating uncertainty did not per se increase risk perception (68). But, within the field of climate change, framing of different uncertainty sources affected risk perception (69). Another study found different sources of climate change uncertainty not to be necessarily self-explanatory to the lay public (70). People are generally interested in learning about the unknowns (71). But whether people benefit from learning about uncertainty or whether it leaves them confused and frustrated (72) remains unclear as well as how to employ uncertainty information (73). Empirical evidence and best practices are lacking in the field of induced seismicity as well as in other fields, such as medical research (74). More specifically, the public's reaction to information about uncertainty and limited expert confidence needs further empirical research.

2.3. Evaluation of risk communication

Risk communication aims to inform decision making of, particularly but not limited to, lay people (22). Therefore, it needs to provide necessary information (75) and the audience needs to be able to understand the information in order to evaluate the risk and its uncertainty (23,44,52,75). Different objective and subjective understanding of risks can have implications on decision making or risk acceptance. Research on communicating risks of climate change showed that decision-making was based on what respondents felt they understood rather than on what they objectively understood of climate forecasts (76). Research on risks of genetically modified food found that subjective understanding was a better predictor for acceptance (77). Trust in the risk communication and its origin, be it responsible persons or organizations, also plays a role in how risk communication is perceived (23,43). Affect influences interpretation of risk communication (78) or can be evoked by it (52). This is why risk communication also needs to be evaluated in how the audience feels about it in terms of concern, worry or fear (44,43); whether it is accessible to the audience (75); catches their attention (52); and is designed in a way that the people like it (43).

2.4. Perception of risks

How the public perceives risks does not only depend on the type or wording of the risk communication. Bodemer and Gaissmaier (79) provide a comprehensive overview of established risk perception models, such as Slovic's model with emphasis on dread and the unknown (80), and moderators in risk perception such as age, expertise, values and numeracy (79). According to Slimak and Dietz (81), worldviews, beliefs and values also influence how risks are perceived and the perception of experts and laypeople can diverge, e.g. laypeople might be more concerned about LPHC risks (81). The social amplification of risk framework (82) and its extension by the role of news media (83) conceptualizes how risks information spreads within society. According to this concept, main factors influencing public risk response are heuristics and values, social group relationships, signal value related to unusualness, and stigmatization (i.e. negative associations of risks) (82). In contrast to former explanatory approaches, Sjöberg suggests that technology attitude strongly influences risk perception (84). This means that if people favor a technology, they will basically see less risks than someone who is opposed to the technology (84). Previous attitudes might also lead people to evaluate how trustworthy the risk communication source is rather than its content (85).

For the case of induced seismicity, a recent study by McComas et al. (86) investigated public perception of earthquakes and found that people react more negatively to man-made than to natural earthquakes causes. Further, prior experience with earthquakes does not seem to matter in how people evaluate the risk of an induced earthquake (86). Considering the variety of factors influencing risk perception, it becomes clear that the public evaluates risk communication in a broader context. Therefore, the generalizability of findings for risk communication from one technology to another and from one context to another is challenging. A starting point for transferability of findings would be to investigate how the public reacts to the same risk, described in identical wording but for different technologies.

3. RESEARCH QUESTIONS

What is lacking from current research is a better understanding of how the public perceives different risk communication formats, information about uncertainty and expert confidence for induced seismic LPHC events from different sub-surface activities. The present study aims to address these four research questions:

i. How do different formats of written risk communication of induced seismicity affect the public's perception of this risk communication in terms of understandability, trust, and concern? We distinguish between three formats: qualitative, qualitative and quantitative, qualitative and quantitative with risk comparisons.

ii. How does a statement of uncertainty and limited expert confidence affect the public's perception of this risk communication in terms of understandability, trust, and concern?

iii. How does the risk communication format affect the public's perception of the risk of induced seismicity?

iv. To what extent does the technology, such as DGE and shale gas, affect the public's perception of the identical risk communication material?

These research questions have encouraged the design of a survey experiment with the public in the style of previous empirical studies on testing risk communication, e.g. Bruine de Bruin (43,87), Gibson (44).

4. METHOD

4.1. Sample

In total, 602 respondents that were recruited through an access panel completed the survey. Because of unrealistically short answering times, answers of 12 respondents were excluded from analysis leading to 590 respondents. Respondents were from the German-speaking part of Switzerland, ranged in age from 18 to 69 years (*M* = 43.74, *SD* = 13.96), and *n* = 299 (50.7%) were female. The majority of respondents completed vocational school (43.6%, *n* = 257), followed by college or university education (20.7%, *n* = 122), with 6 % indicating at least some compulsory education. Compared to the average Swiss population, the sample was slightly older than the Swiss average (*M* = 41.37 years) (88), representative for the Swiss gender ratio of female (50.5%) and male (49.5%) (88) and slightly more educated than the Swiss population (more respondents with college or university degree or secondary education and less respondents with completed compulsory school) (89).

4.2. Risk communication experiment

In order to compare and contrast the public's perception of different risk communication materials, an experimental approach was chosen. To provide a realistic setting, the experiment was implemented online as sub-surface energy project operators often inform the public through this medium. The survey asked respondents to imagine that a site had been chosen for a DGE or shale gas project 5 km away from their community. One risk of such projects was induced seismicity. The operator had finalized a risk study about induced seismicity. Federal environmental authorities and independent experts had approved the risk study. The operator was required to inform the affected community about the risk of induced seismicity on a website. Next, respondents received one out of six risk communication materials that was based on publicly available induced seismicity risk assessments of real sub-surface energy projects (5,90,91). Seismologists had reviewed this risk communication material for plausibility. Risk estimates for induced seismicity referred to one week of drilling and operations, such as DGE reservoir stimulation or hydraulic fracturing for shale gas. This time period, one week of drilling and project operations, was emphasized in the beginning of the risk communication as one study reported ambiguity when interpreting probabilities without clear base rate (46).

The exact same risk information was manipulated for experimental design in two dimensions: format (three levels), statement of uncertainty and limited expert confidence (two levels), and presented for two types of technology (two levels). This resulted in 12 experimental groups (between-subject design, see Table). The key components of the survey are presented in detail in the Appendix.

4.2.1. Risk information formats (three levels)

Qualitative format

The qualitative format (Table) represented the base case for all other formats. The LPHC events were described in purely verbal terms whereas probabilities were expressed by means of the IPCC's likelihood scale (63) and magnitudes of seismic events were expressed by means of the European Macroseismic Scale 1998, EMS - 98 (92). The qualitative format consisted of four risk estimates: (I) micro-earthquakes that are too small for humans to be felt are virtually certain; (II) an earthquake that is lightly noticeable for humans is unlikely; (III) an earthquake that is strongly felt and can cause slight damage (e.g. hair-line cracks or falling of small pieces of plaster) is exceptionally unlikely; and (IV) an earthquake that is severely felt and can cause serious structural damage to average houses (e.g. large cracks in walls, falling of gable parts) is even more unlikely than that, thus also exceptionally unlikely.

Quantitative format

The quantitative format (Table) provided numeric probabilities and earthquake magnitudes in addition to the qualitative format. To facilitate readability in this low probability range, probabilities rather than frequencies were used due to fewer zeros. Literature is ambiguous on the supremacy of frequencies over probabilities (75). Hence, probabilities seemed more fitting in this case. Seismic magnitudes referred to the Richter-scale (generic magnitude M) which is commonly used (93). Providing both, qualitative and quantitative risk information, corresponds to suggested best practice in risk communication (45). Thus, the qualitative sentences were extended with corresponding numbers: (I) none; (II) 5 % chance of magnitude 3 on Richter-scale; (III) 0.01 % chance for magnitude 5 event on Richter-scale; (IV) 0.001 % chance for magnitude 6 event on Richter-scale.

Risk comparison format

The risk comparisons format illustrated the seismic event probability with examples of other, well-known hazards in addition to the qualitative and quantitative format. Examples of these hazards were taken from the Swiss governmental or private online resources (94,95). The probabilities were normalized in terms of area (assumed community’s diameter 5 km) and time (one week). The qualitative and quantitative sentences were extended with risk comparisons: (I) none; (II) as likely as a lightning strike in the community within one week; (III) as likely as a tornado in the community within one week; (IV) as likely as an airplane crash in the community within one week.

4.2.2. Uncertainty and limited expert confidence (two levels)

One half of the risk communication materials (Table) did not include any statement about uncertainty or expert confidence, e.g. Table . The second half of communication materials included such a statement, e.g. Table I. The statement told respondents that processes in the underground cannot always be predicted. This is why forecasts are very uncertain. The experts agree about the good quality of the risk study, but they do not agree on the exact probabilities and the largest possible event.

4.2.3. Technology frame (two levels)

Fluid injection used for DGE and shale gas induces seismicity in similar ways (96). Hence, identical risk estimates were assumed in this study to be applicable for both DGE and shale gas. The first half of the risk communication materials introduced respondents to a hypothetical DGE project, the second half introduced respondents to a hypothetical shale gas project. Section A3 in the Appendix shows the technology description used in the survey.

4.3. Procedure and measurements

Respondents were randomly assigned to one of the 12 experimental conditions. The survey consisted of 10 parts. Depending on their experimental condition, respondents received a short introduction about either DGE or shale gas. It informed respondents about the energy resource, how it differs from better-known energy resources (i.e. heat pumps or conventional gas), and how the energy is captured. The introduction included a visualization that corresponded to the written information. A question with four items was used to assess whether respondents knew any DGE or shale gas projects, whether they knew about the technology, and whether they were interested in learning more about it. Then, a five-item scale introduced by Schweizer-Ries et al. (97,98) assessed respondents' acceptance of a potential EGS project or, respectively, shale gas project in their region. The scale's internal consistency was excellent (Cronbach's alpha = 0.94, *N* = 5). Respondents were able to go back to the introduction of the technology in case they had not read the information thoroughly at first. A “don't know” option was also added.

Within the experimental block of the survey, respondents received one of the six risk communication materials (Table) and reported how they agreed with five items measuring the dependent variables: (a) the information is clear and easy to understand, (b) the information is trustworthy, (c) the information is concerning, (d) the information is exact, and (e) I like the information. Respondents reported their answers on a seven-point Likert scale (1= “totally disagree” to 7= “totally agree”). A “don't know” option was added to the seven-point Likert scale, too. After recoding of the concern variable, the dependent variables yielded an overall scale with good internal consistency (Cronbach's alpha = 0.81, *N* = 5). Following this question, an open item asked for potential comments or questions regarding the information. Afterwards, a five-item scale with good internal consistency (Cronbach's alpha = 0.84, *N* = 5) assessed the respondents' risk perception of induced seismicity. Its items assessed whether respondents found the risk of induced seismicity difficult to estimate; substantial; too high; controllable; and if it was the respondent's decision, would he or she allow a DGE or, respectively, a shale gas project in the region. An open item asked respondents about their concerns regarding DGE or, respectively, shale gas projects. Three items assessed how much respondents trusted experts, the project operator and federal environmental authorities after the given information.

The next part of the survey assessed respondents' experience with seismicity: (a) whether they had experienced an earthquake; (b) if yes, what was the highest magnitude; (c) whether respondents were insured against damages caused by seismicity; and (d) three items assessed respondents' earthquake preparedness, showing good internal consistency (Cronbach's alpha = 0.86, *N* = 3). The scale developed by Fagerlin et al. (99) assessed respondents' subjective numeracy using six-point semantic differentials. The scale yielded good internal consistency (Cronbach's alpha = 0.81, *N* = 8). Lastly, respondents reported socio-demographic variables such as age, community size, federal state, property ownership, household size and children under 18. An open item asked for final questions or remarks. We finally thanked the respondents and emphasized the project's fictitiousness.

4.4. Analysis

Three-way analyses of variances (ANOVAs) were conducted to study the effects of written risk communication format, uncertainty and limited expert confidence statement and technology on respondents' perception of the risk communication and of induced seismicity between experimental conditions. When effects were significant at $\alpha = 0.05$, Bonferroni post-hoc tests were used. Two-way interaction effects were considered and are reported if they reached significance level of $\alpha = 0.05$. "Don't know" answers were coded as missing values.

5. RESULTS

5.1. Experimental check

The twelve experimental conditions were balanced in terms of age, *F*(11, 578) = 1.10, *p* = 0.36; numeracy, *F*(11, 578) = 0.79, *p* = 0.65; education, *F*(11, 578) = 0.28, *p* = 0.99; how much respondents knew about the respective technology, *F*(11, 578) = 0.61, *p* = 0.82; how interested they were in learning more about the technology, *F*(11, 578) = 0.91, *p* = 0.53; sex, χ^2 = 10.10, *p* = 0.52; ownership of earthquake insurance, χ^2 = 19.38, *p* = 0.62; whether they experienced an earthquake, χ^2 = 25.78, *p* = 0.26; earthquake preparedness *F*(11, 578) = 0.91, *p* = 0.53, whether respondents owned their house or flat, χ^2 = 10.00, *p* = 0.53; whether they had children *F*(11, 578) = 0.75, *p* = 0.53; and how many people lived in their household, *F*(11, 578) = 0.91, *p* = 0.82.

5.2. Risk communication formats

As shown in Table III, the risk communication format (qualitative, quantitative or risk comparison) had a significant effect on how exact respondents found the risk information material, *F*(2, 558) = 10.56, *p* < 0.001. According to Bonferroni post-hoc testing, respondents found the quantitative format significantly more exact than the qualitative format (*M* = 4.93, *SD* = 1.45 vs. *M* = 4.29, *SD* = 1.66), *p* < 0.001. Also they found the risk comparison format more exact than the qualitative format (*M* = 4.90, *SD* = 1.49 vs. *M* = 4.29, *SD* = 1.66), *p* < 0.001. There was no significant difference between the quantitative and the risk comparison formats. The risk communication format had a significant effect on how much respondents liked the risk information material, *F*(2, 564) = 6.29, *p* = 0.002. According to Bonferroni post-hoc testing, respondents liked the quantitative format significantly more than the qualitative one (*M* = 5.10, *SD* = 1.49 vs. *M* = 4.65, *SD* = 1.62), *p* = 0.01. Also, respondents liked the risk comparison format significantly more than the qualitative format (*M* = 5.15, *SD* = 1.43 vs. *M* = 4.65, *SD* = 1.62), *p* = 0.003. But there was no significant difference between the risk comparison format and the quantitative format. Similarly, the risk communication format had a significant effect on the summarizing scale that added means of the dependent variables, *F*(2, 539) = 6.11, *p* = 0.002. Bonferroni post-hoc testing revealed a significant difference between the quantitative format compared to the qualitative format (*M* = 4.85, *SD* = 1.11 vs. *M* = 4.54, *SD* = 1.21), *p* = 0.035, and risk comparison format compared to the qualitative format (*M* = 4.94, *SD* = 1.09 vs. *M* = 4.54, *SD* = 1.21), *p* = 0.002. Respondents found the quantitative and risk comparisons format clearer and easier to understand than the qualitative format, *F*(2, 569) = 3.23, *p* = 0.039. However, Bonferroni post-hoc testing was not significant. The risk communication format had no significant effect on how trustworthy or concerning respondents found the risk communication (note that trustworthiness and concern refer to risk communication material and not to the DGE or shale gas project itself).

5.3. Statement of uncertainty and limited expert confidence

As shown in Table III, respondents found the risk communication material with uncertainty and expert confidence statement significantly less clear and easy to understand than risk information material without it (*M* = 5.48, *SD* = 1.49 vs. *M* = 5.79, *SD* = 1.22), *F*(1,567) = 7.05, *p* = 0.008. Also, respondents found risk communication material with uncertainty and expert confidence statement significantly more concerning than without it (*M* = 4.48, *SD* = 1.63 vs. *M* = 4.19, *SD* = 1.65), *F*(1,564) = 4.31, *p* = 0.038. There was a significant interaction effect between format and uncertainty on how concerning respondents found the risk communication material, *F*(2,564) = 4.31, *p* = 0.029. This means that respondents perceived risk comparisons with uncertainty and expert confidence statement less concerning than the two other formats, although they found risk comparisons without uncertainty more concerning than the two other formats. Including a statement of uncertainty and expert confidence had no significant effect on how much respondents trusted the information, how exact they found it, how much they liked it or on the summarizing scale.

5.4. Perceived risk of induced seismicity

The risk communication format had no significant effect on how respondents perceived the risk of induced seismicity itself. However, among the single items of the risk perception scale, adding uncertainty and expert confidence statement had a significant effect on how controllable respondents perceived the risk. They found the risk significantly less controllable when knowing about uncertainty and expert confidence as compared to not knowing about it ($M = 3.47$, $SD = 1.52$ vs. $M = 3.72$, $SD = 1.47$), $F(1,568) = 3.91$, $p = 0.048$. Respondents also found the risk of induced seismicity more often as too high when a statement on uncertainty and expert confidence was included. This was different to not including it $F(1,568) = 3.451$, $p = 0.064$ (n.s.). There was a significant interaction effect between format and uncertainty on how substantial respondents found the risk, $F(2,564) = 4.25$, $p = 0.015$. This means that respondents found the risk more substantial for the qualitative and quantitative format than for risk comparisons with uncertainty and expert confidence, although they found the risk more substantial for risk comparisons without uncertainty.

5.5. Technology framing

Presenting the identical risk communication for two different technologies, DGE and shale gas, had a significant effect on how respondents perceived this communication

(Table IV). Respondents trusted the risk communication material for shale gas significantly less than for DGE ($M = 4.65$, $SD = 1.66$ vs. $M = 5.11$, $SD = 1.46$), $F(1,551) = 11.65$, $p = 0.001$. They found the exact same risk communication significantly more concerning for shale gas than for DGE ($M = 4.60$, $SD = 1.65$ vs. $M = 4.07$, $SD = 1.60$), $F(1,564) = 15.71$, $p < 0.001$, and liked it significantly less for shale gas than for DGE ($M = 4.76$, $SD = 1.60$ vs. $M = 5.18$, $SD = 1.42$), $F(1,568) = 10.532$, $p = 0.001$. Similarly, technology had a significant effect on the summarizing scale ($M = 4.59$, $SD = 1.17$ vs. $M = 4.98$, $SD = 1.20$), $F(1.538) = 14.50$, $p < 0.001$, in that DGE scored better than shale gas. The technology had no significant effect on how clear and easy to understand or trustworthy respondents found the risk communication.

Considering preconditions, respondents were rather unfamiliar with both technologies ($M = 2.37$, $SD = 1.61$) with no significant difference between DGE and shale gas. Respondents were modestly interested in learning more about both technologies ($M = 4.61$, $SD = 1.69$) with no significant difference between DGE and shale gas. When asked to report projects known to them, respondents in the DGE condition referred predominantly to Swiss projects that had been also discussed in media (13). Respondents in the shale gas condition referred predominantly to the USA. Before they were given risk communication materials on induced seismicity, respondents accepted shale gas projects in their region significantly less than DGE projects ($M = 3.47$, $SD = 1.70$ vs. $M = 5.02$, $SD = 1.36$), $t(481) = 11.41$, $p < 0.001$, measured on the acceptance scale introduced by Schweizer-Ries and colleagues (97,98).

After the respondents read through the risk communication material, technology had a significant effect on all risk perception items thus also on the summarizing risk perception scale. It assessed that respondents perceived the risk of induced seismicity to be significantly higher for shale gas than for DGE (*M* = 4.81, *SD* = 1.13 vs. *M* = 4.19, *SD* = 1.14), *F*(1, 589) = 43.832, *p* < 0.001. Respondents trusted experts significantly more in the DGE than in the shale gas condition (*M* = 4.87, *SD* = 1.48 vs. *M* = 4.49, *SD* = 1.70), *t*(588) = 11.41, *p* = 0.002. Similarly, respondents trusted operators significantly more in the DGE than in the shale gas condition (*M* = 3.76, *SD* = 1.57 vs. *M* = 2.96, *SD* = 1.59), *t*(588) = 6.18, *p* < 0.001. There was no significant difference regarding trust in authorities between the two conditions.

6. DISCUSSION

Sub-surface energy activities entail the risk of induced seismicity including low-probability high-consequence (LPHC) events. Good-practice guidelines for project operators have recommended to evaluate and communicate such LPHC events to the public before and throughout the planning of the projects (25,26). The affected communities, of course, might be interested in learning about such risks too. Existing literature lacks empirical evidence of how the public reacts to different written communication formats about LPHC risk, related uncertainty and limited expert confidence, in general and for the specific case of induced seismicity. This study presents an online experiment (*N* = 590) that empirically tested the public's response to different written risk communication formats about induced seismicity, to uncertainty and expert confidence information, and to different technology frames, namely DGE and shale gas.

The main findings are threefold: First, as compared to the qualitative risk communication format, respondents find the quantitative and risk comparison format significantly more exact and like it significantly more. Respondents also perceive the quantitative and risk comparison format as clearer and easier to understand, although this result is not significant. Apparently, quantified probabilities help respondents to understand the risk communication, which attests numbers a certain effectiveness as already argued (38). Contrary to findings from Gurmankin et al.(100), adding numbers does not have a significant effect on trust and concern. Despite recommended caution in literature about risk comparisons (54,55), they are perceived relatively well.

Second, including a statement of uncertainty and limited expert confidence makes the risk communication material significantly less clear and easy to understand and significantly increases concern. This hints at uncertainty as a source for confusion as already noticed (72). Including uncertainty also makes the risk of induced seismicity seem significantly less controllable. This is different from findings by Kuhn (68) where uncertainty has not influenced perception of environmental risk, per se. The interaction effect between format and uncertainty on concern suggests that communicating uncertainty by itself does not increase concern. It is only in combination with exact quantitative information, that it could seem contradicting and thus concerning. Nevertheless, respondents in both uncertainty conditions liked communication materials about the same. Including uncertainty in risk communication might be more challenging for the public, but might convey a more realistic feeling of the risk's complexity (67).

Third, the type of technology for which risk is communicated has a significant effect on how the public responds to identical risk communication and how it perceives the risk itself. Based on pre-existing views, respondents find the exact same risk communication significantly less trustworthy and more concerning for shale gas than for DGE. They also like the same communication significantly less for shale gas than for DGE. Further, after reading the given information of induced seismicity, the respondent still perceives the risk of induced seismicity to be significantly higher for shale gas even though the wording is the exact same as for DGE. This finding is in line with literature which suggests that attitude strongly influences how risks and risk communication are interpreted (84), and that risk perception, trust and acceptance interact (101).

In sum, the careful elaboration and testing of risk communication format and uncertainty statements are very important when designing risk communication and every effort should be put into it. However, risk communication goes beyond the careful wording and description of the risk. Its context, for instance, what technology causes the risk, strongly matters.

There are several limitations to this study. The survey's focus on risk of induced seismicity only could potentially have a bias as compared to real projects, where energy technologies are portrayed and judged more comprehensively, including various risks, costs and benefits. The choice of other risk comparisons could lead to different responses of the respondents. The comparisons used did not refer to critical infrastructure or voluntary risks, where reaction could be different (102). Among multiple ways to describe uncertainty, this study distinguished between uncertainty in general and limited expert confidence in particular. It was meaningful to capture the nature of induced seismicity well, while making it accessible to the public. However, other framings of uncertainty and its source can differently affect the public's perception of uncertainty (69). One has, of course, to keep in mind that individuals were asked in a self-contained situation. That means, it is not obvious whether people would still be less concerned without being informed about uncertainty when somebody (e.g. through the media) argues that some experts disagree with the risk information provided by the project operator. These limitations should be kept in mind when generalizing the findings of this study.

Notwithstanding the survey's limitations, the findings have implications for project operators, authorities and scientific experts involved in DGE, shale gas or other sub-surface energy projects with risk of LPHC induced seismicity. The findings also have implications for communicating LPHC risks, uncertainty and expert confidence beyond sub-surface activities, e.g. in the fields of climate change, nuclear energy or other emerging technologies bearing uncertainties. The careful wording of LPHC events and their elaboration with numbers and risk comparisons seems to be worth the effort as the public likes it and it can help the understanding. Risk comparisons are delicate, however, in that they easily have a persuasive character (56,103) and thus need to be handled mindfully. When revealing uncertainty and lack of confidence to enhance transparency (71), communicators need to be aware of the public's difficulty in understanding such information and unnecessarily increasing concern. Most importantly, the communication context, such as technology, risk issue and pre-existing opinions can lead to very different interpretations and perceptions of identical risk communication. Despite careful wording of risk communication material, attitude is crucial (84). As shown by McComas et al. (86), acceptance of induced earthquakes increases when public engagement is possible. Communication efforts should thus not only include and empirically test written communication material as in this study, but also pay close attention to values, concerns, procedural fairness (104) and trust (85).

A few suggestions for future research can be derived from this survey's findings. First, the communication of uncertainty should be further thought through and empirically tested so that practitioners can get access to robust guidelines of how to communicate transparently without unnecessarily inflating concern or frustration. Second, beyond the careful wording, risk communication for induced seismicity should be researched and empirically tested considering broader, contextual factors, such as the procedural fairness (104), siting procedures (105), and attitudes towards projects (84). Third, risk communication materials could be further tested for other technologies or risks, such as nuclear power, climate change, genetically modified food, in order to produce generalizable insight for science and risk communication.

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TABLES

Table I
Experimental conditions (C) of the survey

Format	Statement of uncertainty and limited expert confidence	Technology	
		DGE	Shale gas
Qualitative	Not included	C1	C7
	Included	C2	C8
Quantitative	Not included	C3	C9
	Included	C4	C10
Risk comparison	Not included	C5	C11
	Included	C6	C12

Table II
Qualitative format (C1, C7)

The risk study concluded for the week-long drilling and project operations in your community:

- Micro-earthquakes are virtually certain. These micro-earthquakes will be too small for humans to be felt.
- An earthquake that is lightly noticeable for humans is unlikely.
- An earthquake that is strongly felt and can cause slight damage (e.g. hair-line cracks or falling of small pieces of plaster) is exceptionally unlikely.
- An earthquake that is severely felt and can cause serious structural damage to average houses (e.g. large cracks in walls, falling of gable parts) is even more unlikely, thus also exceptionally unlikely.

Table I
Quantitative format with uncertainty and limited expert confidence (C4, C10)

The risk study concluded for the week-long drilling and project operations in your community:

- Micro-earthquakes are virtually certain. These micro-earthquakes will be too small for humans to be felt.
- An earthquake of magnitude 3 on the Richter scale that is lightly noticeable for humans has a probability of about 5%.
- An earthquake of magnitude 5 on the Richter scale that is strongly felt and can cause slight damage (e.g. hair-line cracks or falling of small pieces of plaster) is exceptionally unlikely. It has a probability of about 0.01%.
- An earthquake of magnitude 6 on the Richter scale that is severely felt and can cause serious structural damage to average houses (e.g. large cracks in walls, falling of gable parts) is even more unlikely, thus also exceptionally unlikely. It has a probability of about 0.001%.

The risk assessment is based on best available methods. Due to unpredictable reactions in the subsoil, such risk assessments carry uncertainty. Therefore, experts can disagree on the exact probabilities and the largest possible earthquake.

Table III
Effects of risk communication format

Measure	Format						*F(df1, df2)*	Post hoc (Bonferroni)
	1 Qualitative		2 Quantitative		3 Risk comparison			
	M (SD)	*n*	*M (SD)*	*n*	*M (SD)*	*n*		
Clear and easy to understand	5.42 (1.49)	188	5.74 (1.34)	195	5.72 (1.27)	196	(2, 567) 3.23*	n.s.
Trustworthy	4.69 (1.61)	181	4.97 (1.63)	192	4.98 (1.49)	190	(2, 551) 2.00	n.s.
Concerning	4.42 (1.59)	187	4.46 (1.70)	194	4.13 (1.63)	195	(2, 564) 2.58	n.s.
Exact	4.29 (1.66)	188	4.93 (1.45)	191	4.90 (1.49)	191	(2, 558) 10.56***	1-2 ***, 1-3 ***
I like the information.	4.65 (1.62)	186	5.10 (1.49)	193	5.15 (1.43)	197	(2, 564) 6.29 **	1-2 *, 1-3 **
Summarizing scale	4.54 (1.21)	178	4.85 (1.11)	186	4.94 (1.09)	187	(2, 539) 6.11**	1-2 *, 1-3 **

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; n.s. – not significant
Note: Values range from 1= “do not agree at all” to 7= “completely agree”. “Don’t know” option was coded as missing value.

Table III
Effects of including statement of uncertainty and expert confidence

Measure	Statement of uncertainty and expert confidence				*F(df1, df2)*
	Not Included		Included		
	M (SD)	*n*	*M (SD)*	*n*	
Clear and easy to understand	5.79 (1.22)	283	5.48(1.49)	296	(2, 567) 7.05**
Trustworthy	4.79 (1.56)	272	4.80 (1.60)	291	(1, 551) 1.41
Concerning	4.19 (1.65)	282	4.48 (1.63)	294	(2, 564) 4.31*
Exact	4.73 (1.59)	278	4.69 (1.54)	292	(1, 558) 0.50
I like the information.	5.02 (1.52)	281	4.92 (1.54)	295	(1, 564) 0.54
Summarizing scale	4.88 (1.09)	269	4.69 (1.20)	282	(1, 539) 3.22

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$
Note: Values range from 1= “do not agree at all” to 7= “completely agree”. “Don’t know” option was coded as missing value.

Table IV
Effects of technology framing

Measure	Technology				*F(df1, df2)*
	DGE		Shale gas		
	M (SD)	*n*	*M (SD)*	*n*	
Clear and easy to understand	5.72 (1.31)	288	5.54(1.43)	291	(2, 567) 2.83
Trustworthy	5.11 (1.46)	280	4.65 (1.66)	283	(1, 551) 11.65**
Concerning	4.07 (1.60)	286	4.60 (1.65)	290	(2, 564) 15.71***
Exact	4.81 (1.56)	285	4.60 (1.56)	285	(1, 558) 2.14
I like the information.	5.18 (1.42)	286	4.76 (1.60)	290	(1, 564) 10.53**
Summarizing scale	4.98 (1.20)	274	4.59 (1.17)	277	(1,539) 14.50***

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Note: Values range from 1= “do not agree at all” to 7= “completely agree”. “Don’t know” option was coded as missing value.