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Lessons from national approaches: a long uphill struggle in search of sites for repositories for nuclear waste locations

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Abstract. A quarter of a century ago, a long-term expert in the nuclear waste scene stated that "the management of spent nuclear fuel and high-level nuclear waste has the deserved reputation as one of the most intractable policy issues facing the United States and other nations using nuclear reactors for electric power generation" (North, 1999, p. 751). Apart of exceptions, this statement is still true. At some points, however, there is light at the end of the tunnel if we can read the signs of the times. It will be a long hike, in steep terrain, poor visibility and with an approximate destination. We need a safe and acceptable site, tolerated by the affected parties, where a repository can be built, operated and, finally, closed down in reasonable course by a generation to come and with a clear conscience. This contribution does not present the silver bullet (which does not exist) but suggests some criteria and characteristics which have not been respected in the history of final disposal – but they should be. It needs adequate resources: stable structures, competent institutions, learning personnel (in institutions and civil society), mature and open discourse as well as sufficient time. Based on https://doi.org/10.5194/egusphere-egu24-6514 (Flüeler, 2024a).

1 Baseline: technological constraint, complex, multidimensional, systemically "unfair"

The disposition of radioactive waste is the factual technological constraint that the sheer existence of radioactive waste poses. More than 260 000 metric tonnes of high-level waste are piling up in above-ground storage sites (WNA, 2022) (Fig. 3c), close to 90 000 t in the US (GAO, 2024), more than 60 000 t in Europe (WNWR, 2019). And still: zero tonnes have been disposed of, accurately listed in the latest official data, for 2016 (IAEA, 2022a, p. 52). All involved parties are confronted with this precondition. Unlike other controversial technical issues, "nuclear waste policy was not the engine that drove politics, but the product of political, economic, and social engines which drove the politics of nuclear waste" (Jacob, 1990, p. 22)[1]. Given the backlog of waste and the immature technology of other options (partitioning & transmutation, P&T, etc.; Nagra, 2024b; BASE, 2024a) relief is not in sight, even aggravation – in the case of small modular reactors – is possible (Krall et al., 2022); P&T will probably only reduce some fractions of the waste (and only those not posing the highest dose problem) but will not make final disposal unnecessary. Waste disposal is a complex sociotechnical system (Flüeler, 2001b): "a system of action or a working system where human and technical subsystems constitute a unity" (Ropohl, 1999, p. 142f., transl. tf). Radioactive waste governance is characterised by all relevant features of a complex situation (of action) (Dörner, 1989). Many individual attributes have to be considered, often simultaneously and in an interconnected manner, i.e., with all

[1]The eminent relevance of waste disposal was pointed out at the First International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955, already: "The disposal of reactor and fuel processing wastes will be one of the major controlling factors in determining the extent of the use of power reactors competitively with other sources of fuel for energy production .... To dispose of these materials will undoubtedly challenge the ingenuity and imagination of the scientist and industrialist" (Wolman and Gorman, 1956, p. 15).

their side or long-distance effects of a technical, institutional and political nature. These interactions are not static but dynamic and extremely long-term. The system's own momentum with the technical, institutional and political subsystems is to be assessed in their development. Hereby, the situation is not transparent for the actors since they do not have complete information, they do not even know exactly which situation they are in at the moment. Uncertainties about the state of disposition increase with time, let alone about the social setting. In line with this, over 20 years ago, the US National Research Council viewed high-level nuclear repositories as "first-of-a-kind, complex and long-term projects that must actively manage hazardous material for many decades" (NRC, 2002, p. 1).

The worldwide observable stalemate in the disposition of (high-level) nuclear waste is heavily due to the fact that this policy field missed out to recognise the various and diverse dimensions. As explained below, the aspect of control is an example of how in complex sociotechnical fields, especially with respect to technological constraints, dimensions are often debated in reverse order: firstly, the technical and commercial aspects, followed by the political and economic, the social and, finally, the ethical aspects. It ideally should be the other way around: first, one should have a broad debate and decision on political principles over ethical guidelines; this should in turn lead to the selection of the corresponding optimum technical variant, in consideration of ecology, economy and society.

There is consensus that the safety-related management of this waste is of long-term character. But not just that – it is also institutionally tortuous as many technical, societal and political *generations* must deal with it: from site selection to the closure of the facility, possibly beyond (Fig. 1).

The long-term characteristic of the system entails that today's generations have to take decisions for tomorrow, at any rate – "postponement" is a decision as well. Beside "winners" (the waste producing generations), there are potential "losers": the directly affected and the generations to come. This is a formidable risk-benefit asymmetry and long-term management of toxic waste epitomises some relevant distributional issues (Flüeler, 2005):

– local cost and risk vs. general benefit (intragenerational equity issue);

– lay persons' vs. experts' perspectives (evidentiary equity);

– today's vs. future generations (intergenerational equity).

According to Ulrich Beck "large-scale hazards of late industrialism" are characterised as follows (Beck, 1992):

– they cannot be delimited with regard to location, time and population concerned;

– causality and liability cannot, in the long run, be attributed to anyone;

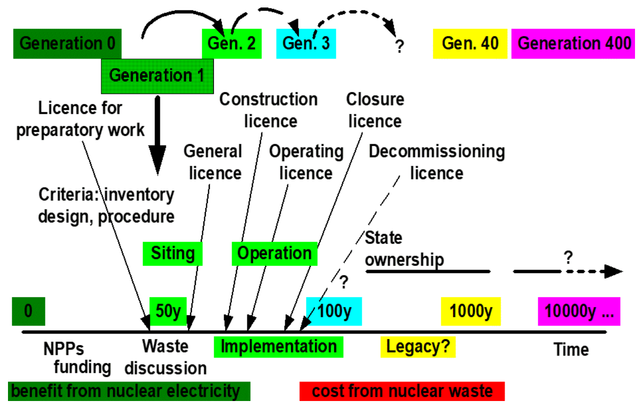

Figure 1. Radioactive waste governance has a long-term safety *and* a long-term project character. It must be backed up by the scientific-technical community, the political decision makers and the general public over decades. While still benefitting from nuclear electricity we, at present, are "Generation 1" having to start implementing. Some duties – of monitoring, etc. – will have to be handed over to "Generation 2" being at the edge of merely bearing risks from waste. "Cost" is meant beyond monetary aspects, in the sense of "burden" such as potential failure or contamination (source: Flüeler, 2004).

– the irreversibility of potential consequences cannot be compensated.

Niklas Luhmann talks of "impositions of rationality" in the case when a transfer takes place from the (self-born, calculated) risk of the decision maker to the (imposed) danger for the people concerned and affected by the decision: "The risk-taking behaviour of one person turns into danger to another one, and the difference of danger and risk becomes a political problem" (Luhmann, 1990, transl. tf).

2 Approach from robustness to resilience

In complex issues, it is very well feasible that conflicting goals exist. The magic spell of "sustainability", a complex goal as well, encompasses protection of, and leeway for, future generations. In the case of a safe disposition of radioactive waste, both passive safety and "active" control or surveillance need due care and attention in parallel (see, e.g., Flüeler, 2006). The aim is to attain, on the one hand and overall, a conservative, passive, and stable system with, on the other hand, control and intervention mechanisms built in during initial phases. The underlying assumption is that dealing with a complex sociotechnical system, such as the disposition of radioactive waste, needs an integrated perspective (Pearce, 1979). Applied to the radioactive waste field, it means that the system calls for technical and geological barriers against releases of radioactivity over time, as well as societal checks to achieve and sustain confidence in technical assessments and, hence, acceptance. It is, in fact, an integration of societal aspects into the defence-in-depth strategy familiar to radioactive waste-performance assessments (IAEA, 1996).

In general, a system is robust if it is not sensitive to significant parameter changes, such as from external impact, and if it rests within well-defined boundaries. Robust procedures, as defined in a narrow sense, can only be achieved when the problem at hand is strictly technical. The system characteristics of radioactive waste, however, are such that regarding long-term safety it "is not intended to imply a rigorous proof of safety, in a mathematical sense, but rather a convincing set of arguments that support a case for safety" (NEA, 1999, p. 11; NEA et al., 1991, pp. 10, 13). Therefore, even technical robustness cannot be treated as in "conventional" technical systems. Nevertheless, it is precisely the robust control systems that are designed to manage the manifold types of uncertainty (stochastic, model, structural, etc.; see e.g., Kurgyis et al., 2024).

Accordingly, "social robustness" can be obtained if most arguments, evidence, social alignments, interests, and cultural values lead to a consistent option (with Rip, 1987, p. 359). Following this argument leads to the insight that robustness falls short in our case of long-term complexity. The advanced concept of resilience (Walker et al., 2004; Buzzanell, 2010) signifies that a system may absorb disturbances *before* it needs restructuring, proactively, not just by way of an additional barrier – and this comprehensively: on the micro-level (individual, staff), the meso-level (group, institution, company) and the macro-level (regional, national, international, supranational) (detailed in Flüeler, 2023).

Interim conclusion: long-term safety of nuclear repositories cannot be proven in the strict sense. The disposition of nuclear waste as an imposed technical constraint is technically complex and societally contentious. The problem is intricate, often called "wicked" (Brunnengräber, 2019; Rittel and Webber, 1973), in my view preferably rather named "messy" (Metlay and Sarewitz, 2012): it is vaguely defined and without clear stopping rules when and how exactly a solution is reached. The selection of a site suitable in terms of safety and societal tolerability in parallel is a first step towards a resilient "solution". There are no silver bullets but the approach must be integrative in the sense that all relevant dimensions (Fig. 2) are sufficiently and continually considered (attempted, e.g., in Schneider and Liebscher, 2024).

3 Highly complex system: product *and* process must be good

We are confronted with an extraordinarily complex constellation: substantively, timewise and with a multitude of alternating players. The proof of safety is intricate where only few experts have it figured out. 99 % of all are laypeople – also the experts in areas where they have no expertise. The whole programme drags along for decades. The conclusion is that from the viewpoint of society the process, and not the product (the facility), stays in the core (Krütli et al., 2012). Confidence in the process and mutual trust in the actors is pivotal. This needs resources: structures, competent institutions, staff, discourse, time, money, and so on.

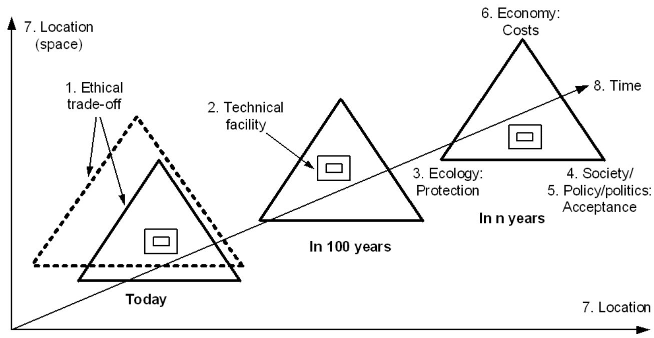

Figure 2. Sustainability of disposition systems. Eight dimensions – not just the three classical ones of the "magical" triangle Ecology-Society-Economy – have to be considered: an ethical trade-off takes place in the design of the facility (technical dimension), along the ecological dimension (protection of humans and the environment), the social and political dimensions (society and balance of power determine acceptance) as well as the economical dimension (costs of disposition including institutional control). This decision bears an eminent spatial (location) and temporal dimension (period of isolation and concern) (source: after Flüeler, 2001a, 2023).

Many are involved. Staff of the key institutions proponents, regulators, advisory committees – really everyone – need:

- an adequately developed discourse culture;
- respect for other people and opinions;
- the grandeur to admit failures;
- stamina *and* flexibility;
- the capability to change perspectives, and
- empathy.

The valid German Repository Site Selection Act of 2017 embraces such an approach by demanding a "participative, science-based, transparent, self-questioning and learning process" (StandAG, 2017; cf. BGE, 2024a). This prerequisite is due to the fact that all former approaches failed (as the seminal German expert group AkEnd was ignored at the time) and, frankly, disposal was a failure story and does not bear any setbacks any more. A liberating move for the new start was BGE's decision to abandon the Gorleben site that had loomed over the entire discourse for more than half a century (Tiggemann, 2019). In general, neither legacies nor permanent (interim) storage, a contradiction in itself, can be a durable solution (Fig. 3). Only a truthful technical and societal discourse in a systematic safety-related site-selection process can have a chance of success.

An inclusive participation and integration of concerns is vital, especially in the conceptual phase, because this is the only feasible way to, in the long run, legitimise well-supported decisions on issues with far-reaching consequences. Besides, Brian Wynne pointed out that information (of any type) only has informational character to those who share the underlying assumptions, otherwise it is (de-)valuated as an artefact (Wynne, 1989). This dynamic approach with mutual learning is indeed time-consuming but likely to be, in the long run, more effective (goal oriented) as well as more efficient (with less frictional costs) than previous approaches.

Since all objectives of all stakeholders can never be attained, they have to be prioritised and negotiated, and according to their respective responsibilities at that (Linnerooth-Bayer and Fitzgerald, 1996). It would be daring – and utterly naïve – to maintain that their belief systems could be changed – certainly not in their core principles, but perhaps modifications are possible in secondary aspects (Sabatier, 1987) – in so far as the actors would identify some common interest or, in Luther Carter's unspecified words, some "common ground" (Carter, 1987, p. 427). The yardstick proposed is, as mentioned, an enlarged notion of sustainability (Fig. 2). The element "society" in the sustainability triangle addresses the participation of, and acceptance by, the public.

The definition of what is "socially robust" of above makes it clear that "process" is not just a question of involvement but that very different aspects from diverging perspectives are addressed and integrated. By focusing on "common ground", rather than "consensus", it has to be emphasised that it is not intended to call for as many voices but for as many perspectives as possible so as to incorporate all relevant facets in the dimensional discourse: ethical, technical, ecological, economical, political, societal, spatial and temporal. This is not to avoid the issue of representativeness or, by no means, to devitalise claims for wider participation (e.g., OECD, 2020), but to focus on an inclusive deliberative discourse. By "deliberation" we mean sufficient agreement on central issues by way of consultation and convincement with substantive arguments (Habermas, 1984): at least consent (no one or just a few say no) instead of consensus (everyone says yes) with regard to a site. In view of this multidimensionality this may be an avenue to reach a societal "closure" of the issue (Berkhout, 1991; Bijker, 1995), at best an attempt to foreclose a "colonization of the future", as the futurist Jungk clairvoyantly cautioned against in the 1950s already (Jungk, 1954).

With criteria from decision science and governance concepts (UNESCAP, 2009) we may operationalise what is termed "common ground" in a stepwise procedure and on three discourse levels (see Flüeler, 2023) (Table 1).

This approach avoids an undue complexity reduction or a decontextualised (historically failed) "technical fix" or, for that matter, "social fix" (with volunteering communities in the forefront). It is based on a long-time in-depth comparison of national radioactive waste programmes, whereby two courses of action stand out, namely the Swiss and the German site-selection procedures, trying to duly acknowledge both sustainability goals protection and control.

If we apply the three discourse levels to reach "common ground" in selected waste programmes to the wider notion of governance against the background of legislation, technical and empirical perception studies, we may reach the fol-

(a)

(b)

(c)


Figure 3. Dystopia or negative goals – an intransparent decision for a site provokes harsh opposition **(a, b)** or a postponement represents false solutions **(c)**. **(a)** Mistrusting civil society (protests against the – former – Gorleben site). **(b)** Leaking research demonstration site and exploited salt mine turned into a so-called "repository" (Asse, Germany). **(c)** Interim storage as a permanent makeshift, with no final disposal in sight (spent fuel dry casks in the open, Indian Point nuclear power plant, USA) (sources: Strangmann DDP; Archive BGE; Ricky Flores).

Table 1. Criteria of decision science and governance frameworks on three discourse levels (steps: *inform, decide, organise*; plus *control*) (source: Flüeler, 2023, modified).

Framework	Decision science (discourse levels)	Governance
Step 1	*Inform yourself* Information gathering	Integrated knowledge production
Discuss	**Problem recognition** Problem identification Problem formulation	Diagnosis
Step 2 **Decide**	*Decide* **Main goal consensus** Options Design Uncertainty handling	**Goals and priorities**
	Resilience/adaptability: reversibility, retrievability, control, pilot facility Conflict management	Strong network *and* flexible structures
	"Rules of the game"	**Procedural strategy** Rules, procedures: legislation, guidelines Determine actions: programme, resources
Step 3 **Implement**	*Organise* Resilience: (regional) sense of ownership and care	Coherent action Resources to execute action: adaptive institutions
(Step 4 **Evaluate)**	*Control/validate* Compare factual/target states	Oversight Long-term effects of measures Check interactive strategic development

lowing on the three discourse levels (Table 2, supplemented by another step: appraisal):

1. Problem recognition: there is consensus that nuclear waste exists and has to be managed, independent of its place of origin.

2. Main goal consensus: domestic solutions are favoured in the nuclear community. The degree of protection and intervention is not unanimously defined (no retrievability in the USA, 500 years of recoverability in Germany, as long as a pilot facility is open in Switzerland). In an adequate goal analysis, the system performance strived for has to be examined as well as the so-called goal-means relations, i.e., the deployment of resources to reach the goals, and the participation in procedures (see "process utilities" below). In view of the sustainability goal relation, "protection versus control" and process- versus outcome-orientation, it is understood that the radioactive waste system has to be dynamic, adaptive and even experimental in its instruments (Cook et al., 1990), but not in its ultimate goal, i.e., the passive protection of present and future generations and environments. Central topics such as final disposal versus retrievability of waste (and, on top, reversibility of decisions) have to be put on the table. This is sensitive and explosive, but it has to be done, in a comprehensive way. Otherwise, it will come back to us or our descendants. The goal hierarchy is protection over control. The goal discussion has to be led in a broad and open manner, also because catchy but simplistic formulae (like the call for "reversibility of all decisions") have to be exposed and fundamental inconsistencies have to be dispelled. Whether and how monitoring and retrievability have positive effects remains to be shown (Mintzlaff et al., 2022). Impacts from unfounded decisions will likely be at the expense of future generations; inconsistencies are detrimental to the credibility of the entire system, and corrections made afterwards are at any rate expensive in view of the dimension of the programme if, at all, practical and efficient.

3. Procedural strategy: as for non-experts it is hard to get a clear view of the whole, it is easier to follow a straightforward procedure. Procedures symbolise the continuity of similar experience and may add to actors retaining and gaining trust in the political system (Luhmann, 1969). In the context of laypeople and probabilistic analysis, Lanning Sowden referred to "process utilities" (Sowden, 1984, p. 297). In so far, technocrats must learn that laypersons may rather be process- than outcome-oriented. And that their own credibility is at stake; trusted procedures are interconnected with trusted and trustworthy players (e.g., Lehtonen, 2020). Clear

"rules of the game" (to start from scratch) were set in Switzerland (with a site-selection procedure called Sectoral plan 2008) and Germany (with Repository Site Selection Act/StandAG, 2013/2017). In the USA, Congress singled out Yucca Mountain as the only site for a high-level waste repository by the 1987 Amendment to the Nuclear Waste Policy Act of 1982, which had foreseen a selection of sites in the east and the west based on technical criteria alone. Finland sticks out in so far as it is the only country to meet its own once-set timetable (NEA, 2019; Metlay, 2021; Economist, 2022). Together with Sweden, it stands alone as being successful – a "game changer" as IAEA Director Rafael Grossi postulates it (IAEA, 2020); geologically difficult conditions are compensated with technical barriers, and that in "nuclearised" communities with high trust in state agencies (Choi, 2018; Lagerlöf, 2023). Trust in Scandinavian civil societies seems so high that control (and monitoring) is not given great importance and retrievability is not planned (Lagerlöf et al., 2018). This is in sharp contrast to, e.g., France (Kojo et al., 2019).

4 "Soft" factors: safety culture, failure culture, organisational culture

We are faced with interactive complex and coupled systems that aggravate learning, processes are incompletely known, they are often unidirectionally defined and there is little room for manoeuvre. Often it is not until grave accidents provoke a change of thoughts and action. The nuclear accident of Three Mile Island (Harrisburg, PA) in 1979 forced the "human factor" to become the new centre of attention in reactor safety (LaPorte, 1984; Perrow, 1983). And it was after the catastrophe of Chernobyl in April 1986 that the International Atomic Energy Agency, IAEA, developed the concept of "safety culture" (IAEA, 1991; NEA, 2016). At the beginning of the same year, the most severe accident of the US space programme till then occurred, the explosion of the Challenger space shuttle 73 s after take-off. After that, NASA must have seen their Apollo 13 flight director's statement "failure is not an option" in a different light (NASA, 2017, cf. Challenger Space Shuttle Disaster, 1986).

Failure is always an option, sometimes even leading to improvements. Admitting failures usually means taking the blame – but it can be reassuring, and a group, a company, an institution may even emerge strengthened out of a mishap or incident if they truly learned their lessons. Examples are the shift from crystalline to sediments as host rocks in the Swiss nuclear disposal programme in the 1990s (HSK, 2001) or, as mentioned, the recent abandonment of Gorleben as a potential site in the respective German programme. In some instances, it is not clear how far learning has gone, e.g., following the 2014 accidents at the US site for transuranic waste WIPP (Klaus, 2019). Recognising the longevity of the processes, each information and knowledge transfer may produce errors, misunderstandings and misinterpretations.

Following the concept of this contribution (integrate issues and perspectives), the notion of "failure culture" applies on several levels, always keeping in mind the precarious relationship between benefits and impairments on the timeline:

- conceptually: implement a robust site selection, allow regress if considered essential;
- regulatory: execute phase-wise safety assessments (site selection, design, construction, operation, closure, post-closure);
- design-wise: e.g., integrate control mechanisms (pilot facility for surveillance and control), ensure (limited) retrievability;
- organisationally, culturally: secure information and knowledge transfer (with possible information losses as failure), assure and document ways to treat minority views, foresee an enlarged assessment, install a process guardian.

Safety culture, and organisational culture at that, encompasses the full range of levels: from top management to the individual collaborator (Schein, 1992). According to the IAEA, it is "the assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, protection and safety issues receive the attention warranted by their significance" (IAEA, 2022b).

Overall, it is essential to allow a comprehensive discourse in society about the matter under scrutiny so that no pertinent issues fall overboard. The approaches in various countries evolved over time (Fig. 4), basically from technocratic to more pluralistic models (Arentsen and van Est, 2023) as the former failed in every case. As a consequence, away from linear decision making (by the authorities and proponents), Japan (Amekawa, 2023) and the United Kingdom ("working with communities", BEIS, 2018) have adopted a voluntarism approach, whereas in Sweden, Finland and Belgium (here for low-level waste with so-called "local partnerships") the proponents reached an agreement with already "nuclearised" communities. In nuclear disposal, Germany and Switzerland unmistakably set (passive) safety first, yet they involve and plan to involve the public on a regional level (Switzerland) or on all levels (Germany). The former needs twice as long as the Government once intended (20 instead of 10 years) but seems to be on target. Upon the crushing verdict of the first-time, technocratic Canadian selection procedure (Seaborn Panel; Carnes et al., 1983: "choice of one is not a choice"; cf. NEA, 2003), there was a promising start with a national dialogue (2005–2010); but currently Canada is stuck with two potential sites (NWMO, 2024). The Netherlands pursue the single option of an above-ground (interim) storage. In Spain, there is a wrangling among political parties even on the centralised storage facility ATC/CSF (Espluga-Trenc

Table 2. Accordance of criteria of "good governance" and "common ground" in selected national radioactive waste programmes (source: Flüeler, 2023, 2024b, expanded).

Discourse level **State of agreement**	**(Good) Governance**	**Switzerland**	**Germany**	**USA**	**Canada**	**Finland**
Step 1 Societal discourse						
Problem recognition	Rule of law Legislation	Waste exists Nuclear Energy Act 2003, phase out decided by national vote	Waste exists Repository Site Selection Act (StandAG) 2013/2017	Waste exists Nuclear Waste Policy Act 1982	Waste exists Nuclear Fuel Waste Act 2002	Waste exists Government decision in 1983
(Organised) debate happening? (regions)	Participatory	National: vote in the past, future vote on site (ca. 2031) Regional (6 → 3 → 1+): sectoral plan	National: repository Search Forum, future decisions in national parliament Regional: to be set up (around 10 siting regions)	National: none Regional: none	Choosing a Way Forward (National dialogue: 2002–2005)	National: none Regional: Municipal Council vote (positive in 2001)
Step 2 Common ground						
Goal consensus	Consensus-oriented	Domestic site (surveys/law)	Domestic site (surveys/law)	Domestic site (surveys/law)	Domestic site (surveys)	Domestic site, ban on imports
Step 3 Implementation						
Procedural strategy (instrumental and institutional goals)	Participatory	National vote Regional collaboration	Future decision in national parliament	Not decided, open	Adaptive Phased Management (2007; NWMO, 2024)	Decision in principle 2001
	Transparent Accountable	Extensive publication National vote ca. 2031	Extensive publication National parliament	Publication Congress (in indetermined future)	Publication Site selection process (2008–2010), currently 2 sites in Ontario	Publication Parliament
	Responsive	Several advisory bodies with reviews	NBG's interactions, participation formats, continuous reviewing	Pros: Bush Cons: Obama, Trump, Biden		Not contested, on track
Step 4 Appraisal						
Evaluation	Validated	None	Ongoing (NBG), research programme	None	None	None
Trust in government (%, rounded, three sources)		62/–/84	36/–/61	–/–/31 (Pew, 2020/2024: 24/22)	49/45/51	47/62/78
Democracy index	Deliberative democracy i.	0.863	0.816	0.711	0.715	0.792
Sources OECD (2023), Our World in Data (2020), World Population Review (2024)	UNESCAP (2009) V-Dem (2023)	BFE, Sectoral plan (2008/2011), BFE (2023)	Kommission (2016), BGE (2020a, b)	NWTRB (2015), Politico (2020), EPA (2024)	Nuclear Fuel Waste Act (2002), NWMO (2005, 2024)	Posiva (2018, 2024a), Choi (2018), Lagerlöf et al. (2018), Kojo et al. (2019)

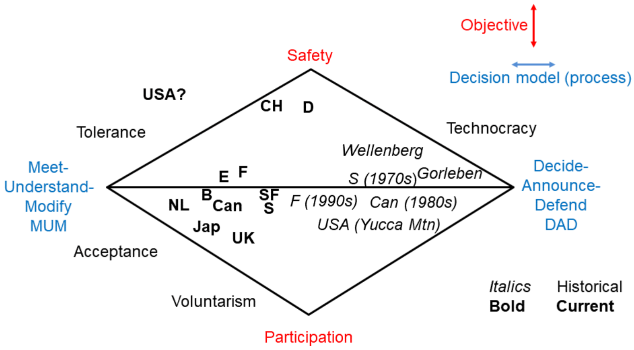

Figure 4. Shift of approaches over time in various countries: emphasis towards objectives "Safety" or "Participation" along with the antagonists of decision modelling "DAD" versus "MUM". Note that indications towards "Participation" do not deny "Safety". B – Belgium, Can – Canada, CH/Wellenberg – Switzerland, D/Gorleben – Germany, E – Spain, F – France, Jap – Japan, NL – Netherlands, S – Sweden, SF – Finland, UK – United Kingdom, USA/Yucca Mtn – United States (source: after Flüeler, 2023; IAEA, 2024).

and Prades, 2023); the roadmap for the back end of high-level waste just denotes general tasks and milestones (Enresa, 2024, pp. 65). The French concept attempts to meet societal demands with a temporally undefined option of retrievability and massive technical investments in an economically deprived region (Andra, 2024). The US Yucca Mountain project was first supported and then dropped by the latest three administrations (abandoned by Obama 2010, Trump 2020 and Biden 2021; Klaus, 2024). The US approach seems to be derailed (e.g., Richter et al., 2022).

5 Long sociotechnical uphill struggle – the German and Swiss cases

The process is lengthy, yet still has to be goal-oriented. In both Germany and Switzerland, it is about finding the "best" ("safest") site by way of a systematic and safety-oriented procedure. "Best" evidently means the most suitable among all systematically investigated sites based on traceable criteria. It cannot be the "best of all ever" as this is, in an epistemic sense, not possible. In Switzerland, the Parliament passed a law stipulating a domestic "deep geological repository" which denotes an amplified notion of final disposal – with a pilot facility to be controlled over a limited period and including retrievability within an "observation period" to be defined by Government (SNEA, 2003). This is endorsed by the electorate as nobody called for an optional referendum, so one may conclude that the disposal concept is broadly supported in the country. Already in 1979, the vast majority of Swiss voters had favoured the Federal Decree on the Atomic Energy Act stipulating "the permanent and safe final disposition and disposal of the … radioactive wastes" (SFD, 1978). Representative surveys showed again and again that disposal should be executed expeditiously, and that domestically. 84 % currently state that "it is only fair that waste is disposed of in Switzerland" and 60 % say that the potential "siting region has deserved the solidarity of whole Switzerland and shall be remunerated" (gfs.bern, 2023). So, on the whole, a fundamental debate took place in the country, reflecting the high score in democracy (Table 2). But two negative public votes (against the Wellenberg low-level waste project in Central Switzerland in 1995 and 2002) were necessary until a systematic site-selection procedure, the Sectoral plan, was established with the 2005 Nuclear Energy Act, starting out from a "blank map" on the basis of safety first (Nagra, 2022a) (Table 3). Even though a German expert group (AkEnd, 2002) had proposed a ground-breaking procedure in 2002 already (basically adopted in the Swiss approach) the national debate in Germany itself did not start before the publication of sub-areas in 2020 by BGE (BGE, 2020b).

Upon expert discussions and on instigation by the nuclear regulator crystalline rocks were, as mentioned, abandoned by Nagra, the Swiss implementer, in the 1990s. Gradually Opalinus clay came to the fore as a suitable sedimentary rock. Contrary to the tectonically overprinted, densely fractured and badly explorable crystalline, Opalinus clay exhibits a pronounced self-sealing capacity with its swelling clay minerals, whereby a certain deformation can be accepted. Concordantly, the Finnish-Swedish safety concept in granite is based on technical barriers (Posiva, 2024b). The German programme foresees such an option but only as "type 2" (without a confinement-providing rock zone). It is advised to rank granite secondary – against the negative features stated and the fact that more than 54 % of Germany are assessed to be "suitable" host rocks, i.e., 200 000 km^2 of clay, salt and crystalline must be investigated by 2031 as prescribed by law.

Even so, the site-selection procedure is hypercomplex – the German law, as mentioned, requires a "participative, science-based, transparent, self-questioning and learning process". For this purpose, a Sub-Area Conference and a Repository Search Forum were established with members from the public in Phase 1, and regional conferences in the then designated most suitable regions are ahead in Phase 2 where sub-areas will be investigated from above ground. The Sub-Area Conference is not just another "participatory format" as labelled by the regulator (BASE, 2024b) but a pluralistic multi-perspective competence base "from below" has sprouted as a fundament of technical insight and process stability. If the Repository Search Forum, now a "core participation element" (BASE, 2024c), is given the chance to guarantee the nation-wide experts–laypersons dialogue it may function as missing link to the regional conferences in Phase 2 (Flüeler, 2021).

The regional conferences in the Swiss context have evolved from an "alibi participation" to serious actors in the past 13 years of the procedure. The Regional Conference Zürich Nordost alone held 40 plenary assemblies since

Table 3. Challenges (*Italics*) and "solutions"/approaches (**bold**) in governing (high-level) radioactive wastes in Switzerland and in Germany. Nagra/BGE respective waste implementers, BfS (formerly responsible) German Federal Radiation Agency, DBE BGE's predecessor, BUND German NGO, Time frame: BGE explored respective adaptations (source: Flüeler, 2022, 2024b, expanded).

Aspects	Switzerland	Germany
Approach	**Safety and participation, safety first, "blank map"**	**Safety and participation, safety first, "blank map"**
Host rocks	**Opalinus clay**	*"Crystalline",* salt, clay(s)
Law, procedure	Deep geological repository **Nuclear Energy Act, Pilot facility, Sectoral plan**	Final repository **StandAG, learning, self-organising, self-questioning**
Time frame	Open, Sectoral plan ($\sim$2031)	*2031 (54 % of country suitable)*
Society	**National vote on Decree,** $6 \rightarrow 3 \rightarrow 1+$, regional conferences, etc.	**National debate** **Sub-areas conference**, regional conferences, etc.
Technical public	**Technical Forum Safety, Working groups in regional conferences**	**Repository Search Forum, Sub-areas conference, (reexamination) checks**
State levels	**Cantons (with experts)**	*German Länder*
History	*Wellenberg*	*Gorleben, Asse, Morsleben*
Reflection	*1 PhD thesis*	**ENTRIA, TRANSENS, etc.**
Oversight	*Advisory Board*	**Natl. Citizens' Oversight Committee NBG**
Discourse	*Nagra* → **Nagra**	*BfS/DBE* → **BGE**
"Dropouts"	**Few (local Green party)**	*BUND, citizens' initiatives, etc.*

September 2011, established the technical working groups "surface infrastructure", "safety", "regional development" and "infrastructure communities", attended numerous workshops and training modules. With respect to content, the unrelenting commitment to clean ground water was in the front, for which Nagra had to carry out extensive hydrogeological investigations from 2015 to 2017. The technical working group "safety" prepared a remarkable report on "process reliability" in 2018 and, two years later, the general assembly called for an extra round of additional potential sites for the surface facility (RK ZNO, 2024). The government of the presumable host canton of Zurich recognised the regional conferences in 2018: "Regional participation … has proven to be successful: … the engagement and acquired competence of the regional conferences in general and the technical working groups in particular were impressive and valuable. They have evolved to important partners of the cantons" (Cantonal Council, 2018). With the possibility to submit applications for subsequent checks issued by law, the future German regional conferences will be given a powerful instrument.

The role of the level between communities and the Swiss national state was strengthened as well. After the Wellenberg disaster, the cantons were deprived of their traditional right of veto with the newly issued Nuclear Energy Act in 2003/2005, and their part was reduced to "affected" stakeholders. Within the Sectoral plan, however, they harnessed their forces (Flüeler, 2014a, b) with a body of political decision makers (the Committee of the Cantons and responsible ministers), a project-leading team and, above all, a technical working group on safety with renowned external experts (KES, 2024). It was they who urged Nagra to withdraw their preliminary decision in Phase 2: "Shelving [the potential siting region] Nördlich Lägern is not justified. The argument of having too little space due to limitations in depth and tectonics does not bear close scrutiny" (laid out in AG SiKa/KES, 2016). Subsequently, the federal nuclear safety authority ENSI imposed additional claims and Nagra continued to investigate Nördlich Lägern. The result was that, in September 2022, Nagra acclaimed this siting region as the best on all aspects and proposed it to be pursued (Nagra, 2022b). As far as one can say, based on available information, political considerations were irrelevant in this decision. Such a major role in the German procedure is not observed with the Länder.

The picture is different if we turn our attention to the scientific examination or the accompaniment of the procedures. Even though mostly made up by members of the academia, the National Citizens' Oversight Committee NBG is accepted and respected by most actors as a warrantor and trust builder for inclusive participation in the German process (Flüeler, 2021, 2022), in line with the intentions of the law (StandAG, 2017). The Advisory Board in the Swiss case, however, has not become clearly visible and has not lived up to its function as a mediation body even though its man-

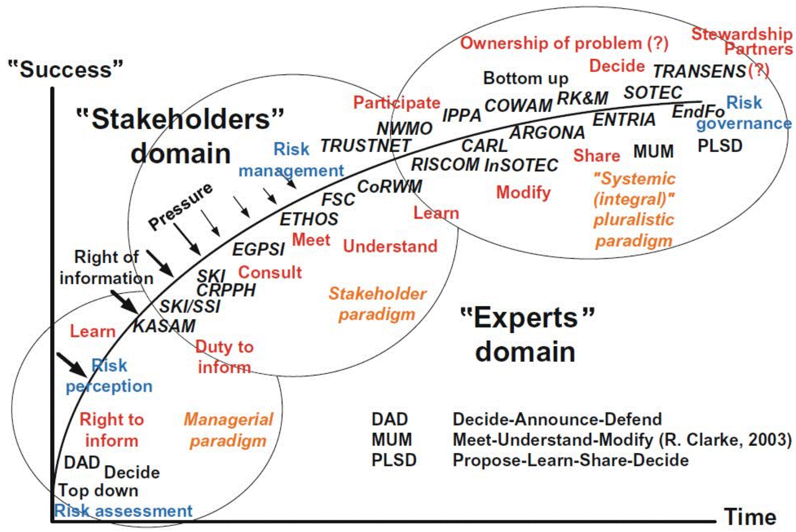

Figure 5. "Learning curve" in participation with respect to radioactive waste governance and integrative research programmes (black) considering stakeholder involvement (red), various decision paradigms ("bubbles", orange) and risk analysis perspectives (blue). ENTRIA, SOTEC, TRANSENS and EndFo are (ongoing) German research platforms (also see Kurgyis et al., 2024). The shape of the curve is merely indicative (source: after Flüeler, 2023, 2024b).

date is to "offer views from an outside perspective" and to "help identify process risks and obstacles at an early stage" (BFE, 2024). Concerning reflective capacity, it is painful to admit that the Swiss procedure, as successful so far as it may be, does not exhibit any scientific accompanying research[2] – quite contrary to Germany where a multitude of research platforms popped up (Fig. 5). Most other national cross-disciplinary research activities are terminated. This is even the case with pioneering Sweden (SKB, 2015).

6 Conclusions: in live discourse, self-questioning and learning the baton change may work

The first step of disposal of nuclear waste is the selection of a site suitable with respect to safety and tolerable by society. This is just, alas, the end of the beginning of the entire enterprise. It is no sprint, not even a marathon but a cumbersome hike in steep and swampy terrain, in poor visibility and with a vague destination. Well equipped (Sectoral plan, StandAG) and in respectful exchange, German and Swiss actors can be on their way. Aside from this objective safety aspect, the governance of (high-level) nuclear waste has a long-term project character: siting, etc., procedures, knowledge transfer and duties (e.g., on-site monitoring) must be handed over to future generations. Handing over the baton must function at all times and on all levels: from today to tomorrow, from a technical, societal and political community to another, from regional conferences to generations to come, continually striving at having them join on the long journey, having to bemoan as few "dropouts" as possible (Table 3). In line with this, it suggests itself to establish some sort of a "guardian" or "future council" of the radioactive waste management policy to overcome discretionary politics and to see to it that the programme is on target (Flüeler, 2024c). In view of the "trans" character of the issue (evidently "transgenerational", also beyond party politics: "transpolitical", and more than an interdisciplinary scientific issue: "transscientific"), it is suggested that the body be pluralistically composed of knowledgeable, trustworthy personalities, highly respected by society and not driven by daily politics – to overcome the Not In My Back Yard (NIMBY) effect but also NIMTOO, Not In My Term Of Office. This demonstrates the interconnection of technoscientific, institutional, societal and political perspectives (Flüeler, 2005, 2023). After all, it is not just about technical control (e.g., with a pilot facility) but about a long-term strategic monitoring of the whole undertaking (Flüeler, 2019). It is a bright spot that the discourse and failure culture has improved quite a bit in both countries in recent years, i.a., via a change of generations and also management.

In Switzerland, most criteria for Arie Rip's "socially robust" procedure were considered: arguments (domestic geologic repository, controlled and retrievable during a limited period), evidence (one host rock, Opalinus clay), social alignments (the majority of the actors in the Sectoral plan) and interests (procedural steps such as transparency and traceability). It is not expected that (main) cultural values among such divergent actors like proponents of nuclear installations and opponents are shared. Whether social robustness also means long-term resilience remains to be seen.

[2]Two documents – on public involvement – originated during 17 years: a PhD and a consultants' report.

7 Outlook or Closing gaps and seizing chances

In Germany, the societal Repository Search Forum was established and the implementer BGE is qualifying 90 sub-areas from category "A" ("optimum suitability") to D ("unsuitable") (BGE, 2024b, c). The Swiss procedure registered Nagra's site proposal as a major milestone in September 2022, they are short of submitting the general licence application (in November 2024; Müller et al., 2023). Handing over the baton is not a discrete and abrupt task after, say, 30 years, but knowledge transfer must take place continually and progressively – no gaps of any kind may occur and emerging opportunities should be capitalised. In this context, it must be criticised that, to date, no comprehensive sociotechnical appraisal of any national programme (Table 2, Step 4) has been carried out, at least not published.

In actual terms, this means in the Swiss case that Nagra must close the gap in their chain of reasoning regarding the preferred siting region of Nördlich Lägern. As it was not "overly cautious" (Braun, 2022) that they had eliminated the said site seven years earlier – on the contrary: it would have been prudent to leave it in the process, otherwise it could not be that "geology has spoken" (id.) or "[g]eology has the final say" (Nagra, 2024a). Geology was identical, in 2015 and 2022, but the data situation and the appraisal of structural engineering have considerably improved since. This is because external experts had forced Nagra to apply 3-dimensional seismics on a much larger area and to sink a sufficient number of deep boreholes. One ought to candidly recognise this crucial error of those days, amendable in the application: who admits mistakes does not lose face – contrary to that: this is *capability* to learn in parallel with *willingness* to learn. It would be an equally positive sign to ramp up research investments in the Mont Terri Underground Laboratory (as in the past), instead of curbing them to around CHF 200 000 as at present. In the remaining time window of a decade, until diggers may drive (given the approval is granted, around 2032), some open issues may be addressed beforehand, independently of the site but in a suitable and transferable geotechnical environment (Opalinus clay), such as backfilling and sealing, retrievability or specifying the requirements for a pilot facility. By that, Nagra would more or less know what to expect and could tackle the underground investigations on the site in a relaxed atmosphere, having gained valuable experience including inevitable (and "normal") mistakes in the experimental lab playground ahead of live fire. On top of that, it would mean preserving expertise (and competent staff), hopefully avoiding major surprises, utilising the remaining time and working off open R&D issues (Nagra, 2024c). Apart of that, it would be up to the regulatory authority ENSI to, finally, after two decades of statutory requirements (SNEA, 2003), investigate what they specifically expect from the implementer in the pilot facility.

In the German case, the Repository Search Forum may close the current "participation gap" (to the regional conferences in Phase 2) and the implementer BGE take the opportunity to eliminate the crystalline rocks from potential host rocks; they would still have to reduce 83 sub-areas in salt and clay to around ten siting regions for surface and then underground investigations in the short period of seven years (until the legal "deadline" of 2031). Without violating criteria of governance or role play, all major actors, also the process owner BASE and its superior Federal Ministry for the Environment, should go forward and seek the dialogue, including with the technical public of the Repository Search Forum, and on possibly extending the timeline for site selection beyond 2031. As this was the case in Switzerland in refocusing towards Nördlich Lägern. In countless meetings of the so-called Technical Forum on Safety (TFS, 2024[3]), in workshops, etc. the Swiss players reached the agreement that Nördlich Lägern be preferred, on – well aware – safety grounds. It was not about taking shortcuts but about collecting all relevant arguments and finding consensus in a fact-based deliberation.

In the end, it is about finding a safe and acceptable site, tolerated by the concerned and affected stakeholders, where a facility can be erected, operated and closed in a reasonable period and in good conscience. You can't squeeze blood from a turnip.

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[3] All relevant players are at the table of this Forum set up and chaired by the Nuclear Safety Inspectorate ENSI: Swiss Federal Office of Energy BFE (leading the Sectoral plan), inspecting and supporting authorities (ENSI, swisstopo), advisory bodies (Federal Nuclear Safety Commission KNS, Expert Group for Nuclear Waste Disposal EGT), German Expert Group Swiss Deep Repository, Nagra, Nuclear Waste Management Advisory Board, Cantons with their experts, Ministry of Environment of the (neighbouring) Land Baden-Württemberg, Environment Agency Austria, State Government of Vorarlberg (Austria), NGOs (including German BUND), representatives of the siting regions (BFE, 2023).

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