The case of nuclear energy and radioactive waste

Excerpts from the end days of an irresponsibly operated system

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‘Of all the changes introduced by man into the household of nature, large-scale nuclear fission is undoubtedly the most dangerous and profound. As a result, ionising radiation has become the most serious agent of pollution of the environment and the greatest threat to man's survival on earth.’[1]
(Ernst Friedrich Schumacher, 1973)

In his highly acclaimed collection of essays, ***Small is Beautiful***, economist Ernst Friedrich Schumacher puts forth his firm position on nuclear energy. This technology, he opines, poses the greatest possible threat to the natural environment and the survival of humanity. The Hungarian nuclear lobby might, as usual, react to Schumacher’s position saying that an economist (that is, a person who is not an energy expert) is not competent in such serious matters, even though in the happier half of Europe not only economists but even social scientists have been considered experts in energy matters for decades now. For the Hungarian nuclear lobby, let us offer some other food for thought:

‘Man, when constructing and operating nuclear power plants, is pushing the limits of his abilities. He had better stop in good time. Indeed, this is evident for professionals and insiders... I think the risk is too great and there is no point in comparing it with any other type of risk. The danger of radiation makes nuclear energy so insidious that mankind must stop playing with this fire immediately. There is too much at stake... I must add that I am not an observer from the sidelines. I have the necessary professional knowledge and personal experience. It is the sense of responsibility which urges me to speak out. The nuclear lobby, headed by the Atomic Energy Agency, will certainly not share my opinion. Their existence is also at stake.’

Ernő Petz (Director of the Paks Nuclear Power Plant from 1991 to 1994)[2]

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[1] E. F. Schumacher (1973). Small is Beautiful: A Study of Economics as if People Mattered https://terebess.hu/keletkultinfo/Schumacher-Small-is-Beautiful.pdf

[2] Polgári Szemle Vol 7, No. 4, 2011 https://polgariszemle.hu/archivum/125-2011-szeptember-7-evfolyam-4-szam/gazdasagstrategia/446-mi-van-ha-megsem-igaz

EXECUTIVE SUMMARY

In nuclear power plants, fuel pellets, which produce the heat for steam turbines, are quite small, even fit into a human hand, but the quantity of waste generated throughout their life cycle is enormous. Given that the average uranium oxide concentration is extremely low (0.1%), the quantity of the rock mass to be moved and processed during mining is 20,000-25,000 times as much. Obviously, this also entails a significant demand for energy. Besides quantity, an important quality-related characteristic of radioactive waste is the very insidious process of ionisation spanning over a period of several hundreds of thousands of years. Consequently, it is in the same time frame that waste requires constant control and guarding, and repositories regular maintenance and monitoring. In essence, the costs are impossible to estimate and, therefore, are not included in calculations of the nuclear power prices and are not charged to consumers.

Seventy years have passed since the advent of the technology, yet the problem of spent fuel storage remains unresolved at every location. As shown by international experience, one thing seems certain: the expected magnitude of costs will be comparable to that of the construction of a nuclear power plant. The operation of other radioactive waste repositories is far from being seamless in Hungary or anywhere in the world. The extremely high number of anomalies and serious malfunctions calls attention to the fact that the optimism shown by some interested expert groups is by no means justified, and the lack of clear communication on their part is indeed an obstacle to the responsible assessment of the severity and significance of the problem by decision-makers.

Radioactive waste is generated not only in the course of normal operation, but also as a result of military attacks and accidents at nuclear power plants. Obviously, this poses a major challenge, as evidenced by the example of the Fukushima disaster of 2011, where no satisfactory solution has been found to store the radioactive cooling water (the current quantity of which is 1.2 million tonnes) or the millions of cubic meters of contaminated soil.

The authors have checked some relevant textbooks prepared for Hungarian university students of engineering and found that they do not make any reference to serious incidents or malfunctions related to radioactive waste. This is unacceptable, given that such textbooks reinforce the idealised and distorted impression that everything is in perfect order in the nuclear industry, as if there were no fundamental problems or unsolved (or unsolvable) issues.

As evidenced by existing operating experience, nuclear energy is not cheap, is not safe and is very far from being clean.

INTRODUCTION

On the 10th anniversary of the Fukushima nuclear disaster and the 35th anniversary of the Chernobyl disaster, society (and decision-makers, who are obliged to serve public interests) must be reminded that nuclear energy is incompatible with today's economic, social or environmental requirements. What is more, some key actors in the field of the energy system opine that it is obsolete in terms of energetics as well.[3] Most of these suggestions are discussed briefly in a recent publication of Energiaklub. The present paper focuses only on the most important but regularly ignored environmental problem: **the issue of spent fuel waste.** Tellingly, **the 230-page 'non-technical summary of the environmental impact assessment' of the Paks II Project[4] dedicates a seven-sentence chapter[5]** to the issue. Instead of discussing actual difficulties, it tries to draw attention to far less significant, albeit more promising subjects; for example, the impacts on the Danube are elaborated in 45 pages.[6]

It is also common for some energy engineers to think that representatives of other disciplines have no say in the matter of energy. But the fact is that nuclear energy goes far beyond what happens within nuclear power plants. It has thousands of implications in and links to even distant disciplines where engineering experts, apparently, are not confident at all. The solution is obvious: only multidisciplinary research teams are in the position to have a sufficiently thorough insight into the correlations of the nuclear energy industry and to elaborate a meaningful strategy in which environmental considerations are much more prominent than they have been to date. The reason for this is that the operation of nuclear power plants, by its very nature, has an environmental impact which, all other unfavourable aspects aside, makes it unsuitable for being taken into serious and responsible consideration as a possible way to humanity's energy needs.

Among these problems, by far the most severe is that of ***high-level radioactive waste*** generated also in the course of normal operation, for which there is no available and proven technology that would offer a satisfactory solution in a time frame of hundreds of thousands of years. The fact that *Homo sapiens sapiens* emerged less than 30,000 years ago (and the industrial revolution started only 250 years ago) adds a very special aspect to the issue of radioactive waste disposal for hundreds of thousands years and

[3] https://energypost.eu/interview-steve-holliday-ceo-national-grid-idea-large-power-stations-baseload-power-outdated/

[4] https://www.paks2.hu/documents/20124/60046/K%C3%B6rnyezeti+hat%C3%A1stanulm%C3%A1ny+-+K%C3%B6z%C3%A9rthet%C5%91+%C3%B6sszefoglal%C3%B3.pdf/5ea368ee-fa34-f276-0c78-eff7f369f2ef

[5] Chapter 20.6.2: Spent fuel

[6] Chapter 12: Expected impacts of the planned development and environmental conditions on the water temperature, exposure to floods, safety of cooling water abstraction and riverbed changes of the Danube

of related challenges. In this context, it is telling that some Hungarian technical experts frequently opine that such stringent requirements for the disposal of high-level radioactive waste are not justified and it would suffice to consider the issue in a time frame of 50—60 years. This only highlights the importance of the involvement of social scientists and natural scientists who have expertise in the field and are able to identify other, equally relevant interrelations (such as geological aspects or aspects of national and environmental security). Obviously, it is no coincidence that Swedish researchers concluded that the application of a time frame of up to one million years would be justified[7].

There are textbooks, manuals and other technical literature on radioactive waste, some of them are available in Hungarian.[8][9] The authors of this paper do not make attempts to offer a systematic exploration of every aspect of the subject. Rather, they intend to discuss some selected issues of particular importance related to spent fuel disposal — issues that have been sadly omitted from textbooks even though an adequate presentation of the topic also requires raising awareness of the problems. Therefore, the authors wish to ensure that this publication, at least in part, makes up for the shortage of relevant information available in Hungarian, and to give new impetus to substantive debate on nuclear energy in Hungary.

The good news is that a summary handbook, ***The World Nuclear Waste Report***, discussing the problem, has also been published recently, with the collaboration of Energiaklub. The full report is available here (in English): https://worldnuclearwastereport.org/
Summary (in Hungarian):
https://energiaklub.hu/files/news/WNWR_%C3%96sszefoglal%C3%B3_0.pdf
The chapter on the Hungarian aspects of the subject is available in Hungarian here:
https://energiaklub.hu/files/news/WNWR_Hungary_1.pdf

[7] Kautsky, U., Saetre, P., Berglund, S., Jaeschke, B., Nordén, S., Brandefelt, J., … Andersson, E. (2016). The impact of low and intermediate-level radioactive waste on humans and the environment over the next one hundred thousand years. Journal of Environmental Radioactivity, 151, 395–403. doi:10.1016/j.jenvrad.2015.06.025 https://www.sciencedirect.com/science/article/pii/S0265931X15300370#!

[8] Szűcs, I. (2013). A nukleáris ipar hulladékkezelési kihívásai (Challenges of waste management in the nuclear industry).
https://dtk.tankonyvtar.hu/xmlui/bitstream/handle/123456789/7657/0021_Nuklearis_ipar_hulladekkezelese.pdf?sequence=1&isAllowed=y

[9] Zagyvai, P. et al. (2013). A nukleáris üzemanyagciklus radioaktív hulladékai (Radioactive wastes of the nuclear fuel cycle).
https://www.energia.mta.hu/~osan/SH_7_2_11/Nuklearis_uzemanyagciklus_radioaktiv_hulladekai_MTA_EK.pdf

‘***When addressing the potential effects from a geological repository for low- and intermediate-level nuclear waste in Sweden, time frames of up to 100,000 years are of interest. For a geological repository for spent nuclear fuel even longer time frames, up to one million years, have to be considered according to the Swedish regulations.***’[10]

A scientific communication issued by the employees of the Swedish Nuclear Fuel and Waste Management Company (SKB) in 2016 offers some sobering insights about the severity and time frame of the problem posed by spent fuel: ***regardless the nature of the technical solution applied, it must guarantee complete isolation of the surroundings for a period of one million years***. Tellingly, EDF (the operator of nuclear power plants) opines that there is no point in making a big deal out of it, and a time frame of 300 years will suffice.[11]

[10] Kautsky, U., Saetre, P., Berglund, S., Jaeschke, B., Nordén, S., Brandefelt, J., … Andersson, E. (2016). The impact of low and intermediate-level radioactive waste on humans and the environment over the next one hundred thousand years. Journal of Environmental Radioactivity, 151, 395–403. doi:10.1016/j.jenvrad.2015.06.025 https://www.sciencedirect.com/science/article/pii/S0265931X15300370#!

[11] https://www.edfenergy.com/for-home/energywise/busting-myths-about-nuclear-energy

FACTS AND FIGURES

The first commercial nuclear power plant was commissioned in the Soviet Union in 1954, and the first facility of the United States started to operate in 1958. This gave a new impetus to the large-scale generation of waste with significant ionising radiation emissions (previously produced only in the framework of military projects).

It is a well-known fact and a key message of the nuclear lobby that ***fuel pellets*** (Figure 1), which generate heat for the steam turbines in nuclear power plants are quite small. Yet the quantity of waste they produce throughout their life cycle is enormous — a fact about which the nuclear lobby remains utterly silent. Given the extremely low uranium oxide concentration (global average: 0.1%), during mining ***20,000 to 25,000 times as much*** rock needs to be moved and processed. (Table 1)[12]. And sooner or later, it becomes waste as well (Figure 2). For the purpose of illustration, let us imagine a bar chart. If the amount of fuel at the end of the production process is represented by a bar of 1 centimetre, then the bar showing the initial quantity of material should be 25 metres, that is, as high as an eight-storey building. (Which is why we must sadly refrain from such a spectacular representation of the correlation). The largest quantity of waste is generated in the mines, given that approximately 85% of the mass moved is waste rock. This means that the problem is posed simultaneously by quantity and quality (radioactivity). Moreover, the application of the technology generates other hazardous wastes: in the course of manufacturing fuel, acidic or alkaline tailings are produced.

[12] Thomson, J. (2020). Nuclear power is clean – if you ignore all the waste. Compare the annual waste produced by a coal-burning power plant and a nuclear generating station. https://www.hcn.org/issues/52.1/nuclear-energy-nuclear-power-is-emissions-free-but-at-what-cost-waste

Figure 1. The nuclear lobby tries to give the impression that radioactive waste management is a problem as small as a fuel pellet. But the incidents of the last 70 years indicate that the challenges posed by waste are not that easy to handle (source of image: www.nrc.gov).

Even if the raw material is extracted not through conventional mining, but with *in situ* leaching, the situation is just as problematic, given ***the large quantities of residual acidic solvent*** containing significant amounts of cadmium, arsenic, nickel and uranium (for example, in the vicinity of Königstein, Germany, the amount is 80—400 times the limit values defined drinking water). The safe storage of waste rock and tailing remains unresolved with this technology, too.[13] Experience has shown that *in situ* leaching may entail contamination of the limited, high-quality drinking water supplies.

[13] Diehl, P. (2011). Uranium Mining in Eastern Germany: The WISMUT Legacy. https://www.wise-uranium.org/uwis.html

Material	Mass (tons)	Ratio (mass%)
Rock in geological column	1,943,624	100.000
Barren rock with low-level radioactivity	1,620,000	83.349
Excavated ore	323,624	16.651
Processed UF_6	912	0.047
Enriched UF_6	113	0.006
Fuel	87	0.004

Table 1. The material flow related to the annual power output (31,000 GWh/year) of the Palo Verde nuclear power plant (3937 MW_e)

In short, waste discharges in the nuclear industry is a problem that needs to be addressed if one wishes to understand the strong criticism of the technology.

Such criticism most commonly calls attention to the irresponsible operation and decision-making practices of the nuclear industry and closely related political groups. The bottom line is that while in these 70 years spent fuel generated by power plants has been accumulating year by year, no feasible solution has been offered, while there has been no lack of promises and pledges. However, this will not suffice, given the unprecedented scale of the problem which, in turn, is attributable to the fact that radioactive waste requires special attention due to two features. The first is its ionising effect, which, in essence, is harmful to all living organisms. Radioactive waste has been proven to cause cancer and genetic changes in humans. The latter can be inherited, as clearly evidenced, for instance, by relevant statistical analyses performed in region affected by the Chernobyl incident[14]. Incineration is not a feasible solution, as radioactive isotopes spread freely in the air, damaging water bodies, the soil and, thus, food produced for human consumption.

[14] Burridge, T. (2016). Chernobyl's legacy 30 years on. https://www.bbc.com/news/world-europe-36115240

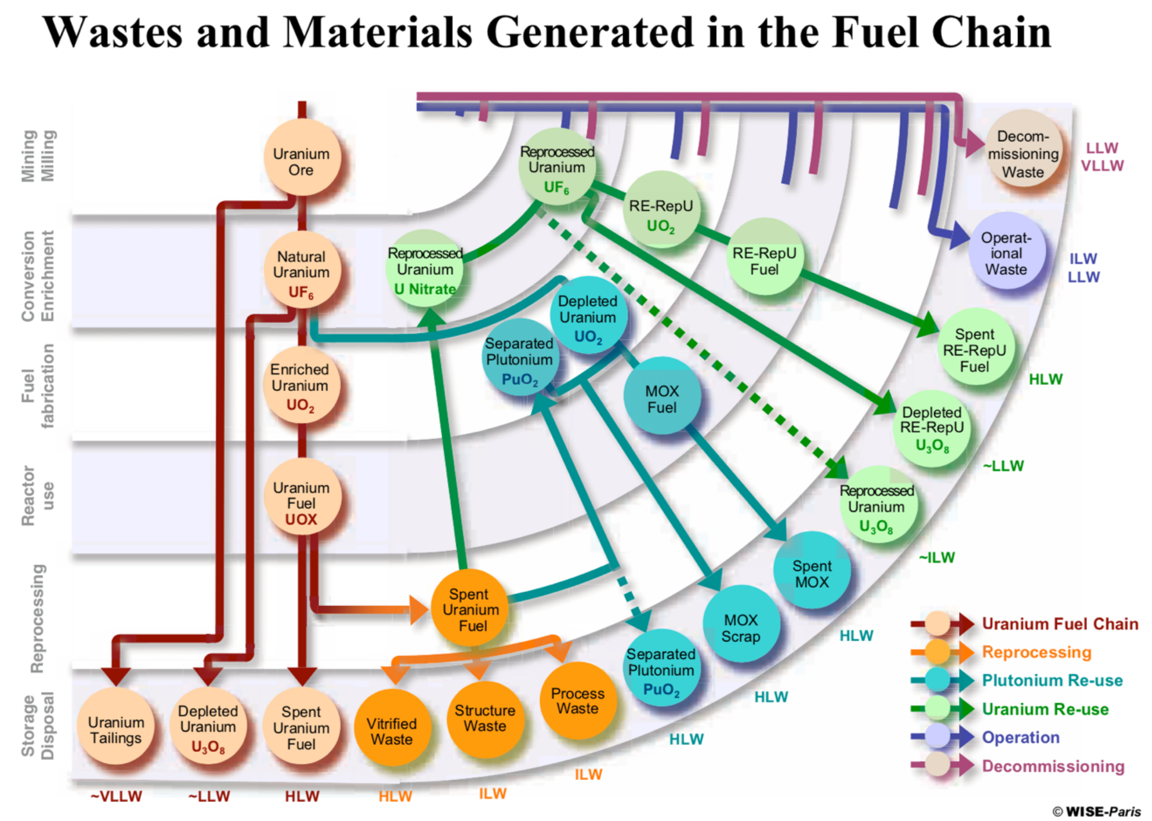

Figure 2. Radioactive waste generated throughout the nuclear fuel cycle[15]

The second characteristic, which aggravates the already serious problems posed by the first one, is the long half-lives of radioactive materials. Practically, this means that ***the technical challenges posed by the use of nuclear energy will undoubtedly survive human civilisation as we know it today***. Given the growing terrorist threat, the importance of continuous monitoring should be evident to all responsible decision-makers, all the more so as the misuse of radioactive materials has taken on astonishing proportions in recent decades. The International Atomic Energy Agency's Incident and Trafficking Database contains the records of almost 4,000 cases of misuse.[16] An illustrative example for the risk posed by radioactive waste is the ***Goiania accident (Brazil)***, where an out-of-use radiotherapy source was stolen, and then dismantled without any expert knowledge, causing the irradiation of 249 persons and the death of four victims in 1987, a year after the Chernobyl incident. Radioactive waste repositories need not only guarding, but regular inspections and maintenance as well. Otherwise radioactive isotopes

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[15] Mycle Schneider (2008). Nuclear Power Made in France The Model?
http://npolicy.org/article_file/Nuclear_Power_Made_in_France-The_Model.pdf

[16] IAEA 2020: Incident And Trafficking Database (ITDB). Incidents of nuclear and other radioactive material out of regulatory control. 2020 Fact Sheet
https://www.iaea.org/sites/default/files/20/02/itdb-factsheet-2020.pdf

may be released to the groundwater or rivers, and if this happens, they will certainly enter the food chain, sooner or later exposing the entire ecosystem to the harmful effects of radiation. Interestingly, in the aftermath of the Fukushima accident, it is precisely this 'solution' (i.e. 'disposal' in the marine ecosystem) that is emerging (for details, see the relevant chapter of this paper).

Radioactive waste is normally categorised as per activity, yet actual practice varies by country and by professional organisation. According to the data of the World Nuclear Association (WNA) — which, however, does not cover the entire life cycle — **high-level radioactive waste** makes up only approximately 3% of the total volume of **radioactive waste emitted by nuclear power plants**, but it accounts for 95% of the radioactivity generated (Table 2). The transportation of high-level radioactive waste requires a high level of radiation protection and, due to decay heat, continuous cooling. The category of high-level radioactive waste includes spent fuel and any material that comes into direct contact with it.

Only the currently operating nuclear power plants will generate a total of ***874 000 m^3 of spent fuel*** until they are permanently closed at the end of their life cycle and become radioactive waste themselves.[17] Yet although the technology is in its final days, the construction of new power plants is still ongoing, above all, in some highly centralised countries, such as China, India or Russia. This further increases the quantity and exacerbates the difficulties of disposal.

Degree of radioactivity	Volume ratio	Radioactivity ratio
Low	90%	1%
Intermediate	7%	4%
High	3%	95%

Table 2. Key parameters of radioactive waste generated by nuclear power plants (WNA 2020)[18]

The deficiencies of the technical solutions developed so far for waste disposal, coupled with the high number of incidents, have shed light on the fact that the scale of the problem is much bigger than what is possible to manage safely. What is more, ***radioactive contamination occurs 'unplanned', which means that it is emitted, from time to time, into the environment due to incidents or malfunctions.*** On the 7-level INES scale (Figure 3), an internationally accepted tool to determine the severity of such events, Level 4 or higher mark very serious malfunctions where the radioactive contamination of the

[17] Jungjohann, A. ed. (2019). World Nuclear Waste Report. https://worldnuclearwastereport.org/

[18] WNA 2020: Radioactive Waste Management. *World Nuclear Association,* London. https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/radioactive-waste-management.aspx

environment is typically not prevented. Based on currently available information, so far ***17 such incidents have occurred*** globally, each of them entailing the generation of radioactive waste. There is some uncertainty to the data as, in many cases, efforts have been made for decades to hide anomalies or disasters, and, therefore, in several cases, the extent of the environmental damage can only be deduced through subsequent research.

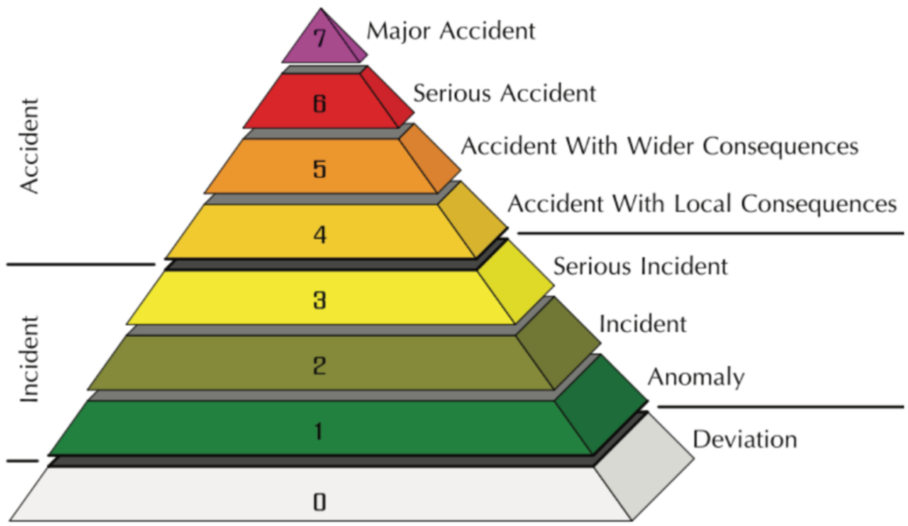

Figure 3. The INES scale[19]

[19] Rhodes, C. J. (2014). The Fukushima Daiichi nuclear accident. Science Progress, 97(1), 72–86. doi:10.3184/003685014x13904938571454

THE HITHERTO UNRESOLVED PROBLEM OF THE FINAL DISPOSAL OF SPENT FUEL

The ignorance (or irresponsibility?) of experts and decision-makers is shown by the fact that in the period from the 1940s to 1993 almost all nuclear waste was 'disposed of' in the oceans. The countries concerned disposed of waste containing ***over 85,100 terabecquerels*** (TBq) of radioactive contamination in this manner, at a total of about ***100 sites***[20]. To illustrate the extent of the environmental impact: ***a nuclear accident which results in the emission of over 10,000 TBq may be classified as a most severe, Level 7 accident***[21] (although the categorisation of events is a far more complex process). Officially, two Level 7 accidents (and contamination) have occurred so far: in Chernobyl and in Fukushima.

Figure 4. Disposal of radioactive waste in the seas
(http://large.stanford.edu/courses/2017/ph241/jones-a2/images/f1big.png)

However, in seawater radioactive waste is not isolated from its surroundings, and, therefore, the pollution will sooner or later leak into the ecosystem. Marine predators at the top of the food chain (for example, seals and dolphins) are at particular risk because radioactive plutonium and caesium

[20] IAEA (1999). Inventory of radioactive waste disposals at sea.
https://www-pub.iaea.org/MTCD/Publications/PDF/te_1105_prn.pdf

[21] The International Nuclear and Radiological Event Scale User's Manual
https://web.archive.org/web/20110515164252/http://www-pub.iaea.org/MTCD/publications/PDF/INES-2009_web.pdf

accumulate in their bodies in detectable amounts.[22] Obviously, the same holds true for individuals who consume relatively large amounts of seafood.[23]

After sea disposal was banned in 1993, other types of waste disposal options had to be considered, resulting in a number of utterly impossible ideas such as launching waste into space or placing it in the asthenosphere[24]. Despite several failed attempts to select adequate disposal sites and despite the eventual abandonment of some storage facilities, ***geological disposal*** became the preferred approach to spent fuel.[25] From a geological point of view, the most suitable location for the construction of storage facilities is ***Precambrian bedrock*** (Figure 5). ***In Finland,*** where the construction process is the most advanced, the storage facility is being built at such a location. The facility is scheduled to be completed by the mid-2020s, in the framework of a project of several decades and a total budget of EUR 3.5 billion (for comparison, the planned estimated costs of the Paks II investment is EUR 12 billion). ***In Sweden***, where the geological conditions are equally favourable, currently there is a great deal of uncertainty because in 2018 Sweden's Environmental Court, citing the possible limitations of the application of the copper canisters planned to be used, ruled that, based on the documentation submitted, the method developed by technical experts is not reassuring and did not give its approval for the construction of geological repository for the time being.[26]

Even under favourable geological conditions, the enormous time frame of one million years should give us pause for thought, especially in the light of the fact that the current period of warmer climate started only 10,000 years ago, after the last glaciation. Before that, in many places, including Europe, huge moving ice sheets were eroding hundreds of metres of surface rock, which raises questions about some key design parameters of radioactive waste disposal facilities.

[22] Watson, W. S., Sumner, D. J., Baker, J. R., Kennedy, S., Reid, R., & Robinson, I. (1999). Radionuclides in seals and porpoises in the coastal waters around the UK. Science of The Total Environment, 234(1-3), 1–13. doi:10.1016/s0048-9697(99)00118-7
https://pubmed.ncbi.nlm.nih.gov/10507144/

[23] European Environment Agency (n.d.). EN13 Nuclear Waste Production. https://www.eea.europa.eu/data-and-maps/indicators/en13-nuclear-waste-production-1/en13

[24] Alden, A. (2017). Why Not Dispose of Waste in Ocean Trenches?
https://www.thoughtco.com/dont-dispose-waste-in-ocean-trenches-1441116

[25] The World Nuclear Waste Report 2019 - Összefoglaló (Summary). Energiaklub, Budapest. 10p
https://energiaklub.hu/files/news/WNWR_%C3%96sszefoglal%C3%B3_0.pdf

[26] Palm, J. (2020). Knowledge about the Final Disposal of Nuclear Fuel in Sweden: Surveys to Members of Parliament and Citizens. Energies 2020, 13, 374; doi:10.3390/en13020374 https://www.mdpi.com/1996-1073/13/2/374/pdf

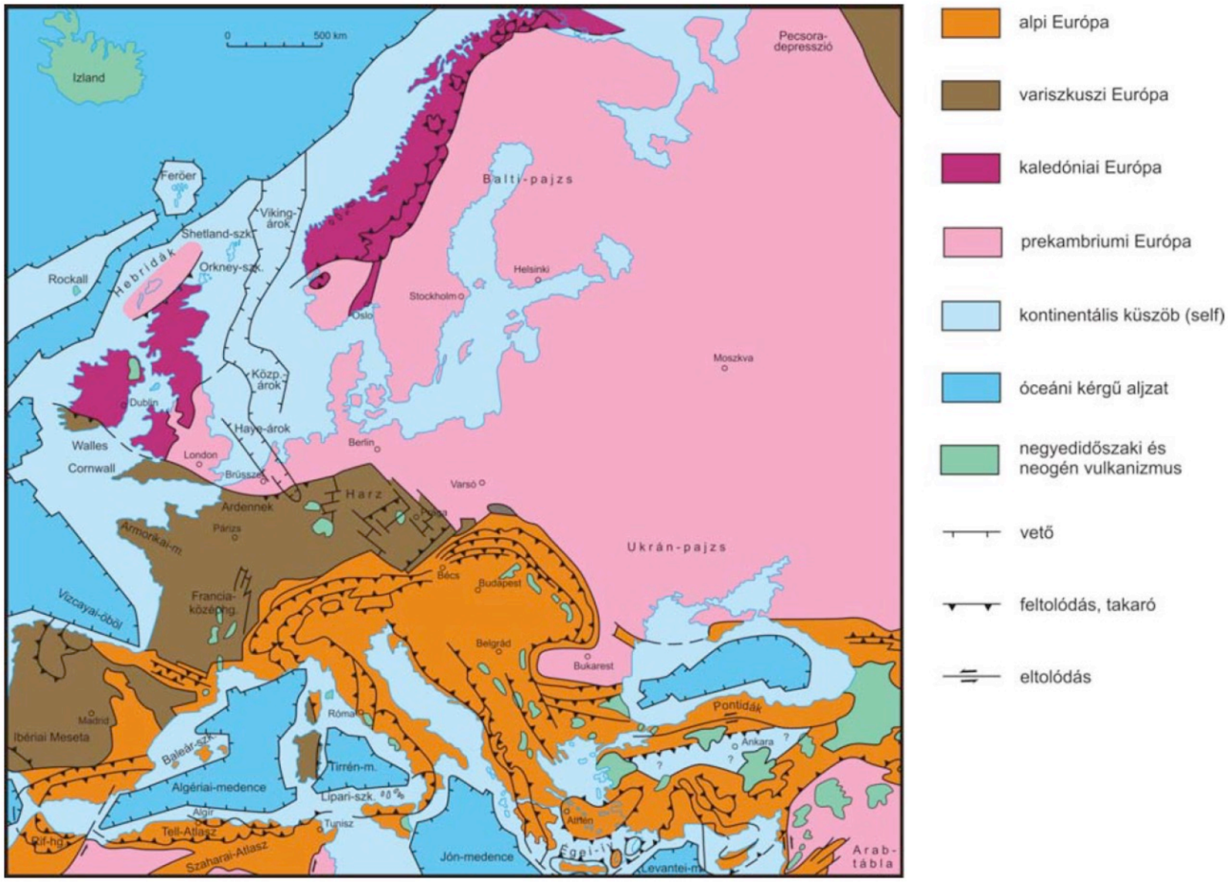

Figure 5. Europe's geological map[27]

(From top to bottom: Alpine, Variscan, Caledonian, Precambrian, continental self, oceanic crust, quaternary and neogenic volcanism, fault, reverse fault, lateral fault)

The figure clearly shows that, in terms of geology, Hungary belongs to the youngest region in Europe: the region affected by Alpine orogeny. It is by no means irrelevant that orogeny is an ongoing process which involves isostatic movements (that is, possible major uplifts which, geologically speaking, take place in a relatively short period of time) and earthquakes occurring at a frequency higher than the average. When it comes to the disposal of spent fuel, neither factor is reassuring.

[27] Budai, T. - Konrád, Gy. (2011). Magyarország földtana (Hungary's geology). http://enfo.agt.bme.hu/drupal/sites/default/files/Mof_jegyzet.pdf

FAILURES. THE ASSE II REPOSITORY[28]

Given the practice of radioactive waste disposal[29], the caution of the Swedish researchers seems to be justified. Even German experts, renowned for their precision, have failed completely in the disposal of radioactive waste, as clearly illustrated by the Asse II repository, a former salt mine where low- and intermediate-level radioactive waste was disposed of from 1967 to 1978. The first banal problem, typical of the time, was posed by the deficiencies of record-keeping, and not only with regard to the waste received, but also to operational problems. As recorded by available documents, water breaches had frequently occurred before in the mine[30] — and even a single water breach is one too many in a radioactive waste disposal facility. In the light of this fact, it is incomprehensible how the location was considered to be suitable for such demanding use in the first place. In any case, the operator tried to buy time by concealing the facts, as is not uncommon in the nuclear energy industry. The final blow to the project was the detection of radioactive contamination in the karst waters of the region, leading to a public outcry.

Eventually, the repository was emptied, but due to water breaches the amount of contaminated material increased fivefold as radioactive waste mixed with the salt. The recovery process started in 2010 and is scheduled to end in 2065. If the project goes ahead as planned and no unexpected costs are incurred, the total cost will be EUR 5 billion at current prices[31] (which equals almost to 50% of planned budget of the Paks II Project). A general question also arises as to the method of decommissioning of the German nuclear power plants and the disposal of waste, especially in the light of the fact that according to preliminary calculations the costs to incur until 2170 (the completion of all the necessary processes) will be around EUR 100 billion. These are the problems that the nuclear lobby has attempted to conceal so far, conveying the message that this is a cheap technology.

A number of analysts opine that this development (along with several other factors) played a decisive role in the political and professional decision about Germany's nuclear phase-out. In the light of the above, ***it is puzzling that the two voluminous Hungarian textbooks*** examined by the authors of this paper and ***aiming to introduce Hungary's future engineers into the subject of radioactive waste,***

[28] Nagy, G. M. (2019). A sóbánya, amely a német atom múltját rejti (A salt mine that hides the past of Germany's nuclear industry). https://magyarnarancs.hu/kulpol/csak-ne-az-udvaromba-117275

[29] Atomcsapda blog - Ha csak egy cikket olvasol el az atomtemetőkről, ez legyen az! (The nuclear trap blog. If you read only one article on nuclear repositories, make it this one)
https://atomcsapda.blog.hu/2017/07/30/ha_csak_egy_cikket_olvasol_el_az_atomtemetokrol_ez_legyen_az

[30] Schwartz, M.O. (2010). Clearing out Asse 2. https://www.neimagazine.com/features/featureclearing-out-asse-2

[31] Stonington, J. (2016). Sticker Shock: The Soaring Costs Of Germany's Nuclear Shutdown
https://e360.yale.edu/features/soaring_cost_german_nuclear_shutdown

fail to address the technical, environmental, economic or social aspects of these events. One of the textbooks, contrary to what is suggested by its title (*Challenges of waste management in the nuclear industry*[8]) does not make a single reference to Asse or any other specific problematic case (that is, real-life challenges). The other textbook refrains from mentioning the U-turn of the German project: '*Decades ago, deep geological repositories were constructed in salt mines in Germany (Morsleben, Asse). From the 2000s onwards, a new concept was introduced: to accommodate low- and intermediate-level waste generated by the German nuclear industry, new shafts will be made in the former Konrad iron ore mine, between 800 and 1300 m below ground level.*'[9] That's it. No more, no less. Case studies of problems are not to be found in this volume either.

FAILURES - THE CARLSBAD INCIDENT AND THE LESSONS LEARNED

In the United States, there is an existing facility which, in many ways, is similar to a repository that may serve as a storage facility for spent fuel. The reason for its existence is that the United States started to perform nuclear tests as early as in the 1940s, resulting in the accumulation of large volumes of radioactive waste that had to be disposed of. At the recommendation of the National Academy of Sciences, from 1957 onwards efforts were made to locate salt beds at great depths suitable for permanent geological storage. In 1974, a site was identified east of Carlsbad, New Mexico. After the completion of the construction work, the Waste Isolation Pilot Plant (WIPP) was commissioned in 1999. The pilot plant is generally considered to represent a cutting-edge technological level as it is designed to safely preserve waste for 10,000 years.[32]

But after 15 years of operation, events took a sharp turn. In the facility, thitherto considered super-safe, two severe incidents occurred in a period of only 10 days. On 5 February 2014, a haul truck caught fire in the maze of tunnels filled with radioactive waste. Six employees needed medical attention. A few days later, on 14 February, elevated radiation levels were detected. The problem was caused by damage to a storage drum which held radioactive waste from the production of a plutonium bomb. Radioactive material blew through the ventilation system, contaminating one-third of the plant's underground tunnels and leaking into the immediate vicinity of WIPP. Twenty-one workers received low doses of radiation.

As a result of the incident due to irregular storage and the radiation leak, the deep repository had to be shut down.[33] The facility was reopened in January 2017, after a clean-up of unprecedented costs (USD 500 million). The total cost of the restoration is estimated to reach USD 2 billion, comparable to the cost of interventions in the aftermath of the severe accident at the Three Mile Island nuclear power plant in Pennsylvania in 1979[34]. The process must be funded from the military budget as soon as possible, because a storage facility is urgently needed given that the US military industry generates far more radioactive waste than the nuclear industry does.[35]

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[32] The Waste Isolation Pilot Plant – History https://wipp.energy.gov/historytimeline.asp

[33] Malone, P. (2015). Repository's future uncertain, but New Mexico town still believes. https://www.santafenewmexican.com/special_reports/from_lanl_to_leak/repository-s-future-uncertain-but-new-mexico-town-still-believes/article_38b0e57b-2d4e-5476-b3f5-0cfe81ce94cc.html

[34] Vartabedian, R. (2016). Nuclear accident in New Mexico ranks among the costliest in U.S. history. https://www.latimes.com/nation/la-na-new-mexico-nuclear-dump-20160819-snap-story.html

[35] Conca, J. (2017). WIPP Nuclear Waste Repository Reopens For Business. https://www.forbes.com/sites/jamesconca/2017/01/10/wipp-nuclear-waste-repository-reopens-for-business/?sh=4704c232052a

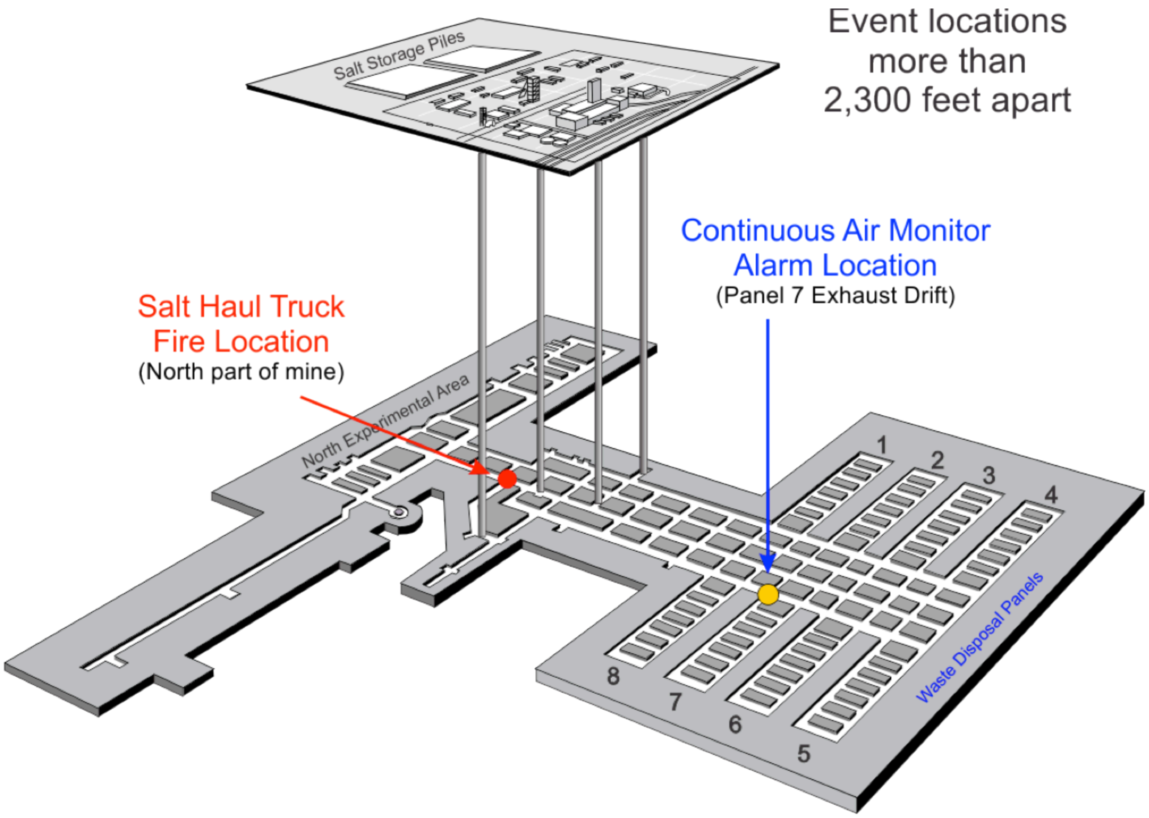

Figure 6. Locations of the incidents in the Carlsbad radioactive waste disposal facility in 2014 (https://wipp.energy.gov/wipprecovery-accident-desc.asp)

PROBLEMS POSED BY WASTE GENERATED BY NUCLEAR POWER PLANT DISASTERS

Fukushima

News reports about the consequences of major disasters continue to appear in the media even decades after they occurred, as clean-up normally takes thousands of years rather than days. It is exactly ten years ago that an accident occurred at the Fukushima Nuclear Power Plant, when a tsunami, triggered by a major earthquake, damaged three reactors of the power plant, causing a complete meltdown. The radioactive contamination released into the environment was about 20—40% of that of the Chernobyl accident. The report drawn up by an independent parliamentary committee for the Japanese government identified ***human negligence*** as the cause[36]. According to the report, both key actors (that is, the operator, Tokyo Electric Power Company (TEPCO) and the public control authority), under the delusion of 'unquestionable nuclear safety', underestimated the risks and, consequently, failed to take basic safety measures.

As a consequence of the accident, molten nuclear fuel will continue to produce significant heat for decades, requiring continuous cooling. Meanwhile, ***cooling water*** is also turning into radioactive waste. So far, ***approximately 1.2 million tonnes*** have accumulated in the plant, which is unsuitable for accommodating more. A Japanese expert committee suggested that the radioactive contaminated water be released into the Pacific Ocean, but the proposal evoked a public outcry. In the meantime, the amount of cooling water is bound to increase for at least another decade, until melted fuel is removed. So far, no concept that would be acceptable to all key stakeholders has emerged. In the meantime, the task of disposing and depositing ***millions of cubic metres of contaminated soil*** has been added to the list of urgent tasks.[37] The chaos around nuclear power is slowly becoming completely unmanageable.

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[36] NAIIC (2012). The official report of The Fukushima Nuclear Accident Independent Investigation Commission. Executive summary. (The National Diet of Japan, NAIIC) https://www.nirs.org/wp-content/uploads/fukushima/naiic_report.pdf

[37] McCurry, J. (2019). Fukushima grapples with toxic soil that no one wants. https://www.theguardian.com/world/2019/mar/11/fukushima-toxic-soil-disaster-radioactive

HOPES AND EXPECTATIONS IN HUNGARY

In Hungary, the demand to designate a location for the disposal of radioactive waste arose in the 1950s, mainly as a result of the commissioning of the research reactor in Csillebérc, in the vicinity of Budapest. Waste was disposed of in the pilot radioactive waste repository in Solymár[38], in the larger area of Budapest, from 1960 to 1974. After the closure of the facility, another site was established in Püspökszilágy. Currently, there are two sites in Hungary which serve for the final disposal of low- and intermediate-level radioactive waste: Püspökszilágy, south-east of Vác (North Hungary) and Bátaapáti, south of Szekszárd (South Hungary).[39]

The unbelievable situation of radioactive waste management in Hungary is illustrated by the fact that, according to the Record of Decisions of the *Periodic Safety Review* of 2017, ***'in the absence of legal requirements, no periodic safety review was performed at the Püspökszilágy site between 1976 and 2016'***.[40] This is probably one of the reasons why the investigation, when finally commenced, revealed a number of problems and deficiencies that had accumulated over decades, for example ***'an increase in tritium and radiocarbon activity concentrations in groundwater'***. It was found that the site accommodates long-lived waste which, after an interim phase, will have to be disposed of in a deep geological repository planned to be opened in the 2060s.

[38] RHK 2016: Magyarország nemzeti programja a kiégett üzemanyag és a radioaktív hulladék kezelésére (Hungary's national programme for the management of spent fuel and radioactive waste). *Radioaktív Hulladékokat Kezelő Kft*. *https://rhk.hu/storage/304/Magyarorsz%C3%A1g-nemzeti-programja.pdf*

[39] OAH 2017: Hatodik jelentés - készült a kiégett fűtőelemek kezelésének biztonságáról és a radioaktív hulladékok kezelésének biztonságáról szóló közös egyezmény keretében (Sixth report. Prepared under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management) *Országos Atomenergia Hivatal*, Budapest
https://www.haea.gov.hu/web/v3/OAHPortal.nsf/79B4771B89AE733AC1258240004AE34C/$FILE/6_Nemzeti_Jelent%C3%A9s.pdf

[40] OAH 2017: A püspökszilágyi Radioaktív Hulladék Feldolgozó és Tároló Időszakos Biztonsági Felülvizsgálatának lezárása. Határozat (Closure of the periodic safety review of the Püspökszilágy Radioactive Waste Processing and Storing Facility. Decision)
https://drive.google.com/drive/folders/1a8AagDBukXJIZhO0g8DW6atgItAEXqiX

Figure 7. Radioactive waste in the village of Püspökszilágy[41]

As for deep geological storage, it is clear at first sight that Hungary does not have a favourable geological environment comparable to that of northern Europe. It is far from being favourable, especially in the vicinity of the Paks nuclear power plant. Deep geological storage requires a hard, impermeable rock mass that does not crack. Research in Hungary has long focused on the Boda area near Pécs, South Hungary. Many consider the Boda Claystone Formation, surfacing in the area, to be suitable for the construction of a repository, yet some geophysicists opine that burial in claystone poses risks. They point out that the rigid rock may crack under significant pressure, and, if that happens, water may seep through the cracks and reach the repository, and act as a medium between radioactive materials and the ecosystem. Moreover, the surrounding Mecsek region is currently undergoing a slight uplift, which can add up to significant movement in a time frame of hundreds of thousands of years. Given the erosion of the surface, the repository would move steadily closer to the surface if the uplift continued.[42] Although international law provides that every country is obliged to solve the problem on its own, for the time being Hungary's geological conditions seem to be far from being suitable for the construction of such a repository. This is yet another important argument against the use of nuclear energy in Hungary.

[41] Fülöp, O. 2019: Kicsit reped, kicsit ereszt, de a miénk – a püspökszilágyi atomtemető (Cracked and leaking a bit, but is ours. The nuclear repository in Püspökszilágy). https://energiaklub.hu/hirek/kicsit-reped-kicsit-ereszt-de-a-mienk-a-puspokszilagyi-atomtemeto-4686

[42] Atomcsapda: a dokumentumfilm 2-4. részek (The nuclear trap. A documentary, 2-4.) Energiaklub, 2018

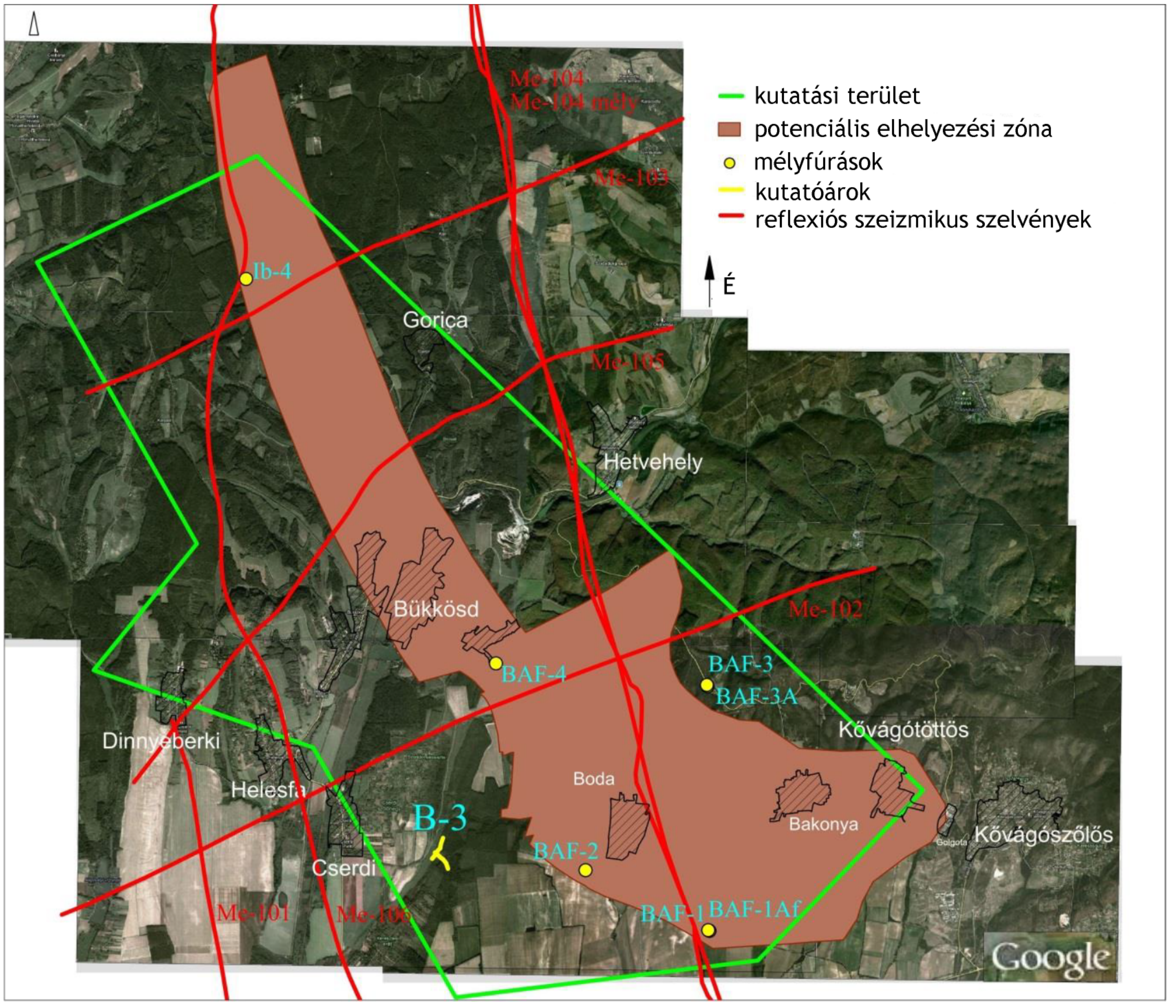

Figure 8. The surface research area of the Boda Claystone Formation (BCF)[43]. As shown by research performed so far, this is the location that can serve as a final repository of spent fuel in an optimal manner (or, rather, in the least unfavourable manner)
(From top to bottom: research area, potential location of repository, deep drillings, trench, reflection seismic sections)

As for the costs, it is to be noted that that the ***Central Nuclear Monetary Fund***, available since 1998, will be able to finance only a fraction of them. This means that currently the users of electricity are not paying enough, which is why it can be repeated again and again that nuclear energy is cheap and which

[43] RKH (2019). A Bodai Agyagkő Formáció telephelykutatási keretprogramjának engedélykérelme. Közérthető összefoglaló (Permit application of the site research framework programme for the Boda Claystone Formation. Non-technical summary). Radioaktív Hulladékokat Kezelő Kft. http://www.nymtit.hu/docs/2019/rhk_kozertheto_osszefoglalo.pdf

is how the government's utility cost reduction programme can be implemented. Therefore, it is our children, grandchildren and their descendants who will largely pay the price of what we consume today.

The ***temporary storage*** of spent fuel alone uses up about half of the payments. Consequently, only the remaining 50% is available for permanent storage. It seems rather problematic that this amount ***barely makes up one tenth of the planned amount***. A further concern is that the amount envisaged does not seem realistic by international standards. In Germany, for example, calculations work with 2—3 times higher costs for this type of tasks. Obviously, underbudgeting raises concerns with regard to technical safety and environmental impact, and such a critical area does not allow for experimenting with half measures.

SUMMARY

The application of nuclear energy for peaceful or belligerent purposes generates problems on such a scale that strongly suggests that humanity must refrain from such applications. Besides all the energy-related, social and economic problems specific to nuclear energy, radioactive waste in itself poses challenges that, given humanity's current scientific knowledge, cannot be met in a satisfactory manner. This consideration is a possible explanation why the majority of developed economies are working on the complete phase-out of nuclear power (and the rest have opted for partial decommissioning as a first phase). A multitude of much cheaper, safer and more reliable energy alternatives are available to mankind in the 21st century.

Globally, the vast majority of countries (84%) do not operate nuclear power plants at all, some major European countries being Austria, Denmark, Portugal, Italy and Poland. The number of countries which do not produce nuclear power is bound to increase, because the technology has failed to meet expectations: ***nuclear energy is not cheap*, *safe or clean***.

The decommissioning of remaining nuclear power plants will be performed, at the latest, by 2022 in Germany, by 2025 in Belgium, by 2035 in Spain and by 2050 in Switzerland. In fact, many countries have already decided on a complete transition to renewable energy. Among other research on opportunities in Hungary, the software analyses performed by the Energy Geography Research Team of ELTE University have shown that a major regulatory shift, coupled with complex interventions (such as significant improvements in energy efficiency), could achieve a 100% renewable energy share in Hungary.[44] [45]

[44] Munkácsy, B. et al. (2011). Erre van előre! Egy fenntartható energiarendszer keretei Magyarországon - Vision 2040 Hungary (This is the way forward. The framework of a sustainable energy system in Hungary. Vision 2040 Hungary).
http://munkacsy.web.elte.hu/ERRE%20VAN%20ELORE%201.2x.pdf

[45] Munkácsy, B. et al. (2014). Erre van előre! A fenntartható energiagazdálkodás felé vezető út. – Vision 2040 Hungary 2.0 (This is the way forward. The journey to sustainable energy management. Vision 2040 Hungary 2.0)
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https://www.energia.mta.hu/~osan/SH_7_2_11/Nuklearis_uzemanyagciklus_radioaktiv_hulladekai_MTA_EK.pdf