Making the future in the present: using Science and Technology Studies to reflect on 40 years of research in the HADES Underground Research Laboratory

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Abstract: The timeframes involved in nuclear waste management often speak to the imagination, and even transcend it: what does it mean to isolate and contain human-made materials for periods up to hundreds of thousands or even a million years? In this article, we reflect on the role played by the HADES Underground Research Laboratory in making the distant future comprehensible today. Our argument starts by focusing on the pioneering role HADES played and plays in knowledge production on geological disposal. It highlights the heterogeneous nature of scientific experiments and experiences, and the performative role these play in defining matters of concern for research and development. Second, attention is directed to how HADES contributes to the defining of what is considered possible and imaginable, and how it therefore not only renders the future more predictable, but also contributes to the making of that future. We end the paper with a reflection on the implications of what 'making the future' could entail from an ethical perspective, discussing how the intergenerational responsibilities that come with these future-making capacities could be handled.

High-level radioactive waste (HLW) remains hazardous over very long time periods, as the radiotoxicity of some elements in HLW requires hundreds of thousands of years to decay to a 'safe' level (OECD NEA 2021, p. 26). While such timeframes speak to the imagination (e.g. Hora and von Winterfeldt 1997), they are in some ways unimaginable. Belonging to *geological* rather than *human* time, they exceed any timespan human societies are used to think about and act upon. Indeed, they might extend beyond the existence of humanity as we know it altogether (Galison in Kruse 2011). A central challenge within radioactive waste management (RWM) lies in making the distant future imaginable and manageable in order to facilitate the safe management of HLW over the very long term.

In this paper, we focus on the HADES (High Activity Disposal Experimental Site) Underground Research Laboratory (URL) in Mol, Belgium, and the role it has played and continues to play in rendering the distant future (more) comprehensible in the present. We explore how HADES and the experiments it has hosted have created and verified technical understandings of the doability of geological disposal (GD) and supported the dominant view that GD is the safest and best available means for managing HLW over the very long term (EC 2011).

We build on insights from the field of Science and Technology Studies (STS), which for decades has been interested in practices of knowledge production (Felt *et al.* 2017). By arguing how scientific knowledge and facts are products of situated processes and practices, rather than objective representations of the world (e.g. Latour 1987), STS highlights how knowledge production contributes to the creation or performance of the worlds it describes. In this light, HADES not only offers an infrastructure for technical research and development, but also a valuable opportunity for social scientific research and reflection on knowledge production practices and their close intertwinement with current and possible future societies (cf. Konrad *et al.* 2017).

What we propose here is that HADES should not only be understood as mapping the path towards a GD future, but also as actively contributing to the creation of this path and the direction it takes for both present and future generations. The practices, decisions and actions taken at HADES leave sociomaterial traces that contribute to the development of certain RWM options, while making others less likely, and thus reminding us that each future followed is another future not taken (Tutton 2017, p. 10).

We seek to highlight that, to quote Donna Haraway (2016), it matters which stories tell stories. In other words, we aim to underscore the importance of reflecting on how knowledge-producing infrastructures and entities such as HADES shape and inform what we think, how we think, how we come to think the thoughts we think, what we

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know, and how we come to know what we know about GD. Becoming reflexive about these processes does not only contribute to better understand what 'doing' research in and around HADES entails, it also creates sensitivity and receptiveness to the moral responsibilities that our current generations have towards future generations, given that the paths embarked upon in the present affect and shape the futures that are possible.

To support these claims, we draw on STS literature and concepts in our exploration of the HADES URL, and its extensive practices of knowledge production. More specifically, we use scientific articles and reports on two key developments in HADES history, the actual construction of the underground facility, and the long-running PRACLAY heater experiment, as illustrations of such knowledge production practices. Our contribution is primarily intended to be a reflection seeking to spark further discussion on the practices and impacts of knowledge production taking place at URLs like HADES. As such, our own, that is the authors', position requires some contemplation. At the time of writing, all three authors were social scientists working at the Program for Integration of Social Aspects in nuclear research (PISA) of the Belgian nuclear research centre SCK CEN. Together with the Belgian waste management organization ONDRAF/NIRAS, SCK CEN forms the Economic Interest Grouping (EIG) EURIDICE that operates and manages the HADES URL. Thus, HADES forms part of the broader organizational and professional contexts we as authors worked in daily, conducting social scientific research on a range of nuclear topics and applications. This also allowed us access to various kinds of information and experiences regarding HADES (e.g. past opportunities to visit it), which indirectly impacted on the reflections presented in this contribution.

We have structured this chapter along three main arguments. First, we discuss STS literatures on knowledge production to explore how HADES strengthens boundaries of what is considered possible and imaginable. Second, we mobilize examples of knowledge production at HADES to reflect on the ways in which the URL plays a crucial role in making the future tangible in the present, and in doing so contributes to the making of that future. Third, we reflect on the ethical implications that come with 'making the future', by elaborating on some aspects of intra- and intergenerational ethics relevant to the disposal of HLW.

Knowledge production at HADES

STS scholars have argued that scientific facts are made through everyday practices that are not different from other social processes (Latour and Woolgar 1979; Latour 1987; Knorr Cetina 1995; Law 2004). As such, they have challenged the positivist account that depicts science as the objective discovery of universal natural truths (e.g. Lynch 1985; Doing 2009). Instead of presenting scientific facts as objective representations of the world, STS scholars describe the ways in which these facts are made in labs through tinkering, negotiations, discussions, interpretations, configurations and re-configurations that transform materials, instruments and expertise into data, which in turn are transformed into statements and publications that then go on to circulate in the wider world (Latour 1987; Havstad 2020). Focus of STS is, then, on how, why and where scientific knowledge is created rather than on scientific outcomes themselves. Much like 'shifting your attention from the stage to the whole machinery of a theatre' (Latour 2008, p. 39), STS directs attention to 'matters of concern', rather than 'matters of fact', and highlights the ways in which things, such as scientific knowledge, are composed out of a myriad of elements, interests, practices and so on (Latour 2004; Michael 2017). A key notion here is that scientific methods tell stories about the world, but they also contribute to the creation of the worlds they tell stories about, meaning that:

> what we tell and how we tell it is not an objective representation of the world as it is. It is always already and inescapably selective. It prioritises some issues over others. It gives more credence to one approach than another. It foregrounds what we consider significant, and by implication ignores … other domains (Adam and Groves 2007, p. xvi).

Underground research laboratories are obvious spaces of knowledge production, as they play a crucial role in the development of geological disposal facilities (GDFs), demonstrating their feasibility and safety (NEA 2013). Focused simultaneously on the generation, verification and revision of knowledge, HADES plays a pioneering role in researching and indicating how GD could be feasible and safe in clay layers. The initial construction of the HADES URL, which took place between 1980 and 1984, is illustrative in this regard, as it demonstrated the doability and practicality of excavating a facility deep in Boom clay (Verstricht 2019). More precisely it showed 'the possibility to dig galleries in non-frozen clay at 250 m depth' and revealed that 'after an initial expansion, the clay body remains unaltered for a very long period of time' (Baetsle *et al.* 1986, p. 55). Based on these observations, Baetsle *et al.* (1986, p. 55) posited that 'it may be anticipated that construction of large diameter galleries (4 to 6 m) without freezing is technically feasible'. Likewise, excavations have confirmed that Boom clay has a self-sealing capacity, meaning that the damage

caused by the excavation of tunnels and galleries in clay will gradually heal and the low permeability of the clay, which supports the containment of nuclear wastes, will be recovered with time (Dizier *et al.* 2017). In this way, the excavation and construction of HADES can be seen as creating knowledge and durable discourses feeding the belief that GD is the most suitable method for achieving the long-term containment of nuclear wastes.

Crucially, this knowledge production is no mere human endeavour. As STS scholars amply argue, the stories underlying scientific facts, are as much the stories of materials, objects, and technologies, as they are the stories of scientists and researchers. Pickering (1993, 1995), for instance, holds that scientists, as human actors, are entangled with nonhuman actors, in a dialectic of resistance and accommodation. These entanglements of human and non-human actors shape the actions and outcomes of scientific practice (cf. Callon 1984; Latour 1987). In the case of HADES, building professionals, scientists, excavation tools, geological layers, frozen ground, and many more elements became entangled and aligned during its construction in such a way that the excavation of vertical and horizontal shafts proved successful, and fed the expectation of replicability in the future. If some of the elements from this materially heterogeneous entanglement would have been removed, the whole endeavour could (literally) have collapsed.

This entanglement of human and non-human elements is also illustrated in another pioneering experiment to which HADES is home: the in-site PRACLAY heater test. Some high-level radioactive wastes emanate significant amounts of heat over extended periods of time, and thus might affect the surrounding engineered barriers and geological layers, heating them up and undermining their containability (Hietala 2018). With the PRACLAY experiment, researchers hope to 'demonstrate the suitability of Boom clay for bearing [this] thermal load' (Li *et al.* 2010, p. 103). As part of the experiment, a gallery in HADES is heated to a constant 80°C for a 10-year period that began in 2014. During the preparatory and construction works, which took several years, more than 1100 sensors were placed in the gallery and its surroundings to monitor the evolution of temperature, pore water pressure, and stress inside the underground clay environment (Dizier *et al.* 2017). The ability of researchers to study clay, thus, relies on the sensors' ability to measure changes in the clay. The high number of sensors used in the experiment stems partly from a need for redundancy, as sensors might fail over time. Indeed, scientists working on the PRACLAY experiment have noted how since the beginning of the experiment, numerous temperature sensors and the majority of strain gauges have stopped functioning, and, hence, contributing directly to the experiment (Dizier *et al.* 2017). Yet, even the failed sensors provide information on the functioning of monitoring equipment in a potential future GDF. Where failures of sensors or abnormal measurements lead to adjustments of the experimental set-up (Dizier *et al.* 2017), they also provide scientists opportunities to reflect on issues such as sensor construction, placement, or timing of sensor failure (see Verstricht *et al.* 2022). Thus, scientists monitor the instruments they use to monitor their experiments, to gain insights into the monitoring of future waste disposal.

What we argue and seek to illustrate here, is how knowledge production is a situated practice that requires the entanglement and alignment of a range of interests and actors, both human and non-human. Looking at the knowledge production practices rather than the knowledge produced at HADES, highlights the plethora of work required to align the interests of scientists and technicians, with actors as diverse as sensors, heat emitters, bentonite, concrete, and clay. While such alignment might prove fragile (e.g. Callon 1984), it stabilizes and comes to be taken as a matter of fact (Latour 2004) when its outcomes are interpreted and translated into data, publications, and established scientific knowledge.

(Re-)opening this 'black-box' (Latour 1987) and treating matters of fact as matters of concern, visibilizes the socio-technical efforts required to achieve what are today perceived as established facts. Exploring the situatedness of knowledge production is moreover crucial for understanding how futures are made and performed in the present. It is to this topic, that we will turn in the next section.

Knowing the future?

Social scientists have highlighted the ways in which futures, like scientific facts, are made and rendered actionable in the present. The expectations, scenarios, and visions of the future that are connected to the development of certain technologies or scientific endeavours are not merely descriptive. They affect what might (or might not) happen, and as such make some futures more likely and others less so (cf. Konrad *et al.* 2017). Expectations about the future mobilize and collate infrastructures and researchers into – and justify research funding for – spaces like HADES. In this way, the future, in its anticipated forms, acts upon the present, and folds into it (Fujimura 2003; Anderson 2010). While it can neither determine the present nor can it be determined in the present, the future shapes the present (Michael 2000). With HADES, the name of the facility hints at its association with a future centred on the *geological* disposal of HLW. Like its illustrious mythical namesake, who 'acted in the manner of a

jailer, ensuring that dead mortals who entered his dark kingdom never escaped back to the light of the sun' (Hard 2004, p. 107), HADES works towards a disposal and long-term containment of HLW underground.

To establish a safe GD future, URLs enable and host large-scale and long-term investigations needed for estimating and understanding the behaviour and interactions of radioactive waste within GDFs over extensive periods of time. In this context, one million years is the often-accepted standard (OECD-NEA 2007), meaning that waste managers, researchers and others engaged in GD face the challenge of having to deal with the discrepancies between geological and human times. These discrepancies between the slow geological time and the fast-burning human time set limits to scientific knowledge production and attempts to make sense of the future. Even with the most advanced present-day modelling tools, it is impossible to map events with detail over a million-year timeframe, which means that geological 'repository evolution is … subject to unavoidable uncertainties that generally increase with time' (OECD-NEA 2007, p. 6). In short, doubts about the functioning of the GDF will remain at the time of implementation (Ewing 2012; Schröder 2016).

To minimize these uncertainties, HADES seeks to act like a time-machine. It brings the future into the present through the socio-technical entanglement of scientists, technicians, geological layers, and mundane material means, such as heaters that mimic the heat output of waste canisters emplaced in the anticipated GDF. Manipulation of time through scientific experiments, enables HADES to tell stories about the future and the safety of disposal that would otherwise be untellable. The construction of HADES discussed above, for example, can be seen as feeding towards a GD future (Konrad *et al.* 2017; Law 2004). It makes such a geological disposal future graspable (through digging into clay and measuring its movement) and actionable (by using these experiences with clay and its behaviour to anticipate and design a potential GDF) (Anderson 2010). Although HADES itself 'will never be extended for use as a repository for radioactive waste' (EIG EURIDICE n.d. *a*), its successful construction feeds the expectation and anticipation that a similar excavation of a 'real' GDF is an attainable future which can be worked towards.

Similarly, EURIDICE researchers seek to confirm and extrapolate knowledge gained through the PRACLAY experiment regarding the behaviour of clay and the integrity of concrete galleries under increased temperatures in circumstances resembling those in a future GDF (EURIDICE n. d. *b*). In effect, researchers working on the PRACLAY experiment seek to create an expected future of HLW disposal in similar clay layers in the present to be better able to map and predict how that future might evolve. Since it is not possible to fully reproduce the timescale, the spatial scale and the boundary conditions of a real GDF, the PRACLAY heater test is conducted under a well-controlled and reasonably conservative combination of thermal, hydraulic and mechanical boundary conditions that mimic the expected conditions of a future GDF (Li *et al.* 2010; Dizier *et al.* 2017). For example, the 80°C temperature to which the HADES gallery and its surroundings will be exposed for a period of 10 years, is in fact even slightly (10°C) higher than the expected temperature in a GDF containing HLW (Li *et al.* 2010; Dizier *et al.* 2017). The future simulated through the PRACLAY experiment is an estimation and an approximation of a potential future GDF and its functioning. Where 'the exact time-dependent heat output of vitrified HLW would not make much sense because all results would only be available after a considerable period of time' (Li *et al.* 2010, p. 104), the PRACLAY experiment foreshortens the expansive future of HLW to a manageable human scale in the present. Moreover, the conservative set-up of the experiment (higher than anticipated temperatures), creates or leaves space for the disposal future to unfold, and the GDF to evolve, along different paths without undermining the knowledge and safety claims produced through the experiments. Selecting and monitoring boundary conditions for the PRACLAY experiment both mimics and performs anticipated disposal conditions and futures.

The PRACLAY experiment, thus, performs the future in the present through its experimental set-up that seeks to emulate conditions within a future GDF. As a seal separates the PRACLAY gallery and its heater system from the rest of HADES (van Marcke *et al.* 2014), two different 'time zones' or realities are created within the URL: the present and the future. For the disposal future to be and remain mappable, the future created within HADES and the present need to be spatially separated. The (underground) conditions in the present and the anticipated future differ, which was noted by the researchers working on the PRACLAY experiment. They observed that the experiment's temperature was slightly lower at the start of the PRACLAY tunnel, which was deemed to be 'certainly an effect of heat dissipation through the seal structure and the windows' (Dizier *et al.* 2017, p. 27). While the future was leaking into the present through the seal and windows, any leakage of the present into the future would undermine the PRACLAY experiment's ability to map and make sense of the future. Thus, sealing the anticipated future from the present is vital for HADES' knowledge production potential.

The positioning of HADES deep underground similarly creates different time zones and cordons it off form the present. In the underground laboratory, one visits a space that has characteristics enabling the performance of a future where HLW is disposed of, while on the surface, such future may currently be unattainable. HADES' ability to order space, to perform different times zones or realities, is at the core of its ability to make (distant) futures tangible objects of inquiry in the present. Meanwhile, EURIDICE researchers' ability to observe, interpret and analyse that future relies on the expected functioning of all the instruments and objects that together compose the experimental set-up, thus again illustrating the entangled nature of knowledge production.

By elaborating on the ways in which HADES aims to alleviate some of the uncertainties related to GD and make sense of the future, we seek to shed light on the intricate relation between certain expectations of the future, and the ways in which these expectations are brought into reality. Being 'constructed to study the feasibility of HLW disposal in the Boom clay layer' (Li *et al.* 2010, p. 103), HADES starts from an expectation that HLW can be safely managed by disposing it deep underground. This expectation is based on scientific knowledge regarding the stability of geological layers, but in turn also 'drive[s] technical and scientific activity, warranting the production of measurements, calculations, material tests, pilot projects and models' (Borup *et al.* 2006, p. 286), which aim to support the suitability of GD for the safe management of HLW, at least until technical and scientific activities might prove otherwise or produce other solutions. It can then be argued that expectations regarding the future are 'both the cause and consequence of material scientific and technological activity' (Borup *et al.* 2006, p. 286), and that HADES contributes to the creation of the future it seeks to understand.

We have no reason to doubt GD as a viable option for long-term RWM. However, what we want to emphasize is that the future is no blank canvas or empty vessel, but is populated by decisions, infrastructures and artefacts from the past and present. It is 'an extremely crowded territory, filled with the actualised desires, hopes and fears of previous generations' (Adam 2008, p. 115). So, our past and current expectations, and the actions we (have) take(n) live on to shape our futures. Regarding the future of RWM, the actions taken, and work done in HADES will contribute to the shaping of the future handling of HLW.

John Urry (2016) stresses how futures and future-making are bound up with existing power dynamics. Citing the sci-fi writer William Gibson, Urry holds that 'the future is already here – it's just not very evenly distributed', meaning that different actors have an uneven ability to make and influence futures (Urry 2016, p. 17). The significance of HADES stems, in part, from this unevenness. While the future cannot be determined by a single actor or singular action, HADES, like other underground research laboratories, is a particularly powerful actor in performing and telling stories about the future, as it plays and continues to play a pivotal role in setting and maintaining GD trajectories in motion. It derives this power from offering a research environment presumed to be closer to actual disposal conditions than those offered by classic laboratories, and therefore more realistic. In other words, HADES 'take[s] advantage of the conditions at depth surrounded by natural rock, none of which can be exactly replicated in a standard surface laboratory' (US Nuclear Waste Technical Review Board 2020, p. 9). Moreover, less than 10 countries worldwide currently operate URLs for GD (US Nuclear Waste Technical Review Board 2020, p. 9), meaning that the number of actors able to offer 'realistic' environments for specific underground conditions (i.e. granite, salt, clay) is limited. This limitation renders HADES both its pioneer status and its power. Alongside other URLs, HADES can be seen almost as an obligatory passage point in the processes of producing knowledge, and ultimately the potential implementation of GD.

Here, it is important to distinguish between site-specific and generic URLs. Where site-specific URLs are excavated and operated under the expectation that the eventual GDF will be constructed at the same site, or that the URL itself eventually will be transformed into a GDF, this is not the case with HADES, as we observed above. As a generic URL, the role of HADES in future-making is to 'gain general experience of site characterization and underground construction techniques, model testing and verification of investigation and measurement techniques' (OECD-NEA 2013, p. 10; see also Wang 2014). However, HADES exists in a particular place on a specific site. STS scholars have pointed out that knowledge production practices are intimately connected to the sites in which they take place (cf. Parotte 2020; Pallesen and Jacobsen 2021). Although HADES will never be extended into a GDF, it was constructed in a specific geological environment for the particular 'purpose of researching the possibility of geological disposal in clay' (Eurad 2021). Thus, the future-making power of HADES has been configured in a specific way, as it can produce certain kinds of knowledge, but not others. Therefore, although (or perhaps especially because) the GDF will be constructed elsewhere, we feel it is important for researchers, policy-makers and others entangled with HADES to reflect on the knowledge produced by HADES, how it might generate certain expectations and routes towards future GD.

On the responsibilities of research

On the whole, the powerful position of URLs in knowledge and future making calls for reflection on the responsibilities and ethics connected to work done in and through them. Scholars have already described the phenomena of 'path dependence' and 'lock-in', which accounts for situations where a historical trajectory of socio-technical development makes it increasingly difficult to switch to other trajectories or solutions (Lee and Gloaguen 2015; Bergen 2016). Bergen (2016, p. 730) has argued how the 'historical process of GD's development and operationalization has brought us to a point where […] societies' symbolic, institutional and material investment in GD makes it difficult and thus unlikely that GD will be replaced with an alternative any time soon'. In other words, working towards one future, excludes other futures.

As such, it should be acknowledged that HADES contributes to and invests in the creation of a future of GD through practices, experiments, and experiences gained in the daily operation of HADES as well as through more mundane, but highly symbolic, aspects such as the naming of the URL. The knowledge and future-making ability of HADES rests on the ability to order natural processes in particular ways, to highlight and examine some, while peripheralizing others, hence guiding and narrowing researchers' gaze to certain processes and certain kinds of futures (Tutton 2017). Decisions regarding experimental set-ups and other activities conducted in and through HADES should not be perceived as purely scientific or technical, but require a broader reflection in terms of their societal impact, both in the present and in the future.

The tenets of responsible research – namely reflexivity, anticipation, responsiveness and inclusive deliberation (Owen *et al.* 2013) – can guide this reflective process regarding the direction and desirability of HADES' future-making. Here, reflexivity means giving thought to the assumptions, questions and motivations underpinning knowledge production at HADES, as well as to the risks, knowns and unknowns related to the knowledge production process and the knowledge produced. Anticipation refers to attentiveness to the potential (un) intended impacts of research conducted at HADES (e.g. in terms of path dependency), while responsiveness highlights the capacity to respond to the requirements of, and changes in, societal and scientific values and desires. Inclusive deliberation, finally, entails 'opening up visions, purposes, questions, and dilemmas to broad, collective deliberation' (Owen *et al.* 2013, p. 38), for example by opening up discussion and debate to those not immediately working in and on HADES. Given the powerful role of HADES (and other URLs) in defining and shaping a future of GD that will affect several future generations, it is these latter two dimensions of responsible research, which call for attention. How to make sure that the desires, concerns, values, and priorities of those potentially affected by the work done at HADES are known and acted upon? Historically, the siting of GDFs has often been met with protest and opposition by potentially affected communities, and delays or cancellations of siting processes (e.g. Bergmans *et al.* 2015). Over the past decades, a 'participatory turn' in radioactive waste management has meant that participatory approaches have been included in various GDF siting processes (e.g. Di Nucci *et al.* 2017; Litmanen *et al.* 2017). However, the knowledge and knowledge production processes that underpin GD tend to remain the domain of scientists, engineers and technicians. Given our argumentation regarding the role of these knowledge production practices in making GD futures, this arguably limits the scope of participation, as focus is directed to one rather than multiple potential futures (Bergmans *et al.* 2015). Below, we delve a little deeper into what it could mean to be reflective about and incorporate the effects of HADES on the generations that will come after us in making and thinking about the future.

Of moral authority and humbleness: HADES as a spiritual site

The previous section has introduced the notion of HADES as a space where heterogeneous assemblages produce knowledge that contributes to the making of specific futures. In this section, we want to develop that reasoning further from the perspective of intergenerational ethics. In a metaphorical way, we could say that HADES, in its entirety, is an example of a scientific hypothesis that is 'released from the laboratory', with a specific but sometimes implicit task: to inform the world of a promising possibility (Meskens 2019). In this case, the feasibility of safe long-term disposal of HLW. HADES should therefore also be considered as the materialization of a scientific hypothesis that lives its own public social and political life while research is still going on, and hence actively contributes to the making of a future. This is similar to how the anthropogenic climate change hypothesis has influenced politics and the socio-economic world since its first formulation last century. The real challenge is not to try to shelter the hypothesis 'until fully proven' but to responsibly deal with its future-making capacities in public. Taking responsibility in this sense means two things. First, it implies involving the potentially affected and other stakeholders in participatory forms of democracy, aiming for joint problem solving and co-production of decisions, where HADES – and

the knowledge produced in/through it – serves as one of multiple spaces in the participatory ecology of long-term radioactive waste management (e.g. Chilvers and Kearnes 2020). Second, and related, it means doing science differently, namely as transdisciplinary science advancing from a holistic perspective and enriched with insights and ideas from the social sciences and the humanities, from lay knowledge and the arts and from civil society and citizens (e.g. Meskens 2019; Renn 2021). More concretely, this could for example mean that researchers working in and around URLs like HADES set up venues (e.g. research projects, groups, networks) that bring together actors with very diverse expertise, both from within and beyond science, to develop new knowledge, and reflect on its potential impacts on our present and future worlds (Turcanu *et al.* 2023).

Such a need to involve various stakeholders in the management of (high-level) radioactive waste has repeatedly been stressed over the past decades (cf. Bergmans *et al.* 2015). Returning to the uneven ability of actors to make and influence futures (Urry 2016), this need for involvement should not only be considered in terms of a moral responsibility towards society today, but also as a moral responsibility towards future stakeholders and societies. As stated above, research on GD is both informed by and makes the future, and the acts performed in and through HADES in this sense impact on those who will come after us. While this is a situation we need to accept, it has consequences for our moral responsibility towards the next generations. More specifically, there are two features of 'intergenerational relations' which need to be taken into account. The first is that there is a lack of direct or 'practical' reciprocity between generations of people who are not contemporaries. The second is a consequence of the first, namely the fact of a permanent asymmetry in 'power-relations' between people living now and those who will live in the future (cf. Adam and Groves 2007). Present generations have 'practical power' over future generations in the way they can create conditions that limit or reduce the options of those future generations or that make them more costly. In other words: as there is no intergenerational practical reciprocity possible, there is an unavoidable intergenerational democratic deficit. This practical power needs to be considered in how we manage our radioactive waste, and hence also in the R&D efforts which form the basis of this management. An important issue to take into account here, is that science can describe different options, and it can help us in making certain choices between these options, but it cannot make the choice for us. Our values, ideas, desires, and interests give weight to these different options. Conducting research in a reflective and transdisciplinary way, explicitly recognizing also the concerns, needs, desires and values of various stakeholders, contributes towards making choices which support the 'common good'.

In this reflection and deliberation, the moral arguments of future generations can however not be fully accounted for, meaning that we, as the present generation, do not only have practical power over future generations, but inevitably also moral power. As those from the future are missing, our moral authority inevitably only 'speaks to ourselves', and invites us to ethically care for the way we make sense of things today. From this follows that not only from an intragenerational ethics perspective, but also from an intergenerational one, involving society in research and political decision making related to HLW governance is motivated from out of a moral responsibility towards that society *today*. In this sense, we also need to acknowledge that while HADES aims to render the future more comprehensible/knowable and ultimately safe(r), this safety is shaped after our moral understandings and concerns regarding what is (un)safe. HADES is not only a place for experimental 'practical' research and a place that invites reflection on how scientific knowledge comes into being and can be used in policy, it is also a 'spiritual' site, in a sense that it invites us to reflect on our situatedness in time and space, and hence our moral responsibility towards future generations. Taking up our moral authority together, wisely and humble, we have one additional task that will benefit both us and those who come after us. A future HLW disposal site should also serve as a site that stores not only radioactive waste, but equally the accounts and stories of our thoughts, reflections and actions. As such, we explain to future generations why and how we – together – thought this was the best we could do.

Conclusions

The HADES URL in Mol, Belgium, has in its 40-year of existence played a pioneering role in developing knowledge on the long-term management of high-level waste. Having to deal with the highly challenging timeframes during which this high-level waste remains potentially dangerous for living organisms, HADES acts as a time machine that brings the future into the present. Applying insights from the field of Science and Technology Studies to the activities conducted in and through the URL, this paper puts the emphasis on processes of knowledge production, highlighting the situated and heterogeneous entanglement of elements involved in these processes, and on how these can also be understood and motivated from an intergenerational ethics perspective. As such, it questions the idea that science entails a pure description of a reality 'out there' and highlights how this reality is

co-performed through scientific practice. Moreover, this also entails that knowledge production at HADES has a performative impact on the future. The experiments and experiences gained in HADES verify and at the same time set certain expectations for a future in which high-level waste is disposed of in deep clay layers. Given this performative nature of knowledge production processes, responsible research requires a reflection on the complex entanglement and mutual impact of science, policy and society, beyond the linear reasoning dominating the positivist approach to science. It is through such reflection, that the requirements and impacts of these entangled domains can be more explicitly attuned to each other, thus also putting a stronger emphasis on the societal importance and relevance of infrastructures like HADES.

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Data availability Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

Correction notice The copyright has been updated to Open Access.

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