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RESEARCH ARTICLE



Positive aspects of high-level waste disposal: what do German citizens think?

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ABSTRACT

The fact that nuclear waste is a problem waiting to be solved is perceived to be a matter of common sense worldwide. Nonetheless, the negative aspects of nuclear waste disposal often dominate public debate. This is also true in the German case of a currently planned deep geological repository (DGR) for high-level nuclear waste (HLW). In studies about risk and benefit perception one may wonder whether the positive aspects proposed by the literature are really part of people's mental models. To date, any positive aspects that the German public associates with a DGR are unknown. In this bottom-up study, we explored the German public's positive perceptions of a DGR based on a sample of $N = 2,490$ survey respondents in 2022. Our most compelling finding was that while some citizens viewed the resolution of the nuclear waste problem as a key benefit of a DGR, the majority either provided no positive feedback or explicitly stated that there were no benefits. Although workplaces and financial incentives are benefits recognized in existing literature, these were not prominent in our sample. Moreover, there was a clear association between the perceptions of risks and mentioned benefits: individuals who perceived high risks identified fewer positive aspects, whereas those with low-risk perception proposed more benefits. Interestingly, some respondents demonstrated ambivalence, recognizing both moderate risks and positive aspects of a DGR. Our findings indicate many people's tendency to focus on the risks associated with a DGR, overshadowing its potential benefits – a result aligning with the availability heuristic, where risks are more salient in public debate about nuclear waste. This suggests that in discussions typically framed around risks, mentioning benefits might seem inappropriate. We propose that discussing the tradeoffs between a DGR and the status quo, particularly surface storage, could broaden the conversation. Emphasizing both positive and negative aspects might shift the focus from solely on DGR risks to a more balanced view. Despite the majority of the respondents' support for DGR rather than continued surface storage, they struggled to articulate positive aspects of the solution. These inconsistencies in mental models can be expected to a certain extent, highlighting the complex nature of public risk perception and benefit recognition.

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HIGHLIGHTS

- German respondents prefer a deep geological repository (DGR) over surface storage of high-level nuclear waste (HLW)
- In response to an open-ended question about possible positive aspects of a DGR, the majority explicitly mention “none”.
- The fact that a DGR would solve the nuclear waste problem is appreciated by a fair number of respondents.
- In general, the positive aspects mentioned do not overlap much with the benefits found in the literature.

Introduction

The fact that nuclear waste is a problem waiting to be solved is perceived to be a matter of common sense, although the proposed approaches for solving it may differ. According to the IAEA classification (International Atomic Energy Agency 2009) several classes of waste can be distinguished in terms of two dimensions (*half-lives of the radionuclides and activity*): from very short-lived waste to very low-level waste, low-level waste, intermediate-level waste and high-level waste (HLW), which is what we are dealing with in this study. Depending on this classification, the suggested treatment of the waste varies considerably. HLW is radioactive waste with activity concentrations high enough to require shielding due to high heat generation and significant amounts of long-lived radionuclides (Ojovan and Steinmetz 2022). While low-level waste may be stored near the surface with some shielding and more or less robust containment and isolation for a few hundred years, high-level radioactive waste should be disposed of in a deep geological repository (DGR). “Deep” here describes depths exceeding approximately 300 metres (Ojovan and Steinmetz 2022). There is an international consensus among experts that this is the most benign solution, for the sake of both human beings and the rest of the ecosystem (Röhlig 2022).

According to surveys, the majority of the European public generally supports this approach (European Commission 2008). However, often, public debate on nuclear waste management revolves around the reasons why citizens would *not* want a facility such as a (DGR) near their home (Peeples et al. 2008). The solution aspect is rarely presented in a positive light, for example, in the sense that the overall safety of a country would be improved if a DGR is constructed. Potential risks to people and the environment and potential safety issues remain in the foreground (Zhao 2023). This is an unfortunate situation when the solution to the problem is perceived primarily as a problem in itself. Some citizens are particularly afraid of a DGR (Seidl et al. 2013). While it does not exhaust the whole debate but provides one possible perspective to it, we focus here on the tradeoff between the status quo with relatively low safety (in this case, distributed surface storage of nuclear waste in 16 above-ground interim storage facilities across Germany) and an agreed safer solution (i.e. a DGR in deep layers of host rock). Often, the debate concentrates mainly on the risks of the latter, while the risks of surface storage and the positive aspects of a DGR are almost absent. It is noteworthy that in Germany, the majority of experts and political parties have reached a consensus in favour of a DGR, the planned construction of which is now part of the law (StandAG 2017).

Therefore, this option is the starting point of our investigation, assuming that the DGR solution is the best from a health and environmental perspective, knowing that other options are still under discussion.

Although this study focuses on risks and benefits perception, other concerns regarding geological disposal may be raised by the public such as perceiving the waste as resource, which should not be buried but reprocessed and reused (Merk et al. 2019) although the technology is not a panacea to the waste problem (González-Romero 2011). Additionally, scepticism or opposition may emerge due to the removal of a “bargaining chip” in the context of the debate surrounding the construction of new nuclear power plants. Alternatively, opposition may arise from a lack of confidence, based on previous negative experiences (Di Nucci et al. 2021). In sum, there are multiple reasons to oppose (and support) DGRs, and the focus on tradeoffs we have set in this paper alone cannot fully capture the diversity of normative standpoints and value systems involved in this debate.

A number of approaches to risk perception (and to the question of why lay judgements differ from a professional risk analysis) have been developed in the social sciences. Primarily due to citizens’ high fear of nuclear facilities (as shown in their survey responses) and unfamiliarity with radioactivity (Slovic et al. 1991; Lindberg and Archer 2022), according to psychometric studies (Slovic 1987), nuclear facilities have been perceived as *high risk*, particularly in Germany (Nuclear Energy Agency 2010). Moreover, these technical facilities (nuclear power plants and nuclear storage/disposal sites) are usually imposed by third parties and not voluntarily chosen compared to individual risky activities, such as smoking or paragliding. The latter also have more obvious positive aspects for some individuals.

Furthermore, in practical terms, for providing a balanced communication of pros and cons (Fischhoff et al. 2011; Blastland et al. 2020) that resonates with people’s own assumptions, knowledge of the positive aspects already prevalent among the German public should be available.

Studies on various topics show the perceived benefits’ (compared to perceived risks’) relevance for the acceptability of a technology (Bronfman and Vázquez 2011), such as nuclear power (Visschers and Siegrist 2013). Some scholars explicitly distinguish between acceptability and acceptance, for example, suggesting that acceptability is an attitude before an infrastructure is built or technology released, whereas acceptance is behavioural and occurs afterwards (Klaus et al. 2020; Moesker et al. 2024). In this study, we address the hypothetical question of whether people would accept a HLW repository, even though the decision on a specific site and the construction of the repository will not take place for several decades.

Furthermore, it has been found that in general, there is an inverse relation between the perceptions of benefits and risks; high perceptions of risks are associated with low perceptions of benefits (Alhakami and Slovic 1994). When the risk – benefit tradeoff is clearly negative, the result is the rejection of a technology instead of its acceptance, which would occur if the benefits prevail.

If the public is unaware of potential benefits, this may bias its opinion. There can be several reasons why talking about the benefits of a DGR for HLW may appear difficult. In the relatively contested case of nuclear waste disposal, discussing its positive aspects may be considered disreputable and not obvious and potentially lead to reactance (Brehm 1966). This would then possibly encourage or create oppositional attitudes.

Recommendations for good communication (Blastland et al. 2020) may therefore be futile, especially if prior attitudes are already critical. Hence, if government authorities emphasize the benefits of a nuclear waste repository to a community, it may discredit their position. They may appear to be untrustworthy attempting to push technology to citizens perceived as harmful (Hannis and Rawles 2013). If risks are more salient and dominate the debate (e.g. because prominent opponents stress risks instead of benefits), citizens cannot make a fair appraisal of their perceived benefit – risk tradeoff. This may be due to a bias introduced by the availability heuristic (Tversky and Kahneman 1974). If negative aspects are more visible in public debate, they may influence people’s opinions more than features that are rarely mentioned and difficult to grasp. That heuristics and benefit perception play a role in public support for a nuclear research reactor in Singapore has been shown in a recent study by Ho et al. (2021).

Although the link between the media and individual risk perception is far from clear (Wählberg and Sjöberg 2000; Vyncke et al. 2017), there may be some bias in public perception of risks and positive aspects due to media bias (Lindberg and Archer 2022). While in countries such as China or Japan nuclear technologies are presented in a more positive light (Ho et al. 2021), in Germany media coverage of radioactive waste tended to focus on risks (Renn 1998; Landsmann and Bräuer 2007) and nuclear power was increasingly questioned about its role in the country’s energy supply after the Fukushima tsunami and the subsequent nuclear accident (Rehner and McCauley 2016).

Moreover, research papers and project reports may include both benefits and risks but do not explicitly cite citizens’ perspectives. They include potential benefits that are intrinsic to a DGR, but may also be the result of government policy and/or industry action. In this vein, the authors of various chapters in the volume edited by Arentsen and van Est (2023) mention and discuss benefits of HLW repositories to communities in different countries, for instance, in terms of economic development and workplaces for local inhabitants (occurring at different phases of the site selection or construction process). In reports by the IAEA (2007) and in scientific literature (Kojo and Richardson 2014; Karita Research Ab 2015), further benefits are discussed, such as jobs, expanded or improved infrastructure, compensation for taking on the burden, general economic or social/community benefits, increased land and property prices,¹ local empowerment, and taxes’ contributions to the local budget.

Is the public aware of these potential positive aspects? It is not yet known what advantageous features of an HLW repository are perceived by ordinary citizens because few studies present this perspective. A mental model approach used in the UK by Skarlatidou et al. (2012) reveals that few positive aspects were named during the interviews conducted by the authors, who do not elaborate on these positive aspects.

We deem it essential to know which benefits are perceived by citizens to compare them to those mentioned in the literature. Germany appears a special case, often cited as particularly challenging for proponents of nuclear facilities (Hocke and Renn 2009; European Commission 2010; Drögemüller 2018; Grunwald 2022; Di Nucci and Brunnengräber 2023). To communicate with citizens in advance of a siting phase (basically, already during the current German site selection phase), it is important to know their opinions and to find a sensitive way to address potential local benefits without causing reactance and provoking opposition (in addition to obvious concerns). It may well be that the benefits mentioned above are unknown to the average citizen, who has often never

heard of a site selection procedure or the disposal of HLW (Seidl et al. 2022; Götte 2023). Therefore, we believe that it is timely and worthwhile to ask citizens about their familiarity with the positive aspects of such a repository. There is also a methodological note to this study. Studies on the acceptance of nuclear waste repositories tend to present lists of risks and benefits mentioned in the literature and ask respondents to rate their levels of agreement. This use of fixed, closed-ended items on the risks and benefits of a particular technology (Gardner et al. 1982; Groothuis and Miller 1997; Seidl et al. 2013) may yield valid results. However, it may still be unknown what benefits, if any, respondents might mention when given the opportunity to elaborate in an open-ended questioning. Knowledge in this domain would also help operationalize theoretical approaches that propose acceptance as being influenced by risks and benefits and other variables, such as trust (Groothuis and Miller 1997; de Groot and Steg 2011; Liang et al. 2023). To our knowledge, German citizens' perceptions of a DGR's potential benefits have not been studied in a bottom-up manner using a representative sample of the German population.

Furthermore, there might be a link between the perceptions of risks and benefits. Our hypothesis was that individuals who were more risk-focused would mention fewer positive aspects compared to those who rated the potential risks of a DGR as low or moderate. In addition to individuals focused on risks or benefits, one would expect to find ambivalent individuals in the sample (Thompson et al. 1995), perceiving risks and benefits on a comparable level (Seidl et al. 2013).

Methods

A survey was conducted to investigate the positive aspects mentioned by the respondents. Moreover, it is of interest to relate the quantity and nature of the identified positive aspects to the respondents' perceptions of risks. Ultimately, the question in our study is whether there exists an alternative to a DGR that offers greater benefits with a reduced risk profile (keeping in mind that concepts such as acceptability, acceptance, resistance, criticism, or support are not just about risk/benefit tradeoffs). In the current investigation, the respondents' preferences for surface storage versus DGR were gauged via a visual analogue scale. Such a scale shows only the endpoints, but no ticks to indicate the subdivision. We then divided our scale into ten levels, with 1 indicating preference for DGR and 10 for surface storage. The details about the sample and the analyses are presented in the next subsections.

Sample

The respondents of our study in 2022 were recruited by the market research company Bilendi (www.bilendi.de). Quotas were set for sex, age, and education to obtain an approximately representative snapshot of the German population in the sample. The following quotas were implemented (each with a 10% mark-up, i.e. 2,750 to reach $N=2,500$, as experience has shown that approximately 10% of the sample must be excluded due to poor data quality). For sex, the sample comprised 50% males and 50% females (i.e. $n=1,375$ each). Five age groups were formed, quantified according to available German statistics,² with the age range covering 18–75 years. Again, based on available statistics,³ the respondents could choose from nine education categories, which

were assigned to three broad educational levels and used for quotas to match the statistics: secondary education certificate, training/vocational education, and university. The basic usable sample size after adjustment (i.e. sorting out dubious or suspicious responses) was $N = 2,490$.

Survey

The rationale behind the survey was to ask citizens an open-ended question about the positive aspects of a DGR in order to know which benefits they actually imagined regarding a DGR. A recent qualitative study from Germany (Drögemüller et al. [under review](#)) revealed that the respondents actually imagined few benefits of a repository. However, the responses in this earlier online survey were not given in response to a question about benefits per se, but as comments as general feedback at the end of the questionnaire. The respondents were not explicitly asked to identify benefits or potential positive aspects. Therefore, in this study, we examined the issue by clearly asking the respondents to identify positive aspects of a DGR.

For all items, a 7-point Likert response scale was used, fully labelled as “7 = applies fully”, “6 = applies almost fully”, “5 = applies to a great extent”, “4 = applies partly”, “3 = applies to some extent”, “2 = does not apply”, and “1 = does not apply at all” (English version, Menold & Tausch, 2016). Higher values would thus indicate greater agreement with the respective statements.

At the beginning of the questionnaire, we assessed the respondents’ interest in the topic of final disposal and their perceived relevance of the nuclear waste management issue. Regarding the first item (“I am interested in the topic of final disposal”), on average, the response was moderate interest ($M = 4.6$, $SD = 1.64$). As for perceived relevance, it was assessed by a reversely posed question (“I do not see radioactive waste as a problem at all”) so that agreeing to it would indicate the topic is of low relevance to respondents. The average response was low ($M = 2.3$, $SD = 1.63$), indicating rather small perceived relevance.

Possible benefits of a repository were asked in an open-ended question (*Please provide bullet points on positive aspects of a repository in your region*). The mentioned positive aspects were qualitatively evaluated by two researchers; the first researcher grouped the 1,561 comments under one or (if necessary) two categories. The second researcher did the same independently. Finally, together, these researchers consolidated the lists and assigned 1,527 comments to one of the categories.

Because they covered more issues than usual 60 comments were allocated to two categories and four comments had to be allocated to three categories. In sum, the categorization was fairly easy since the comments were not overly complex. Therefore, no special coding system was used.

Besides asking for positive aspects of a DGR, we also investigated risk attitudes. We adapted existing items based on the study of Seidl et al. (2022), covering perceived threats to the environment or health risks for future generations, among others.

To investigate potential differences in the mentions of benefits based on attitudes towards repository risks, we conducted a cluster analysis of the risk items using Ward’s method (Ward 1963). We found a four-cluster solution that provided a reasonably interpretable set (as in earlier research, e.g. Seidl et al. 2013).

Results

When asked about the tradeoff between surface storage and deep geological disposal, the majority favoured the DGR solution over continued surface storage. Figure 1 shows the response distribution as skewed to the right, based on the visual analogue scale ($M = 3.17$, $SD = 2.33$). Therefore, although the DGR option appeared controversial in public debate, it was clearly preferred by most participants. This finding made it all the more interesting to see what kind of potential positive aspects of this solution would be named by the respondents.

Here, a rather clear picture emerged from the results of the analysis (see Table 1; the categories are explained in more detail in Table 2): the benefits were obviously not salient for many respondents, but some were mentioned. Predominantly, “no” benefits of a repository were observed for the affected region ($N = 834$ out of 1,560; 53.5%). The most often mentioned positive aspect referred to potential job creation in the region ($N = 133$; 8.5%). The construction of a repository as a solution to the waste disposal problem as such was acknowledged as a positive aspect by a fair number of participants ($N = 97$; 6.2%). Other aspects not related to the positive aspects we asked about, such as the region not being suitable anyway, were mentioned by 25 (1.6%) respondents. Protection of the environment/nature and health were hardly considered at all (12 and 9 times, respectively), despite being the primary goal of final disposal in a DGR.

Risk perception was assessed by presenting seven potential risks to be rated on a 7-point Likert scale. The analysis (Table 3) shows that, on average, the respondents perceived high potential risks, with considerable variations among the respondent groups, differentiated by the cluster analysis. In general, risks to drinking water and groundwater and to the health of future generations were rated highest, while risks to real estate prices and regional products were rated lower, although still above the midpoint of the response scale of 4.

In terms of subgroups (see Table 3, Columns 4–7, Tables 4 and 5) we find considerable differences. We will briefly describe each cluster, highlighting salient differences. Cluster 1 has the highest average age, includes more women, is more interested in the topic than

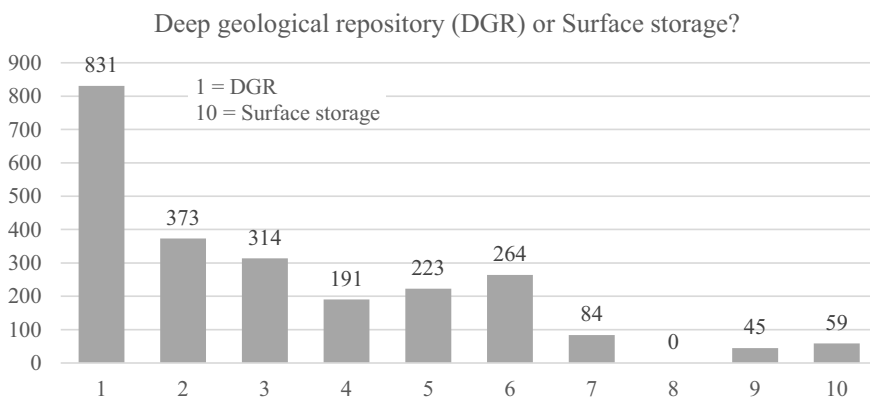


Figure 1. Frequencies of preferences for surface storage or for building a DGR, measured by an analogue scale.

Table 1. Frequency of comments per category. Categories for positive aspects are shown in bold font. Total number = 1,560 (99 = “Don’t know” answers; total number of answers: $N = 1,659$).

Category	Frequency	Percent (of 1,560)
Nothing/none	834	53.5
Other	217	13.9
Work/workplaces/job creation	133	8.5
Disposal/solution itself	97	6.2
Economic advantages	65	4.2
Opportunities	26	1.7
Region is unsuitable anyway	25	1.6
Control/research/innovation	22	1.4
Land/property prices	20	1.3
Further use of nuclear power plants	15	1.0
Ambivalent/undecided	14	0.9
Compensation	14	0.9
Responsibility/contribution	14	0.9
Environment	12	0.8
Awareness	11	0.7
Infrastructure	11	0.7
Regional promotion	11	0.7
Risks	10	0.6
Health protection	9	0.6

the other clusters and has a higher education level. It rated all risks high. Cluster 2, is slightly younger on average than Cluster 1, and has the least number of women of all clusters. It is relatively more politically right-leaning and has the lowest risk ratings of all. In line with the latter, Cluster 2 is moderately interested in the issue, i.e. shows the lowest value for this item, while agreeing relatively more than others with the statement that nuclear waste is not a problem at all. Cluster 3 and Cluster 4 show similar profiles in terms of average age (younger than Clusters 1 and 2) and education, but Cluster 3 includes more women and shows higher risk ratings than Cluster 4.

There appears to be a relationship between the ratings of the risk statements and attitudes towards the issue. Risk perception is higher when nuclear waste is seen as a problem and there is interest in the issue. This can be exemplified by the fact that those who expressed indifference to risks (especially Cluster 2) indicated low interest in the topic and low perceived relevance. On the contrary, the risk-oriented Cluster 1, as well as Cluster 3 (which also shows relatively high risk values), indicate a higher interest in and perceived relevance of the problem. There is also a clear gender bias, with clusters with a higher proportion of women showing a greater perception of risk.

We hypothesized that individuals with a high perception of risks would on average mention no or fewer positive aspects. Further analysis reveals which cluster mentions positive aspects versus explicit “none” statements. The results presented in Figure 2 show that the subgroup that is indifferent to the risks mentions relatively more positive aspects (32%) than explicit “no-positive” answers (22%). For all other clusters, it is the other way around, especially for the risk-focused Cluster 1 the pattern is completely different (10% positive compared to 49% “no-positive” answers). Overall, a fairly linear pattern of positive aspects can be seen as a function of the level of risk perception.

Table 2. Survey respondents’ comments, grouped under the following categories (with descriptions, in alphabetical order).

Category	Description
Ambivalent/undecided	Comments address positive and negative aspects at the same time (e.g. “No, nothing positive but also nothing negative”, “very mixed”, or indecision “not really”).
Awareness	Some respondents assume positive effects for the region, concerning heightened awareness (“National awareness of the region increases”).
Compensation	This refers to expected payments to the region/community for bearing the burden and for compensation for losses.
Control/research/innovation	This category comprises terms and comments concerning the scientific and security aspects, such as “Better control of regional disposal” or “Research on the use of nuclear waste”.
Disposal/solution itself	The DGR is perceived positively as a solution to the waste problem.
Don’t know	This applies to instances when the respondents explicitly state that they do not know. This may include a few comments that actually mean that there are “no” positive aspects.
Economic benefits	These comprise any financial benefits that may accrue to the siting region (e.g. “Taxes for the municipality”, “Cost reduction, quality of life”).
Environment	This encompasses comments and terms mentioning the environment and animals (“Partly good for the environment”).
Continued use of nuclear power plants	This pertains to the idea that a solution to the waste disposal problem could mean extended power plant operation.
Health protection	Protection of one’s health (“Health protection through proper disposal”) is mentioned as a positive aspect.
Infrastructure	This refers to the expectation that “Brownfield land can be put to full use” or simply “infrastructure expansion”.
Land/property prices	Some respondents expect the price of real estate or the value of land to increase.
Nothing/None	This consists of instances when the respondents explicitly state “none” or “there are no positive aspects”.
Opportunities	This includes general talk about “benefits”, such as “I also see opportunities”.
Other	This category contains all terms that could not be assigned to any of the other categories (e.g. “Avoiding overly dense development [in the sense of buildings]”).
Region is unsuitable anyway	Some of the respondents express the opinion that their region would be an unsuitable location for a DGR.
Regional promotion	The respondents mention positive effects on the region, for example, in terms of “increase in security staff, influx of companies” or generally “planning reliability”.
Responsibility/contribution	This refers to the notion that one must show some engagement with/commitment to solving the waste disposal problem.
Risks	Although the question asks for positive aspects, some respondents mention risks instead (e.g. “No, a residual risk always remains”).
Work/workplaces/job creation	These terms refer to work opportunities.

Table 3. Risk items and ratings by cluster (M = mean, SD = standard deviation).

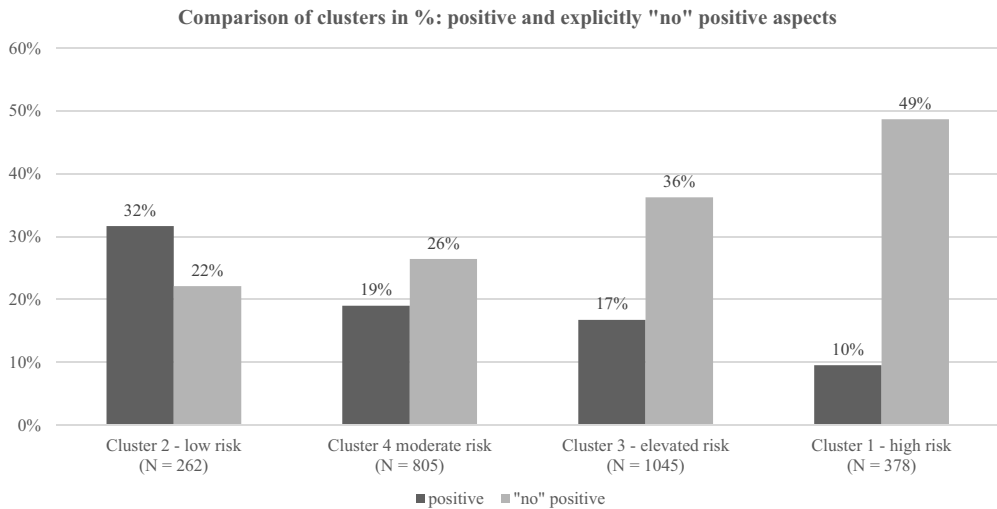
Risk items (N = 2,490)	M	SD	Cluster 1 (N = 378)	Cluster 2 (N = 262)	Cluster 3 (N = 1,045)	Cluster 4 (N = 805)
for drinking water and groundwater for the health of future generations	5.5	1.53	7.0 (0.20)	2.6 (1.16)	6.3 (0.75)	4.6 (0.94)
for animals and plants	5.4	1.54	7.0 (0.22)	2.5 (0.99)	6.2 (0.76)	4.6 (0.92)
for agriculture	5.3	1.58	6.9 (0.29)	2.5 (1.05)	6.1 (0.81)	4.5 (1.04)
for my health	5.2	1.58	7.0 (0.24)	2.3 (0.91)	6.0 (0.85)	4.4 (0.94)
for property prices	5.1	1.64	6.9 (0.23)	2.3 (0.99)	5.8 (1.05)	4.2 (0.98)
for regional products and services	5.1	1.61	6.9 (0.32)	3.7 (1.89)	5.2 (1.48)	4.5 (1.23)
<i>Risk scale</i>	4.9	1.59	6.9 (0.31)	2.4 (0.96)	5.5 (1.09)	4.1 (0.94)
	5.2	1.58	6.9 (0.12)	2.6 (0.85)	5.9 (0.48)	4.4 (0.52)

Table 4. Characterization of the clusters concerning sociodemographic data. Percentages, mean values, and standard deviations (in parentheses).

Risk clusters	Mean age	Women	Men	School/ training	Baccalaureate/ university degree	Political orientation (1 = left, 11 = right)
Cluster 1 (N = 378)	51.4	66.7%	33.3%	30.2%	69.8%	5.7 (1.88)
Cluster 2 (N = 262)	50.8	30.5%	69.5%	35.9%	64.1%	6.2 (1.98)
Cluster 3 (N = 1,045)	46.2	57.2%	42.8%	38.8%	61.2%	5.7 (1.68)
Cluster 4 (N = 805)	46.9	45.7%	54.3%	36.8%	63.2%	5.9 (1.76)

Table 5. The risk clusters' attitudes towards the topic (interest in and relevance of the problem) (M = mean, SD = standard deviation).

Risk clusters	I am interested in the topic of final disposal		I do not see radioactive waste as a problem at all	
	M	SD	M	SD
Cluster 1 (N = 378)	5.0	1.85	1.8	1.53
Cluster 2 (N = 262)	4.1	1.81	3.3	2.03
Cluster 3 (N = 1,045)	4.7	1.54	1.9	1.39
Cluster 4 (N = 805)	4.4	1.51	2.8	1.56

**Figure 2.** Differences among the risk clusters in terms of their reported positive aspects relative to the explicitly "no" positive aspects. Note that the clusters are sorted from highest to lowest percentage of positive aspects (left to right). Only two of the 19 categories are shown (i.e. they do not total 100%).

Discussion

The primary objective of final disposal in a DGR is to protect the environment/nature and human health (International Atomic Energy Agency 2011). This benefits the whole country. However, a community has to take the responsibility and bear the burden. Therefore, some compensation to the host community is appropriate. However, this is a tricky issue because promised benefits such as financial compensation can be interpreted as bribery and generate reactance (Krütli et al. 2010; Hannis and Rawles 2013).

Nevertheless, such a repository for HLW can offer several potential benefits to the local community, depending on the specific circumstances and how the facility is managed. Interestingly, the main goal of “protecting the environment and human health” is mentioned only a few times by our respondents. This could be explained by the perspective of a citizen who imagines being forced to live near an HLW repository. Except those currently living near interim storage sites, it is unlikely that the general citizen would perceive a concrete HLW problem. But an imminent repository near one’s home would probably introduce new (perceived) risks that were not present before. Thus, it may be a comprehensible response to reject a nuclear facility imposed on someone. In addition, the fact that health protection has hardly been considered at all should be taken into account in communication efforts. For the average citizen, it may be necessary to reiterate that the primary objective of disposal in a DGR is to remove HLW from the ecosystem as well as possible (StandAG 2017). The reports and research cited above emphasize the protective functions of a DGR, but these functions are apparently not widely known among our respondents.

Several further potential benefits are mentioned in scientific and grey literature, such as reports by the IAEA or the OECD-NEA (Organization for Economic Co-operation and Development/Nuclear Energy Agency). Work force is needed during construction and once operational, a nuclear waste repository can even provide long-term employment opportunities for local residents in various operations and fields, such as facility maintenance, security, and scientific research. Other positive aspects may be infrastructure investment in the region, education and research opportunities, increased property values, and community investments (e.g. grants or scholarships). While some of these advantages of an HLW repository (such as potential employment opportunities in the region or economic benefits) are in fact mentioned by the majority of the respondents fail to identify any positive aspects. Instead, most of them emphasize that they see “no” positive aspects at all.

However, a (relatively) significant number of respondents welcome the DGR as a solution to the German waste disposal problem or express a sense of responsibility for solving the problem. This result could be used for communication with the public by stressing the disposal issue as a national responsibility (for a Swiss study, see Stefanelli et al. 2017) and the solution as a success in itself.

Further, positive aspects relate to the use of nuclear power, which could be justified by providing a solution to the waste disposal problem. Meanwhile, all nuclear power plants in Germany have been shut down, and a revival of the technology appears unlikely today (Schneider and Froggatt 2023). Communicating positive aspects – in such a way that a solution to the HLW disposal problem would justify further use of nuclear power in Germany – may elicit at least mixed feelings among many citizens. Nonetheless, research and know-how are also needed in the nuclear domain in the coming decades (for medicine and decommissioning of nuclear facilities, to mention only two). As the category control/research/innovation shows, some respondents are aware of this link. In attempts to communicate with a heterogeneous public, it would be a good idea to show the benefits, for example, in the medical use of radioisotopes, and to stress that the decommissioning of closed power plants is unavoidable, which requires continued research and development efforts and the maintenance of skills and competencies. We propose that knowledge is not enough – but it is an important cognitive component.

Rather than paying attention to positive aspects, the public debate about various decision-making efforts often focuses on the risks or negative aspects: “Risk is important. So are benefits. However, risk is often more important for decision makers and for the public than is benefit” (Sjöberg 1998, p. 75). This is all the more true for risks associated with nuclear waste in general and a DGR in particular (Zhao 2023). Despite our request to list positive aspects, some respondents mention potential risks or reasons why their region would be unsuitable as a host community. It seems that for those individuals, even the request for positive aspects does not resonate with them. Instead, they comment on risks or safety issues. This result resembles those of other research where “concepts such as risks, safety and transportation issues were the only ones mentioned by lay participants” (Skarlatidou et al. 2012, p. 15).

It is possible that a broader social significance can be derived from this. Some problems may not be given sufficient consideration because they are not immediately recognizable and cannot be used to achieve short-term political success. If you push a fire-breathing dragon into a crevice, you have solved an acute problem. If you put radioactive waste, which is considered dangerous but whose risks are rather abstract, into a geological layer, the solution to the problem is not so clear. The advantage over the status quo is not immediately tangible, at least for the majority of the people who do not live near interim storage sites. One idea would be to emphasize the negative aspects of the status quo. However, should the risks of the status quo be dramatized? We believe that transparency is necessary, but that the efforts of the responsible organization to maintain the safety of the interim storage sites should be acknowledged (Bundesgesellschaft für Zwischenlagerung 2024).

We also examined how the positive aspects were related to patterns of risk perceptions, confirming the findings of previous studies in Switzerland and Germany that the respondents differed in their relative perceptions of risks and benefits. When positive and negative aspects of an issue are perceived simultaneously, this can be referred to as ambivalence (Thompson et al. 1995). Previous studies found different clusters of risk and benefit perceptions of HLW repositories, revealing subgroups with strong risk perceptions, risk indifference, or ambivalence (Seidl et al. 2013, 2022). People with high risk perceptions tend to rate potential benefits as low. In this study, we examined the relation between risk and benefit perception differently. Benefits were assessed through an open-ended question. The results show that those with high risk perceptions indeed mention fewer (but not zero) positive aspects. The subgroup with low risk evaluations mentions the highest number of positive aspects in contrast to those who explicitly state that there are no positive aspects. This finding confirms the inverse relation observed in previous research using different methods – that is, high risk perception is associated with low benefit perception (Alhakami and Slovic 1994).

A study ($N=42$) conducted in Switzerland on the subject of values and risk perception in relation to a DGR (Seidl et al. 2013) revealed that the majority of the interviewees used long-term safety (36 times) as an argument against the DGR, whereas only two instances were cited in favour of it. That study also showed that the interviewees challenged the essential issue of the long-term safety of such a DGR, although it is considered by a majority of experts the best long-term option in terms of geological and technical requirements (International Atomic Energy Agency 2003). However, the study participants did not explicitly mention the question of a DGR versus surface storage. So, in our study, we made this tradeoff more explicit.

The majority of citizens of European countries favoured DGR as a solution for nuclear waste management (European Commission 2008). Of course, the answers depend on the type of question. In a 2008 survey by the EC, for instance, the question read: “For each of the following statements, please tell me to what extent you agree or disagree. Deep underground disposal represents the most appropriate solution for long-term management of high level radioactive waste”, while in the latest German Survey by Götte (2023), the question was directed towards the current site selection phase. The results indicate that “the repository search in Germany enjoys public support. 59% are unreservedly in favor of searching for a repository in Germany” (Götte 2023, p. 8).

Notably, respondents rarely have to choose between options. Our respondents explicitly prefer DGR to surface storage, although they do not generally support this choice, citing many positive aspects. It could be postulated that a DGR would be perceived as a necessary evil with no tangible benefits, even if it were regarded as superior to surface storage. Further research is required to elucidate this relation. It is necessary to examine the tradeoffs between the risks and benefits of both DGR and surface storage, with a clear discussion of each option. Historically, Gorleben (c.f., Hocke and Renn 2009; Kirchhof 2018) and currently the case of the Asse II site, where low-and medium level waste shall be retrieved (Ilg et al. 2017), the disposal of nuclear waste is commonly associated with negative connotations and negative reporting about the current site selection phase.

Even that most respondents would prefer a DGR over keeping storage of waste on the surface, they do not providing many reasons for their choice. It is common for individuals to display inconsistencies in their mental models (Bostrom 2017). It is not our intention to educate the public in the sense of correcting their cognitions and hoping that they will accept the solutions proposed by experts. Such a “deficit model” approach is clearly outdated (Balog-Way et al. 2020; Dendler 2022). In our experience, however, people are keen to receive trustworthy information (Bearth and Siegrist 2021) that can, ultimately, also change their minds. In turn, researchers may adjust their views or expand their research questions when they learn from citizens (Schulz et al. 2023; Seidl et al. 2024).

In a recent South Korean study that examined risk acceptance by integrating economic individualism and social constructivism, weighing risks and benefits played an essential role in the acceptance of a nuclear power plant (e.g. Nam-Speers et al. 2023). Accordingly, to resolve the tradeoff between positive and negative aspects associated with a nuclear facility, it is crucial to consider both aspects in a balanced communication approach. While the focus here is on risk and benefit perceptions, the authors of the study conclude (and we concur) that their “findings emphasize that risk studies of nuclear energy should pay attention to the social, cultural, and historical contexts of nuclear energy as well as its economic aspects when we examine the determinants of risk acceptability” (Nam-Speers et al. 2023, p. 709).

One potential avenue involves fostering a narrative that portrays a DGR as a potential resolution of the waste management issue. Stressing the long term passive safety aspect of a DGR could resonate with the public’s desire for a timely but safe solution to the waste problem. The German participatory procedure provides ample opportunity for citizens and experts to discuss these issues in more detail. Therefore, this debate should be part of a broader public deliberation (Bergmans et al. 2015).

We propose a reframing of the DGR as a preferable alternative to the continued storage of waste on the surface. Such a proposition would likely necessitate an explicit acknowledgement of the safety tradeoffs inherent in the status quo and the enhanced safety

benefits anticipated from the DGR, as currently planned in Germany. At present (in 2024), we observe an expansion of the debate concerning the interim storage locations because the period required for investigating the underground and planning the repository is longer than previously estimated (originally until 2031, c.f. Berg and Hassel 2022; Ott 2022, 2024; Di Nucci and Brunnengräber 2023) and the approval for those interim locations is limited. Although the majority of the German public can be said to favour a timely and safe solution, the riskiness of this solution is seldom compared to the risks and benefits of the status quo. Nevertheless, it is perhaps important to emphasize that this is not about ignoring people's worries and fears or not taking them seriously. It is a matter of deliberating the actual tradeoffs through participatory procedures. One limitation of our study is that we did not ask respondents to rate DGR and surface storage on both positive and negative aspects simultaneously. There are also positive (better monitoring) and negative (waste exposed to short-term societal changes, terrorist attacks, etc.) aspects of surface storage (as succinctly discussed in Eidemüller 2021). Further research should focus on the arguments for either the DGR or continued surface storage (and other ways of dealing with HLW) that resonate with citizens, not just experts.

Perception and understanding of benefits are not straightforward. Similar to communicating risks and uncertainties (Broomell and Kane 2017; Gustafson and Rice 2020), disseminating information about benefits is a challenge (Peters et al. 2007). Different audiences may have varying levels of knowledge and numeracy skills and thus of the understanding and use of risk – benefit information. In addition, people have different value preferences, but in the case of HLW, people generally value safety highly (Götte et al. 2021; Heiermann and Olszok 2024). However, they may come to different conclusions (for or against a DGR) depending on their perception of risk (Seidl et al. 2013). This aside, it is clear that other variables such as trust and values (e.g. fairness and safety) play a role in public reactions to risky technologies (Seidl and Drögemüller 2024).

Our methodological outlook is that further studies should adopt a more comprehensive bottom-up approach to examine the perceived risks and benefits of both surface storage in interim facilities and a DGR. We suggest more qualitative studies (such as interviews or focus groups) or survey studies that ask respondents open-ended questions rather than relying on closed-ended questions or statements to be rated on a Likert scale. Both should be done in a way that makes tradeoff situations more salient (e.g. prolonged surface storage vs. DGR). We need to know what the public's fears are and what positive aspects they actually see in a particular technology. Otherwise, in closed question formats, statements may be rated by respondents who have never thought about them. We then have a result, but without clarity about its validity. Future research should prioritize the examination of the foundational principles of quantitative methodologies and the development of questionnaire items. We see a need for regular updates to these items.

Notes

1. There is a contrary concern of an expected drop in prices due to a declining image of the host region. However, this concern is difficult to substantiate. At least in Switzerland it could not be verified, c.f., Sombre and Rütter-Fischbacher (2018) neither earlier in Finland, c.f. Avolahti and Vira (1999) Nevertheless, the expected decline in image may be a reason for opposition.

2. <https://de.statista.com/statistik/daten/studie/1365/umfrage/bevoelkerung-deutschlands-nach-altersgruppen/>.
3. <https://www.bpb.de/nachschlagen/zahlen-und-fakten/soziale-situation-in-deutschland/61656/bildungsstand>.

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Data availability statement

The authors confirm that the secondary data supporting the findings of this study are available through this repository: <https://doi.org/10.25835/9vmuf83v>.

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