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Training to embrace uncertainties? The 'Pathway Evolution Process' serious game for assessing toxic waste program

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Abstract

This paper aims to evaluate the 'Pathway Evolution Process' (PEP) serious game method, developed by nuclear regulators and their technical support at the European level (SITEX network). This method aims to organize the exchange of experience and (non-)knowledge between nuclear waste experts, stakeholders, and the public on the safety and management of the long-term radioactive waste program, by placing uncertainty at the center of the evaluation process. Such interdisciplinary dialogue also promotes learning for both players and experts. This paper draws on feedback from its implementation in Belgium in 2021 with engineering and policy researchers, students, and representatives of Belgian Nuclear Regulatory Bodies. Considering this method as a hybrid forum, the paper highlights how the 'game' side allows participants to systematically evaluate and question all the ethical and socio-technical aspects of the program while leaving space for contrasting positions to emerge. It also emphasizes that experts

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can play different roles when interacting with different audiences. More generally, this article questions the value and limits of serious games for knowledge production on sensitive and complex policies.

Keywords

Pathway Evolution Process serious game, safety and vulnerability assessment, Belgian experiment, toxic waste, public participation, expert participation, hybrid forum, lessons-learned game.

Introduction

Radioactive waste is one of the most undesirable and sensitive materials to manage and control in both the short and long term. To this end, the role of nuclear experts remains key, but since the 1950s they have faced a series of well-documented challenges. These challenges include (but are not limited to) the death and lack of succession among nuclear waste experts,[1] the disinterest of (future) stakeholders,[2] strong opposition to site selection,[3] refusal of public participation,[4] and, in some countries, a gap between an advanced research program on radioactive waste management (RWM) and public policies that lag behind in this area.[5]

Slowly and in the wake of strong protests, experts measured that managing this toxic waste is not only a technical issue but also a *socio-technical* one that differs from one national RWM context to another.[6] Nuclear waste experts must address several challenges simultaneously, including how to maintain knowledge, how to raise awareness of the process among all stakeholders, and how to design the long-term assessment of the safety aspects of a public policy. This involves considerations such as how to monitor, what questions to ask, what criteria to adopt, and with whose support.

Several researchers have already shown that nuclear waste experts are under pressure, underlining that they are often caught in the crossfire of the multidimensionality of the toxic object they manage or control. They are "between the 'participatory turn' that almost forces them to open up to wider interaction, and their responsibility to produce technically sound reports likely to inform decision-makers. (...) They have to deal with the

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[1] E.g., Vincent Ialenti, "Death and Succession among Finland's Nuclear Waste Experts", *Physics Today,* Vol. 70, N°10 (October 2017), pp. 48-53.

[2] E.g., Céline Parotte, Catherine Fallon, "The future for long-term management of high-level radioactive wastes and spent fuel in Belgium. Synthesis of the Delphi inquiry", Spiral research Centre, January 30, 2020.

[3] Achim Brunnengräber, et al., eds., *Nuclear Waste Governance. An International Comparison*. Springer VS, 2015.

[4] Brian Wynne, "Public participation in science and technology: performing and obscuring a political–conceptual category mistake", *East Asian Science, Technology and Society: An International Journal*, Vol.1, N°1 (October 2007), pp. 99–110.

[5] Jantine Schröder, Anne Bergmans, and Erik Laes, "Advanced research, lagging policy: nuclear waste governance in Belgium", in *Nuclear Waste Governance,* eds. A. Brunnengräber et al., (Springer VS, 2015) pp. 141–155.

[6] Brunnengräber et al., *Nuclear Waste Governance. An International Comparison*.

double imperative of ensuring social and technical robustness."[7] In practice, the 'socio-technical divide' remains.

In that view, the European Sustainable Network for Independent Technical Expertise for Radioactive Waste Disposal (SITEX), composed of national nuclear regulators and their technical support,[8] with the assistance of Mutadis (a company specializing in public engagement), started designing a serious game in 2015 to innovate and strengthen interactions between nuclear regulatory bodies and civil society. It was intended as an exercise in participatory and comparative assessment of alternative scenarios for the long-term management of radioactive waste, in which civil society has a role to play. The safety authorities were convinced of the need for experts to interact with the various stakeholders as "it is now recognized by regulators that openness and transparency significantly contribute to the continuous improvement of nuclear safety."[9]

Serious games (SGs) involve the application of game elements in non-game contexts. They differ from other games in that they are explicitly designed to develop a specific aspect of knowledge or training rather than simply providing entertainment, thus reconciling two *a priori* paradoxical imperatives.[10] On the one hand, the 'serious' side aims primarily at establishing an educational value: by simulating real-world situations, it encourages players to engage in complex processes.[11] SGs allow players to face the challenges of a given issue and to experience the realistic impact of their decisions, thus influencing the behavior of stakeholders in

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[7] Céline Parotte, Pierre Delvenne, "Taming uncertainty: towards a new governance approach for nuclear waste management in Belgium", *Technology Analysis & Strategic Management* (2015), p. 9.

[8] The purpose of SITEX is to "enhance and foster cooperation at the international level in order to achieve a high quality Expertise Function in the field of safety of radioactive waste management, independent from organizations responsible for the implementation of waste management programs and waste producers, aiming at supporting the Nuclear Regulatory Authorities, as well as the Civil Society". SITEX Network, "Home", accessed March 4, 2024. https://www.sitex.network

[9] Valéry Detilleux, Frank Lemy, Frédéric Bernier, Marina Surkova. "The PEP serious game to explore the complexity of a safe long-term radioactive waste management: a first experience in Belgium", *Eurosafe*, Vol. 5 (2021), p. 1.

[10] Marios Stanitsas, Konstantinos Kirytopoulos, Elise Vareilles, "Facilitating sustainability transition through serious games: a systematic literature review", *Journal of Cleaner Production*, Vol.208 (2019), pp. 924-936.

[11] Marcel Fernandes Dallaqua, Breno Nunes, Marly M. Carvalho, "Serious games research streams for social change: critical review and framing", *British Journal of Educational Technology*, Vol. 55, N°2 (2023), pp. 460-483.

non-game situations.[12] On the other hand, the 'game' side increases engagement and intrinsic motivation, frees players from the pressure of tangible consequences, and allows them to explore all possible futures.[13] In doing so, SGs can enhance the acquisition of cognitive knowledge and skills such as problem-solving, decision-making, and situational awareness,[14] and can prove to be a useful data collection method, including for emergency management,[15] to raise awareness of hazardous pollution,[16] and to collectively explore potential transition processes.[17]

While there are many types of SGs, the one under investigation in this article is a board game called 'Pathway Evolution Process' (PEP) serious game. Its creators define it as "an interactive dialogue tool (...) conceived as an exercise in the form of a serious game, allowing the participative and comparative evaluation of different scenarios for the long-term management of radioactive waste."[18] In 2016, the beta version was first tested by 32 participants at the European level.[19] Since its creation, the game has been tested in several formats (including online) and in several national contexts, including in France (2019), Czech Republic (2017), Switzerland (2021), and Belgium (from 2021 to 2024).

This paper focuses on the Belgian experiments, specifically the first one in 2021. It aims to evaluate this application and to analyze how and why the PEP SG may facilitate learning and interdisciplinary thinking on a complex and sensitive program, as well as the added value and limitations it bears for RWM knowledge production.

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[12] Mario Silic, Paul Benjamin Lowry, "Using design-science based gamification to improve organizational security training and compliance", *Journal of management information systems*, Vol.*37*, N°1 (2020), pp. 129-161.

[13] Gilles Brougère, "Le jeu peut-il être sérieux ? Revisiter Jouer/Apprendre en temps de serious game", *Australian Journal of French Studies,* Vol.49, N°2 (2012), pp. 118–129.

[14] Pieter Wouters, Erik van der Spek, Herre van Oostendorp, "Current Practices in Serious Game Research: A Review from a Learning Outcomes Perspective", in *Games-Based Learning Advancements for Multi-Sensory Human Computer Interfaces: Techniques and Effective Practices*, eds. T. Connoly et al., (Hershey, PA : GI Publishing, 2009), pp. 232–251.

[15] Olivier Borraz, et al., « Peut-on apprendre à décider en jouant ? », *Entreprises et histoire*, Vol.97 (2019), pp. 110-129.

[16] Curt D. Gervich, et al., "Toxic Release! The role of educational games in teaching and learning about hazardous pollution", *Journal of Environmental Studies and Sciences*, Vol.6, N°3 (2016), pp. 589-596.

[17] Stanitsas, Kirytopoulos, Vareilles, "Facilitating sustainability transition through serious games: A systematic literature review".

[18] SITEX Network, "News & Events", accessed December 14, 2023, https://www.sitex.network/events-and-news/.

[19] REC, FANC, Mutadis, "Workshop with civil society". Minutes, Budapest: Hungary, June 2016.

To address these questions, this paper is divided into three sections. The first section elaborates on the theoretical concept of the 'hybrid forum'[20]—which we mobilize to assess whether the PEP SG can be considered as a new space for discussion that favors the encounter between experts and the public—then briefly describes the rules, objectives, and target groups of the PEP SG, as well as the different training sessions and experiments. The second section focuses on the different lessons learned by the non-experts, the nuclear waste experts, as well as the facilitators, and assesses the role of the experts in the debate. The third section discusses the opportunities and the limits of the PEP SG for RWM knowledge production, emphasizing the implications of genuinely addressing the uncertainties inherent to RWM. Finally, we conclude and highlight three main elements from the Belgian session that should be explored in more depth for future PEP SGs.

Theory, methods, and data collection

Theoretical assumptions: assessing the PEP serious game as a hybrid forum

Theoretically, we abductively analyze the PEP SG as a form of hybrid forum method.[21] A 'hybrid forum' is understood as a public space that brings together a variety of heterogeneous voices in the deliberation—such as experts, affected or concerned citizens, political leaders, or civil society organizations. This creates "emergent concerned groups" with "multiple alliances among the various components of these groups."[22]

Such a space of discussion aims to feed the decision-making process on controversial subjects. The technique has already been tested in many countries and contexts, including in the case of RWM in France[23] and

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[20] Michel Callon, Pierre Lascoumes, Yannick Barthe, eds., "In the Search of a Common World", in *Acting in an Uncertain World: An Essay on Technical Democracy*, pp. 107-152. Cambridge: MIT Press, 2009.

[21] Michel Callon, Pierre Lascoumes, Yannick Barthe, *Agir dans un monde incertain. Essai sur la démocratie technique*, (Seuil, 2009), pp. 1-368.

[22] Silvia Macchi, "Contexts of interaction for plural city politics: hybrid forums and cosmopolitics", *Plurimondi,* Vol.5 (2001), p. 9.

[23] Callon, Lascoumes, Barthe, *Agir dans un monde incertain*; Marie Kerveillant, Michael Mangeon, Francois Jeffroy, Olivier Saulpic, "Opening to the public: hybrid forum of reproduction of a technical dialogue between experts? Study of public opening device: the Cigeo Project Security Options File.", Social Sciences and Humanities - HSS, Boulogne-Billancourt: France, December 2019.

Denmark[24], in the case of energy production sites,[25] to compare radiation standards,[26] to ensure sustained collaborations after environmental disasters,[27] or to question the uncertainties of resource extraction.[28] Applied to sensitive policies, a hybrid forum can provide strategic conversations to enable an "open, explicit, shared and flexible sense of future to be developed through a process of interactive and immersive learning that takes place in imagined future situations."[29] The method of hybrid forum suggests transforming sociotechnical controversies produced by experts, non-experts, citizens, and politicians into productive conversations.[30]

Translated into organized activities such as the PEP SG sessions, the hybrid forum aims to promote the co-production of knowledge (and lack of knowledge) between laypeople, experts, and non-human actors (e.g. radioactive waste), without excluding any actor *a priori*.[31] Specifically, it focuses on three different dimensions that we will analyze below: 1) the context of uncertainties; 2) the learning of the actors involved and how their identities are redefined during the meetings; and finally, 3) the diversity of issues to be addressed in the search for a common good.

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[24] Rosa Nan Leunbach, Kristian H. Nielsen, "Exploring the Dialogical Space of Hybrid Forums: The "Predictably Unpredictable" Case of Radioactive Waste Management in Denmark, 2003-2018", *Bulletin of Science, Technology and Society*, Vol. 39, N°1-2 (2019), p. 5.

[25] Nichole Dusyk, "The transformative potential of participatory politics: Energy planning and emergent sustainability in British Columbia, Canada", Doctoral Thesis, University of Bristish Columbia, 2013.

[26] Aya Hirata Kimura, "Standards as Hybrid Forum: Comparison of the Post-Fukushima Radiation Standards by a Consumer Cooperative, the Private Sector, and the Japanese Government", *The International Journal of Sociology of Agriculture and Food*, Vol. 20, N°1 (2013), pp. 11–29.

[27] Ignacio Farias, "Devising hybrid forums. Technical democracy in a dangerous world", *City. Analysis of Urban Change, Theory, Action*, Vol.20, N°4 (2016), pp. 549-62.

[28] Aleksandra Lis, Agata Kinga Stasik, "Hybrid forums, knowledge deficits and the multiple uncertainties of resource extraction: Negotiating the local governance of shale gas in Poland", *Energy Research & Social Science*, Vol.28 (2017), pp. 29-36.

[29] Angela Wilkinson, "Using strategic foresight methods to anticipate and prepare for the jobs-scarce economy", *European Journal of Futures Research*, Vol.4, N°12 (2016), p. 5 (pp. 1-11).

[30] Callon, Lascoumes, Barthe, *Agir dans un monde incertain.*

[31] Emma Cardwell, Claire Waterton, "How to move beyond the dialogism of the 'Parliament of Things' and the 'Hybrid Forum' when rethinking participatory experiments with ANT", in *The Routledge Companion to Actor-Network Theory*, edit. A. Blok, I. Farias, and C. Roberts, C., (Routledge, 2019), pp. 378-388.

First, hybrid forums emerge or are mobilized in controversial and uncertain contexts.[32] Such spaces typically involve unanticipated events and often confrontations, where different perspectives clash and alternative knowledge claims and policy recommendations are made.[33] In the PEP SG, for example, we will see that the design and its applications have been framed to make unexpected events and uncertainties the basis for reflection.

Second, the hybrid forum promotes learning among the actors involved. It organizes interactions for mutual learning to take place, even when there are strong debates and oppositions, taking into account power inequalities that arise in participatory exercises. Lay people gain knowledge but also skills by working with experts, who in turn benefit from the new framings and insights of the former. Moreover, participants must take action, despite the uncertainties. We will see that the PEP SG challenges players to constantly move forward, effectively forcing them to decide.

Third, the issues addressed in a hybrid forum are extremely diverse: they are not exclusively technical, but also philosophical and political. Heterogeneous groups of actors may find common interests or issues. Others may be modified by exposure to the suggestions of new groups. Encouraging diversity and openness in discussions is one of the purposes of the PEP SG, while discussions on different issues and challenges can in turn change the way in which a program is perceived and implemented.

PEP serious game application in Belgium

In Belgium, PEP SG was first applied at the University of Liège in collaboration with the Faculty of Applied Sciences and the Faculty of Law, Political Science and Criminology, and with the support of the national regulatory authorities (the Federal Agency for Nuclear Control—FANC[34]—and its technical support organization, Bel V[35]). This first experiment gathered eighty-eight participants-gamers from engineering and political science studies. A dozen academics—engineers and political scientists—were present to ensure facilitation: each group was supervised by two

[32] Virginie Amilien, Barbara Tocco, Paal Strandbakken, "At the heart of controversies: Hybrid forums as an experimental multi-actor tool to enhance sustainable practices in localized agro-food systems", *British Food Journal*, Vol.121, N°12 (2019), pp. 3151-3167.
[33] Leunbach, Nielsen, "Exploring the Dialogical Space of Hybrid Forums", 2019.
[34] For further information, see the official webpage, accessed on December 15, 2023: https://www.belgium.be/en/contactinfo_en_sites/Urls/http_www_fanc_fgov_be.
[35] For further information, see the official webpage, accessed on December 15, 2023: https://www.belv.be/en/

facilitators, wherever possible with a parity between academic interests to allow for multidisciplinary facilitation. Five representatives from the nuclear regulatory body were tasked with introducing the project and circulating among the different groups during the game sessions to answer socio-technical questions as nuclear waste experts.

This article focuses on the primary data and lessons learned collected during the first edition in April 2021,[36] i.e. the collective written and oral feedback from non-experts and nuclear waste experts at the end of the game sessions, the analysis of the full transcripts of the sixteen PEP SG sessions (each lasting three hours), as well as the written and oral reports of the authors.[37]

In the Belgian version, the PEP SG was organized in four phases, including two short expert presentations, the game session, and collective feedback. During the first short presentation, the nuclear waste experts from nuclear regulatory bodies highlighted the key elements of the Belgian nuclear context, explained what 'radioactivity' means, described the different types of radioactive waste, and exposed the short – and long-term solutions currently under consideration. During the second presentation, they explained the board and cards (Figure 1; Figure 2; Figure 3), the objectives of the PEP SG, and the rules.

Since its birth and early developments, the PEP SG method has stabilized three scenarios (materialized by three game boards) that allow players to debate different strategies and socio-technical preferences enabling an evolution from the current situation of RWM to a final safe situation in the long term. Therefore, the core objective is invariably to reach a *safe terminus*— i.e., the protection of people and the environment as the main objective—while recognizing that this objective can be achieved through different *pathways*.

The first game session was automatically played on the 'closed' game board (Figure 1), imposing that efforts and resources are allocated to a swift implementation of geological disposal. After a short break, a second

[36] Nevertheless, since the first edition, numerous PEP serious game sessions have been conducted in Belgium with different target groups (notably with 13 volunteer citizens in November 2022 and with 10-20 representatives of the regional and federal administration in January, March, November 2023 and March 2024). This accumulated experience has contributed to the authors' analytical reflections and has confirmed many of the empirical elements already identified in this paper.

[37] This paper builds on and extends some of the authors previous reflections on this topic published in French in 2021-2022. Céline Parotte, Nathan Flore, "Expérimenter le Pathway Evolution Process (PEP) Serious Game à l'ULiège. Évaluation de la méthode prospective", Spiral Research Centre, December 12, 2022.

game board was chosen, either the open board[38]—an approach that does not choose from the start a specific technical option as a *safe terminus*—or the oriented board[39]—a step-by-step investigation of geological disposal, with the potential for other options as alternatives.

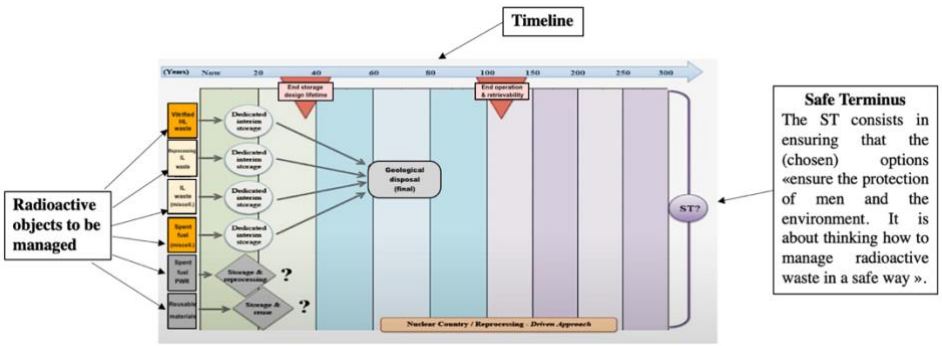

Figure 1 'Closed' game board: driven approach towards geological disposal ©Sitex.

Concretely, the PEP SG has two main effects. First, it confronts the participants, in the more or less long term, with unforeseen and disruptive elements that undermine a particular pathway imposed on them (in this case, one or more RWM options in Belgium). Second, it encourages them to reflect on the sustainability of the pathway based on various indicators: evaluation criteria, risk management, risk transfer, quality of governance, and ethics and values.

Finally, methodological precisions must be made concerning the authors' committed posture and their different roles in data production. In line with pragmatic sociology, we adopted an attitude of engaged researchers: we assume that we are both 'researchers and actors', engaged and involved in various ways—participant-observers, observer-participants, facilitators, player-participants, method evaluators—that affect our object of study. This enrollment was a powerful tool to better understand and adapt the rules and objectives of the game.

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[38] The open approach is based on the implementation of one or more dedicated *robust surface storage* sites, which are planned to last long enough to allow for the development and implementation of a *safe terminus* option that is not yet defined. Rules retrieved in: REC, FANC, Mutadis, "Workshop with civil society". Minutes, Budapest: Hungary, June 2016.

[39] The oriented approach steps from the current *interim storage* to a geological facility which is at first developed as a *geological interim storage*. After some time, the retrievability is given up and either the same site or another one is used as geological disposal, which becomes the *safe terminus*. Rules retrieved in: REC, FANC, Mutadis, "Workshop with civil society".

Below, we will examine the different lessons learned from the facilitator team, nuclear waste experts, and non-experts.[40] Following the iterative process through which the Belgian implementation of the PEP SG was constructed as an analytical guide, the next sections assess (1) how the PEP SG design accentuates the uncertainties, (2) and (3) the questions and issues raised during the game sessions, and (4) the various forms of experts' interventions and their implications.

Lessons learned from facilitators and nuclear waste experts: accentuate uncertainty

The first lessons learned came from the two training sessions organized in April 2021 to prepare the researchers' teams (including PhD students, researchers, and professors) to facilitate the game sessions with interdisciplinary students and nuclear waste experts. These 'test phases' allowed the researchers to evaluate both the rules and the design of the game and led to the implementation of some modifications, highlighting the performative effects of 'learning by doing'.

To meet the initial objectives (to think about safety in times of uncertainty), the facilitation team made four choices which, in practice, tended to accentuate the uncertainties: keeping the complexity, imposing the draw, choosing the strongest initial constraints, and limiting the experts' interventions.

Keeping it complex with simple(r) terms

The first modification addressed the initial complexity of the PEP SG: the titles and descriptions of the cards (namely: 'safe terminus', 'test conditions', 'evaluation criteria') and their articulation in the game were difficult for the facilitator-players to understand. To help future players (in this case, students) better grasp those notions, a translation work was carried out. Initially defined as "a situation in which the safety of all considered categories of waste do not anymore entail an active human contribution,"[41] the *safe terminus* was finally conceptualized and presented as a 'single rule to be respected at all costs: the protection of man and the environment'. Although geological disposal tends to be favored by the scientific community, the notion of *safe terminus* was subject to different interpretations and discussions by the facilitator-

[40] Organising the results based on people's role in the PEP serious game emphasises that this method fosters an eminently collective learning.

[41] REC, FANC, Mutadis, "Workshop with civil society", p. 15.

players. Therefore, it was decided not to introduce the element of 'passive safety' in the definition of the notion. For their part, the cards entitled 'test conditions' were presented as 'disruptive changes, unforeseen events that impose themselves on the players and with which they must contend'.

However, the complexity of both the content and the wording of the cards was almost systematically emphasized by the participants during the game sessions. Yet, instead of hindering discussion, the complexity stimulates it: players reformulated the cards, commented on them, and asked other players or nuclear waste experts for help in deciphering the terms used. These moments also tended to create a friendly atmosphere and a sense of collective effort. Many players recognized the playful and participatory nature of the game as a major strength and felt that it could be applied to many other issues and audiences.

Drawing lots for the 'unexpected events' cards

A second adaptation was to increase the attractiveness of the PEP SG by favoring a random selection of game elements. The game unfolds as follows: a player randomly chooses an 'unexpected event' card (Figure 2) and an 'evaluation criterion' card (Figure 3). He/she then places the first one in the time frame of his/her choice, between zero and three hundred years from now (Figure 1). Once these operations have been carried out, the players evaluate the possibility of reaching a *safe terminus* according to the evaluation criterion in relation to the chosen scenario ('directed', 'oriented', or 'open') and the 'unexpected event'.

Figure 2 Example of 'disruptive event' card ©Sitex.

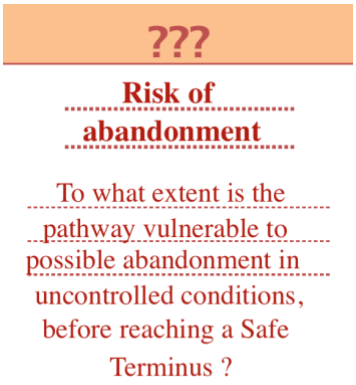

Figure 3 Example of 'evaluation criterion' card ©Sitex.

This modification has two benefits. First, it strengthens the 'game side' by adding a fun factor, as players comment on their luck and the seriousness of the cards they draw. Second, it turns out that randomization helps relieve the pressure felt by the players: chance removes responsibility from an individual player and encourages the emergence of a shared sense of community in the face of an 'unexpected event' that affects them all. Indeed, this collective sense of purpose is necessary to face the question that arises: how to react in a context of uncertainty?

Players welcomed this modification, as randomization allowed them to provoke and nurture debate, repeatedly raise issues they hadn't thought of, and identify different consequences depending on the choice made about the timescale. However, projecting over (extremely) long management timescales is also a challenge for some players, who feel it makes the project less tangible both technically and institutionally.

Challenging players with 'unexpected event' cards and forcing them to choose the timescale they will have to deal with embodies the radical uncertainty that decision-makers face when engaging our societies in difficult-to-grasp timescales.[42] Today's knowledge and data will not be tomorrow's, and this is a major challenge when it comes to defining public policy on RWM.

[42] Sophie Poirot-Delpech, Laurence Raineau, "Nuclear waste facing the test of time: the case of the french deep geological repository project", *Science and Engineering Ethics*, Vol.22 (2016), pp. 1813-1830.

Facing strong constraints first

After the training sessions, it seemed consensual to start the PEP SG with the 'closed' game board, which proposes geological disposal as the preferred management option (Figure 1). This decision was justified by the desire to confront players with strong constraints first, a common preference in scenario-based methods: players found that the 'closed' game board—with clearly defined and identified constraints—limited their choices more, making it easier for them to argue their reactions and (dis)agree with the scenario.

On the other hand, the 'oriented' or 'open' game boards make the game even more complex, as they leave the door open to different options for RWM. Players therefore need to take a more suggestive stance, which is harder to do without a clear diagnosis of the situation. As a result, those boards provoke more contrasted reactions among players: some argue that they make it more difficult to ground the debate due to the increased possibilities, while others praise the opportunity they provide for discussions to get out of the box.

However, some players also expressed frustration with the settings, which did not allow enough freedom despite the more open paths. They highlight that both 'evaluation' and 'unexpected event' cards are powerful tools that can lead players down one path, especially toward geological disposal. While this is considered legitimate in the closed scenario (as it is the imposed solution), some players regret such a restrictive orientation in the case of what should be an open scenario.

Containing the expert interventions

The last adjustments focused on the facilitation of the game. During the training sessions, the facilitator-players highlighted the crucial importance of a facilitation style that effectively balances speaking, does not replace the provision of technical information, and reframes debates when they stray too far from the game's objectives. As a result, two changes were made: first, a more detached facilitation style was proposed to focus on the players' questions and suggestions and encourage interaction. Second, a mixed pair of facilitators from engineering and political science was chosen to ensure the balance and complementarity of their interventions.

The training sessions also revealed that the nuclear waste experts (FANC and Bel V representatives) could provide a lot of additional information before the players took their positions, which quickly created an asymmetry between expert and lay knowledge. Indeed, the priority given

to information produced by experts on possible new contributions from laypeople is a known complexity of public participation processes.[43] To limit this bias and ensure the quality of the exchange between players, the nuclear waste experts were made available *on request*: they were not assigned to a group but were available to answer any questions that arose, thus allowing the players to express their opinions.

Four game changes to create a dialogical space for engaging with uncertainty

The four changes implemented strengthened the core principle on which both the PEP SG and the hybrid forums are based: collectively dealing with uncertain contexts. The game was designed to encapsulate multiple uncertainties and directly confront players with these unknowns, effectively creating a space for (non-)knowledge and expertise to be debated and alternative pathways to be formulated.

The first lesson learned was that creating a dialogical space relies first and foremost on the 'game part' of the PEP SG and its ability to challenge the usual framing of RWM. Instead of relying on the available knowledge of nuclear waste experts, laypeople had to react to the 'unexpected' events (cards) as the starting point of discussion. Similarly, nuclear waste experts were positioned as (not always available) outsiders in the game. These two key components aimed to associate uncertainties as a 'business-as-usual' condition that all players had to constantly address. In other words, the discussion no longer revolved around expert knowledge of RWM, risk calculation, probability assessment of future events, and the presentation of predictive models to assure audiences that every aspect of the program was managed. The goal was to create conditions that would allow each type of event to be considered, regardless of its plausibility or probability, and to observe how all the players—without specific knowledge of nuclear waste—reacted and assessed the situation before proposing several concrete solutions or adaptations to move forward.

By assuming that the unknown and unintended consequences would become a dominant force, a dialogical space including non-experts was created. This, in turn, opened up risks to social definition and construction,

[43] Anne Bergmans, et al., "The participatory turn in radioactive waste management: deliberation and the social–technical divide", *Journal of Risk Research*, Vol. 18, N°3 (2015), pp. 347-363.

making it necessary to extend the debate to a wider public in order to diversify inputs into decision-making.[44]

The next section presents some of the main questions and issues from the players' discussions for dealing with toxic waste programs in uncertain contexts.

Lessons learned from non-experts: 'Living with' uncertainty

First and foremost, the PEP SG raised participants' awareness of the complexity of RWM and the challenges of decision-making in the face of uncertainty, with its multidimensional nature and all its long-term consequences. Indeed, players had to familiarize themselves with technical—but also economic, political, and ethical—concepts to engage with policies.

A first set of players questioned the appropriate attitude to adopt in the face of global uncertainty about the RWM pathway. In response, several players emphasized the importance of taking action: given that the waste has already been produced and could pose a threat to present and future generations, they felt that they had a moral duty to take responsibility.

The type of RWM strategy was also influenced by the need to deal simultaneously with waste and uncertainty. Some RWM options are more durable and provide better safety than others but constrain the future RWM path more than lighter options. For example, some players recognized that irreversible geological storage offers a safety advantage but also a lack of flexibility for future generations.

As debates progressed, the players accepted and assumed that they didn't know everything and had to live with the uncertainties inherent in the toxic waste management project. As one player puts it, "there is no silver bullet. (…) In the end, what's interesting is that it brings us to the eternal problem of politics: making decisions without knowing what the consequences will be." This is the second lesson learned from the non-experts. Like hybrid forums, the PEP SG triggers *collective and generative* learning: rather than simply collecting an aggregation of opinions, the settings force each intervention to add complexity, nuance, or reframe the discussion. By constantly debating, comparing, and reformulating their visions and personal knowledge, participants were confronted with

[44] Ulrich Beck, Peter Wehling, "The Politics of Non-Knowing", in *The Politics of Knowledge*, ed., F.D. Rubio and P. Baert, (Abingdon, Oxon: Routledge, 2012), p. 37.

unfamiliar aspects of the issue they were dealing with. Indeed, knowledge and ignorance are co-produced: the former grows out of the latter, but "non-knowing can also be a consequence of scientific knowledge and its technological application."[45] Any new piece of knowledge acquired (i.e., from nuclear waste experts who provided timely information) raises new unanswered questions.

Lessons learned from the non-experts: deciding under uncertainty

Constantly challenged by unforeseen events that disrupt initial RWM pathways and without having all expert information available, players were nonetheless encouraged to think about the processes that would help them reach the *safe terminus*. In other words, the game was designed to force players to ultimately adopt a *decision-making* mindset. Indeed, the game instruction *'let's keep on playing'*—with or without any scientific knowledge available—allowed more space for fruitful exchanges between players and for pluralistic views to coexist.

While some groups were almost paralyzed by the number of parameters they had to consider to guarantee a safe outcome, players eventually agreed on the need to act. As a result, they developed some concrete strategies for taking positions on complex and high-stakes issues, with or without the support of nuclear waste experts. In this sense, the absence of nuclear waste experts around the table can even be seen as an advantage, as it allows players to systematically identify the questions to be asked and sought before answering the problem. The evaluation criteria and the different sets of assumptions were explicitly formalized. Indeed, despite the lack of information about hazards, laypeople still have a rich conceptualization of risk that reflects valid concerns often excluded from expert risk assessments. Consequently, as the game progresses, experts are also exposed to new ways of *framing* the problems raised by RWM, what Nielsen and Sorensen call the 'unexpected virtue of ignorance.'[46]

[45] Beck, Wehling, "The Politics of Non-Knowing", p. 37.

[46] Kristian H. Nielsen, Mads P. Sorensen, "How to take non-knowledge seriously, or 'the unexpected virtue of ignorance'", *Public Understanding of Science*, Vol.26 (2017), p. 386.

Governance and decision-making: identifying required knowledge

When confronted with the need to propose concrete actions that would help reach a safe terminus, players foregrounded issues of policy evaluation. Many of them recognized the importance of drawing up "*specifications*", assessing "*the pros and cons*" of each choice made in terms of funding, risk, and social or environmental impact, assessing "*knowledge gaps*", and evaluating "*mistakes made*" in the event of an accident. Many players believed it crucial to gather existing detailed, contextualized, and up-to-date information or produce some before making any major decision and moving forward on one or more RWM pathway(s).

Moreover, the very nature of the evaluation process was questioned. The objects of evaluation were multiple and strongly related to unforeseen events: assessing host sites, emerging technologies (and their added value compared to the existing ones), environmental and infrastructural monitoring, and assessing the real potential of future resources could all be the focus of evaluation. The scope and variables to be included also raised questions: when to assess and with what frequency? What are the appropriate levels to make a decision (e.g. local or national level)? On what criteria should decisions be based, and how to establish a hierarchy among them?

Players also discussed the actors responsible for the evaluation and the roles that should be assigned to experts and scientists. The disciplinary composition and independence of a potential scientific council were debated, as was its relationship with political authorities. In that vein, having to decide for (a) RWM pathway(s) calls into question who is legitimate to do so. According to some players, elected decision-makers benefit from a legitimacy that experts and scientists do not have. Nonetheless, players also highlighted that political representatives only held office for a limited time: could that disrupt RWM continuity? Were private companies longer lasting and therefore better suited to the task? Yet, what about their legitimacy or potential diverging interests between public and private structures? Should the public and other stakeholders be consulted?

An interesting movement should be highlighted with this new lesson learned. Players were not unwilling to produce knowledge; rather they were—for those most integrated into the game—at a different level of commitment: they were decision-makers who could *identify* the knowledge and principles required to make informed decisions. In other words, they debated *how to produce knowledge* and what kind of existing and future knowledge was needed to deal with uncertainty.

Remembering: the challenge of ensuring knowledge production continuity

RWM choices will inevitably impact the opportunities and challenges for future generations in relation to radioactive waste. However, the extent to which these choices bind future waste managers varies greatly depending on the nature of the waste disposal. A dilemma emerged during game discussions: remembering the status of the waste and its protective infrastructure versus forgetting it. Each position represents a different relationship between radioactive waste and people.

The first position considers waste and its safety as inseparable from human intervention. In this scheme, remembering waste guarantees transmitting knowledge for safe management. Human involvement in RWM maintains flexibility and openness in the pathway, allowing intervention in waste storage, maintenance, and use of radioactive materials. It also allows diverting the path in case of scientific breakthroughs. Several players consider that treatment techniques may be developed in the future, making storage reversibility crucial. In addition, some participants felt responsible for the management of the waste produced during their lifetime and claimed that forgetting its existence would be tantamount to abdicating this responsibility. The participants who defended this line of argument thus tended to favor reversible waste storage techniques.

The second position argues that irreversible storage should be preferred because human intervention (mishandling, terrorism, or accidental interference) also poses the main threat to the integrity of the radioactive waste storage infrastructure. Accordingly, they propose building a robust infrastructure, conditioning the waste as effectively as possible, and, finally, hiding the storage site from the public. Contrarily to the first argument, players defending this position seem to have more confidence in the technical processes involved in the life cycle of radioactive waste than in human actors.

Several subsequent technical, institutional, and knowledge challenges were raised during game sessions debating this dilemma. The ‘remembering’ position raises challenges about how to protect and transfer the scientific expertise needed to operate, maintain, and transform storage facilities. How can expert knowledge be developed and passed on from one generation to the next if the nuclear industry is dismantled? Do the specialized institutions in the field need to address this long-term problem? Should there be an international organization promoting the production and protection of knowledge? Some players discussed the strategic position of Africa, which could become the guardian of knowledge if it develops its nuclear expertise in the context

of power plant construction. Others mentioned the possible creation of an international library of nuclear waste expertise. In doing so, they demonstrated an ability to think outside the traditional institutional framework of states and their specialized departments.

Path dependency and alternative pathways: relying on existing and future knowledge

During the sessions, players become accustomed to the uncertainty of the pathways and the multiple options available at each step of the RWM process. Faced with unforeseen events, they acquire a sense of anticipation, a way of thinking that leads them to address the main dimensions of the socio-technical challenges at stake. Many players understood and pointed out the path dependency that characterizes the different scenarios of this PEP SG. They were also aware that each storage option has its technical, social, and institutional limits. For this reason, some players proposed to escape the "*depths of uncertainty*" by implementing several storage options at the same time. Building a second storage facility or even preparing a different type of storage is seen as an interesting solution. Other actors were overwhelmed by the uncertainty surrounding the most classical storage solutions and turn to more "*exotic*" ones. For example, they suggested storing radioactive waste in the desert or sending it into space, which led to technical and legal discussions with the nuclear waste experts available during the game session. Multiplying alternatives also raised questions about funding strategies: should states pool together RWM infrastructures? Or involve the private sector?

This lesson shows that a methodological design genuinely taking uncertainties seriously enables players to consider and explore possibilities for multiple RWM pathways. Existing knowledge and currently recommended management options are not neglected, yet they must often be adapted or supplemented to unforeseen events during the game. Therefore, players also identify and rely on other avenues of (future) knowledge production that will allow them to maintain multiple technological options and pathways in the event of additional unforeseen events. In other words, they insist not only on the accumulation of knowledge but also on the diversity and coexistence of research and development programs.

Lessons learned: roles of nuclear waste experts

During the training and game sessions, players asked themselves and nuclear waste experts several questions. During the collective feedback, the former mentioned that they perceived the nuclear waste experts as

providing "*food for thought*", and that they sometimes repositioned themselves according to the information received from those experts.

The players' relationships with those experts varied from one group to another: some involved them very regularly, while others consulted them sporadically. Some followed the guidelines suggested by the experts, while other groups took their cue from them and then moved forward with full knowledge of the facts. Indeed, the role given to the experts, as well as how and when to consult them, was part of the group discussion and left to the responsibility of the players. Hence, once the uncertainties, the ignorance of the other participants, and the limited accessibility to the experts (and through them, to the available knowledge) had been assumed, some groups quickly reclaimed this dialogical space. On the other hand, we found in other groups that the experts' intervention in the discussion was seen as being instrumental: players were piling up questions, asking them how to act, or seeking reassurance about the choices made. In these cases, players generally reintroduced a hierarchy of knowledge, aligning themselves with the experts' proposals.

We also observed that the way the nuclear waste experts responded to the players' questions varied from one expert to another. We identified three forms of expert intervention: the expert '*informant*', the expert '*facilitator*', and the expert '*decision-maker*'. First, strictly following the question asked, some experts provided the most exhaustive possible information on existing scientific knowledge without prejudice. The intervention thus consisted of a list of possible answers to a given question or problem, providing the players with the most complete picture of the socio-technical possibilities and their consequences. The experts aimed to exhaustively *inform* the public.

Some of the experts' interventions were designed to maintain or encourage discussions between participants. These experts asked more questions to the participants, formalizing interconnections between questions and, in some cases, adding more constraints and nuances to push forward collective reflections on one unforeseen event. In this way, questions were sent back to the participants, forcing them to continue thinking and clarifying their thoughts or positions. The experts effectively *facilitated* the debate.

Finally, some experts' answers were more assertive or explicitly reflected the experts' opinions on the topic under discussion. In these cases, as the experts' legitimacy was never in doubt, they were able to steer the discussion through their intervention and effectively *decide* for the players. This type of analytical intervention is worth noting: in the face of uncertainty, it transfers the responsibility for decision-making to the expert.

The players tended to ask the nuclear waste experts more technical inquiries, but governance questions were also raised (Figure 4). Yet, despite the diversity of the questions (some of which involved highly specialized economic, environmental, political, and social expertise), the nuclear waste experts, who are mainly trained in nuclear and engineering sciences, responded indiscriminately to all the questions. Leaning more towards one dimension or the other still depended heavily on the nuclear waste expert. Some took an assertive stance on both governance and technical issues (with a *decision-maker* style), while others preferred to take a more descriptive stance on governance or financial issues (with a *facilitator* or *informant* style).

Technical questions concerned	Governance questions concerned
○ Specific aspects of alternative solutions, e.g.: - the possibility of storing waste under the sea (Group 1) - incineration of waste (Group 3) - cooling of waste (Group 9) - transmutation and its consequences (Groups 3–12) - disposal in the desert (Group 5), in space (Groups 2, 5, 7, 12) - nuclear fusion (Group 12) - environmental, safety and security risks associated with all solutions (Groups 7–9, 12) ○ The current research agendas of nuclear researchers associated with one or other alternative solution. (Group 2) ○ The question of transport. (Group 3) ○ What is (Groups 5–8): - a 'waste package'? - the type of waste the repository is intended to store? - 'final disposal'? - 'geological disposal'? - 'unacceptable risks' in concrete terms? ○ How to organise the monitoring of a repository? (Group 5) ○ How to manage the contaminated nuclear site (Group 5) or the 'damaged' waste already in the repository? (Group 9) ○ What are the types of subsoil considered and the depth of a repository? (Groups 9, 12)	○ The effective implementation of management programmes, e.g., sending waste into space. (Group 2) ○ The relationship between one country and another, as well as the consequences of privatisation. (Group 3) ○ The nature and timing of funding. (Groups 4, 12) ○ The existence of regulatory bodies capable of making binding decisions. (Group 4) ○ Communication in the event of an accident. (Group 12) ○ The competencies of the FANC. (Group 5)

Figure 4 List of questions asked to the nuclear waste experts during the PEP SG

Discussion

This section aims to discuss the added value and the limits of the PEP SG for RWM knowledge production, based on the Belgian experiment. We divided it into three parts in order to question the uncertainty as a precondition for such a sensitive program, the (non-)knowledge co-production and how it distributes responsibilities, and the influence of such an experiment on the Belgian RWM decision-making process.

Uncertainty as a source of lay knowledge

First, we consider that the PEP SG offers a similar added value to the hybrid forum by setting the uncertainty as a precondition before and during the debate (game session). With the game design placing unforeseen and unexpected challenges as the starting point of the discussions, citizens progressively learn to live and deal with uncertainties, forcing them to confront the absence or the lack of knowledge and helping them to integrate that "non-knowledge appears to be a foundational aspect of contemporary knowledge societies based on science and technology."[47]

The rules allow the players to simultaneously address the multiple dimensions of a socio-technical object (RWM is far from being a purely technical issue, and the game offers the opportunity to address political, economic, and ethical questions too) and grasp the complexity of the RWM program.

As in a hybrid forum, the public therefore needs to develop strategies for dealing with such ignorance through *collective and generative learning*, with the occasional support of nuclear waste experts, rather than hoping that it will eventually go away. Results from the Belgian experiment show that players have a rich conceptualization of risks regarding RWM, reflecting on valid concerns that, for some, echo those raised by Belgian stakeholders from the nuclear field in a previous study but,[48] for others, also escape the traditional framing(s) on RWM and explore other avenues. In this sense, uncertainty can also stimulate new thinking and help systematize problem evaluation, including how to frame it and which ethical principles to apply. The absence of scientific and technical knowledge on the part of the players does not mean that they are incapable of reflecting on the problem: they deal with it by identifying the

[47] Nielsen, Sorensen, "How to take non-knowledge seriously, or 'the unexpected virtue of ignorance'", p. 386.

[48] Sacha Frenay, Céline Parotte, "No time to waste: exploring timeprints of radioactive waste management options in Belgium", *TATuP. Journal for Technology Assessment in Theory and Practice*, Vol.31, N°3 (2022), pp. 24-30.

existing and (hoped) future knowledge needed to make an informed decision.

Expert knowledge first?

In the Belgian PEP SG experiment, the analysis showed that there was not a symmetrical *co-production of knowledge* between experts and laypeople. Two hypotheses could be formulated to explain it: the group's characteristics and the type of responsibility that players are prepared to take on in this type of game.

The first hypothesis is that PEP SGs were designed (groups are composed exclusively of laypeople, apart from the facilitators) precisely to avoid the continuous intervention of nuclear waste experts in the discussion. Organizing a direct and sustained relationship between laymen and specialists requires building a collective over a long period of time. Unlike the hybrid forum, the PEP SG participants are not a "concerned group,"[49] i.e. stakeholders who create a community of interest whose bonds are long-lasting and could be reconstituted. In the experimented PEP SGs, players do not exhibit greater concern for RWM than the general population and are likely to participate in only one game session. In other words, they did not claim to have any knowledge to put forward or be heard, as is the case in hybrid forums where each stakeholder is invited, acknowledging and recognizing the multiple areas of expertise around the table. The Belgian players were students, with little or no interest in waste issues prior to the game session.
The second hypothesis is that (non-experts) players mobilize nuclear waste expertise differently depending on the type of responsibility they were willing to take on during the game.

Several players sought and waited for expert knowledge: scientific experts are considered essential before making any decision. In such cases, we have observed that players wait for the experts to frame the issue, and for the experts to ask the right questions or to identify the best options. In short, the players wait for the nuclear waste experts to 'close down' the appraisal[50]. In such a case, the players reproduce a hierarchy between lay and expert knowledge and transfer the full responsibility of decisions to the nuclear waste experts. In Beck's terms, we can say that those players developed strategies of "organized irresponsibilities."[51]

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[49] Callon, "Des différentes formes de démocratie technique", 1998.

[50] Andy Stirling, "'Opening Up' and 'Closing Down' Power, Participation, and Pluralism in the Social Appraisal of Technology", *Science, Technology & Human Values*, Vol. 33 (2008), pp. 262-94.

[51] Ulrich Beck, *World at Risk*, (Cambridge: Polity, 2009).

However, other players—who have best integrated the constraints of the game—have been able to act as decision-makers, effectively identifying both existing and future knowledge needed to make informed decisions and explore multiple pathways. In this case, the experts (if mobilized) are expected to present all possible options, to propose a comparison of options, to provide an overview of the current state of knowledge, to 'open up' the appraisal. These participants do not establish a hierarchy of knowledge, but rather determine and assume responsibility for the type of knowledge required to make their decisions. Players are not unwilling to produce knowledge about RWM (ontological (non-)knowledge about things), but are at another level of commitment: the PEP SG offers new methodological ways to identify things and gain knowledge (epistemological ways of escaping non-knowledge).[52] We could say that the players developed strategies to *organize responsibilities*.

As a nuclear waste expert, it is not a question of taking a position on whether or not a hierarchy between forms of knowledge (expert or lay) is desirable, nor of suggesting a way of hierarchizing knowledge when it exists, confronts, or feeds into one another. It is rather the opportunity to assess the forms of engagement experts are willing to embrace in such debates. In the Belgian experiments, the game facilitators were systematically trained, and the supportive experts were thematic experts from the regulatory systems (most of the time). In the PEP SG sessions, some experts have provided additional information, completed the discussion, suggested new questions, explicitly expressed their opinion, or assumed their non-knowledge on some issues. No matter the forms and the content of the experts' interventions, information provided by the scientific experts was always deemed relevant. Was the players' trust in the nuclear waste experts related to their recognized expertise on the topic or to their administrative role as nuclear 'watchdogs'? Our experiments have highlighted the need to assess more systematically the experts' engagement in the debate—the role performed during the discussion, the roles the expert is comfortable performing, and the role expected from the audience—and the knowledge and non-knowledge they are ready to assume.

Belgian PEP serious game as downstream engagement

The Belgian PEP SG experiment was carried out in a specific context that remains important to examine and understand to assess the scope and potential influence of this type of participative exercise. In Belgium, FANC

[52] Christopher Daase, Oliver Kessler, "Knowns and unknowns in the `War on Terror': uncertainty and the political construction of danger", *Security Dialogue* Vol. 38, N°4 (2007), pp. 411-434.

and ONDRAF have already ratified the RWM method they consider to be the most appropriate, i.e. geological disposal, and have been researching it for more than forty years. At the legislative level, after years of ambiguity, the Royal Decree of 28 October 2022 establishes 'the first part of the national policy' by explicitly establishing geological disposal as the preferred option and laying the first stone towards compliance with the European Directive 2011/70/Euratom. Therefore, despite its publicized purpose of discussing different strategies for RWM, the contribution of the PEP SG comes in, if not at the end, at least after the process of knowledge production by the nuclear waste experts of the regulatory agencies. In a context where both the problem and solution have already been defined, one can question whether the PEP SG fundamentally differs from instances of "downstream engagement,"[53] and whether its outcomes effectively participate in closing the gap between technical and social aspects of RWM.

However, Article 7 of the Royal Decree of 28 October 2022 promotes the principle of 'decision reversibility'—i.e., allowing previous decisions to be reconsidered or reviewed in the light of scientific, technical, social, regulatory, or international developments and changes—and therefore expresses both a willingness to open up decision-making to public debate in the face of uncertainty as well as a possibility to alter prior framings, commitments, and configurations. We emphasize that methods such as the Belgian PEP SG could (re)open the debate on RWM and, as a result, make its socio-technical pathways more robust, thus supporting this principle of 'decision reversibility'.

Conclusion

Serious games can be a relevant method for envisioning futures and assessing expert and lay knowledge under different scenarios for highly sensitive and complex policies. This paper examines a particular SG applied to the long-term future of high-level radioactive waste management: the Pathways Evolution Process (PEP) SG. Developed at the European level by regulators and their technical support, the initial aim of the game was to ensure the robustness of their safety case and to enhance dialogue with civil society and other stakeholders.

By evaluating its testing in the Belgian context through the analytical lens of the *hybrid forum*, we stress that the PEP SG is an interesting method for raising awareness of the complexity and interdependencies of multidimensional RWM, for increasing dialogue between nuclear waste

[53] Bergmans, et al., "The participatory turn in radioactive waste management: deliberation and the social–technical divide", 2015.

experts and civil society, and for taking lay knowledge seriously. We emphasize that the players accepted having to *live with* the uncertainties inherent in toxic waste management projects and that they developed different strategies for doing so. *Making decisions under uncertainty* goes hand in hand with the production of knowledge and ignorance. In our case, deciding means considering a mode of governance that constantly reassesses the need for expert and lay knowledge, depending on unexpected events. We have shown that laypeople have a rich conceptualization of risk that enables them to identify and justify in detail the type of knowledge required for each uncertain situation (format, responsible persons, actors to be involved), as well as how and when to produce it. While the action is strongly linked to existing knowledge (and the path dependency resulting from already favored technological options), players also take account of both future knowledge and accumulated RWM knowledge (e.g., options not favored) that may propose alternative paths. Indeed, they insist on the need for a diversified knowledge production covering several RWM pathways. Besides, for them, deciding also means remembering, maintaining, and sharing the knowledge produced over the long term of the program (beyond the end of its implementation).

In our view, the PEP game session *trains the participants to embrace uncertainty* and to discuss how to jointly address the multiple challenges that are (im)posed to all actors. This relies on the main feature of the game design: considering unknowns and unforeseen consequences as 'business-as-usual' conditions for RWM and creating additional conditions to accentuate uncertainty. It provides a framework that goes beyond contrasting positions for or against a management option or the nuclear program, the plausibility of an event to occur, and the persistent hierarchy between expert and lay knowledge in favor of the former.

Although several unforeseen events have already been encountered in countries actively pursuing a long-term waste management program, the game design cannot be considered a ‘one-size-fits-all’. RWM programs are first and foremost ‘waste-site stories’, far from being applied in a generic way but adapted to the national and local contexts in which they take place. The type of waste produced, the status of spent fuel, the historical and current production sites for radioactive waste, and the profiles of the public concerned, to name but a few, are all recurring questions that require local or national answers. In our view, both the depth and quality of the discussion as well as the collective learning depend on the game’s ability to keep RWM complex in simple terms, and the seriousness of the game will remain if the initial national constraints and cards imposed on the players are regularly updated according to (future) substantial changes in RWM policy.

Similarly, the nuclear waste experts were not to provide one straightforward answer to every question raised during the game sessions. Rather, the debate involved both active listening to the laypeople's expectations and multiple opportunities for the expert to make his current (un)knowledge visible. We highlight that the production of lay knowledge encounters that of nuclear waste experts, and underline two ways of integrating the latter: players either disengage and let the experts make the final decision, or better organize responsibilities by putting the experts at the service of a decision taken by the participants. Our analysis shows that both the (re)production of a hierarchy between expert and lay knowledge and the subsequent transfer of responsibility depend strongly on the form of the experts' interventions—either informing, facilitating, or deciding for the players—as well as on the knowledge and non-knowledge they are willing to assume. It is therefore crucial to systematically assess how experts engage in such dialogical spaces.

Finally, the way in which experts integrate the outcomes of these game sessions into their practice and knowledge production also deserves more attention. How do the outcomes of discussions with stakeholders and audiences *actually* affect the safety culture and the handling of safety cases? How do these discussions change (or not) experts' initial thinking about how to respond to ever-increasing economic, social, technical, and political constraints? The evaluation should therefore focus not only on the timing and content of the SG sessions but also on how these sessions influence or modify the regulatory principles and practices of the management program. Indeed, if used for instrumental purposes, this type of method can have the opposite effect to that intended: it can become a promotional activity aimed at gaining acceptance for a preferred waste management program, and miss the opportunity to make its socio-technical pathways more robust. A genuine involvement of non-experts in knowledge *co-production* is therefore required to *systematically* address uncertainties.