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Crafting effective oversight for the long-term storage of spent nuclear fuel on sites at risk of climate and coastal hazards

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Despite a documented push to expand nuclear energy in the U.S., the status quo of indefinite *in-situ* nuclear waste storage is uncertain and increasingly threatened by climate and coastal hazards. Findings from Humboldt Bay, California, one of the nation's most vulnerable nuclear storage sites, informed recommendations for managing emergent climate and coastal hazards. The existing legislative framework was not designed to address climate and nuclear waste interactions, but more effective oversight leveraging existing federal, state, local, and Tribal government authorities could adapt spent nuclear fuel management to a climate-changed world. More effective oversight requires updated regulations and site-specific risk assessments as well as enhanced coordination across jurisdictions, disciplines, and publics to increase legitimacy, trust, accountability, and creativity in light of failed solutions to a multi-decadal issue.

KEYWORDS

climate and coastal hazards, spent nuclear fuel, participatory justice, community engagement, sea level rise, public trust

1 Introduction

Federal policy developments signal the intent of the United States to position nuclear power as a national energy bridge in a carbon-constrained world. Legislation enacted in 12 states and bills under consideration in 19 states aim to support existing and new nuclear generation,[1] pointing to an era of potentially significant growth for the U.S. nuclear industry. Offsetting carbon-intensive energy sources with nuclear power, however, comes with at least one profound externality: the nuclear fission cycle[2] produces commercial spent nuclear fuel ("SNF"), the extremely long lasting radioactive elements of which complicate safe handling and storage (Funk and Sovacool, 2013; Rodríguez-Penalonga and Moratilla Soria, 2017; Bruno et al., 2020). Despite investments to expand capacity or prolong the operational life of the nation's nuclear fleet (Supplementary Table 1), one critical, unresolved federal policy issue

1 Nuclear Energy Institute Status Report, State Legislation and Regulations Supporting Nuclear Energy (https://www.nei.org/).

2 Backgrounder on Radioactive Waste (NRC.gov).

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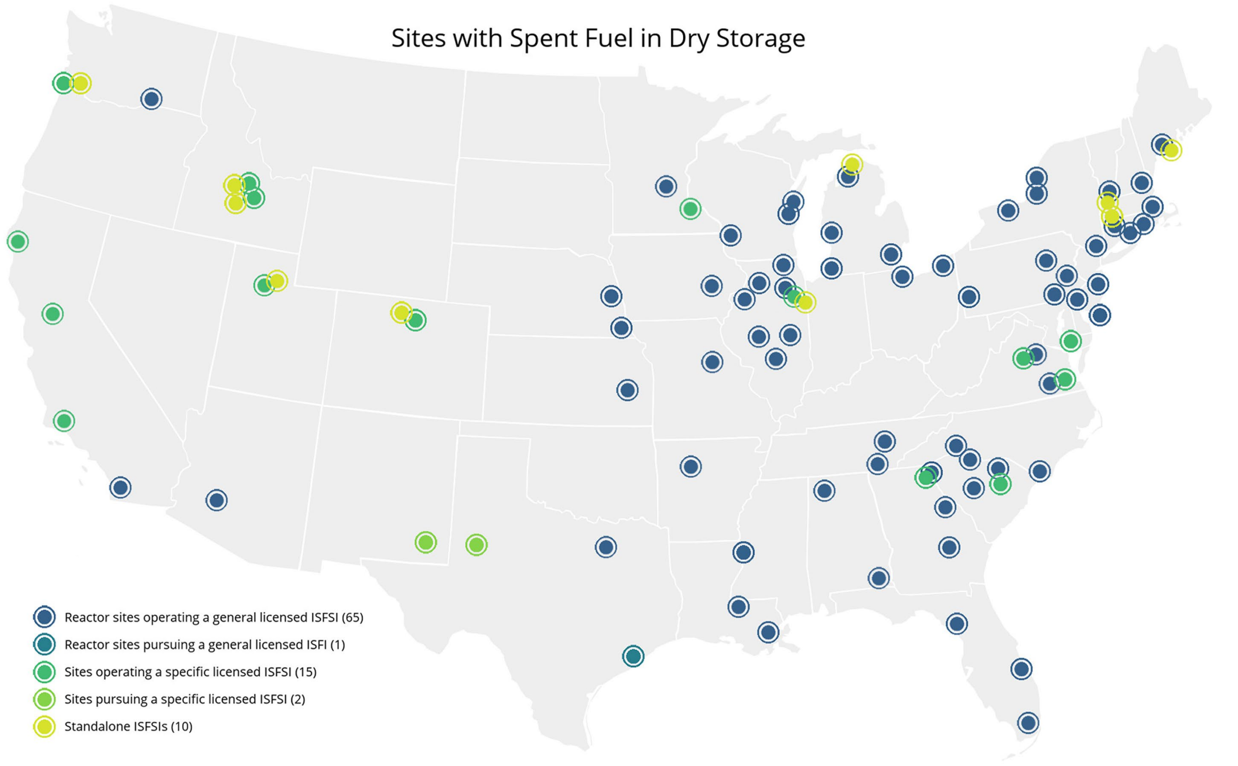

FIGURE 1
Map of spent nuclear fuel locations in the U.S. (as of November 2020). Note: Locations corrected after (Carter, 2020). Source: Diaz-Maurin et al. (2021). Adapted from US NRC, 2020. © 2021 The Author(s) under a Creative Commons BY license. Published by Elsevier B.V.

centers on how to securely, justly, and efficiently dispose of the nation's SNF.

The US has the largest stockpile of SNF in the world (Bowen, 2021)—approximately 88,000 metric tons of SNF stranded at 84 reactor sites across 36 states (MacFarlane and Ewing, 2023) (Figure 1)—but "no clear path forward for the siting, licensing, and construction of a geologic repository" for permanent nuclear waste disposal (National Academies of Sciences, Engineering, and Medicine, 2023: 143), deemed as the safest way to isolate radioactive material (World Nuclear Association, 2023).

The *Nuclear Waste Policy Act* of 1982 ("NWPA")[3] directed the DOE to operate geologic repositories for commercially generated SNF.[4] After an initial process to select multiple repository sites, in 1987 the *Nuclear Waste Policy Amendments Act* ("NWPAA") focused the nation's nuclear waste program exclusively on Yucca Mountain in Nevada.[5] Nevada, which staunchly opposed the project and considered it unsafe, exercised its veto and filed an official "notice of disapproval,"[6] but a Congressional joint resolution overrode the state's objection.[7] Although the NWPA was intended to provide clarity and oversight for streamlining a SNF repository, the failure of NWPAA's expedited sole focus on Yucca Mountain instead became a *fait accompli.*

Although currently, the Department of Energy ("DOE") is pursuing a consent-based siting effort to engage the public in evaluating alternative interim consolidated storage locations,[8] and the NRC has licensed private storage facilities in two states (see Table 1, para. 2), these approaches are subject to potential future budget cuts and pending litigation.[9] The *de facto* approach to long-term SNF management in the U.S. is still *in-situ* SNF storage at operational and decommissioned nuclear reactor sites under uncertain removal timelines.

The impacts of climate change complicate the existing SNF management regime and the purported benefits nuclear power offers to the green energy transition (Alonso and del Valle, 2013; Sheldon et al., 2015; IEA, 2021). Although impending climate impacts may equally affect both operating nuclear power plants and Independent Spent Fuel Storage Installations ("ISFSIs") (the dry storage cask configurations maintained by nuclear utility licensees for interim SNF storage,[10]) operating plants are more stringently regulated. Sea level rise, coastal erosion, earthquakes, tsunamis, and seasonal flooding raise concerns over reliable site access and cask integrity at the nation's most at-risk ISFSI sites. According to the Blue Ribbon Commission Report on America's Nuclear Future, "the storage arrangements in place today were not designed to maximize operational efficiency at a

3 Nuclear Waste Policy Act of 1982, Public Law 97–425, 96 Stat. 2201 *et seq.*, 42 U.S.C. 10101 *et seq.*

4 *Id.* §§ 10,132–10,134 [10 C.F.R. §§ 960, 963].

5 Pub.L. No. 100–203, §§ 5001-5065, 101 Stat. 1330, 1330–227 to 1330–255 (1987) (codified in various sections of 42 U.S.C.)

6 *Supra note* 3 §§ 115–116 and § 10136(b)(2).

7 *Id.* § 10135(c).

8 Consent-Based Siting Process Report-0424 3.pdf (energy.gov).

9 See, e.g., *State of Texas v. NRC*, No. 21–60,743 (5th Cir. 2023).

10 Independent Spent Fuel Storage Installation (ISFSI) (NRC.gov).

TABLE 1 Five notable sources of uncertainty stemming from the Nuclear Waste Policy Act.

1. Susceptibility of SNF disposal policies to the political vicissitudes of changing administrations.	The NWPA allocates administrative power to a cabinet-level department. Despite the submission of the Yucca Mountain license application to NRC for approval in 2008, the incoming Obama Administration suspended Yucca Mountain and focused efforts on alternative disposal options via the Blue Ribbon Commission.[a] Obama's opposition to Yucca Mountain (Funk and Sovacool, 2013) permanently shifted policy away from the proposed site, as evidenced by the DOE's motion to formally withdraw its license application in 2010 "with prejudice"[b] and subsequent decisions to forego funding requests for site development.[c] Congress has not appropriated funds for Yucca Mountain since 2011, effectively nullifying the nation's SNF disposal program. While the new regime will likely delay the entire waste disposal project several more decades and incur billions of additional dollars in cost,[d] a more enthusiastic administration might revive the project, and reverse progress in other siting efforts. These inconsistent cycles of varying support extend the timeline and add greater uncertainty to the disposal formula.
2. Inflexibility/prescriptiveness of the NWPA.	The Act imposes difficulties to adapt or respond to new developments, "whether in the form of new scientific information, technological advances, or (just as important) the expressed concerns of potentially affected publics and their representatives" (BRC, 2012: 23). Monitored retrievable storage facilities were envisioned as providing interim storage pending permanent disposal. However, the Act prevents construction on an MRS facility until NRC licenses construction of a permanent repository.[e] Although there is general mention of the role of private enterprise in interim storage, a recent court case from the Fifth Circuit deemed that the Atomic Energy Act does not confer authority on the NRC to license away-from-reactor SNF storage facilities to private parties.[f] Furthermore, two states with proposed private facilities, Texas and New Mexico, registered strong disapproval. Texas signed into law legislation banning new spent nuclear fuel facilities in the state in 2021.[g] New Mexico sued the NRC for overreaching its authority in issuing a license to a private facility.[h] The interdiction of alternatives to permanent storage can likely only be lifted via Congressional amendment to the NWPA.
3. Unrealistic and rigid deadlines.	Public and industry faith in the DOE to manage either the Yucca Mountain project or its broader obligations concerning civilian SNF management has eroded significantly since the passage of NWPA. The DOE's breach of contract with commercial nuclear power operators beginning in 1998 (discussed below) and the repeated extension of timeline assurances issued by the NRC's Waste Confidence Rulemaking create a sufficient link between these continuous failures and waning confidence in the federal government's competency to deliver effective and timely disposal solutions.
4. Proliferation of free market stagnation/ lack of industry leadership and ingenuity.	The statutory regime established in the NWPAA has artificially stunted the search for viable alternatives, especially from the private sector. Utility companies and public commissions that paid into the Nuclear Waste Fund filed a suit against DOE's assertion that the absence of an operational repository precluded the Agency from disposing of SNF by the 1998 deadline. The D.C. Circuit Court disagreed, citing Congress's expressly stated statutory deadline and contractual obligation for the transfer of title of SNF to DOE, independent of the availability of a permanent repository.[i] Subsequent cases with similar claims contended that administrative relief (i.e., DOE securing title to the waste) was not adequate compensation,[j] leaving the utilities to pursue judicial relief via monetary damages. According to DOE's 2022 Financial Report: 44 suits have been settled involving utilities […] for partial breach of [Agency] contract. Under the terms of the settlements, the Judgment Fund, 31 U.S.C. 1304, paid $7.4 billion as of September 30, 2022 to the settling utilities for delay damages they have incurred. The remaining liability is estimated to be approximately $31.0 billion.[k] The result of such elevated damages is that waste producers are now disincentivized to pursue alternative, and perhaps more effective, long-term methods of waste disposal (Spencer, 2008; see generally Pistor, 2019).
5. Suboptimal methods for engaging the public	In striving to deliver a viable SNF disposal repository by 1998, DOE's myopic focus on a single repository location abrogated many of its duties to the public, namely by marginalizing local and Indigenous community input and minimizing efforts to enhance social justice and public participation. Furthermore, DOE, by fixating on technical solutions "at the expense of nuanced public feedback, fell into a 'complexity-exclusion trap,' by trying to reduce nuclear waste management to a technological problem, and side-stepping the more complicated social and political aspects of siting a nuclear waste repository in a democracy" (Di Nucci and Brunnengräber, 2019; see also Richter et al., 2022)

[a]The Blue Ribbon Commission was established to consider "a wide range of technological and policy alternatives" (123). The report draws conclusions that a consent-based approach to siting nuclear waste storage facilities would be preferred to the Yucca Mountain policy.

[b]*See* Dep't of Energy Motion to Withdraw, In re U.S. Dep't of Energy (High-Level Waste Repository), Docket No. 63-001, ASLBP No. 09-892-HLW-CAB04 (United States Nuclear Regulatory Commission) (2010). In its motion, the DOE asserts that "a geologic repository at Yucca Mountain is not a workable option for long-term disposition of these materials" (p. 1). With regard to dismissing the application with prejudice, the DOE clarified that "it does not intend ever to refile an application to construct a permanent geologic repository… at Yucca Mountain" (p. 3).

[c]*See* Office of Chief Fin. Officer, U.S. Dep't of Energy, DOE/*CF*-039, 5 FY 2010 Congressional Budget Request (2009) FY 2010 Volume 5 (energy.gov) at 504: "…implements the Administration's decision to terminate the Yucca Mountain program while developing nuclear waste disposal alternatives. All funding for development of the Yucca Mountain facility would be eliminated, such as further land acquisition, transportation access, and additional engineering." *See also* Garvey (2012) at 3: "DOE's FY2011, FY2012, and FY2013 budget proposals requested no funding for the Yucca Mountain facility."

[d]Although the Administration established the Blue Ribbon Commission, the recommendations will extend the search for alternative disposal pathways and will require Congress to amend the NWPA.

[e]42 U.S.C § 10168(d)(1).

[f]*State of Texas v. NRC*, No. 21-60743 (5th Cir. 2023).

[g]Available at: https://capitol.texas.gov/BillLookup/Actions.aspx?LegSess=872&Bill=HB7; *see also State of Texas v. NRC*, No. 21-60743 (5th Cir. 2023).

[h]Available at: https://nuclearactive.org/wp-content/uploads/2021/04/Attorney_General_Balderas_Announces_Lawsuit_to_Halt_Holtec_Nuclear_Storage_Facility.pdf.

[i]*Indiana Mich. Power Co. v. Dep't of Energy*, 88 F.3d 1272, 1273 (D.C. Cir. 1996) *at* 1274, 1277.

[j]*See Me. Yankee Atomic Power Co. v. United States*, 225 F.3d 1336, 1342 (Fed. Cir. 2000).

[k]US Department of Energy, Agency Financial Report FY 2022 at 120.

system level or to respond to unforeseen events, much less for indefinite storage" at decommissioned reactor sites (BRC, 2012: 35).

America's prospective "nuclear renaissance" (Duffey and Pioro, 2019; Hochman and Hochman, 2022; Nuttall, 2022) conflicts with climate change and the nationwide SNF impasse. Where the "wicked problems" of climate change (Incropera, 2015) and nuclear waste (Di Nucci and Brunnengräber, 2017; Brunnengräber, 2019) intersect, a unique opportunity exists to craft effective oversight to rectify SNF management deficiencies by future-proofing SNF storage sites from the harms of climate change. The same opportunity may apply more broadly to other climate mitigation technologies, including carbon capture and storage and carbon dioxide removal. Nevertheless, federal preemption over radiological safety poses particular challenges to efforts to expand federal oversight over aspects of the nuclear power lifecycle (Congressional Research Service and Heflin, 2023: 2, FN 12). Innovative ways to navigate the climate change nuclear waste nexus are thus essential, whether they apply, challenge, or exist outside contemporary law and policy frameworks. In this Policy Brief, we will focus on leveraging existing frameworks.

2 California's Humboldt Bay, a case study: building resilience in places where SNF storage and climate change converge

2.1 The Humboldt Bay ISFSI: one of the nation's most at-risk SNF sites to sea level rise

The Humboldt Bay ISFSI ("HB ISFSI") in King Salmon, California, is one of the most climate vulnerable nuclear facilities in the nation (Jenkins et al., 2020). Similar to ISFSI licensees operating decommissioned nuclear sites elsewhere, Pacific Gas and Electric ("PG&E") contends that the DOE will commence waste retrieval by 2031 (United States Department of Energy, 2017; PG&E, 2019: 8–4). Projected climate risks are circumvented by this tentative timeline, which also assumes consolidated repository availability by 2048 (United States Department of Energy, 2013).

Meanwhile, Humboldt Bay is experiencing the fastest rate of relative sea level rise in California (Anderson, 2018; Patton et al., 2023). It remains uncertain whether 37 tons of SNF can be safely stored on an erosive coastal bluff "in perpetuity" (California Coastal Development Permit, 2005; California Coastal Commission, 2011). For example, 1 m of sea level rise during a king tide would island the HB ISFSI (Laird, 2019) (Figure 2), compromising site access and integrity should existing shoreline barriers be breached. Figure 3 depicts projected bluff inundation and shoreline retreat in the event that the rip rap wall currently deflecting wave energy from the bay entrance fails. Tsunami risk is also a potential hazard, given the site's proximity to the seismically active Cascadia Subduction Zone and the Mendocino Triple Junction (Padgett et al., 2021).

2.2 Case study findings

To discuss the climate risk to the Humboldt Bay SNF site, in 2022, we convened a diverse coalition of community and regional experts—Native American Tribes, elected officials, government agency staff, non-profit organizations, and academics with experience or involvement in nuclear power plant decommissioning and waste management. The goal of our convening was to situate local conditions and expertise as fundamental complements to the expert-driven technical and regulatory approach guiding long-term SNF management thus far. Semi structured interviews ($n = 24$) and three deliberative scenario planning workshops revealed barriers to public knowledge and engagement as well as opportunities to leverage existing local and state decision-making bodies to inform decision making around responsible and climate resilient SNF site management. The following findings substantiate the importance of realigning safety standards to reflect climate and coastal hazards, while recognizing associated challenges and uncertainties.

Research participants recognized the basic need to update annual safety reports as new scientific information emerges. For example, PG&E's safety reporting for the HB ISFSI assumes tectonic uplift (PG&E, 2021), despite scientific consensus and research produced by some of our study participants that subsidence is causing Humboldt Bay to experience the highest rate of relative sea level rise in California (Patton et al., 2023). Additionally, although PG&E's current safety reports submitted to the Nuclear Regulatory Commission ("NRC") analyze risks to the stored fuel from a magnitude 8.8 earthquake (PG&E, 2021: 172, 216, 218), a geologist at Cal Poly Humboldt specialized in tectonics evaluated the probable risk to be higher:

> "So if you ask me, should we prepare for a 9.2 Cascadia Megathrust event? I would say, absolutely, yes."

Similarly, the Natural Resource director of a local Humboldt Bay Tribe emphasized how hazards might converge when asked about the perceived risks to the HB ISFSI:

> "[H]ow will groundwater intrusion, combined with sea level rise and potential storm surge, and if everything comes together at once, [impact the site]?"

The NRC has stated that risks to the Humboldt site are negligible,[11] including climate risks in the indefinite long-term.[12] Many research participants communicated distrust, however, around NRC safety assumptions. One participant noted the paramount value of public trust:

11 For example, the NRC only requires licensees to protect ISFSIs from probable design basis events. Beyond-design-basis events, deemed outside the scope of likelihood and not applicable in the original design basis at the time of the design, analysis, licensing, or deployment of a dry spent fuel storage system, include earthquakes greater than the original design basis, floods and tsunami generated by BDB earthquakes, and storage operations lasting longer than the initial license period due to delay in final disposal.

12 "There's no accident scenario" that would lead to a radiation release according to David McIntyre, NRC spokesman. Available at: https://www.northcoastjournal.com/NewsBlog/archives/2021/11/18/pgande-reactor-officially-decommissioned-nuclear-waste-not. *See also* Section 3.1 regarding NRC's waste confidence decisions and Generic Environmental Impact Statement. *See also* Figure 4.

FIGURE 2
Tidal inundation of King Salmon Avenue, PG&E's HB ISFSI and generating station, two access roads, and a portion of the sea wall on Humboldt Bay during MAMW or king tides with 3.3 feet (1.0 m) of sea level rise (9.8 feet NAVD 88) assuming shoreline barrier structures do not exist or are breached. From "Humboldt Bay Area Plan: communities at risk strategic sea level adaptation planning report," by Laird, 2019, *Humboldt Bay Area Plan*, p. 16. © Laird, 2019. Reprinted with permission.

> "The whole argument about thin-wall and thick-wall casks, it's got nothing to do with the thickness of the cask. It's got everything to do with the fact that the people who live next to it had virtually no say in how the decision was arrived."

In sum, our study found that the merits of best available science, technical and regulatory control, and public trust require equal consideration when crafting effective strategies to examine and mitigate potential climate risks to SNF storage sites.

3 Policy options and implications: the policy and regulatory landscapes of federal SNF disposal

3.1 A legacy of (dis)trust follows decades of expert-driven decision making

The contemporary techno-political realities underpinning the US nuclear waste stalemate have roots in the antecedent periods of SNF decision-making. The 1954 Atomic Energy Act leveraged a technological determinism rationale (Wyatt, 2008) and a "discourse of trust" in technical experts (Blowers, 2016) to promote peaceful applications of a once "destructive atom" (Jasanoff and Kim, 2009) and convince the public of the manageable risks of nuclear power and waste. Over time, field preemption and an overreliance on technical expertise subsumed more democratic forms of management, establishing a precedent of "policies without publics" (Birkland and Warnement, 2017: 125). Following a series of accidents and failed attempts to dispose of Department of Defense waste, and an intensified public distrust borne of the Agency's emphasis on production over safety (Richter et al., 2022), widespread doubt was cast on the government's ability to effectively manage SNF. California's 1974 moratorium on new nuclear power plant construction pending a "demonstrated technology or means for the disposal of high-level nuclear waste"[13] captured the shifting public attitudes of the 1970s (Slovic et al., 1991; Baron and Herzog, 2020).

3.2 The Nuclear Waste Policy Act and the failure of Yucca Mountain: perpetual uncertainty around the SNF impasse

The blunders that precipitated from the NWPAA and the failure of Yucca Mountain demonstrate the need for SNF management decisions to "focus on the conditions for social and political acceptability, within the constraints identified by physical science and engineering" (Rosa et al., 2010: 762). Moreover, DOE's customary "decide-announce-defend" model of engagement (Hendry et al., 2004) failed to address public perceptions of distrust and illegitimacy. To date, no commercial SNF has been stored at Yucca Mountain, despite its binding legal designation as the country's sole repository under the

13 California Public Resources Code § 25524.2 (2023).

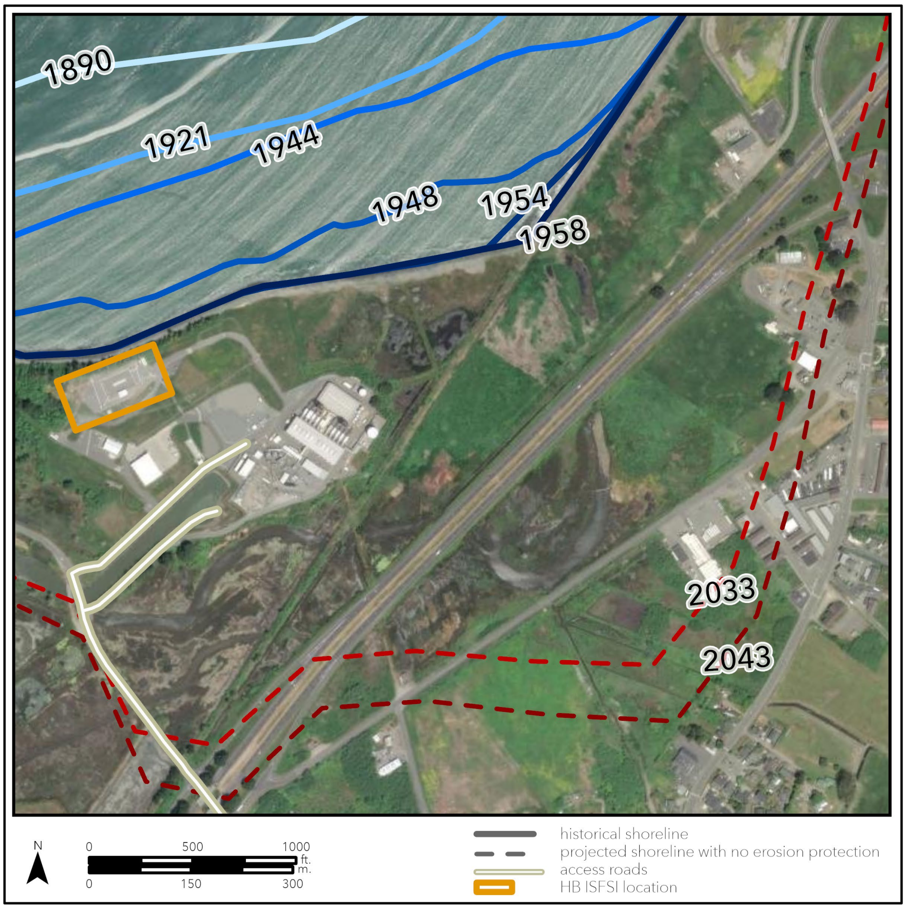

FIGURE 3
Historic shoreline retreat and projected retreat on Humboldt Bay if protective infrastructure is compromised. Projected shorelines were generated using the USGS Digital Shoreline Analysis System (DSAS) v5 software from historical digital shorelines retrieved from the Laird et al. (2007) Historical Atlas of Humboldt Bay and Eel River Delta. Basemap 2023 Maxar Imagery.

NWPA, leaving nuclear waste management in a perpetual state of uncertainty (Table 1). In the wake of its political failure, Yucca symbolized the iconic "lack of democratic governance and energy justice in decision-making" (Bell and MacFarlane, 2022: 1) that continues to characterize SNF management. Yet emergent climate risks open up this paradigm to interrogation and rethinking.

3.3 Federal and state authorities at the nuclear climate nexus

In 1983, the United States Supreme Court affirmed that the Atomic Energy Act ("AEA") of 1954 granted the Nuclear Regulatory Commission federal preemption over "the entire field of nuclear safety concerns," thus preempting states from regulating radiological safety.[14]

Despite the introduction of several policy proposals for updating the spent nuclear fuel management regime, Congress has not adopted new nuclear waste legislation since the Nuclear Waste Policy Act was amended in 1987 (Congressional Research Service and Holt, 2021: 19–27). One hazards-relevant bill, the Spent Fuel Prioritization Act,[15] introduced to the House in 2022, would require the DOE to prioritize the removal of SNF from decommissioned nuclear facilities based on nearby population size, seismic risk, and national security concerns. Notably, however, exposure to climate and coastal hazards is not considered a factor for prioritized removal.[16]

SNF storage site exposure to climate and coastal hazards appears to be an area of policy uncertainty and neglect. The issue may, nevertheless, present limited opportunities to enlist certain existing federal and state authorities in novel ways that may not be preempted by the Atomic Energy Act and that do not require new legislation. Under the AEA, Congress intended:

> that the federal government should regulate the radiological safety aspects involved in the construction and operation of a nuclear plant, *but that the states retain their traditional responsibility in the*

14 *Pac. Gas & Elec. Co. v. State Energy Res. Conservation & Dev. Comm'n*, 461U.S. 190, 205, 212 (1983).

15 Text – H.R.6685 – 117th Congress (2021–2022): Spent Fuel Prioritization Act of 2022 | Congress.gov | Library of Congress.

16 For this reason, the Spent Fuel Prioritization Act (2022) should be modified to include a weighted risk factor for site vulnerability to climate and coastal hazards.

> *field of regulating electrical utilities for determining questions of need, reliability, cost, and other related state concerns* (emphasis added).[17]

Notable areas of relevant state authority include licensing, rate-setting, and land use. State-level regulatory proceedings, such as the California Public Utility Commission's Nuclear Decommissioning Cost Triennial Proceedings ("NDCTP"), have been used as a forum for requiring PG&E to perform an updated tsunami hazard assessment for the HB ISFSI that incorporates "the most current information about sea level rise and tsunamigenic earthquakes benchmarked against the similar analysis performed for the SONGS ISFSI" (California Public Utilities Commission, 2023: 14). South of Humboldt, the Action for Spent Fuel Solutions Now Coalition is leading a multiparty strategic planning process considering options for relocating the San Onofre Nuclear Generating Station ("SONGS") fuel away from coastal hazards under current NRC licensing regulations without requiring statutory changes (Northwind, 2021: 116).[18] Furthermore, the DOE's consent-based siting process, which seeks to work "collaboratively with members of the public, communities, stakeholders, and governments at the Tribal, state, and local levels" on siting a consolidated interim SNF storage location (United States Department of Energy, 2023: 5, 9) is authorized by current law, particularly Subtitle C of Title I of the NWPA of 1982, as amended, with funding from Consolidated Appropriations Acts of 2021, 2022, and 2023 (United States Department of Energy, 2023: 9). The program also aligns with Executive Orders 12898, 13985, and 14008 on environmental justice, advancing racial equity, and tackling the climate crisis, respectively.

Finally, the NRC, consistent with its fundamental regulatory objectives to provide "adequate protection of the public health and safety" (NRC, 2012: 4–5), could amend or issue new regulations under existing authorities to accommodate updated and emergent science that could impact the safe storage of SNF long-term in locations at risk of climate and coastal hazards (NRC, 2014: 48).

4 Actionable recommendations

4.1 Update NRC regulations to address conditions for at-risk sites

Despite legitimate proposals for complete regulatory overhaul (e.g., Meng, 2018), a targeted approach to SNF management should leverage existing mechanisms to address climate and coastal hazards given that Congress is unlikely to pass new legislation under the current political climate. First, we recommend that the NRC shift from a one-size-fits all generic approach to locally tailored but nationally comprehensive SNF regulations that emphasize fine-scale and site-specific conditions for at-risk sites.

Illustrating this point, in *New York v. NRC*, 681 F.3d 471, the D.C. Circuit Court of Appeals vacated NRC's 1979 Waste Confidence Ruling (D.C. Cir. 2012), which historically provided "reasonable assurances" to justify the safety of continued on-site storage of SNF. In 2014, on remand to the NRC, the agency produced a Generic Environmental Impact Statement ("GEIS")[19] to evaluate the environmental impacts of continued storage at a single generically profiled commercial facility across three timelines: short-term (60 years after the end of a reactor's licensed life), long-term (100 additional years), and indefinite (assuming a repository never materializes). The NRC concluded that the environmental, climatic, and accident-related impacts of continued storage would not vary significantly across sites nor timelines, "despite variations in site-specific characteristics" (79 FR 56242).

This conclusion, codified in NRC regulation 10 CFR 51.23, drives nuclear licensees and the NRC to overlook the dynamic risks of coastal and climate processes to ISFSI sites. Thus, the NRC should revise the GEIS rule to require site-specific analyses of ISFSIs at risk of climate and coastal hazards. Under this proposed change, at-risk ISFSI licensees would be more likely to accommodate projected impacts that fall outside the range of a GEIS approach in their risk analyses.

Furthermore, the NRC's GEIS rule was restricted to analysis of "postulated design basis accidents," events "that a nuclear facility must be designed and built to withstand without loss to the systems, structures, and components necessary to ensure public health and safety."[20] Current NRC regulations require *operating nuclear reactor facilities* to mitigate Beyond-Design-Basis Events after the 2011 Fukushima Japan natural disaster (instigated by the greatest earthquake ever recorded in Japan followed by a 46-foot-high tsunami).[21] However, holders of a general or specific 10 CFR part 72 ISFSI license, such as PG&E's HB ISFSI license, are exempt from such regulations (10 CFR § 50.155: 39699).

We recommend that the NRC reevaluate the ISFSI exemption to the Rule for Mitigation of Beyond-Design-Basis ("BDB") accident events and amend the rule to be applicable to any ISFSI site where convergent coastal and climate hazards makes a BDB worst-case accident reasonably plausible. Additionally, we recommend that the NRC and affiliated bodies[22] conduct a consequence analysis of BDB accident scenarios at high-risk ISFSI sites, such as those we postulated for the HB ISFSI (Figure 4).

4.2 Other solutions to attain more effective oversight: engaging state, tribal, and community support

Current opportunities exist to craft more effective oversight for long-term storage of SNF at hazard-prone sites by leveraging existing state, Tribal, and local policies and institutions. In states like California, the public trust doctrine could be used to gap-fill federal protections, for example. As coastal erosion and sea level rise shifts state jurisdiction landward with migrating tidelands (Peloso and Caldwell, 2011; Lester, 2021), public assertion of the rights of present

17 *Supra note* 14.

18 Congressional action would be required, however, to apply Nuclear Waste Funds or other sources of federal funding to this approach.

19 *NUREG-2157 Vol 1, "Generic Environmental Impact Statement for Continued Storage of Spent Nuclear Fuel: Final Report (Sept. 2014)" (nrc.gov).

20 *Id.* at 11–7.

21 Mitigation of Beyond-Design-Basis Events Rule 84 FR 39684 (2019).

22 These could include the Nuclear Energy Institute, Electric Power Research Institute, Nuclear Programs Division, and the Advisory Committee on Reactor Safeguards.

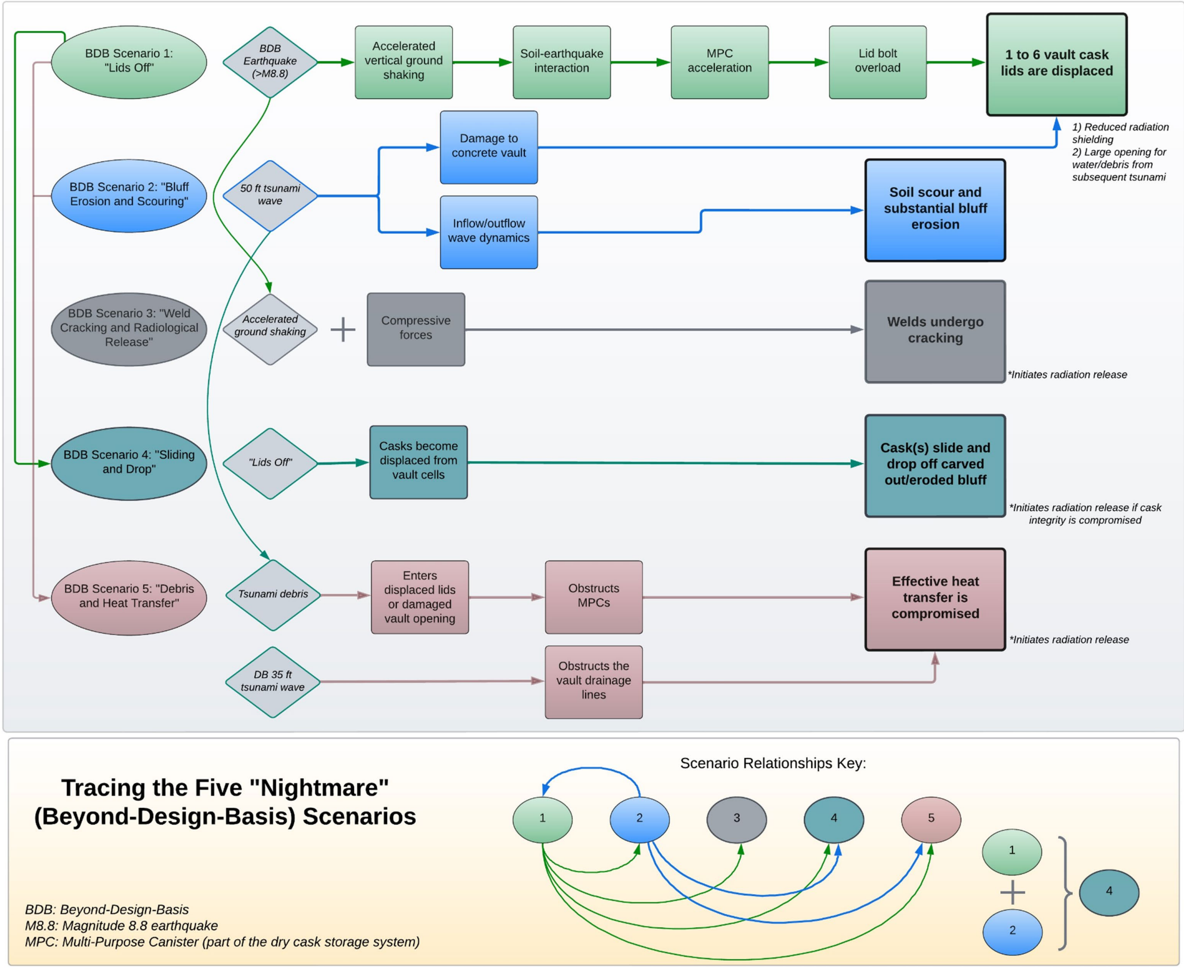

FIGURE 4
Beyond-design-basis events at the HB ISFSI warranting heightened attention.

and future generations to use and enjoy public trust waters impinging on coastal ISFSI sites could further guard against the threat of a worst-case accident.

Additionally, contingency planning, such as California's amendment of the SONGS ISFSI permit to include special conditions for assessing earthquakes, tsunamis, coastal risks, and sea-level rise (California Coastal Commission, 2022), could be pursued at the HB ISFSI to align NRC's public safety mandates with California's public trust obligations. Similarly, the state could consider pursuing an amendment for Humboldt Bay modeled after Diablo Canyon's, which mandates that PG&E assess climate change and sea-level rise impacts on coastal roads (California Coastal Commission, 2023).

Finally, the Nuclear Energy Innovation and Modernization Act (2017)[23] calls for the formation of Community Advisory Boards ("CABs") to foster communication and information exchange between licensees, local and state agencies, Tribes, and the public regarding ongoing and planned activities at nuclear facilities. CABs are intended to be in place throughout the decommissioning process, but extending the life of CABs via charter terms can sustain community engagement in post-decommissioning activities such as management of climate and coastal risk to SNF sites. State-sponsored CABs could also be granted statutory authority over certain decommissioning decisions under the state's authority, such as those impacting public trust resources, thus endowing CABs with more decision making power than their advisory status currently confers (Nuclear Decommissioning Collaborative, 2020).

4.3 A "whole of government" approach to sharing SNF's regulatory space

Despite prioritizing safety across the nuclear industry, NRC and DOE regulations overlook the site-specific impacts of climate change and coastal hazards on stranded SNF sites. Exclusively expert-driven quantitative approaches to deep uncertainty induces disparity between proposed agency actions and risk mitigation, often resulting in maladapted decisions (Phillips-Robins, 2022). Consequently, certain

23 Text – S.512 – 115th Congress (2017-2018): Nuclear Energy Innovation and Modernization Act | Congress.gov | Library of Congress.

checks and balances in decision-making across institutions and disciplines are warranted to "temper emergent liminalities" arising from climate change and political gridlock (Bell and MacFarlane, 2022: 8). Departing from 'single-agency focus' and coordinating with a 'whole of government' approach (Freeman and Rossi, 2012) could improve the overall quality of decision-making and enhance public safety at hazard vulnerable ISFSI sites.

As such, a statewide independent science and ethics review committee, informed by localized climate and coastal hazard risks and environmental justice considerations, could assess emergent risks to California's three coastal nuclear storage facilities. The newly formed committee could act as a liaison between the federal government, state publics, Tribes, and CABs, funneling upward local challenges, needs, and interests, while disseminating updated hazard information and planning decisions that integrate local input downward. Environmental equity and justice Executive Orders could connect governing bodies diagonally and expressly consider the integral role states, communities, and Tribes play in furthering NRC's public safety agenda.[24]

Lastly, we recommend early and open dialogue with host communities of existing SNF sites at risk of climate and coastal hazards. Failure to accomplish this task has historically generated local resistance to on-site storage, public distrust, and opposition to nuclear power expansion (Stewart, 2008). Instead, deliberative public participation, negotiations, and contributions from multiple stakeholders, in addition to effectively facilitating high quality scientific information exchange (Gibbons, 1999; Pellizzoni, 2001; Mauser et al., 2013; Clark et al., 2016), could enhance the quality and legitimacy of decisions (Leino and Peltomaa, 2012), build trust and mutual understanding (Stern and Dietz, 2008), and foster "more consensual points of view between previously antagonistic groups" (Bergmans et al., 2008: 15), all while achieving important regulatory objectives as the climate changes.

Such negotiated engagements could eventually build public support for new federal legislation. While we work to craft more effective oversight within the rigid parameters of the current federal program (Congressional Research Service and Heflin, 2023), climate challenges are contributing to the growing momentum to build support for proposals that expand the current SNF management regime to local, state, and Tribal governments, raising the prospects of future statutory changes to the AEA and NWPAA.[25]

5 Conclusion

Decades-long tensions continue to shape the political stalemate over the role states and host communities play in relation to the federal aims and goals of US SNF management (Richter et al., 2022). The existing legislative framework was never designed to address interactions between climate and nuclear waste, but more effective oversight leveraging existing federal, state, local, and Tribal government authorities could adapt SNF management to a climate-changed world. We suggest that governments with oversight over SNF and SNF storage sites: (1) refine climate and hazard risk approaches to more appropriate local or site-specific scales; (2) reconsider the value of *qualitative* tools and frameworks in tandem with *quantitative* analysis; and (3) apply existing policies and regulations that coordinate risk adaptation approaches so that SNF management frameworks are more receptive to change, uncertainty, and to local knowledge, values, and interests. Until a more "permanent" solution is secured, it will be imperative to explore effective strategies that engage, not disengage, with diverse publics for addressing climate and coastal hazards to SNF sites.

24 Equity and Environmental Justice Policies (ca.gov).

25 *See* BRC (2012: 56). (Recognizing "that defining a meaningful and appropriate role for states, tribes, and local governments under current law is far from straightforward .... Nevertheless, we believe it will be essential to affirm a role for states, tribes, and local governments that is at once positive, proactive, and substantively meaningful").

Author contributions

AB: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. JM: Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. JS: Writing – review & editing, Visualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2024.1356724/full#supplementary-material

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