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Socio-technical evaluation of long-term spent nuclear fuel management options: The case of San Onofre, California

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Abstract

In the absence of a federal geologic repository or consolidated, interim storage in the United States, commercial spent fuel will remain stranded at some 75 sites across the country. Currently, these include 18 “orphaned sites” where spent fuel has been left at decommissioned reactor sites. In this context, local communities living close to decommissioned nuclear power plants are increasingly concerned about this legacy of nuclear power production and are seeking alternative options to move the spent fuel away from those sites. In this paper we use a newly proposed socio-technical multi-criteria evaluation (STMCE) framework and method for nuclear waste management strategies and apply it to the case of the decommissioned San Onofre Nuclear Generating Station (SONGS) in California. The case of SONGS illustrates the issues encountered for the long-term management of commercial spent fuel in the United States and how local communities attempt to participate in decision-making for plant decommissioning and spent fuel

management and disposal. The case study was conducted with a group of Stanford graduate students who helped test the method. The analysis presented in this paper corresponds to the first iteration of the STMCE framework that requires the participation of stakeholders. The STMCE framework brings together social and technical dimensions of analysis, as well as concerns for the social impact of feasible options. STMCE also provides a method consisting of mathematical procedures for the multi-criteria evaluation and social conflict analysis. The case study at SONGS provides insights on how coalitions of socio-technical actors can form and how compromise solutions can be identified to inform the policy decisions. We conclude by discussing the potential impact that such an approach could have on the management of commercial spent fuel in the United States.

Keywords: radioactive waste; multi-criteria analysis; conflict analysis; impact assessment

1. Introduction

Worldwide, almost all national efforts since the 1980s to site deep geological repositories for highly-radioactive waste have encountered either public opposition or technical difficulties (US NWTRB, 2009). In the United States, despite plans for geological disposal, the back-end of the nuclear fuel cycle, so far, has not gone beyond the surface storage of spent fuel at the sites where it has been generated (Diaz-Maurin and Ewing, 2020a; Reset Steering Committee, 2018). This situation results in an increasing amount of spent fuel being stored in dry casks at many different spent fuel storage installations, all located at or near reactor sites. As of end of 2017, approximately 82,500 metric tons of commercial spent fuel are stored at 79 different locations, including 64 operating reactor sites in 34 states (Carter, 2018). If no geologic repository becomes available, projections

indicate that approximately 140,000 metric tons of spent fuel will be in surface storage by 2050 (Rechard et al., 2015). To accelerate the removal of spent fuel from reactor sites, draft legislations have been introduced in Congress for interim storage facilities (EPW U.S. Senate Committee, 2019). Interim storage is a temporary surface storage solution to the management of spent fuel and high-level waste pending the licensing and construction of the deep geologic repository for permanent disposal. Moving spent fuel to interim storage facilities could help prevent the creation of “orphaned sites” where spent fuel is stranded at decommissioned nuclear power plants (Reset Steering Committee, 2018). Interim storage facilities could also improve the integration of the back-end of the nuclear fuel cycle by adding flexible repackaging options that suit geologic disposal requirements and thus avoid the construction of facilities dedicated to repackaging at other sites. Yet, there is currently no interim storage facility in the United States and amendments are needed to the Nuclear Waste Policy Act (NWPA) of 1982 before federal interim storage facilities with a substantive capacity can be licensed and operated. In fact, under the NWPA (42 U.S.C. §10101 et seq. (1982)), the U.S. Department of Energy (DOE) can spend funds only on the Yucca Mountain site for a federal geologic repository. The law does not allow the U.S. DOE to study other potential sites either for geological disposal or interim storage unless approved by Congress.

In the absence of interim storage or geologic disposal capacity, there were 18 orphaned sites hosting spent fuel in the U.S. in June 2020—a number expected to increase to 20 sites by 2025 (Reset Steering Committee, 2018). In this context, local communities living close to decommissioned nuclear power plants are increasingly concerned about these legacy wastes (US DOE, 2016) and are seeking alternative options to move the spent fuel away from orphaned sites (SONGS Task Force, 2020; St John, 2018a; Victor, 2014).

The San Onofre Nuclear Generating Station (SONGS), located 50 miles north of San Diego, California and owned by Southern California Edison, is an orphaned site and has the largest spent fuel inventory stored at a shutdown power plant in the U.S. (Carter, 2018). The reactors at SONGS were shut down in 2013, and the spent nuclear fuel is being moved progressively from water pools to dry casks located at two dedicated storage areas. The local community at SONGS has been actively involved in process of decommissioning and spent fuel management with the creation of the San Onofre Community Engagement Panel by Southern California Edison in 2010—prior to the shutdown of last two reactors.

The present paper applies a new multi-criteria evaluation framework and method for spent fuel management in U.S. This methodology provides local communities and states a tool for their evaluation of alternative options for the long-term management of commercial spent fuel at decommissioned reactor sites. Section 2 provides an overview of the socio-technical multi-criteria evaluation (STMCE) approach to spent fuel management strategies. Section 3 presents the material and data used for the application of the STMCE approach to the case of SONGS at San Onofre, California. Section 4 presents and discusses the results of the analysis at SONGS. This analysis corresponds to the first iteration of the STMCE process and seeks to support long-term spent fuel management strategy definition, comparison and choice at SONGS. Finally, Section 5 discusses the policy implications of the STMCE approach for nuclear waste management in the United States.

2. Method

We adopt the *multi-criteria evaluation* framework first proposed by Munda for conflict analysis and management in environmental and public policy decisions (Greco and

Munda, 2017; Munda, 2019). Unlike *multi-criteria decision analysis* that searches for optimal solutions, multi-criteria evaluation recognizes that, often, there is no optimal solution for all of the criteria at the same time; therefore, *compromise solutions* have to be found (Munda, 2008). This is particularly true of decision problems that convey potential health and environmental risks, such as the remediation and management of hazardous substances. A major advantage of multi-criteria evaluation—over multi-criteria decision analysis—is its ability to deal with various conflicting evaluations by achieving the comparability of incommensurable dimensions and values. In particular, Munda’s social multi-criteria evaluation approach extends the multiple criteria decision support to also include the concerns of the socio-technical actors, thus allowing for an integrated analysis of the problem. In operational terms, a social multi-criteria evaluation process consists of seven main steps:

1. Description of the relevant social actors that can include an institutional analysis;
2. Definition of the social actors’ values, desires and preferences performed either through focus groups, interviews or questionnaires;
3. Generation of policy options and selection of evaluation criteria based on the information collected in step 2;
4. Construction of the multi-criteria impact (or evaluation) matrix that synthesizes the performance of each alternative according to each criterion;
5. Construction of a social impact matrix (*i.e.*, an assessment of the socio-technical actors’ preferences for each alternative expressed using linguistic variables such as “Good”, “Bad”, “Very bad”);
6. Application of a mathematical procedure (or algorithm) that aggregates the criterion scores (*i.e.*, the expected outcome of each option are assigned a numerical score on

a strength of preference scale for each criterion, generally extending from 0 to 100) and generates a final ranking of the proposed alternatives;

7. Sensitivity and robustness analysis that seeks to look at the sensitivity of the ranking to the exclusion/inclusion of criteria, criterion weights and dimensions (Saltelli et al., 2008).

We adapted elsewhere Munda's framework and extended it to both technical and social dimensions of analysis for the comparison of spent nuclear fuel management options (Diaz-Maurin et al., 2020). Our socio-technical multi-criteria evaluation (STMCE) method consists of (i) a multi-criteria evaluation that provides an ordinal ranking of alternatives based on a list of criterion measurements; and (ii) a social impact analysis that provides an ordering of options based on the assessment of their impact on concerned socio-technical actors. STMCE can handle quantitative, qualitative or both types of information. It can also integrate stochastic uncertainty on criteria measurements and fuzzy uncertainty on assessments of social impacts. We briefly present in Section **A.1** of **Appendix A** the mathematical procedures used in the STMCE method. More details about the method used in this paper can be found in Diaz-Maurin et al. (2020).

The present paper aims at testing the STMCE approach for the management of spent fuel in the United States. For this, we use the case of the San Onofre Nuclear Generating Station (SONGS) in California. The case study was conducted with students during a research seminar at Stanford University (**Table 1**); thus, it corresponds to the first iteration of a STMCE process that requires involving socio-technical actors. During the workshop, students worked together, based on materials provided by us, to address a series of specific goals:

- (1) Assessment of the influence and interest of the various relevant socio-technical actors;
- (2) Validation of selected criteria and management options;
- (3) Assessment of the social impact of selected management options;
- (4) Development of “what-if” scenarios to test the robustness of the ranking of options;
- (5) Search for socio-technical compromise solutions; and
- (6) Formation of coalitions of stakeholder groups to implement compromise solutions.

As the present paper focuses on testing the STMCE approach, the SONGS case study thus serves to illustrate the potential of this approach to address nuclear waste management issues in the United States. That is, although we used actual material and data about SONGS (Section 3), the case study is an illustrative example and the results presented in this paper (Section 4) should not be used to make direct policy recommendations at SONGS. To be complete, the STMCE process must include iterations so coalitions can form, and compromise solutions can be found. An actual application of the method would therefore include the participation of the relevant socio-technical actors (such as those identified in the institutional analysis) through engagement activities (such as focus groups, in-depth interviews and questionnaires). Although a stakeholder engagement process at SONGS is outside the scope of this paper, it has happened elsewhere (SONGS Task Force, 2020; Victor, 2014), and these findings were used as material for the study.

The data and results of this analysis are described in a related data article (Diaz-Maurin and Ewing, 2020b).

3. Material and data

3.1. Background information on SONGS

The San Onofre Nuclear Generating Station (SONGS) is located between Los Angeles and San Diego in California (**Fig. 1**). SONGS is owned by the utilities Southern California Edison (approx. 78%) and San Diego Gas & Electric (approx. 20%), and by the city of Riverside (approx. 2%). SONGS is operated by Southern California Edison. Between 1968 and 2012, SONGS operated three electricity-generating nuclear pressurized water reactors (PWRs). Unit 1 (456 MW capacity) operated from 1968 to 1992 when it was shutdown, decommissioned and then dismantled. Units 2 and 3 (1127 MW capacity each) operated from 1982/1983 to 2012. In early 2012, Unit 3 suffered a radioactive leak inside the containment building leading to a release of radionuclides to the environment, although below allowable limits (Jaczko, 2012). The Unit 3 reactor was shut down per standard procedure, whereas Unit 2 was already in outage for routine refueling and replacement of the reactor vessel closure head. After more than a year of investigation and analysis, it was found that the leak in Unit 3 came from faulty steam generators which had been replaced in 2011 on both units (Jaczko, 2012). As a result, Southern California Edison decided that SONGS would be permanently closed and decommissioned. The plant was officially shutdown in June 2013 and has not yet been dismantled.

In over 40 years of reactor operations, SONGS generated 3,855 spent fuel assemblies corresponding to 1,609 metric tons of initial Uranium (MTU), as well as 98 MTU (270 spent fuel assemblies) from SONGS 1 that was already transferred to a spent fuel pool at an independent storage facility owned and operated by General Electric-Hitachi

Nuclear America, LCC (GE) in Morris, Illinois.¹ In the absence of a geologic repository for the disposal of fuel, the spent fuel assemblies at SONGS have been transferred from water pools to dry cask storage. However, the used fuel assemblies must first be stored in pools for about 5 years to cool before they can be transferred to dry casks.

In August 2018, during the transfer operations at SONGS a “near-miss” event occurred when a 50-ton canister filled with fuel assemblies remained suspended for about 45 minutes without being supported on the inner-ring of the underground dry cask (Nikolewski, 2020). The canister was eventually safely lowered to its position, but the incident resulted in a special inspection by the U.S. Nuclear Regulatory Commission, causing a delay in fuel transfer operations for nearly a year. Local watchdog groups complained that Southern California Edison violated the NRC rules of fuel transfer by not immediately reporting the incident (McDonald, 2019a).

In March 2020, during the first outbreak of the coronavirus pandemic, the Governor temporarily halted deconstruction work considered as non-essential activities under the “safer at home” directive (Governor of California, 2020). However, fuel transfer operations were considered essential activities and thus have been maintained during the pandemic. Fuel transfer operations to dry cask storage were completed in August 2020 (SCE, 2020a). In the analysis, we consider the year 2020 as the starting year for the long-term spent fuel management scenarios spanning 200 years.

¹ The 270 SONGS 1 fuel assemblies were transferred between 1974 and 1976 to the GE facility in Morris, Illinois, to be reprocessed at that facility. However, in 1977 President Carter indefinitely deferred the spent fuel reprocessing program and the SONGS 1 fuel assemblies remain stored in a pool along with those from four other nuclear power plants. In 2050, DOE will accept the fuel stored at Morris, transfer it to shipping containers that will be provided by DOE, and transport it at another site. The GE facility in Illinois is a good example of the possibility of moving irradiated fuel to another site or to an interim storage site which, in the case of SONGS, was transferred from another state. However, in this case, the fuel transfer was incentivized by the prospects of reprocessing, thus, of the potential economic return on investment from the re-use of the reprocessed uranium and plutonium in reactors.

3.2. Institutional analysis

Given the current stalled situation in which the U.S. DOE has been unable to move stranded spent fuel from orphaned sites to either a geologic repository or an interim storage facility, some are concerned that SONGS's spent fuel may remain on site forever (St John, 2018b). Local municipal governments and many members of the public near SONGS strongly oppose leaving the spent fuel on site indefinitely (**Table 2**, see also (Reset Steering Committee, 2018)). Concerns are motivated first by a singular location: "SONGS is located just 100 feet from the shoreline, on a receding bluff, near a fault line, on the outskirts of the coastal surf town of San Clemente, yards away from world renowned surf breaks, next to one of the nation's busiest freeways, and within roughly 50 miles of the densely populated City of San Diego" (Day, 2017). To improve the dialogue between the different social-economic actors, the SONGS plant's main owner, Southern California Edison (SCE), created in 2010 a Community Engagement Panel (CEP) to provide public input into the decommissioning process. Yet, conflicts remain between some local groups and SCE over the spent fuel management and plant decommissioning strategy.

In November 2015, Citizens Oversight, a community watchdog, sued SCE and the CSCC over a coastal development permit CSCC issued to Edison to store spent nuclear onsite (Bruno, 2017). In November 2017, both parties reached a settlement agreement after a judge ruled not to dismiss the suit. The out-of-court settlement requested Edison to make "commercially reasonable" efforts to relocate the waste to another facility and to hire a panel of independent experts to advise SCE on how and where this could be moved (Citizens Oversight and Southern California Edison, 2017). In October 2019, the plaintiffs

issued a motion requesting that a judge enforce the settlement with the plaintiffs claiming that the current practice of fuel transfer to dry casks “will likely compromise, if not make it impossible, to transfer the spent nuclear fuel to an off-site storage facility as required by the settlement agreement” (McDonald, 2019a). In June 2019, SCE finally engaged a team of experts (the “Experts Team”) to study any option to move the spent fuel from SONGS to an offsite storage facility (SCE, 2019a). This effort, the “Strategic Plan Initiative”, is led by North Wind, Inc. and will run until December 2020, when the Experts Team is expected to publish their recommendations for a strategic plan.

Separately, in August 2019, another local group opposed to the long-term onsite storage, Public Watchdogs (PW), sued SCE, SDG&E, Sempra Energy, Holtec International, and the U.S. NRC over decommissioning plan at SONGS (Public Watchdogs, 2019). According to PW’s allegations, SONGS has had numerous instances of poor safety and regulatory compliance and these issues of mismanagement were posing “an imminent, significant, and unreasonable threat to the public health and safety of millions of people that live and work anywhere near SONGS” (Public Watchdogs, 2019). In July of the same year, Public Watchdogs had withdrawn another lawsuit, also naming SCE, after the court offered the group the opportunity to amend the complaint. However, the lawsuit was soon after dismissed by SCE who considered it as “wrong on the law [...], on the science and on the engineering of spent fuel storage” (SCE, 2019b). In December of the same year, a federal judge dismissed the lawsuit ruling that PW could not demonstrate it suffered harm and that the lawsuit, filed to the U.S. District Court for the Southern District of California, was not within federal courts’ limited jurisdiction (Sforza, 2019; US District Judge, 2019).

Even for SCE, who is responsible for the spent fuel management and plant decommissioning, leaving the fuel indefinitely onsite is not a desirable option. SCE’s

current strategy is to complete the fuel transfer from wet to dry storage so it can decommission the rest of the plant and return the property to the U.S. Navy, as indicated in its original lease (McDonald, 2019a). In addition, despite the absence of a federally licensed facility to accept commercial spent nuclear fuel from reactor sites, SCE's top priority is to move SONGS's spent fuel off-site (SCE, 2019a)—which is the objective of SCE's Strategic Plan Initiative led by the Experts Team.

The institutional analysis summarizes the social “atmosphere” by listing the relevant socio-technical actors (persons or organizations), their stakes and position over the long-term storage of spent fuel at SONGS. **Table 2** illustrates that a large pool of local, state and national socio-technical actors directly or indirectly concerned by SONGS has a broad range of stakes and positions regarding the fate of the spent fuel at SONGS.

We then classified the socio-technical actors according to their level of power and interest (Aaltonen, 2011). In strategic management, *power* (or influence) refers to the ability of individuals or groups to persuade, induce or coerce others into following certain courses of action; whereas, *interest* (or stake) refers to ownership, right, wealth, benefit, risk, or any other tangible or intangible aspects that a given stakeholder considers as relevant and potentially affected, positively or negatively, by a given issue or decision (Johnson et al., 2008). We used a power/interest plane (also called a stakeholder map (Bonke and Winch, 2002), an extension of the power/interest matrix (Johnson et al., 2008; Olander and Landin, 2005), in which participants can position every identified stakeholder, including their own, relative to the others on a plane. **Fig. 2** represents the stakeholder map produced with Stanford students (**Table 1**). The position of socio-technical actors in the plane gives an indication of their relative levels of power and stakes.

Stakeholder mapping is better performed through participation with actual socio-technical actors. In that case, representatives of each socio-technical actor are asked to visually distribute the actors on a power/interest matrix and disclose which stakeholder they feel the closest to. Once all actors have performed this exercise, it is then possible to compile the maps and reveal possible gaps in the perception of the role of the different actors over a given issue. A deliberation may be required to reach a consensus over the final stakeholder matrix. Alternatively, it is possible to use ranges of power and interest levels that reflect the perception gaps. In the present case study, the stakeholder map is therefore an approximation of the power/interest relations among the socio-technical actors for its use in the social impact and conflict analysis (Section 4.2).

3.3. Spent fuel management processes

For a given reactor site, the long-term management of commercial spent fuel in the U.S. involves four basic processes (Diaz-Maurin and Ewing, 2020a): (a) storage onsite; (b) storage at an interim storage facility; (c) permanent disposal at a geologic repository; and (d) transport from the reactor site to an interim storage and/or geologic disposal facility. We discuss each process in the U.S. context and their relevance for the SONGS study.

3.3.1. Onsite storage

With approximately 1,600 MTU, SONGS is the largest inventory in the country of spent fuel located at an all-units shutdown site (Carter, 2018). The away-from-reactor storage system at SONGS consists of two dry casks storage areas (**Table 3** and **Fig. 3**): (1) an underground dry storage module, called HI-STORM UMAX, hosting used fuel from

units 2/3 in 73 multi-purpose canisters (MPCs); and (2) a horizontal dry storage module, called NUHOMS, hosting older spent fuel from unit 1 and part of units 2/3 in 50 dual-purpose canisters (DPCs). We detail below the two dry cask storage systems:

1) The NUHOMS system, supplied by Areva USA (now Orano TN), is a horizontal storage module for dry casks (Orano TN, 2020). It consists of concrete storage modules with a Dry Shielded Canister (DSC) made of up to 5/8-inch thick corrosion-resistant stainless steel. Aluminum heat conductive pathways and crisscrossed slotted plates allow the heat to be removed from the fuel assemblies to the side of the canister where the heat is then dissipated by the air flow. NUHOMS has an NRC-licensed cask to transport in-canister high burn-up fuel (**Table B.3** in Error! Reference source not found.). At SONGS, the NUHOMS storage module hosts 17 and 33 dual-purpose canisters (DPCs) from units 1 and 2/3, respectively. The 50 DPCs host up to 24 fuel assemblies each.

2) The HI-STORM UMAX system, supplied by Holtec International, is an underground Vertical Ventilated Module (VVM) for dry casks. It is engineered to be fully compatible with all currently certified MPCs, such as the HI-STORM 100 (under USNRC Certificate of Compliance (CoC) No. 72-1014) and HI-STORM FW (under CoC 72-1032) dry cask storage systems (Holtec International, 2020a). At SONGS, the HI-STORM UMAX storage module hosts 73 multi-purpose canisters (MPCs) that host up to 37 fuel assemblies each.

The evolution of the total radioactivity and decay heat power of spent fuel stored in dry casks at SONGS have been estimated using published data from simulation codes for typical PWR UO₂ fuel assemblies (**Table 5**).

3.3.2. *Interim storage*

Consolidated interim storage of spent fuel is now considered as a serious option in the U.S. spent fuel management policy landscape (Reset Steering Committee, 2018). Moving spent fuel to interim storage facilities would indeed bring several advantages. First, it would end the creation of orphaned sites—such as SONGS—where spent nuclear fuel is the only remaining liability at decommissioned nuclear power plants. Second, interim storage facilities could provide more flexible repackaging options so waste packages better meet repository requirements; thus, helping to resolve the absence of a standardized waste packaging strategy at reactor sites.

In 2013, DOE proposed a new strategy to build interim storage facilities—starting operations at a preliminary site by 2021 and to a more suited interim storage facility by 2025 (US GAO, 2014). However, this federal interim storage strategy was deemed unrealistic due to DOE’s lack of authority to implement this strategy thus requiring legislative amendments to the NWPAA, a timeframe not compatible with NRC’s licensing process, technical issues with spent fuel transportation, and the siting process of federal interim storage facilities likely to encounter the same issues of public acceptance as geologic repositories. Given the issues associated with the federal interim storage strategy, two private initiatives have been launched to develop interim storage facilities.

First, Holtec International and the Eddy-Lea Energy Alliance (ELEA) are proposing an interim storage facility on land owned by ELEA near Carlsbad, in Southeastern New Mexico (point 6 in **Fig. 4**). New Mexico is already hosting a repository called the Waste Isolation Pilot Plant (WIPP) for transuranic military waste—the world’s only operating geologic repository. The Holtec-ELEA facility, named HI-STORE interim storage facility, would have a capacity of up to 500 canisters corresponding to approx. 8,680 metric tons of

uranium (MTU) of commercial spent fuel, with possible future extension for up to 10,000 canisters (approx. 120,000 MTU). The license application for the HI-STORE interim storage facility was submitted to the U.S. NRC in March 2017 and accepted by the U.S. NRC in February 2018 (Docket No. 72-1051) (Holtec International, 2020b).

In the second initiative, Interim Storage Partners—a joint venture between Orano USA (formerly Areva USA) and Waste Control Specialists (WCS)—is proposing an interim storage facility at the WCS site in Andrews County, in Western Texas, on the border with New Mexico (point 7 in **Fig. 4**). The Orano-WCS facility would host up to 40,000 MTU of spent fuel (approx. 3,300 canisters) to be developed over eight modular phases. The license application for the Areva-WCS interim storage facility was submitted to the U.S. NRC in April 2016 and accepted by the U.S. NRC in January 2017 (Docket No. 72-1050). However, the NRC review of the license application was suspended in April 2017 at the request of WCS and resumed in August 2018 (Orano USA and Waste Control Specialists, 2020). As of writing, the two license applications for an interim storage facility were still under review with the U.S. NRC.

Even if privately-owned interim storage facilities were to be licensed and operating, interim storage alone will not resolve the issues of spent fuel management in the U.S. To ensure an effective investment, sound management strategy and consistent policy, interim storage capacity must be based both on the production from running power plants *and* the availability of an endpoint through geological disposal (IAEA, 2015). Yet, in the current U.S. nuclear waste policy, given no endpoint has been identified, the future repository constraints are still unknown. In this situation, the introduction of interim storage will not help to align waste repackaging practice with transport and disposal requirements. Second, in the absence of a geologic repository, interim storage could extend for several hundred

years. Yet, there is currently no lifetime requirements for dry casks so that the integrity of the casks could be compromised over such a long time (Reset Steering Committee, 2018). Moreover, not only the casks will be subject to evolving weather conditions, spent fuel properties will significantly evolve over time (Ewing, 2015), thus potentially affecting the integrity of the canister from the inside (Bruno et al., 2020). This creates uncertainties about the safety of long-term interim storage.

In the SONGS analysis presented in Section 4, we considered the following assumptions for interim storage:

- An interim storage facility is located in New Mexico or Texas at proposed sites or in California facilitating minimum transport distance (Section 3.3.4);
- The average cask lifetime is between 50 to 100 years;
- The replacement rate of canisters and casks is estimated using the “three-sigma rule” of a normal distribution.

3.3.3. Deep geological disposal

Deep geological disposal is considered the only solution that offers safe, long-term disposal of highly radioactive nuclear waste (Ewing et al., 2016). Geological disposal relies on the “defense-in-depth” principle consisting of multiple levels of protection (or containment barriers) that ensure several safety functions (Ewing et al., 2016; Norris, 2017): (1) isolation of radioactive materials from humans and the environment, (2) containment (immobilization) of radionuclides in waste form and waste package (engineered barriers), and (3) retardation (delay) and reduction of radionuclides migration through the dilution and sorption processes along the transportation path to the biosphere

(geological barriers). A deep geological repository is a complex system defined by a unique combination of waste types and properties, engineered and geological barriers, and host rock geochemistry and hydrologic conditions over time (Diaz-Maurin and Ewing, 2018). Different disposal concepts exist that mainly include deep, mined geologic repositories emplacing waste canisters at depths of hundreds of meters in either crystalline rock (Hedin and Olsson, 2016; Laverov et al., 2016), argillaceous (clay) rock (Grambow, 2016; NAGRA, 2002), salt rock (Berlepsch and Haverkamp, 2016; Robinson et al., 2012), or volcanic tuff rock (Swift and Bonano, 2016) – and deep borehole disposal that emplaces waste at even greater depths, up to five kilometers (Brady et al., 2017).

Currently, the Yucca Mountain repository project in Nevada is officially the only site proposed for the disposal of commercial spent fuel in the U.S. Its license application was submitted by the U.S. DOE to the U.S. NRC in 2008. In 2010, however, the Obama administration attempted to withdraw the license application in response to the growing opposition in the state of Nevada over the Yucca Mountain repository project. This decision was overturned in 2013 by a U.S. Court that ordered the NRC to resume the license application review using available funds given that the Administration had stopped funding the Yucca Mountain repository. The technical and environmental reviews of the Yucca Mountain application were completed in 2016. An adjudicatory hearing must now be completed before a licensing decision can be made, but it is currently suspended.

Beside the Yucca Mountain repository project, which is in unsaturated volcanic tuff rock (Swift and Bonano, 2016), the U.S. DOE and its national laboratories have continued to be involved in international collaboration activities in different geologic disposal environments (Birkholzer, 2015).

In the SONGS analysis presented in Section 4, we considered the following assumptions for geological disposal:

- A geologic repository is located either at the proposed Yucca Mountain repository site in Nevada or in California considering the minimum transport distance (Section 3.3.4);
- The technical and social feasibility of a geologic repository at those and other sites is not within the scope of this study.

3.3.4. *Transport*

As both interim storage and geological disposal can be considered inside and outside California, we considered several locations for interim storage facilities and geologic repositories (**Fig. 4**). Possible locations of interim storage facilities and geologic repositories were estimated applying the principle of minimum transport distance. Note that these locations are used for illustrative purposes related to transport. An actual site would have to satisfy social and technical requirements (US NWTRB, 2015). That is, these locations were estimated without the consideration of constraints such as the technical feasibility of hosting either an interim storage facility and/or a geologic repository, environmental protection of natural areas, and the local political, social and economic context—all being outside the scope of the analysis.

In the SONGS case study, points 2-4 represent three possible locations of an interim storage facility and/or a geologic repository in the state of California depending on the inventory to be transported, whereas points 5-7 represent known locations of proposed geologic repositories and interim storage facilities. Using these locations, we can then

estimate the minimum transport distance for each one of the possible itineraries from SONGS to an interim storage facility and/or geologic repository, and from an interim storage facility to a geologic repository (**Table 6**).

In the analysis, no considerations were made about the type of transport systems used. A study by the U.S. National Research Council indicated that both routes by trucks or trains are two effective transport options implying different trade-offs in relation to management, safety and costs (National Research Council, 2006a). We consider the same average characteristics of transportation systems for all the transportation routes considered in the analysis (**Table 6**).

3.4. Generation of scenarios

In 2018, the Surfrider Foundation identified five long-term management options at SONGS, which they ranked by order of their decreasing preference (Nelsen, 2018): (1) a federally-approved permanent storage (disposal), (2) a consent-based (federal) interim storage, (3) the dry cask storage on “the Mesa” at the Marine Corps Base Camp Pendleton, (4) the extended dry cask storage on site, and (5) leaving the waste in the cooling pools. Of these five options, two are already outdated. First, the storage in pools can no longer be considered as a long-term option as the transfer operations of all fuel assemblies to dry casks stored onsite were completed in August 2020 (SCE, 2020a). Second, the dry cask storage on the Mesa complex appears not possible given the Marine Corps’ intention to claim back the land for other uses (**Table 2**).

Feasible long-term storage options at SONGS were explored as part of the research seminar with students (**Table 1**). In order to compare options, we considered a time horizon

of 200 years after 2020 which allows their comparison up to the point of disposal at a geologic repository or interim storage at an interim storage facility. Considering the management processes presented in Section 3.3, four generic long-term management options can be identified: (1) the fuel is left onsite at SONGS until a permanent solution emerges in the future (“do nothing”)²; (2) the fuel is transported to an offsite interim storage facility and stored there until a permanent solution emerges (interim storage); (3) the fuel is transported directly to a geologic repository and permanently stored there (direct disposal); and (4) the fuel is stored first at an offsite interim storage facility and then disposed of at a geologic repository (indirect disposal).

Yet, the technological and political contexts may change fundamentally over such multi-decade time horizon. Therefore, the scenarios used in the analysis must be built around these main sources of uncertainty, so each scenario remains (as much as possible) valid over a time horizon of 200 years. Then, uncertainties internal to each scenario will be considered in the sensitivity/uncertainty analysis (Section 4.1). For the long-term management of spent fuel at SONGS, scenarios can be distinguished according to onsite storage, interim storage and geological disposal. As shown in the Fig. 5, we distinguished whether new facilities for the interim storage and/or geological disposal will be in California or in another state. From these combinations, we identified 8 possible scenarios of long-term spent fuel management at SONGS (Fig. 6). Table 7 provides a detailed description of each scenario.

² Leaving spent fuel onsite for an extended period, when the only permanent solution is its disposal in a geologic repository is still a decision (“do nothing”) which will require some maintenance, such as the monitoring and replacement of dry casks and canisters as needed.

Each one of the processes of onsite storage, interim storage and geological disposal may vary broadly depending on a series of variables that require the examination of additional scenarios. **Table 8** presents a list of parameters required for the characterization of each process. The duration (mean/minimum/maximum) for each scenario is specified in **Table 9**.

3.5. Selection of evaluation criteria

The scenarios are evaluated against multiple criteria organized into four dimensions of analysis: (1) management, (2) occupational safety, (3) public safety and (4) economic viability. These dimensions can be grouped in pairs, so they represent either the technical view from the perspective of management operations (Management and Occupational Safety dimensions) or the societal view from the public perspective at the level of California (Public Safety and Economic Viability dimensions). Based on these groups, we will proceed to three multi-criteria evaluations (Section 4.1): (1) a multi-criteria evaluation from the technical view; (2) a multi-criteria evaluation from the societal view; and (3) a multi-criteria evaluation considering all dimensions combined.

For each one of the dimensions of analysis, a set of criteria was compiled. Criteria were selected so that they maximize exhaustivity and minimize redundancy in the description of each dimension. In total, 22 criteria were selected—11 for the dimensions considered in the technical view and 11 for those of the societal view. In the analysis, no weights were attributed to the criteria. In the *no criterion weighting* assumption, having the same number of criteria guarantees that the two technical and societal views will have the same weight in the full multi-criteria evaluation. However, as recalled by Munda, having the same number of criteria for different dimensions “is quite unnatural and artificial and

even dangerous. Analysts could be tempted to choose the same number of criteria for each dimension even if these criteria were completely redundant” ((Munda, 2008), p.81; emphasis added). **Table 10** and **Table 11** show that the criteria selected are complementary, but not redundant. Yet, as shown, some criteria may be correlated so that they evolve together either in same or opposite direction. In the sensitivity/uncertainty (Section 4.1), direct or inverse linear correlations between these criteria are considered for a more realistic definition of random samples in the Monte Carlo simulations. We now provide details about each one of the selected criteria for every dimension of analysis.

3.5.1. Management

Canisters hosting the fuel assemblies have a lifetime estimated to 50 years or even up to 100 years (Victor, 2014). Some fuel assemblies will thus need to be repackaged in new canisters during the extended onsite storage. The replacement rates of canisters were estimated using the “three-sigma rule” of a normal distribution (**Table 12**). Storage casks hosting the canisters in the two dry storage areas at SONGS have unspecified lifetimes. Considering that casks are subject to lower thermal and radiation exposures, we considered that one cask will be replaced for every 10 canisters replaced. The number of canisters and casks replaced during onsite storage (criteria *1.1*, *1.2*) and interim storage (*1.5*, *1.6*) were then estimated considering the duration of storage as indicated in **Table 9**.

The repackaging of canisters before transport (*1.3*) will be required in the situation when the Holtec HI-STAR 190 transportation cask hosting the 73 HOLTEC MPC-37 canisters will not be certified by the U.S. NRC (**Table B.3** in Error! Reference source not found.). In this situation, we assumed that the 37 fuel assemblies of each MPC will be repackaged by groups of 24 fuel assemblies into approx. 113 smaller DPCs. The base

scenario considers that the HI-STAR 190 cask will be certified for transportation and disposal, hence no canister repackaging will be required for the 73 MPCs already loaded at SONGS.

The loading/unloading to/from transportation casks concerns all canisters (*1.4*). One loading/unloading cycle is required for each canister and for each transportation campaign to an interim storage facility and/or a geologic repository. In the case of indirect disposal (scenarios 6-8), we assumed the geologic repository at the same location of the interim storage facility (one transportation campaign), except for scenario 7 which considers an in-state interim storage followed by an out-of-state geological disposal (two transportation campaigns).

3.5.2. Occupational safety

When constructing indicators, one must be aware of their meaning. For instance, different types of safety indicators can have different role and utility (Schwenk-Ferrero and Andrianov, 2017), but all entail tradeoffs. For instance, *risk* is a direct indicator of impact on humans and enables the direct comparison with other hazards, but it poses problems in communicating impact and in estimating probability (Schwenk-Ferrero and Andrianov, 2017). For its part, *dose*, which is also a direct indicator of impacts on humans, is well established and understood, but it does not take likelihood of exposure into account. In this analysis, we used dose indicators rather than risk indicators to measure occupational and public safety (Section **3.5.3**). We focused on the dose received by workers and the public from normal operations during storage, transport and disposal; that are radiation exposures certain to occur (probability of 1). This avoids the issue of having to estimate

probably functions of events (accidents) that may generate conflict among different stakeholders over their potential occurrence.

The total cumulative individual worker dose of normal operations during *on-site storage* (1.7) includes (1) operation, maintenance and surveillance, (2) re-packaging canisters, and (3) loading/unloading casks. The cumulative individual worker dose estimates for operation, maintenance and surveillance were estimated considering reported average values of 15 mSv/year during maintenance of dry storage systems (per site, for operations and maintenance) and at current radioactivity levels (Weck, 2013). We assumed a $\pm 20\%$ variation for the minimum/maximum values. The cumulative individual worker dose during maintenance operations is proportional to the duration of onsite storage (2.1). The dose estimates were also adjusted to account for the reduction of the radioactivity due to the aging of the spent fuel over the period of onsite storage. Second, the cumulative individual worker dose from re-packaging canisters was estimated considering the average of reported values for wet re-packaging (2.5 mSv/canister average for NUHOMS canisters) and dry re-packaging (2.2 to 3.93 mSv/canister) of dry casks and at current radioactivity levels (Weck, 2013). We assumed a $\pm 20\%$ variation for the minimum/maximum values for wet re-packaging and the average of the reported minimum/maximum values for dry re-packaging. The cumulative individual worker dose from re-packaging canisters is proportional to the number of canisters replaced due to aging/failure (1.1) and repackaged from MPCs to DPCs before transportation (1.2). Similar to maintenance, the dose estimates from re-packaging were adjusted to account for the reduction of the radioactivity due to the aging of the spent fuel over the period of onsite storage. Finally, the cumulative individual worker dose from loading/unloading of casks was estimated considering reported maximum worker dose for out-loading a DPC for transportation (0.40 mSv/cask) (Weck, 2013). We

assumed a minimum value of 0.20 mSv/cask and a mean value of 0.30 mSv/cask. These dose estimates were adjusted to account for the reduction of the radioactivity due to the aging of the spent fuel over the period of onsite storage. We considered one loading/unloading cycle (two doses) for each canister being replaced/repackaged during onsite storage (*1.1* and *1.2*), as well as for each cask being replaced due to aging/failure (*1.3*).

The total cumulative individual worker dose of normal operations during *interim storage* (*1.8*), like the individual worker dose during onsite storage, includes (1) operation, maintenance and surveillance, (2) re-packaging canisters, and (3) loading/unloading casks. In that case, however, there is no contribution from the re-packaging of canisters before transport as this process is performed onsite at SONGS. Worker doses are thus due to exposure during replacement of canisters and casks due to aging/failure and associated cycles of loading/unloading casks. As for *1.7*, dose estimates were adjusted to account for the reduction of the radioactivity due to the aging of the spent fuel over the period of interim storage.

The total cumulative individual worker dose from loading/unloading casks for *transport* (*1.9*) corresponds to the radiation exposure during the transfer of canisters from dry storage systems to transportation casks. Transport concerns only those scenarios with interim storage and/or geologic disposal (Section 3.4). The worker dose from loading/unloading of casks was estimated as for *1.7* and *1.8* and adjusted for the age of the spent fuel when transport will occur. The cumulative individual worker dose from loading/unloading casks for transport depends on the total number of canisters at SONGS, which is either 123 as currently planned or 163 in the case the 73 MPCs of the HI-STORM UMAX storage module will need to be re-packaged into approx. 113 smaller DPCs

(Section 3.5.1). We considered one loading/unloading cycle (two doses) for each transportation route from one site to another. Consequently, indirect disposal after interim storage will account for two transportation routes.

The collective dose to workers during transport (1.10) was calculated using estimates from U.S. DOE's 2002 Yucca Mountain repository Environmental Impact Statement (EIS) for routine transport (*i.e.*, with a probability of occurrence of 1) as reported by the U.S. National Research Council (National Research Council, 2006a). The 2002 EIS transport scenario considered a total Yucca Mountain repository capacity of 70,000 MTHM with casks being transported over an average distance of 1,600 miles. The 2002 EIS transport scenario considered a worker collective dose received over 24 years (starting in 2010) assuming specified crew sizes for loading, transport, and inspections (total numbers of workers not specified). The worker collective dose from the 2002 EIS was estimated to be 29,000 person-rem for a mostly-truck scenario and 7,900–8,800 person-rem for a mostly-rail scenario. For the calculations, given the transportation systems are not discussed (Section 3.3.4), we used the mostly-truck scenario as the maximum value (29,000 person-rem), the mostly-train scenario as the minimum value (7,900 person-rem), and the average of minimum and maximum values are the mean value (18,450 person-rem). The dose estimates were then adjusted to account for the inventory at SONGS (1,609 MTU), the transport distance specific to each scenario, and the reduction of the radioactivity due to the aging of the spent fuel until transportation occurs.

Finally, the total individual worker dose during *geologic disposal* (1.11) was calculated using estimates from U.S. DOE's 2008 Yucca Mountain repository Environmental Impact Statement (EIS) for normal operations at the surface facilities (US DOE, 2008, Table D-8). The 2008 EIS geologic disposal scenario considered a maximum

individual annual dose to workers during surface operations of 15 mrem/year; for an annual waste acceptance rate at the geologic repository of 3,600 MTHM/yr and for pre-closure surface operations occurring from 2017 to 2067. We assumed a $\pm 20\%$ variation for the minimum/maximum values for the dose estimates. The dose estimates were also adjusted to account for the size of the inventory at SONGS (1,609 MTU).

3.5.3. *Public safety*

The first three criteria correspond to durations which are indirect measures of safety from the local, state and national perspectives. Criterion **2.1** measures the duration of on-site storage, which corresponds to the delay before removing the spent fuel from SONGS after 2020 (**Table 9**). Criterion **2.2** measures the duration of storage in California until the in-state disposal or transport out-of-state, which corresponds to the delay before transporting the spent fuel outside California after 2020 (only for scenarios considering an out-of-state interim storage facility and/or geologic repository). Criteria **2.1** and **2.2** are maximized to 200 years if, by the end of the scenario, the spent fuel is still stored at a surface storage facility at SONGS or elsewhere in California, respectively. The favorable direction of change of criteria **2.1** and **2.2** is minimization. That is, a proposed long-term management option will be considered as safer if it minimizes the duration of storage at SONGS, from a local perspective, and the duration of surface storage in California, from a state perspective. Finally, criterion **2.3** corresponds to the number of years before the end of the scenario (*i.e.*, before 2220) during which the spent fuel will be permanently isolated in a geologic repository. Criterion **2.3** is minimized to a value of 0 for scenarios not considering geologic disposal. The favorable direction of change for this criterion is maximization. That

is, a proposed long-term management option will be considered as safer if it maximizes the duration of permanent isolation in a geologic repository, from the local, state and national perspectives.

The next two criteria correspond to risk exposure potentials that are also indirect measures of safety from the local and state perspectives. Instead of probabilistic risk indicators that may pose communication problems (IAEA, 1994) due to a lack of meaning from the perspective of potentially affected populations (Diaz-Maurin, 2018a), we constructed two indicators of risk potential of public exposure to radiation that correspond to the amount of (decreasing) radioactivity times the duration during which this inventory is stored at the surface, hence not permanently isolated in a geologic repository. Criterion **2.4** measures the cumulative public radiation exposure risk during on-site storage at SONGS (in Ci-person-year); whereas, criterion **2.5** measures the cumulative public radiation exposure risk during interim storage in California (in Ci-person-year). As with the occupational safety indicators, the radioactivity of the inventory was reduced to account for the aging of the spent fuel over the periods of on-site and/or interim storage. For criterion **2.4**, we considered the population living within a 10-miles radius of SONGS as the potentially exposed population. We also considered a mean/minimum/maximum 10-year population growth in the San Diego County, California of 2%/0%/4%, respectively. For criterion **2.5**, we considered an interim storage facility in California to be located in a 10 times less populated area than at SONGS, hence $1/10^{\text{th}}$ of the potentially exposed population of criterion **2.4**.

Finally, the public collective dose during transport (**2.6**), like for the collective dose to workers (**1.10**), was calculated using estimates from U.S. DOE's 2002 Yucca Mountain repository EIS (National Research Council, 2006a). The 2002 EIS transport scenario

considered a public collective dose distributed across 10.4 million people for a mostly-truck scenario and 16.4 million people for a mostly-rail scenario over 24 years (starting in 2010). The public collective dose from the 2002 EIS was estimated to be 5,000 person-rem for a mostly-truck scenario and 1,200–1,600 person-rem for a mostly-rail scenario. For the calculations, we used the mostly-truck scenario as the maximum value (5,000 person-rem), the mostly-train scenario as the minimum value (1,200 person-rem), and the average of minimum and maximum values as the mean value (3,100 person-rem). However, given the exact transportation routes are not known (Section 3.3.4), the potentially exposed population is also unknown. Therefore, we converted the collective dose estimates into minimum/mean/maximum annual individual doses of 3.0×10^{-3} , 9.6×10^{-3} , and 2.0×10^{-2} mrem/year, respectively. We also considered a minimum/mean/maximum duration of each transportation campaign of the SONGS inventory (from/to SONGS/interim storage facility and/or interim storage facility/geologic repository) of 1/3/5 years.

3.5.4. *Economic viability*

The total operating cost of on-site storage at SONGS (2.7) was estimated considering the annual operating cost of an interim storage facility (10 M\$/year; US GAO 2009 in (Alvarez, 2013)) and the cost of new dry casks (1 M\$/cask; Supko 2012 in (Alvarez, 2013)). The total cost of interim storage and/or disposal in California (2.8) intends to include all the costs of managing the SONGS spent fuel within California, in addition to the on-site storage costs. For the scenarios considering in-state interim storage costs, we considered the same costs as for on-site storage with the addition of an average

capital cost of a new interim storage facility (2.2 M\$/cask; after (Weisenmiller et al., 2006)).

The total cost of transport (2.9) was calculated using reported cost estimates for different spent transport scenarios in the U.S. (Kalinina and Busch, 2014). These estimates were made for a large-scale transportation campaign of 137,000 MTU. In the analysis, we considered also a regional (1/4th of the large-scale campaign, thus 34,250 MTU) and a SONGS-specific (1,609 MTU) transportation campaigns. In the analysis, we assume that the unitary cost of transport (in \$/cask-mile) is lower for a larger transportation campaign due to the economy of scale. Consequently, a regional and SONGS- specific transportation campaigns will have higher unitary costs than a large-scale campaign. We calculated a scale factor as the log of the difference of campaign inventory versus large-scale for the regional (factor of 1.6) and SONGS-specific (factor of 2.9) transportation campaigns. **Table 13** presents the unitary costs for the different transport scenarios and different transportation campaign sizes. The total transportation costs were then calculated using the transportation distances (Section 3.3.4) and number of casks to be transported (Section 3.5.1).

The economic impact compensation during storage in California (2.10) corresponds to the STRANDED Act introduced by Sen. Duckworth (D-IL) in the U.S. Senate in 2019 (*Sensible, Timely Relief for America's Nuclear Districts' Economic Development Act of 2019 or the STRANDED Act of 2019*, 2019) and by Rep. Schneider (D-IL-10) in the U.S. House of Representatives in January 2020 (*Sensible, Timely Relief for America's Nuclear Districts' Economic Development Act of 2020 or the STRANDED Act of 2020*, 2020). The STRANDED Act seeks economic compensation for communities living near orphaned sites with stranded spent fuel across the U.S. in the application of the Nuclear Waste Policy Act

of 1982 that: (1) outlined the U.S. DOE to make annual impact assistance payments to States or local government to mitigate the social and economic impacts for the construction and operation of an interim nuclear waste storage capacity; and (2) established the rate for impact assistance payments at \$15 per kilogram of spent nuclear fuel. Given that there is no federal interim storage site or geologic repository, orphaned sites with stranded fuel have become *de facto* interim storage sites for which the bill seeks economic compensation for the local communities. The bill, if passed as law in Congress, would correspond to an economic impact compensation rate of 24 M\$/year for the SONGS inventory. In the analysis, we considered either no compensation (minimum value), a compensation covering the period of onsite storage at SONGS (mean value), or a compensation covering the overall period of surface storage in California until it is either disposed of in California or shipped to another state (maximum value). The favorable direction of change of criterion **2.10** is maximization from the perspective of the state of California and of local communities.

Finally, we constructed a financial risk indicator (**2.11**) that accounts for the financial impact of postponing in the future investment costs required for disposal. The financial risk (in 2016-\$B-year) was calculated considering the estimated life-cycle repository cost per unit of spent fuel for different repository types as reported in (Hardin, 2016). The life-cycle repository costs were adjusted linearly to the repository capacity required for the SONGS inventory. It has been reported that the Yucca Mountain repository concept in unsaturated rock implies a particularly high financial risk due to the required installation of a titanium drip shield before the repository closure—an investment of approx. \$750 million dollars per year over 10 years (Hardin, 2016). For scenarios that include disposal, we considered no financial risk from postponed investment costs as the

minimum value, a financial risk corresponding to the costs of repository closure for a Yucca Mountain repository concept as the maximum value, and half of the costs of repository closure as the mean value. For the financial risk due to repository closure, we considered a required investment period of 10 years postponed by 100 years after the end of the scenario for the maximum value and an investment period of 5 years postponed by 50 years for the mean value.

4. Results

4.1. Multi-criteria evaluations

Using data presented in Section 3.5, we generate the multi-criteria impact matrix of the technical view (Tables C.1 and C.2 in Error! Reference source not found.) and the societal view (Tables C.3 and C.4 in Error! Reference source not found.). Feeding these impact matrices as input to the mathematical procedure from Error! Reference source not found., we ran three multi-criteria evaluations:

1. Multi-criteria evaluation with the criteria of the technical dimensions;
2. Multi-criteria evaluation with the criteria of the societal dimensions; and
3. Multi-criteria evaluation combining the criteria of the technical and societal dimensions.

Each multi-criteria impact matrix is composed of 11 indicators evaluated for 8 scenarios. Each criterion is given mean, minimum, and maximum values so that each matrix has a total of 264 entries. As discussed in Section 3.4, the time horizon of the analysis is 200 years (after 2020), no matter if the spent fuel has been disposed of or is still stored at the surface in California or elsewhere. The aggregation convention was then used

to rank the scenarios (Section A.1 in Error! Reference source not found.). **Table 14** presents the ranking of scenarios for the three multi-criteria evaluations performed.

The results of the multi-criteria evaluations show that, from a technical perspective, the “do nothing” (scenario #1) option has nearly the same performance as the direct disposal options (#4 and #5). Although qualitatively very different, the results show that the various criteria compensate each other in the analysis. That is, over a time horizon of 200 years, the early disposal of the waste in a geologic repository without the need for interim storage does not offset the occupational dose from maintenance operations during extended onsite storage at SONGS. This is because spent fuel transportation to a geologic repository will necessarily imply occupational dose during loading/unloading casks and transport operations. Moreover, even in a direct disposal strategy, a geologic repository is likely not to be available before at least 2050, thus repackaging operations of canisters during onsite storage may still be required thus increasing radiation exposure to workers. For the same reasons, other scenarios considered in the analysis are found to be even less well performing from a technical viewpoint, with off-site interim storage (without disposal) being the least performing option. Note that the analysis considers only normal operations, where handling operations generate public and occupational dose from radiation exposure (probability of 1) but no accident occurs (zero probability). The possibility of an accident cannot be dismissed during the many fuel handling operations that will be required over a period of 200 years—as has occurred at SONGS already (Section 3). The safety implications of low-probability events during storage at interim storage facilities, as well as during transport and disposal operations are discussed elsewhere (Almmani et al., 2017; Alvarez et al., 2003; Diaz-Maurin and Ewing, 2019; Ewing et al., 1999; National Research Council, 2006a, 2006b; US NRC, 2007). The results show that, from a technical

perspective, leaving the spent fuel at SONGS is as safe as direct disposal in California or in another state. This highlights a lack of technical incentive for the stranded spent fuel to ever be moved from SONGS to another site.

The ranking of options from the societal view demonstrates significant differences and similarities as compared to the technical view. Similar to the technical view, in-state interim storage without disposal (#2) is the least performing option from the perspective of California. However, the “do nothing” (#1) option shows also as a low performance option in the societal view, almost the opposite of the technical view. Even the in-state interim storage followed by out-of-state disposal (#6) does not appear to be a highly performing option. These options (#1, #2, #6) would imply higher public doses and economic costs due to the extended surface storage period, either at SONGS or at another site in California. Therefore, from a societal perspective, there seems to be no incentive *per se* to remove the spent fuel from SONGS, unless the strategy includes either disposal or out-of-state interim storage. Yet, the out-of-state interim storage (#3) does not show a much better performance either. Still from a societal perspective, out-of-state direct disposal (#5) shows the highest performance, followed by interim storage and disposal (#8) and in-state direct disposal (#4). This is because these three scenarios (#4, #5, #8) offer the shortest, and most certain, strategies to either move the fuel away from SONGS or to their permanent isolation in a geologic repository and, therefore, they minimize the risks and costs for the local community and the state of California.

When combining the 22 criteria of the technical and societal views, the “do nothing” (#1) and the in-state interim storage (#2) scenarios are also among the three least performing options as in the societal view. On the other end of the ranking, direct disposal, either in California (#4) or elsewhere (#5), show the highest performance. This is because,

even though a geologic repository will be delayed, geological disposal still is the only permanent solution that allows for the isolation of spent fuel and, therefore, eliminates the risks and costs of storing spent fuel at the surface. Therefore, this analysis shows that direct disposal represents an optimal solution from the technical and societal perspectives over the long-term spent fuel management issues at SONGS. The sensitivity/uncertainty analysis will test the robustness of this result.

We ran a Monte Carlo simulation varying each criterion of the multi-criteria impact matrices within the range of possible values (Section A.2 in Error! Reference source not found.). Fig. C.1 in Error! Reference source not found. shows that 500 random samples are enough to obtain convergence of the ranking for each multi-criteria evaluation. It shall be noted that the random variable generation in the Monte Carlo simulation uses the R function `set.seed` which can produce the same sequence. Fig. 7 presents the results of the sensitivity/uncertainty analysis for the three multi-criteria evaluations.

The sensitivity/uncertainty analysis first shows that, when considering the uncertainty on the criteria values, most rankings overlap each other so that no alternative significantly dominates. That is, the likely ranges of variation (the IQR) of the ranking of scenarios (illustrated by the boxes in Fig. 7) are significantly overlapping, thus indicating that they are statistically equally performing. Second, we observe that any scenario can take the extreme ranking values (1 and 8) in all three analyses with a statistically significant probability of 1.5 IQR. Yet, this statistical similarity between scenarios inherently comes from the type of *discrete* decision problem evaluated (Diaz-Maurin et al., 2020; Munda, 2008) where ranking values can be given only natural numbers (1, 2, ..., 8), thus reducing the statistical accuracy of the analysis.

The Monte Carlo simulation also shows that criteria uncertainty significantly affects the rankings, as illustrated by the number of scenarios for which the mean rank from the standard analysis falls outside of the IQR. The societal and combined views are more affected by such rank shifting (2 and 4 scenarios, respectively) than the technical view (one scenario). That is, the ranking of the technical view is less affected by the uncertainty than the societal and combined views. Ideally, an analysis directly involving stakeholders would help reducing the uncertainty on the criteria measurements. Yet, ultimately, such a reduction would be limited because the technical and societal views are subject to qualitatively different forms of uncertainty. Repository scientists and engineers typically make the distinction between *epistemic uncertainty*, which they consider reducible as arising from a lack of knowledge about the system, from *aleatory uncertainty*, which they consider irreducible as arising when the system under study can behave in many different ways (Helton and Burmaster, 1996). Yet, when dealing with complex systems, genuine ignorance exists as some of the outcomes of the system are unknown (Diaz-Maurin, 2014). In such a situation, irreducible uncertainty is considered as a systemic property of emergent complexity in the system (Funtowicz and Ravetz, 1994). For this reason, the overall uncertainty of engineered systems, such as cask storage systems, is more reducible than the uncertainty affecting complex systems, such as human institutions and geologic repositories. In the analysis, the technical view provides a more deterministic representation of the decision problem by considering the dimensions of management and occupational safety, whereas the societal view considers the public safety and economic viability dimensions that involve more interactions with human institutions. Therefore, we can expect that even in a more realistic analysis, the societal view will be subject to relatively more uncertainty than the technical view. In Section A.3 of Error! Reference source not

found., we provide an extension of the framework that addresses *fuzzy uncertainty* that refers to the ambiguity in the information about the system and thus generates fuzziness in the preferences of the stakeholders.

In the combined view, the interim storage (#2, #3) and direct disposal (#4, #5) options are subject to ranking shifts in the opposite directions. That is, the interim storage options are positively affected by uncertainty (IQR and median value shifting toward the left in **Fig. 7**), whereas direct disposal options are negatively affected by uncertainty (IQR and median value shifting toward the right). This is mainly due to the higher uncertainty about the duration of onsite storage at SONGS before direct disposal can occur (**Table 9**). In the analysis, we considered that direct disposal, even delayed in time, may occur up to 100 years from now. However, we considered that interim storage, if it happens, will occur sooner and not more than 40 years from now. This is justified by (1) the stalemate which has affected the U.S. disposal program over the past decades (Reset Steering Committee, 2018), (2) the uncertainty concerning the licensing of the Yucca Mountain repository (Section 3.3.3), and (3) the current progress in the licensing application reviews of two commercial interim storage facilities in New Mexico and Texas (Section 3.3.2). The uncertainty analysis shows that, overall, out-of-state interim storage, with or without disposal (#8 and #3, respectively), are the two most statistically performing options from the technical and societal perspectives combined.

4.2. Social impact analysis

We now perform an analysis of the social impact of the alternatives on the interests of the socio-technical actors. For this, we first constructed a social impact matrix based on the information collected with the students during the workshops. The impacts of each the

proposed scenarios are assessed using seven linguistic variables: “Very bad”, “Bad”, “More or less bad”, “Moderate”, “More or less good”, “Good”, and “Very good”. We thus obtain a social impact matrix of the impact of the 8 scenarios on the 20 socio-technical actors (**Table 15**).

Table 15 shows that two scenarios—out-of-state interim storage (scenario 3) and out-of-state interim storage and disposal (scenario 8)—appear to positively impact every socio-technical actor. On the contrary, the “do nothing” option (scenario 1) appears to be the most negatively impacting option for all socio-technical actors, except Holtec International. Indeed, it can be considered that Holtec would benefit from supplying new canisters and new casks as needed during the extended period of on-site storage at SONGS. Similarly, the out-of-state direct disposal (scenario 5) appears to be positively impacting all actors except, again, Holtec International as this scenario minimizes the dry storage period at SONGS or at an interim storage facility.

We then compare the linguistic variables by computing their semantic distances using fuzzy sets. Fuzzy sets are necessary in order to introduce some level of uncertainty within linguistic variables. *Fuzzy uncertainty* refers to the degree of ambiguity in the information about the system that generates fuzziness in the evaluation of the impact of alternatives on the socio-technical actors’ interests. A fuzzy clustering procedure can then be applied that groups socio-technical actors by similarity degrees (Section A.3 in Error! Reference source not found.). **Fig. 8** presents the results of the fuzzy clustering analysis for the SONGS case study. The similarity degree and its associated dendrogram help to characterize the level of convergence and conflict that exists between groups of stakeholders, thus forming potential coalitions.

We then ranked the alternatives for each one of the four coalitions from **Fig. 8** using the same aggregation convention as for the multi-criteria evaluation as described in Section **A.1** of Error! Reference source not found.. The ranking also uses the same *equal weighting* assumption as in the multi-criteria evaluations. Even if weights would be considered to account for different levels of stakes, these would not have impact on the ranking by coalitions since actors are already grouped by similarity of assessment of social impacts. We also performed a test of using weights for actors based on the power/interest matrix (**Fig. 2**), but these did not generate any substitutions in the ranking of alternatives. **Table 16** presents the rankings of scenarios at SONGS based on the social impacts for all actors combined and by coalitions. Analyzing the rankings obtained, there seem to have a clear potential consensus, from the perspective of social impacts, over out-of-state interim storage with or without disposal (scenarios 3 and 8), which are ranked first across all coalitions (although they are tied with other scenarios in some cases). Our analysis of the social impacts at SONGS seems therefore to reveal the existence of socially optimal solutions—something that is not often the case in real-world situations. However, recall that the analysis would need to be iterated with the participation of stakeholders at SONGS to confirm the results. Yet, out-of-state interim storage options do not rank high from the multi-criteria evaluations, especially when considering the technical dimensions (**Table 14**). The two types of analyses therefore imply the existence of conflicts between the technical evaluation and the social impact analysis. In the next section, we use a procedure that supports the search for compromise solutions that reduce these conflicts.

4.3. Searching for compromise solutions

The ranking of options based on the social impacts revealed the conflicts among the options, despite some being optimal in their technical performance or from a social impact perspective (but not both). A decision toward an option showing a high degree of conflict would result in a vulnerable and “not a workable” option—as happened already when the Obama administration attempted to withdraw the license application for the Yucca Mountain repository project in the U.S. (US DOE, 2010). The search for *compromise solutions* that reveals a lower degree of conflict is therefore an essential step of the STMCE process.

To address this issue, we use a proportional veto function giving a coalition the ability to veto any subset of alternatives proportionally to the fraction of socio-technical actors it contains (Section A.4 in Error! Reference source not found.). When applying the proportional veto function to the SONGS case study, we obtain that coalition 1 can veto the “do nothing” (1) option, whereas coalition 2 can veto the “do nothing” (1), in-state direct disposal (4), and out-of-state direct disposal (5) options. However, coalitions 3 and 4 cannot veto options given they contain only 4 actors and 1 actor, respectively.

Fig. 9 shows the mean ranking of scenarios for every coalition and for the whole group of socio-technical actors according to the social impact analysis, in comparison with the multi-criteria evaluation with the social and technical dimensions combined. In the figure the options that can be vetoed are not shown (*i.e.*, the “do nothing” and the two direct disposal options) so that we focus on the options that can be compromise solutions. We thus obtain the following non-unique ranking of compromise solutions at the level of the whole set of actors:

- 1) Out-of-state interim storage with or without disposal (options 3 and 8);

- 2) In-state interim storage and out-of-state disposal (option 7);
- 3) In-state interim storage (options 2);
- 4) In-state interim storage and disposal (option 6).

In **Fig. 9**, we see that out-of-state interim storage and disposal (option 3) clearly stands out as the “best” option from the perspectives of both the social impact on every coalitions and the multi-criteria evaluation. The out-of-state interim storage without disposal (option 8) has a similar impact on actors, but it is less well performing according to the multi-criteria evaluation. The other options are affected by large ranking variations that illustrate the existence of conflicts among the coalitions (although less than the vetoed options) as well as between the social impacts and the socio-technical performance. These options correspond to the possible combinations with in-state interim storage. Among those options, in-state interim storage with out-of-state disposal (option 7) appears to be the most stable. Finally, in-state interim option without disposal (option 2) is nearly the least performing option according to the combined multi-criteria evaluation, whereas in-state interim with in-state disposal (option 6) is the most socially conflicting option.

5. Discussion and conclusions

In the past, various efforts were made by the U.S. Department of Energy (DOE) to improve the process of siting nuclear waste management facilities, including the State Planning Council on Radioactive Waste Management in the early 1980s, the Office of the Nuclear Waste Negotiator in the early 1990s, the work of the two Secretaries Watkins and O’Leary throughout the 1990s, and the recent consent-based siting approach of the 2010s (Diaz-Maurin, 2018b). Yet, these efforts were hampered by a systemic lack of trust

affecting DOE, the federal agency responsible for the management of the nation's inventory of commercial spent nuclear fuel. This lack of trust has contributed to the stalemate of the U.S. nuclear waste management and disposal program for over half a century (Blue Ribbon Commission, 2012; Davis et al., 2012; Reset Steering Committee, 2018).

This paper provides an application of the socio-technical multi-criteria evaluation (STMCE) method for nuclear waste management (Diaz-Maurin et al., 2020). For this, we use the case of the San Onofre Nuclear Generating Station (SONGS) in California as an illustrative example. The application of STMCE to the SONGS case study seeks to support long-term spent fuel management strategy definition, comparison and choice at SONGS. Specifically, the analysis shows that: (1) It is possible to develop a consistent decision-support framework that brings together social dimensions and technical dimensions of analysis—despite some serious challenges (Diaz-Maurin and Ewing, 2018); (2) It is also possible for such framework to bring together quantitative measurements of performance indicators and qualitative perceptions about the social impacts of different options—as well as their associated types of uncertainty; and (3) Our framework can help reduce social conflict by *focusing on the search for compromise solutions* rather than optimal solutions—as is the case of most multi-criteria decision-analysis frameworks.

As explained, the analysis, as performed and presented in this paper, is only the first iteration of a STMCE process that requires the implication of socio-technical actors. In fact, to be successful and accepted, decisions in nuclear waste management must go through a participatory process (Bergmans et al., 2015; Brunnengräber and Di Nucci, 2019)—although participation is *not a sufficient condition* for a successful social multi-criteria evaluation process (Munda, 2019). STMCE offers an analytical tool that supports—but

does not replace—discussion, deliberation and decision. Therefore, the application of the STMCE framework and method presented in this paper cannot pretend to make policy recommendations at SONGS. Yet, despite these limitations in scope, the SONGS case study demonstrates how STMCE can provides new insights on how coalitions of socio-technical actors can form and how compromise solutions can be identified to inform the policy decisions. For this reason, we believe STMCE can be an important step forward in nuclear waste management policy in the U.S.

The implementation of the STMCE approach could have profound implications for commercial spent fuel management in the United States by shifting the focus from the national level to the level of localities, tribes, states and groups of states. At the local level, the STMCE approach can help to compare the socio-technical implications of different management options focusing on one specific site. Communities living close to commercial nuclear reactor sites in the U.S. face the transition from nuclear energy to nuclear waste. They are among the socio-technical actors with the highest stakes, yet they have a relatively low level of direct power of decision. Decisions will have to be made about the long-term storage strategies in the U.S. From an ethical perspective, even the absence of a federal geologic repository in the foreseeable future constitutes a national choice. Yet, long-term *national* strategies are likely to continue to encounter many barriers as they are focused on getting the waste to a federal geologic repository. Therefore, the possibility of co-creating socio-technical compromise solutions for storage and disposal *from the bottom up* should be explored. In order to empower localities, tribes and states, platforms must be developed that allow to create their own scenarios and outcomes, supported by independent teams of researchers. By evaluating concrete options, localities will be in a better position to negotiate with the federal government and state agencies over long-term solutions of spent

fuel management that directly affect them. The STMCE method presented in this paper supports such an empowerment approach and provides an example of how to conduct a socio-technical multi-criteria evaluation of long-term storage options using SONGS in California as a relevant and timely example.

In addition, this approach can support states or groups of states to define and implement long-term management strategies by focusing on the formation of coalitions and the search for compromise solutions. In fact, such a regional strategy is not new to nuclear waste management. As early as 1985, the U.S. Congress passed the Low-level Radioactive Waste Policy Amendments Act, which made each state responsible for the disposal of their own low-level radioactive waste and allowed states to enter into “compacts” (*i.e.*, groups of states) to construct and operate regional disposal facilities for low-level radioactive waste (*Low-level Radioactive Waste Policy Amendments Act of 1985*, 1985). This paper provides an analytical framework that can support a regional strategy approach to the management of commercial spent fuel in the United States.

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Tables

Table 1. Summary of the activities conducted by the research team and Stanford students.

Topic	Activity	Dates
Perceptions, alternatives, and criteria	Institutional analysis	17/01/2019
	Stakeholder mapping	22/01/2019
	Generation of alternatives	29/01/2019
Multi-criteria evaluation	Selection of dimensions and evaluation criteria	05/02/2019
	Computing criterion scores and uncertainties	†
	Ranking of alternatives	†
Conflict analysis	Social impact of alternatives	04/2020 (remotely)
	Coalition formation	†
	Ranking of alternatives	†

Note: All activities were conducted during workshops with a group of 7 students and one researcher (FDM), except those indicated with † which were conducted by FDM. The workshops were organized as part of the graduate-level course “Managing Nuclear Waste: Technical, Political and Organizational Challenges” (GEOLSCI 266 / INTLPOL 266) offered during the Winter quarter of 2018-2019 at the Center for International Security and Cooperation (CISAC), Stanford University.

Table 2. Socio-technical actors, scale of action, stakes and position regarding long-term spent fuel storage at SONGS.

ID	Socio-technical actor	Scale	Stakes	Position	Ref.
1	Southern California Edison (SCE)	Local	Main owner (approx. 78%) of SONGS as well as the spent fuel until it will be transferred to another geologic repository or interim storage site. SCE is in charge of planning and implementing SONGS's decommissioning.	Positive on dry cask storage system but considers relocating spent fuel off-site a priority. Wants to complete the decommissioning of the plant and return the land to the U.S. Navy. In 2019, SCE assembled a team of experts in charge of finding options to move the spent fuel off-site.	(SCE, 2020b, 2019a)
2	San Diego Gas & Electric (SDG&E)	Local	Owens 20% of SONGS.	Positive on dry cask storage system.	(Garcia and Levin, 2017)
3	City of Riverside	Local	Owens approx. 2% of SONGS	Public opinion is unknown.	("What are Nuclear Electric Costs?," 2020)
4	San Diego County's District 5 Supervisor Jim Desmond (R)	Local	SONGS located in district 5 of the San Diego county.	District Supervisor is confident about SONGS decommissioning plan. Position about long-term storage at SONGS is unknown. In 2015, San Diego city attorney Mike Aguirre sued the California Coastal Commission for granting a permit to store the waste onsite. Public opinion about SONGS is unknown.	(St John, 2018c)
5	49th California's Congressional District Representative Mike Levin (D)	Local	SONGS is within the boundaries of the 49 th congressional District.	Position over long-term storage at SONGS is unknown. Congressional District Representative raised concerns over the release of partially treated sewage in March 2020 and over SCE's Pandemic Protocol in response to the COVID-19 pandemic. Public opinion is unknown.	(Levin, 2020)
6	San Luis Rey Band of Missions Indians (native populations)	Local	None. Need to be consulted about land uses since historically owned part of that land before colonization.	No public position.	(Gilio-Whitaker, 2011)
7	SCE's Community Engagement Panel (CEP)	Local	None. Facilitates dialogue and information exchange between co-owners and the communities.	CEP is neutral. Positions from CEP members vary.	(Victor, 2014)
8	Committee to Bridge the Gap	Local	None.	Not outright opposed to dry cask storage system is concerned about the need for mechanisms to isolate radioactivity from the environment in case of damage or	(Douglas, 2018)

ID	Socio-technical actor	Scale	Stakes	Position	Ref.
				leaks and the need for casks to be properly monitored and inspected.	
9	Sierra Club's Angeles Chapter	Local	None.	Supports the proposal to move waste from pools to dry cask storage but wants immediate removal of casks from the area.	(Sierra Club Angeles, 2015)
10	Surfrider Foundation's local chapter	Local	None.	Approves dry cask storage system but would like the spent fuel off the location as soon as possible. Opposed to permanent or long-term storage at SONGS.	(Surfrider Foundation, 2015)
11	Citizens Oversight (CO)	Local	None.	Opposed to storage at SONGS. Petitioned for redesigned cask system or alternative siting. Sued SCE and the CSCC in November 2015 over a coastal development permit CSCC issued to Edison to store spent nuclear onsite. Filed a motion in 2019 asking a judge to order Edison to halt the transfer of spent fuel from wet to dry storage at SONGS.	(Bruno, 2017; Citizens Oversight, 2018; McDonald, 2019b)
12	Public Watchdogs	Local	None.	Opposed to storage at SONGS. Sued SCE, SDG&E, Holtec International, and the U.S. NRC in 2019 over decommissioning plan at SONGS.	(Public Watchdogs, 2019; St John, 2018a)
13	California State Governor Gavin Newsom (D)	State	SONGS located within the Governor's constituency.	New Governor has not made public statement about long-term storage at SONGS. Governor temporarily halted deconstruction work, but maintained fuel transfer activities, under the "safer at home" directive in response to the COVID-19 pandemic.	(Governor of California, 2020)
14	California State Senator Dianne Feinstein (D)	State	SONGS located within the Senator's constituency.	Senator has not made public statement about long-term storage at SONGS. Senator stated that SCE's decision to shut down reactors at SONGS in 2012 was the safest option for Southern California.	(Feinstein, 2013)
15	California State Parks (CSP)	State	SONGS located within CSP's constituency.	No specific position on SONGS.	(California State Parks, 2020)
16	California State Lands Commission (CSLC)	State	SONGS located within CSLC's constituency.	Unclear on their position, but their documents capture the concerns of the general public. Mention concerned about the new basket shim not being the right size.	(California State Lands Commission,

ID	Socio-technical actor	Scale	Stakes	Position	Ref.
					2018)
17	California State Coastal Commission (CSCC)	State	SONGS located within CSCC's constituency.	Granted a permit to SCE to store the waste onsite.	(Nikolewski, 2019)
18	Holtec International	National	Supplier of the dry cask storage system (HI-STORM UMAX) used for units 2/3. No mandate on SONGS decommissioning plan. Proponent of a privately-owned interim storage facility in Southeastern New Mexico.	Positive about dry cask storage systems either onsite or at an interim storage facility.	(Holtec International, 2020c)
19	U.S. Department of Energy (DOE)	National	According to the NWPAs, will become the owner as soon as the fuel is moved from SONGS. Pays a court-ordered fee to utilities for storing the spent fuel.	Neutral about SONGS decommissioning plan. Supports the development of a geologic repository at Yucca Mountain in Nevada.	(Reset Steering Committee, 2018)
20	U.S. Department of the Navy, Marine Corps Base Camp Pendleton (DoN)	National	Landowner of the base hosting SONGS under easement to SCE.	Wants to claim back the land for other uses. Opposed to storage on base where the Mesa Complex, which is off the beach on opposite side of I-5 and at a higher level (Fig. 1b).	(St John, 2017)

Table 3. Main characteristics of spent fuel by dry cask types used at SONGS. Sources: (Alvarez, 2013; after Carter, 2018; Palmisano, 2018; Xu et al., 2005)

Dry cask storage type	Number of canisters in storage (2019, est.)	Total amount of spent fuel (MTU)	Number of fuel assemblies	Estimated total activity in 2020 (MCi)
Unit 1 - AREVA NUHOMS - 24PT1	17	146	395	40
Unit 2/3 - AREVA NUHOMS - 24PT4	33	455	1077	480
Units 2/3 - HOLTEC MPC-37	73	1007	2383	481
Total	123	1609	3855	1001

Table 4. Average characteristics and properties by dry cask types used at SONGS. Sources: (after Alvarez, 2013; Palmisano, 2018)

Dry cask storage type	Average number of fuel assemblies per canister	Average number of fuel rods per canister	Average spent fuel load per canister (MTU)	Average burn-up at discharge (MWd/kg)
Unit 1 - AREVA NUHOMS - 24PT1	24	4320	8.6	41.2
Unit 2/3 - AREVA NUHOMS - 24PT4	24	5664	13.8	50
Units 2/3 - HOLTEC MPC-37	37	8732	13.8	50

Table 5. Total radioactivity and decay heat power of dry casks at SONGS. Sources: (Alvarez, 2013; after Carter, 2018; Xu et al., 2005)

Spent fuel activity	Unit	Year 2020	Year 2040	Year 2060	Year 2080	Year 2120	Year 2160	Year 2220
Radioactivity	MCi	1039	504	301	228	88	44	20
Decay heat power	MW	3.6	1.9	1.4	1.2	0.75	0.63	0.44

Table 6. Transport distance between points shown in previous figure.

Itinerary	Location point		Distance (miles)	
	Start	End	Direct	By road
SONGS to STATE minimizing point (CA only)	1	2	142	216
SONGS to REGIONAL minimizing point, excl. WA (CA, OR, AZ)	1	3	118	208
SONGS to REGIONAL minimizing point (CA, WA, OR, AZ)	1	4	193	264
SONGS to Yucca Mountain repository site, NV	1	5	247	310
SONGS to HI-STORE interim storage facility in NM	1	6	803	969
SONGS to ORANO-WCS interim storage facility in TX	1	7	843	1011
HI-STORE interim storage facility in NM to Yucca Mountain repository site, NV	6	5	781	1000
ORANO-WCS interim storage facility in TX to Yucca Mountain repository site, NV	7	5	820	1002
STATE minimizing point to Yucca Mountain repository site, NV	2	5	226	420
REGIONAL minimizing point to Yucca Mountain repository site, NV	4	5	59	60

Note: Location points as shown in **Fig. 4**. Direct distance estimated considering a mean earth's radius of 6,371 km (3,959 miles). Distance by road estimated considering shortest itinerary using Google Maps, including highways.

Table 7. Description of the selected scenarios at SONGS.

ID	Scenario	Pathway	Assumption
1	Do nothing	Spent fuel storage at SONGS for 200 years (t0 = 2020) + repackaging every 50-100 years	This “do nothing” scenario assumes no interim storage facility or geologic repository becomes available before 2220.
2	In-state interim storage	20-40 years in dry casks at SONGS + shipment to an interim storage facility in California + storage 160-180 years at interim storage facility	This scenario assumes a privately-owned or state-owned NRC-licensed interim storage facility will be located in California but no geologic repository becomes available before 2220.
3	Out-of-state interim storage	20-40 years in dry casks at SONGS + shipment to an interim storage facility in south-east or north-west location + storage 160-180 years at interim storage facility	This scenario assumes a privately-owned NRC-licensed interim storage facility will be located in another state but no geologic repository becomes available before 2220.
4	In-state direct disposal	20-40 years in dry casks at SONGS + shipment to a geologic repository in California	This scenario assumes a privately-owned or state-owned NRC-licensed geologic repository will be located in California, with no interim storage.
5	Out-of-state direct disposal	20-40 years in dry casks at SONGS + shipment to a geologic repository in another state	This scenario assumes a federal NRC-licensed geologic repository will be located in another state, with no interim storage.
6	In-state interim storage and disposal	20-40 years in dry casks at SONGS + shipment to an interim storage facility in California + 20-40 years storage at interim storage facility + permanent disposal at a geologic repository at same or other location in California	This scenario assumes a privately-owned or state-owned NRC-licensed interim storage facility will be located in California and a privately-owned or state-owned NRC-licensed geologic repository at same or other location in California.
7	In-state interim storage and out-of-state disposal	20-40 years in dry casks at SONGS + shipment to an interim storage facility in California + 20-40 years storage at interim storage facility + shipment to and permanent disposal at a geologic repository in another state	This scenario assumes a privately-owned or state-owned NRC-licensed interim storage facility will be located in California and a federal NRC-licensed geologic repository in another state.
8	Out-of-state interim storage and disposal	20-40 years in dry casks at SONGS + shipment to an interim storage facility in south-east or north-west location + 20-40 years storage at interim storage facility + permanent disposal at a geologic repository at same or other location	This scenario assumes a privately-owned NRC-licensed interim storage facility will be located in another state and a federal NRC-licensed geologic repository at same or other location.

Note: Abbreviations: NRC, U.S. Nuclear Regulatory Commission.

Table 8. Main parameters and associated value ranges for each selected scenario at SONGS.

Parameters	Unit	Scenario 1	2	3	4	5	6	7	8
		Do nothing	In-state interim storage	Out-of-state interim storage	In-state direct disposal	Out-of-state direct disposal	In-state interim storage and disposal	In-state interim storage and out-of-state disposal	Out-of-state interim storage and disposal
Duration of onsite storage at SONGS	Years	200	20-40		20-100			20-40	
Duration of interim storage at interim storage facility	Years	n/a	160-180		n/a			20-100	
Average lifetime of storage canisters/casks	Years				50-100				
Repackaging required	% of canisters		100%-400%		0%-200%			0%-280%	
Need for new NRC-approved transportation casks	Number of casks	n/a				0/73			
Transportation distance to interim storage facility	Miles	n/a	0-300	300-1000	n/a		0-300		300-1000
Transportation distance to geologic repository	Miles		n/a		200-300	300-400	0-200	60-300	0-1000
Transportation campaign scale factor (regional and local)	Log of diff. vs. large-scale	n/a	1.6-2.9	1-1.6	1.6-2.9	1-1.6	1.6-2.9		1-1.6
Estimated life-cycle repository cost per unit of SNF	k\$/MTU		n/a				180-830		
Annual economic compensation to host community per unit of SNF	\$/kg-year				0/15				
10-year population growth in San Diego county, California	-				0%-4%				

Note: “xx-yy”, full range of values is considered (normal distribution); “xx/yy”, only discrete values are considered (binary analysis).

Table 9. Duration of storage considered for each selected scenario at SONGS.

Sc. #	Scenario	Storage at SONGS (years)			Storage at an interim storage facility (years)		
		mean	min	max	mean	min	max
1	Do nothing	200	200	200	0	0	0
2	In-state interim storage	30	20	40	170	160	180
3	Out-of-state interim storage	30	20	40	170	160	180
4	In-state direct disposal	60	20	100	0	0	0
5	Out-of-state direct disposal	60	20	100	0	0	0
6	In-state interim storage and disposal	30	20	40	60	20	100
7	In-state interim storage and out-of-state disposal	30	20	40	60	20	100
8	Out-of-state interim storage and disposal	30	20	40	60	20	100

Note: Scenario starts in year 2020.

Table 10. Selected criteria describing the technical view.

Dimension	Cr. #	Criterion	Unit	Direction	Correlation
Management	1.1	Repackaging of canisters during onsite storage	Number of canisters	Minimize	2.1
	1.2	Repackaging of storage casks during onsite storage	Number of storage casks	Minimize	2.1
	1.3	Repackaging of canisters before transport	Number of canisters	Minimize	
	1.4	Loading/unloading to/from transportation casks	Number of load./unload.	Minimize	
	1.5	Repackaging of canisters during offsite storage	Number of canisters	Minimize	
	1.6	Repackaging of storage casks during offsite storage	Number of storage casks	Minimize	
Occupational Safety	1.7	Total cumulative individual worker dose of normal operations during onsite storage	rem	Minimize	2.1
	1.8	Total cumulative individual worker dose of normal operations during interim storage	rem	Minimize	
	1.9	Total cumulative individual worker dose from loading/unloading casks for transport	rem	Minimize	1.4
	1.10	Collective dose to workers during transport	person-rem	Minimize	
	1.11	Total individual worker dose from normal surface operations during geologic disposal	mrem	Minimize	

Notes: Correlations are direct linear, except those with a minus (-) that are inverse linear (when applicable). Correlations referring to criterion **2.1** of the societal view will be considered only in the multi-criteria evaluation combining the two technical and societal views.

Table 11. Selected criteria describing the societal view.

Dimension	Cr. #	Criterion	Unit	Direction	Correlation
Public Safety	2.1	Duration of onsite storage at SONGS (after 2020)	Years	Minimize	
	2.2	Duration of storage in California until in-state disposal or transport off state (after 2020)	Years	Minimize	
	2.3	Duration of isolation in a geologic disposal facility (before 2220)	Years	Maximize	
	2.4	Public radiation exposure risk during onsite storage at SONGS	Ci-person-year (x10 ¹⁵)	Minimize	2.1
	2.5	Public radiation exposure risk during interim storage in California	Ci-person-year (x10 ¹⁴)	Minimize	2.2
	2.6	Public dose during transport	mrem	Minimize	
Economic Viability	2.7	Total cost of onsite storage at SONGS	M\$	Minimize	2.1
	2.8	Total cost of interim storage and/or disposal in California	M\$	Minimize	
	2.9	Total cost of transport	M\$	Minimize	
	2.10	Total economic impact compensation during storage in California	M\$	Maximize	2.2
	2.11	Financial risk from postponed investment costs of disposal (incl. repository closure)	B\$-year	Minimize	2.3

Note: Correlations are direct linear, except those with a minus (-) that are inverse linear (when applicable).

Table 12. Replacement rates of canisters depending on the storage duration.

Duration of storage	Mean	Min.	Max.
20 years	0%	0%	0%
40 years	0%	0%	70%
60 years	4%	0%	120%
100 years	100%	0%	200%
140 years	140%	30%	280%
160 years	160%	70%	320%
180 years	180%	100%	360%
200 years	200%	100%	400%

Note: Each set of estimates (mean/minimum/maximum) considers a lowest conceivable value (LCV) and a highest conceivable value (HCV) for the lifetime of canisters. For each set, the mean value (μ) is equal to $(HCV+LCV)/2$ and the standard deviation (σ) is equal to $(HCV-LCV)/6$ following the three-sigma rule of a normal distribution. Mean distribution with HCV=100 and LCV=50; Minimum distribution with HCV=200 and LCV=100; and Maximum distribution with HCV=50 and LCV=25. When storage lasts longer than HCV, a second cycle of replacement starts with the same distribution, so that values can be higher than 100%.

Table 13. Unitary costs for different transport scenarios and transportation campaign sizes (source: after Kalinina and Busch, 2014).

Transport scenario	Unit	Large-scale	Regional	SONGS-specific
Scale factor	-	1.0	1.6	2.9
Transportation to repository (DPCs) - no interim storage facility	\$/cask-mile	70	112	203
Transportation to repository (DPCs and MPCs) - no interim storage facility	\$/cask-mile	107	172	312
Transportation to interim storage facility then repository (DPCs only) - interim storage facility in SE location	\$/cask-mile	54	86	156
Transportation to interim storage facility then repository (DPCs and MPCs) - interim storage facility in SE location	\$/cask-mile	82	131	237
Transportation to interim storage facility then repository (DPCs only) - interim storage facility in NW location	\$/cask-mile	48	78	140
Transportation to interim storage facility then repository (DPCs only) - repository at same location	\$/cask-mile	84	134	243

Table 14. Ranking of scenarios for the multi-criteria evaluations performed at SONGS.

Scenario	Technical view	Societal view	Combined
(1) Do nothing	2	7	6
(2) In-state interim storage	6	8	8
(3) Out-of-state interim storage	8	5	7
(4) In-state direct disposal	1	3	2
(5) Out-of-state direct disposal	3	1	1
(6) In-state interim storage and disposal	4	6	4
(7) In-state interim storage and out-of-state	7	4	5
(8) Out-of-state interim storage and disposal	5	2	3

Note: Scenarios are ranked from 1 (most performing) to 8 (least performing).

Table 15. Social impact of scenarios on the socio-technical actors at SONGS as assessed by the students.

ID*	Socio-technical actor	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
		DO NOTHING	IN-STATE INTERIM	OUT-OF-STATE INTERIM	IN-STATE DIRECT DISPOSAL	OUT-OF-STATE DIRECT DISPOSAL	IN-STATE INTERIM & DISPOSAL	IN-STATE INTERIM & OUT-OF-STATE DISP	OUT-OF-STATE INTERIM & DISPOSAL
1	Southern California Edison (SCE)	Very bad	Very good	Very good	More or less good	More or less good	Very good	Very good	Very good
2	San Diego Gas & Electric (SDG&E)	Very bad	Very good	Very good	More or less good	More or less good	Very good	Very good	Very good
3	City of Riverside	Very bad	Good	Very good	Good	Very good	More or less good	Good	Very good
4	San Diego County's District 5 Supervisor Jim Desmond (R)	Very bad	Good	Very good	More or less good	Good	More or less good	Good	Very good
5	49th California's Congressional District Representative Mike Levin (D)	Very bad	Good	Very good	Good	Very good	More or less good	Good	Very good
6	San Luis Rey Band of Missions Indians (native populations)	Very bad	Very good	Very good	Good	Good	Very good	Very good	Very good
8	Committee to Bridge the Gap	Very bad	Very good	Very good	Good	Good	Very good	Very good	Very good
10	Surfrider Foundation's local chapter	Very bad	Very good	Very good	Good	Good	Very good	Very good	Very good
13	California State Governor Gavin Newsom (D)	Very bad	Bad	Very good	More or less bad	Very good	Bad	Good	Very good
14	California State Senator Dianne Feinstein (D)	Very bad	Bad	Very good	More or less bad	Very good	Bad	Good	Very good
15	California State Parks (CSP)	Bad	Bad	Very good	Bad	Very good	Very bad	Bad	Very good
16	California State Lands Commission (CSLC)	Bad	Bad	Very good	Bad	Very good	Very bad	Bad	Very good

17	California State Coastal Commission (CSCC)	Very bad	More or less good	Very good	Good	Very good	More or less good	Good	Very good
18	Holtec International	Very good	Good	Very good	Very bad	Very bad	Bad	Bad	Very good
19	U.S. Department of Energy (DOE)	Moderate	Very good	Very good	Very good	Very good	Very good	Very good	Very good
20	U.S. Department of the Navy, Marine Corps Base Camp Pendleton (DoN)	Very bad	Very good	Very good	Very good	Very good	Very good	Very good	Very good

Note: This table is for illustrative purposes. The actual application of the STMCE methodology at SONGS would require the participation of all affected parties.

Table 16. Mean ranking of scenarios from social impact analysis at SONGS as assessed by the researchers.

Scenario	All	Coalition 1	Coalition 2	Coalition 3	Coalition 4
(1) Do nothing	8	8	8	7	1
(2) In-state interim storage	4	5	1	6	4
(3) Out-of-state interim storage	1	1	1	1	1
(4) In-state direct disposal	7	7	6	5	7
(5) Out-of-state direct disposal	5	3	6	1	7
(6) In-state interim storage and disposal	6	6	1	8	5
(7) In-state interim storage and out-of-state disposal	3	4	1	4	5
(8) Out-of-state interim storage and disposal	1	1	1	1	1

Note: Scenarios are ranked from 1 (most performing) to 8 (least performing). Tied scenarios are ranked with highest value of the concerned positions. Coalition composition are as in **Fig. 8**: C1 = actors 1–5, 17; C2 = actors 6–12, 19, 20; C3 = actors 13–16; and C4 = actor 18.

Figures

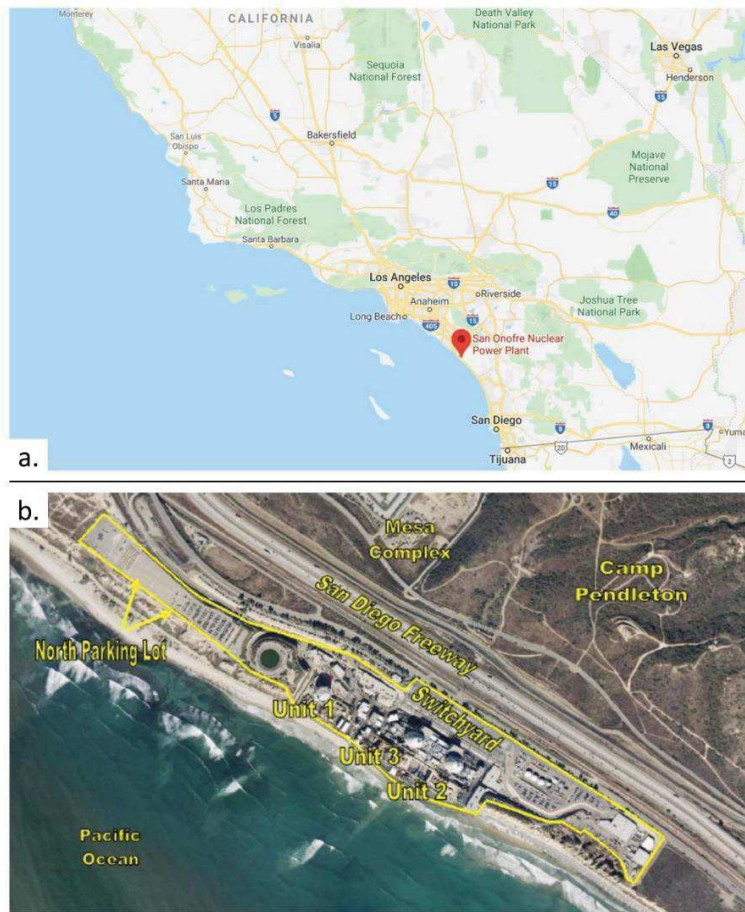


Fig. 1. (a) Location of the San Onofre Nuclear Generation Station (SONGS) in Southern California. Source: Google Maps. (b) View of the Marine Corps Base Camp Pendleton hosting the SONGS plant site. Source: (Alvarez, 2013).

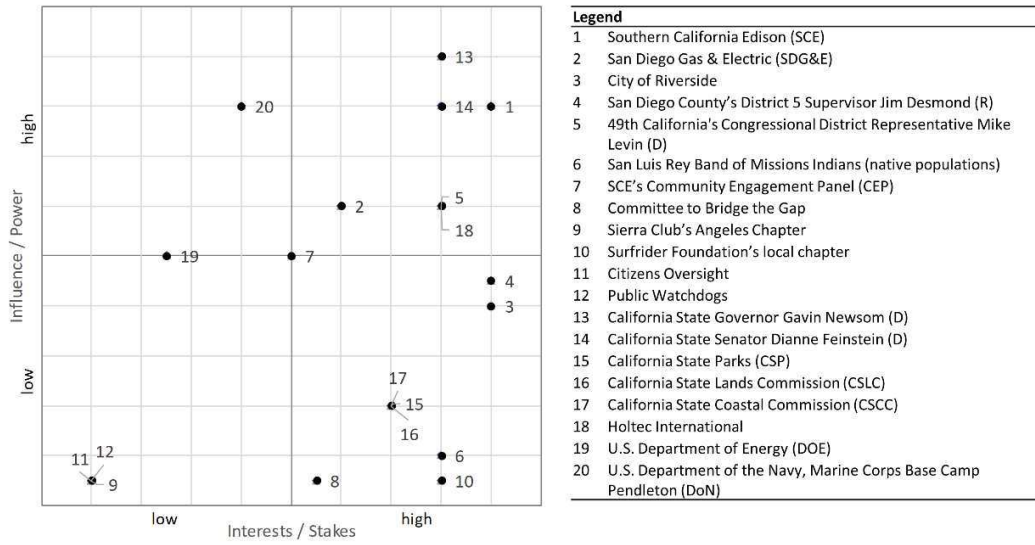


Fig. 2. Power/interest matrix of socio-technical actors at SONGS as assessed by students.

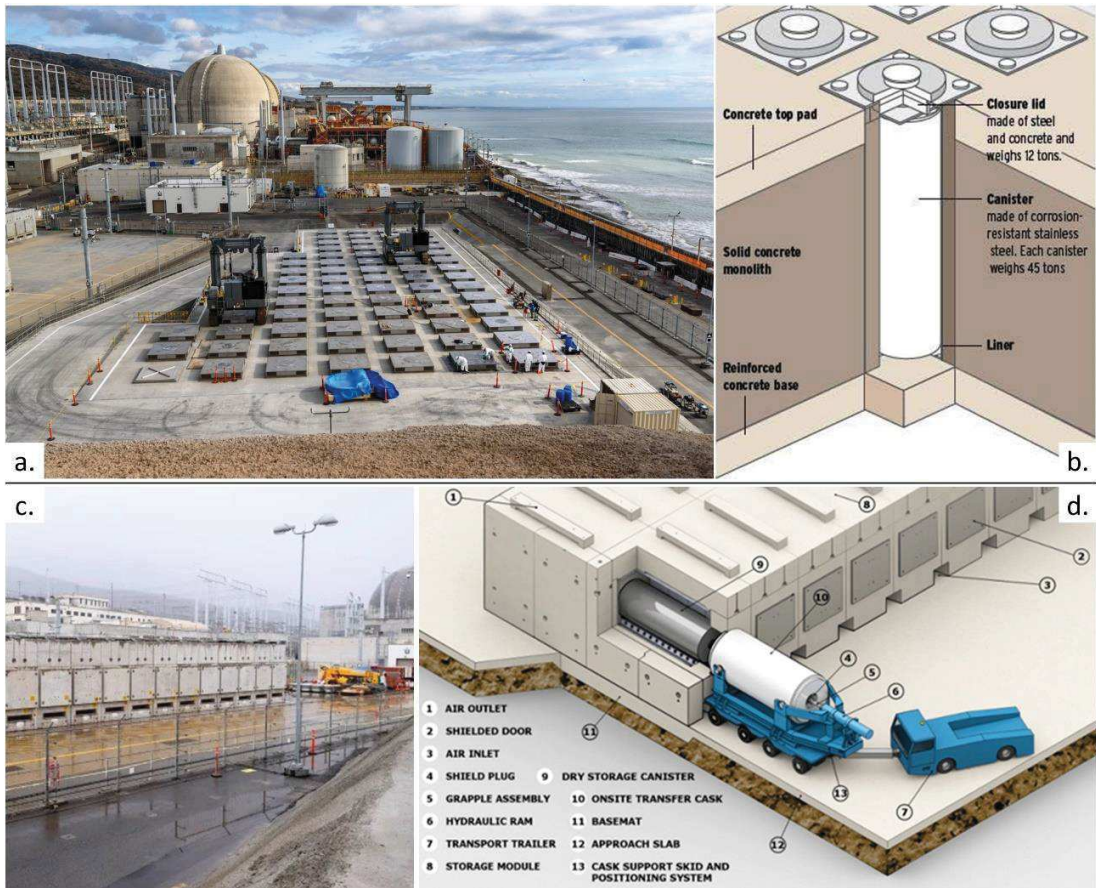


Fig. 3. Dry storage areas at the San Onofre Nuclear Generating Station (SONGS), California. (a) Holtec’s HI-STORM UMAX underground dry storage system hosting 73 MPCs. Source: Southern California Edison. (b) Main components of the HI-STORM UMAX system. Source: Southern California Edison. (c) AREVA’s NUHOMS horizontal dry storage system hosting 50 DPCs. Source: photo by Paul Bersebach, Orange County Register; (d) Main components of the NUHOMS system. Source: Areva / Orano.

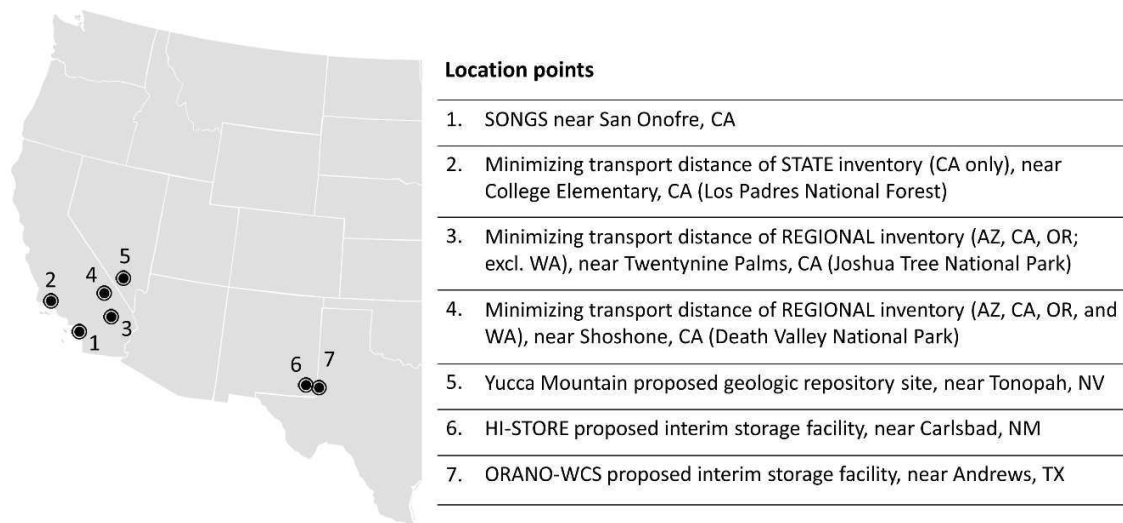


Fig. 4. Location of destination points considered in the analysis. Point 1 represents the current location of the spent fuel at SONGS. Points 2-4 represent possible interim storage facilities and/or geologic repositories located in California. Points 5-7 represent currently proposed geologic repository (5) and interim storage facilities (6 and 7) located outside of California. Note: These location points are used for illustrative purposes related to transport. An actual site would have to satisfy social and technical requirements (US NWTRB, 2015).

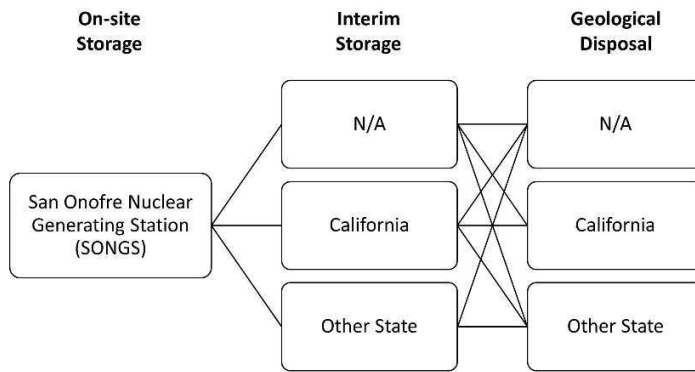


Fig. 5. Key processes of any spent fuel management strategy at SONGS.

Scenario #			Description
1	SONGS		<i>Do nothing</i>
2	SONGS	➡ Interim storage facility in CA	<i>In-state interim storage</i>
3	SONGS	➡ Interim storage facility in other state	<i>Out-of-state interim storage</i>
4	SONGS	➡ Geologic repository in CA	<i>In-state direct disposal</i>
5	SONGS	➡ Geologic repository in other state	<i>Out-of-state direct disposal</i>
6	SONGS	➡ Interim storage facility in CA ➡ Geologic repository in CA	<i>In-state interim storage and disposal</i>
7	SONGS	➡ Interim storage facility in CA ➡ Geologic repository in other state	<i>In-state interim storage and out-of-state disposal</i>
8	SONGS	➡ Interim storage facility in other state ➡ Geologic repository in other state	<i>Out-of-state interim storage and disposal</i>

Fig. 6. Selected long-term spent fuel management scenarios at SONGS.

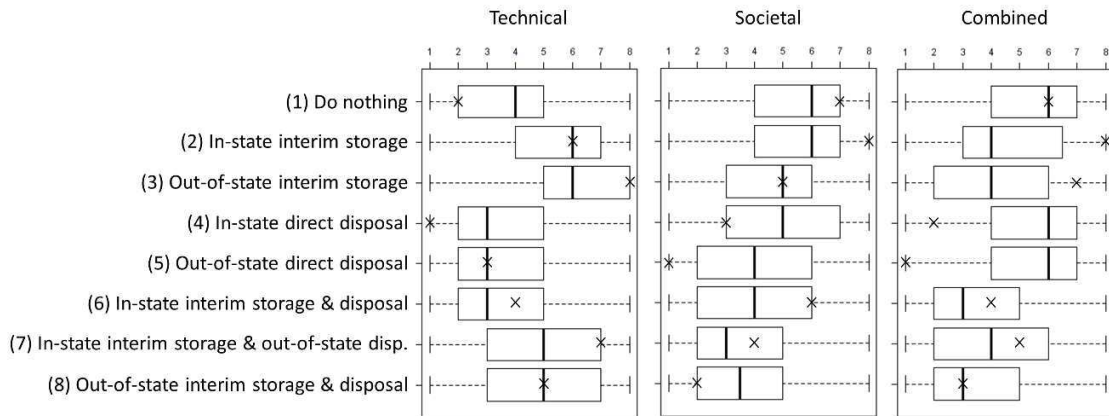


Fig. 7. Ranking of the scenarios at SONGS from the Monte Carlo simulation for 500 random samples. Note: Scenarios are ranked from 1 (highest performance) to 8 (lowest performance). The box contains points within the 25–75 percentile (Q1–Q3) range, dotted lines are points within 1.5 times the interquartile range (IQR), white circles (not shown in figure) are suspected outliers either 1.5xIQR or more above Q3 or 1.5xIQR or more below Q1, the black line is the median, and the cross is the mean value from

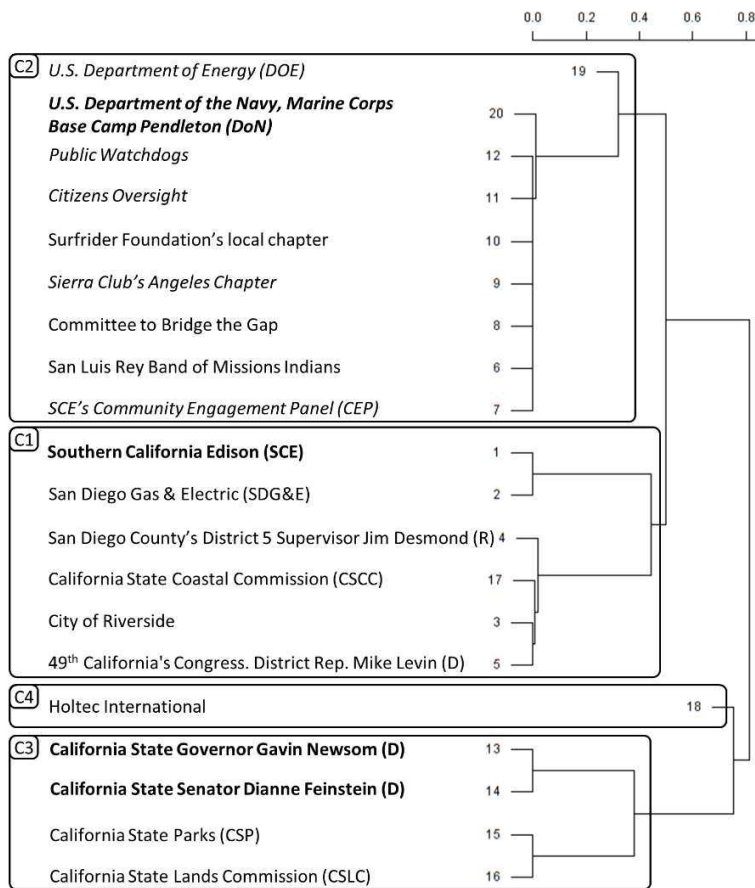


Fig. 8. Dendrogram of the coalition formation process at SONGS. Notes: IDs as in **Table 2**; in **bold**, socio-technical actors with highest levels of power and interest as in **Fig. 2**; in *italics*, socio-technical actors with lowest level of interest as in **Fig. 2**.

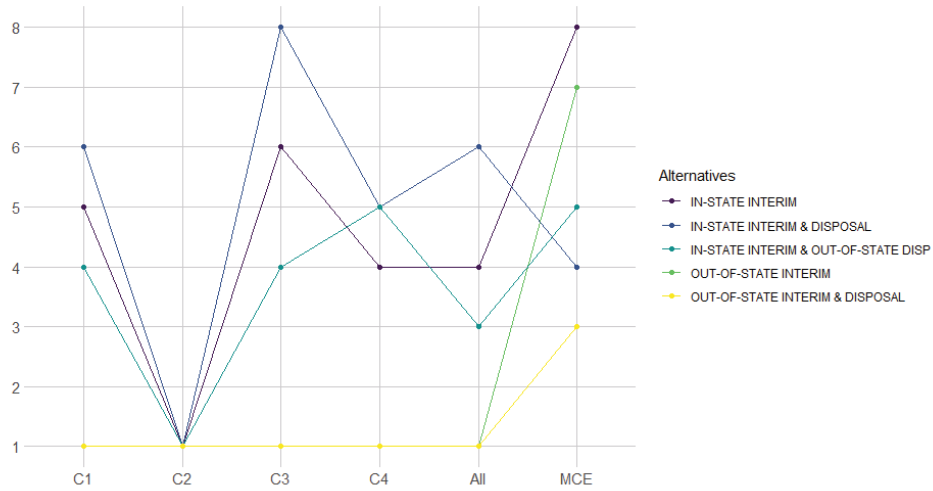


Fig. 9. Mean rankings of scenarios at SONGS from the social impact analysis for each coalition (“C1” to “C4”), all actors combined (“All”) as well as from the multi-criteria evaluation for all dimensions combined (“MCE”). Note: Options that can be vetoed are not shown. Tied scenarios are ranked with highest value of the concerned positions (*e.g.*, if two scenarios are tied in the 6th position are both given a value of 6).

Appendix A. Supplementary Method

We summarize the procedures used for the multi-criteria evaluations and the social impact analysis. The mathematical details of the STMCE methodology can be found in Diaz-Maurin et al. (2020).

A.1. Aggregation convention

An aggregation convention was developed to perform the multi-criteria evaluations. We adapted the aggregation convention originally developed by Munda (2012, 2008). The multi-criteria evaluation consists of (1) the pairwise comparison of alternatives according to a set of criteria, and (2) the generation of an ordinal ranking of alternatives using the aggregated criterion scores (values). The aggregation convention considers that the performance (*i.e.*, the criterion score) of an alternative with respect to a judgement criterion is based on an *interval or ratio* scale of measurement. In order to rank alternatives, we introduce an *indifference threshold* that indicates the degree of difference up to which two options are considered equivalent and, consequently, the degree of difference from which a preference relation exists. An indifference threshold (q) determines the difference in the criterion performance of individual variants, at which they can be considered to be equally good (Wątróbski et al., 2019). In this paper, we consider an indifference threshold q equal to the standard deviation σ for each range of values taken by each criterion (**Table A.1** and **Table A.2**). Although this assumption is acceptable for the present case study, ideally, the indifference thresholds should be set independently from the individual values of the criteria and, therefore, independently from the scenarios considered in the analysis.

Table A.1. Indifference thresholds for the technical multi-criteria impact matrix of the SONGS analysis. Source: After **Tables C.1-C.2** in **Appendix C**.

Crit. #	Criterion	Unit	Indifference threshold
1.1	Repackaging of canisters during onsite storage	Number of canisters	82
1.2	Repackaging of storage casks during onsite storage	Number of casks	8.2
1.3	Repackaging of canisters before transport	Number of canisters	19
1.4	Loading/unloading to/from transportation casks	Number of load./unload.	109
1.5	Repackaging of canisters during offsite storage	Number of canisters	67
1.6	Repackaging of storage casks during offsite storage	Number of casks	7.4
1.7	Total cumulative individual worker dose of normal operations during onsite storage	rem	43
1.8	Total cumulative individual worker dose of normal operations during interim storage	rem	18
1.9	Total cumulative individual worker dose from loading/unloading casks for transport	rem	2.1
1.10	Collective dose to workers during transport	person-rem	93
1.11	Total individual worker dose from normal surface operations during geologic disposal	mrem	0.29

Table A.2. Indifference thresholds for the technical multi-criteria impact matrix of the SONGS analysis. Source: After **Tables C.3-C.4** in **Appendix C**.

Crit. #	Criterion	Unit	Indifference threshold
2.1	Duration of onsite storage at SONGS (after 2020)	Years	30
2.2	Duration of storage in California until in-state disposal or transport off state (after 2020)	Years	30
2.3	Duration of isolation in a geologic disposal facility (before 2220)	Years	30
2.4	Public radiation exposure risk during onsite storage at SONGS	Ci-person-year (x10 ¹⁵)	2.0
2.5	Public radiation exposure risk during interim storage in California	Ci-person-year (x10 ¹⁴)	0.7
2.6	Public dose during transport	mrem	0.033
2.7	Total cost of onsite storage at SONGS	M\$	390
2.8	Total cost of interim storage and/or disposal in California	M\$	484
2.9	Total cost of transport	M\$	5.4
2.10	Total economic impact compensation during storage in California	M\$	804
2.11	Financial risk from postponed investment costs of disposal (incl. repository closure)	B\$-year	46

Based on these indifference relations between two alternatives, we can construct an out-ranking matrix. The outranking matrix is constructed under the *equal weighting* assumption where all the criteria and dimensions have the same importance. The ranking of a given alternative can then be determined by means of its position in the set of aggregated scores. The alternative with the highest aggregated score will be ranked first.

A.2. Monte Carlo simulation

A Monte Carlo sampling procedure was used in the sensitivity/uncertainty analysis to generate the distribution of the possible rankings considering the uncertainty on the criteria scores. The Monte Carlo simulation consists of repeatedly running the multi-criteria evaluation based on randomly generated samples of criteria scores. This method allows us to determine the most likely ranking of alternatives, given a range of values for the criterion scores. For each Monte Carlo simulation, each criterion score is sampled considering a normal distribution from the known score's mean, minimum, and maximum (**Appendix C**). While the mean for each distribution is known, the standard deviation is not given and thus must be estimated. We used the "Three-Sigma Rule" which states that approximately 99.73% of all values of a normally distributed parameter fall within three standard deviations of the mean (Duncan, 2000). Formally, assuming a normal distribution for each criterion and given the lowest conceivable value (LCV) and highest conceivable value (HCV) among all the possible individual values are known, the standard deviation was approximated as (Duncan, 2000):

$$\sigma = \frac{(HCV - LCV)}{6}$$

The Monte Carlo sampling was formalized by calculating the deviation from the mean of the sampled value. The sampling algorithm was conducted in R (R Core Team, 2019) using a seed function so that the same samples can be reproduced. We then conducted post-sampling adjustments on some of the criteria sampled values. First, for some criteria, a normal distribution could not be considered because their criterion value was fixed (“either/or” condition). In these cases, the randomly generated values were set to the closest known values (mean, minimum or maximum). This concerned 3 criteria out of a total of 22 (criteria **1.3**, **1.4** and **2.10** in **Appendix C**). Second, some criteria were considered correlated with one another. That is, we considered the value sampled from one score’s distribution to be conditional on the value obtained from a correlated score’s distribution. For example, if the duration of onsite storage was longer, the operational cost of onsite storage shall increase proportionally too. To control for this, we performed a direct or inverse linear adjustment to the sampled values of correlated criteria. This concerned one correlation in the technical evaluation, 5 correlations in the societal evaluation, and 9 correlations in the combined evaluation (**Tables 10** and **11**).

We thus obtain a set of randomly sampled and adjusted criterion scores which can be used in the multi-criteria evaluations. Each one of the three multi-criteria evaluations was performed for the number of random samples for which we obtain convergence of the results. The number of Monte Carlo random samples was determined empirically (**Fig. C.1** in **Appendix C**).

A.3. Fuzzy cluster analysis

To contrast the results of the multi-criteria evaluation, we perform an analysis of the social impact of the alternatives on the interests of the socio-technical actors. For this, we adapted the same framework as proposed by Munda (2008, 1995). The impact of each alternative on each socio-technical actor is evaluated by the analysts based on their assessment of how they are impacted. This step can be done by reviewing available material and eventually by asking opinions through focus groups, interviews or questionnaires. The social impact of each alternative on each socio-technical actor can then be recorded by means of a *linguistic variable* (very good, good, etc.). For the case study, the social impact was recorded using 7 linguistic variables: “Very bad”, “Bad”, “More or less bad”, “Moderate”, “More or less good”, “Good”, and “Very good”. With this, we constructed a social impact matrix of the preferences of each socio-technical actor in relation to each alternative (**Table 15**).

To make comparisons between linguistic variables, we computed their semantic distances using *fuzzy sets*. Fuzzy sets are based on the idea of introducing a degree of membership of an element with respect to some sets (Munda, 1995). Fuzzy sets are necessary in order to introduce some level of uncertainty within linguistic variables. *Fuzzy uncertainty* refers to the degree of ambiguity in the information about the system which generates fuzziness in the evaluation of the impact of alternatives by the socio-technical actors. We then used the semantic distance between any pair of socio-technical actors as a conflict indicator (Munda, 2009).

By using the semantic distance as a conflict indicator of the preferences among the socio-technical actors, a similarity matrix for all possible pairs of actors can be obtained. From the similarity matrix, we can then create a dendrogram to visualize the level of

similarity between the socio-technical actors based on the perceived impacts. This allows to study the level of similarity between socio-technical actors based on the assessment of how they are impacted by each alternative. For this, a fuzzy cluster algorithm can be used that synthesizes similarities/diversities among socio-technical actors (Munda, 2009).

By applying the fuzzy clustering procedure to the social impact matrix and by using the assumption of equal weighting of the socio-technical actors, the dendrogram is obtained (**Fig. 8**). This clustering method defines the distance between two clusters to be the maximum distance between their individual components. The hierarchical clustering process consists in making pair-wise comparisons of all elements of the similarity matrix. At every step of the clustering process, the two nearest clusters are merged into a new cluster. The process is repeated until the whole data set is agglomerated into one single cluster.

We then rank the alternatives using the same aggregation convention as for the multi-criteria evaluation (Section **A.1**). We perform the aggregation for the K coalitions formed by the dendrogram. The number of coalitions K is determined by the user after inspecting the results of the dendrogram. So, in addition to the ranking of alternatives for all socio-technical actors, K rankings are similarly made for each coalition.

A.4. Proportional veto function

The proportional veto function consists in giving a coalition of actors the ability to veto any subset of alternatives proportionally to the fraction of socio-technical actors it contains. This rule allows to eliminate any ‘extreme’ solution that would be considered

feasible only by a too small number of parties relatively to the set of socio-technical actors included.

We follow Moulin's (1981) theorem on the proportional veto principle which says that any group with x percent of socio-technical actors has the ability to veto up to x percent of alternatives. Formally, this takes the form of a proportional veto function, which is defined as (Munda, 2009):

$$V_{P,N}(c_i) = \left(N \cdot \frac{|c_i|}{P} \right) - 1$$

where (x) is the largest integer bounded below by x , P is the number of socio-technical actors, N is the number of alternatives, and c_i is the i 'th group out of the K coalitions (Section A.3).

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<https://doi.org/10.1016/j.omega.2018.07.004>

Appendix B. Supplementary Material and Data

Table B.1. Estimated evolution of the activity per dry cask type (MCi/canister). Source: (after Xu et al., 2005)

Dry cask storage type	Year 2020	Year 2040	Year 2060	Year 2080	Year 2120	Year 2160	Year 2220
Unit 1 - AREVA NUHOMS - 24PT1	2.4	1.4	1.0	0.7	0.3	0.2	0.1
Unit 2/3 - AREVA NUHOMS - 24PT4	15	7.3	4.3	3.3	1.3	0.6	0.3
Units 2/3 - HOLTEC MPC-37	6.9	3.3	1.9	1.5	0.6	0.3	0.1

Table B.2. Estimated evolution of the thermal output per dry cask type (kW/canister). Source: (after Xu et al., 2005)

Dry cask storage type	Year 2020	Year 2040	Year 2060	Year 2080	Year 2120	Year 2160	Year 2220
Unit 1 - AREVA NUHOMS - 24PT1	8.3	6.2	5.5	4.4	3.0	2.8	2.0
Unit 2/3 - AREVA NUHOMS - 24PT4	53	27	20	18	11	8.8	6.2
Units 2/3 - HOLTEC MPC-37	24	12	9.0	8.0	4.8	4.0	2.8

Table B.3. Transportation readiness of dry cask types used at SONGS. Sources: (after Carter, 2018; Palmisano, 2018a, 2018b)

Dry cask storage type	# canisters ready for transp. (2019, est.)	# canisters ready for transp. (2030, est.)	Type of transp. cask	Status of certification by NRC (as of end 2018)
Unit 1 - AREVA NUHOMS - 24PT1	1	17	Transnuclear MP-187	Expired 11/30/2018
Unit 2/3 - AREVA NUHOMS - 24PT4	33	33	Transnuclear MP-197HB	Expired 8/31/2017
Units 2/3 - HOLTEC MPC-37	0	73	Holtec HI-STAR 190	Application under review

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Appendix C. Supplementary Results

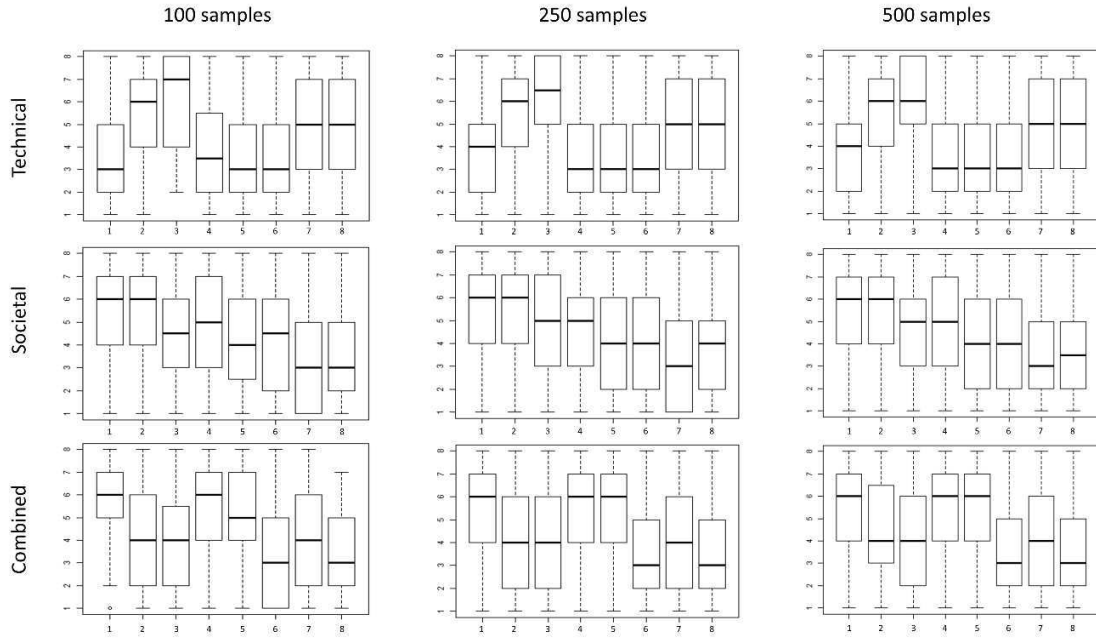


Fig. C.1. Ranking of scenarios at SONGS for the three multi-criteria evaluations for three number of random samples, $n = 100, 250, 500$.

Table C.1. Technical multi-criteria impact matrix of the SONGS analysis. Scenarios 1-4.

Crit. #	Criterion	Unit	Scenario 1			Scenario 2			Scenario 3			Scenario 4		
			DO NOTHING			IN-STATE INTERIM			OUT-OF-STATE INTERIM			IN-STATE DIRECT DISPOSAL		
			mean	min	max	mean	min	max	mean	min	max	mean	min	max
1.1	Repackaging of canisters during onsite storage	Number of canisters	246	123	492	0	0	88	0	0	88	6	0	246
1.2	Repackaging of storage casks during onsite storage	Number of casks	25	12	49	0	0	9	0	0	9	1	0	25
1.3	Repackaging of canisters before transport	Number of canisters	0	0	0	0	0	113	0	0	113	0	0	113
1.4	Loading/unloading to/from transportation casks	Number of load./unload.	0	0	0	246	246	326	246	246	326	246	246	326
1.5	Repackaging of canisters during offsite storage	Number of canisters	0	0	0	246	123	404	246	123	404	0	0	0
1.6	Repackaging of storage casks during offsite storage	Number of casks	0	0	0	21	9	44	21	9	44	0	0	0
1.7	Total cumulative individual worker dose of normal operations during onsite storage	rem	188	136	271	31	17	98	31	17	98	56	15	186
1.8	Total cumulative individual worker dose of normal operations during interim storage	rem	0	0	0	66	35	111	66	35	111	0	0	0
1.9	Total cumulative individual worker dose from loading/unloading casks for transport	rem	0	0	0	2.9	1.9	5.1	2.9	1.9	5.1	1.6	1.1	2.9
1.10	Collective dose to workers during transport	person-rem	0	0	0	58	0	83	172	68	278	66	45	83
1.11	Total individual worker dose from normal surface operations during geologic disposal	mrem	0	0	0	0	0	0	0	0	0	1.5	1.2	1.8

Table C.2. Technical multi-criteria impact matrix of the SONGS analysis. Scenarios 5-8.

Crit. #	Criterion	Unit	Scenario 5			Scenario 6			Scenario 7			Scenario 8		
			OUT-OF-STATE DIRECT DISPOSAL			IN-STATE INTERIM & DISPOSAL			IN-STATE INTERIM & OUT-OF-STATE DISP			OUT-OF-STATE INTERIM & DISPOSAL		
			mean	min	max	mean	min	max	mean	min	max	mean	min	max
1.1	Repackaging of canisters during onsite storage	Number of canisters	6	0	246	0	0	88	0	0	88	0	0	88
1.2	Repackaging of storage casks during onsite storage	Number of casks	1	0	25	0	0	9	0	0	9	0	0	9
1.3	Repackaging of canisters before transport	Number of canisters	0	0	113	0	0	113	0	0	113	0	0	113
1.4	Loading/unloading to/from transportation casks	Number of load./unload.	246	246	326	246	246	652	492	492	652	246	246	492
1.5	Repackaging of canisters during offsite storage	Number of canisters	0	0	0	6	0	198	6	0	198	6	0	198
1.6	Repackaging of storage casks during offsite storage	Number of casks	0	0	0	0	0	9	0	0	9	0	0	20
1.7	Total cumulative individual worker dose of normal operations during onsite storage	rem	56	15	186	31	17	98	31	17	98	31	17	98
1.8	Total cumulative individual worker dose of normal operations during interim storage	rem	0	0	0	19	5	53	19	5	53	19	5	53
1.9	Total cumulative individual worker dose from loading/unloading casks for transport	rem	1.6	1.1	2.9	3.5	2.3	12.3	7.0	4.6	12.3	3.5	2.3	12.3
1.10	Collective dose to workers during transport	person-rem	93	68	111	58	45	83	87	68	100	305	68	555
1.11	Total individual worker dose from normal surface operations during geologic disposal	mrem	1.5	1.2	1.8	0.6	0.5	0.7	0.6	0.5	0.7	0.6	0.5	0.7

Table C.3. Societal multi-criteria impact matrix of the SONGS analysis. Scenarios 1-4.

Crit. #	Criterion	Unit	Scenario 1			Scenario 2			Scenario 3			Scenario 4		
			DO NOTHING			IN-STATE INTERIM			OUT-OF-STATE INTERIM			IN-STATE DIRECT DISPOSAL		
			mean	min	max	mean	min	max	mean	min	max	mean	min	max
2.1	Duration of onsite storage at SONGS (after 2020)	Years	200	200	200	30	20	40	30	20	40	60	20	100
2.2	Duration of storage in California until in-state disposal or transport off state (after 2020)	Years	200	200	200	200	200	200	30	20	40	60	20	100
2.3	Duration of isolation in a geologic disposal facility (before 2220)	Years	0	0	0	0	0	0	0	0	0	140	180	100
2.4	Public radiation exposure risk during onsite storage at SONGS	Ci-person-year (x10 ¹⁵)	9.9	7.8	13.1	1.7	1.1	2.3	1.7	1.1	2.3	3.0	1.1	5.4
2.5	Public radiation exposure risk during interim storage in California	Ci-person-year (x10 ¹⁴)	0	0	0	3.5	4.5	2.5	0	0	0	0	0	0
2.6	Public dose during transport	mrem	0	0	0	0.029	0.003	0.1	0.029	0.003	0.1	0.029	0.003	0.1
2.7	Total cost of onsite storage at SONGS	M\$	2,271	2,135	2,541	300	200	497	300	200	497	607	200	1,271
2.8	Total cost of interim storage and/or disposal in California	M\$	0	0	0	2,241	2,006	2,611	0	0	0	657	287	1,333
2.9	Total cost of transport	M\$	0	0	0	6.6	0	11	11	3.4	21	7.6	3.6	11
2.10	Total economic impact compensation during storage in California	M\$	4,826	0	4,826	724	0	4,826	724	0	965	1,448	0	2,413
2.11	Financial risk from postponed investment costs of disposal (incl. repository closure)	B\$-year	132	57	275	132	57	275	132	57	275	2.4	0	17

Table C.4. Societal multi-criteria impact matrix of the SONGS analysis. Scenarios 5-8.

Crit. #	Criterion	Unit	Scenario 5			Scenario 6			Scenario 7			Scenario 8		
			OUT-OF-STATE DIRECT DISPOSAL			IN-STATE INTERIM & DISPOSAL			IN-STATE INTERIM & OUT-OF-STATE DISP			OUT-OF-STATE INTERIM & DISPOSAL		
			mean	min	max	mean	min	max	mean	min	max	mean	min	max
2.1	Duration of onsite storage at SONGS (after 2020)	Years	60	20	100	30	20	40	30	20	40	30	20	40
2.2	Duration of storage in California until in-state disposal or transport off state (after 2020)	Years	60	20	100	90	40	140	90	40	140	30	20	40
2.3	Duration of isolation in a geologic disposal facility (before 2220)	Years	140	180	100	110	160	60	110	160	60	110	160	60
2.4	Public radiation exposure risk during onsite storage at SONGS	Ci-person-year (x10 ¹⁵)	3.0	1.1	5.4	1.7	1.1	2.3	1.7	1.1	2.3	1.7	1.1	2.3
2.5	Public radiation exposure risk during interim storage in California	Ci-person-year (x10 ¹⁴)	0	0	0	1.3	0.6	1.6	1.3	0.6	1.6	0	0	0
2.6	Public dose during transport	mrem	0.029	0.003	0.1	0.058	0.006	0.2	0.058	0.006	0.2	0.058	0.006	0.2
2.7	Total cost of onsite storage at SONGS	M\$	607	200	1,271	300	200	497	300	200	497	300	200	497
2.8	Total cost of interim storage and/or disposal in California	M\$	0	0	0	1,537	761	2,902	880	474	1,569	0	0	0
2.9	Total cost of transport	M\$	6.0	3.4	8.5	5.9	4.4	9.0	4.2	2.4	5.8	15	1.8	32
2.10	Total economic impact compensation during storage in California	M\$	1,448	0	2,413	724	0	3,379	724	0	3,379	724	0	965
2.11	Financial risk from postponed investment costs of disposal (incl. repository closure)	B\$-year	2.4	0	17	3.0	0	21	3.0	0	21	3.0	0	21