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Processing High-Level Radioactive Waste in the U.S.

A Mathematical Model

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Agenda

1) Motivation

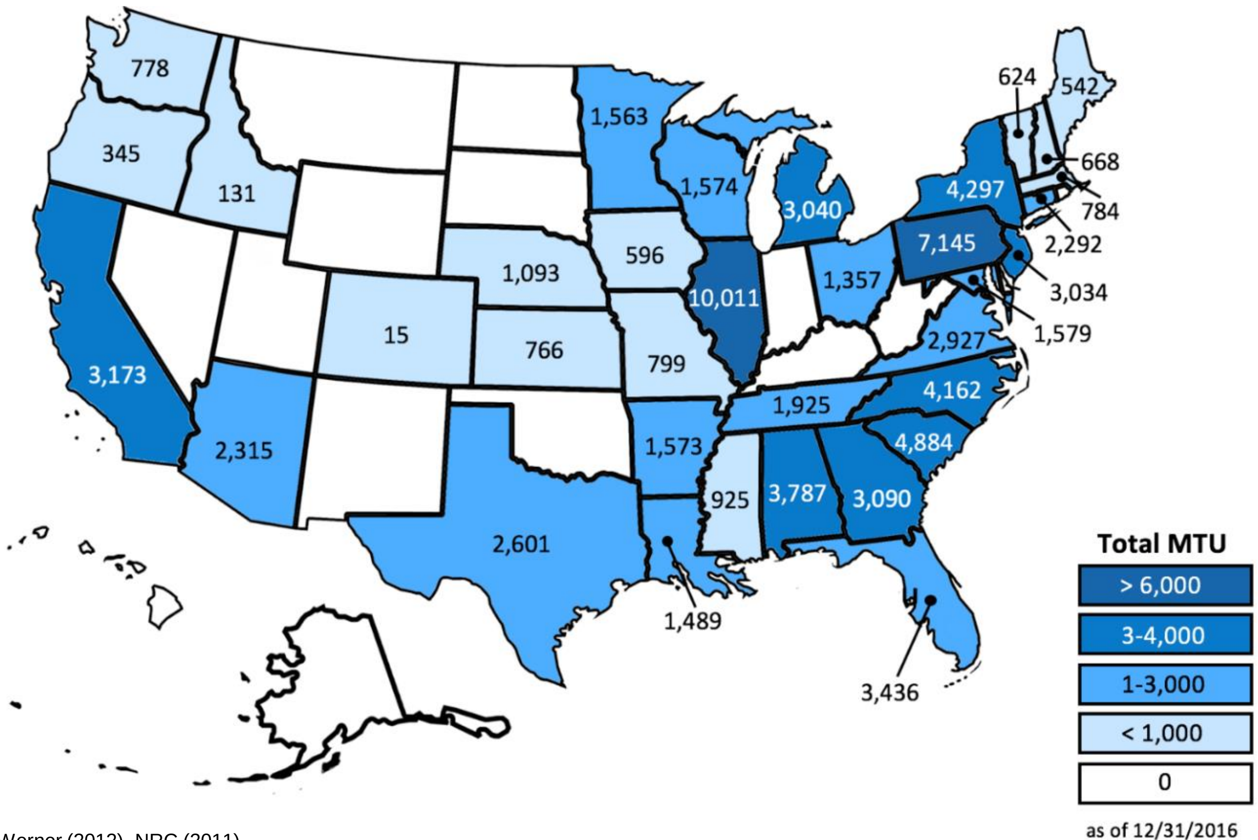
2) Technological System

3) Model Description

4) Results and Conclusion

Regional distribution of high-level nuclear waste in the U.S.

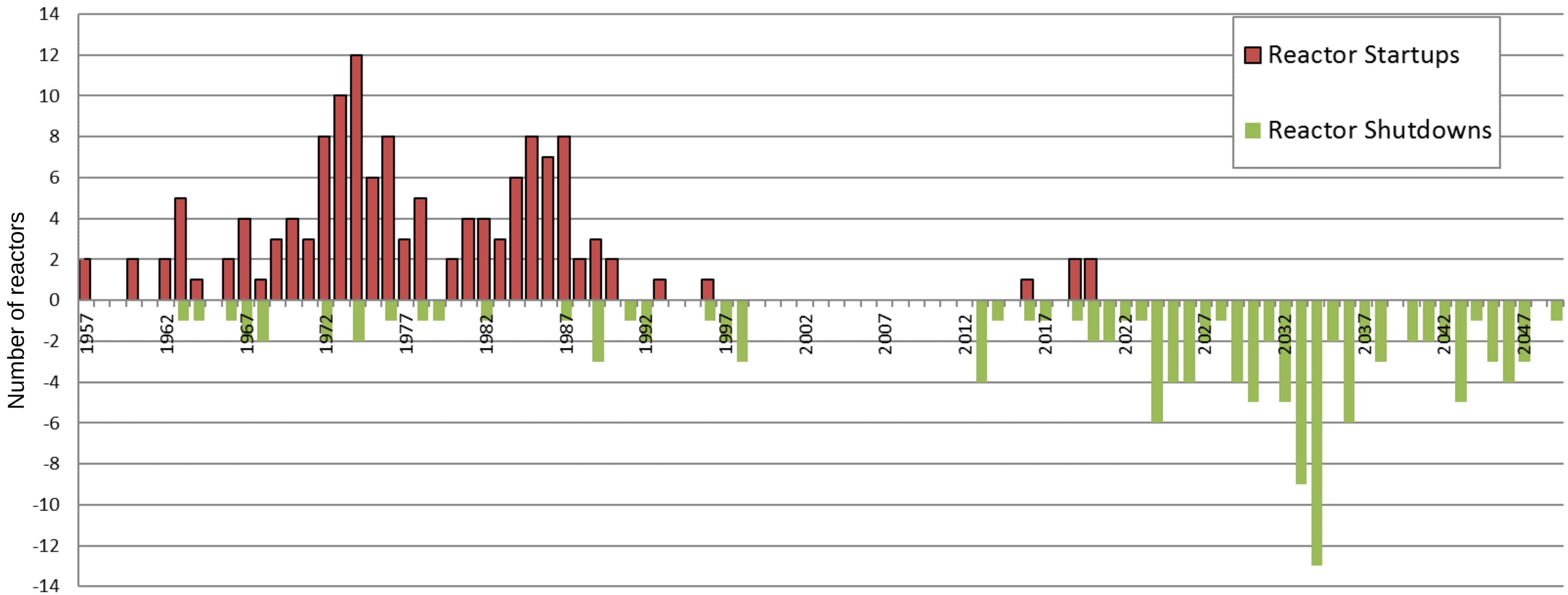
- **Over 70,000 metric tons of commercial spent fuel were accumulated in the USA as at the end of 2016**
- **The total increases by 2,000 to 2,400 metric tons annually**



Source: Own illustration based on Werner (2012), NRC (2011)

U.S. nuclear power reactor grid connections and permanent shut-downs

- **Until 2050 most reactors will be shut down, leaving even more Independent Spend Fuel Storage Installations (ISFSI) behind**
- **Department of Energy (DOE) has already spent $10 B in legal penalties for failure to deliver HLW disposal facility**



Source: Wegel et. al (2017)

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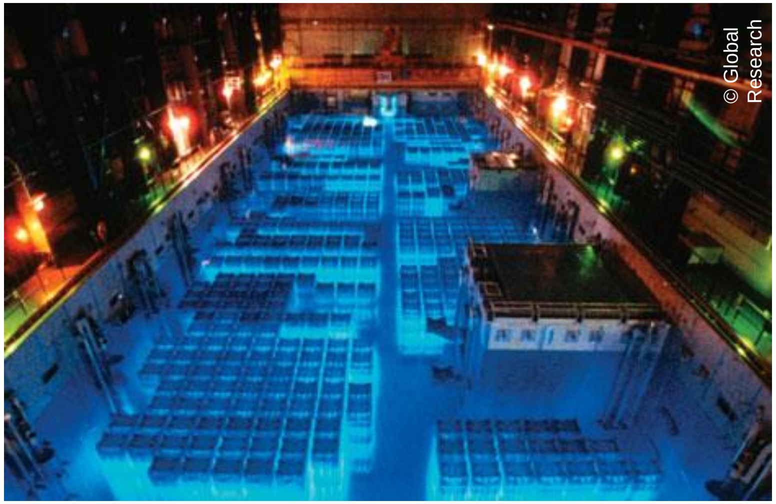
Spent fuel storage in the U.S.

Spent fuel pools

- Used in all U.S. nuclear power plants
- Robust constructions made of reinforced, several-feet-thick concrete with steel liners
- Approximately 40 feet deep
- Water for shielding the radiation and cooling the rods
- ~78% of overall HLW



Dry cask storage

- Used when pools reach capacity
- Fuel is cooled for at least 5 years in pools before being transferred to casks
- NRC has authorized transfers as early as 3 years, industry norm is 10 years
- Special, one-car-garage-sized canisters filled with inert gas
- Stored above ground
- ~22% of overall waste

Source: U.S. NRC (2015)

Permanent repository − possibilities

1. Yucca Mountain (Nevada)

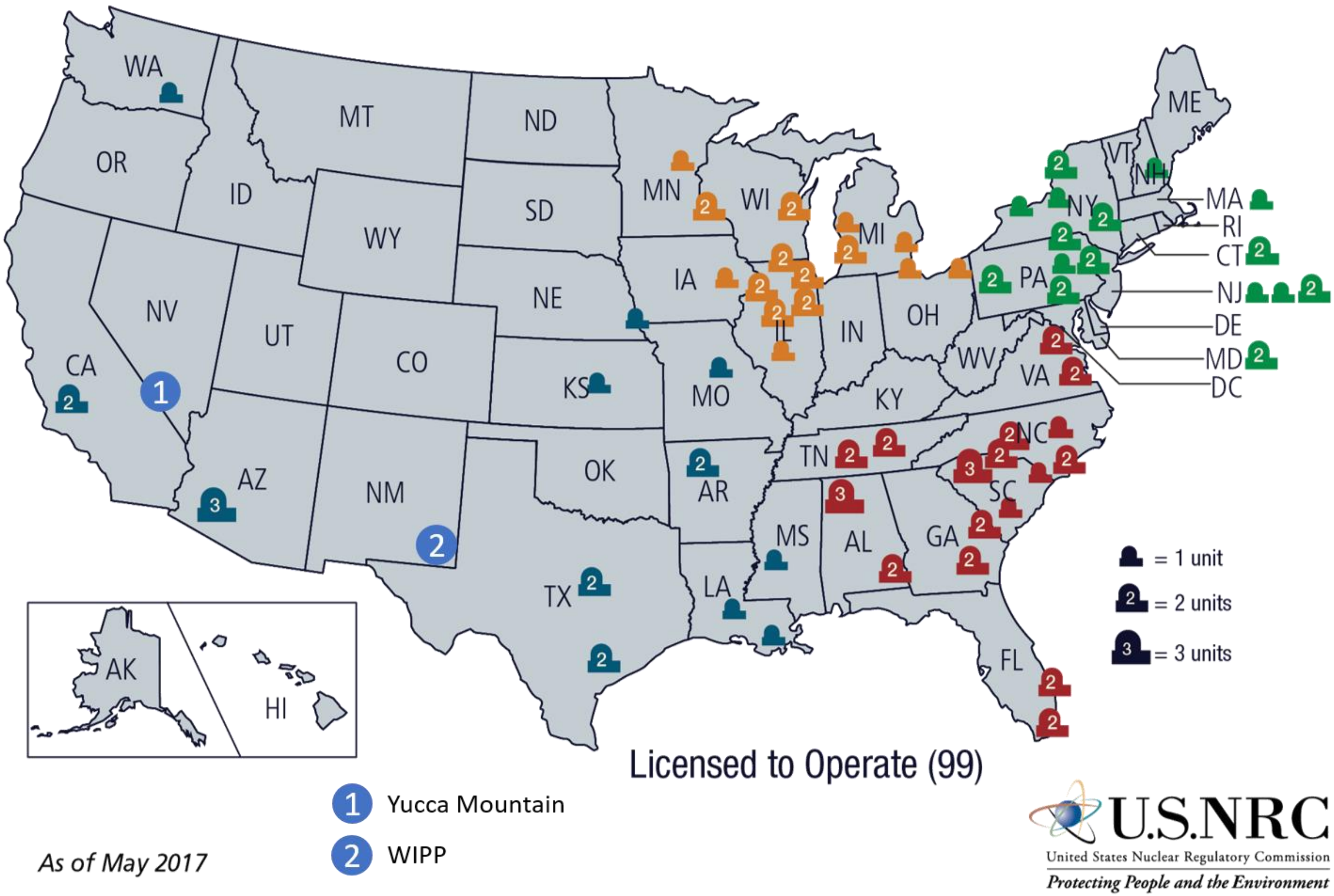
- Federal law allows for it to store HLW
- Research has been conducted, qualified for HLW to be stored (capacity: 70,000 MTU)
- Ready-to-go until 2008 when Obama administration decided to put the project on hold
- Trump administration announced budget for reactivation
- Problem: Inhabitants and politians are not willing to host a repository for HLW (land is sacred to native americans)

2. Waste Isolation Pilot Plant (New Mexico)

- Deep geological repository licensed to permanently dispose of transuranic radioactive waste from military use
- Approximately 26 miles east of Carlsbad
- Problems:
  a) Inhabitants are not willing to host a repository for HLW
  b) Current federal law (including the WIPP Land Withdrawal Act) will need to be changed
  c) Research would have to be conducted to find out whether the conditions fit for HLW

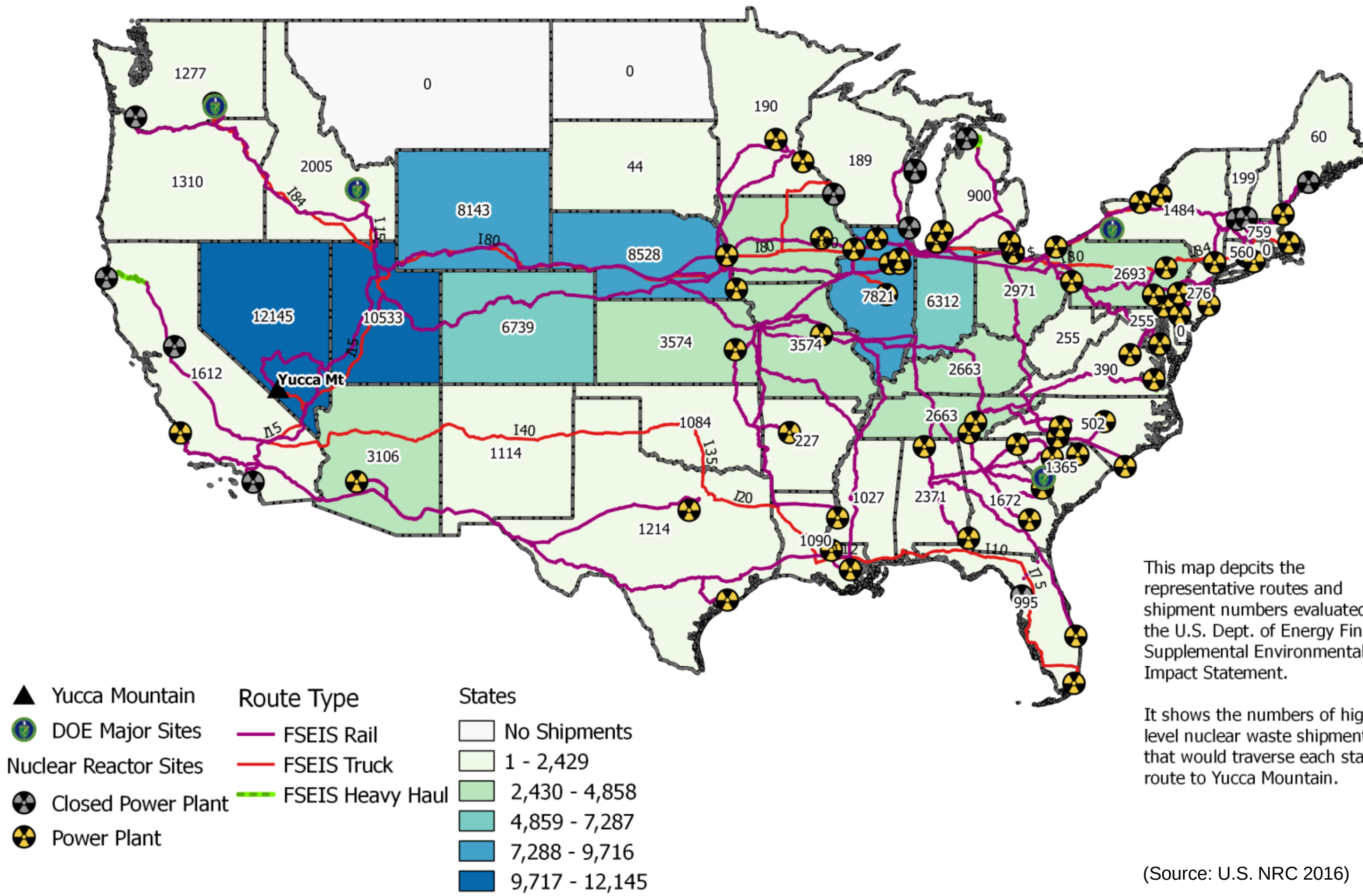
3. Alternatives to Yucca Mountain need at least 30 years until they can operate

Location of reactors and final repositories



NRC approved transportroutes

Fig. 13: Representative Transportation Routes to Yucca Mountain and Transportation Impacts (Cask Shipments by State)



This map depcits the representative routes and shipment numbers evaluated in the U.S. Dept. of Energy Final Supplemental Environmental Impact Statement.

It shows the numbers of high-level nuclear waste shipments that would traverse each state en route to Yucca Mountain.

(Source: U.S. NRC 2016)

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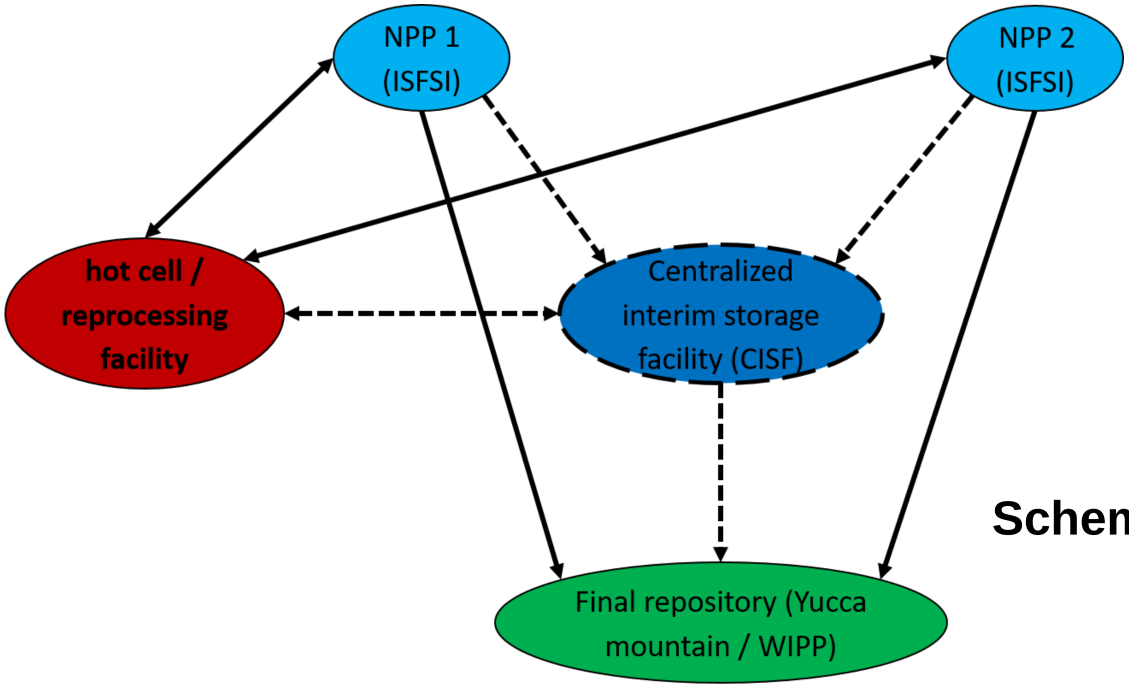
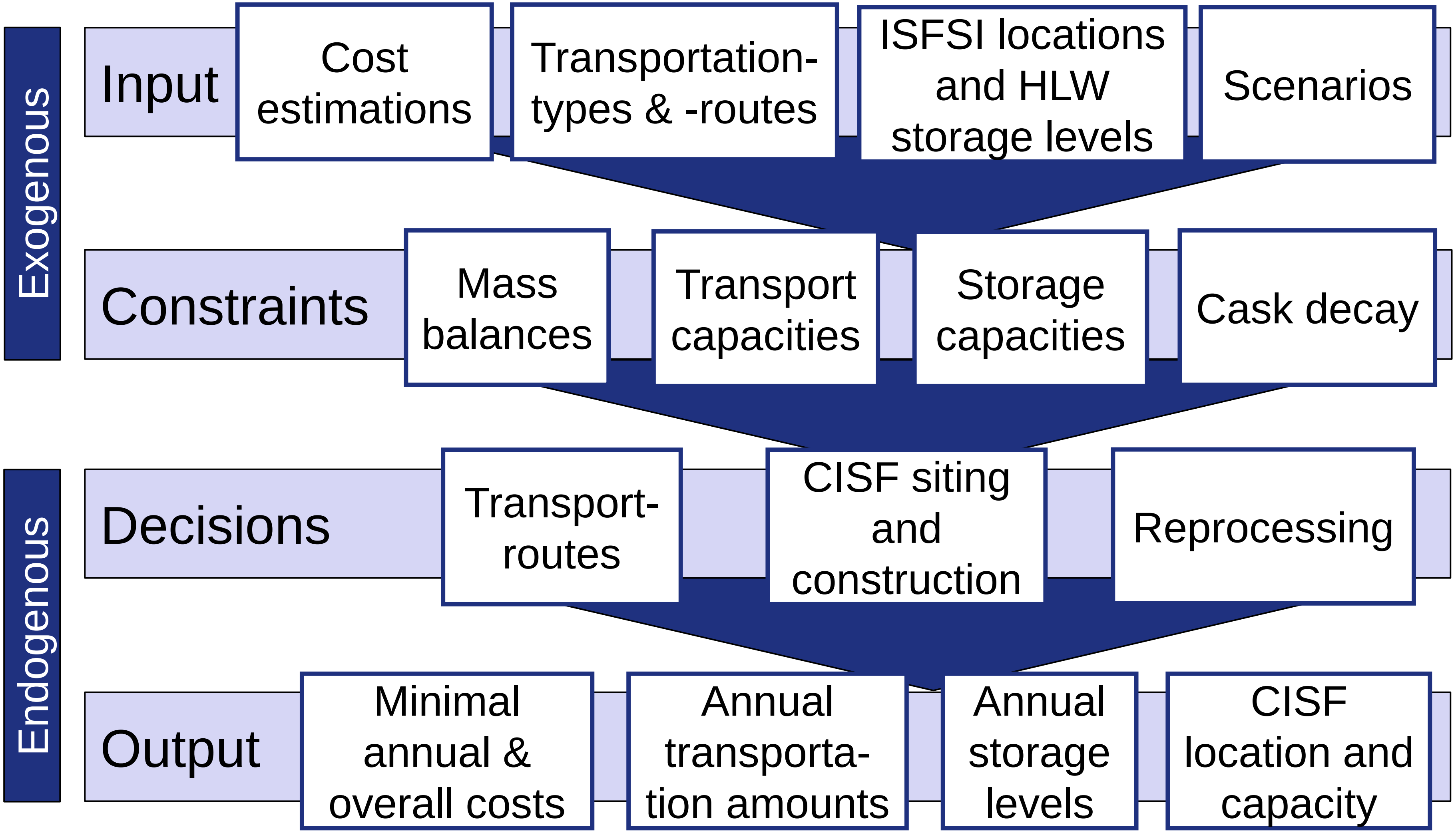
Model description

- **Mixed-Integer Problem (MIP)**
- **Minimizing the overall costs from a macroeconomic point of view**
- **Evaluates process of handling HLW between NPPs and final repository**
- **Does not evaluate the costs occuring inside the NPPs, inside the final repository and occuring from decomissioning (only LLW, ILW)**



Scheme of model network

Scheme of model



Objective

Objective: Minimizing the total costs consisting of

- **Transportation costs**
- **Storage costs**
- **Construction costs for new Centralized Interim Storage Facilities (CISF)**
- **Cost from decay of casks**
- **(Reprocessing costs)**

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

Constraints

The model is bound by the following constraints:

- **Mass balance for Spent Nuclear Fuel (SNF) in NPP**

$$\sum_{nn} (SNF\_t_{nn,r,y}) - \sum_{nn} (SNF\_t_{r,nn,y}) + gen\_SNF(r,y) + (SNF\_s_{r,y-1})\, if\, (ord\,(y) > 1) - SNF\_s_{r,y} = 0 \qquad \forall\, r \in R, y \in Y$$

- **Mass balance for SNF in all nodes but NPP and hot cells**

$$\sum_{nn} (SNF\_t_{nn,n,y}) - \sum_{nn} (SNF\_t_{n,nn,y}) + (SNF\_s_{n,y-1})\, if\, (ord\,(y) > 1) - SNF\_s_{n,y} = 0 \qquad \forall\, n \in N, y \in Y$$

- **Mass balance for vitrified was in all nodes but hot cells**

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

Constraints

- **Local storage capacity**

$$SNF\_s_{n,y} + WASTE\_NC\_s_{n,y} + WASTE\_VI\_s_{n,y} \leq s\_cap_{n,y}$$

$$\forall\, n \in N, y \in Y$$

- **Transportation capacity**

$$SNF\_t_{n,nn,y} + WASTE\_NC\_t_{n,nn,y} + WASTE\_VI\_t_{n,nn,y} \leq dist_{n,nn} \cdot BIG$$

$$\forall\, n, nn \in N, y \in Y$$

- **Reprocessing capacity**

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

- **Mass balance for hot cells**

$$\sum_{n} (SNF\_t_{n,hc,y} - WASTE\_NC\_t_{hc,n,y} - v\_effect \cdot WASTE\_VI\_t_{hc,n,y}) = 0$$

$$\forall\, hc \in HC, y \in Y$$

Constraints

- **Restriction of hot cell processing**

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

- **Constraints for building CISFs**

$$\sum_{y} (B_{i,y}) \leq 1 \qquad \forall\, i \in I$$

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

- **Simulation of cask decay**

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

Scenarios analyzing different final repository and reprocessing options

Scenario	Final repository				Reprocessing
	Opening of Yucca Mountain		Opening of second final repository (WIPP)		
	2030	2040	2030	2040	
1 – BAU					
2a – Yuc_2030	✓				
2b – Yuc_2040		✓			
3a – Yuc+_2030	✓		✓		
3b – Yuc+_2040		✓		✓	
4 – Reproc					✓
5 – Yuc_reproc	✓				✓

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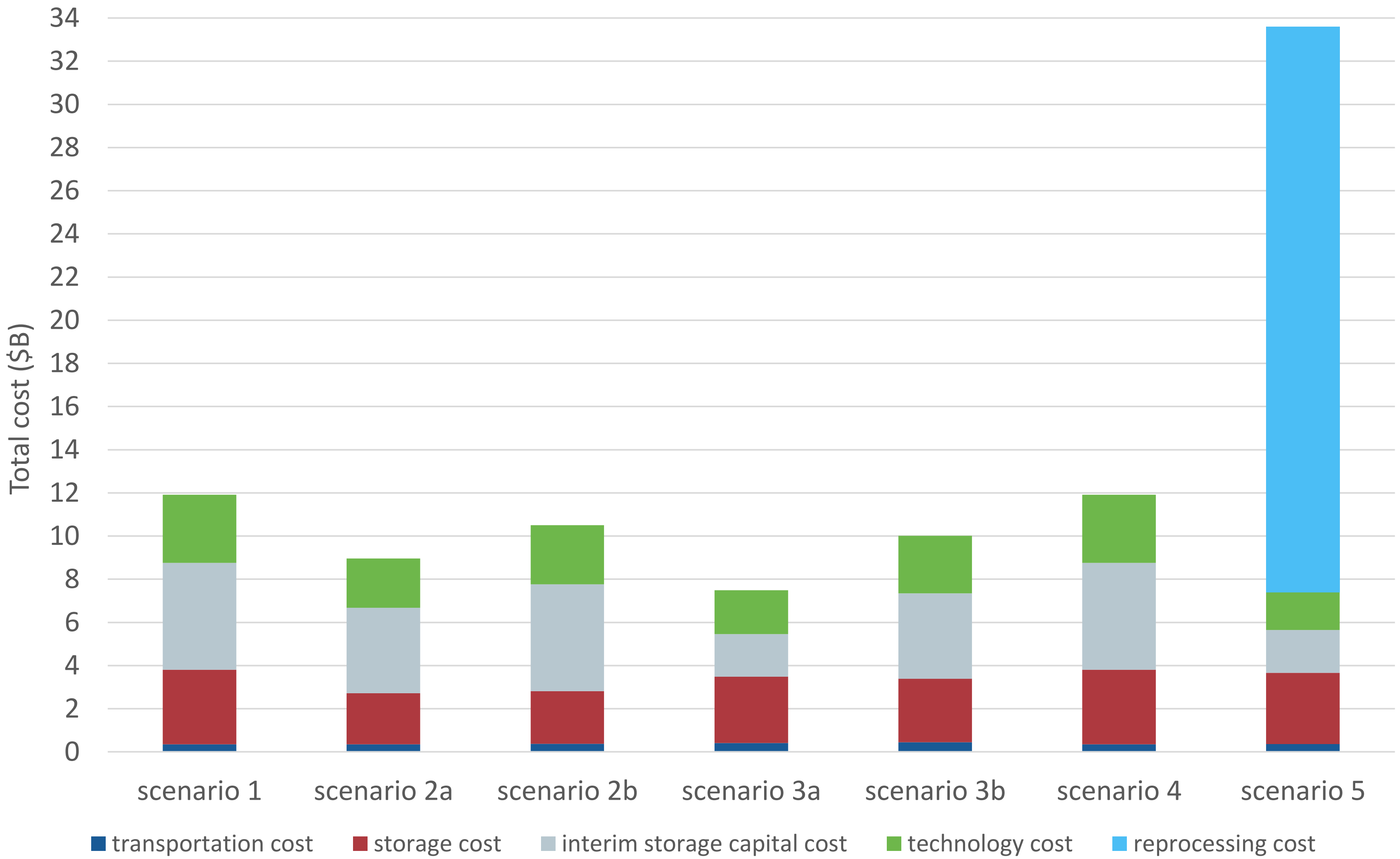
Overview results

Scenario	1 - BAU	2a – Yuc_2030	2b – Yuc_2040	3a – Yuc+_2030	3b – Yuc+_2040	4 - Reproc	5- Yuc_Reproc
Total costs [$B]	11.9	8.9	10.5	7.5	10	11.9	33.6

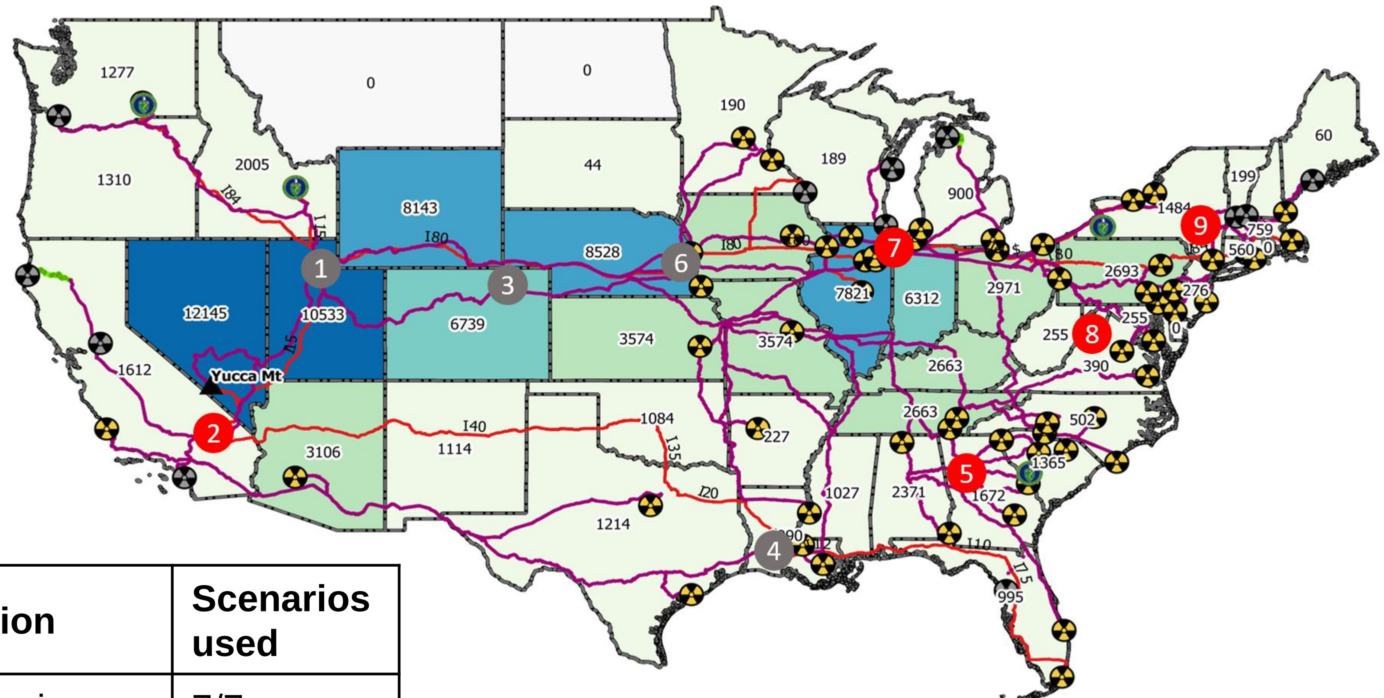
Cost comparison scenarios



Overview results

Scenario	1 - BAU	2a – Yuc_2030	2b – Yuc_2040	3a – Yuc+_2030	3b – Yuc+_2040	4 - Reproc	5- Yuc_Reproc
Total costs [$B]	11.9	8.9	10.5	7.5	10	11.9	33.6
Number of CISF built (needed capacity [MTU])	5 (100,000)	4 (80,000)	5 (100,000)	2 (40,000)	4 (80,000)	5 (100,000)	2 (40,000)
Number of CISF that can be shut down (after how many years)	none	1 (30 years)	1 (33 years)	2 (26, 30 years)	3 (30, 33, 37 years)	none	2 (40 years)
Locations of CISF	2, 5, 7, 8, 9	2, 7, 8, 9	2, 5, 7, 8, 9	2, 8	2, 5, 7, 8	2, 5, 7, 8, 9	2, 8

Centralized interim storage facility locations



#	Name of location	Scenarios used
2	Barstow, California	7/7
5	Barnsville, Georgia	4/7
7	Lasalle, Illinois	5/7
8	Newville, Pennsylvania	7/7
9	Old Chatham, New York	4/7

1 = chosen locations for CISF

1 = possible locations for CISF that have not been chosen

=> Mostly located at the East cost close to reactors and one close to final repository

Overview results

Scenario	1 - BAU	2a – Yuc_2030	2b – Yuc_2040	3a – Yuc+_2030	3b – Yuc+_2040	4 - Reproc	5-Yuc_Reproc
Total costs [$B]	11.9	8.9	10.5	7.5	10	11.9	33.6
Number of CISF built (needed capacity [MTU])	5 (100,000)	4 (80,000)	5 (100,000)	2 (40,000)	4 (80,000)	5 (100,000)	2 (40,000)
Number of CISF that can be shut down (after how many years)	none	1 (30 years)	1 (33 years)	2 (26, 30 years)	3 (30, 33, 37 years)	none	2 (40 years)
Locations of CISF	2, 5, 7, 8, 9	2, 7, 8, 9	2, 5, 7, 8, 9	2, 8	2, 5, 7, 8	2, 5, 7, 8, 9	2, 8
After how many years can the last ISFSI be closed?	never	25 years	26 years	23 years	26 years	never	24 years
Percentage of casks that have to be refilled	96%	66%	81%	59%	79%	96%	50%

Conclusions

1. **Centralized interim storage facilities are cost efficient in every scenario (congruent to Department of Energy 2016 study and also safer)**
2. **Even more capacity for interim storage needed than Department of Energy has planned for 2025 (between 40,000 and 100,000 MTU)**
3. **From the point of logistics, locating the CISF strategically close to NPPs at the East coast and close to a final repository would be best**
4. **Closing of all independant spent fuel storage installations within the next 26 years possible if centralized interim storage facilities are build and a final repository is operational by 2040**
5. **Any delay in finding a final repository increases overall costs (by 15-25 % for ten years)**
6. **Reprocessing is not cost efficient for the next hundred years**
7. **By reprocessing 45 % of the overall spent nuclear fuel, Yucca Mountain would be sufficient as a final repository for all high-level waste in the U.S.**

Thank you very much for you attention!

Contact

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Limitations and need for further research

The results have to be looked at very critical, regarding some limitations:

- **Data on HLW are limited to official U.S. Government data**
- **No experience in processing of HLW (for most costs strong assumptions have to be made)**
- **No consideration of costs occuring inside the reactors and the final repository**
- **Only macroeconomical point of view, no consideration of other aspects (e.g. safety, social and ecological aspects)**
- **A limited number of scenarios**
- **A limited timeframe of 40 years (100 years)**