Benefits of Siting a Borehole Repository on Non-Operating Nuclear Facility

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ABSTRACT

This work evaluates a potential solution for two pressing matters in the viability of nuclear energy: spent fuel disposal and power plants that no longer operate. The potential benefits of siting a borehole repository at a shut down nuclear power plant facility are analyzed from the perspective of myriad stakeholders. This assessment indicates that integrated siting will make economic use of the shut down power plant, take advantage of spent fuel handling infrastructure at those sites, minimize transportation costs, expedite emptying the crowded spent fuel storage pools accross the country, and will do so at sites more likely to have consenting communities.

INTRODUCTION

Creative solutions are necessary to meet the spent nuclear fuel (SNF) disposal challenges faced by the United States. This work proposes and evaluates a strategy that leverages the remaining resources inherent in a shut down nuclear reactor site toward a new purpose:a spent fuel repository facility.

Domestic nuclear power plants are at risk of shutdown in areas with surplus electricity capacity from coal and natural gas. Kewaunee and Crystal River have already closed and numerous other plants are at risk in the near term [1]. Simultaneously, the Department of Energy (DOE) has begun to move forward with consent-based siting of a nuclear spent fuel repository [2]. The proposed solution in this work seeks to combine these efforts toward a more economic and politically feasible solution.

This work considers the potential benefits of siting a borehole-type repository at the site of a shut-down nuclear power plant. The expected benefits of this proposed integrated siting strategy include reduced radioactive waste transportation burden, increased likelihood of consent from the local community, and improved expediency achieved through leveraging existing infrastructure and skill.

The siting strategy will be compared to a reference case at Yucca Mountain through quantitative metrics. The incentives of various stakeholders will also be modeled as a weighted linear sum of these metrics.

Motivation

The proposed integrated siting strategy takes advantage of three technical benefits of borehole repository designs: modularity, broad geological suitability, and footprint efficiency. Modularity enables regional repositories to scale in size according to the local spent fuel burden. Additionally, the necessary geological characteristics required for borehole disposal, crystalline basement rocks at $2,000m - 5,000m$ deep, are relatively common in stable continental regions [3]. Finally, the surface footprint requirements of a borehole repository are comparable to the available footprint of a nuclear power reactor site, with only $30km^2$ required for the total SNF amount proposed for Yucca Mountain [4].

Integrated siting also has potential economic benefits. One significant cost inherent to borehole repository concepts is the repacking of spent fuel assemblies into smaller-diameter waste canisters representing over 15% of estimated per-borehole cost [5]. However, siting a repository at a non-operating power plant facility, especially one with a dry-cask storage site, will take advantage of already existing infrastructure and local human talent for spent fuel handling and packaging. Many candidate non-operating reactor sites, such as those mapped in Figure 1, may be appropriate for integrated siting if they are located above crystalline basement formations and include dry cask packaging facilities.

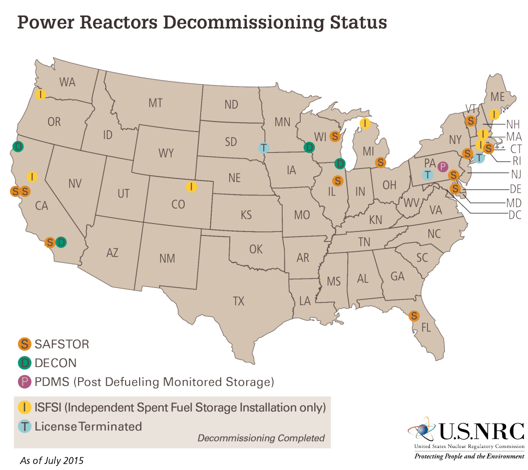

Fig. 1. Non-operating facilities status [6].

Finally, integrated siting may be more practically and politically feasible. Preliminary work [7] indicates integrated siting is appealing to many stakeholder groups. For example, a consent-based approval process may be feasible because communities local to power plants may be uniquely receptive to the incentives of hosting a repository. This paper seeks to quantify the impact of these and other features of the proposed siting strategy.

CASE DEFINITIONS

This paper proposes siting a borehole repository at a shut down nuclear power plant such as one similar to the Clinton Power Plant in Illinois. This proposed case is then compared to a reference case at Yucca Mountain.

The paper focuses on the benefits that arise from the strategic siting of a repository on a non-operating nuclear facility, and not the benefits that arise from the repository design. The borehole design follows the Sandia Report Reference Design and Operations for Deep Borehole Radioactive Waste [5]. Selection of an alternative borehole concept could impact the details of the repacking needs and facility design, but will not significantly impact the siting comparison here.

Case I: Reference Case

The reference case, upon which the proposed case seeks to improve, is to build a standalone 70,000 metric ton of heavy metal (MTHM) mined repository at the Yucca Mountain site.

The reference case is presented in order to demonstrate the cost savings and efficiencies that arise from the proposed case. The base case mimics the Yucca Mountain Project. Costs include new licensing and processing facility for repacking the spent fuel assemblies.

Case II: Shut Down Plant Case

The imminent shutdown of the Clinton Nuclear Power Station has recently been averted by an act of the state legislature. In this sense, Clinton is representative of a class of at-risk nuclear reactors in the Midwest and eastern United States. A borehole repository sited at the Clinton Nuclear Power station site is therefore hypothetically considered here to represent integrated repository siting at a reactor facility faced with potential shutdown.

The Clinton Nuclear Power Station is owned by the Exelon Corporation. It has a licensed land area of approximately $58km^2$ and a $20km^2$ cooling heat sink, the Clinton Lake. Of the licensed land area, only $0.6km^2$ is used for the facility. [8]. This leaves enough room left for a 70,000 MTHM borehole repository without additional land purchase from the public.

Potential Plan: Combined Case

As an aside, given that one 70,000 MTHM repository is already insufficient for domestic SNF needs [9], a potential plan for the future can be proposed, a dual-repository scenario. In this scenario, both the Yucca Mountain repository and the near-Clinton borehole repository are sited and someday become operational. The proposal that a pair of repositories, east and west, is not new. Indeed, it was originally envisioned before the Yucca Mountain site selection was made.

In this scheme, eastern reactors send their spent fuel to the eastern repository site while western reactors send theirs to the western site. Thus, the less-nuclear western region will not bear the burden of hosting a repository for the eastern region, which has a larger percent of nuclear energy.

For this scenario, spent fuel west of the 92 west meridian is considered west, which will send its SNF to Yucca Mountain. Conversely, spent fuel east of the 92 west meridian is considered east, which will send its SNF to the proposed Clinton power plant. The 92 west meridian is chosen because it is the meridian just west of Illinois state borders, so that no Illinois power plants have to transport their spent fuel to Yucca Mountain. This plan will be analyzed in the paper but should not be a comparison to the previous two cases because it has different capacities.

METHODOLOGY

This work will evaluate **2 scenarios** for repository siting according to **6 metrics** of performance considered from the perspective of **4 stakeholders.**

Preliminary work [7] suggests that integrated siting will reduce costs, construction, time (both for construction and licensing), transportation distances, and resistance from the local community. The goal of this paper is to compare this siting strategy with the business-as-usual base case via quantitative metrics capturing the key priorities of stakeholders. Accordingly, the present work will compare case one and two along these axes.

This work will evaluate the potential impacts of each siting strategy according to the following 6 quantitative measures:

- Transportation Burden $[MTHM \cdot km]$: A site is preferred by most stakeholders if it can minimize the distance SNF must travel.
- Workforce Utilization $[-]$: A repository site is preferred by many stakeholders if it utilizes an already situated skilled local workforce.
- Expediency $[y]$: Many stakeholders will benefit if the removal of dry casks from current storage pads is expedited.
- Consent Basis $[\frac{nuclearMW}{\text{capita}}]$: If the community beneifts from nuclear energy, they are more likely to be consenting to site a repository. If there is a basis for a consent-based siting process to succeed, many stakeholders benefit.
- Site Access $[-]$: Rail access to the site is essential for beginning operations.
- Site Appropriateness $[-]$: A site must be geologically appropriate and of sufficient area.

Finally, recognizing that these measures are valued differently by each, we consider possible weighting factors that may capture the perspectives of 4 key stakeholder groups:

- the federal government,
- the state government,
- the local government / community,
- and the owner of the non-operating plant.

EVALUATION METRICS

This paper introduces six metrics of siting performance. These metrics and their definitions draw upon previous [10, 7] as well as original work. In the following sections, the metrics are defined in more detail, and normalized so that in the final section, they are applied to comparatively evaluate each case.

The normalization of the metrics are done to a scale of 0 to 1 using the equation below, where 0 is the worst possible value, and 1 the best. Metrics like transportation burden, expediency, and consent basis, are normalized in such a matter. Metrics without units are booleans, where values only exist in values of 0 or 1. For example, a 0 value for site access means that there is no existing site access infrastructure.

$$\text{NV} = \frac{x - \text{W}}{\text{B} - \text{W}} \tag{1}$$
$$NV = \text{normalized value for the metric} \tag{2}$$
$$x = \text{considered case value for the metric} \tag{3}$$
$$B = \text{best case value for the metric} \tag{4}$$
$$W = \text{worst case value for the metric} \tag{5}$$
$$\tag{6}$$

Transportation Burden

In order to minimize transport cost, a central location is preferred. To capture this, a metric for representing the distance a mass of spent fuel must be transported, the transport burden, is introduced. This transportation burden is the product of the SNF mass and the distance it has to travel from its current storage location to the proposed repository. This results in a metric in units of $MTHM \cdot km$.

To arrive at the transportation burden for each case, a distance analysis was completed using the Haversine formula [11]. First, the coordinates of each power plant were obtained by scraping public data [12]. The distance between each storage site (i.e. reactors and Independent Spent Fuel Storage Installation (ISFSI)) was then calculated by using the Haversine formula on the geographical coordinates of the receiving and sending sites (1 and 2).

$$\Phi_1, \Phi_2 = \text{latitude in radians} \tag{7}$$
$$\lambda_1, \lambda_2 = \text{longitude in radians} \tag{8}$$
$$\Delta\lambda = |\lambda_1 - \lambda_2| \tag{9}$$
$$\Delta\Phi = |\Phi_1 - \Phi_2| \tag{10}$$
$$a = \sin^2(\Delta\Phi) + \cos(\Phi_1)\cos(\Phi_2)\sin^2\left(\frac{\Delta\lambda}{2}\right) \tag{11}$$
$$c = 2 \cdot arctan2(\sqrt{a}, \sqrt{1-a}) \tag{12}$$
$$d = (6,371km) \cdot c \tag{13}$$

$$b_i = m_i d \tag{14}$$
$$B = \sum_i^N b_i \tag{15}$$

where

$$b_i = \text{spent fuel transport burden from facility i} \tag{16}$$
$$m_i = \text{mass of spent fuel at facility i} \tag{17}$$
$$B = \text{total spent fuel transport burden} \tag{18}$$
$$N = \text{total number of facilities with spent fuel on site.} \tag{19}$$

This analysis used GC-859 spent fuel inventory data available from U.S. Energy Information Administration (EIA) through private communication [13] as well as Centralized Used Fuel Resource for Information Exchange (CURIE), a web interface to the Oak Ridge National Laboratory (ORNL) universal database[14]. From the list of 74 sites, several candidates which minimize $B[MTHM \cdot km]$, spent fuel transportation burden, are listed in Table 1.

TABLE I. Reactors with relatively small spent fuel transportation burden $[MTHM \cdot km]$.

Reactor	State	$MTHM * km$	License Area $[km^2]$
Clinton	Illinois	**77,352,339**	**57.87**
Dresden	Illinois	**77,663,969**	3.856
Peach Bottom	Pennsylvania	85,563,135	2.509
Indian Point	New York	84,097,374	.967
Yucca Mountain	Nevada	209,575,157	N/A

The Clinton Power Plant was chosen as the site for the proposed case due to its small $MTHM \cdot km$ value and substantially large license area[8]. Considering that only $30km^2$ is required for all the total SNF amount, the licensed area at Clinton power plant allows more than enough space to site a borehole repository, which avoids possible conflicts with the community from purchasing and utilizing more land.

The proposed case would require enormous cooperation from the utility that owns the power plant. In the case of Clinton, that would be Exelon Corporation. Were Clinton facing shutdown, Exelon would have a strong incentive to cooperate in order to utilize the facility property in a lucrative manner. In particular, Exelon would be able to save on decommissioning of Clinton by selling the property as well as the infrastructure to the government. Though the reactor facility may need to be decommissioned, this responsibility could be transferred to the federal government (or an independent SNF management agency [15]) upon purchase of the land.

Also, with recent events, the possibility of Yucca Mountain Repository's revival is on the rise. This brings a potential combined case, where the new borehole repository will operate with the Yucca Mountain Repository.

However, partitioning west and east with respect to the 92 west meridian yields the Yucca Mountain Repository site approximately $14,000[MTHM]$ of SNF, much less than its proposed capacity of 70,000 MTHM. On the other hand, the Clinton repository SNF burden would be reduced to 61,777 MTHM. The transportation burden is $53,945,200[MTHM \cdot km]$ for Yucca Mountain, and $17,940,959 MTHM \cdot km$ for the Clinton repository. This adds up to a sum of $71,886,160 MTHM \cdot km$, which is about 7% less than that of Clinton repository alone. This does not provide a comparable advantage. Other reactor sites were tested in the transportation burden analysis but also failed to provide a substantial advantage. Also, the selection of potential sites was limited by the geological constraints shown in Figure 2.

If the power total MTHM value were to be equal, a line can be drawn at the 84 west meridian, which yields $39,942 MTHM$ for the east repository, and $36,649 MTHM$ for the Yucca Mountain repository. One of the original candidates, the Peach Bottom reactor in Pennsylvania is then chosen for its central location in the east area. However, this analysis yields a $MTHM \cdot km$ value of $92,575,081 MTHM \cdot km$, which is substantially larger than that of having one repository in Clinton. Also, the Peach Bottom reactor site has little licensed land, which will require additional land purchase for the repository.

TABLE II. Transportation Burden for Each Case

Case	Transportation Burden [$MTHM \cdot km$]	NV
Case I	209,575,157	0
Case II	77,352,339	1

Site Appropriateness

To host a borehole repository, the site must satisfy geologic requirements. Figure 2 is a map indicating the geological fitness of various regions of the United States. The proposed site at Clinton sits above a crystalline basement which lies at an appropriate depth.

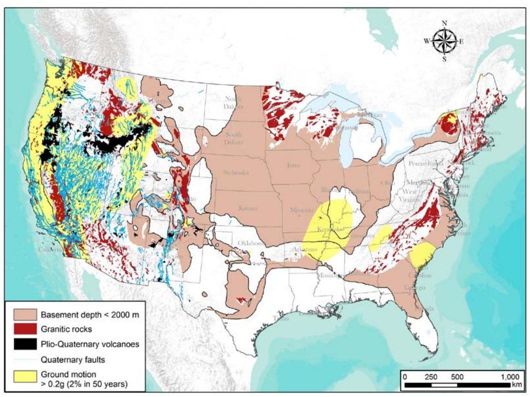

Fig. 2. From [16], a map of areas in the US with crystalline basement rock at less than 2000 meters depth. Tectonic activity impacting siting considerations are also mapped: Quaternary faulting, volcanism, and seismic hazard (yellow shading = 2% probability of exceeding 0.2 g of ground acceleration in 50 years).

Also, it should be noted that the Clinton area is a well studied geologic host area. Ample data on the stratigraphy of the Decatur region, such as Figure 3 has already been collected as part of the Decatur Carbon Sequestration Project which is less than 50 miles south of the Clinton power plant.

TABLE III. Site Appropriateness for Each Case

Case	Site Appropriateness
Case I	1
Case II	1

Workforce Utilization

Building a spent nuclear fuel repository is no easy task. It is a task that requires numerous experts and laborers. Also, operating and maintaining a nuclear power plant requires numerous experts and laborers. In case of the proposed case, the Clinton Power Station has approximately 700 employees living

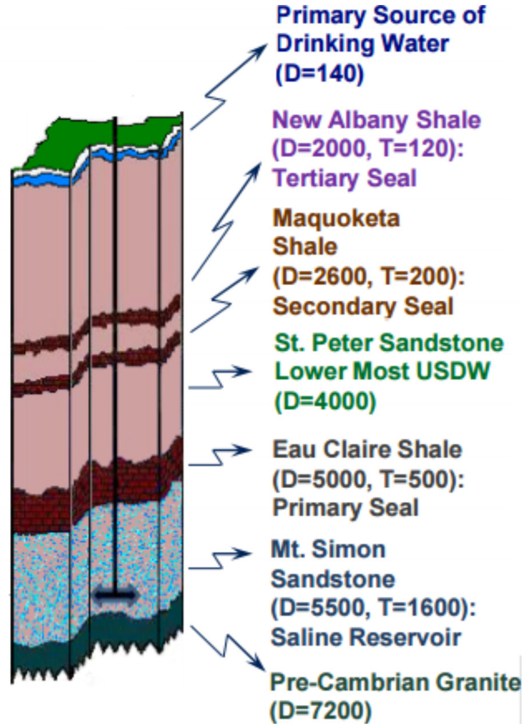

Fig. 3. Stratigraphy of the Decatur Region, D is depth in feet. [17].

in nearby counties with an additional several hundred contractors during fuel outages[18]. The existing skilled workers and local talent for maintenance, transport and catering services can be utilized without bringing a whole new group of workers to the area [19]. Also, the shutdown of Clinton Power Plant would cause a dramatic loss of jobs in the community.

The void created by the shutdown of the Clinton plant can be, though not completely, filled by the new construction of a borehole repository. The construction will prioritize local hires as an incentive to ease local opposition on repository siting. Employment during the operation of Yucca Mountain was estimated to range from 2,000 to 5,000 jobs, [20] which means that the borehole repository would at least require half of the workforce for the same capacity.

Additionally, an estimate by the Illinois State University on fracking the New Albany Shale in southern Illinois estimated that such a project can create 1,000-47,000 jobs [21]. Translating the workforce to central Illinois and the borehole project should create somewhere in the low and medium estimate, which is about 10,000 jobs.

The proposed case has a larger advantage over the base case in the sense that there are already existing facility in regards to spent fuel handling and worker lodging and catering services. It is assumed, for the sake of argument, half of the construction cost of the repacking facility in the base case is used to expand the existing facility in the proposed case.

TABLE IV. Workforce Utilization for Each Case

Case	Workforce Utilization
Case I	0
Case II	1

Consent Basis

International SNF siting experiences have shown that a consent-based approach to siting a repository is crucial to success [15, 2, 22, 10]. Furthermore, the Swedish precedent [23] shows that municipalities near nuclear facilities are more likely to volunteer to site a repository in their community.

Because populations local to operating reactor sites are more likely to be favorable toward nuclear power, and the proposed integrated siting is in an already-nuclear community by design, this siting strategy inherently maximizes the local consent basis.

The source of this favorable attitude varies by site. The local community is the beneficiary of various economic benefits including job creation and the substantial property taxes paid by the utility toward regional governmental budgets. In the case of the Clinton Power Plant, Exelon pays $15 million in property taxes each year, which amounts to about $923 per resident in the host Dewitt county [24]. The plant also provides a total payroll of more than $50 million to its workers. The eventual shutdown of the plant would have caused a dramatic loss of the economic inflow. It is also speculated that 13,300 jobs would be lost in Illinois after five years of plant shutdown [25].

A similar phenomenon might be expected at the state level as well, because Illinois generates more nuclear energy than any other U.S. state with a net capacity of 11,441 megawatts in 2010 [26]. Nevada, on the other hand, hosts zero nuclear power plants. Thus, it can only be natural for Nevada to consider a national repository as an unjust burden, despite economic benefits.

The consent basis, driven by proximity to an operating nuclear plant and corresponding greater likelihood to be favorable toward hosting an SNF repository, should be quantifiable by a measure of the benefit experienced by the community. For simplicity, we quantify the proximity to nuclear energy at the state level based on power consumed. The corresponding state and regional metrics (expressed in MW of nuclear power per capita) are listed in Table V. This analysis uses nuclear power generation capacity and population data from the U.S. EIA [26] and the U.S. Census [**?**].

TABLE V. Nuclear MW Per Capita (NMWPC) values for different states

State	Net Nuclear Capacity (MW)	Census Population	NMWPC (10^{-3})
South Carolina	6,486	4,625,401	1.4
Alabama	5,043	4,780,127	1.05
Vermont	620	625,745	.99
Illinois	11,441	12,831,549	.89
Nevada	0	2,705,000	0
Average Nuclear States	101,167	265,386,569	.38
Average National	101,167	309,300,000	.33

The state of Illinois has the highest generating capacity, and is fifth in the NMWPC value, while Nevada has zero generating capacity with zero MW per capita value. Illinois' NMWPC value is also well above the national average. Judging from the table, it is no surprise that the state of Nevada rejected the idea of having a national spent fuel repository on its land. On the other hand, Illinois is more familiar with nuclear and also somewhat reliant on nuclear, which can lead to a consent-based process in a state-level.

TABLE VI. NMWPC values for Each Case

Case	NMWPC (10^{-3})	NV
Case I	0	0
Case II	.89	.635

Site Access

Site access necessary to transport radioactive material to the repository site poses one of the greatest logistical challenges in siting a repository.

In the case of Yucca Mountain, the opposition from the state of Nevada to the proposed Caliente rail corridor blocked construction of the rail line and indefinitely postponed acceptance of SNF at Yucca Mountain [27].

Operating reactors, conversely, are much more likely to be located along rail lines. In the case of the Clinton nuclear power plant, the Canadian National rail line [7] has a station in Clinton and dedicated tracks leading into the reactor facility, as shown in Figure 4. An already existing railway can avoid costs and delays related to building a new infrastructure.

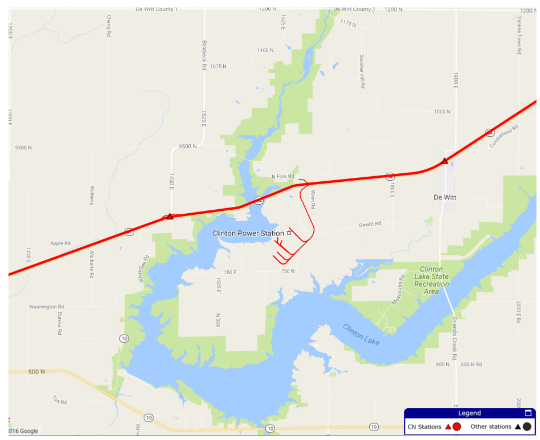

Fig. 4. From [28], a map of Clinton Power Station in Clinton,IL with the Canadian National rail passing through.

The proposed site's proximity to other power plants means that the transport routes pass through fewer states and communities, which lessens the potential for conflict.

The capacity of the state to handle nuclear materials is also important. The state of Illinois established a Division of Nuclear Safety in its Illinois Emergency Mangament Agency (IEMA) which connects the state police and the Illinois Commerce Commission (ICC) to successfully transport 480 shipments of spent nuclear fuel since 1983 [29]. If a repository is built and operational, the already existing, experienced state organization will be able to handle the transportation logistics and security.

In comparison, the transportation route to Yucca Mountain is identified to traverse 955 counties with about 177 million persons, which is about 56% of the US total [27]. SNF transit is a sensitive topic to some states, and may demand reroutes that cause unexpected cost increases in transportation. Also, new railways would need to be constructed in order to ship the spent fuel inventories by rail.

TABLE VII. Site Access for Each Case

Case	Site Access
Case I	0
Case II	1

Expediency

Leveraging existing infrastructure at an integrated site will allow for expedited acceptance of SNF from temporary dry cask storage sites nationwide.

Dry casks are the result of the perpetual delay of a repository construction. The proposed case would allow reactor sites to empty their spent fuel pools, which would no longer necessitate dry storage campaigns. For example, Maine Yankee's ISFSI cost was $149.3 million in 2001 dollars, with an annual operating fee of $10 million per year [30].

The proposed case, once completed, will allow faster acceptance of SNF and, accordingly, resumed collection of the Nuclear Waste Fund (NWF), which will fund the repository operation and maintenance.

The reference Yucca Mountain case does not require land purchase because the land near Yucca Mountain is part of the Nevada Test Site. However, it is lacking in infrastructure for SNF handling.

As mentioned previously, the licensed land area in the Clinton case is sufficient to support a 70,000 MTHM repository without purchase of land from the public. However, the federal government would need to purchase the licensed area of the Clinton site from Exelon. Thus, the nuclear waste fee would need to be leveraged toward paying Exelon for its land and the facilities on site when Exelon shuts down the reactor.

This would suggest a beneficial trade for both parties, since the government can purchase infrastructure and land simultaneously, and because Exelon can vastly save the cost of decommissioning by selling off the reactor site. The reactor core and power-generating component of the reactor site needs to be decommissioned, however. As a comparison, Maine Yankee, a Pressurized Water Reactor (PWR) with a capacity of 860MWe, had a decommissioning cost of 635 million [31].

The proposed case, being a once-operating nuclear power plant, has the facility to repack the spent fuel assemblies into a disposal cask. Its dry cask infrastructure is currently in use. However, this facility needs to be upgraded to increase its throughput, and should be preferably automatic, to minimize worker exposure. The transported spent fuel assemblies are repacked and inspected at the upgraded facility, and is sent to the emplacement tubes for final disposal. Not having to build an entirely new above-ground facility should greatly ease the consent-based process, for it seems like there would be minimal impact.

The utility has a very high incentive since it will save on its decommissioning fee. The construction of the repository next to the reactor site would substantially reduce the cost of decommissioning, and it would not have to expand its dry storage to empty out the pools. Exelon would be earning a profitable margin out of a used nuclear power plant, which would otherwise be a cost burden to handle.

The base case requires a new above-ground facility, which not only costs a great amount, but also will be considered problematic in the public's eye.

A metric for expediency is then proposed which is inversely proportionate to the number of years until the federal government takes possession of the spent fuel. Estimating the likely timelines for each case is a challenge beyond the scope of this work. However, a bounding estimate can be derived from the time saved from use of existing infrastructure at the integrated facility. Avoiding that handling facility delay will save at least 5 years and likely much more on the timeline of Case II over that of Case I [32]. Since the majority of SNF would be destined for the eastern repository, in the combined case, approximately the same time savings could be assumed.

TABLE VIII. Expediency in Each Case

Case	Time Saved [y]	NV
Case I	0	0
Case II	5	1

RESULTS AND DISCUSSION

To model the impact of these measures on the incentives of each stakeholder, the list of stakeholders considered follows in Table IX alongside the weights indicating the magnitude of the importance of the incentive.

TABLE IX. Metrics and Weight for Each Stakeholder

Metric	Federal	State	Local	Utility
Transportation Burden	3	2	1	1
Site Appropriateness	3	2	1	1
Workforce Utilization	3	2	2	2
Consenting Locals	3	2	3	2
Site Access	3	2	1	1
Expediency	3	2	1	3
Case I total	3	2	1	1
Case II total	16.9	11.2	7.9	9.2

Results show that it is far more attractive for various stakeholders to site a repository at a non-operating nuclear power plant. Through strategical siting, all the parties involved can benefit.

Given the current circumstances, a repository is crucial for the survival of nuclear power. By siting one in a central location with sufficient licensed land, a repository with sizable capacity can be built cheaper, more efficiently, and in a consent-based manner with the local community.

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