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Transporting and Storing High-Level Nuclear Waste in the U.S.—Insights from a Mathematical Model

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Received: 31 March 2019; Accepted: 5 June 2019; Published: 14 June 2019

Abstract: The nuclear industry in the United States of America has accumulated about 70,000 metric tons of high-level nuclear waste over the past decades; at present, this waste is temporarily stored close to the nuclear power plants. The industry and the Department of Energy are now facing two related challenges: (i) will a permanent geological repository, e.g., Yucca Mountain, become available in the future, and if yes, when?; (ii) should the high-level waste be transported to interim storage facilities in the meantime, which may be safer and more cost economic? This paper presents a mathematical transportation model that evaluates the economic challenges and costs associated with different scenarios regarding the opening of a long-term geological repository. The model results suggest that any further delay in opening a long-term storage increases cost and consolidated interim storage facilities should be built now. We show that Yucca Mountain's capacity is insufficient and additional storage is necessary. A sensitivity analysis for the reprocessing of high-level waste finds this uneconomic in all cases. This paper thus emphasizes the urgency of dealing with the high-level nuclear waste and informs the debate between the nuclear industry and policymakers on the basis of objective data and quantitative analysis.

Keywords: nuclear waste disposal policy; transportation modeling; interim storage; United States of America; nuclear energy; energy policy

1. Introduction

The United States of America have more nuclear power plants (NPPs) than any other country in the world. Currently a total of 99 NPPs are operating while another 35 have already been shut down [1]. The scale of the industry results in great amounts of nuclear waste: The commercial production of electricity has also produced over 70,000 metric tons of spent nuclear fuel (SNF), meaning high-level waste (HLW), over the last decades [2]. For the time being, the majority of the SNF is stored at reactor sites in wet pools where HLW is to be stored for the first few years to cool off and have the radiation shielded. However, the absence of a long-term repository for HLW results in these pools reaching capacity [3]. To cope with this, independent storage installations were built at the reactor site, where the waste is stored in dry casks. Hence, although this way of storage seems to work more or less for the present, both means of storage are meant to be only temporary as they harbor various risks ([3], pp. 70–71). Therefore, a new storage solution has to be found in order to deal with the continuously increasing amount of waste [4].

The main source of HLW is SNF which is used fuel from a reactor whose fission process has slowed too much to be able to create electricity efficiently, but is still thermally hot, highly radioactive and therefore potentially harmful [2] (the International Atomic Energy Agency (IAEA) distinguishes three main kinds of nuclear waste that are mainly distinguished by their radiation and half-life: low-level waste, intermediate-level waste and HLW. The latter one is the one dealt with in this paper because firstly, special problems and thus costs are connected to it and secondly, a permanent storage solution for low-level waste (LLW) as well as for most parts of intermediate-level waste (ILW) exists at this time). As a decay heat greater than 2 kW/m^3, radioactivity that varies between 5×10^4 and 5×10^5 TBq/m^3 and a long decay are characteristic for HLW [5] a deep geological disposal is needed for storage in order to contain the danger arising from these features. Due to long decay that can take hundreds of thousands of years, any solution thought of must be long-term [2].

However, the current situation in the U.S. is anything but long-term. There are two stages of on-site storage of SNF (After the fuel rods are extracted from the reactors, they are put into steel-lined, seismically designed concrete storage pools, under about 40 feet of water, which serve by cooling down the fuel rods with pumps, that supply continuously flowing water, and shielding the radiation the SNF emits [2]. The SNF must be stored in those pools for several years until it has cooled down enough to be removed. Afterwards, if the pools reach capacity, the SNF must be moved into so-called dry-cask storage. The dry casks are metal canisters filled with inert gas and welded shut after being filled with SNF. They are usually stored above ground in one-car-garage-sized concrete containers on a flat field [2]. Those storage sites are called independent spent fuel storage installations and exist at the reactor sites as well as away-from-reactor at decommissioned reactor sites). Currently around 78% of all SNF is stored in pools, whereas the remaining 22% is stored in dry casks [2]. Due to an increasing number of reactors that exceed their pool capacity, the amount stored in dry casks storage increases continuously. The reason why this method of storing can only be seen as a short-term solution is that the casks are exposed to the weather and they are also potential terror targets. In addition both ways of on-site storage are very expensive [3].

There is a permanent storage solution for LLW and ILW (Except for the so-called "greater than class C" waste i.e., ILW with high concentrations of radio-nuclides) in the U.S., but none for HLW. The Waste Isolation Pilot Plant (WIPP)—licensed to dispose of transuranic waste from the nuclear weapons production—near Carlsbad in the state of New Mexico is the world's third deep geological repository and the only long-term storage site of the U.S. However, due to both technical and legal reasons WIPP cannot store HLW from the civil nuclear sector at this given moment (Only the change of current federal law including the WIPP Land Withdrawal Act would allow the site near Carlsbad to store it ([6], p. 2). In addition to that research on the suitability of WIPP as a storage facility for HLW would have to be conducted, especially regarding some incidents with leakage of radioactive material in 2014 (Vartabedian, R. Nuclear accident in New Mexico ranks among the costliest in U.S. history. *Los Angeles Times* 2016. Accessed via the internet on 29.01.2018 at http://www.latimes.com/nation/la-na-new-mexico-nuclear-dump-20160819-snap-story.html).

Yucca Mountain, which is located in Nevada, has been considered a possible storage site for HLW since the mid-1980s. The location could hold up to 70,000 metric tons of nuclear waste [2] and was approved by the U.S. Congress in 2002 [6]. However, the Obama administration put the whole project on hold, much to the relief of the Western Shoshone and Southern Paiute, two Native American tribes who consider Yucca Mountain and the surrounding lands sacred [7]. However, the 2018 budget of President Trump provides $120 million to restart the licensing process for the Yucca Mountain as a permanent nuclear waste repository as well as to initiate a "robust interim storage program" to safely store nuclear waste for 10,000 years (World Nuclear News. Perry speaks out for Yucca Mountain, 2017. Accessed via the internet on 29.01.2018 at http://www.world-nuclear-news.org/NP-Perry-speaks-out-for-Yucca-Mountain-2306178.html) These funds are probably not sufficient to start using Yucca Mountain as a permanent repository but they are a step towards a possible opening of a long-term storage site. At this given point, it is also the only step in this direction as in the status quo the site in Nevada remains the only relevant option. To explore other options would firstly require at least 30 years before being able to operate [6], and secondly imply very speculative potential locations.

These facts lead to the decision that in the following only the sites of Yucca Mountain and WIPP shall be taken into account. Both serve only as an example as WIPP is a military installation and can therefore not accept any civilian waste and there have been some concern that Yucca Mountain does not have the necessary geology to keep the waste from migrating ([8], p. 15) and ([9], p. 228–232). Their locations, however, seem sensible as possible long-term repositories due to the fact that the Nuclear Waste Policy Amendments Act (NWPAA) of 1987 singled-out Yucca Mountain as the only repository site to be studied and abandoned all studies on the East Coast (e.g., Granite in New Hampshire); any other site would need congressional action [3,10]. Furthermore, WIPP lies in a salt deposit which are generally fitting geological conditions ([9], p. 181).

Another possible way of dealing with SNF is reprocessing it to recover plutonium and uranium in order to partially reinsert the plutonium into nuclear reactors (thereby between 25% and 30% more energy can be gained from the original uranium and the volume of the material that has to be disposed as waste can be reduced to about one fifth of the original volume [11]. At the moment (only) plutonium is reintroduced as mixed oxide fuel into nuclear reactors). Although France, Japan, Russia, and India currently practice reprocessing (The United Kingdom abandoned reprocessing recently in 2018), one has to at least acknowledge that these countries are nuclear weapons states (except for Japan). The U.S. has practised reprocessing for many years for mostly military reasons to gain plutonium for nuclear weapons (three reprocessing plants for commercial use were built, but only one in West Valley, New York was operating from 1966–1976 [12]). However, in 1977 President Carter suspended all reprocessing for civil purposes in the U.S. Factored in that decision were technological, economic, and safety problems, but the main concerns were about proliferation [13]. The plutonium is contained in the SNF and essentially inaccessible; thus, a proliferation risk only exists if it is extracted by reprocessing [14]. In 2005/2006 the Global Nuclear Energy Partnership (GNEP) and the Energy Policy Act revived reprocessing prospects. Therefore, and for the sake of evaluating all options, which are limited when it comes to HLW, the model presented takes reprocessing into account in some of the scenarios.

The great amounts of HLW are located very unequally in the different states. As can be seen in Figure 1, the distribution of HLW is mainly focused on the Eastern states, especially the coastal ones, where also most NPPs are situated. The importance of this observation is that there are not only big amounts of HLW that need to be transported but the distance to the final repository, no matter whether in the are of Yucca Mountain or WIPP, will be very long as well. Therefore, it becomes obvious that the handling of nuclear waste is partly a transportation problem, and why the location of possible intermediates storages must be chosen wisely. However, research exists stating that transportation costs have little impact on the nuclear waste management system ([15], p. V). Still, this paper focuses on infrastructure and transportation costs because optimization is possible, depending on the processing management. Many more decisive and cost relevant decisions are political and cannot be made by an economic model. According to a study prepared for the Department of Energy (DOE) in 2016, the impact of the overall transportation costs is about 7%, in contrast to the impact of the at-reactor costs which cover the remaining 93% ([15], p. VI). Nevertheless, keeping in mind that the at-reactor costs can hardly be optimized and that the overall transportation costs, with about $4.1 billion, are still a significant amount of money, a modeling and optimization of these costs seems appropriate.

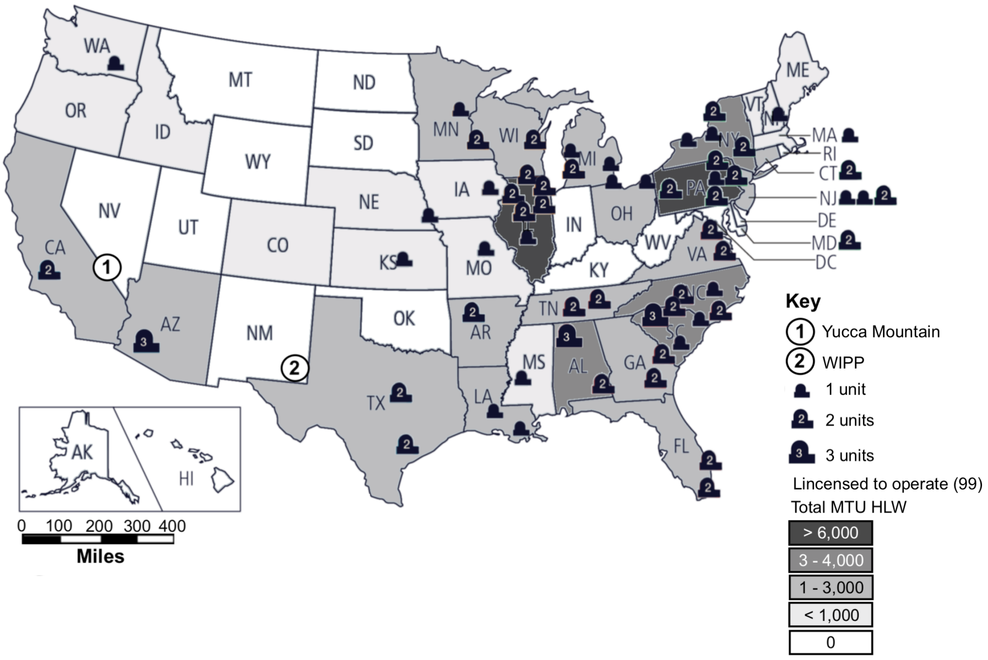

Figure 1. Regional distribution of high-level nuclear waste and nuclear power plants in the U.S. (source: own representation based on [2,16,17], and own estimations.)

The urgency of finding new storage solutions is emphasized when looking at current development in the nuclear energy sector. In Figure 2 the construction and shut-down of all reactors in the U.S. since 1958 can be seen. Furthermore, there is a forecast of future shutdowns, based on corporate announcements and reports by the Nuclear Regulatory Commission (NRC). As one can see the construction of new reactors came almost to a complete end after 1996 since only two new units are currently under construction (two have been abandoned recently [18]). The rate of reactor shutdowns will most probably increase rapidly during the next 17 years and will almost be complete by 2050 ([1], p. 1). The reason for this development is the loss of competitiveness of nuclear energy in the energy market as described in Wealer et al. ([1], p. 2) and Lovins [19]. Correlating with this increasing rate of reactor shutdowns is an even greater amount of HLW to be stored in independent storage installations as the reactors—this includes the storage pools—are going to be dismantled. Therefore, the problem the U.S. have with their nuclear waste tightens and the pressure of finding low-cost and permanent storage solutions increases.

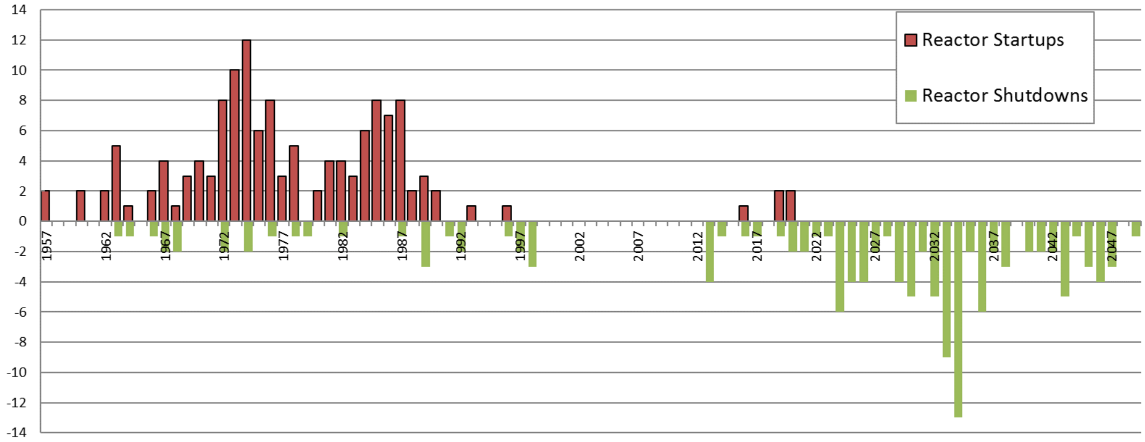

Figure 2. U.S. nuclear power reactor grid connections and permanent shut-downs (1957–2050). Source: own representation based on IAEA (IAEA Power Reactor Information System: the database on Nuclear Power Reactors. Accessed via the internet on 31.01.2018 at https://www.iaea.org/PRIS/home.aspx; NRC. List of power reactor units. Accessed via the internet on 31.01.2018 at https://www.nrc.gov/reactors/operating/list-power-reactor-units.html; Schneider, M.; Froggatt, A.; Hazemann, J.; Fairlie, I.; Katsuta, T.; Maltini, F.; Ramana, M.V. World Nuclear Industry Status Report 2016, 2016. Accessed via the internet on 27.07.2016 at http://www.world-nuclearreport.org/IMG/pdf/20160713MSC-WNISR2016V2-HR.pdf) [2,20], and own estimations.

The DOE is responsible for the high-level nuclear waste management. Hence, the transport as well as the disposal costs of HLW are financed by the Nuclear Waste Fund and Governmental funding [21] and an optimization of this process is in the public interest. The DOE was not able to come up with disposal solutions until now and is currently paying significant amounts of money to the energy companies running the NPPs in order to compensate them for having to store the nuclear waste for such long periods of time. According to the DOE the total damage amounts to $20.8 billion if the federal government begins accepting SNF in 2020 (as presumed in the model presented in this paper), but could increase by hundreds of millions of dollars annually for any further delay of doing so ([4], p. 79).

However, the DOE is working on solutions. One example is the 2012 report by the Blue Ribbon Commission (BRC) on America's Nuclear Future (The BRC was created in 2010 to conduct research and recommend a plan of action for the U.S. waste management and disposal of SNF) [4], inciting the DOE to release a strategy paper the following year. This strategy paper contains a program the Administration plans to implement in order to approach the HLW storage problem and to fulfill its obligations regarding the waste management. Among other things, the DOE plans to build a pilot interim storage facility and have it operate by 2021 with an initial focus on accepting used nuclear fuel from shut-down reactor sites. Furthermore, a larger consolidated interim storage facility (CISF) should be available by 2025 that will have a sufficient capacity of 20,000 metric tons or greater and will therefore allow for storage of enough used nuclear fuel to reduce government liabilities [22]. In addition, the CISF should reduce overall storage costs and provide flexibility and economics of scale for the waste management system. Although, the major challenge is that the DOE lacks the legal authority under the Nuclear Waste Policy Act (NWPA) from 1982 to provide it, the Congress would need to license Yucca Mountain for this first. Given the delays, a number of private companies have sought licenses for interim storage facilities as they are not bound by the rigidity of the NWPA ([3], p. 72).

The overall resulting research question is how the storage of HLW in the U.S. has to develop over time in order to accumulate the waste at fewer locations while reducing costs. With respect to the current situation, we developed a model of HLW transportation and storage in the U.S. It is a transportation model which includes a network consisting of all reactors in the U.S., as well as potential final repositories and potential locations for interim storages. We define six scenarios that diverge in the timing of the repositories availability as well as different technical solutions applied. It is a mixed integer model minimizing total costs over the entire period of transporting and storing the HLW.

The rest of this paper is structured in the following way: Section 2 provides a brief overview of existing literature. Section 3 presents the methodology, including the sets, parameters and variables used as well as the objective and constraints formulated. Section 4 presents the data and open issues related thereto, and Section 5 describes and discusses the results. Section 6 concludes and draws policy implications.

2. Literature Review

Although the storage of HLW is one of the main issues we are facing today [23], little literature is available on this topic. Högselius [13] puts the different national spent nuclear fuel policies in a historical perspective and explains some countries opt for direct disposal, reprocessing or SNF export. Rogers [10] gives a detailed overview of different national SNF disposal policies and discusses the need for a global approach to cope adequately with increasing SNF inventories. Brunnengraeber et al. [24] give an overview and comparison on the different international nuclear waste governances. Different case studies have been conducted for various countries, e.g., Canada Ramana [25], the European Union (e.g., Neumann [26]), or Germany [27]. Alley and Alley [9] provide an account of the controversies surrounding disposal of nuclear waste in the U.S. Sovacool and Funk [3] give a comprehensive overview of the development and perspectives of U.S. nuclear waste policy; considering the huge dilemmas in the short- and long-term, they argue that it does not look good for the U.S. nuclear power industry. North [6] provides a perspective both on the Blue Ribbon Commission on America's Nuclear Future Report (2012) and a potential path towards progess in meeting the federal obligation. Sanders and Sanders [28] provide a legal and historical view on the radioactive waste disposal strategies of inter alia the U.S. Kessides [29] points out that existing studies and forecasts of future costs of nuclear generation vary significantly and often lack a basis in microeconomics. Furthermore, he states that the future of nuclear power greatly depends on amongst others solving the problem of radioactive waste management. Schaffer [23] deals with the lack of a suitable permanent storage site in the U.S. from a technological point of view and argues that current oppurtunities for waste reduction are overlooked. Borges Silverio and Lamas [30] give an overview of the development and research on spent nuclear fuel reprocessing. The Congressional Research Services gives a recent and comprehensive overview of the issues civilian nuclear waste disposal has posed to Congress [21].

This paper is able to close a research gap on combining the operational research methodology of mixed integer programming with the current policy issues concerning U.S. nuclear waste disposal. One of few other examples of similar research is Briggs et al. [31], who have applied a multi-criteria analysis to analyze the timing, siting and financing of radioactive waste management and disposal, considering different points of view of different actors in the decision-making process. A more detailed approach on choosing short routes for transporting nuclear spent fuel on the U.S. Interstate highway system can be found in Miaou and Chin [32].

The data used in this paper is taken from numerous literature sources, among others the NRC [2], DOE [22], and Jarrell et al. [15].

3. Methodology

3.1. Model Overview

For our model we chose a mixed-integer problem (MIP) as the mathematical basis to be able to model the linear optimization of transportation and storage and include the binary decision of building optional interim storage facilities at different locations. The given problem is a transportation problem and can be modeled as a network consisting of four kinds of nodes.

- The first kind are the NPPs that produce the HLW, which also store amounts of HLW in independent spent fuel storage installations (ISFSI) until further transportation.

- From here on, the waste can be transported either directly to the final repository or to an CISF. The model has the option to build these facilities when needed, at predefined locations.
- There are two nodes representing two hot cells (hot cells are shielded nuclear radiation containment chambers. They protect operators from radiation by providing a safe containment box in which they can open the casks containing SNF and either refill it into other casks or extract it for reprocessing purposes (Engineering360. Hot Cells Information, 2018. Accessed via the Internet on 29.01.2018 at http://www.globalspec.com/learnmore/lab_equipment_scientific_instruments/lab_safety/hot_cells), to which HLW can be transported either from the reactors or from the interim storages.
- Once in the final repository the waste can not be accessed again.

Each type of node had a given storage capacity with specific storage costs. The storage costs in the final repository were neglected, as we were only considering the costs of the process until the waste is in the final repository. All existing transportation routes were included with their respective distance and type of transport which is either rail or road (truck). The model chose the type of transport, also taking into account the NRC's regulation on some routes.

The intermediate repositories can be built at nine different given locations (Grantsville (Utah), Barstow (California), Watkins (Colorado), Rayne (Louisiana), Barnesville (Georgia), Lucas (Iowa), Lasalle (Illinois), Newville (Pennsylvania), Old Chatham (New York)). These were chosen exogenously at interceptions of main possible transport routes. The model decides endogenously whether the capacity of those facilities is needed and in what year they are built. The facilities built are identical, with the exact same capacity as well as the same building cost. This decision is modeled using a binary variable.

The model differentiates between three types of waste.

- First of all there was the SNF from the NPPs.
- The second type was waste that has been vitrified, after the original SNF has been reprocessed and thereby its volume has been decreased. It was important to mention that during the vitrification process, the waste has to be refilled into a new cask.
- Likewise, the third type was waste that had simply been refilled into a new cask within a hot cell as the casks containing the suffer from decay. Therefore the HLW had to be refilled into a new cask when the old casks expire after their lifetime.

Figure 3 portrays the most important parts and the general build up of the model. Exogenous input in form of collected data and the framework scenarios are given and bound by several constraints that are mostly based on technological assumptions. The model then endogenously decided on which transport routes to take, which CISF to build and whether or not reprocessing is an cost-efficient alternative. Finally the output data such as costs, transportation amounts and storage levels are given.

A total of six scenarios concerning the long-term waste management options are considered for this model and the results are then compared. All scenarios are presented here and will be discussed regarding the different results. Table 1 gives an overview over the characteristics of each scenario. The basic time frame for all scenarios is 80 years starting in 2020, until the year 2100, assuming that all reactors are shut down and a final storage solution for the remaining waste has to be found by then.

The business as usual (BAU) scenario assumes that the U.S. will find no long term solution for their HLW during the next 80 years. Thus the waste can only be stored at the reactor sites or in newly build interim storages. Yuc_2030 assesses an opening of Yucca Mountain within 10 years, assuming it is operational in 2030. Regarding the case of further delay of the opening date of Yucca Mountain caused by political or technological reasons, the Yuc_2060 scenario is implemented defining its opening date as 2060. Scenarios Yuc+_2030 and Yuc+_2060 consider the opening of another final repository in addition to Yucca Mountain. For the reasons mentioned above the WIPP serves as an example for a second final repository, but other sites are conceivable. In Yuc+_2030 a fast opening of Yucca Mountain and the second repository in 2030 is assumed, whereas in Yuc+_2060 a delay of 30 years (2060) is considered. The last scenario (Yuc_reproc) then examines the combination of a final repository and reprocessing, the main focus being the question how much reprocessing would be needed to make the final repository sufficient for a long term storage of all HLW in the U.S. Therefore the model is constraint to having stored all HLW in Yucca Mountain by 2100, leaving no choice but to reprocess some of it.

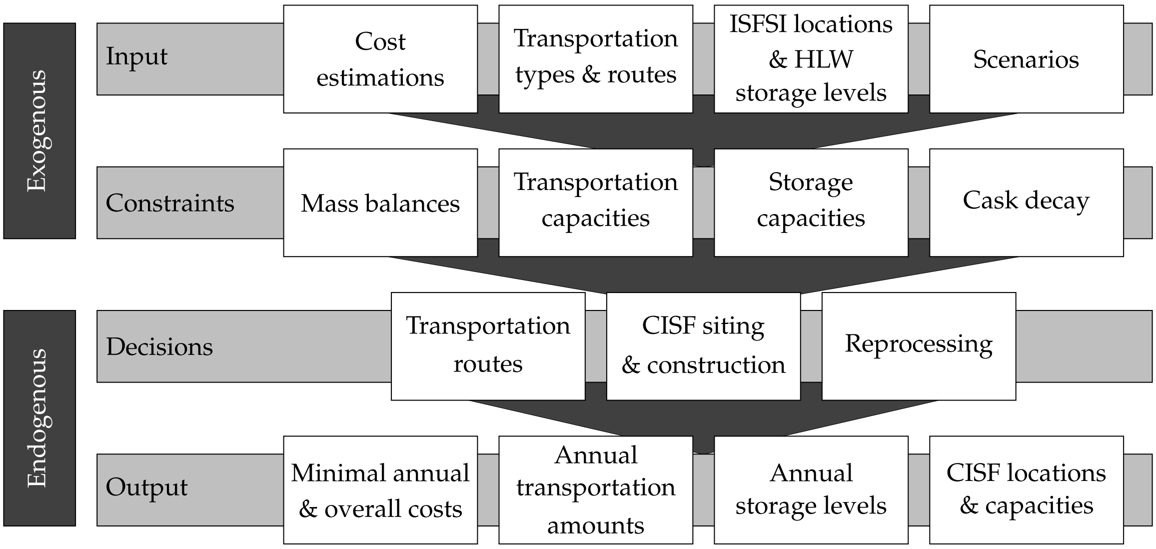

Figure 3. Scheme of model. Source: own representation.

Table 1. Scenarios implemented in the model.

Scenarios	**Final Repository**				**Need to Store all Waste in Yucca Mountain**
	Opening of Yucca Mountain		**Opening of Second Final Repository**		
	2030	**2060**	**2030**	**2060**	
BAU					
Yuc_2030	✓				
Yuc_2060		✓			
Yuc+_2030	✓		✓		
Yuc+_2060		✓		✓	
Yuc_reproc	✓				✓

Source: own representation.

To keep calculation time within a reasonable frame but provide detailed enough information, the model calculated in five year steps. All used sets, scalars and parameters as well as the variables defined can be found in Tables A1 and A2 in the Appendix A.

3.2. Objective Function

The objective of the model was to minimize total costs. Costs are composed of four elements: transportation cost, storage cost, infrastructure cost and technology cost.

- Transportation costs result from each transport between two nodes n and nn and therefore depends on the distance $dist_{n,nn}$, as well as on the transportation type allowed between those two nodes $tt_{t,n,nn}$. The transportation cost was calculated cask-wise and did not depend on the different contents such as SNF or vitrified waste, yet each cask caused fixed transportation costs $cost\_t\_fix_t$ due to loading and unloading as well as variable transportation cost $cost\_t\_var_t$

(although in reality only full casks were transported, we assumed that the high number of casks to be transported allowed modeling the number of casks as real numbers for the sake of a linear model).

- The storage cost depended on the amount of casks—independent of their content—stored in a single node per year and further depends on the local storage cost $cost\_s\_var_n$.
- The infrastructure cost refers to the optional cost which are caused by building new CISFs $cost\_B_i$.
- The technology cost were the combination of both vitrification cost $cost\_VI$ as well as cost due to cask decay which will require the waste to be refilled into a new cask $cost\_NC$. Although both these processes can only be conducted inside the hot cells, which requires further transportation, the technology cost refers only to the technological process.

All costs are discounted by a constant rate, due to technological development. We chose a discount rate of 1%, which seems in the reasonable range, and has been chosen by a similar study [27].

$$\begin{aligned} min\ totalcost = \sum_y \Bigg(\Bigg(\sum_{n,nn} \Bigg(\sum_t \Bigg(& (tt_{t,n,nn} \cdot (cost\_t\_fix_t + cost\_t\_var_t \cdot dist_{n,nn})) \cdot \Big(SNF\_t_{n,nn,y} \\ & + WASTE\_NC\_t_{n,nn,y} + WASTE\_VI\_t_{n,nn,y} \Big) \Bigg) \Bigg) \\ & + \sum_n \left(\left(SNF\_s_{n,y} + WASTE\_NC\_s_{n,y} + WASTE\_VI\_s_{n,y} \right) \cdot cost\_s\_var_n \right) \\ & + \sum_i \left(B_{i,y} \cdot cost\_B_i \right) + \sum_{n,hc} \Big(SNF\_t_{n,hc,y} \cdot cost\_NC \Big) \\ & + \sum_{hc,n} \Big(v\_effect \cdot WASTE\_VI\_t_{hc,n,y} \cdot cost\_VI \Big) \Bigg) / \left(1 + interest\right)^y \Bigg). \end{aligned} \quad (1)$$

3.3. Constraints

The mass balance for SNF was formulated independently for reactors since they generate waste. Further, for all years but the first year, the amount stored in the year before must be taken into account.

$$\begin{aligned} & \sum_{nn} \left(SNF\_t_{nn,r,y} \right) - \sum_{nn} \left(SNF\_t_{r,nn,y} \right) + gen\_SNF(r,y) \\ & \qquad + \left(SNF\_s_{r,y-1} \right) if\ (y > 1) - SNF\_s_{r,y} = 0 \qquad \forall\, r \in R, y \in Y. \end{aligned} \quad (2)$$

For all nodes but reactors and hot cells, the mass balance for SNF was defined.

$$\begin{aligned} & \sum_{nn} \left(SNF\_t_{nn,n,y} \right) - \sum_{nn} \left(SNF\_t_{n,nn,y} \right) + \left(SNF\_s_{n,y-1} \right) if\ (y > 1) - SNF\_s_{n,y} = 0 \\ & \qquad \forall\, n \in N, y \in Y. \end{aligned} \quad (3)$$

As refilling waste into new casks was only done in hot cells, the waste $WASTE\_NC$ can be considered—model-wise—to be generated in hot cells. For all other nodes therefore the standard mass balance holds.

$$\begin{aligned} & \sum_{nn} \left(WASTE\_NC\_t_{nn,n,y} \right) - \sum_{nn} \left(WASTE\_NC\_t_{n,nn,y} \right) \\ & \qquad + \left(WASTE\_NC\_s_{n,y-1} \right) if\ (y > 1) - WASTE\_NC\_s_{n,y} = 0 \qquad \forall\, n \in N \notin HC, y \in Y \end{aligned} \quad (4)$$

In analogy to $WASTE\_NC$, vitrified waste $WASTE\_VI$ was only generated in hot cells and the standard mass balance therefore holds for all other nodes.

$$\sum_{nn}\left(WASTE\_VI\_t_{nn,n,y}\right)-\sum_{nn}\left(WASTE\_VI\_t_{n,nn,y}\right)$$
$$+\left(WASTE\_VI\_s_{n,y-1}\right) if\ (y>1)-WASTE\_VI\_s_{n,y}=0 \qquad \forall n \in N \notin HC, y \in Y. \quad (5)$$

Each node n can be described by its storage capacity $s\_cap_{n,y}$. In all years the amount of waste stored in the node—independent of the nature of the waste—must not exceed the local storage capacity.

$$SNF\_s_{n,y}+WASTE\_NC\_s_{n,y}+WASTE\_VI\_s_{n,y} \leq s\_cap_{n,y}$$
$$\forall n \in N, y \in Y. \quad (6)$$

This constraint expresses whether a transport between two nodes is possible. For all non existing connections between two nodes the $dist_{n,nn}$ was zero, meaning transportation was not possible. For all other connections the transportation capacity was unlimited, due to our assumptions.

$$SNF\_t_{n,nn,y}+WASTE\_NC\_t_{n,nn,y}+WASTE\_VI\_t_{n,nn,y} \leq dist_{n,nn} \cdot BIG$$
$$\forall n, nn \in N, y \in Y. \quad (7)$$

An overall reprocessing/vitrification capacity v_cap was defined per year, which resulted from the capacity of the hot cells.

$$\sum_{n}\left(v\_effect \cdot WASTE\_VI\_t_{hc,n,y}\right) \leq v\_cap \qquad \forall hc \in HC, y \in Y. \quad (8)$$

This specific mass balance for hot cells took into account that the amount of waste can be reduced through vitrification by the factor v_effect. Therefore, all incoming waste was either transformed to the same amount of newly casked waste $WASTE\_NC$ or into a reduced amount of vitrified waste $WASTE\_VI$.

$$\sum_{n}\left(SNF\_t_{n,hc,y}-WASTE\_NC\_t_{hc,n,y}-v\_effect \cdot WASTE\_VI\_t_{hc,n,y}\right)=0$$
$$\forall hc \in HC, y \in Y. \quad (9)$$

Neither the waste in new casks, nor vitrified waste can be processed in a hot cell. Therefore the amount of units transported to all hot cells in each year of both these kinds of waste must be zero.

$$WASTE\_NC\_t_{n,hc,y}+WASTE\_VI\_t_{n,hc,y}=0 \qquad \forall hc \in HC, n \in N, y \in Y. \quad (10)$$

Each interim storage facility can only be built only once, therefore the binary decision over all years must be smaller or equal to one.

$$\sum_{y}\left(B_{i,y}\right) \leq 1 \qquad \forall i \in I. \quad (11)$$

Neither can waste be stored in, nor transported to or from an interim storage facility in each year, unless it has been built before the current year, taking into account that the building takes five years.

$$\sum_{y \leq yy} (B_{i,y}) \cdot BIG \geq \sum_{y,ify \leq yy} \Big((SNF\_s_{i,y} + WASTE\_NC\_s_{i,y} \\ + WASTE\_VI\_s_{i,y}) + \sum_{n} (SNF\_t_{n,i,y} + SNF\_t_{i,n,y} + WASTE\_NC\_t_{n,i,y} \\ + WASTE\_NC\_t_{i,n,y} + WASTE\_VI\_t_{i,n,y} + WASTE\_VI\_t_{n,i,y}) \Big) \qquad \forall i \in I, yy \in Y. \quad (12)$$

Cask decay is a result of the security requirements regarding storage of nuclear waste. Before a casks lifetime expires, the waste must be filled into a new cask. In this model, we assumed that each year a certain percentage of casks *decay_SNF* expired and must therefore be sent to a hot cell for refilling into a new cask or reprocessing, as reprocessing demands extracting and refilling the waste as well. The percentage of waste that must be sent to the hot cells to be refilled depends on the amount of waste of that certain type which has been generated before.

$$\sum_{hc,n} \left(SNF\_t_{n,hc,y} \right) \geq decay\_SNF \cdot \sum_{n} (SNF\_s_{n,y-1}) \qquad \forall y \in Y. \quad (13)$$

4. Data

4.1. At Nuclear Power Plants

The reactors adopted by the model (99 overall) consist only of the commercial ones for electricity production that are regulated by the NRC itself, others are omitted as the ones considered make up most of the existing NPPs in the U.S. [2]. Each NPP is assumed to have the same storage capacity of 1000 MTU [33] and costs of $30,000 per cask per year [34]. In addition, a NPP stops producing energy and thus waste the year its license expires. We do not consider the possible expansion of the operating licenses, as more and more reactors shut down prematurely due to rising safety and performance problems and loss of operational competitiveness due to rising operational costs and cheap natural gas and renewable energy. The number of shut-downs is likely to increase in the coming years without new policies [35]. In addition, it does not seem sensible—from a public perspective—to extend operations to 60 or even 80 years and, hence, have 20 to 40 additional years of waste generation if the question of permanent storage is not solved.

Casks with an equal size of 10 MTU and a limited lifespan of 100 years [36] are assumed throughout the model for storage and transport. Delays in availability of storage and transport casks are not considered in this model as only a best-case analysis is performed. The amount of waste each reactor harbors is a key issue for the total cost of the model. It is calculated based on the commissioning date and power output.

4.2. Transportation and Processing

Although four means of transport exist (air, sea, road and rail), only rail and road are considered. The conveyance by airplane is too dangerous given the amounts that would be transported and the possibility of a crash, either because of technical failure or also due to a terrorist attack, meaning the hazardous waste could freely escape into the atmosphere. Sea transportation does not seem like a valid option in the U.S. where little rivers exist for an east-west connection; as most of the reactors considered are located at the East Coast, whereas the final repositories, that will be depicted later in this chapter, are either in Nevada or in New Mexico. This deliberation is congruent with representative routes evaluated by the NRC [37].

The data taken as a basis for the costs for rail and road transport are depicted in Table 2. They are based on Feizollahi et al. [38] and adjusted to the assumed cask size.

Table 2. Transportation cost per cask for rail and road transport.

Distance	Price Rail	Price Road
<200 miles	\$20.5 per mile	\$47.82 per mile
200–1000 miles	\$12.7 per mile	\$16.70 per mile
>1000 miles	\$10.3 per mile	\$14.37 per mile

Source: own representation based on Feizollahi et al. [38].

Reprocessing is a way of reducing waste and therefore a potential option for waste management (if the proliferation risk is not considered) if the final storage space is not sufficient. Shielded nuclear radiation containment chambers (hot cells) are necessary for reprocessing nuclear waste [11]. They are also needed for recasking the waste if no pool is available, e.g., at shut down reactor sites [11]. Our model includes these hot cells at two locations: one is near New York City in West Valley, close to the old commercial reprocessing facility and one is close to WIPP in Carlsbad (New Mexico), as there is already a hot cell for dealing with LLW and ILW at WIPP. For simplicity reasons a possible reprocessing facility is co-situated with a hot cell. Other reprocessing options abroad are not considered in the model due to political reasons. The diminution of weight is factored in through a fixed percentage of 4% [39]. As the process of reprocessing demands for the debris to be removed from the cask it conforms with the procedure of recasking. It is much more expensive though, the value being around \$5,850,000 per cask (based on [40]), not including installation costs of reprocessing facilities which have a limited capacity of 170 casks per year each (Capacity taken from the largest operating reprocessing facility in France, which has a capacity of 1700 MTU per year [12]).

4.3. Interim and Final Storage

After the opening of the repositories a constant annual acceptance rate of 3000 MTU is assumed [15]. The storage costs in the final repositories are not included, as the model only considers the process and occurring costs until the goal of storing the waste in a final repository is met.

Based on the existing “nuclear geography”, we have identified sites for potential CISFs. Firstly, locations near junctions that connect different routes from reactors to Yucca Mountain were searched, and secondly, coordinates were looked up on a map of the U.S. that belong to seemingly larger areas without dense habitat. Detailed information about the exact locations can be found in Table A3 in the Appendix A.

The layout of the interim storage facilities is designed using data from a cost study prepared for the DOE [15]. We assume the facilities to each cost \$1 billion when being constructed and to have reduced storage costs compared to the reactors. Furthermore, they have a total storage capacity of 20,000 MTU and take five years to be built, similar to the capacity and time frame planned by the DOE [22].

5. Results and Discussion

5.1. Business as Usual

In the BAU scenario, no final repository is available, so most of the HLW is transported to interim storage facilities. The total cost amount to \$ 15.3 billion in total. The costs for building the interim storage facilities make up the biggest part (42%), followed by the storage cost with 29% and the cost for refilling casks (technology cost) due to cask decay with 26%. The transportation cost make the smallest portion with only 3% (Figure 4). Directly at the start of the projection, five interim storages are built and all waste is transported from the sites near the reactor to these facilities after five years of construction time which is visible as a peak in the transport cost in 2025. The storage cost increase slightly over time, as the total amount of HLW increases. However, at the opening of the CISF the storage cost drop to a fourth. After 2055 the storage cost slightly decrease due to the discount factor. Continuously throughout the years, casks must be transported to the hot cell to be refilled into new casks. Caused by the assumption of a fixed percentage of casks that have to be refilled every year, the amounts and thus the costs of this process decrease exponentially.

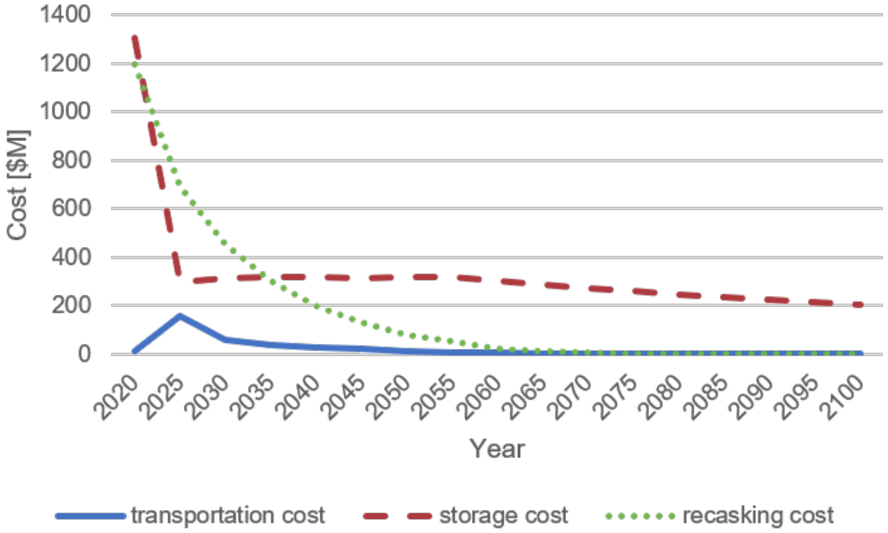

Figure 4. Distribution of costs over time in the business as usual (BAU) scenario. Source: own representation.

From 2025 on all waste was transported into the newly built interim storages and by 2050 their full capacity is reached. After that point the construction of any further interim storages seems inefficient, thus the remaining waste over the last 50 years was continuously stored by the NPPs/reactors where it occurs.

There were six interim storages build, five of them in the East of the U.S., where the density of reactors was very high, and also one repository near by Yucca Mountain. Five of them were built in the beginning of the model horizon and one after five years in 2025, thus the overall construction cost sum up to about $ 6 billion.

5.2. Comparison of Scenarios

When comparing the different scenarios some interesting similarities and differences can be revealed (Table 3). First of all the overall costs (except for the Yuc_reproc scenario) lie in the range between $7.2 and $15.3 bn. The opening of a final repository in 2030 reduced costs by 30%, the opening of two repositories by 50% compared to the *BAU* scenario. The opening in 2060 did not reduce costs that much. The overall cost composition differed only slightly between the scenarios, except for the CISF capital costs that cause the biggest difference (Figure 5). Regarding the total cost, the perfect foresight in the model resulting in a best case scenario of an omniscient central planner has to be kept in mind. Strategic behavior or unforeseen events could increase overall costs.

The total cost in all scenarios were lower compared to other estimations. The DOE [22] calculates between $50 and $60 bn. of overall lifecycle cost for HLW. This difference can be explained by regarding the cost composition of our model (the model only took costs between dry cask storage at the ISFSIs and the long-term repository into account. Not considered are at-reactor costs, e.g., for spent fuel pools and filling the spent nuclear fuel SNF into dry casks as well as costs that occur at the final repository for storing the HLW there. These two sources of costs had a huge impact on the overall costs for waste disposal but are not considered in the model since they are not part of the optimization) as well as by regarding the limited time frame and the rough estimation of storage cost due to the lack of public information. However, the relative difference in cost between the different scenarios seems valid.

Table 3. Overview of the results of all scenarios.

Scenarios	BAU	Yuc_2030	Yuc_2060	Yuc_2030+	Yuc_2060+	Yuc_reproc
Total costs [$B] in 80 years	15.3	10.3	15	7.2	13.5	33.8
Number of CISF built (needed capacity [MTU])	6 (120,000)	3 (60,000)	6 (120,000)	none	5 (100,000)	1 (20,000)
Number of CISF that can be shut down (after how many years)	none	none	3 (65, 70, 80 years)	none	5 (45, 50, 50, 55, 60 years)	1 (80 years)
Locations of CISF (see Figure 6)	2, 5, 6, 7, 8, 9	7, 8, 9	2, 5, 6, 7, 8, 9	none	2, 5, 6, 7, 8	8
After how many years can the last ISFSI be closed?	never	25 years	60 years	30 years	40 years	25 years
Percentage of casks that must be refilled	100%	66%	100%	59%	98%	2%
Overall amount of HLW in 2100 [MTU]	124,000	124,000	124,000	124,000	124,000	70,000

Source: own representation.

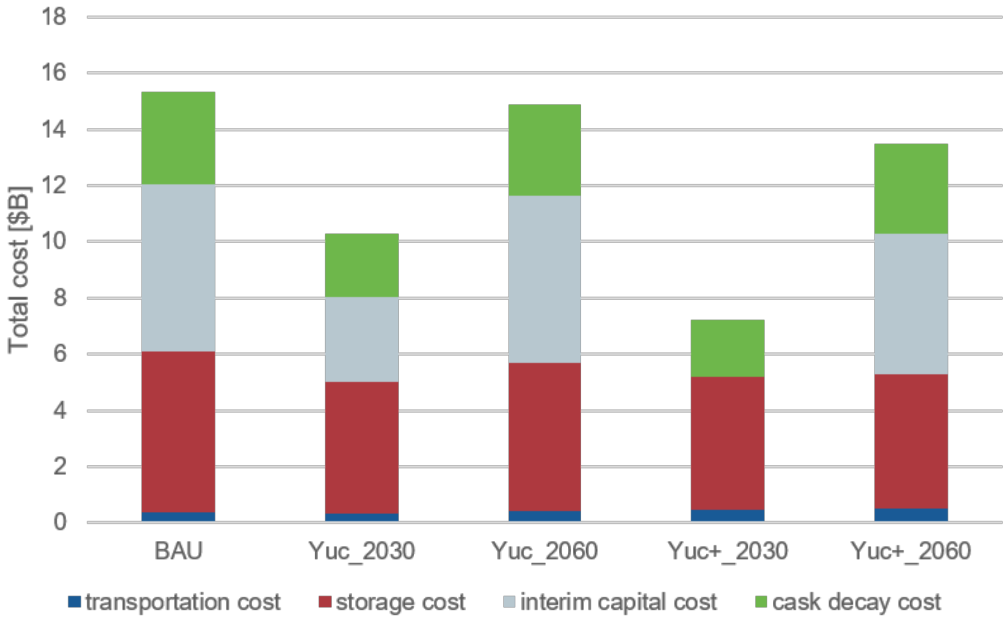

Figure 5. Comparison of the overall costs in all scenarios without reprocessing. Source: own representation.

In every scenario with a final repository available all ISFSIs at the reactors sites could be closed by 2080 at the latest. More critical is the timing of the opening of final repositories to the construction of the CISFs. In every scenario it was cost efficient to built at least one of those, providing a capacity of 20,000 MTU. But in some scenarios up to 120,000 MTU of storage capacity in CISFs were needed in order to reduce storage costs before transportation to a final repository. Also the number of CISFs that can be shut down within the model horizon varied depending on the timing of final repository availability and capacity. It should be emphasized that the providing of solely one long-term repository is not sufficient for the amount of waste and thus, some CISFs would never be shut down. Even in the case that Yucca Mountain is operational by 2030 or 2060, three CISFs would have to store HLW forever.

All CISFs were built following a similar scheme (Figure 6). The CISFs at Barstow, California was built in every scenario, as it is close to the final repository Yucca Mountain and provided storage capacity for the few NPPs at the West coast of the U.S. All other interim storages are built close to the East cost, where the vast amount of NPPs and ISFSIs is located. The location of Newville, Pennsylvania had been chosen in every scenario, and also Barnesville, Georgia and Lasalle, Illinois and Old Chatham, New York seem to be efficient locations for CISFs from a logistic point of view.

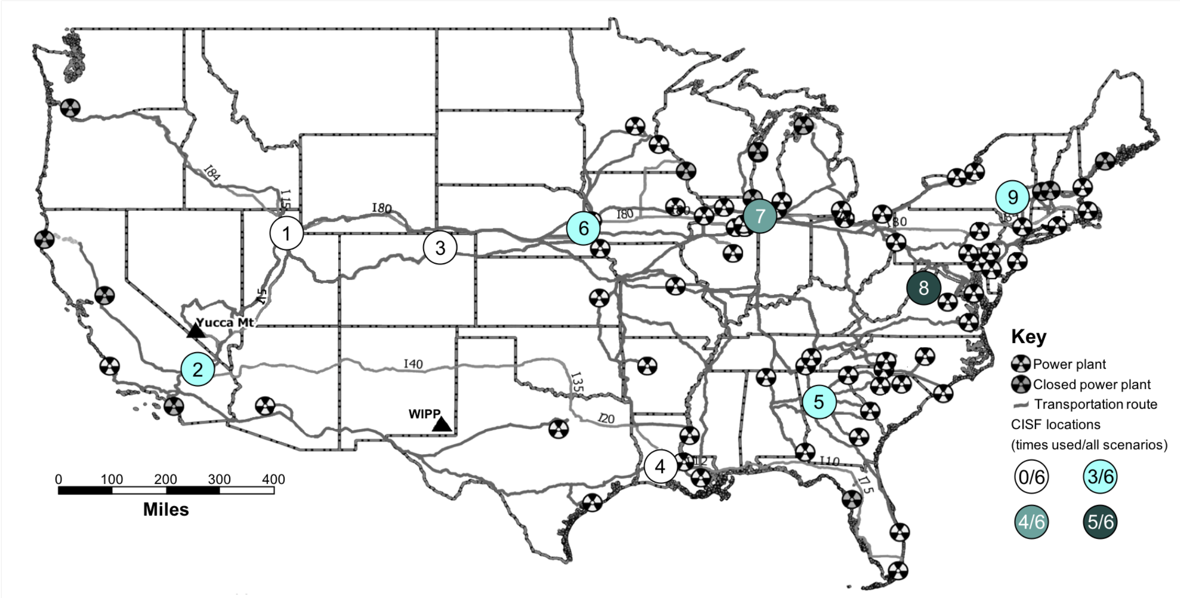

Figure 6. Realized consolidated interim storage facility (CISF) locations in all scenarios. Source: own representation based on [37].

Furthermore, the percentage of casks that are refilled in every scenario can be compared. Without a final repository or reprocessing, the entire SNF has to be filled into new casks by 2100 because of the decay of the old ones. The availability of final repositories reduces this portion up to only 59% assuming that no recasking is necessary in the final repository. When reprocessing waste in the Yuc_reproc, the portion of SNF filled into new casks can even be reduced to only 50%. Although this reduced costs and risks linked to the recasking, the total cost and risk increased due to the reprocessing.

An additional sensitivity analysis on the discount factor for the overall costs, which we have assumed to be 1%, was performed to evaluate its impact on the overall results. It shows that a variation of this factor between 0% and 5% only slightly changed the overall costs, but did not effect the timing of processes nor the relative cost differences between the scenarios. For values higher than 5% major investments, mainly the CISF construction, were postponed to later periods, but no change in the number of CISF to be built nor in the economic feasibility of reprocessing (see below) can be observed.

5.3. Reprocessing

Even if the option of reprocessing SNF were implemented in every scenario, it would not be performed due to the high costs that make it economically inefficient. An additional sensitivity analysis on these costs was performed to further evaluate the assumed reprocessing costs. It indicates that it would be necessary to reduce them by 90% (from \$585,000 to about \$58,500 per MTU) to include reprocessing as an economically viable option.

Reprocessing is therefore only performed in Yuc_reproc due to the binding constraint that forces the model to have all HLW stored in Yucca Mountain by 2060. For allowing this, the total costs almost tripled compared to every other scenario, as they amount up to $33.8 billion (Figure 7). The reason for this were the reprocessing costs, that make almost 80% of the overall costs in this scenario. But it was debatable whether the costs can be compared to the other scenarios as the scenario outcome (including the remaining volume of waste) was different. Reprocessing in this scenario begins in 2020, causing high costs in the beginning of the model horizon, and very low cost due to decreased storage and transport in later years (Figure 8). The amount of waste that was reprocessed every year seems to be decreasing exponentially, similar to the recasking.

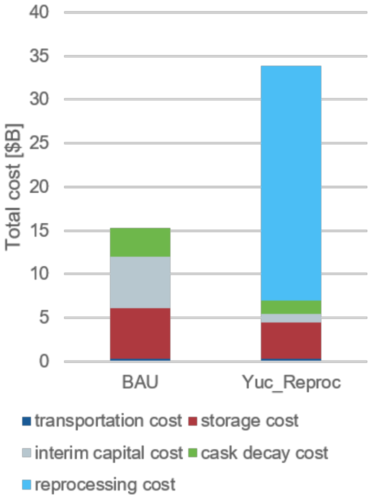

Figure 7. Comparison of the BAU and Yuc_reproc scenario. Source: own representation.

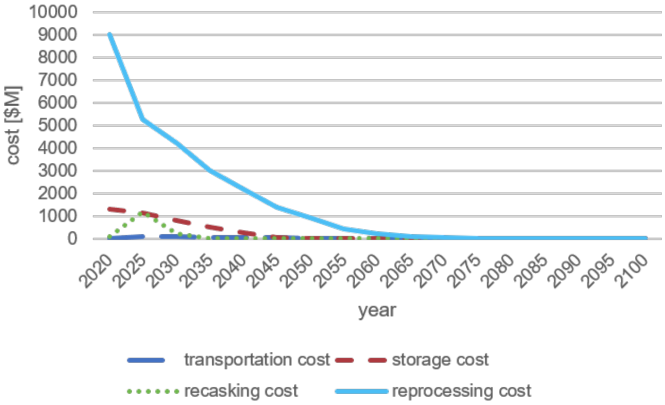

Figure 8. Distribution of costs over time in the Yuc_reproc scenario. Source: own representation.

Figure 9 shows the overall storage level of SNF and vitrified waste after reprocessing. After 25 years all ISFSIs are empty and can be shut down. Beyond that point the waste remaining in the two CISFs is being transported and partly reprocessed before all HLW is stored in Yucca Mountain in 2100 and the CISF can also be shut down.

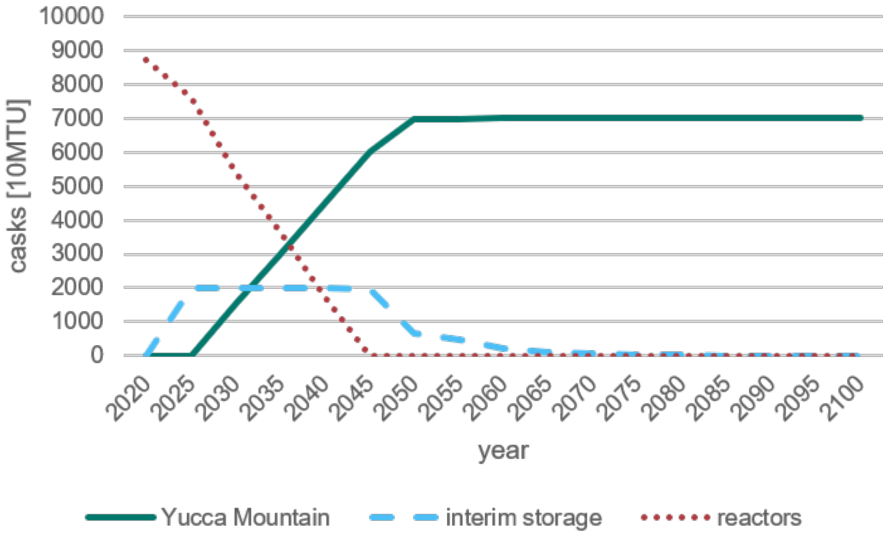

Figure 9. Storage levels in the Yuc_reproc scenario. Source: own representation.

In addition to the development of the overall amounts of SNF, SNF in new casks and vitrified waste is shown in Figure 10. One can see the amount of SNF decreases exponentially according to the casks decay. After 10 years of reprocessing of SNF, no more casks had to be refilled into new casks, leading to the conclusion that enough reprocessing is done to fulfill the cask decay constraint. Therefore the cost of refilling the casks can be saved, even though they are very little compared to the reprocessing costs. Figure 11 portrayed the development of the overall amount of vitrified waste per year. One can see that about 222 MTU are being stored in Yucca Mountain by 2100. Therefore, it can be concluded that reprocessing 45% of the overall HLW would make Yucca Mountain sufficient as a final repository for all HLW in the U.S. Nevertheless, even then it would seem like a distant possibility for political, technological and economic reasons.

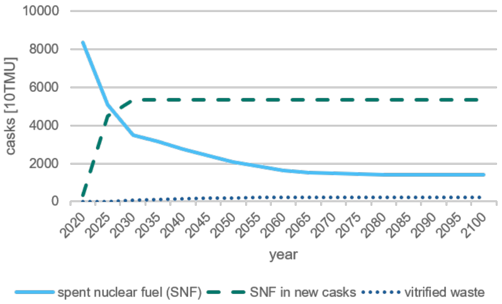

Figure 10. Overall storage levels of different types of waste. Source: own representation.

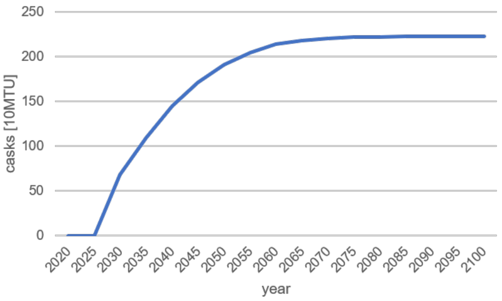

Figure 11. Overall storage level of vitrified waste. Source: own representation.

6. Conclusions and Policy Implications

Based on the results obtained from the comparison of the different scenarios, several basic conclusions can be drawn. Due to the reduced storage costs in the CISFs, the construction of them is cost efficient in almost every scenario. This reduction in costs can be explained by economies of scale in the CISFs and the decreased penalty fees the DOE has to pay to the NPP operators. These results are congruent to the DOE study (2016) concluding that there is a total cost avoidance in total system lifecycle costs, especially post-shutdown at-reactor storage costs for any opening date of a final repository. In addition, the storage at an CISF is also safer than at an independent storage facility in terms of protecting the HLW against any natural or human impact.

More capacity for interim storage is needed than the DOE has planned to provide by 2025. Depending on the scenario, CISFs with overall capacities between 20,000 and 120,000 MTU have been built in the model. Since the opening of a final repository in 2030 is rather unlikely this indicates that the capacity of 20,000 MTU the DOE has planned to provide by 2025 is not sufficient to save more costs and follow the best economic strategy. Furthermore, all CISFs are built in the first year of the model, which shows that the construction of those facilities would have to start immediately in order to reduce cost.

From the point of logistics, locating the CISFs strategically close to the NPPs at the East coast and close to a final repository would be best. In half of the scenarios the location near Yucca Mountain has been chosen to build a CISF. In addition, further CISFs have been built at different locations near the East cost, where the majority of all NPPs is located. Therefore, it can be concluded that the location closest to the final repository (Yucca Mountain) as well as any location nearby the NPPs are preferable, due to decreased transportation cost.

Any delay in finding and opening a final repository increases total cost, as seen by the cost differences between the 2030 and 2060 scenarios. The difference lies in the range of 15–30% for every ten years of delay. If CISFs are built and a final repository is operational by 2060, all independent spent fuel storage installations by reactor sites could be closed by 2080. Independent from the exact opening date and the number of final repositories, all scenarios including a final repository have in common that all HLW currently stored by the reactor sites in ISFSIs is transported to CISFs or the final repository at the latest by 2050. Therefore this seems to be a realistic time frame for shutting down ISFSIs, given that the mentioned conditions are fulfilled.

Reprocessing is not efficient due to very high costs. Only by reducing them by 90%, reprocessing becomes more cost efficient than to leave all the waste in ISFSIs and CISFs. The evaluation of an even longer time frame seems not useful, considering technological development and the change of costs coming along with new innovations in the field of nuclear waste processing. Furthermore, the reduction of volume of HLW does not seem like a good-enough reason to produce plutonium, a bomb material and therefore proliferation risk, through the irradiation of uranium fuel.

A simple yet relevant addition to the work presented would be the inclusion of further scenarios addressing the date of opening of Yucca Mountain as well as other final repository options. Also, the perspective of having to store the HLW for many more years without having a final repository could be examined which seems plausible regarding the political development during the past years. Even though it might make economic sense and be safer to have a final repository, the public acceptance in the affected region is a key problem. Similar issues with public acceptance that have to be taken into consideration can be seen in many large infrastructure problems regarding e.g., electricity lines, airports or highways. It is, however, even more important for nuclear storage due to the toxicity of radioactive waste and, therefore, needs to be considered wisely by the regulator. As long as local politics oppose the federal plan for a final repository, as is the case in Nevada, the opening of Yucca Mountain might not be feasible. Moreover, the impact of changes in the U.S. nuclear energy policy, e.g., a continuation of operation or expansion of NPPs, could be assessed. In addition, it needs to be stressed that only a best-case analysis is performed in this paper as no delay in logistical availabilities is included; these should be considered in political decisions.

Concerning the results presented in this paper an analysis of those from different points of view (political, social, ecological etc.) would be necessary in order to assess and value them. Especially regarding the CISF siting the locations would need further assessment in order to decide on their suitability. The DOE strategy proposes a consent based approach to the siting, which would require the inhabitants agreement to siting the CISFs at the locations presented. Also the impact of the transportation along the transportation routes mainly used would need to be assessed. For integrating safety aspects and environmental impact into the optimization process one could expand the model, making it a multi-objective problem.

Wrapping up, one can say that even though the Trump administration wants to restart Yucca Mountain as permanent storage facility, there are several policy issues the U.S. are facing concerning HLW. The CISFs must be built immediately. Even though the DOE announced in 2013 that a pilot interim storage facility would be operational by 2021, until today (March 2019) nothing has happened to fulfill this announcement. In addition to that, Yucca Mountain has no sufficient capacity for all HLW of the U.S. Therefore, either a second long-term repository has to be explored, or, when building the CISFs, it has to be clear that they are going to be used as long-term repositories. It is of great importance that policy makers as well as researchers start dealing more with this problem and stop postponing it.

Author Contributions: conceptualization, V.C. and S.W.; methodology, V.C., S.W. and P.-Y.O.; software, S.W.; validation, B.W.; formal analysis, V.C. and S.W.; investigation, V.C. and S.W.; resources, P.-Y.O. and B.W.; data curation, V.C.; writing—original draft preparation, V.C. and S.W.; writing—review and editing, P.-Y.O. and B.W.; visualization, V.C. and S.W.; supervision, P.-Y.O.; project administration, P.-Y.O.

Funding: Funding was provided by the German Federal Ministry for Education and Research (BMBF) in the project "CoalExit" (01LN1704A). We acknowledge support by the German Research Foundation and the Open Access Publication Fund of TU Berlin.

Acknowledgments: Earlier versions of the paper were presented at the 15th European Conference of the International Association for Energy Economics (IAEE, September 2017, Vienna, Austria), the 12th Enerday (April 2018, Dresden, Germany), the 41st International Conference of the IAEE (June 2018, Groningen, Netherlands), the 6th World Congress of Environmental and Resource Economists (WCERE, June 2018, Gothenburg, Sweden), the 36th North American Conference of the IAEE (September 2018, Washington, D.C.), as well as the DIW Berlin (German Institute for Economic Research) internal sustainability Cluster Seminar (May 2018). We thank the conference and seminar audiences, as well as Christian von Hirschhausen, Tim Scherwath, Franziska Holz, and Julia Rechlitz for helpful discussions and suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BAU	Business as usual
BRC	Blue Ribbon Commission on America's Nuclear Future
CISF	Consolidated interim storage facility
DOE	Department of Energy
GNEP	Global Nuclear Energy Partnership
HLW	High-level waste
IAEA	International Atomic Energy Agency
ILW	Intermediate-level waste
ISFSI	Independent spent fuel storage installations
LLW	Low-level waste
MIP	Mixed-integer problem
NPP	Nuclear power plant
NRC	Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
NWPAA	Nuclear Waste Policy Amendments Act
SNF	Spent nuclear fuel
WIPP	Waste Isolation Pilot Plant

Appendix A

All input such as sets, scalars and parameters is described in Table A1.

Table A1. Sets, scalars, and parameters.

Sets	Description
$n \in N$	nodes (alias (n, nn))
$i \in I \subset N$	potential new intermediate storages (CISF)
$r \in R \subset N$	reactors
$hc \in HC \subset N$	hot cells
$y \in Y$	years (alias (y, yy))
$t \in T$	nodes transportation types possible
Scalars	**Description**
$interest$	interest rate due to technological development
$cost\_NC$	cost of refilling HLW into a new cask
$cost\_VI$	vitrification cost per cask of SNF
BIG	large number
v_cap	vitrification capacity per hot cell per year
v_effect	inverted change of volume decrease due to vitrification
$decay\_SNF$	percentage of SNF casks which suffer decay and therefore must be refilled into a new cask
Parameters	**Description**
$gen\_SNF(r, y)$	amount of SNF casks generated at each reactor r in each year y
$s\_cap(n, y)$	storage capacity of node n in year y
$cost\_t\_fix(t)$	fixed transport cost of transportation type t
$cost\_t\_var(t)$	variable transport cost of transportation type t
$dist(n, nn)$	distance between two nodes n and nn
$cost\_s\_var(n)$	variable storage cost of node n
$cost\_B(i)$	fixed construction cost of a new intermediate repository (assumption: all newly to be build intermediate repositories are equally expensive)
$tt(t, n, nn)$	binary option whether transportation type t exists between n and nn
$tt\_rail(n, nn)$	binary option whether transportation type 'rail' exists between n and nn
$tt\_road(n, nn)$	binary option whether transportation type 'road' exists between n and nn
$t\_cap(n, nn)$	transportation capacity between n and nn

Source: Own representation.

Table A2 presents and explains the model variables.

Table A2. Variables.

Positive Variables	Description
$SNF\_t(nn, n, y)$	Amount of casks containing SNF transported between node n and node nn in year y
$WASTE\_NC\_t(nn, n, y)$	Amount of casks containing either SNF or decommissioned waste—which have been filled into a new cask due to cask decay—transported between n and nn in year y
$WASTE\_VI\_t(nn, n, y)$	Amount of casks containing the vitrified waste—remaining after SNF has been reprocessed—transported between n and nn in year y
$SNF\_s(n, y)$	Amount of casks containing SNF stored in node n in year y
$WASTE\_NC\_s(n, y)$	Amount of casks containing either SNF or decommissioned waste—which have been filled into a new cask due to cask decay—stored in node n in year y
$WASTE\_VI\_s(n, y)$	Amount of casks containing SNF which has been vitrified—thereby reducing volume—stored in node n in year y
Binary variables	**Description**
$B(i, y)$	Option whether to build a new intermediate repository i in year y
Free variables	**Description**
$totalcost$	Decision variable for overall costs

Source: Own representation.

Table A3 shows exact coordinates of the chosen possible interim storage facility locations as well as the names of cities close by. No detailed regional analysis has been performed to test for technical safety or public acceptance at these locations.

Table A3. Location coordinates of the possible interim storage facility locations.

Interim Storage Facility	Location Coordinates (Latitude, Longitude)	Name
1	40.57, −112.39	Grantsville, Utah
2	34.81, −117.03	Barstow, California
3	39.75, −104.52	Watkins, Colorado
4	30.25, −92.22	Rayne, Louisiana
5	33.10, −84.08	Barnesville, Georgia
6	41.11, −93.51	Lucas, Iowa
7	41.36, −89.05	Lasalle, Illinois
8	40.16, −77.34	Newville, Pennsylvania
9	42.45, −73.58	Old Chatham, New York

Source: Own representation.

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