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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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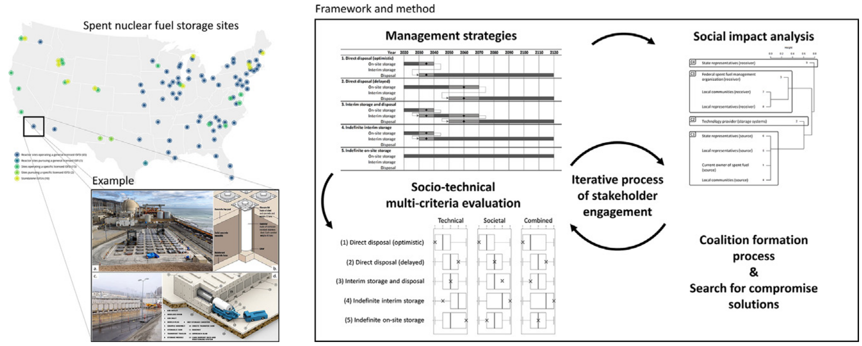
HIGHLIGHTS

- We discuss the systemic issues of commercial spent fuel management in the U.S.
- A literature review of previous uses of multi-criteria analysis methods is provided.
- We present a new socio-technical multi-criteria evaluation framework and method.
- The approach searches for compromise solutions rather than optimal solutions.
- A generic example illustrating the method to stakeholders is provided.

GRAPHICAL ABSTRACT



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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.

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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 (Diaz-Maurin and Ewing, 2020; 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 2019, approximately 84,445 metric tons of commercial spent fuel are stored at 79 different locations, including 65 operating reactor sites in 35 states (Carter, 2020). 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: *(i)* 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; *(ii)* 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; Diaz-Maurin and Ewing, 2018); *(iii)* 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); *(iv)* local autonomy often conflicts with state control over repository siting and selection of transport routes (Bonano et al., 2011); and *(v)* 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). This 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, 1993)—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). 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).

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 spent nuclear fuel 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, 1993). Therefore, to be successful, the framing of spent nuclear fuel management strategies—including 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,

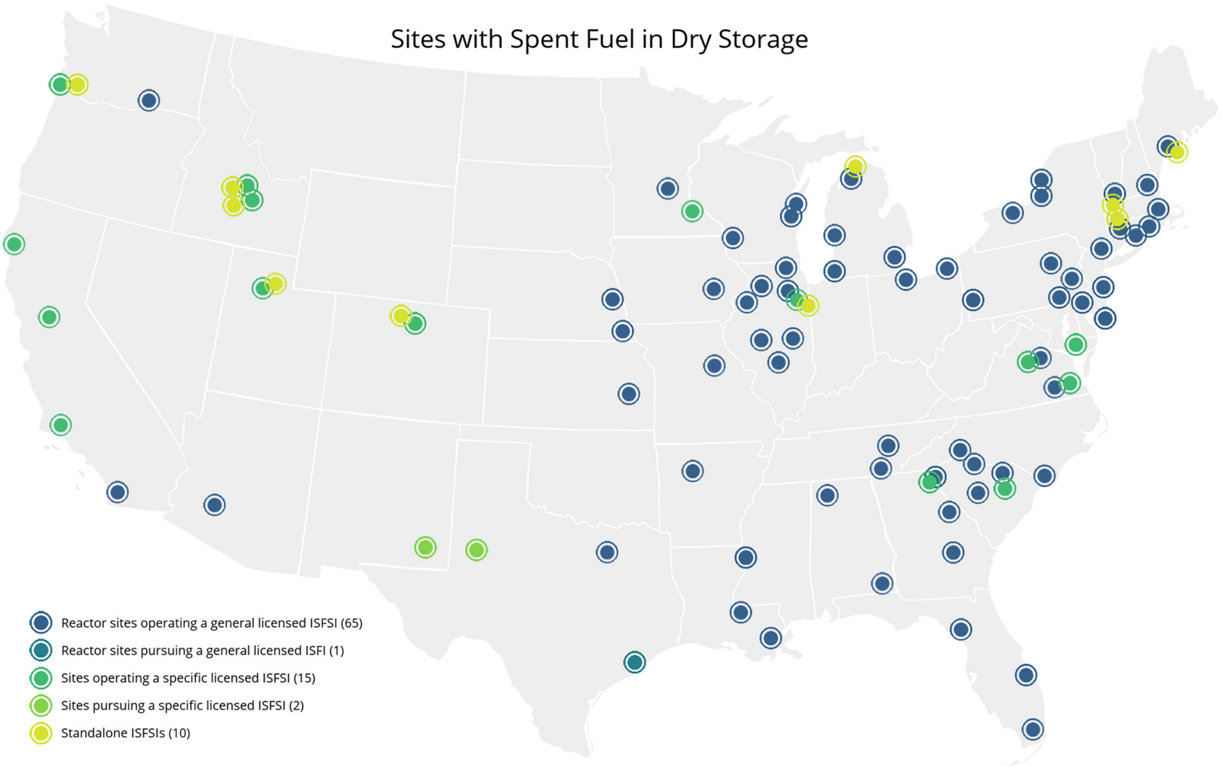

Fig. 1. Map of the independent spent fuel storage installations (ISFSIs) authorized to store dry spent fuel in the U.S. (as of November 2020). Note: Locations of ISFSIs corrected after (Carter, 2020).
Source: adapted from (US NRC, 2020).

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 (receivers) 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 (source and receiver at both local and state levels) 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 one 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 in the negotiations. 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 social 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 federal 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 (Diaz-Maurin et al., 2021).[1]

5. **Hierarchy**: 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 but it 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 social 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 3855 spent fuel assemblies (approx. 1609 metric tons)—the largest spent fuel inventory stored at an all-unit shutdown power plant in the country (Carter, 2020). 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 STMCE 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 (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.

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

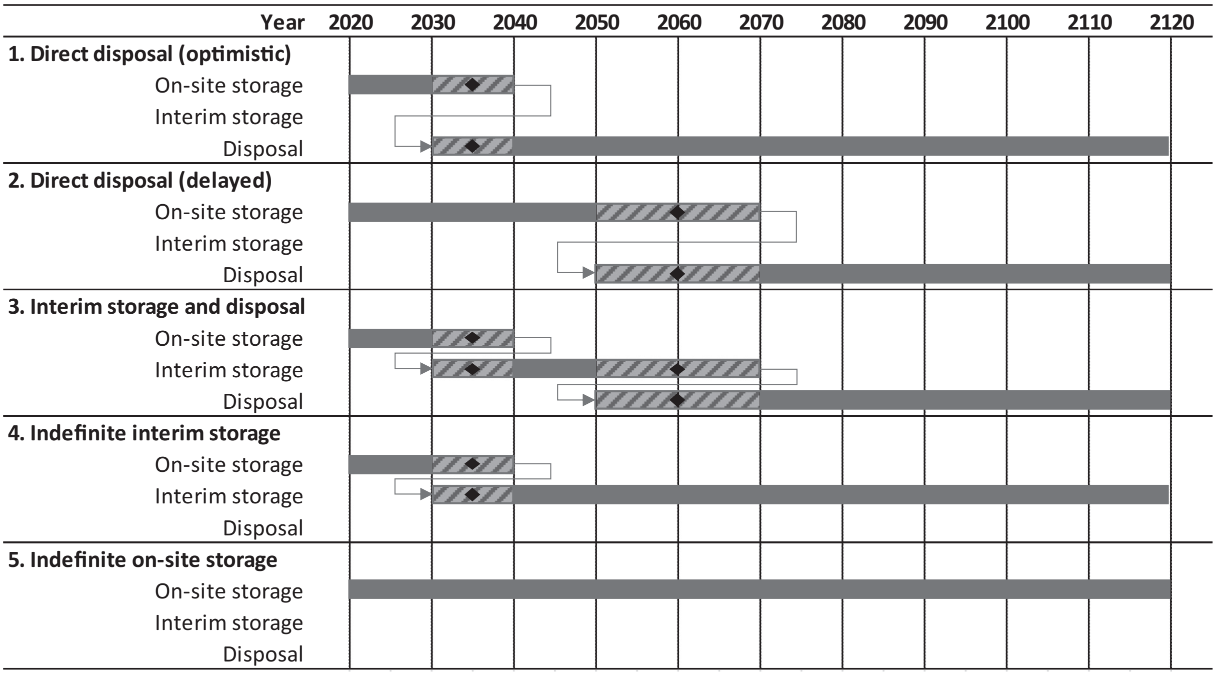

Fig. 2. Pathways of the five generic long-term management strategies considered in the analysis. Note: Scenarios start at year 2020.

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 on site; (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 on site 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 still not be disposed of in a geologic repository before at least one hundred years from now (scenarios 4 and 5).

Each one of the processes of on-site 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

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	$\times 10^{-2}$	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	$\times 10^{-2}$	Quant.	Stoch.	Minimize	
1.5	Probability of fractional release event during on-site storage	$\times 10^{-2}$	Quant.	Stoch.	Minimize	
1.6	Probability of fractional release event during interim storage and disposal	$\times 10^{-2}$	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.

(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).[2] 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 (Diaz-Maurin et al., 2021). Fig. 3 presents the results of the sensitivity/uncertainty analysis for the three multi-criteria evaluations.

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 1.5 × IQR. 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

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.

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[2] Equation numbers refer to Section B.3 of the supplementary method.

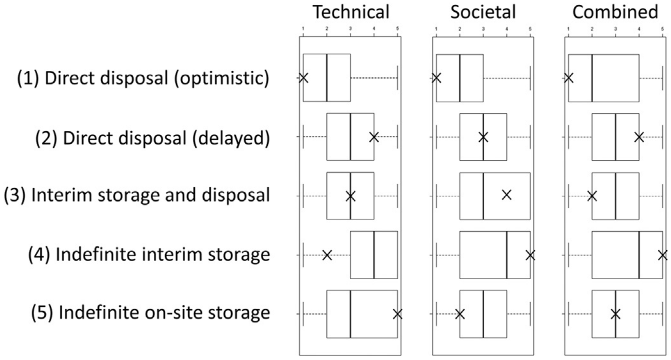

Fig. 3. Rankings of the generic long-term spent fuel management strategies obtained from the Monte Carlo simulation for 500 random samples. Note: Strategies are ranked from 1 (highest performance) to 5 (lowest performance). Each box corresponds to the interquartile range (IQR) which is a measure of statistical 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 1.5 × IQR or more above Q3 or 1.5 × IQR or more below Q1, the black line is the median, and the cross is the mean value from Table 3.

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 cluster 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 one 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).

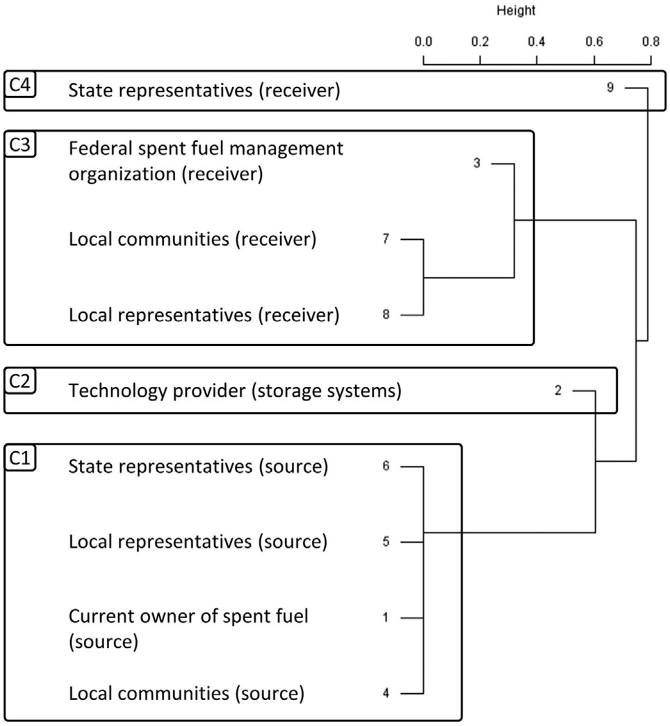

Fig. 4. Dendrogram of the coalition formation process based on the social impact matrix (Table C.4 of the supplementary material and data).

5. Discussion

5.1. Limitations

5.1.1. 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, 2011), 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

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 5 (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.

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.

5.1.2. 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 risk—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.

5.1.3. 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 the maximization of a utility or value function (Section B.2). 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 (a review in Munda, 2019).

5.1.4. 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, 1993)—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.

5.1.5. 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 case 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 (H.R.1083, 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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CRediT authorship contribution statement

François Diaz-Maurin: Conceptualization, Methodology, Resources, Investigation, Writing – original draft, Writing – review & editing. **Jerold Yu:** Software, Visualization. **Rodney C. Ewing:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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