

RESEARCH ARTICLE

Nuclear waste as a socio-technical problem

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Abstract • In public discussion, high-level nuclear waste is often referred to as an exceptional environmental problem. It is indeed an exceptional problem, but not primarily because of the permanent threat that nuclear waste poses to future generations, as is usually argued. Its exceptionality rather stems from socio-technical factors that create deadlocks and dilemmas, thus hampering and delaying decision-making. This article provides an overview of major socio-technical issues pertaining to nuclear waste, including some that have been neglected in previous literature, and thus contributes to technology assessment in this field.

Atommüll als soziotechnisches Problem

Zusammenfassung • In der öffentlichen Diskussion wird hochradioaktiver Atommüll oft als ein außergewöhnliches Umweltproblem bezeichnet. Es ist in der Tat ein außergewöhnliches Problem, aber nicht in erster Linie wegen der dauerhaften Bedrohung, die der Atommüll für zukünftige Generationen darstellt, wie meist angeführt wird. Seine Außergewöhnlichkeit geht vielmehr auf soziotechnische Faktoren zurück, die zu Blockaden und Dilemmata führen und so die Entscheidungsfindung behindern und verzögern. Dieser Artikel gibt einen Überblick über wichtige soziotechnische Fragen im Zusammenhang mit Atommüll, darunter einige, die bisher in der Literatur vernachlässigt wurden, und leistet somit einen Beitrag zur Technikfolgenabschätzung in diesem Bereich.

Keywords • nuclear waste, intermediate storage, siting, radiological protection, multiple barriers

Introduction

High-level nuclear waste consists mainly of spent fuel from energy-producing reactors and refuse from reprocessing plants and the production of nuclear warheads. There are two ways to treat the spent fuel from a nuclear reactor. One option is to treat it as waste to be ultimately placed in a final repository. The other option is to treat it as a resource. It is then sent to a reprocessing plant, where plutonium and uranium are recovered and used to produce new reactor fuel. This is usually Mixed oxide (MOX) fuel, which contains both uranium and plutonium. Reprocessing gives rise to long-lived high-level waste, and so do reactors using MOX fuel (Feiveson et al. 2011). However, the total amount of high-level waste is reduced by a factor of five as compared to the option without reprocessing (Arslan 2009). Reprocessing is used in France, Russia, Japan and India, whereas most other countries refrain from reprocessing due to environmental and occupational risks, nuclear proliferation issues, and not least the forbiddingly high costs. To date, about 30 % of all spent fuel that has been generated in nuclear reactors has been reprocessed (IAEA 2020, p. 17).

Due to the heat produced by decaying short-lived isotopes, spent fuel is kept in water pools for at least a decade after being removed from the reactor. The water must be continuously cooled in order to prevent dry boiling that could lead to release of radioactive material into the atmosphere. Failure of the cooling system in a spent fuel pool was one of the major problems in the 2011 Fukushima nuclear disaster. After the decay heat has declined sufficiently, the spent fuel can be transferred to dry cask storage, usually in steel cylinders. This is how most of the world's high-level nuclear waste is currently stored. Neither water pools nor steel casks are suitable for final disposal. It is generally agreed that for that purpose, high-level waste should be placed in containers with minimal risk of leakage, and these containers should be deposited in deep geological repositories (Feiveson et al. 2011; OECD 2020, p. 22).

The reactions in a nuclear reactor give rise to highly radioactive nuclides, including some with very long life, such as plutonium-239 with a half-life of 24,000 years and neptunium-237 with a half-life of 2,140,000 years. Consequently, the safety of

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nuclear waste disposal has to be discussed in a time perspective reaching hundreds of thousands of years into the future. This article first asks if this time perspective is unique. It then suggests to view nuclear waste as one of several long-term dangers, but points to the specific socio-technical nature of the problem, which on the one hand disqualifies the economic and policy practice of ‘discounting’, and, on the other hand, brings to attention the dilemmas of unsafe interim storage. In conclusion, technology assessment (TA) is discussed as an adequate approach to tackle the socio-technical problems of nuclear waste treatment.

One of several long-term dangers

There are strong indications that anthropogenic climate change and losses in biodiversity can have severe effects on living conditions on the planet in millions of years to come (Barnosky et al. 2012; Lenton et al. 2019; Faurby et al. 2022). Notably, both climate change and massive losses of biodiversity will affect all parts of the globe, whereas the serious effects of failure to contain nuclear waste are expected to be mainly local or regional.

Furthermore, some forms of chemical waste can have severe toxic effects far into the distant future. One example of this is mercury, which is highly toxic for both humans and the environment (Eisler 2004; Rice et al. 2014). Contrary to the radio-toxicity of nuclear waste, the toxicity of mercury waste does

harmful effects far into the future. In policy discussions about costs and benefits of measures against climate change, discounting has a prominent role. By contrast, although some economic analyses of nuclear waste management have employed discounting (Barron and Hill 2019), they do not seem to have had much influence.

Discounting is a method of economic analysis that reduces the values of both positive and negative effects that are expected to take place in the future. Discounting has its origin in monetary calculations in the relatively short run. If we assume a constant deposit rate of 3 per cent, then € 10,000 ten years in the future are worth about € 7,440 today. Similarly, a debt of € 10,000 to be paid in ten years’ time can be equated with a debt of € 7,440 payable today. In cost-benefit analysis, the same mode of thinking is applied to values that are not straight-forwardly convertible into money. For instance, with a 3 per cent discount rate, the loss of 31 human lives in fifteen years will be considered to incur the same loss in value as the loss of 20 lives today. (This is because $20 \times 1.03^{15} \approx 31$.) Similarly, if we assume that the extinction of a species in 2023 will result in a loss of value of € 1,000,000 in 2123, then discounting at 3 percent would lead us to put the loss in the present at only € 52,000. (This is because $52,000 \times 1.03^{100} \approx 1,000,000$.) As these examples show, discounting tends to make the “present value” of environmental losses so low that costly measures to prevent them cannot be justified by the economic calculation.

Unfortunately, the long-term perspective of nuclear waste treatment is not unique.

not diminish with time. According to the European Union’s legislation, mercury waste in liquid form has to be converted to solid form (e.g., mercury sulfide) for final disposal. Such disposal has to take place in salt mines, deep underground hard rock, or above-ground facilities with the same degree of safety (EU 2017). The rules of storage for mercury waste have some similarity with those for nuclear waste, but there is a remarkable lack of details on the quality and the time perspective of the permanent disposal.

These examples of non-radioactive dangers confirm that the long-time perspective that is adequate for nuclear waste is also relevant for other health-related and environmental issues. In this respect, nuclear waste is not exceptional. However, it is exceptional in other, more social and socio-technical respects.

Valuing future damage

One of the most conspicuous differences between nuclear waste and other major environmental issues, in particular climate change, concerns the role of discounting in the evaluation of

Discounting has been much criticized for this and other reasons (Hansson 2010; Rendall 2019), but it is still standardly used in environmental and climate economics. As noted by Beck and Omen (2021, p. 176), “the decision to incorporate a high discount rate into mitigation pathways displaces the burden of climate mitigation from the present into the future”.

In contrast, discounting is virtually absent from policy discussions about nuclear waste. A major reason for this may be that in the established time scale for the safe deposition of nuclear waste, discounting would have absurd consequences. Even with a yearly discount rate of 0.5 per cent, which is considered very low by most economists, the death of one person today would be worse than the death of 10,000,000,000 persons in 4620 years. Disasters taking place 100,000 years from now would have only minuscule present-day values. This is certainly not how most of us would think about our responsibility for future generations.

Instead of discounting, some regulations of waste disposal refer to a maximal period in time, in which safety must be upheld. For instance, German nuclear waste legislation requires the “best possible safety for durable protection of humans and the environment” in the next one million years (Bundesministerium

der Justiz 2017). A period of one million years is difficult for us to grasp and relate to (Berg and Hassel 2022), but importantly, one million years without discounting implies a much stronger protection of the environment than any discounting scheme that has ever been seriously proposed.

Discounting over long periods is also problematic for ethical reasons. This can best be seen by considering the underlying assumptions of discounting. The fundamental justification refers to money at different points in time. Under the assumption of constant interest rates, discounting can be used to compare monetary values at different points in time. But when we are discussing radioactive effects on life, or climate change, this argument cannot be applied directly, for the simple reason that there is no interest rate on human life or environmental destruction. Instead, discounting of these values has to be based on three assumptions. First, the value of human lives etc. today has to be convertible into present-day monetary values. Secondly, present-day and future monetary values have to be exchangeable through discounting, and thirdly, future lives etc. have to be convertible into money at that same future point in time. The first of these exchanges is certainly difficult and problematic, but suppose that we settle for some conversion values, perhaps based on how much we are prepared to pay for saving a human life or a species. The second exchange may be reasonable in the short term, but not for the long time periods that are relevant for nuclear waste and major environmental issues. The ancients did not have interest rates in our sense (Hudson 2000). We have no means to know whether economies thousands of years into the future will have interest rates – or even if they will have money. The third exchange is ar-

tergenerational and potentially intercivilizational. For such issues, including nuclear waste, sustainability is a much better guideline. It tells us to do what we can to meet the needs of those who live now without compromising the ability of future generations to meet their needs (Hansson 2010, pp. 276–277).

Unsafe intermediate storage

Nuclear power was called into question already in the early 1960s. In the 1970s and 1980s it was a major political issue in many countries. But already in 1961, some scientists were worried that the environmental movement's focus on nuclear power was the wrong priority, since the greenhouse effect from combustion of fossil fuel posed a much greater threat to life on the planet (Suess 1961). One of the anti-nuclear movement's major arguments was – and still is – that there is no known method for safe final disposal of the high-level waste. They have therefore consistently opposed all proposals for such disposal. Since final disposal is expensive, the nuclear industry lacks economic incentives to speed up the transition from interim storage to final disposal. In addition, the risk of severe social conflicts over siting is a disincentive for both government and industry. Indeed, governments and the nuclear industry have been remarkably slow in taking actions that can lead to safe methods and sites for final disposal. Still today, almost seventy years after the first nuclear power plants were built, only a few countries have started to construct facilities for final disposal, and no high-level waste has yet been deposited in such facilities. (The Finn-

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guably the most problematic of the three. The valuation of lives, health and the environment has changed drastically over the years. There is no way to support the assumption that this valuation will be made in the same way far into the future as it is made today. Notably, such discounting of values far into the future is not only inter-generational but also inter-civilizational. The uncertainty is so momentous that we have strong reasons to refrain from using such calculations for decision-making purposes.

All these problems with discounting are good reasons to resist any proposals to introduce the practice of discounting future harms into nuclear waste management. It would be more sensible for analysts of climate change and other long-term issues to learn from the practice in nuclear waste management, and refrain from using discounting as a tool for deprioritizing harms affecting future generations. Discounting can be useful for relatively short-term monetary issues, but it is misleading for issues that are in-

ish and Swedish governments have approved the construction of underground facilities for final disposal in the respective countries, but in both countries additional decisions are needed before actual disposal can take place.)

In Germany, whose last operating nuclear power plants were permanently shut down in April 2023, the law requires the siting decision for a permanent nuclear waste repository to be made in 2031, but this is generally considered to be unrealistic (Smedinck et al. 2022, p. 11; Schwarz 2022, p. 40). Thus, it seems as if plans for final disposal of the waste will continue to be at a preliminary stage long after the phasing out of nuclear energy in the country. Many other countries are in a similar situation. In retrospect, it seems rather obvious that the political and industrial decision-makers who started the development of nuclear energy should have paid much more attention to the waste problem. Unfortunately, some present-day decision-makers seem to

repeat the historical mistake. Small modular reactors (SMR) are enthusiastically promoted in several countries as a key energy source for the future. However, very little attention is paid to the waste that these reactors will produce. Depending on the type of SMR, the waste may require another solution than the nuclear waste that has been produced by other reactors in the respective country (Krall et al. 2022).

The amount of high-level waste kept in interim storage has grown rapidly. It is currently estimated at about 400,000 (metric) tons, distributed among hundreds of sites across the world (Le 2020). Storage of high-level radioactive waste requires stringent safety measures, but unfortunately, such measures have not always been applied. Two severe accidents in Soviet military

advantages in comparison to currently planned deep geological repositories, for instance in terms of dependence on human attention and protection against malevolent access. There is also wide agreement that we should solve the waste disposal problem in a way that does not leave the burden to future generations.

Therefore, nuclear waste policy faces a dilemma, which we can call the *dilemma of prolonged interim storage*. It has a structure similar to that of the well-known lawn-crossing problem in decision theory: Each crossing of a lawn seems to be innocuous, but a large number of crossings can destroy the lawn. In nuclear waste management, the potential advantages of additional investigations have to be weighed against the potential risks and disadvantages associated with prolonged interim storage. This is a

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storage in 1957 and 1967 led to spread of radiotoxic substances in the environment (Aarkrog et al. 1992; Mikhailovskaya et al. 2002). The safety of interim storage is still deficient in many places. Many of these are surface facilities, which makes them vulnerable to acts of war, terrorist attacks, and major natural disasters. Recent Russian attacks on the Zaporizhzhia nuclear power plant in Ukraine have made it clear that ruthless and illegal attacks on nuclear facilities cannot be excluded in today's world (Borger 2022).

Since final disposal is expensive and contentious, there is an obvious risk that sites for interim storage will be "converted" into final repositories. In one case, such a conversion already appears to have taken place. A backfilled previous lake in Russia that was involved in the 1957 and 1967 accidents is now described as "a near-surface permanent and dry nuclear waste storage facility" (Anon. 2016).

The dilemma of prolonged interim storage

The construction of a deposition site that remains safe hundreds of thousands of years into the future is no easy task. Unsurprisingly, all proposed constructions have been subject to criticism and to demands for additional investigations. It does not seem possible to construct a spent fuel repository that satisfies everyone. Arguments can always be made for further studies of potential problems and for the development and evaluation of alternative constructions. At each point in time, it seems reasonable to wait just another year or so for additional investigations. However, if years are added to years in this way, then the outcomes of these investigations may not outweigh the disadvantages of prolonged interim storage. There are large variations in the safety of interim storage facilities, but even the best of them have dis-

dilemma that none of the major participants in the discussion on nuclear waste has an incentive to bring up. The owners of unsafe interim storage facilities do not want to put focus on possible problems in their ongoing activities. The anti-nuclear movement does not wish to start a discussion that could undermine one of their major arguments against nuclear power, namely the unacceptability of all proposed solutions to the final disposal problem. But nevertheless, this is a real dilemma that decision-makers will have to face.

Multiple barriers

Current plans for nuclear waste management are all based on a system of multiple barriers, arranged with the aim to make each barrier as independent as possible of its predecessors in the sequence. If the first barrier fails, then the second is still intact, etc. For instance, the nuclear industry in Sweden and Finland has developed a repository design with the following barriers:

- „– the spent fuel is encapsulated in tight, corrosion resistant and load-bearing canisters,
 - the canisters are disposed in crystalline bedrock at a depth sufficient to isolate the encapsulated spent fuel from the surface environment,
 - the canisters are surrounded by a buffer that prevents the flow of water and protects them, and
 - the cavities in the rock that are required for the deposition of canisters are backfilled and closed.“
- (Posiva SKB 2017, p. 9)

The idea is that if one these barriers fails, then the remaining ones will suffice to keep the radionuclides below the surface (Jensen 2017; Lersow and Waggit 2020, pp. 282–287).

Multiple safety barriers have an important role in modern safety engineering (Hansson 2023, pp. 82–85). The barriers often form a temporal rather than spatial sequence. A common mistake in the evaluation of multiple barrier systems is to only evaluate each barrier by itself. Much more effort should be put into the identification and analysis of potential events that can damage all or most of the barriers in one fell swoop. In nuclear waste management, this can include natural events such as a large meteorite or a volcanic eruption, but also man-made disasters such as those inflicted by terrorists or an invading army.

The roles of nations and local communities

The current consensus is that each country should arrange for safe final disposal within its territory of all nuclear waste generated within that territory. This is a relatively recently established consensus. For instance, well into the 1990s, large parts of the Finnish nuclear waste were exported to the Soviet Union and later to Russia (Kumpula et al. 2022, p. 11). Like many other countries, Finland now has a law that prohibits importation and exportation of nuclear waste, and requires final disposal within the country of all domestically produced nuclear waste (Kojo et al. 2022).

From a pragmatic point of view, strict national responsibility for safe final disposal seems to be the best way to avoid the risk of unsafe dumping in countries with low levels of environmental protection. Such unsafe dumping is still, despite the Ba-

much-prolonged use of intermediate storage facilities, or to permanent deposition in a suboptimal geological formation. The Swedish and Finnish sites for final disposal are both situated in a municipality that has a nuclear power plant within its borders. The siting process may be more difficult in countries where no municipality with that experience has suitable geological conditions for a permanent repository. Understanding of local traditions and concerns can be important in a process leading up to a siting decision that is as consensual as possible.

Is irretrievable disposal possible?

There has recently been much discussion on whether the waste repository should be permanently sealed, or left accessible so that future generations can retrieve the waste (OECD 2012; Tondel and Lindahl 2019; Barthe et al. 2020). It is commonly assumed that sealing will relieve future generations from the arduous task of taking care of an open repository, but on the other hand, it will reduce their freedom to do what they want with the repository (Sierra and Ott 2022, p. 48). However, this dichotomy is based on a highly uncertain technological prediction, namely that sealing intended to make the waste irretrievable will make it irretrievable for hundreds of thousands of years. For a simple comparison, a heavy object dumped into the sea at a depth of 500 meters a couple of centuries ago was considered to be irretrievable at the time, since no diver could reach it. Today it may be retrievable with an underwater robot. We have no means of knowing how long sealing with today's technology can make the

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sel Convention, a large problem for other types of hazardous waste (Hansson 2009). Complaints have been made that it may be too expensive for small countries to develop their own nuclear waste facilities (Frenay and Parotte 2022, p. 27). However, nothing prevents a country from reducing its costs by using waste treatment methods, canisters and a general disposal design that have been developed in another country. Finland, for example, plans to use a disposal method that has its origin in the Swedish nuclear industry and has been further developed in close Swedish-Finnish cooperation.

Another difficult issue is what role the local population should have in the siting of an underground waste repository. Siting at a place where the local community says “no” would be undesirable for many reasons. But on the other hand, it would be irresponsible to let difficulties with local opinions lead to

disposed nuclear waste irretrievable. Perhaps the ongoing development of tunneling robots and automated mining vehicles will lead to new technologies that defy the very notion of irretrievable disposal of nuclear waste.

Remarkably, German law requires the repository to be permanently sealed 500 years after the disposal operations have been finished (Bundesministerium der Justiz 2017). According to some experts, those operations will finish about 100 years from now. We have no means of knowing whether meaningful sealing will at all be possible at that point in time. Another problem with this decision is the presumed longevity of the jurisdiction. From the viewpoint of temporal distance, a decision now about what should be done in about 600 years is roughly as binding for those living then as the bans of so-called heresies decided by the Council of Constance are to us now.

What technology assessment can do

The nuclear waste problem is a socio-technical problem in need of a solution. In many countries, its social dimensions have not been adequately dealt with, which has led to a deadlock that blocks progress towards a solution. This is a situation in which technology assessment with its experience of addressing problems at the science-policy and technology-policy interfaces can have an important role.

Technology assessment can contribute to a realistic understanding of what science can achieve in this area. It would be unwise to implement a solution that is not supported by science. Here, as in other areas, a scientific consensus has been achieved when the vast majority of scientific experts agree on an assessment. It is not required that no one disagrees or that no one asks for additional investigations (Dellsén 2021). Only with a realistic understanding of how science works can it be effectively used to help us solve complex socio-technical problems, such as that of nuclear waste management and disposal.

Technology assessment has a long tradition of scenario development that can be highly useful in this area. Various scenarios relating to long-term safety have already been developed and thoroughly investigated. We also need scenarios describing potential problems in the interim storage facilities. With 400,000 tons of waste lying in interim storage, we urgently need to find safe, sustainable and socially tolerable solutions to the waste disposal problem, irrespective of what decisions are made on the future of nuclear energy.

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