Contribution ID: **77** Type: **not specified**

From Energy System Pathways to Spent Fuel Inventories: Scenario-Based Assessment of High-Level Radioactive Waste and Disposal Capacity

Friday 27 March 2026 16:50 (20 minutes)

Abstract

Worldwide, nuclear power remains part of national energy strategies in the context of climate policy, energy security, and decarbonization debates. Expansion plans are often linked to the low-carbon nature of nuclear electricity production, and discussions focus on energy system costs and the integration of nuclear-renewable energy systems for long-term decarbonization (Göke, Wimmers, and Von Hirschhausen 2025). Thereby, however, the challenges of the nuclear back-end, i.e., decommissioning of closed nuclear power plants, and nuclear waste management, are often neglected (Wimmers et al. 2024).

Nuclear power plants generate different types of radioactive waste in different stages of their lifetime (Besnard et al. 2019). During their operations, primarily in the form of spent nuclear fuel, whose final disposal remains unresolved in most countries. Although deep geological repositories for high-level radioactive waste are under development in a small number of cases, only Finland has reached the stage of trial emplacement, while other projects remain decades away from operation. Existing repository concepts are generally designed for current reactor fleets, raising questions about their adequacy under extended operating lifetimes or additional waste generation (Ahlswede, Graefje, and Schopmans 2026).

A central challenge is that future volumes of spent nuclear fuel are directly determined by long-term energy system pathways, yet internationally comparable and harmonized data on high-level radioactive waste inventories are scarce and fragmented. Despite reporting obligations under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, no comprehensive and up-to-date database that allows for a systematic assessment across countries exists (Böse et al. 2025). Future waste volumes are further characterized by uncertainty because currently envisioned expansion plans and lifetime extensions of light-water reactors and the potential emergence of non-light water reactor concepts or small modular reactors are subject to high degrees of uncertainty themselves (Ramana 2021; Rothwell 2022).

This paper aims to investigate the implications of continued operations of current reactors and envisioned fleet expansions on the development of waste volumes and, therefore, the implications on current and planned waste repository projects. Initially, we limit the assessment to high-level waste, i.e., spent nuclear fuel. It begins with a compilation of a harmonized database on high-level radioactive waste inventories based on national reports submitted under the Joint Convention. Building on this database, an initial scenario-based analysis is conducted to estimate future spent fuel volumes in selected European countries, by drawing on results from energy system modelling (Barani et al. 2026) and methods proposed by the IAEA (2008). The analysis aims to assess whether currently planned or envisaged disposal capacities appear consistent with projected waste generation under various long-term nuclear energy pathways. By highlighting the scale of high-level radioactive waste generation and the uncertainties surrounding disposal capacity, this work contributes to a more transparent assessment of an unresolved and often underreported challenge in nuclear energy policy.

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Session Classification: Carbon Removal & Transition Pathways