Geothermal Energy

https://doi.org/10.1186/s40517-026-00373-w

Article in Press

Participatory monitoring in geothermal projects: a combined socio-geophysical approach to seismicity, risk perception and acceptability

Received: 24 Oct 2024

Accepted: 22 Jan 2026

Published online: 07 February 2026

Judith Bremer, Jérôme Azzola, Nicola Moczek & Thomas Kohl

Cite this article as: Bremer, J., Azzola, J., Moczek, N. *et al.* Participatory monitoring in geothermal projects: a combined socio-geophysical approach to seismicity, risk perception and acceptability. *Geotherm Energy* (2026). https://doi.org/10.1186/s40517-026-00373-w

Participatory monitoring in geothermal projects: a combined socio-geophysical approach to seismicity, risk perception and acceptability

Judith Bremer[1*], Jérôme Azzola[1], Nicola Moczek[2], Thomas Kohl[1]

[1]Karlsruhe Institute of Technology - KIT; [2]PSY:PLAN GbR – Institute for Architectural and Environmental Psychology

*Corresponding author: judith.bremer@kit.edu

Key words: deep geothermal energy, public engagement, seismicity, seismic monitoring, risk perception, technology acceptance, acceptability, citizen science, participatory monitoring

Abstract

The interplay between geothermal technologies, risk perception, social acceptability and acceptance is critical in the context of geothermal energy projects. Induced seismicity is of particular concern to citizens, and the perception of seismic risk plays an important role in the acceptability of geothermal projects. Starting point for our considerations is the DeepStor research infrastructure project and observations made within this research environment. We establish a conceptual framework for participatory monitoring of seismicity in geothermal projects and explore its possible influence on socio-psychological factors related to risk perception and technology acceptability and acceptance. The participatory monitoring is based on a citizen science approach in which citizens are invited to actively participate in seismic measurements around a geothermal project using plug-and-play seismometers. The potential individual, societal and scientific implications of this approach are analyzed by introducing established participatory and social scientific concepts within the geothermal context. Our conceptual analysis suggests that participatory monitoring could effectively address seismic risk perception and acceptability by enhancing transparency, providing non-experts with first-hand experiences, and fostering informed decision-making. From a technical perspective, implementing this approach to create dense seismic networks enhances the evidence base in research projects and supports more balanced risk management strategies. This article lays the conceptual groundwork for combining social scientific and geophysical approaches and recommends citizen science demonstration projects accompanied by social scientific research to evaluate this approach. As case example, the planned implementation of the participatory monitoring approach within the DeepStor project is presented. Our findings aim to contribute

to the ongoing discourse on sustainable energy transition, risk management and governance, and the role of public participation in geothermal energy development.

Introduction

The transformation of the conventional energy system into a decarbonized and sustainable regime presents major challenges for society. The energy transition requires not only disruptive technologies for a renewable energy supply and an efficient storage, but involves also profound changes in the economy and society at both the public and private levels (Papadis and Tsatsaronis 2020; Miller et al. 2013). Technological leaps will only be possible to implement if the human factor is taken into account in a techno-sociological framework (Steg et al. 2015; Geels et al. 2017). As pointed out by Manzella et al. (2019) and Spijkerboer et al. (2022) this is also true for advancements in geothermal technologies. In this paper, we link a specific aspect of techno-scientific geothermal research to participatory and social scientific approaches.

Society's response to the energy transition and new technologies such as geothermal is multifaceted and complex (Batel and Devine-Wright 2015). It depends on particular sociotechnical configurations and are embedded within wider systemic interrelations (Stephanides et al., 2025). For the implementation of the emerging renewable energy technologies (RET), the technology's acceptability is a prerequisite. Acceptability refers to the degree to which an energy technology meets the values, norms, expectations, and ethical or social criteria of stakeholders (Moesker et al. 2024). A lack of acceptance or even opposition and protest can be a severe hindrance to the implementation of necessary infrastructures (Wüstenhagen et al. 2007; Spiess et al. 2019; Batel 2018; Meller et al. 2018). Acceptance is described as positive response towards a technology through attitudes, intentions, and behaviors, which can range from tolerance to a positive attitude or even active commitment. Conceptual models conclude that acceptance of energy technologies is a complex and dynamic construct with multiple dimensions (e.g., personal and collective; market, community, political, and societal), levels (e.g., individual, household, community, general) and factors (e.g., psychological, social, and cultural) (Upham et al. 2015). Used without deficit-based assumptions about a public that is simply lacking in knowledge, or top-down notions of public understanding, acceptance models offer a way to capture aspects of the complex cognitive, affective, and contextual dynamics underlying societal responses to new technologies.

Amongst the socio-psychological factors affecting acceptance, the perceived benefits and risks are particularly relevant. In contrast to the objective, data- and fact-based risk analysis carried out by experts, subjective risk perception involves intuitive judgments and a complex interplay between emotions and rational thought (Slovic et al. 2004). Less familiar technologies, such as geothermal energy, tend to be consistently associated with higher levels of risk perception. Personal risk assessment involves guesswork, and if personal experience is lacking, a fundamental element of risk assessment is missing, affecting the outcome of the assessment (Groot et al. 2020; Flynn et al. 2006).

Social acceptability is especially relevant to the successful implementation of deep geothermal projects. While deep geothermal technologies have great potential for contributing to the energy and heat transition for heat and power provision as well as storage from a scientific and technological perspective (Bracke and Huenges 2021; Stricker et al. 2020), they also present a particularly high potential for conflicts among RET (Kunze and Hertel 2017). Hirschberg et al. (2015) found that, at a societal level, attitudes towards deep geothermal technologies were often generally neutral or positive, in contrast to a more skeptical and negative attitude and behavior at a local level with respect to specific projects.

Perceptions and responses to deep geothermal projects are complex and community specific (Benighaus and Bleicher 2019; Chavot et al. 2018; Manzella et al. 2019). In studies, citizens express concerns mainly about possible groundwater contamination, unknown risks, and, most often, about induced seismicity (Knoblauch et al. 2019; Hoşgör et al. 2013; Cousse et al. 2021; Kluge et al. 2015; Hildebrand et al. 2022). The later refers to earthquakes triggered by human activities, which can be caused by fluid injection or extraction operations that modify the stress conditions in the surrounding geological formations. (e.g., Ellsworth 2013). On one hand, microseismicity, characterized by weak seismic events that remain unperceived at the surface, is crucial for reservoir monitoring and offers insights into subsurface behavior. On the other hand, cases of felt induced seismicity may have an impact on infrastructure, raise public concern and can jeopardize project acceptance. To manage and mitigate the associated risks, Traffic Light Systems (TLS) or more advanced implementations (Grigoli et al. 2017) provide a structured approach to risk management, using decision variables such as earthquake magnitude or peak ground velocity to trigger operational decisions. Furthermore, site-specific risk governance frameworks are increasingly used to accommodate the complexity and diverse dimensions of each project (Trutnevyte and Wiemer 2017). The interplay between induced seismicity, risk perception, and acceptability underscores the importance of robust and trustworthy seismic monitoring.

Access to information, dialogue between stakeholders, and the active involvement of citizens has been shown to contribute to constructive solutions to the challenges of the energy transition and to the successful implementation of RET (Schweizer et al. 2016). Participation has the potential to improve the quality of the projects by incorporating the knowledge and perspective of the involved citizens (Renn et al. 2017). Rohse et al. (2024) highlight that inclusive, early, and continuous societal engagement is crucial to maximizing the benefits and social legitimacy of geothermal technologies.

Research plays an important role in the energy transition and encouraging public participation in the research process could foster transdisciplinary knowledge production. Citizen science (CS) is one of several suitable formats in this regard: CS promotes participatory engagement by empowering citizens to actively collaborate with scientists in the research process to generate new knowledge that supports informed decision-making (Vohland 2021). In particular, the research format promises to unfold its full potential in transformation processes that encompass research, technology development and implementation and society (Sauermann et al. 2020; Gönner et al. 2023). However, it is far from realizing its potential in the context of energy system transformation and in geothermal research in particular. In a literature review, Gooding et al. (2024) found only nine relevant CS projects worldwide in the context of the energy transition – in contrast to numerous CS projects in ecology, biology, or astronomy. In the field of geothermal research and operation, there are, to the best of our knowledge, no scientifically documented and evaluated CS projects. It has been shown that CS has an impact on research, participants (knowledge, skills, attitudes toward science, and pro-sustainable and pro-environmental behavioral changes), and socio-political processes (Gönner et al. 2023; Zilliox and Smith 2018). But the link between CS or participatory monitoring of RET projects, risk perception and RET acceptance has not been studied explicitly yet. Several factors and existing challenges indicate that CS – among other engagement formats and factors – could have an impact on risk perception and RET acceptance. The objective of this paper is to integrate participatory monitoring within a CS framework, along with considerations of risk perception and RET acceptability, conceptually exploring the potential of CS projects to address the mentioned challenges.

The DeepStor research project, a geothermal research infrastructure planned at a campus of the research university KIT (Karlsruhe Institute of Technology, Germany) to investigate deep geothermal storage in depleted oil reservoirs (Stricker et al. 2020; Banks et al. 2021), has highlighted some of these aspects. An illustrative event from the DeepStor context is taken as a starting point of the analysis (section 2), underlining how context and risk perception can influence the public reaction to ground vibrations. The participatory and social scientific based concepts, on which the approach is based, are then outlined (section 3). These are combined with geophysical approaches to seismic monitoring in geothermal projects to propose a framework for participatory monitoring in geothermal research projects. The potential impact of participatory monitoring on risk perception and other socio-psychological factors along the impact axes of CS is outlined (section 4). Coming back to the DeepStor case, the participatory monitoring implementation in the frame of the research infrastructure is presented (section 5). Finally, we discuss chances, challenges, and limitations of the proposed framework and possible guidelines for its implementation. The findings aim to contribute to debates on sustainable energy transitions, risk management and governance, and the significance of public engagement in the research and development of geothermal energy.

Starting point: The DeepStor research environment

The research context of DeepStor

The DeepStor project is situated in the Upper Rhine Graben, a trinational region with the highest geothermal anomaly in Central Europe (Baillieux et al. 2013). These conditions offer huge potential for geothermal exploitation (Frey et al. 2022; Stricker et al. 2020). At the same time, deep geothermal projects are a contested technology in this densely populated area (Meller et al. 2018; Chavot et al. 2018). The DeepStor geothermal research project explores the technical feasibility of high-temperature heat storage within the research environment of a KIT campus, starting with an initial exploration well to be drilled to a depth of approximately 1,400 meters (Stricker et al. 2024).

This campus can serve as a model for geothermal projects in complex urban settings. The relevance of this analogy lies in the campus's scale of about 2 km^2, the number of employees of over 5000, the diversity of infrastructures, including some highly sensitive facilities, conflicting land uses (above and below ground), and the wide range of stakeholders involved. Hence, this complex and sensitive environment must be carefully considered within a geothermal risk management strategy. Moreover, the discussions and controversies regarding hazards and risks, with input from various stakeholders, mirror the broader public discourse on these issues and emphasize the need for a comprehensive dialogue approach.

To develop the infrastructure and potential future energy uses, DeepStor has conducted participatory research through a co-design project involving non-specialist KIT employees and citizens from neighboring communities. This project highlighted a high risk perception of stakeholders, the requirement for a dense monitoring network with stringent and transparent risk management schemes, and the need for collaborative solutions. Participants explicitly expressed their wish to be actively involved in future environmental monitoring activities, including seismic monitoring (Schill et al. 2021).

To illustrate the interplay between seismological observations and social responses, we describe in the following an event involving an accidental explosion on the KIT Campus North that generated ground vibrations comparable to those of a seismic event in this specific environment. The incident provided an opportunity to analyze the resulting vibrations in relation to the thresholds of the TLS designed to protect vibration-sensitive research infrastructures in the DeepStor project.

Seismological setting

Ground motion and seismic monitoring is planned to comply the recommendations and regulatory framework (Barth et al. 2015). Hence, a seismic network of eight sensors – including three-component (3C) seismometers and vibration measuring devices installed in buildings – is designed for local permanent seismic monitoring of the underground operations.

In view of the research environment with sensitive infrastructures, the thresholds of the TLS were defined based on a risk analysis and set to exceed typical requirements. According to the German regulation under the norm DIN4150-3 (DIN 2016), a peak ground velocity (PGV) of 3 mm/s in the frequency range of 1-10 Hz is taken as the threshold for damaging seismic activity. In view of the DeepStor reservoir geometry, this threshold is linked to a moment magnitude of Mw = 2.1. In comparison, the threshold for human perception (PGV of 0.3 mm/s) is estimated at a magnitude of Mw = 1. To protect existing research infrastructures with sensible experiments, a PGV of 0.05 mm/s (in the 1-40 Hz bandwidth) is proposed as a threshold of harmlessness in DeepStor. Considering an additional safety margin for sensitive research infrastructures on the campus, a PGV of 0.02 mm/s has been set as a preventive threshold for alert triggering.

The seismic network was initiated in 2021 during the planning phase of the DeepStor project, when an initial record of seismic activity and of ambient wavefields were established. This baseline provides a reference point for understanding the natural background seismicity in the region. During this initial phase, the network included one Nanometrics Trillium Compact Horizon 20 s seismometers (CNN01 in Figure 1a) and three short period Mark L4C-3D, 1 s corner period seismometers (CNN02, CNN03 and CNN06 on the map).

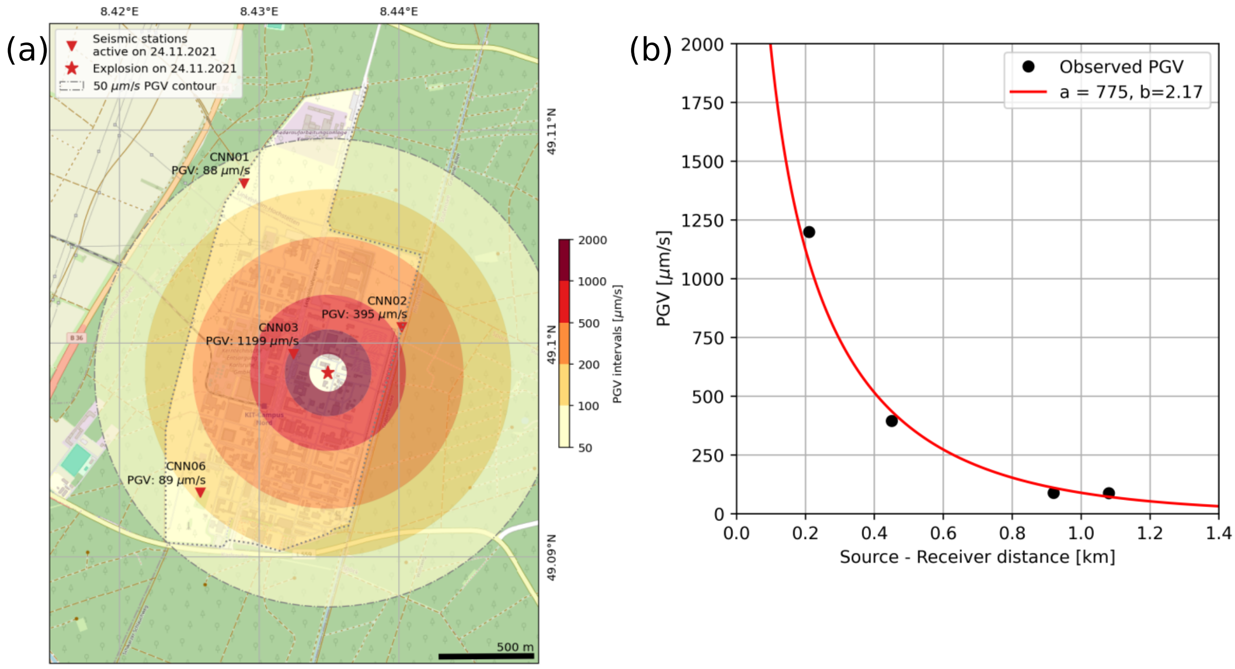

Figure 1: (a): Map of KIT Campus North with the location of the seismic stations during the early-monitoring phase (red triangles). The seismometers recorded the explosion that occurred on the campus at the location of the red star on 24.11.2021. Vertical peak ground velocity (PGV) measured at each station for the largest explosion are indicated as labels. The values are extrapolated (see panel (b)) and represented as colored rings at the scale of the campus. (b) Extrapolation of the recorded PGV values accounting for geometrical spreading and exponential amplitude decay with distance.

Accidental explosion and media coverage

Three consecutive accidental explosions occurred at the campus on 24.11.2021 during laboratory experiments. Figure 1a shows the location of the explosion on the campus and of the sensors installed and recording at the time of the event. The explosions were accompanied by loud bangs, and caused small material damages (KA news 24.11.2021).

The event received limited media coverage, which is taken as an indicator of the public reaction to this event. Only a few media outlets reported the explosion. News articles were published in local online media (Minet 11/24/2021; BNN 11/15/2021; KA news 24.11.2021; Robinson et al. 2018; RHEINPFALZ Redaktion 11/24/2021; Hofheinz 11/24/2021). The main regional radio and TV station published a short news article (SWR 11/24/2021). In social media, a video of the blast was published (r/KaIT 2021). The articles were short and written on a factual level and in an emotionally neutral style. At that time, the event was far from being perceived as dangerous by the media and the public. It appears that the event and the resulting ground vibrations were not perceived as significant or particularly dangerous.

Ground vibration of accidental explosion

Vibrations associated with the explosions could be measured across the campus and characterized in terms of Peak Ground Velocity (PGV). The measurements are illustrated in Figure 1a were the focus is on the third explosion of the series, which is the largest in terms of released energy and recorded ground vibrations. The PGV is measured on the vertical component of the 3C-seismometers. The values, ranging from 88 to 1199 mm/s, are detailed in Table 1. These recordings were characterized on a larger scale using an extrapolation model (see colored rings in Figure 1**Error! Reference source not found.**a or extrapolated trend in Figure 1**Error! Reference source not found.**b). Although the stations installed during the preparatory phase of DeepStor do not fully comply with the DIN 4150 standards for PGV measurements (2016) used in TLS, Figure 1 and Table 1 indicate that the PGV values observed after the largest explosion exceeded the alert threshold defined in the frame of the DeepStor TLS by a factor of 4.

Station name	PGV [µm/s]	Source to receiver distance [km]
CNN03	1199	0.2
CNN02	395	0.45
CNN06	89	1.1
CNN01	88	0.9

Table 1: Peak ground velocity and associated distance to the explosion.

The colored rings in Figure 1**Error! Reference source not found.**a depict interpolated PGV intervals, where the observations of Table 1 are extrapolated following 2-D geometrical spreading, according to Eq. (1). The exponential amplitude decay as a function of distance r in Eq. (1) characterizes the attenuation of surface waves. The parameters *a* and *b* are calibrated by fitting the equation to the observed PGV values (see Figure 1b), where the best fit is obtained with $b = 2.17\ \text{km}^{-1}$ and $a = 775\ \mu\text{m s}^{-1}\ \text{km}^{1/2}$.

$$\text{PGV}(r) = \frac{1}{\sqrt{r}} \bullet a \bullet e^{-b \bullet r} \quad (1)$$

Implications

Quantifying the explosion in seismic terms provides a means to contextualize it within DeepStor. It suggests that an event induced by geothermal activities with comparable ground vibrations would have had serious consequences for geothermal operations, with the likely possibility of alerting the media and local residents – as experienced, e.g., in the Landau geothermal project (Meller et al. 2018). On the seismological side, this case example underlines the significance of extensive monitoring measures for the precise characterization of seismic events. On the social scientific side, this event is interesting because of the reaction to the unforeseen but well understood and traceable event, occurring in a non-geothermal context and a familiar environment. It highlights the significance of experience, reference knowledge and trust on risk perception. These aspects correspond to some of the factors that could be constructively affected by CS and participatory monitoring in a geothermal research project, which will be discussed below based on the framework conceptualized in the following.

Social scientific concepts

This chapter lays the conceptual and methodological basis and introduces the concepts of CS, acceptance and acceptability, and risk perception. These concepts form a basis for the conceptual participatory monitoring framework presented below.

The concept of Citizen Science projects and citizen seismology

The practice of CS dates back to the early 20th century when citizens collected data in the natural environment (Lintott 2020; Guida 2019). As term and formalized concept, CS began to develop in the 1990s. It was developed in parallel from the natural sciences, with a focus on the advancement of science through data collection and scientific understanding by citizens (Bonney 1996), and from the social sciences motivated by the tense relationship between science, the public and environmental matters and risks (Irwin 1995). This indicates that the interconnected natural scientific and social scientific aspects of CS were evident from the outset.

CS has developed rapidly in recent years, driven by citizens' wish to participate in research processes and the more and more pressing need to find solutions to societal challenges. CS is widely used in natural sciences, ecology and nature conservation. There are also examples from geosciences and seismology. In the project "*Detecting Earthquakes*", citizen scientists outperformed a trained AI in identifying dynamically triggered seismic events. Using the Zooniverse platform, participants reliably detected weak local earthquakes and successfully distinguished them from noise and other signals (Tang et al. 2020). The project "*Did You Feel It?*" gathers crowdsourced reports from people who experienced earthquakes, creating maps of perceived shaking and damage (Quitoriano and Wald 2020). This data supports calibration of global earthquake loss models via the *ShakeMap Atlas (Marano et al. 2024)*.

Another reason for the strong growth and development of CS projects in recent years is the emergence of digital technologies (Bonney et al. 2014) and low-cost and user-friendly technologies (Baker 2016). These technologies facilitate access to CS projects, data collection and motivate collaborations. In geoscience, plug-and-play seismometers such as Raspberry Shake® sensors are one of those tools that are already actively used by interested laypeople around the world. They have started up to be a suitable tool in "citizen seismology", referring to a specific CS approach in seismology, incorporating citizens and schools in seismological monitoring and educational outreach projects to enhance awareness and preparation toward natural seismic hazards (Chen et al. 2020). It In a pioneering project to more accurately monitor natural seismicity, Schlupp et al. (2019) densified the permanent seismic network (RESIF) in southern Alsace, France, through citizens hosting seismometers in a cooperative framework with dialogue events and discussions. A similar network was established in Haiti with local citizens, providing critical near-field data that enabled rapid understanding of the earthquake mechanism and improved assessments of hazardous aftershocks (Corbet et al. 2023). All these projects focused on natural seismicity.

To the best of our knowledge, there is no conceptualization or documentation of a participatory monitoring network forming part of a CS project within the context of geothermal research or a geothermal plant. First examples show the usability of plug-and-play seismometers in science education around geothermal projects: In the United Downs project, local schools are provided with Raspberry Shake sensors to enhance the monitoring network (Holmgren and Werner 2021) and to involve the public via schools into the geothermal project (Farndale 2021). Azzola and Bremer (2023) used these sensors in an educational role-playing game around a geothermal plant to raise awareness and knowledge on natural and induced seismicity and seismic monitoring in geothermal projects.

A meaningful engagement of citizens through innovative tools in CS projects requires more than their engagement in data collection as in usual “contributory” CS projects. It means incorporating their ideas, experiential knowledge and concerns in “collaborative” or even “co-created” projects, in which citizens participate along the research process (Shirk et al. 2012; Senabre Hidalgo et al. 2021; Giel et al. 2024). This can bring transdisciplinary into projects to drive innovations with societal relevance (Shirk and Bonney 2018).

Turrini et al. (2018) and Gönner et al. (2023) showed that CS projects have a significant innovation potential and transformative impact along three conceptual axes:

1. The first axis refers to research itself including data acquisition, knowledge generation, increase in societal relevance, and increase in acceptance.
2. The second axis is related to the effects on participants, e.g., by learning, experience of self-efficacy, etc.
3. The third axis concerns civic participation and socio-political processes, e.g., by providing an evidence base for decision-making and transformations.

These three axes define the potential impact space for CS projects that will be considered below for the participatory monitoring of geothermal projects.

Acceptance models for renewable energy technologies

The public as a relevant factor for the implementation of RET has been studied since the 1980s (Barac et al. 1983). In the 1990s, it became clear that social acceptance is decisive for the implementation of RET. The social science concept of acceptance became one of the most politically relevant concepts in this field. Research focused on understanding the reasons for the “social gap” between a general acceptance of RET and the opposition on a local scale, and the “not-in-my-backyard” (NIMBY) syndrome (Freudenburg and Pastor 1992). The perspective paper of (Wüstenhagen et al. 2007) proposed a new model for social acceptance represented by socio-political, market and community dimensions. It set the basis for a research period in which social acceptance is regarded as a dynamic multi-level, multi-actor and multi-factor phenomenon (Batel 2020). On a citizens’ level, socio-psychological factors play a major role for the development of positive attitudes and acceptance, mainly cognition, affect and behavior (Upham et al. 2015).

A comprehensive framework for citizen acceptance of RET was proposed by Huijts et al. (2012) based on empirical data and three psychological concepts: the theory of planned behavior (TPB), the norm activation model (NAM), and theories on affects influencing attitudes. It serves as basis for case specific acceptance models to explain RET acceptance.

The TPB (green rectangle in Fig. 1) builds the backbone of the Huijt’s conceptual model and assumes that social norms, perceived behavioral control, and attitudes are determining factors for a specific behavior (Ajzen 2001; Ajzen 1991). Applied to the acceptance model, this refers to behavior towards the acceptance or rejection of a RET. Within TPB, social norm refers to influence of the judgment of persons that are significant to the individual (Cialdini and Jacobson 2021). The concept of perceived behavioral control refers to an individual's perception of their ability to control a specific behavior (Smelser and Baltes 2007; Kiriakidis 2017). This notion is closely associated with the concept of self-efficacy, which emphasizes internal factors that influence an individual's belief in their capability to execute a certain behavior. In this regard, perceived behavioral control can be viewed as a reflection of mainly external factors that shape an individual's behavior (Kiriakidis 2017). The attitude is a result of a positive or negative outcome of gain evaluations – in this case, perceived costs, risks and benefits of a RET. Attitudes are influenced not only by cognitive evaluations, but also by emotions (positive or negative affects; Fig. 1, blue mark). The NAM (Fig. 1, purple rectangle) proposes that the intention to accept is also influenced by one’s personal norms based on the awareness of consequences of a considered behavior, moral evaluations and pro-social considerations (Onwezen et al. 2013).

The factors shaping the attitude towards or against a new technology are highly sensitive to the context. This means that the involved actors, locations, and processes have a significant influence on evaluations. Trust and perceived fairness determine feelings, evaluations and finally attitudes (Fig. 1, yellow rectangle). All factors of the model are based on experiences made and knowledge acquired by citizens.

In developing a technology, it is important to consider its acceptability. This term emphasizes judgement aspects of a technology (Moesker et al. 2024): It describes the attitude towards a technology and includes moral judgements guiding the development and implementation of a technology. It concerns whether something is considered appropriate in principle, even before a specific project realization occurs. Acceptability of a technology can be defined as a condition in which the risks associated with a technology are minimal in comparison to the added value it provides. It is imperative that certain risks, particularly those related to health, safety and the environment, are eliminated or reduced to a minimum (Meller et al. 2018). While models based on acceptance are more oriented toward outcomes, acceptability considerations focus more on the development process towards a technology that is acceptable to wide parts of society or communities.

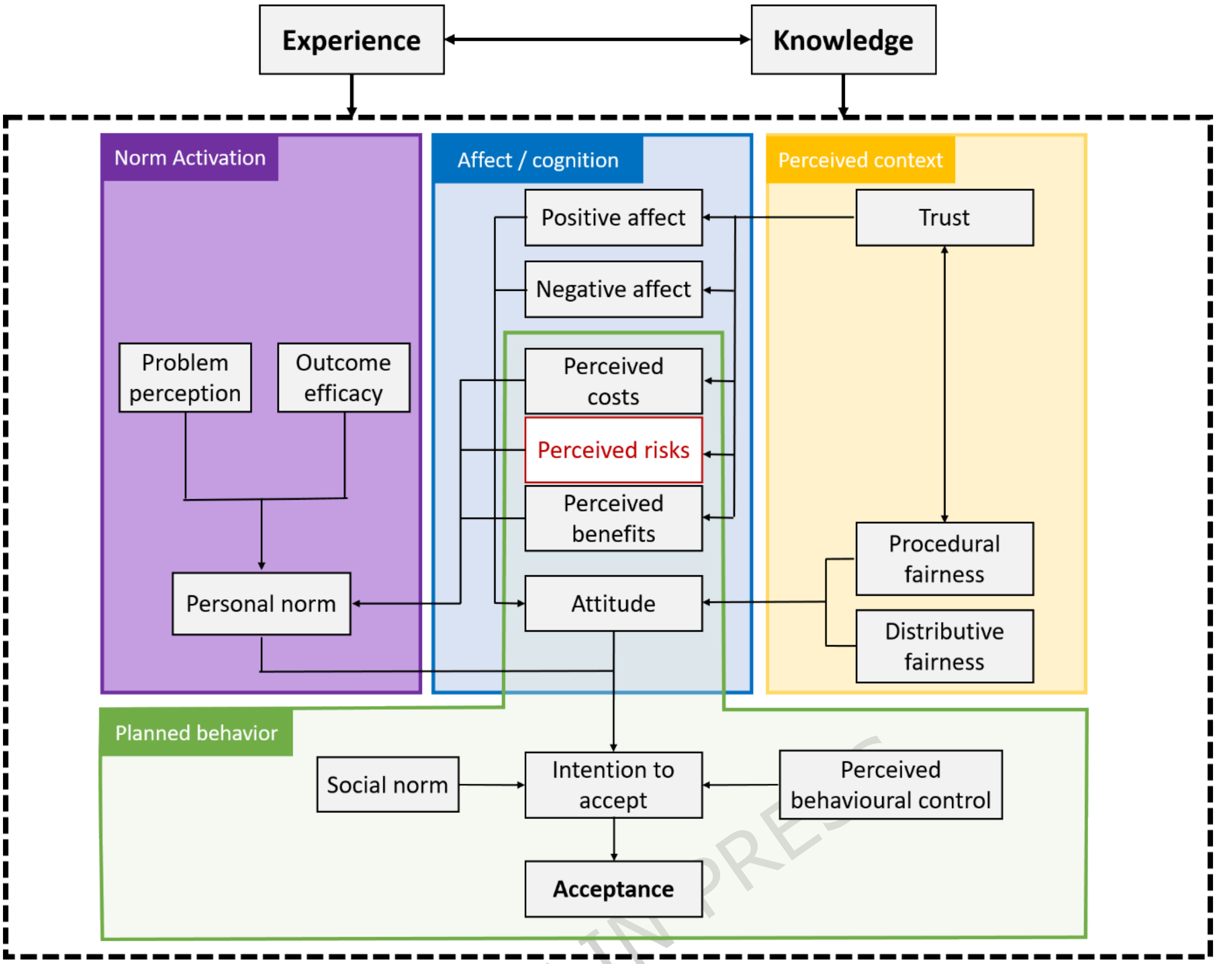

Figure 2: The framework for renewable energy technology acceptance described by socio-psychological factors adapted from Huijts et al. (2012).The underlying theories are highlighted: Theory of planned behavior (TPB; green), affect/cognition theories (blue), the Norm Activation Model (purple), and concepts on context-related perceptions (yellow). Personal experiences and knowledge have an influence on all the identified factors within the dashed line. Although not always the most important, perceived risk (red) is a central factor, particularly for specific technologies such as geothermal.

Risk perception concepts

Perceived risks play a central role in acceptability and in the above-described acceptance model (Figure 1Figure 2, highlighted in red). Moreover, there is an overlap and interconnection between socio-psychological factors influencing technology acceptance and those shaping risk perceptions. However, risk perception is a complex phenomenon, and the link between judgment and behavior has not been fully explored. A model by Renn and Rohrmann (2000) identifies four nested levels of influencing factors for risk perception, each interconnected and operating at both collective and individual levels: heuristics of information processing, cognitive-affective factors including reference knowledge, social-political institutions, and cultural background.

Risk perception at the societal level is characterized by a tension between scientific-technical risk analysis - based on probability and impact or severity - and personal risk perception, which is influenced by psychological, sociological, and cultural factors. Sometimes this difference between experts' assessments of technologies and the result of risk evaluations by the public gets large. Then, the risk associated to a certain hazard is socially amplified (or attenuated), with ripple effects spreading from the individual to other stakeholders and domains and impacting society and economy (Kasperson et al. 1988). Comparable tendencies may also be observed in the context of geothermal energy. In this case, an intensified societal dialogue is needed.

Examining deep geothermal technologies within the context of risk perception models underlines the importance of factors such as the familiarity with the technology, knowledge and experience, level of trust and benefits, unfamiliar risks and uncontrollable hazards. Prior experience and knowledge have been shown to have a strong influence on the perception of risks, as new evidence is interpreted in the light of existing beliefs (Slovic 1987). Li and Li (2023) and Midden and Huijts (2009) show that this gets particularly evident in the case of unfamiliar technologies and novel hazards and risks, and that trust in the actors and institutions involved plays a crucial role in shaping risk perception. Slovic (1987) found that perceived risks and attitudes are also strongly influenced by the perception of unknown and unfamiliar hazards and risks and by the perceived controllability and possibly catastrophic nature of a hazard.

Indeed, deep geothermal can be considered as relatively novel outside volcanic areas, and not widespread. Citizens tend to be unfamiliar with the technology and the complex underlying mechanisms. Most people lack experience with geothermal plants in their vicinity. Deep geothermal energy is associated with hazards such as induced seismicity, whose associated risks are difficult to quantify and predict. It is also difficult for untrained citizens to interpret quantitative information on (micro-)seismicity and environmental seismic noise due to lacking prior knowledge and experience. It can be assumed that the cultural-historical background also plays a role in risk perception. Gross (2013) hypothesized that the perception of the subsurface as the “unknown” plays an additional role in this context. Besides positive associations such as origin, truth and shelter, the term "deep" also has a negative and anxiety-provoking connotation: The deep functions as a projection space for the dark, the irrational, and the threatening - for forces perceived as uncontrollable (Kimmich and Müller 2020). The recent analysis of public perceptions reveals symbolic and emotional ambiguities, indicating that attitudes toward subsurface technologies are shaped by cultural as well as technical and economic factors (Lambert et al. 2025; Manzella et al. 2025). Thus, the theoretical advantage of geothermal systems being less visible on the surface may turn into a negative, as the deep underground may be perceived as something unknown and threatening.

The above-described theories and concepts suggest that deep geothermal technologies tend to be perceived as risky. Indeed, although experts' risk assessments often assign manageable risks, individuals' risk perceptions are typically higher, at least at the local level. Cousse et al. (2021), Kluge et al. (2015) and Ejderyan et al. (2019) show that this is particularly true for unknown hazards, associated with a feeling of uncontrollability and a perceived lack of information on hazards and drawbacks. This is particularly the case for induced seismicity. Knoblauch et al. (2019) conclude that the risk of induced seismicity is crucial for the acceptance of deep geothermal energy, and while the heat benefits are acknowledged, they do not fully offset the seismicity risk.

A framework for participatory monitoring in geothermal Citizen Science projects

In this chapter, we link the social scientific concepts to geophysical monitoring to establish a framework for participatory monitoring in geothermal projects. We explore its impact on factors relevant to risk perception, RET acceptability and societal dialogue. Finally, we present the planned implementation of a participatory monitoring CS project within the DeepStor framework.

Participatory geothermal projects as a means of collaboration

Research creates fundamental scientific knowledge for the development of a technology and helps to quantify risks on a scientific-technical basis. However, Renn and Rohrmann (2000) argue that this quantification is not sufficient to evaluate the acceptability of the risks associated with a technology. With regard to risk perception and its impact on risk governance, Renn et al. (2016) claim that the primary challenge involves initiating a dialogue that acknowledges scientific knowledge's limits and uncertainties and at the same time starts a learning process to address evident misperceptions. This way a legitimate interpretation framework could be collectively established. This is relevant for geothermal energy projects, especially with respect to the risk of induced seismicity. Based on above presented concepts of CS, RET acceptance and acceptability, and risk perception as well as geophysical monitoring approaches, participatory projects and collaborative monitoring in geothermal projects may be a suitable means to address this challenge.

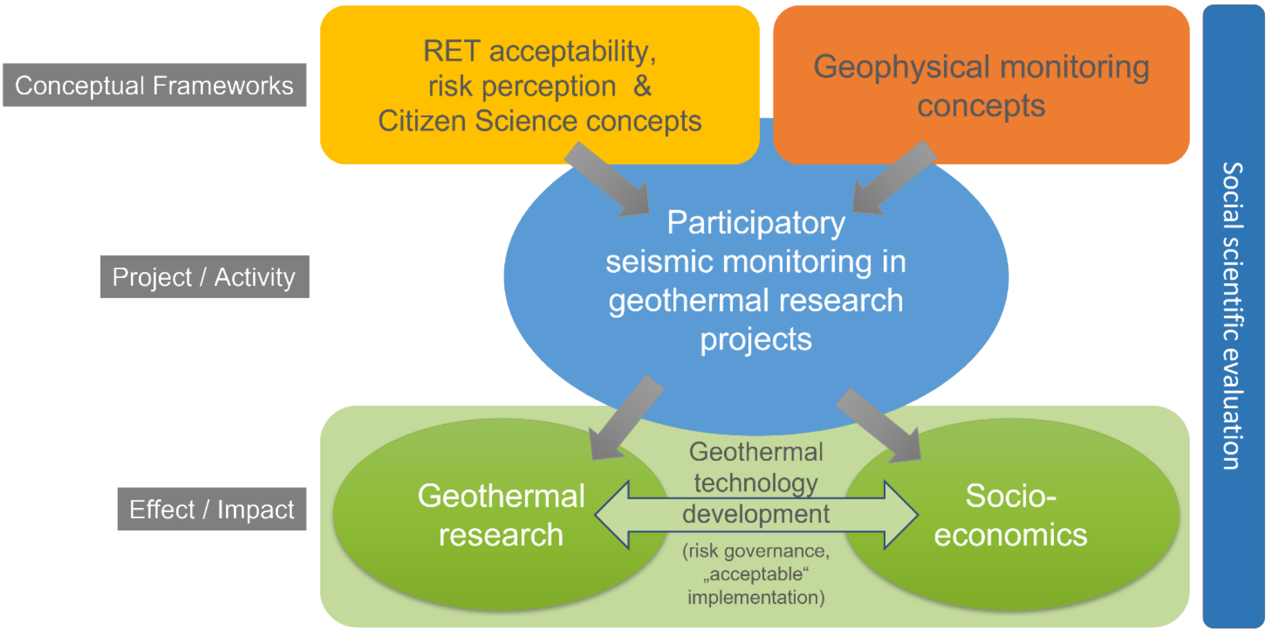

Figure 3: Participatory projects in geothermal research can bring together social scientific and geophysical approaches and have the potential to have an impact on a sustainable geothermal technology development on both the scientific-technological and the socio-economic level.

We propose that participatory projects in geothermal research could actively involve citizens in the seismic monitoring of a geothermal project by hosting cost-effective, compact and user-friendly seismometers. These could be installed in private and public spaces such as in homes, on the premises of actively involved citizens, or in schools and supervised by citizens or students. To move beyond a contributory CS project and actively integrate participating citizens into the research beyond mere data collection, we propose involving them more deeply than just hosting a sensor, thereby unlocking the broader potential of the CS approach. Workshops, the joint interpretation of measurements and research results, and joint dissemination efforts could create a framework for dialogue and collaboration. Such an approach enables deeper engagement with citizens. This way, we see potential for project outcomes with an impact on geothermal technology development on both the techno-scientific and the socio-economic side (Figure 3**Error! Reference source not found.**).

Accompanying research using social science evaluation methods is essential to assess both the conceptual and methodological foundations of a CS project, as well as to better understand participants' knowledge, attitudes, and how these may change through their involvement. Of particular interest is whether such participation influences the perception of seismicity-related risk and contributes to acceptance of deep geothermal projects, along with the broader implications these changes may entail.

Impact on risk perception and technology acceptability along the three axes of CS projects

We propose the hypothesis that engaging citizens in geothermal research projects might have an impact on RET acceptability and acceptance and risk perception factors within the three impact axes of CS projects (**Error! Reference source not found.**). Participatory monitoring as CS approach may help to define, assess and improve specific aspects of the acceptability of geothermal technologies.

Along the first axis of CS projects, such an approach could contribute to the generation of scientific knowledge by increasing the measurement density and improving the data basis. Hybrid networks combining inertial seismometers fitting legal frameworks, innovative recording techniques such as Distributed Acoustic Sensing (Azzola et al. 2023), and low-cost geophones considerably increase the density of the measurement network, which contributes to the seismic event detection capabilities and to the reliability of the processing results.

Interpreting seismic measurements requires a basic understanding of the underlying physics and geomechanics. Providing learning opportunities with adequate information material on these geophysical principles or workshops is a prerequisite for enabling citizens to play an active role in the project. It might promote scientific literacy and, by playing a meaningful part in the project, increase the sense of technical self-efficacy. This active role could enable a self-reinforcing effect for the acquisition of further knowledge and skills according to the second axis of CS projects.

Collaboration, learning opportunities, and the joint creation of new data and knowledge in a research project are supposed to be a prerequisite for building trust between the parties involved. Furthermore, through the measurement and collaborative interpretation of seismic data, citizens have the opportunity to gain reference knowledge and experience related to geothermal energy technologies and seismology that could be applied outside the CS project. It will include an understanding of the processes linked to the production of this energy source and could help individuals to develop an intuitive understanding of both microseismicity and seismicity.

Trust, knowledge and experience, in line with the concepts of risk perception and technology acceptability discussed above, strongly influence how geothermal technology risks are perceived. They affect the extent to which geothermal projects are accepted or rejected by citizens. Benefits in the first two axes enable also outcomes and impacts of CS projects to extend into the third axis, which includes the socio-economic-political level (Gönner et al. 2023). Participatory research projects bring together researchers, citizens and various stakeholders involved in geothermal projects, thus promoting dialogue and mutual understanding. Geothermal research could be more closely linked to issues of societal relevance, potentially increasing the acceptability of research and geothermal technologies. Collaborative geothermal projects including scientists and citizens could improve the evidence base for the formulation of science-informed regulations and serve as a basis to guide decision-makers on how to design acceptable geothermal projects.

Frequent exposure to geothermal through learning and research opportunities, and ideally open discussion of RET scenarios, could help to generate interest and an informed opinion on geothermal as a potential alternative to fossil fuels. Huijts et al. (2012) refer to this as "problem perception". CS projects might also have an impact beyond the directly involved participants; e.g., CS school projects could be a good multiplier in this respect (Kloetzer et al. 2021; Azzola et al. 2023).

Following the "Citizen Science Evaluation Framework" by Kieslinger et al. (2018), the project's effects should be assessed along the potential impact axes of CS and with a focus on the potential effects in **Error! Reference source not found.**. A formative evaluation (conducted during implementation) would enable adjustments at every phase of the project. Defining metrics or indicators for the success of the participatory monitoring approach will be a crucial and challenging part of the conceptual phase. The broader innovation potential of the considered CS approach should also be assessed in relation to its contribution to societal transformation and sustainability goals (Kieslinger et al. 2018; Passani et al. 2022; Schaefer et al. 2021; Moczek et al. 2021).

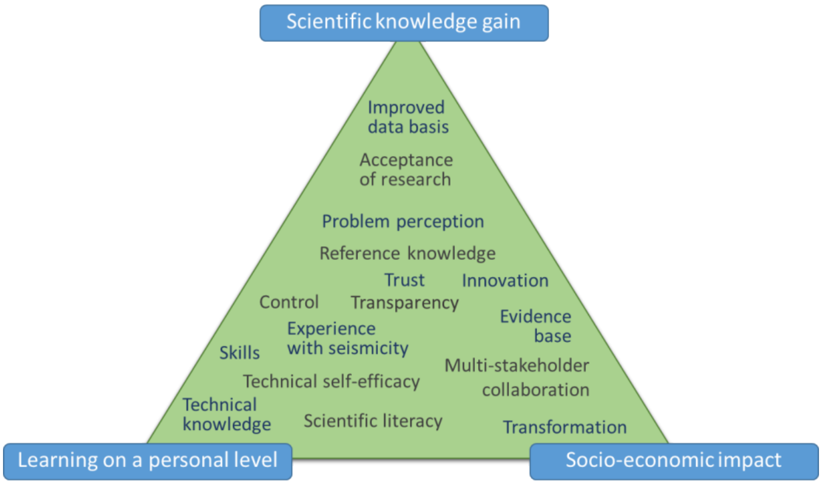

Figure 4: Factors influencing risk perception and technology acceptability in a sustainable innovation and transition process. The factors are categorized (approximately) within the three impact axes of CS according to Turrini et al. (2018) and von Gönner et al. (2023) in terms of scientific knowledge gain, learning and development on a personal level, and socio-economic effects. These factors might come into effect in research projects involving participatory seismic monitoring.

Community-deployable seismometers

To facilitate meaningful contributions from citizens to seismic monitoring, the seismometers used must be affordable, accessible, straightforward to install and simple to operate. The most widespread devices meeting these requirements with an existing broad community are Raspberry Shakes® seismometers (Raspberry Shake, S.A accessed 11/15/2025). Built on a Raspberry Pi platform, their compact size, user-friendliness and relatively low cost compared to traditional professional seismometers increase accessibility for a wide range of users, which contributes to their adoption in both amateur and professional seismology applications. In seismic monitoring frameworks, such sensors can considerably increase the density of seismic stations and enhance the spatial coverage of data collection, thereby enhancing monitoring operations and site characterization efforts. On the other hand, technical limitations include the sensor's sensitivity, which may result in less accurate recordings of low-magnitude earthquakes compared to state-of-the-art inertial seismometers, and reliance on consumer-grade components that may lead to lower durability and reliability in demanding environmental conditions. Nevertheless, previous studies by, e.g., Anthony et al. (2019) have shown that Raspberry Shake sensors can effectively support earthquake research and monitoring. Studies by Lecocq (2020), Noriega-Linares & Navarro Ruiz (2016), or Diaz et al. (2020) have demonstrated their capabilities not only in detecting natural seismicity but also in assessing seismic noise conditions. In terms of data integration, the use of low-cost seismometers within standard monitoring practices was explored to improve the density of the permanent French institutional observation network (RESIF) (Schlupp et al. 2019).

Implementation in the DeepStor project

Citizen science project setup

Based on the above-described framework, it is planned to implement a CS project with participatory monitoring of the DeepStor site. The CS project is set up in two phases. Phase 1 started during the DeepStor preparation phase and involves distributing Raspberry Shake sensors on the KIT Campus North (see **Error! Reference source not found.**a) to involve a broad range of KIT institutes and employees in the data collection process. This network includes to date thirteen Raspberry Shake 3C- geophones (RS3D), hosted by interested non-specialist employees outside the geosciences, who are not involved in the DeepStor project. Participants receive a short training on accessing and understanding the openly available online data (Raspberry Shake accessed 11/25/2025). This requires an understanding of the device and the measurement principle to clarify the measured and monitored variables. The instruction also covers the interpretation of the measurements, based on the graphical tools available on the online platform. This includes the visualization of time series in near real time as well as associated spectrograms, or daily time series. This initial sensor-distribution lays the foundation for the planned broader deployment around the DeepStor drilling site. It will serve as a testbed for evaluating and developing technical requirements, such as data transmission methods, as well as non-technical aspects, such as the recruitment and training of participants, for a successful rollout.

Phase 2 is planned to start after the evaluation of phase 1 and before the start of drilling activities. In this phase, the CS project will extend its reach to surrounding communities and include KIT Campus North to a greater extent. It is planned to densify the network within a 4 km radius around the drilling site, thereby fostering CS collaborations within the local community context (see **Error! Reference source not found.**b). A further perspective is the integration of the RS3D data streams into standard monitoring practices of the DeepStor project. Basis for the recruitment of participants will be a stakeholder analysis to ensure that a broad and diverse range of societal groups is addressed – including those who may hold critical views on geothermal energy.

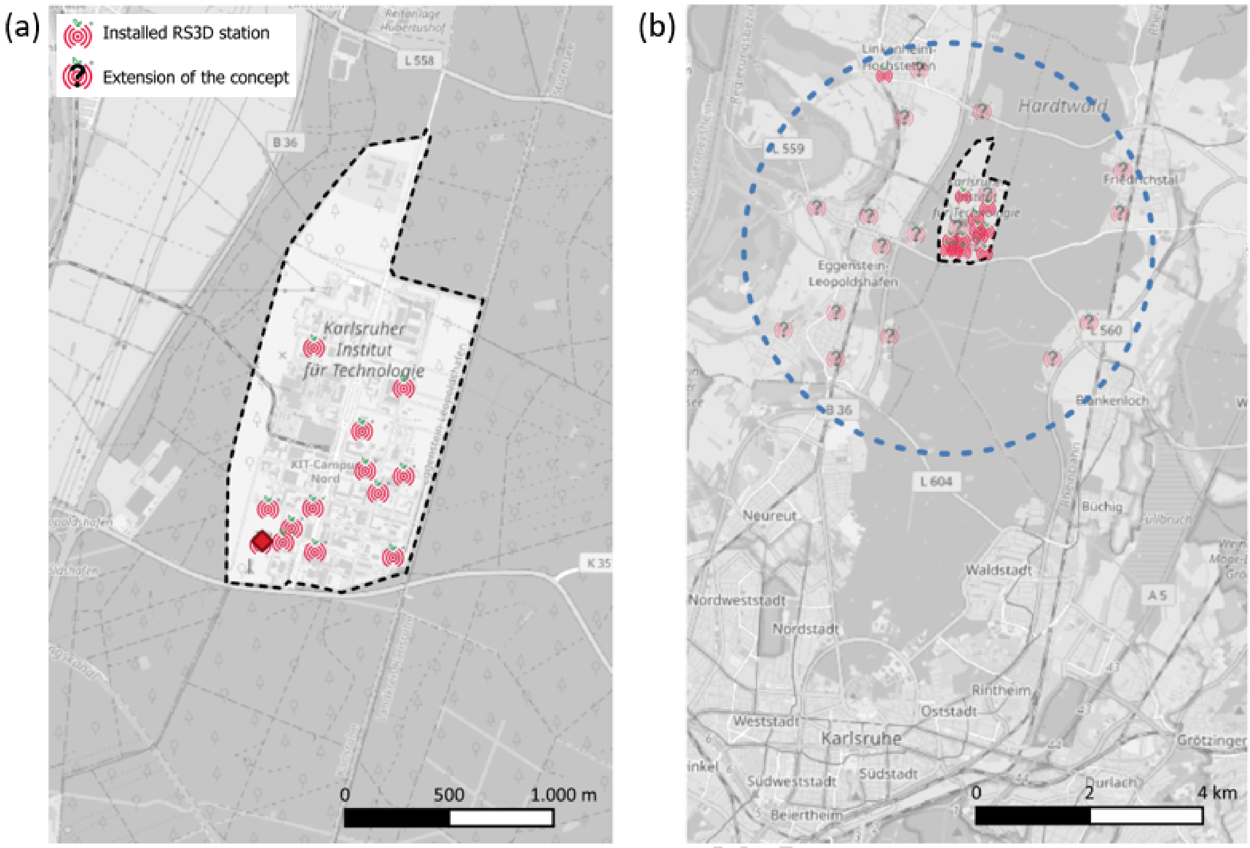

Figure 5: Spatial distribution of seismic citizen scientists' stations in the context of the DeepStor project. Panel (a): Zoom on the KIT Campus North area (dashed black boundary), highlighting installed 3C-Raspberry Shake sensors (RS3D). The location of the DeepStor project is shown by a red diamond. Panel (b): Overview map showing also hypothetical station locations within a 4 km radius (blue dashed circle) around the KIT Campus North.

Monitoring benefits

In addition to the legal framework introduced above ("**Error! Reference source not found.**"), the local network of RS3D strengthens the seismic network and increases its density. To illustrate the possible monitoring benefits by an extension of the legally required network, the sensitivity of the presently installed network of RS3D is evaluated based on ambient seismic wavefield measurements. **Error! Reference source not found.**a presents a probabilistic representation of Power Spectral Densities (PSD) measured between 0.1 and 50 Hz with successive 30-minute-long data-windows over October 2025 at station R985B. The measurement characterises the recording environment of the station. The characteristic trend, illustrated by the 90th percentile of individual PSDs (black curve) shows a relatively high level of ambient noise on the KIT campus where the station is located, which results in higher amplitudes above 1 Hz. The sensitivity of the Raspberry Shake network is inferred from comparable ambient vibration measurements at all stations, following the methodology of Pezzo et al. (2013). **Error! Reference source not found.**b shows the spatial variation of the minimum detectable magnitude, derived from two-weeks long recordings on the vertical component of each RS3D. The analysis focuses on the 5–40 Hz frequency range, which is critical for detecting small-magnitude seismic events at reservoir depths. **Error! Reference source not found.**b shows that the theoretical detection threshold at the DeepStor site itself reaches down to a magnitude of Mw = 0.7. These results highlight the promising capabilities of the Raspberry Shake network, despite a noisy recording environment and its use of low-cost sensors. While the final monitoring system will rely on a dedicated array of more standard and higher-grade sensors, the Raspberry Shake network could serve as a valuable complementary asset that enhances spatial resolution, improves system redundancy, and offers early-stage insight during the project's preparatory phase.

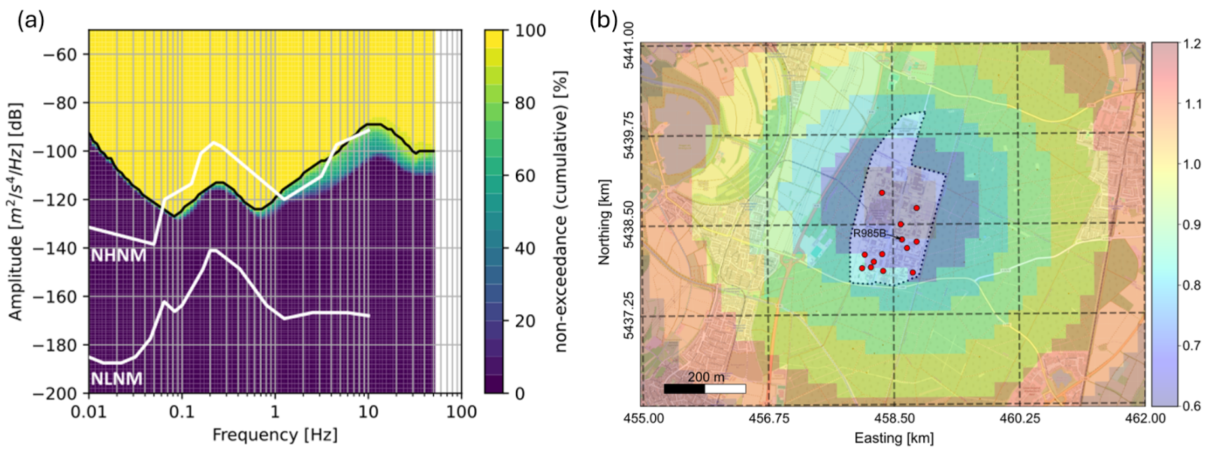

Figure 6: (a) Probabilistic Power Spectral Density (PPSD) to assess the noise-characteristics of the station R985B installed on the KIT Campus North and measured with one-month recordings over October 2025. The characteristic trend, illustrated by the 90th percentile of individual PSDs (black curve), is compared with standard high (NHNM) and low (NLNM) noise models, shown as white lines (Peterson 1993). (b): Detection threshold of the Raspberry Shake network from noise measurements at all stations. The color background shows the minimum moment magnitude MW detectable by the RS3D network for hypocenters at the depth of the reservoir (1260 m below ground level). The black dashed line shows the border of the campus. Coordinate system: UTM Zone 32N, EPSG:32632.

Collaboration between CS participants

In the collaborative CS project that is planned to start in project phase 2, citizens and researchers will work together in four interrelated work packages with co-design elements (Figure 7). Work Package 1 involves the installation and operation of a seismometer network by scientific experts, complemented by Raspberry Shake sensors deployed by citizen scientists to densify the network. They will be also invited to contribute to the understanding of data by documenting events with high vibration intensity recorded by their station and by relocating the sensor to enhance the characterization of local site responses. Work Package 2 on the seismological evaluation is primarily conducted by scientific experts and encompasses programming, data processing, and the integration of heterogeneous data sources. Interpretation of the resulting datasets is carried out collaboratively in workshops, allowing citizen scientists to contribute to drawing conclusions. Work Package 3 centers on the co-design of digital tools, including a mobile application and web-based platforms, to facilitate data input, access and visualization. Suitable data processing levels of the highly complex and large data sets as well as presentation formats on websites etc. are determined jointly. Project outcome including recommendations for future projects and politics are jointly discussed. Work Package 4 addresses the socio-economic and environmental-/socio-psychological dimensions of the project. Experts conduct a conceptual and methodological evaluation, also in cooperation with citizen scientists, along the three above-described core dimensions of CS – learning, knowledge production, and societal impact – also with a focus on risk perception and technology acceptance. This includes identifying and addressing project dynamics constructively. Furthermore, the project's outputs, outcomes, and broader impacts are assessed, with conclusions and recommendations developed in collaboration with citizen scientists.

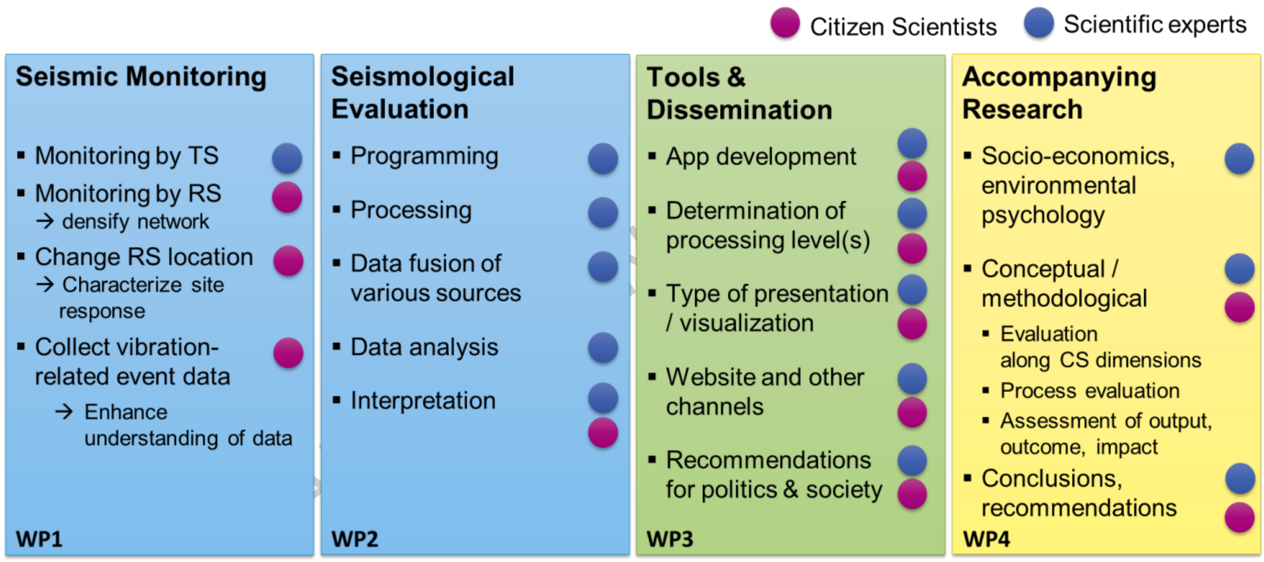

Figure 7: Concept for a participatory CS monitoring project focusing on geothermal infrastructure, using the DeepStor project around the KIT North Campus as an example. The concept comprises four work packages on seismic monitoring and data analysis (blue), tool development and dissemination (green), and accompanying social science research to evaluate the project (yellow). The main actors in the various activities are indicated by the purple and blue circles.

Discussion

Socio-technical frameworks: Importance and limitations

Collaborative monitoring initiatives in CS or similar formats are often planned from a technical perspective and without knowledge of underlying social scientific concepts. This is the first time that participatory seismic monitoring in geothermal research is discussed in relation to CS, risk perception and RET acceptance concepts. Defining this link is important for understanding the underlying mechanisms and potential implications on geothermal development and implementation as a complex socio-technical process.

Technology acceptance models are a means of analyzing the implementation process of RETs. The aim is to gain insight into underlying mechanisms and societal concerns, minimize misperceptions, and promote informed opinion-forming and conflict resolution, thus enhancing society's ability to manage risks in an effective and efficient manner (Renn and Rohrmann 2000; Renn et al. 2016; Klinke et al. 2021). However, it is important to keep in mind the models' limitations and potential misuse (Upham et al. 2015).

It shall be noted that the term "technology acceptance" has been criticized for its resonant "deficit" and top-down character. It suggests in particular that something needs to be "fixed" and citizens' opinions need to be corrected (Upham et al. 2015; Batel and Devine-Wright 2015; Batel et al. 2013). Individual judgments – whether positive or negative – must, of course, remain respected and autonomous. Moesker et al. (2024) highlight the importance of shifting the focus from outcomes (acceptance or not) to the processes that shape them. Thus, developing sustainable, "acceptable" technologies is put in the focus. Chavot et al. (2018) argue that a primary focus on risk perception for acceptability presents a distorted picture and proposes to take into account concepts of social identity and social worlds. Stephanides et al. (2025) suggest to move beyond focusing on public acceptance and societal acceptability and emphasize the need for a systemic approach to societal responsiveness that challenges prevailing paradigms, which still insufficiently capture the social complexities of the transition.

The present study focuses on CS. Nevertheless, it is not always straightforward to differentiate the CS format from others, and this is also the case with the presented concept. The plurality of CS is high and the methodological landscape of CS is diverse and subject to constant further development (Vohland 2021; Haklay et al. 2021; Schrögel and Kolleck 2019). Furthermore, there is a certain overlap to the multitude of participatory research frameworks depending on the focus of the research project, the participants, and its aim, which can also evolve during the project (Vaughn and Jacquez 2020; Schrögel and Kolleck 2019; Bruckermann et al. 2025; Schrögel 2025). Often, a variety of participatory formats and methods are used in practical implementations. There is also a large overlap or close link between research methods and approaches and specific formats in implementation, such as co-design workshops as part of various participatory research project formats (Bruckermann et al. 2025).

Analyzing dynamics and impacts: The need for contextual social science evaluation

When applied to a specific technology such as geothermal, the presented general risk perception and acceptance concepts should be evaluated in social scientific studies based on implemented CS projects. The used acceptance framework by (Huijts et al. 2012) was conceptualized as basis for case specific acceptance models and is widely recognized in the literature. However, it should be kept in mind that such a general framework may make individual adaptations necessary depending on the studied technology, the framework conditions and the research questions being addressed. These adaptations may include additional causal relationships between variables, as in a study on hydrogen fuel station acceptance (Huijts et al. 2014), the explicit differentiation between local and general acceptance when examining public acceptance of RET in the German energy transition (Emmerich et al. 2020), or a focus on the neighborhood scale (Morton et al. 2025).

Likewise, this framework needs to be examined in the context of actual geothermal projects, and case-specific acceptance models are necessary to adequately capture the particularities of geothermal technologies and their socio-technical environments. For example, local aspects have been proven to be important in geothermal projects (Pellizzone et al. 2015; Chavot et al. 2018; Manzella et al. 2025) and this should be taken into account in corresponding concepts. While the work of Cousse et al (2021) and other studies provide an important basis for analyzing risk perception and acceptance of geothermal technologies, social scientific studies accompanying various local projects would be beneficial to analyze the explanatory power of the proposed models, such as the framework of Huijts et al. (2012), and, if necessary, to modify them or assess the significance of certain factors. Milani et al. (2024) state that research on the acceptance of RET within psychology is still relatively underdeveloped compared to more established areas of environmental or social psychology.

Contemporary research emphasizes the significance of risk perception and attitudes, as well as the critical roles of risk communication, participation, and trust in shaping a certain risk acceptance, management, and governance (Klinke et al. 2021). The approach in this paper uses the hypothesis that information, dialogue and participation as well as personal learning and making own experiences with seismicity and ambient noise in a transparent research project tend to lower the high seismic risk perception and enlarge trust. However, it is also possible that the constant preoccupation with the topic of seismicity and the awareness of a constant seismic background noise increases the perception of risk. As Azzola and Bremer (2025) have shown, preliminary indications of this possibility were obtained in the context of a school project. This underscores the significance of three key considerations: (i) establishing appropriate processing levels and employing data visualization techniques, (ii) incorporating a discussion on risk management strategies, and (iii) integrating social scientific research that encompasses both short-term and long-term effects.

In parallel to the social scientific evaluation along the potential CS impact axes, the levels of process evaluation and project dynamics should be considered. Process evaluation involves a systematic examination of the procedures and activities within a project or programme. The aim is to evaluate and understand the implementation and execution of the measures and how they contribute to achieving the project objectives. This should also critically reflect on the project's conditions and resources, such as infrastructure, personnel, volunteer management, communication, materials, and scientific impact (e.g., number of publications). Impact evaluation, on the other hand, focuses on individual changes among the researchers and the participating citizen scientists. However, it is essential to ensure that the participating citizens are not treated as mere objects of science, but can contribute to the project and the evaluation in a relatively equal manner through various formats. Experimental study designs that leave respondents unclear about the research questions (such as before-and-after designs in attitude research) conflict with the understanding of transparency (Moczek et al. 2021). In addition to the effects on citizens, the collaboration between institutional scientists and volunteers, as well as the impacts on the scientists themselves, should also be considered.

Technical considerations and broader applications

Future geophysical research needs to verify that plug-and-play seismometers can meet the requirements for reliable participatory measurements in geothermal monitoring network – both from the geophysical and societal perspective. A geophysical question is the type of installation to be recommended, including the location of the sensor in the building, to ensure the sensitivity of the measuring station. Another aspect is how best to combine data from a small number of professional sensors with numerous low-cost sensors in a network of increased density to increase its sensitivity and the quality of the resulting measurements. From a science communication perspective, the question is how to visualize the complex signal of seismometers to make it understandable and interpretable to non-professionals. This task can be addressed through collaboration with participants of a CS project.

This study approaches CS initiatives in the field of geothermal energy from the angle of seismic monitoring, considering plug-and-play seismometers as an example of interface between scientists and citizens. However, the study's insights also apply to other formats and subjects. Plug-and-play seismometers could also be suitable tools for other educational and participatory formats such as workshops, co-design projects, transformative project courses, real-world laboratories, or low-threshold formats such as school projects, workshops, Science Cafés, and open marketplace formats (Azzola et al. 2023). For effective learning, the chosen format should include the possibility of learning together with opportunities for direct social interaction

(Gönner et al. 2023). Some of these formats could reach more people than a CS project, which requires cooperation over a longer period and a rather high level of commitment.

Participatory monitoring in geothermal research projects could also be applied to the monitoring of other environmental variables, such as radon air concentration. Radon is a naturally occurring radioactive gas that can accumulate along fracture zones in crystalline rocks (Seyis et al. 2010). Similarly, participatory monitoring could also contribute to track groundwater quality and levels, or acoustic disturbances.

Participatory monitoring could be one, albeit not the only, element to 'locally anchor' a geothermal project, a prerequisite for a successful implementation highlighted by Chavot et al. (2018). This supposes that cooperation is not initiated for the sake of appearances, but is honestly practiced, with joint interpretation of the collected data and findings, and joint drawing of conclusions. It is essential that discussions provide space for differing opinions, perceptions and assessments, and an autonomous opinion-forming. On the legislative side, it could be beneficial if more dynamic frameworks for local projects beyond certain minimum standards could be offered, so that solutions developed jointly by scientists and citizens can be realized.

CS projects conducted within the framework of publicly funded research initiatives offer a relatively protected space for open dialogue, collaboration and opinion-forming, as they are not driven by profit orientation and economic constraints. This setting fosters mutual trust and creates favorable conditions for reflective and inclusive engagement processes — and also provides a strong basis for accompanying social science research aimed at evaluating the participatory monitoring approach and understanding participation dynamics, knowledge gain, learning processes, and social responses. Once scientifically evaluated, participatory seismic monitoring could be also applied in local operable geothermal projects beyond research in a defined framework of duties and rights of involved parties.

Conclusions

Participatory seismic monitoring in CS projects has the potential to impact the complex process of risk perception of induced seismicity, which is a key concern in geothermal projects, as well as the acceptability of geothermal technologies. It can be hypothesized that, by measuring seismicity in a research project in collaboration with other citizens over a period of time, citizens can gain experience in evaluating measured ground vibration values. This could empower laypeople to develop an informed perspective on the seismic risks associated with geothermal projects, potentially counteracting the amplification of risk.

Conceptual models suggest that the proposed CS projects could have multifactorial effects via the experience of technical self-efficacy, the specification of problem perception, perceived behavioral control, and multi-stakeholder collaboration. In particular, participants could build up reference knowledge, gather own hands-on experiences, and possibly advance and strengthen trust in research and geothermal risk management strategies. The interdisciplinary linking of the underlying participatory social scientific concepts with geophysical approaches proposes a more nuanced understanding of public engagement and supports the development of socially robust approaches in deep geothermal energy. The next step is to carry out CS demonstration projects based on the presented concept and evaluated by social sciences.

Recent insights into systemic societal responsiveness (Stephanides et al. 2025) suggest that participatory approaches should not only be implemented at the operational level of geothermal projects, but already at the research stage of pilot projects. This early integration strengthens the legitimacy and societal relevance of research activities. In line with this consideration, CS seismic monitoring projects, and other participatory formats using this approach, offer an opportunity to enrich research and the process of defining acceptable risks, managing risks, and designing and implementing accepted risk governance strategies. First, the proposed participatory monitoring could improve the evidence base for science-informed risk assessment. Secondly, experts and lay people have the opportunity to learn from each other and to bring together the techno-scientific perspective based on theories and data with the subjective perspective influenced by values, attitudes, social influences and cultural identity (Zwick 2002). Merging perspectives could contribute to more robust risk management strategies, which do not merely perceive the public as a source of risk.

CS developed from both the natural sciences and the social sciences. CS projects on seismic monitoring could also incorporate influences from both disciplines and benefit both. From a scientific perspective, participatory projects such as CS have the potential to foster scientific research and the development of risk management strategies. From a socio-economic perspective, CS is one element of empowering communities, aligning geothermal research and demonstration projects with local framework conditions and supporting the implementation of this RET.

The widespread implementation of geothermal systems to utilize the unexploited potential of deep geothermal reservoirs for the energy transition necessitates the participation of various stakeholders at different stages of the project. There are numerous potential avenues for engagement, particularly in the context of geothermal projects undertaken by municipal utilities. These include initiatives such as science education, collaborative decision-making processes and co-design, as well as the exploration of co-ownership models, which have the potential to significantly enhance both procedural fairness and distributive fairness of geothermal projects (Manzella et al. 2025). CS formats for seismic monitoring, as well as similar participatory monitoring formats, could be one piece of the puzzle in implementing demonstration projects for the energy transition, not as a top-down process, but as a constructive, collaborative innovation process.

References

Ajzen I. The theory of planned behavior. Organizational Behavior and Human Decision Processes. 1991;50(2):179–211. doi:10.1016/0749-5978(91)90020-t.

Ajzen I. Nature and operation of attitudes. Annu Rev Psychol. 2001;52:27–58. doi:10.1146/annurev.psych.52.1.27.

Anthony RE, Ringler AT, Wilson DC, Wolin E. Do Low-Cost Seismographs Perform Well Enough for Your Network? An Overview of Laboratory Tests and Field Observations of the OSOP Raspberry Shake 4D. Seismological Research Letters. 2019;90(1):219–28. doi:10.1785/0220180251.

Azzola J, Bremer J. Applied geophysics in schools to raise knowledge and awareness about geothermal energy and seismology. Societal Impacts. 2025;5:100116. doi:10.1016/j.socimp.2025.100116.

Azzola J, Thiemann K, Gaucher E. Integration of distributed acoustic sensing for real-time seismic monitoring of a geothermal field. Geotherm Energy. 2023;11(1):1–31. doi:10.1186/s40517-023-00272-4.

Baillieux P, Schill E, Edel J-B, Mauri G. Localization of temperature anomalies in the Upper Rhine Graben: insights from geophysics and neotectonic activity. International Geology Review. 2013;55(14):1744–62. doi:10.1080/00206814.2013.794914.

Baker B. Frontiers of Citizen Science. BioScience. 2016;66(11):921–7. doi:10.1093/biosci/biw120.

Banks J, Poulette S, Grimmer J, Bauer F, Schill E. Geochemical Changes Associated with High-Temperature Heat Storage at Intermediate Depth: Thermodynamic Equilibrium Models for the DeepStor Site in the Upper Rhine Graben, Germany. Energies. 2021;14(19):6089. doi:10.3390/en14196089.

Barac C, Spencer L, Elliott D. Public awareness of renewable energy: a pilot study. International Journal of Ambient Energy. 1983;4(4):199–211. doi:10.1080/01430750.1983.9675888.

Barth A, Schmidt B, Joswig M, Baisch S, Fritschen R, Gaucher E, et al. Empfehlungen zur Erstellung von Stellungnahmen zur seismischen Gefährdung bei tiefengeothermischen Projekten. Forschungskollegium Physik des Erdkörpers (FKPE), AG Induzierte Seismizität 2015. doi:10.5445/IR/1000045751.

Batel S. A critical discussion of research on the social acceptance of renewable energy generation and associated infrastructures and an agenda for the future. Journal of Environmental Policy & Planning. 2018;20(3):356–69. doi:10.1080/1523908X.2017.1417120.

Batel S. Research on the social acceptance of renewable energy technologies: Past, present and future. Energy Research & Social Science. 2020;68:101544. doi:10.1016/j.erss.2020.101544.

Batel S, Devine-Wright P. Towards a better understanding of people's responses to renewable energy technologies: Insights from Social Representations Theory. Public Underst Sci. 2015;24(3):311–25. doi:10.1177/0963662513514165.

Batel S, Devine-Wright P, Tangeland T. Social acceptance of low carbon energy and associated infrastructures: A critical discussion. Energy Policy. 2013;58:1–5. doi:10.1016/j.enpol.2013.03.018.

Benighaus C, Bleicher A. Neither risky technology nor renewable electricity: Contested frames in the development of geothermal energy in Germany. Energy Research & Social Science. 2019;47:46–55. doi:10.1016/j.erss.2018.08.022.

BNN. Explosion auf dem Gelände des KIT Campus Nord. Badische Neuste Nachrichten. 11/15/2021.

Bonney R. Citizen science: A lab tradition; 1996.

Bonney R, Shirk JL, Phillips TB, Wiggins A, Ballard HL, Miller-Rushing AJ, Parrish JK. Citizen science. Next steps for citizen science. Science. 2014;343(6178):1436–7. doi:10.1126/science.1251554.

Bruckermann T, Henke J, Schrögel P, Sturm U. Die Vielfalt der Partizipation in der Forschung: Begriffe, Methoden und Perspektiven; 2025.

Chavot P, Heimlich C, Masseran A, Serrano Y, Zoungrana J, Bodin C. Social shaping of deep geothermal projects in Alsace: politics, stakeholder attitudes and local democracy. Geotherm Energy 2018. doi:10.1186/s40517-018-0111-6.

Chen KH, Bossu R, Liang W-T. Editorial: The Power of Citizen Seismology: Science and Social Impacts. Front. Earth Sci. 2020. doi:10.3389/feart.2020.610813.

Cialdini RB, Jacobson RP. Influences of social norms on climate change-related behaviors. Current Opinion in Behavioral Sciences. 2021;42:1–8. doi:10.1016/j.cobeha.2021.01.005.

Corbet A, Fallou L, Calixte N, Hurbon L, Calais E. From a Seismological Network to a Socio- Seismological One: A Citizen Science Experiment in Haïti to Reduce Seismic Risk: Analysis of a “Small Box” that Can Do a Lot. CSTP. 2023;8(1):2. doi:10.5334/cstp.481.
Cousse J, Trutnevyte E, Hahnel UJ. Tell me how you feel about geothermal energy: Affect as a revealing factor of the role of seismic risk on public acceptance. Energy Policy. 2021;158:112547. doi:10.1016/j.enpol.2021.112547.
Del Pezzo E, Bianco F, Castellano M, Cusano P, Galluzzo D, La Rocca M, Petrosino S. Detection of Seismic Signals from Background Noise in the Area of Campi Flegrei: Limits of the Present Seismic Monitoring. Seismological Research Letters. 2013;84(2):190–8. doi:10.1785/0220120062.
Diaz J, Schimmel M, Ruiz M, Carbonell R. Seismometers Within Cities: A Tool to Connect Earth Sciences and Society. Front. Earth Sci. 2020. doi:10.3389/feart.2020.00009.
DIN 4150-3:2016-12: Erschütterungen im Bauwesen - Teil 3: Einwirkungen auf bauliche Anlagen 2016.
DIN. DIN 4150-3:2016-12, Erschütterungen im Bauwesen_- Teil_3: Einwirkungen auf bauliche Anlagen 2016. doi:10.31030/2579353.
Ejderyan O, Ruef F, Stauffacher M. Geothermal energy in Switzerland: Highlighting the role of context. In: Geothermal energy and society. Cham: Springer, 2019; 2019.
Ellsworth WL. Injection-Induced Earthquakes. 0036-8075. 341(6142):1225942. doi:10.1126/science.1225942.
Emmerich P, Hülemeier A-G, Jendryczko D, Baumann MJ, Weil M, Baur D. Public acceptance of emerging energy technologies in context of the German energy transition. Energy Policy. 2020;142:111516. doi:10.1016/j.enpol.2020.111516.
Farndale H. GEL RASPBERRY SHAKE PROJECT: A Bridge Between Industry, Local Communities and Citizen Scientists 2021.
Flynn R, Bellaby P, Ricci M. Risk Perception of an Emergent Technology: The Case of Hydrogen Energy. Forum qualitative Sozialforschung 2006. doi:10.17169/fqs-7.1.58.
Freudenburg WR, Pastor SK. NIMBYs and LULUs: Stalking the Syndromes. Journal of Social Issues. 1992;48(4):39–61. doi:10.1111/j.1540-4560.1992.tb01944.x.
Frey M, Bär K, Stober I, Reinecker J, van der Vaart J, Sass I. Assessment of deep geothermal research and development in the Upper Rhine Graben. Geotherm Energy 2022. doi:10.1186/s40517-022-00226-2.
Geels FW, Sovacool BK, Schwanen T, Sorrell S. Sociotechnical transitions for deep decarbonization. Science. 2017;357(6357):1242–4. doi:10.1126/science.aao3760.
Giel KE, Bremer J, Rieß-Stumm S, Gregg B, Fritz A, Klemm I, et al. Enriching a randomized controlled treatment trial for anorexia nervosa by lived experience-Chances and effects of a lived experience council in the SUSTAIN study. Int J Eat Disord. 2024;57(6):1300–10. doi:10.1002/eat.24050.
Gönner J von, Herrmann TM, Bruckermann T, Eichinger M, Hecker S, Klan F, et al. Citizen science’s transformative impact on science, citizen empowerment and socio-political processes. Socio Ecol Pract Res. 2023;5(1):11–33. doi:10.1007/s42532-022-00136-4.
Gooding L, Pateman RM, West SE. Citizen science and its potential for aiding low carbon energy transitions. Energy Research & Social Science. 2024;117:103702. doi:10.1016/j.erss.2024.103702.
Grigoli F, Cesca S, Priolo E, Rinaldi AP, Clinton JF, Stabile TA, et al. Current challenges in monitoring, discrimination, and management of induced seismicity related to underground industrial activities: A European perspective: CHALLENGES IN INDUCED SEISMICITY. 87551209. 2017;55(2):310–40. doi:10.1002/2016RG000542.
Groot JIM de, Schweiger E, Schubert I. Social Influence, Risk and Benefit Perceptions, and the Acceptability of Risky Energy Technologies: An Explanatory Model of Nuclear Power Versus Shale Gas. Risk analysis: an official publication of the Society for Risk Analysis. 2020;40(6):1226–43. doi:10.1111/risa.13457.
Gross M. Old Science Fiction, New Inspiration. Science Communication. 2013;35(6):810–8. doi:10.1177/1075547012469184.
Guida M. 1928. Popular bird-watching becomes scientific: The first national bird census in Britain. Public Underst Sci. 2019;28(5):622–7. doi:10.1177/0963662519839555.
Haklay M, Fraisl D, Greshake Tzovaras B, Hecker S, Gold M, Hager G, et al. Contours of citizen science: a vignette study. R Soc Open Sci. 2021;8(8):202108. doi:10.1098/rsos.202108.
Hildebrand J, Jahns A, Schwarz L, Barich A. Public perceptions of Geothermal Projects – new ways of measuring and monitoring local acceptance and social impacts 2022. doi:10.5281/ZENODO.7602373.
Hirschberg S, Wiemer S, Burgherr P, editors. Energy from the earth: Deep geothermal as a resource for the future? Zürich: vdf; 2015.
Hofheinz M. Explosion & Rauchentwicklung auf dem Gelände des KIT Campus Nord. meinKA. 11/24/2021.
Holmgren JM, Werner MJ. Raspberry Shake Instruments Provide Initial Ground-Motion Assessment of the Induced Seismicity at the United Downs Deep Geothermal Power Project in Cornwall, United Kingdom. The Seismic Record. 2021;1(1):27–34. doi:10.1785/0320210010.
Hoşgör E, Apt J, Fischhoff B. Incorporating seismic concerns in site selection for enhanced geothermal power generation. Journal of Risk Research. 2013;16(8):1021–36. doi:10.1080/13669877.2013.788058.
Huijts N, Molin E, Steg L. Psychological factors influencing sustainable energy technology acceptance: A review-based comprehensive framework. Renewable and Sustainable Energy Reviews. 2012;16(1):525–31. doi:10.1016/j.rser.2011.08.018.

Huijts N, Molin E, van Wee B. Hydrogen fuel station acceptance: A structural equation model based on the technology acceptance framework. Journal of Environmental Psychology. 2014;38:153–66. doi:10.1016/j.jenvp.2014.01.008.

Irwin A. Citizen science: A study of people, expertise and sustainable development. London, New York: Routledge; 1995.

KA news. Experiment führt zu kleinerer Explosion auf KIT-Campus Nord: Keine Personen verletzt. ka-news.de. 24.11.2021.

Kasperson RE, Renn O, Slovic P, Brown HS, Emel J, Goble R, et al. The Social Amplification of Risk: A Conceptual Framework. Risk Analysis. 1988;8(2):177–87. doi:10.1111/j.1539-6924.1988.tb01168.x.

Kieslinger B, Schäfer T, Heigl F, Dörler D, Richter A, Bonn A. Evaluating citizen science - Towards an open framework. In: Haklay M, Bowser A, Makuch Z, Vogel J, Bonn A, eds. Citizen Science: Innovation in Open Science, Society and Policy. Erscheinungsort nicht ermittelbar: UCL Press; 2018. p. 81–95.

Kimmich D, Müller S. Tiefe. De Gruyter; 2020.

Kiriakidis S. Perceived Behavioural Control in the Theory of Planned Behaviour: Variability of Conceptualization and Operationalization and Implications for Measurement. In: Kavoura A, Sakas DP, Tomaras P, eds. Strategic innovative marketing: 4th Ic-sim, Mykonos, Greece 2015. Cham, s.l.: Springer International Publishing; 2017. p. 197–202. doi:10.1007/978-3-319-33865-1_25.

Klinke A, Renn O, Goble R. Prologue: The "Brave New World" of Social Sciences in Interdisciplinary Risk Research. Risk Analysis. 2021;41(3):407–13. doi:10.1111/risa.13716.

Kloetzer L, Lorke J, Roche J, Golumbic Y, Winter S, Jõgeva A. Learning in Citizen Science. In: Vohland K, Land-zandstra A, Ceccaroni L, Lemmens R, Perelló J, Ponti M, et al., eds. The Science of Citizen Science. Cham: Springer International Publishing; 2021. p. 283–308. doi:10.1007/978-3-030-58278-4_15.

Kluge J, Kowalewski S, Ziefle M. Inside the User’s Mind – Perception of Risks and Benefits of Unknown Technologies, Exemplified by Geothermal Energy. In: Duffy VG, ed. International Conference on Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management. Cham: Springer: Springer; 2015. p. 324–334. doi:10.1007/978-3-319-21073-5_33.

Knoblauch TA, Trutnevyte E, Stauffacher M. Siting deep geothermal energy: Acceptance of various risk and benefit scenarios in a Swiss-German cross-national study. Energy Policy. 2019;128:807–16. doi:10.1016/j.enpol.2019.01.019.

Kunze C, Hertel M. Contested deep geothermal energy in Germany—The emergence of an environmental protest movement. Energy Research & Social Science. 2017;27:174–80. doi:10.1016/j.erss.2016.11.007.

Lambert CE, McComas K, Balog-Way D, Trutnevyte E, Cousse J. The uncanny underground: Psychological and cultural associations of subterranean technologies for climate mitigation. Energy Research & Social Science. 2025;128:104341. doi:10.1016/j.erss.2025.104341.

Lecocq T, Hicks SP, van Noten K, van Wijk K, Koelemeijer P, Plaen RSM de, et al. Global quieting of high-frequency seismic noise due to COVID-19 pandemic lockdown measures. Science. 2020;369(6509):1338–43. doi:10.1126/science.abd2438.

Li C, Li Y. Factors Influencing Public Risk Perception of Emerging Technologies: A Meta-Analysis. Sustainability. 2023;15(5):3939. doi:10.3390/su15053939.

Lintott C. Citizen science: The past 200 years. Astronomy & Geophysics. 2020;61(2):2.20-2.23. doi:10.1093/astrogeo/ataa028.

Manzella A, Allansdottir A, Pellizzone A, editors. Geothermal energy and society. Cham, Switzerland: Springer; 2019.

Manzella A, Allansdottir A, Pellizzone A. Geothermal Energy and Society. Cham: Springer Nature Switzerland; 2025.

Marano KD, Hearne M, Jaiswal KS, Thompson EM, Bruce Worden C, Wald DJ. ShakeMap Atlas 4.0 and AtlasCat: An Archive of the Recent and the Historical Earthquake ShakeMaps, and Impacts for Global Hazard Analyses and Loss Model Calibration. Seismological Research Letters. 2024;95(2A):879–99. doi:10.1785/0220220324.

Meller C, Schill E, Bremer J, Kolditz O, Bleicher A, Benighaus C, et al. Acceptability of geothermal installations: A geoethical concept for GeoLaB. Geothermics. 2018;73:133–45. doi:10.1016/j.geothermics.2017.07.008.

Midden CJH, Huijts NMA. The role of trust in the affective evaluation of novel risks: the case of CO2 storage. Risk Anal. 2009;29(5):743–51. doi:10.1111/j.1539-6924.2009.01201.x.

Milani A, Dessi F, Bonaiuto M. A meta-analysis on the drivers and barriers to the social acceptance of renewable and sustainable energy technologies. Energy Research & Social Science. 2024;114:103624. doi:10.1016/j.erss.2024.103624.

Miller CA, Iles A, Jones CF. The Social Dimensions of Energy Transitions. Science as Culture. 2013;22(2):135–48. doi:10.1080/09505431.2013.786989.

Minet R. POL-KA: (KA)Eggenstein-Leopoldshafen - Explosion im Rahmen eines Versuchs auf dem Gelände des KIT Campus Nord. Presseportal Blaulicht. 11/24/2021.

Moczek N, Hecker S, Voigt-Heucke SL. The Known Unknowns: What Citizen Science Projects in Germany Know about Their Volunteers—And What They Don’t Know. Sustainability. 2021;13(20):11553. doi:10.3390/su132011553.

Moesker K, Pesch U, Doorn N. Making sense of acceptance and acceptability: Mapping concept use in energy technologies research. Energy Research & Social Science. 2024;115:103654. doi:10.1016/j.erss.2024.103654.
Morton C, Larimian T, Timmis A, Palaiologou F, Masera C, Monsuur F. Public acceptability of electric vehicle chargepoint installation in neighbourhoods: A psychometric approach to assess resident reaction. Cities. 2025;163:105961. doi:10.1016/j.cities.2025.105961.
Noriega-Linares J, Navarro Ruiz J. On the Application of the Raspberry Pi as an Advanced Acoustic Sensor Network for Noise Monitoring. Electronics. 2016;5(4):74. doi:10.3390/electronics5040074.
Onwezen MC, Antonides G, Bartels J. The Norm Activation Model: An exploration of the functions of anticipated pride and guilt in pro-environmental behaviour. Journal of Economic Psychology. 2013;39:141–53. doi:10.1016/j.joep.2013.07.005.
Papadis E, Tsatsaronis G. Challenges in the decarbonization of the energy sector. Energy. 2020;205:118025. doi:10.1016/j.energy.2020.118025.
Passani A, Janssen A, Hölscher K, Di Lisio G. A participatory, multidimensional and modular impact assessment methodology for citizen science projects. fteval JOURNAL. 2022(54):33–42. doi:10.22163/fteval.2022.569.
Pellizzone A, Allansdottir A, Franco R de, Muttoni G, Manzella A. Exploring public engagement with geothermal energy in southern Italy: A case study. Energy Policy. 2015;85:1–11. doi:10.1016/j.enpol.2015.05.002.
Peterson JR. Open-File Report 1993. US Geological Survey: US Geological Survey. doi:10.3133/ofr93322.
Quitoriano V, Wald DJ. USGS "Did You Feel It?"—Science and Lessons From 20 Years of Citizen Science-Based Macroseismology. Front. Earth Sci. 2020. doi:10.3389/feart.2020.00120.
r/KaIT. Explosion am KIT Nord vor 3 Wochen kolloriert. 2021. https://www.reddit.com/r/KaIT/comments/rh3sj4/explosion_am_kit_nord_vor_3_wochen_kolloriert/.
Raspberry Shake SA. DataView accessed 11/25/2025. Chiriqui, Panama.
Raspberry Shake, S.A. Raspberry Shake: Detect Earthquakes & Watch the Earth Move accessed 11/15/2023.
Renn O, Rohrmann B. Cross-Cultural Risk Perception: State and Challenges. In: Renn O, Rohrmann B, eds. Cross-Cultural Risk Perception. Boston, MA: Springer US; 2000. p. 211–233. doi:10.1007/978-1-4757-4891-8_6.
Renn O, Klinke A, Schweizer P-J, Hoti F. Risk Perception and Its Impacts on Risk Governance. In: Shugart HH, ed. Oxford research encyclopedia of environmental science. Oxford: Oxford University Press; 2016. doi:10.1093/acrefore/9780199389414.013.2.
Renn O, Köck W, Schweizer P-J, Bovet J, Benighaus C, Scheel O, Schröter R. Öffentlichkeitsbeteiligung bei Planungsvorhaben der Energiewende. In: Schippl J, Grunwald A, Renn O, eds. Die Energiewende verstehen - orientieren - gestalten: Erkenntnisse aus der Helmholtz-Allianz ENERGY-TRANS. 1st ed. Baden-Baden: Nomos Verlagsgesellschaft mbH & Co. KG; 2017. p. 547–568. doi:10.5771/9783845278957-547.
RHEINPFALZ Redaktion. Explosion im KIT bei einem Experiment. Die Rheinpfalz. 11/24/2021.
Robinson LD, Cawthray JL, West SE, Bonn A, Ansine J. Ten principles of citizen science. In: Bonn A, Vogel J, Makuch Z, Bowser A, Haklay M, Hecker S, eds. Citizen Science: Innovation in Open Science, Society and Policy. London: UCL Press; 2018. p. 27–40. doi:10.2307/j.ctv550cf2.9.
Rohse M, Barich A, Bossennec C, Loschetter A, Manzella A, Pellizzone A, et al. Prioritise Inclusive, Early, and Continuous Societal Engagement to Maximise the Benefits of Geothermal Technologies. In: Crowther A, Foulds C, Robison R, Gladkykh G, eds. Strengthening European Energy Policy. Cham: Springer Nature Switzerland; 2024. p. 31–43. doi:10.1007/978-3-031-66481-6_3.
Sauermann H, Vohland K, Antoniou V, Balázs B, Göbel C, Karatzas K, et al. Citizen science and sustainability transitions. Research Policy. 2020;49(5):103978. doi:10.1016/j.respol.2020.103978.
Schaefer T, Kieslinger B, Brandt M, van den Bogaert V. Evaluation in Citizen Science: The Art of Tracing a Moving Target. In: Vohland K, ed. The Science of citizen science. Cham, Switzerland: Springer Nature; 2021. p. 495–514. doi:10.1007/978-3-030-58278-4_25.
Schill E, Bauer F, Schätzler K, Rösch C, Mbah M, Benighaus C, et al. Co-production of knowledge: towards a co-design of geothermal heat utilization 2021.
Schlupp A, Chavot P, Grunberg M, Bes-De-Berc M, Jund H, Ajak F, et al. SeismoCitizen: A project combining seismology and human science approaches based on a deployment of a dense low cost seismic network hosted by citizens. In: European Geothermal Congress. EGU2019-15478.
Schlupp A, Chavot P, Grunberg M, Bes–De-Berc M, Jund H, Ajak F, et al. SeismoCitizen: A project combining seismology and human science approaches based on a deployment of a dense low cost seismic network hosted by citizens. Geophysical Research Abstracts. 2019;21(1).
Schrögel P, Kolleck A. The Many Faces of Participation in Science. S&TS. 2019:77–99. doi:10.23987/sts.59519.
Schweizer P-J, Renn O, Köck W, Bovet J, Benighaus C, Scheel O, Schröter R. Public participation for infrastructure planning in the context of the German "Energiewende". Utilities Policy. 2016;43:206–9. doi:10.1016/j.jup.2014.07.005.
Senabre Hidalgo E, Perelló J, Becker F, Bonhoure I, Legris M, Cigarini A. Participation and Co-creation in Citizen Science. In: Vohland K, ed. The Science of citizen science. Cham, Switzerland: Springer Nature; 2021. p. 199–218. doi:10.1007/978-3-030-58278-4_11.

Seyis C, İnan S, Streil T. Ground and indoor radon measurements in a geothermal area. Acta Geophys. 2010;58(5):939–46. doi:10.2478/s11600-010-0012-y.
Shirk JL, Ballard HL, Wilderman CC, Phillips T, Wiggins A, Jordan R, et al. Public Participation in Scientific Research: A Framework for Deliberate Design. Ecology and Society. 2012;17(2).
Shirk JL, Bonney R. Scientific impacts and innovations of citizen science. London: UCL Press; 2018.
Slovic P. Perception of risk. Science. 1987;236(4799):280–5. doi:10.1126/science.3563507.
Slovic P, Finucane ML, Peters E, MacGregor DG. Risk as analysis and risk as feelings: some thoughts about affect, reason, risk, and rationality. Risk Anal. 2004;24(2):311–22. doi:10.1111/j.0272-4332.2004.00433.x.
Smelser NJ, Baltes PB. International encyclopedia of the social & behavioral sciences; 2007.
Spiess H, Bättig M, Carabias-Hütter V, Eberle A. Akzeptanzforschung für die Energiewende. GAIA - Ecological Perspectives for Science and Society. 2019;28(1):58–60. doi:10.14512/gaia.28.1.14.
Spijkerboer RC, Turhan E, Roos A, Billi M, Vargas-Payera S, Opazo J, Armiero M. Out of steam? A social science and humanities research agenda for geothermal energy. Energy Research & Social Science. 2022;92:102801. doi:10.1016/j.erss.2022.102801.
Steg L, Perlaviciute G, van der Werff E. Understanding the human dimensions of a sustainable energy transition. Front Psychol. 2015;6:805. doi:10.3389/fpsyg.2015.00805.
Stephanides P, Chilvers J, Honeybun-Arnolda E, Hargreaves T, Pallett H, Groves C, et al. Beyond public acceptance: Towards systemic societal responsiveness of net zero infrastructures. Energy Research & Social Science. 2025;127:104251. doi:10.1016/j.erss.2025.104251.
Stricker K, Grimmer JC, Egert R, Bremer J, Korzani MG, Schill E, Kohl T. The Potential of Depleted Oil Reservoirs for High-Temperature Storage Systems. Energies. 2020;13(24):6510. doi:10.3390/en13246510.
Stricker K, Egert R, Schill E, Kohl T. Risk of surface movements and reservoir deformation for high-temperature aquifer thermal energy storage (HT-ATES) 2024. doi:10.5445/IR/1000168289.
SWR. Explosion bei Experiment auf KIT-Gelände. 11/24/2021.
Tang V, Rösler B, Nelson J, Thompson J, van der Lee S, Chao K, Paulsen M. Citizen Scientists Help Detect and Classify Dynamically Triggered Seismic Activity in Alaska. Front. Earth Sci. 2020. doi:10.3389/feart.2020.00321.
Trutnevyte E, Wiemer S. Tailor-made risk governance for induced seismicity of geothermal energy projects: An application to Switzerland. Geothermics. 2017;65:295–312. doi:10.1016/j.geothermics.2016.10.006.
Turrini T, Dörler D, Richter A, Heigl F, Bonn A. The threefold potential of environmental citizen science - Generating knowledge, creating learning opportunities and enabling civic participation. Biological Conservation. 2018;225:176–86. doi:10.1016/j.biocon.2018.03.024.
Upham P, Oltra C, Boso À. Towards a cross-paradigmatic framework of the social acceptance of energy systems. Energy Research & Social Science. 2015;8:100–12. doi:10.1016/j.erss.2015.05.003.
Vaughn LM, Jacquez F. Participatory Research Methods – Choice Points in the Research Process. Journal of Participatory Research Methods 2020. doi:10.35844/001c.13244.
Vohland K. The Science of Citizen Science. Erscheinungsort nicht ermittelbar: Springer Nature; 2021.
Wüstenhagen R, Wolsink M, Bürer MJ. Social acceptance of renewable energy innovation: An introduction to the concept. Energy Policy. 2007;35(5):2683–91. doi:10.1016/j.enpol.2006.12.001.
Zilliox S, Smith JM. Colorado's Fracking Debates: Citizen Science, Conflict and Collaboration. Science as Culture. 2018;27(2):221–41. doi:10.1080/09505431.2018.1425384.
Zwick MM, editor. Wahrnehmung und Bewertung von Risiken: "Ergebnisse des Risikosurvey Baden-Württemberg 2001" ; gemeinsamer Arbeitsbericht der Akademie für Technikfolgenabschätzung und der Universität Stuttgart, Lehrstuhl Technik- und Umweltsoziologie. Stuttgart: Akademie für Technikfolgenabschätzung in Baden-Württemberg; 2002.

Declarations

- Availability of data and materials
  - The data generated or analyzed as part of this study will be made available to the public after publication of the article, using the KIT Open repository. During peer- reviewing, the data are made available to the reviewers using the KIT file sharing system at following URL: https://bwsyncandshare.kit.edu/s/d3aSHyFoJ4m58e7.
- Competing interests
  - The authors declare that they have no competing interests.

- Funding
  - This study was funded by the Helmholtz Association.
- Authors' contributions
  - JB contributed to the conceptualization of the study, writing, and visualization. JA carried out the data analysis and interpretation, contributed to the conceptualization, writing, and visualization. NM and TK contributed to the conceptualization and writing. All authors reviewed and approved the final version of the manuscript.

- Acknowledgements
  - We thank Silke Schlichting for her contribution to the media analysis. Johannes Käufl implemented the seismic network involved in this study and performed a first data analysis and interpretation. This study is part of “Geoenergy” in the research program “MTET—Materials and Technologies for the Energy Transition” of the Helmholtz Association.
- Authors' information
  - JB is a geoecologist with a focus on dialogue formats in geothermal energy research. JA is a seismologist with particular expertise in monitoring geothermal projects using innovative methods. NM is an environmental psychologist specializing in citizen science and social science effectiveness research and evaluation. She headed the German Geothermal Energy Association from 2009 to 2011. TK holds the chair of Geothermal Energy & Reservoir Technology at KIT and has an extensive background in geothermal research.