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Perception spillover from fracking onto public perceptions of novel energy technologies

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Public opposition to new energy technology can harm the chances of successful deployment. Less is known about knock-on effects on the wider energy system, including whether such opposition impacts public perceptions of other technologies. Here we present a mixed-methods study into 'perception spillover', examining whether the controversy over fracking for oil and gas affects public attitudes to two novel low-carbon energy technologies: deep 'enhanced' geothermal systems and 'green' hydrogen. We argue that perception spillover is multi-faceted, and we conceptualize and test *spontaneous*, *prompted* and *primed* forms, examining how and why particular types occur. Using a nationally representative UK survey and two focus groups, we show that perception spillover from fracking could lead to widespread negative perceptions of deep geothermal energy, influencing the conditions that deep geothermal would be expected to meet. Conversely, a minority of participants expressed more positive perceptions of green hydrogen because they deemed it dissimilar to fracking.

Transforming energy supplies to reach targets for 'net zero' emissions probably requires the development and large-scale deployment of novel energy technologies[1]. Public support or opposition towards such technologies can be decisive in whether they are deployed successfully[2]. Clearly, a huge range of actors and multi-layered dynamics are involved in processes of social acceptance (or rejection) of technologies[3,4]. Yet the responses of publics at both community and socio-political levels can sometimes play a crucial role, as illustrated by the case of hydraulic fracturing ('fracking') for oil and gas. Public opposition influenced the halt of fracking activity in multiple jurisdictions around the world, in particular via influence on political mandates at local and national scales[5–7]. Public concerns over fracking have included: water supply impacts[8,9], greenhouse gas emissions[10,11], lack of personal control over risks[12], intrusion into the underground environment[12,13], induced seismicity (earth tremors)[14] and procedural and distributional equity[5,7,15].

While public perceptions of technologies such as fracking are often well understood, research has tended to treat them as stand-alone rather than taking a whole-systems approach to understanding attitude formation[16,17], which has the effect of hiding the impact of alternatives and 'competing' technology evaluation on acceptance judgements[18]. Opinions of other technologies may be particularly important when considering trade-offs within a portfolio of options, such as in the energy system[18–21]. What is less established, however, is the impact of opposition and controversy on such evaluations. Technology controversies have been shown to generate 'technology spillover' in policy formation[17]. We explore whether the strong public response to fracking might impact public perceptions of other technologies, affecting their chances of successful deployment. The concept of 'perception spillover' appears in the marketing literature[22–25], referring to a situation where 'existing perceptions influence beliefs that are not directly related to the original perception object' (ref. 23), but has not yet been applied in empirical energy research.

Building on the idea of the 'representativeness heuristic'[26], whereby people estimate the probability of an event in relation to an existing (similar) prototype in their minds, Visschers et al.[27] demonstrate that people often call on knowledge of more familiar risks when

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forming opinions about an unknown risk such as a new technology. Such 'risk associations' may relate to the technologies or techniques being used[28], or to societal dimensions such as trust in expertise[29]. For example, the Bovine Spongiform Encephalopathy (BSE) crisis in the United Kingdom affected perceptions of genetic modification technology due to loss of trust in regulatory authorities[30,31]. Marketing research identifies the importance of 'brand similarity' to perception spillover[24,25], but the likelihood of such spillover occurring within the complex and interconnected energy system is less clear. We aim to extend the research on risk associations by testing perception spillover from fracking in relation to technologically 'similar' and 'dissimilar' energy technologies. Deep or 'enhanced' geothermal system is posed as a similar technology due to its use of deep underground drilling, while green hydrogen from electrolysis (without underground storage) is posed as dissimilar (Methods). Following the risk association literature, we focus on spillover effects in unknown risks and novel technologies; further work would be needed to explore whether established technologies would encounter the same issues.

We hypothesize that perception spillover might take the following forms when someone is presented with a novel energy technology: *Spontaneous*, where the person or group makes an unprompted association between the novel technology and fracking; *Prompted*, where after fracking is mentioned, the person or group then makes an association between the novel technology and fracking, based on their pre-existing opinions; and *Primed*, where the person or group makes an association between the novel technology and fracking when detailed information on fracking is provided. These categories were developed to reflect how perception spillover from fracking is likely to occur according to our model, as follows: *Spontaneous* spillover indicates that fracking has a high level of salience for the person. In social communication settings (face-to-face or online), one person's spontaneous spillover, when voiced, leads to *prompted* spillover in others, particularly among those who are already familiar with fracking. Subsequently, as further details of fracking are discussed in a group setting or received via media, *primed* spillover might occur, particularly among those who were less familiar with fracking in the first place. Our primary hypothesis is that controversy over fracking would lead to more negative perceptions of the novel technology (which we term 'negative spillover'); however, each type of spillover could also theoretically work in the opposite direction, acting to attenuate risk perceptions ('positive spillover'). Gaining insight into these tiers of perception spillover could help to inform how risk associations may impact novel technologies, with relevance far beyond just deep geothermal and green hydrogen.

Using a combination of a nationally representative UK survey ($n = 927$) and two focus groups conducted and analysed in parallel (Methods), the goal of this research is to determine, (1) whether perception spillover exists in the case of fracking in the United Kingdom and to what extent; (2) the dynamics underlying any spillover and (3) the role that technological 'similarities' play in any spillover effects. Survey respondents were randomly assigned to a hydrogen condition ($n = 464$) or a geothermal condition ($n = 463$). Consistent with UK government statistics[32], 86.6% had heard of fracking before. Participants received information about green hydrogen or deep geothermal and were asked questions on their perceptions of the technology, before and after receiving information on fracking. Two focus groups ($n = 13$) were conducted online in South Wales, using the same information provided in the survey. All focus group participants had heard of fracking before.

In this paper, we find multiple lines of evidence that suggest that negative perceptions of fracking are an important factor in people's perceptions of deep 'enhanced' geothermal energy. A small proportion of the population make spontaneous connections between deep geothermal and fracking, and when prompted to consider fracking (triggering latent associations), nearly half the sample exhibit spillover. We find a lower incidence of prompted spillover from fracking to green hydrogen, with some participants feeling more positive about it because it is perceived as different from fracking.

Spontaneous spillover

Spontaneous spillover for deep geothermal energy was clearly present in the focus groups, with participants comparing deep geothermal to fracking within the first few sentences of the discussion and raising concerns related to their experiences of fracking: 'The one thing that I was not aware of is the fact that [fluid is] actually pumped into the ground in the same way [as it] would be used for fracking. That bothers me now slightly' (Focus Group 1, Participant 3). This reveals a risk association being made in relation to pumping underground. Another concern was over tremors, which were mentioned in the vignette: 'It sounds a little bit like fracking, which, I know it's different but it does seem to have that potential to cause earth tremors, which isn't something that I would want going on near my property, even if I did get some fairly flimsy reassurances' (FG2, P2).

By contrast, the focus groups did not produce evidence of spontaneous spillover for hydrogen. In Group 1, where participants received information on hydrogen and geothermal at the same time, the spillover from fracking to geothermal made participants more inclined to favour hydrogen: 'The fact that geothermal is akin to fracking… given what I've read, would probably push me towards hydrogen' (FG1, P1). The contrast between this and deep geothermal suggests that perceived technological similarities may play an important role. In Group 2, where we deliberately discussed hydrogen before introducing geothermal (Methods), participants made no mention of fracking. Hydrogen was viewed fairly positively in Group 2, for instance as a potential 'interim' solution while transitioning away from fossil fuels (FG2, P7), and participants called for more trials and research, suggesting fairly high levels of trust: 'We just have to try it' (FG2, P6). In both groups the perceived risks of hydrogen mainly related to safety and energy requirements.

In the survey, spontaneous spillover was identified for a small minority of participants in the deep geothermal condition but not in the green hydrogen condition. An open-ended question elicited reasons for support or opposition of each technology. Twenty-seven respondents in the geothermal condition (5.8%) mentioned the word 'fracking' in their response; most opposed deep geothermal, and their answers focused on the similarities to—and potential negative consequences of—fracking, for example, 'Like fracking, it doesn't seem a good idea to me to mess with the earth!' and 'Could cause earthquakes as such is likely to meet strong opposition from anti-fracking groups'. Again, these quotes suggest a role for (perceived) technological similarity, particularly in relation to the underground. That said, a further 30.8% made reference to 'tremors' or 'earthquakes' without mentioning fracking, for example, 'Tremors in the earth should not be caused by human interference. We could be damaging the planet for future generations'. Thus for this larger proportion of respondents, their initial evaluation of deep geothermal may have been based on its potential consequences, which are similar to fracking but in themselves do not imply a causal spillover effect. In the hydrogen condition, fracking was mentioned by only two respondents (0.4%), both of whom saw green hydrogen as positive by comparison: 'It's more sustainable than natural gas, especially if fracking is required to obtain it' and 'Green hydrogen is clean, an alternative to fossil fuels and fracking, and the only by-product is water'. Again, hydrogen concerns mainly referred to safety and the explosive nature of the gas; 47 people mentioned 'danger(ous)' in the hydrogen condition compared with 18 in the geothermal condition (Supplementary Note 5).

Prompted spillover

In the focus groups, 'prompted spillover' occurred after one participant had mentioned fracking, thus prompting other participants to consider it, before we presented any information on fracking. During the initial discussions on deep geothermal, comparisons with fracking were generally linked to similarities in the techniques used such as drilling and pumping water underground and their potential negative consequences: 'I had no idea that it was a water-pumping process, which sounds similar to fracking' (FG1, P4). Fracking was also used as an example of the types of unpredictable and potentially irreversible risks that can arise when dealing with the deep underground: 'Something makes me feel a little bit uneasy about digging in…it's the whole fracking thing coming up again, there's something that makes me feel like that can't really be undone' (FG2, P5).

Spillover from the fracking controversy related not only to physical risks of deep geothermal but also to the potential for project delays and cancellations due to public opposition, drawing attention to the broader processes by which public opposition can impact social acceptance of technologies: 'If they started digging around here and there was one story [in the media], I don't know, tremors—that would be the end of the project really, like we saw in Lancashire' (FG2, P7). Another participant highlighted how fracking spillover could drive opposition to another technology where similar risks are perceived: 'We've seen long-term impacts from America, where [fracking] damaged the water tables…if that's the same with geothermal, then you have the people who are opposed to fracking joining the anti-geothermal groups' (FG1, P4).

That said, initial negative perceptions of deep geothermal were not fixed, with many participants saying they would need more information to form an opinion. Some highlighted the distinction between geothermal as a form of renewable energy and fracking as a source of fossil fuel: 'From what I can see, they're not completely the same because the fracking is releasing gas, which is a fossil fuel, whereas geothermal isn't' (FG1, P5). Interestingly, in both groups, some stated that their affective (that is, emotional) responses to fracking were directly influencing their responses to deep geothermal: 'When I read [the geothermal vignette], I thought 'this sounds like quite a sensible way of doing things'. But the kind of non-rational, non-scientific part of me says 'this just feels wrong', and it's probably because I'm making that connection to fracking' (FG2, P4). There was also a sense of dissonance between the information on deep 'enhanced' geothermal and participants' pre-existing positive perceptions of shallow geothermal energy: 'Drilling and flushing through water, I think, oh no, that's horrendous, whereas if it was hot like the geysers in New Zealand and Iceland, I thought that'd be quite nice. I think I'm being a bit too romantic and unrealistic about it' (FG1, P2). This shows that perception spillover might not occur in the same way for all geothermal techniques and may relate to the depth and perceived intrusiveness of the drilling (see also ref. [33]). Perceptions of novel techniques can also be unstable and dynamic[34], and it is worth noting that a different study on deep geothermal found higher levels of support than our study and an increase in support following workshop discussions[33].

In the survey, respondents with prior knowledge of fracking were asked whether it had affected their opinions towards green hydrogen or deep geothermal. A much higher percentage in the geothermal condition indicated that fracking had influenced their opinion (Fig. 1). For geothermal, the large majority of self-reported prompted spillover was associated with more negative perceptions, with similar discourses to those found in the focus groups: for example, 'Because I know it's dangerous; also promoted by people I don't trust' and 'They tried fracking near my local area and in spite of assurances, it caused tremors and the site has been closed'. Prompted spillover was considerably more prevalent than spontaneous spillover, which is unsurprising because our methods for eliciting spontaneous spillover were not able to identify underlying or latent associations; in other words, people may have been making associations with fracking without stating them spontaneously. Twenty-eight out of 29 people who exhibited spontaneous spillover also recorded prompted spillover, in effect confirming that fracking had influenced their opinion. Interestingly, 14.5% reported a more positive opinion of green hydrogen because of perceived differences with fracking: 'I am anti-fracking because of the drilling involved; hydrogen doesn't need this to my knowledge' and 'Fracking is a far more destructive means of energy production with the potential to cause massive environmental damage. With hydrogen, this is far less likely to be the case'. This finding is supported by the focus groups, which indicated that association with a controversial and unpopular energy technology such as fracking may sometimes have a positive impact on techniques that are perceived to be dissimilar.

Primed spillover

During the second half of both focus groups, participants viewed a vignette containing information about fracking and were asked for their opinions about the technique before being asked about similarities with hydrogen and geothermal. Examining primed spillover in a deliberative setting is challenging because responses will have been influenced by the preceding discussion; therefore this session focused on perceptions of fracking and explicitly querying connections with geothermal and hydrogen. Participants mostly had strong pre-existing negative opinions of fracking: 'It's nasty, it's horrible, it needs to be banned' (FG1, P2), and it was seen as incompatible with desirable or logical pathways for future energy systems: 'It's still a fossil fuel, it's a nineteenth century fuel. Even if fracking was completely benign, didn't use water, didn't use chemicals, didn't cause tremors, we know that the gas has got to stay in the ground' (FG2, P2). In the survey, 86.6% were opposed to fracking with only 8.2% in support.

However, when relating fracking to the earlier conversation about geothermal, the discussion about renewable energies became more complex and ambivalent. Some participants reasserted earlier discourses, arguing that deep geothermal could result in similar consequences to fracking and felt that tackling climate change should not outweigh all other considerations: 'Just because something is renewable doesn't mean it's the best option' (FG1, P5). However, others argued that the need for an energy transition would make it worth researching a broader portfolio of renewables, potentially including those with an underground drilling component: 'It's only now that I've deeply thought about it, whatever the energy source we choose, there's still going to be an impact and all we can really do is…is mitigate (FG1, P1)'. Some supported the portfolio idea but argued that geothermal is not necessarily appropriate for the United Kingdom if the techniques used in Iceland are not exploitable at scale. A frank debate occurred in Group 1 over whether deep geothermal could be managed responsibly to predict and control risks to communities and the environment; the debate revolved around the lessons learned from the UK controversy over fracking, particularly regarding policy, regulation and the prediction and monitoring of induced seismicity. Overall though, the general sense from participants was a desire for more information: 'I'd really want to know what the impact to the environment is for both [hydrogen and geothermal] before making any decisions. I don't necessarily think that because it's frack-esque that geothermal is necessarily worse' (FG1, P1). Participants in both groups continued to actively question their own affective assumptions, particularly those which had been brought about by spillover effects: 'Digging a hole into the earth, we instinctively feel unhappy about that….I instinctively think hydrogen [would be preferable] but I'm kind of questioning whether that's irrational or not' (FG2, P4).

In the survey, 'primed' spillover was measured by the change of opinion after reading about fracking. All survey participants (both previously aware and unaware of fracking) were reminded of their previous answer to the geothermal/hydrogen opinion question and asked again. After conservative data cleaning (Methods), opinion change was reported by 11.8% of hydrogen participants (10.3% positive, 1.5% negative) and 22.5% of geothermal participants (8.8% positive, 13.7% negative). For geothermal, this is a lower proportion of negative opinions than for spontaneous and prompted spillovers,

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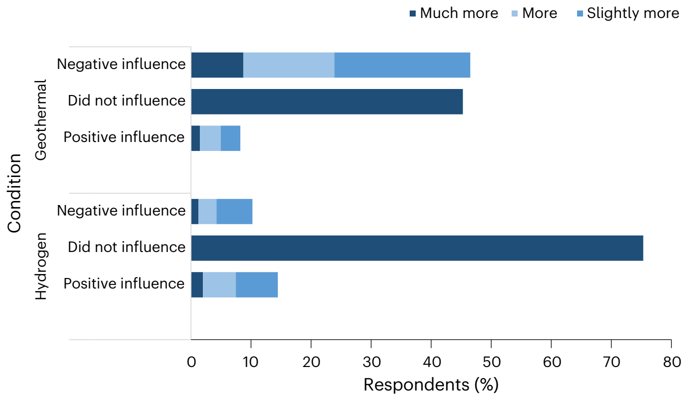

Fig. 1 | Prompted spillover. Percentage of respondents for whom fracking had influenced their opinion of deep geothermal or hydrogen. Question only received by those with prior awareness of fracking (86.6%). Geothermal condition $n = 402$. Hydrogen condition $n = 401$.

and 40 participants actually said that they had become more positive about deep geothermal as a result of reading about fracking, indicating reluctant acceptance (see also ref. [35]), for example, 'Fracking is much more dangerous; geothermal is the lesser of two evils'. For hydrogen, self-reported positive spillover outweighed negative spillover by a factor of seven. Paired samples t-tests on the full dataset (Supplementary Table 7) showed that participants' initial opinions on geothermal ($M = 0.42$, SE = 0.08) became less positive after receiving information about fracking ($M = 0.19$, SE = 0.08), which was significant as $t(462) = 5.16$, $p = <0.01$, BCa 95% CI (0.14, 0.31), although the effect size is relatively weak (Cohen's $d = 0.24$). For hydrogen there was no significant change (before $M = 0.81$, SE = 0.07, after $M = 0.74$, SE = 0.75; $t(463) = 1.40$, $p = 0.162$, BCa 95% CI (−0.02, 0.17), $d = 0.07$).

As an additional check, a hierarchical multiple regression was run to determine whether the addition of the 'fracking opinion' variable improved the prediction of opinions on green hydrogen and deep geothermal over and above gender, education level, political affiliation and environmental identity. In the hydrogen condition, the full model was statistically significant, $R^2 = 0.046$, $F(7{,}427) = 2.937$, $p = 0.005$, but the addition of fracking opinion (Model 2) did not lead to a statistically significant increase in R^2, $F(1{,}427) = 0.587$, $p = 0.444$. In the deep geothermal condition, the full model was also statistically significant, $R^2 = 0.214$, $F(7{,}427) = 16.593$, $p = <0.001$, as were covariates gender, education and (in Model 1) environmental identity. The addition of fracking opinion to the prediction of deep geothermal opinion (Model 2) led to a statistically significant increase in R^2 of 0.084, $F(1{,}427) = 45.378$, $p = <0.001$, and fracking opinion significantly predicted geothermal opinion (Standardised beta coefficient $\beta = 0.43$, $p = <0.001$). Thus fracking perceptions are moderately associated with deep geothermal perceptions (Table 1). Of course, this could be due to some additional variable not included in our test; our choice of covariates was based on literature suggesting these are likely to drive opinion of energy technologies (Methods), but a missing variable could potentially be acting to influence opinions of both geothermal and fracking. A regression analysis does not demonstrate causality and therefore must be taken alongside the other evidence presented in this paper.

Comparing different types of spillover

Figure 2 shows the percentage of respondents recording each type of self-reported spillover in the survey. Numbers for primed spillover are low because most respondents had already reported at least one of the other types of spillover, as we would expect from the high prior awareness of fracking. All types of perception spillover are more common for deep geothermal than for green hydrogen, and the spillovers for geothermal are predominantly negative, whereas for hydrogen, they are predominantly positive. In other words, risk associations with fracking tend to decrease favourable opinions of deep geothermal and may in some circumstances increase favourable opinions of green hydrogen.

Discussion

This paper builds on notions of 'controversy spillover'[17] by conceptualizing and empirically testing spillover effects in public perceptions of similar and dissimilar novel technologies. We present multiple lines of evidence that suggest negative perceptions of fracking are an important factor in people's perceptions of deep 'enhanced' geothermal energy. In fact, a small proportion of the population make *spontaneous* connections between deep geothermal and fracking, demonstrating that the fracking controversy is salient enough to act as the primary risk association that informs their (negative) opinions. When people are *prompted* to consider fracking in relation to deep geothermal, thus triggering latent associations, the proportion of negative spillover increases markedly to nearly half the sample in our survey (Fig. 1). Conversely, we found no evidence of spontaneous perception spillover from fracking to green hydrogen, and only a very small amount of self-reported primed spillover that was not supported by statistical comparisons, although we did find some evidence of prompted spillover (Fig. 2). For green hydrogen, participants in both the survey and focus groups reported feeling more positive about it because it is perceived as different from fracking. Of course, there is not always a clear distinction between 'similar' and 'dissimilar'; for example, our focus groups suggested that 'shallow' geothermal does not encounter spillover in the same way, yet it is challenging to determine exactly where a drill becomes 'deep', either technologically or in perception terms (see also ref. [36]).

People's evaluations of energy technologies may be influenced by comparisons between options, and the trade-offs these sometimes imply[19,20], thus our participants' responses may simply reflect a comparison against the disliked option of fracking. Indeed, many factors can influence risk perceptions, and perception spillover probably constitutes one influence among many, albeit one that is understudied and in need of further testing. Here we argue that the backdrop of controversy and opposition creates a particular socio-political context which appears to have influenced participants' perceptions, particularly illustrated by their qualitative responses. Overall, when considered alongside existing research on Carbon Capture and Storage[28,29], the results suggest that techniques perceived to be 'similar', especially those with an underground drilling/injection component, are likely to be most vulnerable to perception spillover effects from fracking. Our qualitative findings align with previous research on underground energy techniques, wherein the deep underground is perceived as unknowable, containing an intrinsic threat, and where changes are potentially irreversible[13]. Perception spillover from fracking could therefore impact many other techniques not included in this study, including CO_2 injection, compressed air energy storage and hydrogen storage. Interest in subsurface storage of hydrogen is growing[37], and any potential societal impacts (including but not limited to perception spillover from fracking) need to be considered alongside technological challenges.

Perceptions of novel technologies tend to be highly dynamic, malleable and responsive to events[34,38]. One important insight from our research was the degree of reluctant and conditional acceptance of deep geothermal energy, even in the presence of negative spillover effects. Focus group participants expressed considerable ambivalence towards deep geothermal, in particular over whether its status as a renewable energy source is sufficient to justify its pursual despite concerns over the risks of drilling and induced seismicity. Thus, rather than leading to outright rejection of a technique, perception spillover might point towards the types of important *conditions* that must be met, with many people being willing to consider new underground

Table 1 | Regression results

	Hydrogen condition				Geothermal condition			
	Model 1		Model 2		Model 1		Model 2	
Variable	Unstandardized beta coefficient (*B*)	Standardized beta coefficient (*β*)	*B*	*β*	*B*	*β*	*B*	*β*
Constant	−0.72		−0.68		−0.89		−0.65	
Gender[a]	0.46	0.15	0.45	0.15	0.77**	0.23	0.71**	0.21
Education	0.07	0.07	0.07	0.07	0.22**	0.17	0.23**	0.19
Env. identity	0.04	0.02	0.08	0.03	−0.53**	−0.20	−0.12	−0.05
Politics: right of centre[b]	0.33	0.09	0.35	0.09	−0.58	−0.14	−0.55	−0.14
Politics: left of centre	0.54	0.18	0.55	0.18	−0.42	−0.12	−0.36	−0.10
Politics: undecided	0.26	0.06	0.27	0.07	−0.49	−0.10	−0.38	−0.08
Fracking			0.05	0.04			0.43**	0.33
R^2	0.05		0.05		0.13		0.21	
F	3.33**		2.94**		10.69**		16.59**	
ΔR^2	0.05		0.00		0.13		0.08	
ΔF	3.33		0.59		10.69**		45.38**	

Hierarchical multiple regression predicting opinion on hydrogen and deep geothermal from gender, education level, political affiliation, environmental identity (env. identity) and opinion on fracking. $n=464$ (hydrogen), $n=463$ (geothermal). *$p<0.05$ **$p<0.001$ [a]Gender: recoded into binomial variable (Methods). Female=1, Male=2 [b]Political affiliation: recoded into dummy variables 1=right of centre; 2=left of centre; 3=undecided. (Reference category 'Would not vote').

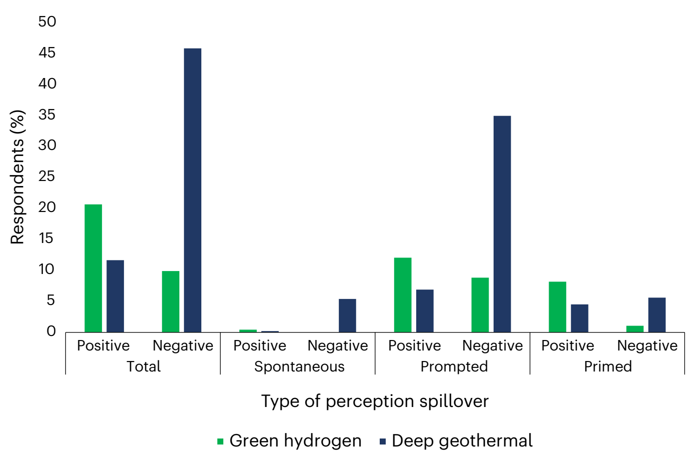

Fig. 2 | Comparing types of spillover. Percentage of respondents recording each type of perception spillover. Each percentage is based on the entire sample to facilitate comparison. To avoid double counting, data include only the initial type of spillover reported by each participant.

technologies on the condition that they are designed and deployed in a well-controlled and transparent manner and that they represent a shift away from fossil fuels. Where perception spillover from fracking occurs, however, such conditions might be fairly stringent and in many cases directly related to the conditions which fracking was perceived to have failed to meet.

Fracking has created public controversy in many locations, and opposition continues in areas including Australia, South Africa, Colombia and several US states. Perception spillover effects from fracking could therefore occur beyond our UK sample, and this paper presents a transferable methodology for exploring this. Further understanding could be gained from cross-national studies, which might tell us more about drivers of spillover in response to different contexts of public communication, policy and controversy. The degree of prior knowledge of the controversy is an important aspect of perception spillover, particularly in the distinction between 'prompted' and 'primed' forms, and thus it remains crucial to better understand the social construction and dissemination of such knowledge and its impact on perceptions, including across different publics (see also refs. [15,31,39]).

Understanding how and why spillover occurs in particular contexts would also benefit from larger and more diverse qualitative samples; in particular, qualitative methods can help to overcome some of the challenges we encountered in identifying causality from a cross-sectional design. In the case of fracking in the United Kingdom, opposition is high and has been growing steadily during a prolonged controversy[40,41]; therefore, we suggest that a longitudinal study may have been fairly redundant at this late stage. Yet future emerging controversies would clearly benefit from early longitudinal research into perception spillover to identify the social processes that lead to each type of spillover and how the different types influence one another. For instance, our focus groups indicated how spontaneous spillover from one participant leads to prompted (and perhaps primed) spillover in others, supporting prior evidence of how public deliberation on technologies can lead to increased or decreased perceptions of risk[42]. Many different publics were involved in the fracking controversy, and Devine-Wright et al.[38] explore this and the impact of specific events by including temporal social media analysis in a mixed-methods research design. Of course, this area of study need not be limited to fracking or the energy sector: meeting social challenges such as climate change, population growth and global health will probably involve new technologies and new controversies, and perception spillover could be relevant in a wide range of sectors, as already demonstrated in the fields of bio- and nano-technology[30,43].

Perception spillover is multi-faceted and arises in different ways, depending on the individual or group and their means of seeking and receiving information. Our model of perception spillover helps to understand how risk associations relating to new technologies may spread in response to communication from peers, organizations and social and traditional media. While a minority of people may spontaneously make a connection between a familiar and an unfamiliar technology, a greater proportion are likely to see the connection once prompted by the mentioning of the familiar technology, even if any similarity between the two is not explicitly stated.

Of course, individuals' perceptions are not a proxy for broader social acceptance of technologies, and this study has not attempted to examine the multi-layered processes, actor networks or socio-political conflicts that impacted the success of fracking or how these might play out in the case of deep geothermal and green hydrogen. Perception spillover illuminates just one of many such processes, yet acts as an important reminder that public opposition and controversy can have far-reaching impacts. Judging by the spontaneous and latent associations we identified between deep geothermal and fracking, we suggest that attempting to ignore or downplay similarities may backfire[17], particularly if geothermal creates induced seismicity as has happened in several countries[44,45]. Rather than trying to avoid perception spillover or to 'communicate around' it, it may be more beneficial to openly acknowledge and attempt to move past it, for instance, by supporting climate policy narratives that commit to the phase out of fossil fuels and by offering local communities a genuine voice in decisions that affect them.

Methods

Study background and design

This study builds on two small qualitative studies that helped to generate the hypothesis that risk perceptions around fracking might spill over to impact other technologies. A focus group study by Gough et al.[28] found that communities near exploratory drilling sites for fracked gas in Lancashire in the northwest of England experienced a breach of trust between the community and the local government, which negatively impacted their perceptions of carbon capture and storage (CCS). An exploratory study by Cox et al.[29] used secondary analysis of data from a series of UK deliberative workshops to argue that the fracking controversy had negatively impacted public attitudes towards CO_2-removal technologies, particularly those with an underground CCS component. CCS involves drilling down into the earth and therefore may be seen as similar to fracking[28]; yet associations between fracking and CO_2-removal technologies were also found to be driven by underlying societal issues such as faith in the ability of scientists to predict and control risks[29].

We used a mixed-methods design involving a large-*n* quantitative/qualitative survey and small-*n* qualitative focus groups, because these methods can act in support of one another. In situations of low prior knowledge, survey responses can be difficult to interpret and can be vulnerable to 'pseudo-opinions'[46]; qualitative data can help with this, while maintaining a statistically representative component. The survey and focus groups ran in parallel (dates below) with the aim of analysing the full corpus of data together, although we also conducted an initial thematic analysis of Focus Group 1 and used it to make small changes to the design of Focus Group 2 (explained below). It should be noted that when used in this way, surveys and focus groups both emphasize individuals' attitude formation and thus require contextualization from understanding broader processes of collective discourse and socio-technical change.

To test the extent of perception spillover across different technologies, we selected two renewable energy technologies that may contribute towards the decarbonization of energy systems but that are still relatively novel and do not currently play a major role in the UK energy mix. Deep or 'enhanced' geothermal is a form of geothermal heat extraction that creates man-made reservoirs within low-permeability rocks by pumping fluid via an injection well; the fluid is heated through contact with hot rocks deep underground and returned to the surface[47]. There is no strict definition of what constitutes 'deep'—the UK government defines it as >500 metres, but heat greatly increases with depth, meaning many project proposals go much deeper[48]. We emphasize that the information provided to participants explicitly discussed 'enhanced geothermal systems' (that is, those involving fractures in the rock); other forms of >500 m geothermal could potentially work without fracturing, although these may be less geographically widespread[49]. Green hydrogen is a means of producing hydrogen gas using renewable electricity for electrolysis; the resulting gas is an energy carrier that can be used in fuel cells to generate electricity or heat or as a replacement for natural gas in transport, heating and industrial processes. Currently, hydrogen is used in manufacturing, but the majority is produced using fossil fuels, although production could theoretically be coupled with CCS technology to produce low-carbon, fossil-fuel-based 'blue hydrogen'. Green hydrogen proposes to decarbonize hydrogen by using energy from renewables[50]. Deep geothermal was chosen for its technological similarities to fracking (for example, injecting fluids deep underground and fracturing of low-permeability rocks[47]), whereas green hydrogen without an underground storage component was chosen because it is less similar, at least from a purely technological perspective. Such evaluations of 'technological similarity' were based on expert assessment; in particular, attention in the United Kingdom has recently turned to the potential for deep geothermal as a route forward for the research, expertise and infrastructure left over from the stalled fracking industry[51,52]. However, a limitation of our method is that we did not include specific questions eliciting perceptions of 'similarity' in the survey, and expert assessments may not reflect lay public evaluations.

A UK sample was chosen for this study because its history of public opposition to fracking[5] means that it provides a good basis for understanding the impacts of fracking and of public opposition more broadly. Public awareness of fracking increased from 42% to 78% from 2012 to 2020, while support decreased from 52% to 8% (refs. [32,41]). Moratoria were issued (at different times) in each of the United Kingdom's four devolved administrations. The most recent moratorium in England in 2019 was widely perceived to be politically expedient in the run up to a general election, demonstrating the impact of growing public opposition on policy processes[38].

Focus groups

We conducted two focus groups on Zoom with participants living in South Wales, each lasting two hours in May and July 2021. South Wales was chosen as a location that is distant from sites of fracking licensing activity and site-specific protests, which mostly occurred in southeast and northwest England and in Scotland. This allowed us to test the existence of perception spillover beyond locally situated dynamics. It is also distant from enhanced geothermal test wells (mainly Cornwall) and took place before a high-profile seismic event there in March 2022. Participants were recruited 'topic blind' via opportunity sampling, using advertisements placed on social media community groups in South Wales; we targeted generic community groups and avoided those with a specific environmental focus. We used a short screening questionnaire on Qualtrics[53] to elicit information on gender, age, ethnicity and location of residence. Although our focus groups were not intended to be representative of the general population, we did aim for a mix of gender, age and ethnicity. We also aimed for an equal mix of urban and rural participants; however, due to two no shows, the majority of participants in Group 1 were from rural areas, and we corrected the balance with a majority from urban areas in Group 2. Participant characteristics are shown in Supplementary Table 1. Participants were paid £30 via bank transfer for taking part. Full informed consent was collected online beforehand. Ethical approval was granted by the Cardiff University Psychology Ethics Committee.

Full focus group protocols are available in Supplementary Tables 2 and 3. Following introductions and a brief facilitator presentation on the topic of 'renewable energy' (Supplementary Note 2), participants were introduced to deep geothermal and green hydrogen via vignettes ('Materials', below). We used Google Slides to enable participants to read the information individually and refer to it during the discussion. In Group 1, we aimed to avoid ordering bias by providing the hydrogen and geothermal vignettes simultaneously, inviting participants to choose which to read first; this was followed by open discussion of the two techniques. Following Group 1, we realized that spontaneous spillover from fracking was more prevalent than expected for deep geothermal and therefore might be biasing the hydrogen discussion; therefore, in Group 2 we did the hydrogen vignette and discussion first, enabling us to confirm our hypothesis that spontaneous spillover effects were not present for hydrogen. After a coffee break, participants were introduced to fracking via a third vignette on Google Slides, followed by discussion about fracking. This included some prompt questions designed to interrogate perception spillover and the reasons for it (for example, 'Do aspects of fracking seem similar to the previous technologies we discussed?') and questions designed to explore social, political and place-based parameters (for example, 'Can you imagine how your community would respond if one of the technologies was planned nearby?'). The focus groups ended with a short question-and-answer session, scheduled at the end to reduce bias arising from our responses to participant questions.

Focus groups were audio and video recorded using embedded Zoom software. The recordings were transcribed by a third-party transcriber, using the video to accurately identify speakers, and the transcripts were checked for accuracy by the research team and fully anonymized. The transcripts were analysed thematically, using a deductive approach to identify information specifically relating to our perception-spillover hypothesis, alongside an inductive coding approach to identify broad themes relating to perceptions and their drivers. Separate qualitative analyses were initially conducted by each of the authors to improve robustness. Once the key themes had been identified and agreed, the recordings were listened to again alongside the transcripts to check the analysis. Anonymized transcripts are available from the UK Data Service[54].

Materials

Participants were introduced to deep geothermal, green hydrogen and fracking via vignettes, consisting of an image with labels created in Adobe Illustrator and a half-page description (Supplementary Note 3). Each technique was illustrated using clip-art-style drawings, because using realistic photos or artists' impressions has been shown to potentially create bias[55]. The vignettes were developed with input from technical experts working on deep geothermal, hydrogen and fracking to ensure that the technical details were correct while maintaining a high level of accessibility for our non-expert participants. The vignettes used were the same across both focus groups and the survey. For the green hydrogen vignette and survey questions, we chose not to include the word 'green', because the word implies a nature-based framing that could strongly impact perceptions[56]. Therefore we used the term 'hydrogen' for a more balanced framing but explained the difference between so-called 'blue' and 'green' hydrogen in the vignette text. Following Group 1, small adjustments were made to the vignettes. To add clarity, a scale line was added to the geothermal and fracking diagrams to indicate how deep underground the process went, and a 'not to scale' label was added. 'Geothermal' was changed to 'deep geothermal' to differentiate between deep and shallow geothermal, and a sentence was added stating, 'there are other forms of geothermal energy production, such as shallow geothermal (the kind used in Iceland), but this requires specific geology.'

Survey

Survey participants were recruited using Prolific[57], integrated with Qualtrics[53] for survey design, in June 2021. We recruited a nationally representative sample of UK participants ($n = 927$) according to age, sex and ethnicity; 50.8% were female, 48.2% were male and <1% were other and prefer not to say. Supplementary Table 4 provides full demographic details. Participants were paid £1.25 for completing the survey, which took an average of seven minutes to complete. Participants were randomly assigned to one of two conditions, either Geothermal ($n = 463$) or Hydrogen ($n = 464$). In the hydrogen condition, 86.4% of participants had heard of fracking before, as had 86.8% in the geothermal condition.

Full survey protocol is given in Supplementary Note 1. After consenting to take part, participants were introduced to the topic of renewable energy. They were then shown a vignette according to their survey condition and asked, 'Having read the information, do you support or oppose [hydrogen or deep geothermal] as an energy source to be used in the UK?' (seven-point Likert scale) and 'Please list the reasons why you support/oppose [hydrogen or deep geothermal] as an energy source in the UK' (open-ended). This second question was used to identify spontaneous spillover. To detect prompted spillover, participants were then asked, 'Have you ever heard of 'fracking' as a method of gas production?' (yes/no). Participants who did have prior knowledge of fracking were asked, 'Did your knowledge of fracking influence your opinion of Hydrogen/ Geothermal?', on a seven-point Likert ('made me much more positive' to 'made me much more negative') and an open-ended question, 'Please tell us how and why fracking influenced your opinion'. The inclusion of multiple open-ended questions was intended to enable us to explore in more depth the reasons behind people's decisions, in essence adding to the qualitative dataset and enabling us to explore the mechanisms by which spillover (or lack of it) occurs. Participants who had indicated that they had not heard about fracking were not asked about prompted spillover. Finally, we showed all participants the fracking vignette and asked about their support/opposition to fracking (seven-point Likert). We measured changes in participants' perceptions of hydrogen/deep geothermal as a response to the fracking information with the question: 'You previously answered that you [strongly support] [hydrogen]. After reading about fracking, we are interested in whether your opinion on [hydrogen] has changed at all or stayed the same?' (seven-point Likert, strongly support to strongly oppose, plus another 'how and why' open-ended question). The survey ended with questions about environmental identity, using the six-item New Ecological Paradigm (NEP) scale[58]. Finally, participants answered demographic questions on gender, age, residence location, education level, income and which political party they are 'most likely to support'.

Survey analysis was conducted in SPSS (Versions 25 and 27). Survey data, including numerical and open-ended data, are available via the UK Data Service[54]. For the open-ended responses, word frequency counts were used to find the most common words (conjunctions removed). A targeted word frequency count was then conducted to ensure phrases and misspelled words were counted. A multiple hierarchical regression analysis was run to determine the additional variance explained by the fracking opinion variable, once other potentially important variables of gender, education level, political affiliation and environmental identity had been taken into account. Previous studies on perceptions of energy technologies indicate that socio-demographic variables are likely to be important, including gender and education level: we might expect men and more highly educated groups to be more supportive of new energy technologies[2]. Due to the very low proportion of non-binary respondents, we recoded gender into a binomial variable (female 1, male 2). Political affiliation may also be important: support for right-of-centre political parties is associated with stronger support for fracking[40], and support for renewable energy technologies has been found to follow political lines[2]. The UK political landscape is complex with ten political parties included in our survey; therefore, we grouped them into broadly 'right-of-centre' and 'left-of-centre', plus 'undecided' and 'would not vote', using dummy variables for the four categories. Finally, individuals' environmental identity has been shown to influence attitudes towards new technologies and towards fracking[59,60], and we might expect participants with a higher NEP score to hold more positive opinions of renewable energy technologies. Principal component analysis identified a one-factor solution across the six NEP items (Cronbach's $\alpha = 0.813$), and scores were summed.

Separate regression analyses were carried out for the two survey conditions. Model 1 included four independent variables: gender, education, political identity and environmental identity (NEP score). The dependent variable was 'After reading this information, do you support or oppose hydrogen/geothermal as an energy source to be used in the UK', seven-point scale treated as a continuous variable[61]. For Model 2 in the hierarchical regression, we entered fracking opinion from the question, 'Do you support or oppose fracking as an energy source to be used in the UK', similarly treated as continuous. For both conditions, a plot of studentized residuals against predicted values showed that the assumptions of linearity and homoscedasticity had been met. The assumption of normality was also met, as assessed by P–P plots. A Durbin Watson statistic of 1.926 in the hydrogen condition and 2.058 in the geothermal condition demonstrated independence of residuals. There was no evidence of multicollinearity, as all Variance Inflation Factor (VIF) values were well below 10. There were no studentized residuals greater than ±3 standard deviations, no leverage values >0.2 and no Cook's distance values >1.

Primed spillover was elicited using the question measuring opinion change, plus an open-ended question 'Please tell us how and why fracking influenced your opinion'. However, analysis of the open-ended data revealed several issues that needed to be taken into account when interpreting the opinion change data. Some respondents appeared to have misread the question and simply expressed their opinion of fracking, rather than explaining how the fracking information had affected their opinion of hydrogen or geothermal. These respondents were removed from the opinion change data (Fig. 2). To avoid overstating primed spillover, we also removed those respondents for whom it was not obvious from their open-ended responses that they had understood the question as intended. Furthermore, some respondents said in the open-ended question that their opinion had not changed yet reported a change of opinion in the quantitative question, despite being reminded of their original response. In these cases, the open-ended answer was taken at face value and these respondents were removed. The remaining respondents' answers indicated that they had understood the question as intended and were genuine cases of primed spillover; therefore, our results are conservative in this regard. Our use of open-ended responses thus enabled a more detailed interpretation of the results than would have been possible from a purely quantitative approach, allowing us to identify definite cases of spillover.

The cross-sectional design of this study makes demonstrating causality challenging. Our survey methodology asked people directly about the influence of fracking, rather than trying to elicit spillover using experimental methods (for example, refs. [24,25]) because we wished to explore mechanisms other than priming by which spillover might occur. However, this may have created some response bias wherein participants attempted to respond in a way that they felt was expected of them. Our qualitative data assists with this because of the ability to probe participants' reasoning and ask 'why' questions. However, study recruitment was impacted by the COVID-19 pandemic; our Welsh sample may have been influenced by the earlier fracking moratorium in Wales, and focus groups in other locations such as close to sites of fracking protests or deep geothermal pilot projects would have been useful.

Ethics

Ethical approval for this study was granted by the Psychology Ethics Committee at Cardiff University in accordance with British Psychological Society Code of Human Research Ethics. All participants were given an information sheet with information about the study and about how their data would be used prior to taking part. Participants then gave their informed consent via an online form. In accordance with UK data protection regulations, focus group participants were also asked whether they consented to being contacted again by the research team, for instance, to ask for clarification; anyone who did not give this consent had their contact details deleted immediately following the study. We did not record the contact details of survey participants.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data from this study are available via the UK Data Service at https://doi.org/10.5255/UKDA-SN-856047 (ref. [54]). Source data are provided with this paper.

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Author contributions
S.W. wrote the original draft, designed and facilitated the workshops and analysed the qualitative and quantitative data. C.H.D.J. wrote the original draft, designed the survey and analysed the qualitative and quantitative data. E.C. wrote the post-review draft, assisted with research design and analysis and acquired funding.

Competing interests
The authors declare no competing interests.

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The data from this study is available via the UK Data Service at https://doi.org/10.5255/UKDA-SN-856047

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☒ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Mixed-methods study - nationally-representative UK survey (n=927) and two non-representative focus groups in South Wales (n=6, n=7). . Focus group 1 was followed by survey, then focus group 2. All data was analysed simultaneously.
Research sample	Survey sample = nationally-representative of the UK population according to gender, age and ethnicity. 50.8% female, 48.2% male, 0.9% other. Age 18-24: 13.2%. 25-34: 17.5%. 35-44: 17.2%. 45-54: 18%. 55-64: 23.7%. 65+ 10.1% Ethnicity: White 83.3%. Asian: 8%. Black: 4%. Mixed: 2.5%. Other: 1.8% Focus groups = South Wales residents, chosen because of their distance from sites of fracking controversy. Urban/rural split; gender and age balance
Sampling strategy	Survey sample = random sampling (using web survey tool 'Prolific'). Survey sample aimed for 1000 participants, as this would achieve representation of the UK population with a 3% margin of error (95%CI) within the budget constraints for this study. However, only 927 were returned by Prolific within the allotted time. This is large enough to meet the criteria for representation of the UK population. Focus group samples were recruited using social media (explained in Methods). We aimed for 8 per focus group, as this is the largest number feasible for meaningful deliberation online. Number of focus groups limited by funding.
Data collection	Survey data collection was online Focus group data collection was via audio and video recording, transcribed by a third party transcription service, checked and anonymised by the research team. Only the research team were present for the focus groups. The researchers were not blinded to the experimental condition or study hypothesis.
Timing	May 2021 to July 2021 continuous
Data exclusions	Survey data was excluded from the analysis of 'primed spillover' according to participants' open-ended responses; these exclusions have been fully explained in the methods. 23 participants were excluded from the survey because they did not complete all the mandatory elements - for instance, because they failed the attention checks.
Non-participation	3 no-shows in the focus groups. No reasons were given for non-attendance, we were unable to contact these participants.
Randomization	Participants randomly allocated into one of two survey conditions.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study	
☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology and archaeology
☒	☐	Animals and other organisms
☐	☒	Human research participants
☒	☐	Clinical data
☒	☐	Dual use research of concern

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging

Human research participants

Policy information about studies involving human research participants

Population characteristics	See above

Recruitment	Survey - recruitment via Prolific (selected 'nationally-representative sample') Focus groups - recruitment via social media (Facebook community groups). We deliberately avoided targeting groups with an environmental focus. We targeted specific groups to get an urban/rural split - groups located in Cardiff, and groups located in the Brecon Beacons. . Recruitment was 'topic blind' to mitigate self-selection bias. All participants had to have an internet connection and a bank account to take part; this may have biased results away from those without internet and on precarious incomes. The use of Facebook community groups will have biased recruitment toward people using Facebook (as opposed to other social media platforms, or no social media), and towards people with an interest in their community. However, focus groups were not intended to be 'representative' of the population. Prolific use a database for their recruitment, and therefore may include professional survey-takers. Our sample also had a higher than average education attainment level.
Ethics oversight	Cardiff University Psychology Ethics Committee

Note that full information on the approval of the study protocol must also be provided in the manuscript.