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Socio-technical multi-criteria evaluation of long-term spent nuclear fuel management strategies: A framework and method

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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 strategies to move the spent fuel away from those sites. In this paper, we present a framework and method for the socio-technical multi-criteria evaluation (STMCE) of spent fuel management strategies. The STMCE approach 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 outranking of options based on the assessment of their impact on concerned social 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 conducted an application of the STMCE method using data from the decommissioned San Onofre Nuclear Generating Station (SONGS) in California. This example intends to facilitate the preparation of stakeholder engagement activities on spent fuel management using the STMCE approach. The STMCE method provides an effective way to compare spent fuel management strategies and support the search for compromise solutions. 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; geological disposal; interim storage; multi-criteria analysis; conflict analysis; impact assessment

1. Introduction

In the United States, despite plans for geological disposal, spent fuel, so far, is stored at surface storage facilities at the sites where it has been generated (Reset Report, 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 (**Fig. 1**). 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 Report, 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 Report, 2018). In this context, local communities living close to decommissioned nuclear power plants are increasingly concerned about the legacy of nuclear power production and are seeking alternative options to move the spent fuel away from those sites (Reset Report, 2018). The management of spent nuclear fuel is thus increasingly seen not only as a technical challenge, but also as a societal issue affected by social, environmental, political and legal constraints (Ramana, 2018). This situation means that spent fuel management is no longer limited to a discussion among experts and scientists who advise the federal government on the "best" technical and policy choices to be approved by Congress and regulators. Rather, the scope of the discussion and decision-making must be broadened to consider both technical and societal dimensions (Bonano et al., 2011; Ramana, 2019; US NWTRB, 2015). In addition, there has been an expansion in the number and diversity of social actors, at the level of local communities, Native American tribes and states, willing to participate in the debates over the future of spent fuel stranded at or near reactor sites across the country (US DOE, 2016a). The complex nature of the socio-technical problem of nuclear waste management in the U.S. thus poses methodological challenges about how to make decisions that account for the diversity of perspectives from the various interested social actors.

Three critical issues affecting the U.S. spent fuel management program explain the need for a socio-technical decision-support approach (For more details, see supplementary introduction in **Appendix A**):

1. **An ineffective management program**, where the spending mechanism of the government's Nuclear Waste Fund —established for covering exclusively the cost of the disposal of commercial nuclear waste so it would be free from the Federal budget constraints—requires annual Congressional approval through budgeting appropriations; thus, the disposal program has to compete every year for federal

funding that makes it subject to the budget constraints and uncertainties that the Fund was especially created to avoid (Saraç-Lesavre, 2018).

2. **An imbalanced power distribution**, where localities and tribes have had no real negotiating power with the federal government or regulatory agencies about which sites are selected and how the safety of a repository project is assessed; the implementer of the nuclear waste management program, the U.S. DOE, is not required to respond to comments and recommendations from independent scientific commissions and boards (Alley and Alley, 2012); local communities are more likely to accept hosting a federal repository or interim storage facility that will bring jobs and tax income if they are economically impoverished (Ramana, 2013); local autonomy often conflicts with state control over repository siting and selection of transport routes (Bonano et al., 2011); and, because states are not involved in the negotiations over nuclear waste management strategies in the U.S., they are more likely to use of their legal powers through vetoing or challenging in courts any decision being proposed.
3. **Competing risk rationalities**, where legal and regulatory frameworks demand a very rigorous and objective form of knowledge so that courts and regulatory agencies can make technological decisions (Jasanoff, 1990), thus led to the creation of specific methods of risk analysis that rely on the unbounded quantification of risk levels (Porter, 1995). Yet, this "rationalization" of risk—made at the expense of the plurality of legitimate perspectives about the very nature of the risk (Funtowicz and Ravetz, 1993a)—has become the preferred strategy to mitigate the overwhelming

public distrust by federal regulatory agencies unable to negotiate solutions with communities over environmental conflicts (Jasanoff, 1990; Robinson et al., 2017).

To address these issues, national and international experts and observers have long recommended that the U.S. program's decision-making process shifts from *seeking the social acceptance of a technically rational choice* to *negotiating the technical feasibility of a societal choice*. That is, social acceptability cannot be forced upon but, rather, needs to result from a process of continuous interaction between science and society based on trustful relations (La Porte and Metlay, 1996). In nuclear waste management, then a new decision-making process must be designed that leads to effectively co-create such solutions.

The present paper provides a framework and method for the comparison of alternative spent fuel management strategies based on socio-technical dimensions of analysis and multiple perceptions of social impacts by the different interested parties. Specifically, the socio-technical multi-criteria evaluation (STMCE) approach has four objectives that seek to respond to the following needs of the U.S. spent fuel management program:

(1) Increasing the pool of perspectives. In any decision problem in environmental and public policy, it is crucial to account for the diversity of perspectives from the various interested social actors, especially in situations where stakes are high, facts are uncertain, and values are in dispute over what the "best" solution is (Funtowicz and Ravetz, 1993b). Therefore, to be successful, the framing of nuclear waste management strategies as well as the design of geological disposal and interim storage systems should reflect national, state, and local community concerns and preferences (Bonano et al., 2011). In the STMCE approach, all types of social actors with potential interest in the outcome of the decision can be considered in the problem framing and structuring—from localities to tribes, citizen groups, local and national NGOs, state governments and agencies, utilities, vendors, regulators and federal government and agencies. In addition, the relative level of interest (or stakes) of all concerned actors can be assessed (either by the analyst or by the actors themselves through a participatory exercise), thus allowing to attribute (or not) weights to their perceived impacts of each solution. By considering a broader range of perspectives from all potentially interested social actors, the analytical and decision-making process becomes more inclusive and thus more trustworthy.

(2) Supporting host communities. Institutional trust is improved when potentially impacted parties receive support that allows them to hire their own experts who will conduct and publish their own reviews (Reset Report, 2018). In the U.S. program, this would allow potential host communities, defined as both local communities and states on the one hand or tribal nations in the U.S. context, to make their own judgement on proposed solutions and, thus, increase their negotiating power with the federal government. More importantly, if the technical feasibility of a solution proposed by the implementer is confirmed through an independent review process, it would dramatically increase the social acceptability of this solution. This paper thus seeks to support potential host communities by offering a tool for the rapid appraisal and comparison of alternative spent fuel management strategies.

(3) **Searching for compromise solutions**. In spent nuclear fuel management, like in other complex decision problems in environmental and public policy, there is a need to search for compromise solutions that are not necessarily the "best" solutions either technically or socially. It is now well accepted that a workable approach to spent fuel management is towards finding solutions that can be demonstrated to provide adequate levels of both safety and social and political acceptance (Bonano et al., 2011). The STMCE framework considers technical and societal dimensions to be *equally important* in the description of a decision problem. Specifically, one can compare the performance of long-term spent nuclear fuel management strategies based on technical dimensions, societal dimensions, and their combination. In addition, the method includes a coalition formation process based on the perceived impact of the solutions proposed. This process supports the negotiation between parties over proposed alternatives and the identification of potential compromise solutions.

(4) **Reallocating power among parties**. The reallocation of power among the parties involved in the U.S. program has been already recommended by independent national and international experts (Reset Report, 2018). In particular, the national managing organization (at the moment the U.S. DOE) should engage with localities, tribes, and states to co-design a decision-making process and establish appropriate control mechanism over this process. In the STMCE method, the reallocation of

power is made through the use of a 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 social 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 social actors included. This approach thus reallocates power among parties where communities, tribes and states can have a strong, but conditional, veto power, so the decision will be made only among non-extreme solutions.

This paper presents a socio-technical multi-criteria evaluation (STMCE) framework and method that supports the search for *compromise solutions* for commercial spent fuel management. Section **2** presents the framework and method of the STMCE approach. Sections **3** and **4** provide a numerical example of the STMCE method based on the case of a decommissioned nuclear power plant in San Onofre, California. Section **5** discusses the advantages and limitations of the STMCE approach. Finally, section **6** concludes the paper.

2. Framework and methods

2.1. Framework

Many multi-criteria decision analysis approaches and methods are available to decision makers that can be applied to a virtually infinite number of specific decision problems often requiring the method to be adapted to each situation (Doumpos et al., 2019; Greco et al., 2016). In this paper, we adopt the *social 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, social 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 social actors, thus allowing for an integrated analysis of the problem. This framework thus overcomes the pitfalls of technocratic approaches to decision support by allowing the integration of different methods of sociological research and by highlighting distributional conflicts among options and social actors. By searching for compromise solutions rather than optimal solutions, social multi-criteria evaluation acknowledges that scientific knowledge and technological systems are themselves social constructions (Bijker et al., 2012; Jasanoff, 2006).

In operational terms, the social multi-criteria evaluation process consists of seven main steps (adapted from Munda, 2009):

1. Description of the relevant social actors, which 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 is 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).

A detailed discussion about the social multi criteria evaluation framework is provided in the supplementary method (**Appendix B**, section **B.1**).

2.2. Method selection

We now apply Munda's framework to the socio-technical multi-criteria evaluation (STMCE) of commercial spent nuclear fuel management strategies in the U.S. We provide a review of existing multi-criteria techniques and previous applications to nuclear waste management in the supplementary method (**Appendix B**, section **B.2**). The STMCE method presented here uses the outranking technique. Outranking methods are based on the concept of *partial comparability*. They consist in comparing criteria by means of partial binary relations based on indexes of concordance/discordance and then to aggregate these relations (Greco and Munda, 2017). Various approaches exist to generate and treat outranking relations depending on the type of decision problem at hand. Typical outranking methods seek to eliminate alternatives that are "dominated" by other in a particular comparison domain (DCLG, 2009). They thus attribute weights to criteria so they have more influence than others on the ranking of options. However, the disadvantage of weighing criteria in a social multi-criteria evaluation process is that social actors will unavoidably disagree about which criteria to weight more than others. In turn, their disagreement will make it more difficult to have the multi-criteria analysis method accepted and implemented. In the STMCE method, we avoid this problem by considering all criteria under the *equal weighting* assumption (Munda, 2009).

Different criteria can be used to select a multi-criteria analysis technique for decision support. Such criteria may include the internal consistency and logical soundness of the technique, its transparency, its ease of use, the amount of data required not being inconsistent with the importance of the issue considered, a realistic amount of time and manpower resource required for the analysis process, the ability of the technique to provide an audit trail, and whether it offers some software availability, where needed (DCLG, 2009). Outranking methods typically do not rank high on these criteria. However, outranking methods are comparatively better to address social conflicts and to account for the political realities of decision making; thus, they can be an effective tool in nuclear waste management. Recall that our objective is not to develop a multi-criteria analysis method for the exclusive use of decision-makers, *e.g.* the government. Rather, the STMCE method seeks to be used as an exploration and facilitation tool engaging with the various concerned parties in spent fuel management to highlight potential performance and preference gaps between options and how coalitions of actors over compromise solutions can form.

2.3. Main features

A multi-criteria technique must exhibit desirable properties if it is to be used in a social multi-criteria evaluation process (**Table B.1** of the supplementary method). Based on our objectives (section **1**), STMCE addresses each one of these desirable properties as follows:

1. **Compensation:** STMCE is based on a *partial compensation* of criteria that avoids the problem of trade-offs between the technical and societal dimensions by performing two separate multi-criteria evaluations as well as a combined evaluation. This allows one to reveal distributional conflicts and support the search for compromise solutions.
2. **Importance coefficient:** Even in social decisions, weights are never importance coefficients, *they are always trade-offs* seeking the complete compensation between values and criteria (Munda, 2008). STMCE avoids this issue by: *(1)* explicitly considering *indifference/preference thresholds* in the multi-criteria evaluation

(Munda, 2004), and *(2)* introducing weights only as *importance coefficients* and not as trade-offs in the social impact analysis (Munda, 2009).

3. **Mixed information:** The STMCE method uses an impact (or evaluation) matrix that may include quantitative, qualitative or both types of information. Specifically, information can be crisp, stochastic or fuzzy measurements of the performance of an alternative with respect to an evaluation criterion (Munda, 2012). The ability to handle mixed information is very flexible for real-world applications, especially for evaluating the performance of alternatives from a socio-technical perspective.
4. **Simplicity:** One important feature of the STMCE method is the relative simplicity of its mathematical procedure. This ensures the transparency of the overall multi-criteria process and allows social actors to use the analytical tool to generate their own rankings. To run a STMCE analysis, the user only needs to prepare a multi-criteria impact matrix and a social impact matrix (*e.g.*, a spreadsheet) to be loaded into STMCE.
5. **Hierarchy:** As in AHP, STMCE can include hierarchical relations across the various dimensions of analysis and criteria. This can be useful in complex systems such as geologic repositories that can be described across temporal, spatial and functional scales (Diaz-Maurin and Ewing, 2018). However, since the multi-criteria evaluation is based on a *no criterion weighting* approach, assigning the same weight to all the criteria does not guarantee that all dimensions of analysis (*e.g.*, management, occupational safety, public safety, economic) will have the same weight. This would be the case only under the condition that all dimensions have

the same number of criteria. Yet, forcing dimensions to have the same number of criteria would inevitably introduce redundancy (if criteria are added) or reduce exhaustiveness (if criteria are removed), which is an undesirable property of any multi-criteria evaluation. An alternative approach can be to assign the same weight to each dimension and then to distribute proportionally each weight among the criteria. As one understands, the question of weighting criteria inherently implies trade-offs. Assigning the same weight to all criteria implies that different dimensions are weighted differently, whereas assigning different weights to criteria would guarantee that all the dimensions are equally weighted. In STMCE, criteria are not weighted ab can work with both approaches.

6. **Discrete decision problem:** The STMCE method is used to evaluate long-term spent fuel management options framed as a discrete multi-criteria decision problem where feasible options are known. One important principle of STMCE is that, like in Munda's approach, *dominated* alternatives shall not be eliminated from the evaluation. Indeed, as the evaluation seeks compromise solutions rather than optimal solutions, having a ranking of alternatives will be more useful than simply knowing what the "best" option is. In fact, in the case of spent fuel management in the United States, having a federal geologic repository is evidently the best option from the perspective of the permanent isolation of the waste. Yet, it is also the most controversial solution from a political and social point of view because of the issues associated with selecting a site and demonstrating its long-term safety (Reset Report, 2018; US NWTRB, 2015). Given the current stalemate of the U.S. disposal

program, it may be more preferable from the perspective of local communities and states to implement a spent fuel management strategy that ranks second (and so, not necessarily technically "bad") but that may reduce social conflicts and help to achieve the ethical imperative of handling radioactive waste (Carter, 1987).

7. **Thresholds:** As mentioned, STMCE considers explicit *indifference/preference thresholds* in the multi-criteria evaluation. When comparing alternatives, an indifference threshold determines the difference in the criterion performance, at which they can be considered to be equally good (Wątróbski et al., 2019). However, in STMCE, it is possible to define strict preference and indifference areas, in place of the notion of "weak preference" (Roy, 1996) where an agent hesitates between indifference and preference (Munda, 2008). This can be justified by the long time scale involved in any scenario of spent nuclear fuel management—from decades of (interim) storage to over a hundred of years before geological disposal is achieved and the repository is closed. Over such period of time, one understands that there is as much uncertainty about the present preferences as there is about the future outcomes (Shrader-Frechette, 2000). For this reason, STMCE does not consider *fuzzy uncertainty* on the threshold values. However, STMCE introduces fuzzy uncertainty on the qualitative measurements by means of linguistic variables; as well as *stochastic uncertainty* on the quantitative measurements.
8. **Conflict analysis:** In the social impact analysis, STMCE uses the semantic distance between the linguistic variables (*e.g.*, "Good", "Bad", "Very bad") of any pair of social actors as a *conflict indicator* (Munda, 2008). The semantic distance allows

one to perform a fuzzy cluster analysis in which similarities/diversities among social actors are identified, thus coalitions (clusters) of multiple actors can form. In addition, STMCE can perform several multi-criteria evaluations for different dimensions of analysis (sets of criteria). For instance, in the spent fuel management decision problem, STMCE would first rank scenarios according to the two technical and societal impact matrices and then integrate both dimensions in one matrix. This will allow one to highlight potential conflicts in the ranking of alternatives.

Based on these features, the 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. Of particular interest, STMCE can handle quantitative, qualitative or both types of information. It can also integrate stochastic or fuzzy uncertainty on criteria measurements and fuzzy uncertainty on assessments of social impacts. A detailed description of the STMCE method, including mathematical procedures, is provided in the supplementary method (**Appendix B**, section **B.3**).

3. Material and data

We now provide a numerical example to illustrate how the STMCE method works and to facilitate the organization of stakeholder engagement activities. The numerical example corresponds to a simulation conducted based on materials from diverse sources (scientific papers, technical reports and media articles) about the case of a decommissioned nuclear power plant in San Onofre, California. The San Onofre Nuclear Generating Station (SONGS), located 50 miles north of San Diego, stores 3,855 spent fuel assemblies (approx. 1,609 metric tons)—the largest spent fuel inventory stored at an all-unit shutdown power plant in the country (Carter, 2018). The reactors at SONGS were shut down in 2013 and spent fuel assemblies have progressively been moved from water pools to dry casks located on two dedicated storage areas. Although storage in dry casks is considered as safe as storage in pools (National Research Council, 2006), this is not a permanent solution, and spent fuel assemblies will eventually have to be moved to another site. Background information and material supporting this numerical example are provided as supplementary material and data (**Appendix C**).

Although we use information about SONGS to conduct the analysis, we remind the reader that this is a simulation to demonstrate the efficacy of the methodology as it might be applied to the management of spent fuel in the U.S. The actual application of the method to a real situation of spent fuel management would require engaging with social actors (*e.g.*, through workshops, focus groups, in-depth interviews, questionnaires) over several months or years in order to (1) select the relevant social actors based on an assessment of their influence and interest; (2) select the relevant evaluation criteria and management strategies; (3) assess the social impact of the selected management strategies; (4) develop "what-if" scenarios to test the robustness of the ranking of strategies; (5) search for compromise solutions; and, finally, (6) support the formation of coalitions of stakeholder groups to implement these compromise solutions (**Fig. B.1**). Consequently, the results of the analysis presented here should not be used to make specific policy recommendations at SONGS or any other site storing spent fuel. Although a stakeholder engagement process is outside the scope of this paper, it has happened at SONGS (SONGS Task Force, 2020; Victor, 2014) and its findings were considered as part of the material for the simulation.

3.1. Management strategies

For a given reactor site, the long-term management of commercial spent fuel in the U.S. involves four basic processes: (i) storage onsite; (ii) storage at an interim storage facility; (iii) permanent disposal at a geologic repository; and (iv) transport from the reactor site to an interim storage and/or geologic disposal facility. More details about each process in this example are provided in the supplementary material and data (**Appendix C**). Using these key processes, we derive five generic long-term management strategies: (1) the fuel is transported directly to the proposed Yucca Mountain geologic repository in Nevada and permanently stored there (direct disposal); (2) after a period of on-site storage, the fuel is transported to and permanently stored at a federally-approved geologic repository (delayed direct disposal); (3) the fuel is stored first at a centralized interim storage facility and then disposed of at a geologic repository (interim storage and disposal); (4) the fuel is transported to an offsite interim storage facility and stored there until a permanent solution emerges (indefinite interim storage); and (5) the fuel is stored onsite at SONGS until a permanent solution emerges in the future (indefinite on-site storage). **Fig. 2** illustrates the pathways of each one of these long-term spent fuel management strategies and **Table C.2** of the supplementary material and data provides a detailed description of each strategy.

In order to compare the five strategies, we considered a time horizon of 100 years after Year 2020. Typically, in such long-term scenarios, analyses are bounded by an end-state of disposal. Indeed, the current strategy in the U.S. is that the spent fuel will have to eventually get to a geologic repository and that indefinite storage is not an option. Yet, the current stalemate of the U.S. disposal program—where no single group, institution or governmental organization is incentivized to find a solution (see discussion in **Appendix A**)—is questioning this assumption. In the analysis, we consider the possibility that spent fuel will not be disposed of in a geologic repository before the end of the century (scenarios 4 and 5).

Each one of the processes of onsite storage, interim storage and geological disposal may vary according to different variables. Uncertainties internal to each strategy are considered in the sensitivity/uncertainty analysis. **Table 1** presents the input parameters and associated value ranges considered for each long-term management strategy.

3.2. Evaluation criteria

The long-term management strategies are comparatively evaluated against multiple criteria organized in two dimensions of analysis: technical and societal. The technical dimension seeks to represent the perspective of management and business/commercial operations (back-end integration, cask repackaging, loading/unloading, occupational safety, etc.), whereas the societal view represents the perspective of local communities and states (costs, economic benefits, perceived risks to public safety, political uncertainty, etc.) where spent fuel is being stored (source) and where it will be stored and/or disposed (receiver).

For each one of the technical and societal dimensions, a set of criteria was selected. Criteria were selected so that they maximize exhaustivity and minimize redundancy in the description of each dimension. In this numerical example, we selected a total of 14 criteria—7 criteria for each dimension of analysis (**Table 2**). Recall that this is a simulation to illustrate the STMCE approach. The selection of criteria in a real application would require the involvement of relevant stakeholders. In this 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 when combining the two dimensions in the multi-criteria evaluation. However, having the same number of criteria for different dimensions is quite artificial and can be dangerous. Analysts could be tempted to choose the same number of criteria for each dimension even if these criteria were completely redundant (Munda, 2008). In the sensitivity/uncertainty, direct linear correlations between the criteria are then considered for a more realistic definition of random samples in the Monte Carlo simulations.

4. Results

4.1. Multi-criteria evaluations

Considering the five generic scenarios of long-term spent fuel management (**Fig. 2**), we evaluate their socio-technical performance against 14 indicators (**Table 2**). This problem can be synthesized in the multi-criteria impact matrix described in **Table C.3** of the supplementary material and data. Feeding this impact matrix as input to the mathematical procedure (see section **B.3.2** of the supplementary method), we run three multi-criteria evaluations: (1) with the 7 criteria of the technical dimensions; (2) with the 7 criteria of the societal dimensions; and (3) combining the 14 criteria of the technical and societal dimensions. For each multi-criteria evaluation we compare each pair of options according to each single indicator. For this, we apply the threshold model described in Eq. (1). In this example, we consider an indifference threshold q equal to the standard deviation σ for each range of values taken by each criterion. Although this assumption is acceptable for the present 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.

By introducing the indifference relations between alternatives, we then obtain the outranking matrix as described in Eq. (2). Finally, by applying Eq. (3), a mean ranking is obtained for each one of the three multi-criteria evaluations performed (**Table 3**). We then performed 500 Monte Carlo simulations varying each indicator of the evaluation matrix within its range of possible values (**Table C.3** of the supplementary material and data). For this example, 500 random samples are enough to obtain computational convergence of the rankings. Note that the random variable generation uses the `R` function `set.seed` that can produce the same sequence; hence, the Monte Carlo simulation is replicable.[1] **Fig. 3** presents the results of the sensitivity/uncertainty analysis for the three multi-criteria evaluations.

[1] The `R` Shiny application and data files used to perform the analysis are available at https://github.com/francoisdm/STMCE-SNF

The sensitivity/uncertainty analysis shows that, in this example, most rankings overlap each other so that no management strategy significantly dominates. That is, the likely ranges of variation of the ranking of management strategies (illustrated by the boxes in **Fig. 3**) are significantly overlapping, thus indicating that they are statistically equally performing. In a real application, considering a larger number of scenarios and more precise estimates of criteria values and preference thresholds would result in options being more discriminated from one another, that is, more robust rankings. Moreover, results show that any strategy can take the extreme ranking values (1 and 5) in all three analyses with a statistically significant probability of 1.5xIQR. However, this statistical similarity between management strategies ultimately comes from the type of *discrete* decision problem evaluated where ranking values can be given only natural numbers (1, 2, … , 5), thus reducing the statistical accuracy of such analysis.

In the analysis, both technical and societal views are subject to epistemic uncertainties for the criteria evaluated using linguistic variables evaluated by experts or stakeholders (criteria 1.2, 1.3, 1.7, 2.2, 2.3 and 2.5-2.7). For such criteria, uncertainty is treated using fuzzy sets that account for the ambiguity in the information about the system and thus the fuzziness in the estimated values—like for the social impact analysis.

4.2. Social impact analysis

We now perform an analysis of the social impact of the management strategies on the interests of social actors. For this, we consider a social impact matrix showing the perceived outcome of each one of the five scenarios according to 9 typologies of social actors (**Table C.4** of the supplementary material and data). We can then compare each pair of options according to each single actor's impact assessment. We apply the semantic distance described in Algorithm 1 and Eq. (11) (see section **B.3.3** of the supplementary method). We then compute the fuzzy indifference relations to obtain the similarity matrix as described in Eq. (12). **Fig. 4** presents the dendrogram obtained after applying the fuzzy clustering analysis to the social impact matrix (**Table C.4**). In this example, the dendrogram shows four possible coalitions C_i formed by:

- C_1 = actors 1, 4–6;
- C_2 = actor 2
- C_3 = actors 3, 7, 8; and
- C_4 = actor 9.

We can then rank the alternatives for each one of the four coalitions. Note that the ranking uses the *equal weighting* assumption of actors (see discussion in section **B.3.3**). **Table 4** presents the rankings of scenarios based on the social impacts for all actors combined and by coalitions.

We can now apply the proportional veto function as described in Eq. (14). In this example, a coalition can veto one strategy if it contains at least 4 social actors. We obtain that coalition C_1 (actors 1, 4–6) can veto the indefinite on site storage (5) strategy whereas coalitions C_2 , C_3 and C_4 cannot veto any strategy because they contain only one actor, three actors and one actor, respectively.

The use of the proportional veto function thus provides one or several coalitions with the ability to veto any subset of strategies proportionally to the fraction of social actors it contains. This allows to identify and eliminate the solutions that are affected by a high level of conflict. In a real application, however, a social impact analysis must include the participation of stakeholders to assess the impact of proposed management strategies on their interests. Moreover, the decision problem is asymmetrical in that the spent fuel is already stored on site. Therefore, even if the indefinite on-site storage (strategy 5) would be vetoed, the decision to remove the fuel requires linking the source and receiver in a same decision problem and to find mechanisms that make locally designed decisions binding at state and federal levels. Such mechanisms require important policy changes in the current U.S. nuclear waste management strategy (Reset Report, 2018).

5. Discussion

5.1. Limitations

Purpose: Any normative model suggesting how individuals should make multi-criteria evaluations or choices can be subject to criticism (DCLG, 2009). In its attempt at "rationalizing" the dimensions of choice when the "irrational", as some put it, often strongly affects outcomes in nuclear waste management (Bergmans et al., 2015; Tuler and Kasperson, 2010), STMCE is no immune to such criticism. For instance, because it uses mathematical procedures, STMCE can seem still attached to the idea that one can "solve" the waste problem (Ramana, 2018). But STMCE is not limited to a quantitative evaluation method. STMCE is embedded in a decision-support framework of the same name that takes the form of a social multi-criteria evaluation process. A large body of research now recognizes that decisions in nuclear waste management, to be successful and accepted, 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. That is, STMCE provides evaluations and highlights conflicts, but it cannot substitute for the decision-making process itself. Yet, because it highlights conflicts between actors' perspectives and identifies potential compromise solutions, STMCE can be an important step forward in spent fuel management policy in the U.S.

Scope: The paper focuses on the spent nuclear fuel management situation in the United States. As such, we did not review the siting processes used in the management programs of other countries. As discussed in the introduction, the U.S. program exhibits very specific characteristics—most notably the influences of national politics, the complex role of states, and the quantitative approach to safety—to which the method has been tailored. Countries with most advanced spent fuel disposal programs, such as Finland, Sweden and France, all have a very different political structure (Metlay, 2016). Moreover, as explained, STMCE is not a siting process method but, rather, an analytical and decision-support approach that contains a procedure to evaluate the socio-technical performance and social conflict of alternative strategies of spent fuel management.

Second, the paper does not explicitly discuss the consent-based siting approach that has been proposed by the federal government (US DOE, 2017, 2016b). Yet, the consent-based siting approach has not been implemented in the U.S., despite independent experts made it a central recommendation since almost a decade (Blue Ribbon Commission, 2012; Metlay, 2013; Reset Report, 2018).

Last, in the application, we considered typologies of social actors assuming that they are each representing a homogeneous perception about the impact of management strategies. In a real application, these typologies would have to be disaggregated to account for a variety of perceptions. The selection of relevant actors is a key aspect of the social multi-criteria evaluation process that requires a social process in itself.

Approach: The social multi-criteria evaluation approach is not well known in the nuclear waste management communities, including the analysts and planners developing management system evaluation frameworks as well as the engineers and scientists carrying reliability and safety analyses. In fact, the STMCE approach is a departure from conventional multi-criteria decision analysis (MCDA) methods that typically search for optimal solutions through a mathematical framework and are implemented by scientists hired by decision-makers in a "speak truth to power" approach. In contrast, STMCE is an approach that primarily seek to reallocate power among parties, highlight socio-technical conflicts on the proposed alternatives and search for compromise solutions. Simplicity, transparency and reproducibility are important features of the STMCE approach—as must be any use of "models" for public policy (Saltelli et al., 2020). The paper provides a discussion of multi-criteria frameworks and justifies our choice of the social multi-criteria evaluation framework over MCDA (section **2**). Moreover, the social multi-criteria evaluation approach—used as the foundation of STMCE—is a proven methodology that has been tried and applied in many real-world environmental and public policy problems (Munda, 2019).

Method acceptability: Among the various multi-criteria techniques available the outranking technique—used in STMCE—is well suited to indirectly capture some of the political realities of decision making (DCLG, 2009). Yet, the outranking approach can be dependent on some arbitrary definitions on what constitutes “outranking” and how the threshold values are set and can be subject to manipulation by the decision-makers. This can become a difficulty in implementing the technique because potentially concerned parties will try to influence on the choice of criteria and threshold values considered. The STMCE partially avoids this issue by performing the downgrading of options not according to the criteria (in the multi-criteria evaluation) but through the use of a proportional veto principle in the social impact analysis.

In a real-world situation, the STMCE method is likely not to be consensually viewed as authoritative. In fact, our objective is not to have STMCE accepted by the decision-makers and then applied to a decision problem framed by them. Otherwise, there would be no value in applying STMCE over other social multi-criteria evaluation and MCDA approaches. Rather, we see STMCE as a bottom-up, independent approach that provides a way to systematically and comparatively evaluate the socio-technical performance of different options against multiple criteria and to measure the level of conflict between the impacts perceived by social actors on these different options. This provides a new set of information that may be considered by stakeholders in the deliberation and decision-making process. Empowering social-actors, especially localities, tribes and states in their negotiation with the federal government and regulatory agencies, is a core objective of this approach.

Last, when applying STMCE to a real-world situation, social actors must be able to quickly and fully understand how the method works before they can participate to the selection of alternatives and criteria as well as to the assessment of preferences and impacts of alternatives. For this reason, a STMCE framework can be conducted only through a step-wise, iterative process that spans several months or years. In fact, such process must allow the so-called "extended peer community" (Funtowicz and Ravetz, 1993b)—which includes decision-makers and other concerned social actors—to critically review the assumptions of the analysis. Such quality control process, in turn, will add to the credibility and legitimacy of the methodology and, thus, to the trustworthiness of the process by the parties.

Method implementation: At a minimum, the social multi-criteria engagement process will require actors to participate in framing the decision problem, identifying alternatives, deciding on the criteria and threshold values and generating the social impact matrix. Yet, this process can be difficult to implement because of the difficulty to capture the preferences of the decision-makers and other concerned actors in a consistent fashion. In fact, there has been significant research and numerous applications on situations where the preferences of the decision maker (*e.g.*, a government agency) depend on the separate preferences of the actors, as well as other criteria. The extent to which a decision-maker or any actor cares about the decision is based on the potential consequences of the alternatives.

To structure any social multi-criteria evaluation therefore requires significant work defining the decision problem, decide on a set of alternatives for the decision, and list all the relevant criteria for their assessment. Naturally, the actors should be involved in the process. In addition, there is the necessity to establish useful measures for each criterion. To thoroughly structuring the decision to be faced, the analysts must therefore spend a significant amount of time with each actor to help them understand and express their preferences accurately. The use of linguistic variables coupled with a fuzzy set approach can facilitate this step (see section **B.3.3**). Moreover, STMCE is by nature an iterative process (**Fig. B.1** of the supplementary method). These issues must be considered in any application of the STMCE approach.

5.2. Advantages

Despite these limitations, 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 municipalities, tribes, states and groups of states. At local levels, the STMCE approach can help to compare the socio-technical implications of different management strategies considering the perspectives of both the source and receiver(s) of spent fuel. Communities living close to commercial nuclear reactor sites in the U.S. face the transition from an energy source to a waste storage. They are among the social actors with the highest stakes, yet they have a relatively low direct influence on spent fuel management strategies. Decisions will have to be made about the long-term spent fuel management strategies in the U.S. Yet, in the absence of a federal geologic repository in the foreseeable future, the long-term *national* strategy is likely to continue to encounter many issues preventing the achievement of geological disposal of the Nation's current spent fuel inventory. In this context, the possibility of creating a combined socio-technical compromise solution for storage and disposal *from the bottom up*—that is, at local levels between sources and receivers—should be explored. In order to empower local entities, tribes and states, platforms must be developed that allow them to create their own strategies and outcomes, supported by independent teams of experts. By evaluating concrete strategies, 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 objective and provides an example of how to conduct a socio-technical multi-criteria evaluation of long-term management strategies using the example of a decommissioned nuclear power plant in California.

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.

6. Conclusions

This paper presented a socio-technical multi-criteria evaluation (STMCE) framework and method for the comparison of long-term spent nuclear fuel management strategies and for conflict resolution through the search for compromise solutions—in contrast to optimal solutions typically sought for in most multi-criteria decision-analysis frameworks. In particular, the STMCE approach seeks to support local communities and states—both the sources and potential receivers of spent fuel—in the search of alternative management strategies for spent fuel that, in the absence of federal interim storage or geologic disposal capacity, is stranded at 15 decommissioned reactor sites across the country (Reset Report, 2018).

This paper provides (1) a discussion about the issues faced by the spent fuel management program in the U.S.; (2) a review of existing multi-criteria analysis methods; (3) a detailed description of the STMCE framework and method; (4) a numerical example showing how the method can be applied to other specific situations; and, finally, (5) a discussion about the method’s advantages and limitations. The STMCE approach responds to the stated objectives of (i) increasing the pool of perspectives through the introduction of the concept of *social actor* into the analysis; (ii) supporting host communities by offering an independent, transparent and replicable tool for the comparison of the socio-technical impact of spent fuel management strategies; (iii) searching for compromise solutions by performing a coalition formation process; and (iv) reallocating power among parties through the application of the proportional veto principle.

Besides commercial spent nuclear fuel management, the STMCE framework could be used also in other decision problems of the nuclear fuel cycle having socio-technical implications. In particular, it could be useful for the selection of sites for disposal of low- and intermediate-level nuclear waste, the selection of remediation strategies for radioactively contaminated structures and soils, the performance comparison of nuclear waste repositories in different geologic settings, as well as, the choice of new nuclear fuel designs and advanced reactor types with appropriate nuclear waste management and environmental considerations.

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Tables

Table 1. Input parameters and associated value ranges for each long-term management strategy.

Input parameters	**Unit**	**Scenario 1**	**2**	**3**	**4**	**5**
		Direct disposal (optimistic)	**Direct disposal (delayed)**	**Interim storage and disposal**	**Indefinite interim storage**	**Indefinite on-site storage**
Duration of on-site storage	Years	10-20	30-50	10-20		100
Duration of interim storage at CISF	Years	0		10-40	80-90	0
Repackaging during storage (replacement)	Nb. canisters	0			0/123	
Repackaging before disposal (MPC-37 into smaller DPCs)	Nb. canisters	0/73			0	
Transportation distance to CISF and/or repository	Miles	250-2000		500-3000	250-1000	0
Total unitary transportation cost	$/cask-mile	70-170		48-130	70-170	n/a
Probability of fractional release event during repackaging	$x10^{-2}$	0-0.55			0-0.79	

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

Table 2. Criteria used for the numerical example.

Criterion		Unit	Type of var.	Type of uncert.	Direction	Corr.
Technical dimension						
1.1	Duration of surface storage (after 2020)	Years	Quant.	Stoch.	Minimize	
1.2	Improving back-end integration	-	Ling. var.	Fuzz.	Maximize	
1.3	Business/commercial soundness	-	Ling. var.	Fuzz.	Maximize	
1.4	Probability of fractional release event during transport	$x10^{-2}$	Quant.	Stoch.	Minimize	
1.5	Probability of fractional release event during on-site storage	$x10^{-2}$	Quant.	Stoch.	Minimize	
1.6	Probability of fractional release event during interim storage and disposal	$x10^{-2}$	Quant.	Stoch.	Minimize	
1.7	Risk of external events with potential public safety implications	-	Ling. var.	Fuzz.	Minimize	
Societal dimension						
2.1	Total cost of storage, transport and disposal (when applicable)	M$	Quant.	Stoch.	Minimize	
2.2	Economic benefits from on-site storage (source)	-	Ling. var.	Fuzz.	Maximize	
2.3	Economic benefits from interim storage and/or disposal (receiver)	-	Ling. var.	Fuzz.	Maximize	
2.4	Financial risk from postponed investment costs of disposal (incl. repository closure)	B$-year	Quant.	Stoch.	Minimize	1.1
2.5	Risk perception of public exposure during on-site storage (source)	-	Ling. var.	Fuzz.	Minimize	
2.6	Risk perception of public exposure during interim storage and/or disposal (receiver)	-	Ling. var.	Fuzz.	Minimize	
2.7	Social, political and international uncertainty potentially affecting management strategy	-	Ling. var.	Fuzz.	Minimize	1.1

Notes: Correlations are direct linear (when applicable). Correlations across technical and societal dimensions are considered only in the multi-criteria evaluation combining the two dimensions. Abbreviations: Bin., binary; Corr., correlation; Fuzz., fuzzy; Ling., linguistic; Quant., quantitative; Stoch., stochastic; uncert., uncertainty; var. variable.

Table 3. Mean ranking of management strategies from the multi-criteria evaluations.

Strategy	**Technical view**	**Societal view**	**Combined**
(1) Direct disposal (optimistic)	1	1	1
(2) Direct disposal (delayed)	4	3	4
(3) Interim storage and disposal	3	4	2
(4) Indefinite interim storage	2	5	5
(5) Indefinite on-site storage	5	2	3

Note: Strategies are ranked from 1 (most performing) to 5 (least performing). Rankings based on 500 Monte Carlo simulations.

Table 4. Mean ranking of management strategies from the social impact analysis.

Strategy	**All**	**Coalition 1**	**Coalition 2**	**Coalition 3**	**Coalition 4**
(1) Direct disposal (optimistic)	2	1	5	1	3
(2) Direct disposal (delayed)	4	4	4	3	2
(3) Interim storage and disposal	1	1	1	2	3
(4) Indefinite interim storage	3	1	1	5	3
(5) Indefinite on-site storage	5	5	3	4	1

Note: Strategies are ranked from 1 (most performing) to 8 (least performing). Tied strategies are ranked with highest value of the concerned positions. Coalition composition are as in **Fig. 4**: C1 = actors 1, 4–6; C2 = actor 2; C3 = actors 3, 7, 8; and C4 = actor 9.

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Figures

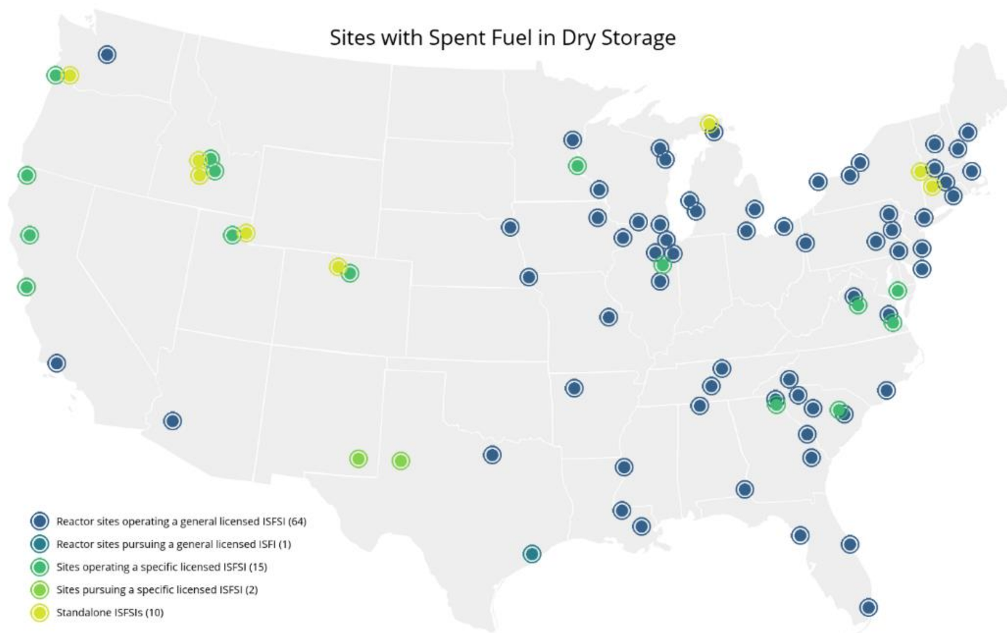

Fig. 1. Map of the independent spent fuel storage installations (ISFSIs) authorized to store dry spent fuel in the U.S. (as of March 2018). Source: adapted from (US NRC, 2018).

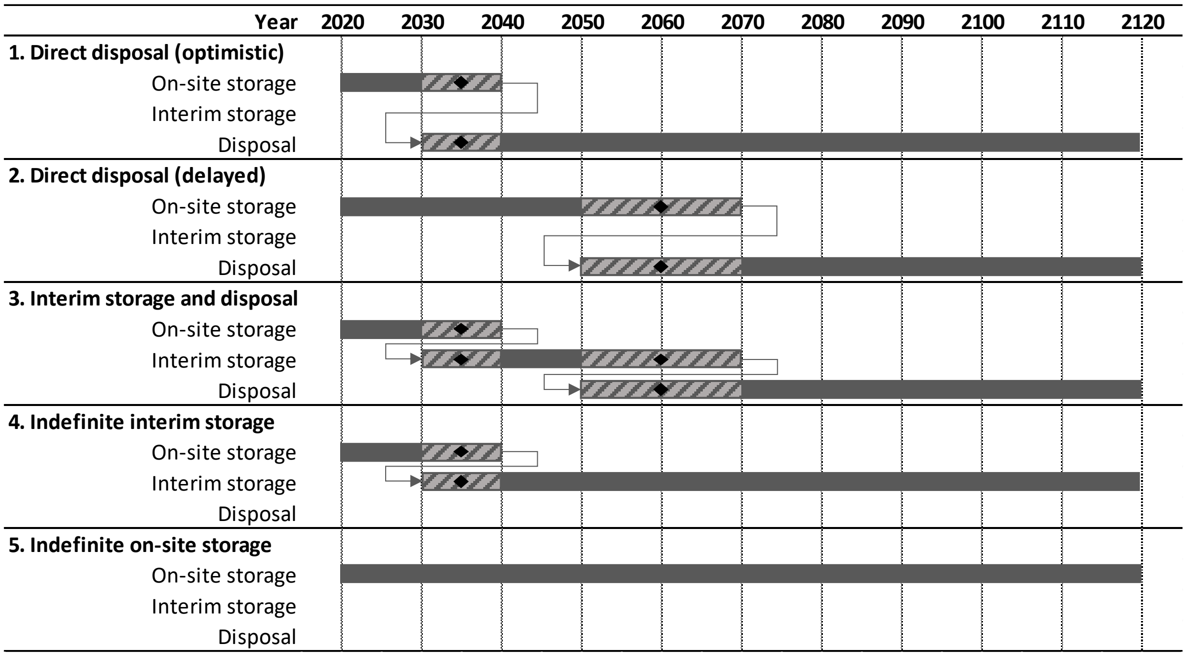

Fig. 2. Pathways of the five generic long-term management strategies considered in the analysis. Note: Scenarios start at Year 2020.

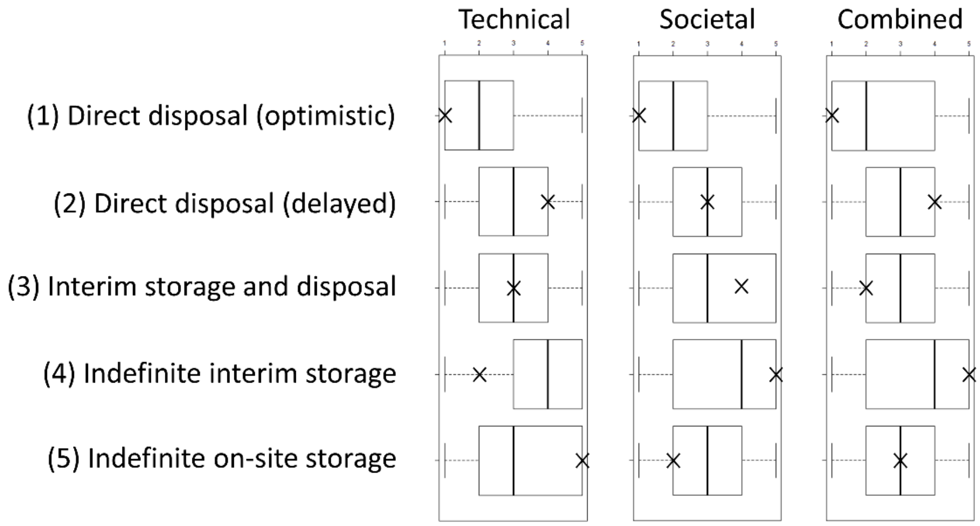

Fig. 3. Rankings of the generic long-term spent fuel management strategies obtained from the Monte Carlo simulation for 500 random samples. Note: Strategies are ranked from 1 (highest performance) to 8 (lowest performance). Each box corresponds to the interquartile range (IQR) which is a measure of statistical dispersion, being equal to the difference between 25th (Q1) and 75th (Q3) percentiles. Dotted lines are points within 1.5 times the 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 **Table 3**.

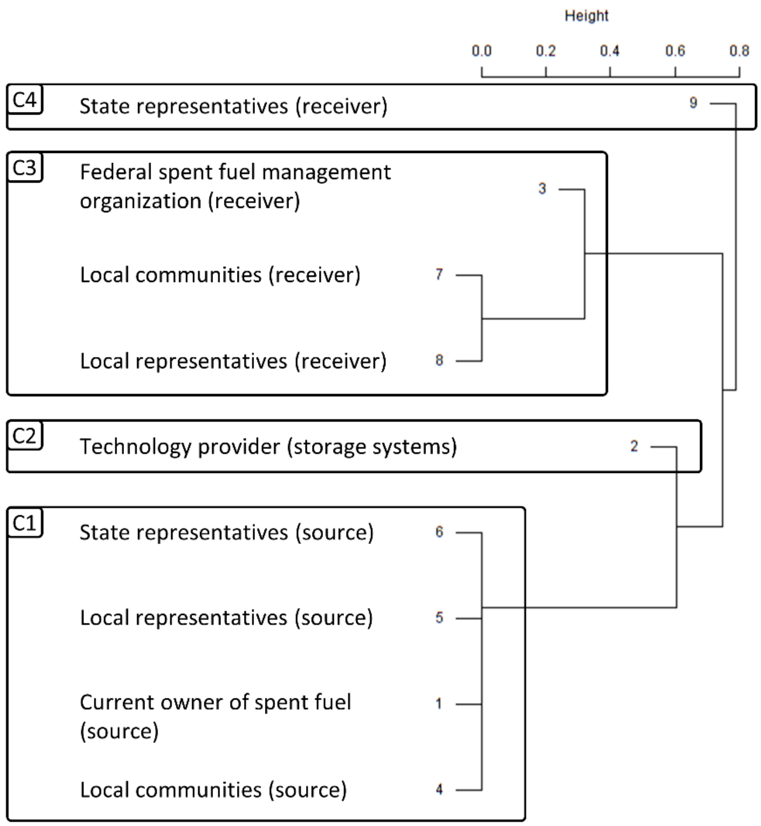

Fig. 4. Dendrogram of the coalition formation process based on the social impact matrix (**Table C.4** of the supplementary material and data).

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Appendix A. Supplementary introduction

A.1. Issues of spent fuel management in the U.S.

For decades, the U.S. spent nuclear fuel management program has suffered from many factors that made it progressively ineffective, imbalanced and even contested. These factors include major changes to the original law, a succession of amendments to the Nuclear Waste Policy Act of 1982, a changing regulatory framework, an unpredictable funding, significant policy changes with changing administrations, conflicts between Congressional and Executive policies, as well as an inadequate public engagement in decisions about nuclear waste storage and disposal strategies (Reset Report, 2018). These factors profoundly affected the U.S. program which became (Reset Report, 2018, p. 1): "an ever-tightening Gordian Knot—the strands of which are technical, scientific, logistical, regulatory, legal, financial, social and political—all subject to a web of agreements with states and communities, regulations, court rulings and the Congressional budgetary process. There is no single group, institution or governmental organization that is incentivized to find a solution, nor is any single institution entirely responsible for the failure of the U.S. program." Three critical issues affecting the U.S. spent fuel management program justify the need for a socio-technical decision-support approach.

A.1.1. Ineffective management program

Under the Nuclear Waste Policy Act, the federal government, through the U.S. Department of Energy (DOE), is the sole responsible for the disposal of the nation's commercial spent nuclear fuel (US GAO, 2014). Yet, the failure of the federal government to take ownership on the spent fuel since 1998 has led to court-ordered compensation payments to the utilities charged with the safe temporary storage at or near reactor sites until a geologic repository becomes available for disposal (Reset Report, 2018). The reasons for the government's failure to have a federal repository for commercial nuclear waste constructed and operating are multiple and complex. However, there is a broad consensus among experts that the U.S. nuclear waste management program has become a partisan issue in national politics drawing on diverging public opinions (Blue Ribbon Commission, 2012; Reset Report, 2018; US NWTRB, 2015).

The political maneuvering affecting the nuclear waste management program has been evident as regard its financing. In the U.S., nuclear waste disposal is already financed since the 1982 NWPA by the ratepayers through the collection of a fixed fee of one-tenth of one cent per each kilowatt-hour of nuclear-generated electricity (revised annually, though never changed) following the principle of the "polluters pays" (Blue Ribbon Commission, 2012). The revenues from the collected fee are then contributing to the government's Nuclear Waste Fund. The Fund was established for covering exclusively the cost of the disposal of commercial nuclear waste so it would be free from the Federal budget constraints. In that sense, it was often referred to in Washington D.C. as a "trust fund" giving the impression of being immune from political intervention (Saraç-Lesavre, 2018). However, the spending mechanism of the Fund depends on the annual budgeting process that is subject to the approval by Congress through appropriations. Thus, the disposal program has to compete every year for federal funding that makes it subject to the budget constraints and uncertainties that the Fund was especially created to avoid. Over time, this dependence of the Nuclear Waste Fund on the annual federal budgeting process has hampered the long-term planning that the U.S. spent nuclear fuel management program requires by making the Fund vulnerable to immediate budgetary politics (Saraç-Lesavre, 2018). But because the U.S. was not making progress in developing a geologic repository, a Federal court ruled in 2014 to suspend the collection of the fee (Reset Report, 2018). By 2015, the Fund total had accumulated over $40 billion and it continues to grow significantly thanks to interest. Besides, due to successful lawsuits against the Federal government for not taking ownership of the fuel at sites across the country, the utilities now receive approximately $650 million per year in compensation from the Judgement Fund (not related to the Nuclear Waste Fund). By 2018, the Judgment Fund, paid for by taxpayers, had paid out $5.3 billion and payments are projected to reach $23.7, even if the federal government begins to accept spent fuel before 2030 (Reset Report, 2018).

To protect the long-term budgeting of the spent nuclear fuel management program from political influences, some experts have recommended passing new legislation that provides access to the Nuclear Waste Fund and fees independent of the annual Congressional appropriations process while still being subject to rigorous independent financial and managerial oversight (Reset Report, 2018). In addition, other independent expert panels have called for the creation of a new federal agency that would take over the responsibility of managing commercial radioactive waste in the U.S.; thus, independently from the changing political context (Blue Ribbon Commission, 2012; Davis et al., 2012). Such a reform of the U.S. program by the creation of a new national radioactive waste management organization with a new funding mechanism, however, is likely to become itself a political battle. Congress has been shown in multiple occasions unwilling to cede significant power to the states and tribal nations (US NWTRB, 2015). For instance, the 1997 Nuclear Waste Policy Amendments Act included the creation of the Office of the Nuclear Waste Negotiator in charge of identifying a volunteer site for either a centralized interim storage facility or, less likely, a geologic repository. But, just as the Negotiator was starting negotiations with the Mescalaro Apache nation, Congress disbanded the office. Therefore, even if successful, reforming the U.S. program would still take many years, especially if a new management organization is to be authorized by Congress, funded, staffed and fully launched.

A.1.2. Imbalanced power distribution

Under the current U.S. policy, local communities and tribal nations have virtually no power on the decision-making process other than, indirectly, through elections at state level. So far in the U.S., localities and tribes have had no real negotiating power with the federal government or regulatory agencies about which sites are selected and how the safety of a repository project is assessed. Moreover, the implementer of the nuclear waste management program, the U.S. DOE, is not required to respond to comments and recommendations from independent scientific commissions and boards, such as the National Academies or the Nuclear Waste Technical Review Board, despite having expressed diverging views on multiple occasions as regard those of the Administration (Alley and Alley, 2012; Diaz-Maurin and Ewing, 2018). This power imbalance is reinforced by the existence of strong socio-economic drivers of public acceptance. That is, local communities are more likely to accept hosting a federal repository or interim storage facility that will bring jobs and tax income if they are economically impoverished (Ramana, 2013). In particular, because of the severe and long-lasting socio-economic impacts from nuclear power plant closure and decommissioning (NDC, 2020), local communities would be even more likely to volunteer to become host communities for potential disposal and storage sites if they live close to an operating or decommissioned plant (Greenberg, 2009). Yet, support from local communities is not sufficient to achieve public acceptance as nuclear waste management strategies necessarily involve larger regions, namely the state (Ramana, 2018). In fact, because of a specific political structure, in the U.S., local autonomy often conflicts with state control over repository siting and selection of transport routes (Bonano et al., 2011). In fact, state-level actors often exhibit diverging perceptions and preferences over proposed solutions as compared with local communities and federal agencies. For an example, see supplementary material and data (**Appendix C**).

In the U.S., states are widely viewed among experts as one main obstacle to nuclear waste management by preventing local communities from negotiating solutions directly with the federal government and unduly using of their veto power. For instance, in the late 1990s, when local communities expressed interest in hosting a repository, their states vetoed the agreements with the Nuclear Waste Negotiator. Later, in 2002, the state of Nevada vetoed the President's decision to host a repository at Yucca Mountain despite strong local support by the potential host county, Nye County (Bonano et al., 2011). Yet, past decisions by Congress and the Administration help explain the skepticism of states over proposed solutions. In the 1980s, when the Administration's strategy was toward having multiple regional repositories, states had no voice in selecting sites that were instead selected by Congress based on a list made by the Administration (Carter, 1987; US NWTRB, 2015). Later, after the strategy had changed to only building one repository and the state of Nevada vetoed the Yucca Mountain project, the Administration revised its siting rule and had Congress pass a resolution, by simple-majority vote under the current Law, overriding Nevada's veto power and approving the Yucca Mountain site (US NWTRB, 2015; Vandenbosch and Vandenbosch, 2007). Because states are not involved in the negotiations over nuclear waste management strategies in the U.S., they are more likely to use of their legal powers through vetoing or challenging in courts any decision being proposed.

A.1.3. Competing risk rationalities

Nuclear energy facilities are different from other energy technologies and public policy issues in that their risks are strictly regulated. In the U.S., federal regulatory agencies, such as the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Environmental Protection Agency (EPA), and federal management organizations, such as the U.S. DOE, are expected to account for both technical and social dimensions in their responsibilities. Yet, the legal and regulatory frameworks demand a very rigorous and objective form of knowledge so that courts and regulatory agencies can make technological decisions (Jasanoff, 1990). This has led to the creation of specific methods of risk analysis that rely on the unbounded quantification of risk levels as calculated by mathematical models (Porter, 1995). However, this "rationalization" of risk is said to be made at the expense of the plurality of legitimate perspectives about the very nature of the risk

(Funtowicz and Ravetz, 1993). Seeking objectivity in the regulatory process, and consequently, in the decision process, has resulted in a standard of rationality that has become the preferred strategy to mitigate the overwhelming public distrust by regulatory agencies unable to negotiate solutions. In fact, U.S. regulatory agencies have long been unable to negotiate solutions with communities over environmental conflicts (Jasanoff, 1990; Robinson et al., 2017). A prime example of this problem can be found in the regulation of chronic long-term risk from low-level radiation exposure affecting communities in Missouri's North St. Louis County (Diaz-Maurin, 2018). This conflict has highlighted the cultural gap that exists between the federal bureaucracy and lay people's lives over the perception of what risk is—a widespread and long-observed phenomenon (Wynne, 1992). Such gap sustains public distrust in the institutions in charge of regulating risk and implementing risk mitigation plans. More generally, the existence of incommensurable perceptions between "insiders", mostly focusing on the technical impacts and financial costs, and "outsiders", mostly focusing on the social, economic and environmental impact, is at the origin of the controversy of nuclear energy technologies (Diaz-Maurin, 2014; Diaz-Maurin and Kovacic, 2015).

Although there is no legal link between the operation of nuclear power reactors and the disposal of radioactive waste materials, these two technologies are undeniably connected in the public perceptions (Greenberg, 2012). The link between nuclear power and radioactive waste management is reinforced with U.S. regulatory agencies using for geologic repositories the same probabilistic risk analysis methods that were first developed for nuclear reactors (Diaz-Maurin and Ewing, 2019). However, since its inception in the late 1970s, this “rationalization” approach to risk and regulation has been challenged by earth scientists, geotechnical engineers and social scientists who expressed concern over the use of mathematical models for assessing the risks of geological disposal (Bredehoeft et al., 1978; Ewing, 2006; Ewing et al., 1999; Metlay, 2000; Oreskes et al., 1994; Shrader-Frechette, 1993). In contrast, proponents of the rationalization of risk, mainly nuclear engineers and mathematicians, have consistently dismissed public concerns over this approach as being irrational (e.g., Peterson, 2017) and rooted in ignorance (Bergmans et al., 2015; Flynn et al., 1992; Greenberg, 2012; Leiss, 1995; Rossignol et al., 2017; Slovic et al., 1991; Tuler and Kasperson, 2010). But, case in point, using risk assessment methods when strong knowledge about the probabilities and outcomes does not exist has also been credited as being irrational and unscientific (Ewing et al., 1999; Stirling, 2007). For over 40 years now, nuclear waste management has been a case of “competing rationalities” of risk between the optimistic view of technocratic rationalists and the cautionary view of concerned public and scientists (Lee, 1980).

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Appendix B. Supplementary method

Supplementary method to this article can be found online at:

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Appendix C. Supplementary method

C.1. Background information on SONGS

The San Onofre Nuclear Generating Station (SONGS) is located between Los Angeles and San Diego in California. 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.[2] 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

[2] 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 differed 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; that is, by the potential economic return on investment from the re-use of the reprocessed uranium and plutonium in reactors.

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).

C.2. Institutional analysis

This section provides an example of an institutional analysis that describes the relevant social actors and their positions regarding long-term spent fuel storage at SONGS. This discussion is for illustrative purposes and does not claim to be exhaustive of the history at SONGS. The institutional analysis summarizes the social "atmosphere" by listing relevant social actors (persons or organizations), their stakes and position over, in this example, the long-term storage of spent fuel at SONGS. In the STMCE approach, the institutional analysis seeks to support the social impact analysis for the selection of relevant actors and for the assessment of the social impact of proposed management strategies.

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, 2018a). Local municipal governments and many members of the public near SONGS strongly oppose leaving the spent fuel on site indefinitely (**Table C.5**; see also (Reset Report, 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 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 strategy. 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.

C.3. Application

C.3.1. Key processes

For a given reactor site, the long-term management of commercial spent fuel in the U.S. involves four basic processes: (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 now describe each process in the context of this paper.

Onsite storage

Currently in the U.S., two storage methods exist for the spent fuel after it is removed from the reactor (Bruno et al., 2020). Spent fuel is either stored in specifically designed water pools at individual reactor sites or stored in dry cask storage systems at independent spent fuel storage facilities (ISFSIs) located at reactor sites or away-from-reactor sites. At SONGS, the transfer operations of all fuel assemblies from pools to dry casks stored onsite were completed in August 2020 (SCE, 2020a). The away-from-reactor storage system consists of two dry casks storage areas (**Fig. C.5**): (1) 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/casks (DPCs) with up to 24 fuel assemblies each; and (2) an underground dry storage module, called HI-STORM UMAX, hosting used fuel from units 2/3 in 73 multi-purpose canisters (MPCs) with up to 37 fuel assemblies each.

Interim storage

Consolidated interim storage of spent fuel is now considered a serious option in the U.S. spent fuel management policy landscape (Reset Report, 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 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 NWPA and, among other issues, a 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, a state already hosting a repository called the Waste Isolation Pilot Plant (WIPP) for transuranic military waste. 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, 2020a).

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—only 40 miles away from the proposed HI-STORE interim storage facility. 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.

In the analysis, we considered the following assumptions for interim storage:

- An interim storage facility is located either in New Mexico, Texas or California.
- The estimated cask lifetime is 100 years, after which it requires to be replaced.

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.

In the analysis, we considered the following assumptions for geological disposal:

- A geologic repository is located either at three possible sites: in the west (*e.g.*, at the proposed Yucca Mountain repository site in Nevada), in the east or in California.
- The technical feasibility and social acceptability of a geologic repository at a specific site is not within the scope of this generic example. For instance, California may not have a suitable geology to host a repository. Therefore, in-state geological disposal is considered for illustration purposes in this example.

Transportation

In the U.S., both routes by trucks or rail are two effective transport options implying different trade-offs in relation to management, safety and costs (National Research Council, 2006). Yet, with over 20,000 MTU of spent fuel already in large dual-purpose canisters/casks (DPCs) then transportation will mostly be by rail, whereas large heavy-haul trucks or barges would be used to move the DPCs to intermodal transfer stations where they would be put on rail. In the analysis, we considered the most recent cost estimates available for commercial spent fuel transportation (Kalinina and Busch, 2014).

In the analysis, since both interim storage and geological disposal are hypothetically considered inside and outside California, we considered several generic locations for interim storage facilities and/or geologic repositories: in the west, in the east and in California (*i.e.*, in-state). These locations are used for illustrative purposes in this paper. An actual site would have to satisfy social and technical requirements (US NWTRB, 2015). That is, these generic locations are used 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.

Using these locations, we then estimated the approximate transport distance for each one of the hypothetical itineraries from the SONGS site to an interim storage facility and/or geologic repository, and from an interim storage facility to a geologic repository.

Refer to as: Diaz-Maurin, F.; Yu, J.; Ewing, R.C. Socio-technical multi-criteria evaluation of long-term spent nuclear fuel management strategies: A framework and method. *Science of the Total Environment* **In press**. Available at: [10.31223/X5459S](10.31223/X5459S).

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Table C.5. Social actors, scale of action, stakes and position regarding long-term management of spent fuel at SONGS.

Social actor	Scale	Stakes	Position	Ref.
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)
San Diego Gas & Electric (SDG&E)	Local	Owns 20% of SONGS.	Positive on dry cask storage system.	(Garcia and Levin, 2017)
City of Riverside	Local	Owns approx. 2% of SONGS	Public opinion is unknown.	("What are Nuclear Electric Costs?," 2020)
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, 2018b)
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)
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)

Social actor	Scale	Stakes	Position	Ref.
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)
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 leaks and the need for casks to be properly monitored and inspected.	(Douglas, 2018)
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)
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)
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)
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, 2018c)
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	(Governor of California, 2020)

Social actor	Scale	Stakes	Position	Ref.
			"safer at home" directive in response to the COVID-19 pandemic.	
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)
California State Parks (CSP)	State	SONGS located within CSP's constituency.	No specific position on SONGS.	(California State Parks, 2020)
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, 2018)
California State Coastal Commission (CSCC)	State	SONGS located within CSCC's constituency.	Granted a permit to SCE to store the waste onsite.	(Nikolewski, 2019)
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, 2020b)
U.S. Department of Energy (DOE)	National	According to the NWPA, 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 Report, 2018)
U.S. Department of the Navy, Marine	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	(St John, 2017)

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Social actor	Scale	Stakes	Position	Ref.
Corps Base Camp Pendleton (DoN)			Complex, which is off the beach on opposite side of I-5 and at a higher level.	

Refer to as: Diaz-Maurin, F.; Yu, J.; Ewing, R.C. Socio-technical multi-criteria evaluation of long-term spent nuclear fuel management strategies: A framework and method. *Science of the Total Environment* **In press**. Available at: 10.31223/X5459S.

Table C.6. Description of the generic long-term spent nuclear fuel management strategies.

ID	Scenario	Description	Assumptions
1	Direct disposal (optimistic)	10-20 years on-site storage + shipment to YM geologic repository	This scenario assumes the Yucca Mountain (YM) repository is licensed and opens by 2035 (+/-5 yrs).
2	Direct disposal (delayed)	30-50 years on-site storage + shipment to YM or other geologic repository	This scenario assumes the YM repository or another federally-owned NRC-licensed geologic repository opens by 2060 (+/-10 yrs).
3	Interim storage and disposal	10-20 years on-site storage + shipment to CISF + 10-40 years storage at CISF + shipment to YM or other geologic repository	This scenario assumes a privately-owned NRC-licensed CISF opens by 2035 (+/-5 yrs) and the YM repository or another federally-owned NRC-licensed geologic repository opens by 2060 (+/-10 yrs).
4	Indefinite interim storage	10-20 years on-site storage + shipment to CISF + 80-90+ years storage at CISF	This scenario assumes a privately-owned NRC-licensed CISF opens by 2035 (+/-5 yrs) and no geologic repository becomes available before 2120.
5	Indefinite on-site storage	100+ years on-site storage	This scenario assumes the Yucca Mountain repository is cancelled and no CISF or geologic repository becomes available before 2120.

Note: Geologic repository assumed to include a canister processing facility for wet repackaging of some dual-purpose canisters/casks (DPCs) before disposal. Abbreviations: CISF, consolidated interim storage facility; NRC, U.S. Nuclear Regulatory Commission; YM, Yucca Mountain.

Refer to as: Diaz-Maurin, F.; Yu, J.; Ewing, R.C. Socio-technical multi-criteria evaluation of long-term spent nuclear fuel management strategies: A framework and method. *Science of the Total Environment* **In press**. Available at: 10.31223/X5459S.

Table C.7. Example of socio-technical impact matrix of spent fuel management strategies.

Cr. #	**Scenario**				
	1	**2**	**3**	**4**	**5**
Technical dimension					
1.1	15 [10, 20]	40 [0, 88]	0 [0, 88]	6 [0, 246]	6 [0, 246]
1.2	High	High	Very high	High	Very low
1.3	Average	Moderately high	High	Very high	High
1.4	0.99 [0.49, 5.2]	0.99 [0.49, 5.2]	2.0 [0.99, 7.8]	0.99 [0.49, 5.2]	0 [0, 0]
1.5	1.1 [1.1, 1.4]	1.1 [1.1, 1.4]	1.1 [1.1, 1.4]	1.1 [1.1, 1.1]	0.9 [0, 1.9]
1.6	1.1 [1.1, 2.0]	1.1 [1.1, 2.0]	2.2 [2.2, 3.4]	1.5 [1.1, 1.9]	0 [0, 0]
1.7	Very low	Moderately low	Very low	Low	Average
Societal dimension					
2.1	860 [610, 1190]	1110 [590, 1910]	1390 [760, 2370]	1400 [1170, 1620]	1060 [1000, 1120]
2.2	Very low	Very low	Very low	Very low	Moderately high
2.3	High	High	Very high	Very high	Very low
2.4	0.32 [0, 2.6]	0.86 [0, 4.3]	0.86 [0, 3.4]	66 [23, 160]	66 [23, 160]
2.5	Moderately high	High	Moderately high	Moderately high	Very high
2.6	Moderately high	Moderately high	High	Very high	Average
2.7	Moderately high	Very high	Very high	High	Very low

Note: Values are indicated as Median [Minimum, Maximum] (stochastic uncertainty). Linguistic variables using fuzzy set theory (fuzzy uncertainty).

Table C.8. Simulation of the social impact of spent fuel management strategies on typologies of social actors.

ID	**Social actor**	**Scenario 1**	**2**	**3**	**4**	**5**	**Position (hypothetical)**
		Direct disposal (optimistic)	**Direct disposal (delayed)**	**Interim storage and disposal**	**Indefinite interim storage**	**Indefinite on-site storage**	
1	Current owner of spent fuel (source)	Very good	Bad	Very good	Very good	Very bad	Wants to sell the plant site for decommissioning
2	Technology provider (storage systems)	Bad	More or less bad	Very good	Very good	Good	Supplies casks/canisters at current site and is owner of proposed commercial CISF
3	Federal spent fuel management organization (receiver)	Very good	Good	Good	Very bad	Very bad	Supports direct disposal strategy
4	Local communities (source)	Very good	Bad	Very good	Very good	Very bad	Against on-site storage (NIMBY)
5	Local representatives (source)	Very good	Bad	Very good	Very good	Very bad	Against on-site storage (NIMBY)
6	State representatives (source)	Very good	Bad	Very good	Very good	Very bad	Against on-site storage (NIMBY)
8	Local communities (receiver)	Very good	Good	Very good	Very bad	Neutral	In favor of CISF and repository (volunteer) but only if leads to disposal
9	Local representatives (receiver)	Very good	Good	Very good	Very bad	Neutral	In favor of CISF and repository (volunteer) but only if leads to disposal

Note: This table is for illustrative purposes. An actual social impact matrix requires the participation of relevant stakeholders. Abbreviations: CISF, consolidated interim storage facility; NIMBY, “not in my back yard”.

Figures

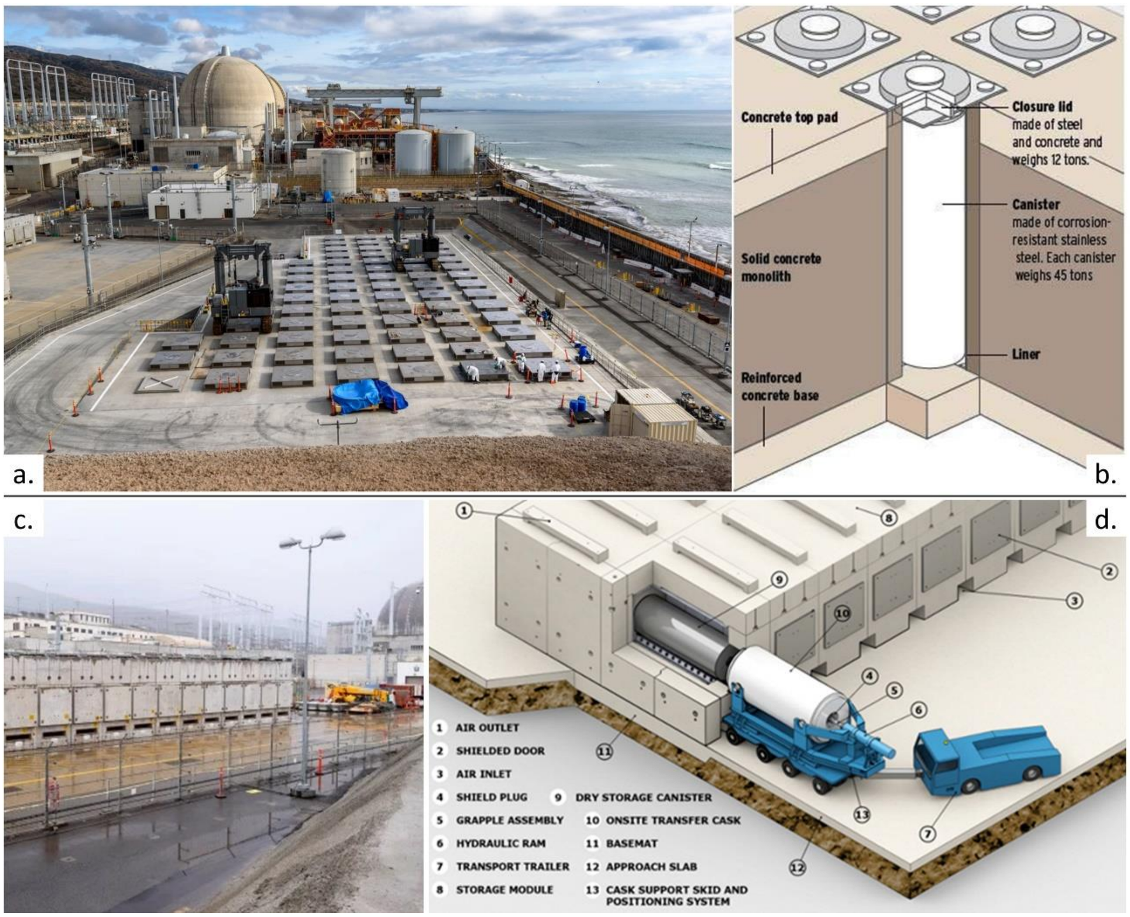

Fig. C.5. Dry storage areas at the San Onofre Nuclear Generating Station (SONGS), California. (a) Holtec’s HI-STORM UMAX underground dry storage system hosting 73 MPCs. Source: Southern California Edison. (b) Main components of the HI-STORM UMAX system. Source: Southern California Edison. (c) AREVA’s 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.