New Nuclear Design for Electric Power Systems

FINAL REPORT

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Revised: 27APR2024 Version 1.0

Executive Summary

Development Standards & Practices Used

The research and proposal of a recommended design for a modern nuclear power plant involved gathering information and data from a large variety of resources. It is of the utmost importance that our team properly documents and reports the sources of the information incorporated into our project. Our team has elected to use the IEEE standard of resource citing to ensure transparency and accountability for the information that we use in our project.

The quality and accuracy of the information and data that we use is vital to the overall success of our project. To safeguard the integrity and reliability of the information, our team has elected to closely regulate the resources used for information. Resources will primarily consist of government and higher education websites/publications, along with information coming directly from the manufacturers of the nuclear power plant designs we are reporting on.

Summary of Requirements

- Identify practical "New Nuclear" designs that fit into the general guidelines outlined in the project proposal.
- Develop a report outlining the strengths and weaknesses of each identified design/technology and a cost-benefit ratio estimate.
- Identify unique design elements that may be effective in "New Nuclear" energy.
- Identify a single "recommended design" from the researched information and analysis performed.
- Describe and illustrate the recommended design and identify any design flaws.
- Provide an argument for the recommended design in terms of a "Benefit to Cost" ratio showing why the ratio is better than the other designs.
- (Optional) Utilize tools to evaluate the value and usability of a particular nuclear source.

Applicable Courses from Iowa State University Curriculum

EE 303, EE 455, EE 456, EE 457, IE 305.

New Skills/Knowledge acquired that was not taught in courses

- Level Cost of Electricity (LCOE) Assessment
- Use of a Co–optimized Expansion Planning Model Software (Made by Ali Jahanbani Ardakani)
- Nuclear Power System Designs
- Benefit-to-Cost Ratio Analysis

1 Introduction/Background

1.1 Problem Statement and Design Content

This project seeks to find a new nuclear design that is cost-effective and provides a clean and reliable source of electricity while prioritizing safety for both users and the environment. Our primary objective is to identify a nuclear power plant design that offers a dependable source of clean electricity characterized by practicality, reliability, and efficiency, and that will be a good supplement to renewable forms of energy.

1.2 Intended Users and Uses

The intended use of the design is reliable and clean power generation that will be used as a supplement to renewable energy and a replacement of fossil fuels. A power plant of this type would also be used for "load following," which is the ability to adjust power output based on demand. As far as intended users of the design, we would include utilities, independent system operators, investors, and energy consumers.

2 Revised Design

2.1 Design Requirements

Shown below are the design requirements outlined in the initial project proposal:

1. Identify all reasonably practical "new nuclear" designs that have been suggested so far. Develop a summary report of these technologies that identifies their strengths and weaknesses. Estimate the Benefit to Cost ratio of each design.

2. Based on the various technologies surveyed in step 1, identify a "recommended design" (RD). The RD could be one of the technologies surveyed, or it could be an extension of one of them, or it could be an integration of two or more of them.

3. Illustrate and describe the RD in detail. Identify any significant problems with the design and describe solutions for these problems. Provide a convincing argument that the RD's Benefit to Cost ratio is better than all other designs considered.

4. Identify and evaluate tools useful in designing and assessing the performance of the nuclear power plant.

2.2 Engineering Standards

The research and proposal of a recommended design for a modern nuclear power plant will involve gathering information and data from a large variety of resources. It is of the utmost importance that our team properly documents and reports the sources of the information incorporated into our project. Our team has elected to use the IEEE standard of resource citing to ensure transparency and accountability for the information that we use in our project.

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2.3 Security Concerns & Countermeasures

Security concerns related to our design all involve the ability to control the nuclear reactor. Any form of illegitimate access to reactor controls, whether that be physical or digital, would be the only concern. All security standards currently in place for existing power plants such as physical barriers, security systems, encrypted communication and wireless controls, and security personnel must be maintained. There are no additional security concerns specific to our design.

2.4 Design Evolution

The scope of our design has seen multiple iterations since the project was initially started. Initially, the project took on a more research-oriented approach that focused on determining which "off the shelf" product would work best for the proposed application. One of the major evolutions in our design process was the addition of CEP software to better analyze nuclear reactor designs. The addition of the CEP analysis has allowed us to focus on how investable and economically beneficial the design is alongside the features that we had previously deemed desirable. Overall, the design has evolved to be more dependent on economics while also allowing us to have more of a design approach as compared to a research-focused approach.

3 Implementation Details

3.1 Detailed Design

The proposed small modular reactor (SMR) design combines the best features from 6 chosen leading reactor designs after extensive research, testing, and evaluation. Top candidates like Natrium, ARC-100, and BWRX-300 were studied using simulation software such as the CEP and Benefit-Cost calculator analysis. The Prism and VOYGR designs were excluded due to their high capital costs, which led to suboptimal performance in simulations and economic assessments.

3.2 Description of Functionality

1) **Reactor Core:** The core technology is a sodium-cooled fast reactor (SFR). The reactor uses liquid sodium as coolant which provides excellent heat transfer properties and eliminates the risk of boiling, thus, allowing the reactor to operate at near-atmospheric pressure while reducing the likelihood of coolant loss accidents. Liquid sodium, the coolant used in SFRs, is chemically less reactive and corrosive compared to the molten salt coolants used in MSRs
2) **Thermal Energy Storage:** Drawing from the Natrium design, an integrated energy storage system is incorporated. This system enables the reactor to operate at a constant power level while providing dispatchable power generation and load-following capabilities. Excess heat generated by the reactor is stored as thermal energy and can be used to produce electricity during periods of high demand.

3) **Passive Safety:** A key feature is the "walk-away" passive safety system. This allows the reactor to automatically shut down and cool itself without operator intervention or external power sources. The system relies on natural processes like gravity and convection to safely cool the reactor core in case of an accident or emergency.
4) **Fuel Selection:** Conventional low-enriched uranium (LEU) fuel with typical U-235 concentration is used to generate heat. This fuel choice is driven by its widespread availability, abundant supply, and cost-effectiveness, ensuring a reliable and economical fuel source.
5) **Underground Siting:** To enhance overall safety and security, the reactor will be located underground. This underground sitting provides an additional barrier against external threats like aircraft impacts and natural disasters, reinforcing the plant's safety and security.

3.3 Notes on Implementation

Natrium reactor design by TerraPower is the most comprehensive option, incorporating many of the recommended features mentioned in section 3.2. The proposed SMR design combines industry-leading technologies and innovative features optimized through simulations and cost-benefit analyses. By integrating advanced safety systems, efficient energy storage, and proven fuel technology, the design delivers a safe, reliable, and cost-effective small modular reactor solution.

Additional features that could be implemented if cost were not a factor include:

- Scalable Output: The flexibility to scale the overall power output by combining multiple reactor modules at a single site, allowing for more adaptable energy generation capacity.
- Advanced Fuel: The use of more advanced fuel types, such as metallic fuels (e.g., uranium-zirconium or uranium-plutonium alloys) or TRISO (Tri-structural Isotropic) particle fuel. These advanced fuels offer higher temperature resistance and enhanced containment of fission products but come with more complex manufacturing processes and higher costs.
- Remote Refueling: A remote refueling system that enables the reactor to be refueled without shutting down operations, with the capability for remote and automated refueling without the need for on-site operators.

4 Testing

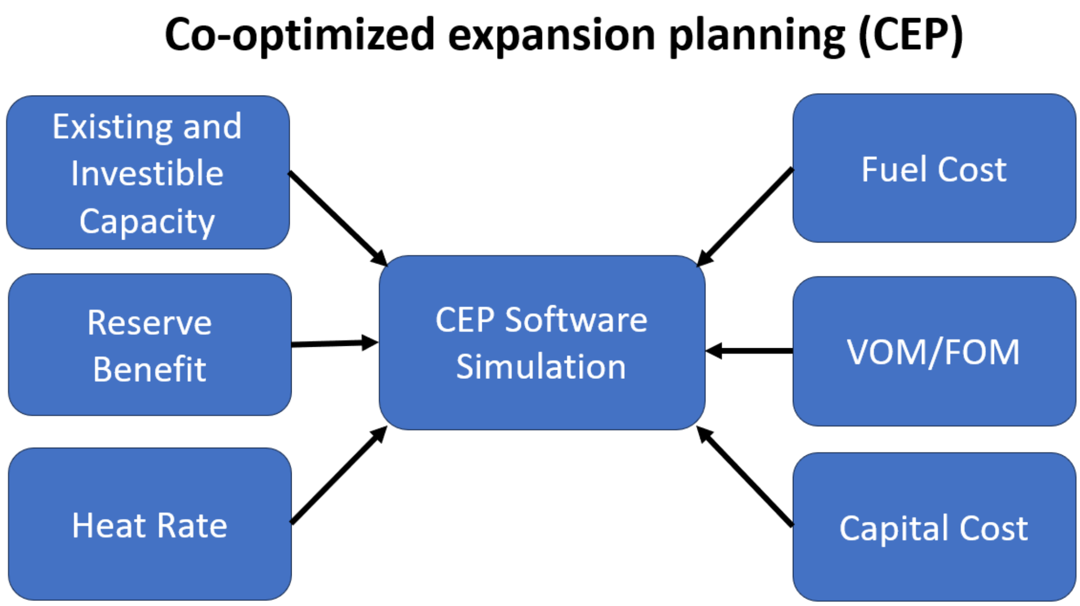
4.1 Co-optimized expansion planning (CEP) software

Co-optimized Expansion Planning software, or CEP, is widely used in the power industry to maximize the economic performance and efficiency of power systems. The software aids investors and system owners/operators by making the following types of recommendations:

1) **What** power system technologies to invest it
2) **Where** in the power system to invest in each power technology
3) **When** to make the investment
4) **How much** to invest in each power technology

Additionally, the program makes recommendations for how to best utilize existing power technology. With these recommendations, power system stakeholders can make informed decisions on how to expand and utilize the power production technology at their disposal. Users of the software can input how much preexisting and investible capacity is available for each technology in the system.

CEP software makes calculations based on a variety of power generation technology characteristics provided by the user. A functional diagram of the inputs provided to the software is shown below:



CEP software inputs:

- **Existing and Investible Capacity-**This refers to the amount of generation capacity that is already built on each bus within a power system, along with how much capacity could be added to each bus to facilitate power system expansion.
- **Reserve Benefit-** The financial benefit given to power plants operating below their maximum capacity. This is offered by system operators to incentivize maintaining reserve margins within a power system.
- **Heat Rate-** The inverse of thermal efficiency. Heat rate is a metric that describes how efficiently power plants can convert heat from burning fuel into electricity.
- **Fuel cost-** Cost associated with nuclear reactor fuel consumption.
- **Variable and Fixed Operations and Maintenance costs (VOM/FOM)-** This is the cost associated with running the plant and upkeep. Variable O&M cost depends on the plant's output, while fixed O&M remains constant regardless of plant utilization.
- **Capital costs-** Cost associated with physically constructing the power plant.

To test and compare the economic performance and power production efficiency of each of the six small modular reactors in our project, our team utilized a version of CEP software developed by Dr. Ali Jahanbani Ardakani, an electric power systems professor at Iowa State University. The tests our team conducted focused on the response of three buses in a large power system. The buses each contained elements of renewable and non-renewable energy, along with new nuclear technology. The buses containing small modular reactor (SMR) technology were setup in the following manner:

Bus	Conditions
Bus #1	• Capacity equivalent to 1 plant preexisting • No investible capacity
Bus #2	• No preexisting capacity available • Capacity equivalent to 1 plant available for investment
Bus #3	• Capacity equivalent to 1 plant preexisting • Capacity equivalent to 1 plant available for investment

4.2 CEP Testing Results

Testing results from CEP simulations are summarized in the following tables:

Natrium simulation results: [3] [4] [5] [6]

Bus	Results
#1	• 345 MW (max preexisting capacity) utilized in all 4 time intervals.
#2	• 345 MW (max investible capacity) invested in time interval 3 (2032). • 345 MW utilized in time intervals 3 and 4 (after investment).
#3	• 345 MW (max investible capacity) invested in time interval 3. • 345 MW utilized in time intervals 1 and 2, 690 MW utilized in intervals 3 and 4 (after investment).

Analysis for Natrium (*with rationale*):

All available investible capacity utilized - *Natrium had the 2nd lowest Capital expenditure ranking (2.9 Billion $ / GW).*

All existing/preexisting capacity was utilized in each time interval - *At 41% thermal efficiency, Natrium has the highest efficiency of the SMRs tested.*

VOYGR simulation results:[15] [16] [17] [18]

Bus	Results
#1	• 462 MW (max preexisting capacity) utilized all 4 time intervals.
#2	• No investments made all 4 time intervals.
#3	• No investments made all 4 time intervals. • 264.05 MW utilized in time interval 1. • 462 MW (Max preexisting capacity) utilized in time intervals 2-4.

Analysis for VOYGR (*with rationale*):

No new investments made into VOYGR- *VOYGR had the highest Capital expenditure rating of all SMRs tested (7.79 Billion $ / GW)*

Preexisting capacity not utilized fully in first time interval- *With a thermal efficiency of 30%, VOYGR tied for the lowest efficiency of the SMRs tested.*

SMR-160 simulation results: [9] [10] [19]

Bus	Results
#1	• 80 MW (half of preexisting capacity) utilized in time interval 1. • 160 MW utilized in time intervals 2-4.
#2	• 160 MW (max investible capacity) invested in time interval 4. • 160 MW (max existing capacity) utilized in time interval 4.
#3	• 80 MW (half of preexisting capacity) utilized in time interval 1. • 160 MW utilized in time intervals 2-3. • 160 MW (max investible capacity) invested in time interval 4 • 320 MW utilized in time interval 4.

Analysis for SMR-160 (*with rationale)*:

All available investible capacity utilized- *SMR-160 had the third highest capital expenditure ranking of the SMRs tested (6.25 Billion $/GW)*

Preexisting capacity not utilized fully in first time interval- *With a thermal efficiency of 30%, SMR-160 tied for the lowest efficiency of the SMRs tested.*

BWRX-300 simulation results: [1] [2] [8]

Bus	Results
#1	• 300 MW (max preexisting capacity) utilized in all 4 time intervals.
#2	• 300 MW (max investible capacity) invested in time interval 3 (2032). • 300 MW utilized in time intervals 3 and 4 (after investment).
#3	• 300 MW (max investible capacity) invested in time interval 3. • 300 MW utilized in time intervals 1 and 2, 600 MW utilized in intervals 3 and 4 (after investment).

Analysis for BWRX-300 (*with rationale)*:

All available investible capacity utilized- *BWRX-300 had the lowest capital expenditure ranking of the SMRs tested (2.33 Billion $ / GW)*

All existing/preexisting capacity was utilized in each time interval- *At 34.5% thermal efficiency, BWRX-300 has the 4th highest efficiency of the SMRs tested.*

ARC-100 simulation results: [7]

Bus	Results
#1	• 100 MW (max preexisting capacity) utilized in all 4 time intervals.
#2	• 100 MW (max investible capacity) invested in time interval 3 (2032). • 100 MW utilized in time intervals 3 and 4 (after investment).
#3	• 100 MW (max investible capacity) invested in time interval 3. • 100 MW utilized in time intervals 1 and 2, 200 MW utilized in intervals 3 and 4 (after investment).

Analysis for ARC-100 (*with rationale*):

All available investible capacity utilized- *ARC-100 has the 3rd lowest capital expenditure ranking of the SMRs tested (4 Billion $ / GW)*

All existing/preexisting capacity was utilized in each time interval- *At 38% thermal efficiency, ARC-100 has the 2nd highest efficiency of the SMRs tested.*

Prism simulation results: [11] [12] [13] [14]

Bus	Results
#1	• 311 MW (max preexisting capacity) utilized all 4 time intervals.
#2	• No investments made all 4 time intervals.
#3	• 311 MW (max preexisting capacity) utilized all 4 time intervals. • No investments made all 4 time intervals.

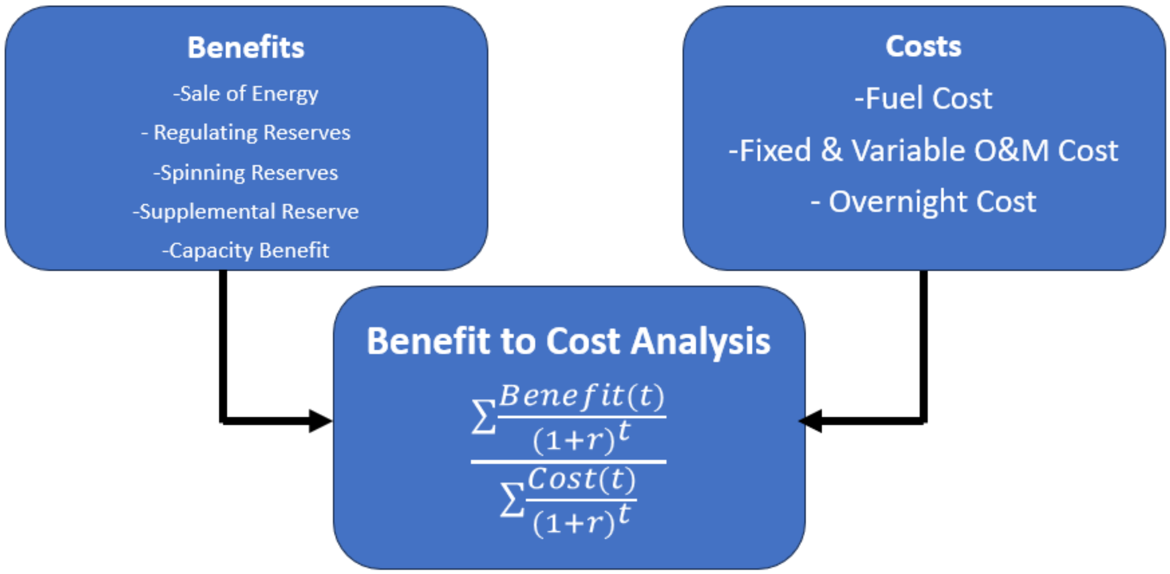
Analysis for Prism (*with rationale*):

No new investments made into Prism- *Prism had the 2nd highest capital expenditure rating of all SMRs tested (6.43 Billion $ / GW)*

All existing/preexisting capacity was utilized in each time interval- *At 37% thermal efficiency, Prism has the 3rd highest efficiency of the SMRs tested.*

4.3 Benefit-to-Cost Analysis

An additional layer of testing and economic feasibility, our team also did a benefit-to-cost analysis of all six final reactors. Benefit-cost analysis is a method used to test the economic feasibility of an investment. It involves taking the present value of all future benefits from the investment, and dividing that number by the present value of all future cost.



Ideally, this ratio is greater than or equal to one. Ratios less than one are not economically feasible, as they will accumulate more costs over the lifetime of the project than benefits. Ratios greater than one mean more benefits than costs, and the higher the ratio the better.

Our team assumed a 10-year project period with a discount rate of 8% (average industry weighted average cost of capital). This discount is relatively low when compared to typical discount rates, but utilities generally have lower costs of capital than other entities due to the stability of their business model.

Below are the considered benefits and costs, as well as their assumed values:

Benefits

- Sale of Energy - $35/MWh
- Regulating Reserve - $110/MWh
- Spinning Reserve - $65/MWh
- Supplemental Reserve - $10/MWh
- Capacity Benefit - $150/MW-day

Costs

- Fuel Costs - $6.10/MWh

- Fixed O&M - $106,920/MW
- Variable O&M - $3.38/MWh
- Overnight Cost – varies by reactor.

The benefit values were all found from historical data from the Midcontinent Independent System Operator (MISO). MISO is the grid operator in Iowa and the surrounding states, and has real time, day ahead, and historical pricing data to view.

The fuel costs were also taken from MISO data. Fixed and variable O&M were assumed to be the same for each plant and were found using the average costs for small nuclear reactors from this website. Overnight costs were all taken from manufacturer's specifications or latest available data.

The results from our analysis can be found in the table below:

Reactor	1st Build Benefit-Cost Ratio	Nth-Build Benefit-Cost Ratio
Natrium by TerraPower	0.85	2.33
VOYGR by NuScale	0.98	1.94
PRISM by GE Hitachi	0.99	1.68
SMR-160 by Holtec	1.39	1.39
BWRX-300 by GE Hitachi	2.14	2.62
ARC-100 by ARC	1.91	1.91

There are five numbers that we would like to highlight. The first three are the first in class builds for Natrium, VOYGR, and PRISM. While all of these are relatively close to being feasible, they aren't quite there. In the case of Natrium and VOYGR, we believe this is because newer data shows these plants may be more expensive than previously assumed. In the case of VOYGR, there was a project in Utah cancelled due to rising costs.

The other two numbers are the nth-build costs for Natrium and BWRX-300. These are the two highest numbers from our analysis, meaning they are the most economically feasible. This matches our results from our CEP simulations, giving us a good basis to recommend either of these reactors assuming costs over time would approach the given nth-build figures.

5 Broader Context

There are quite a few relevant considerations related to the project that are outlined by the categories below:

Public health, safety, and welfare:

- Power plants, by nature, are in close proximity to the public. In the interest of public health, any emissions and waste produced by our design will need to be minimal and safely contained. A plant of this type would also require personnel to run it, so there would likely be more jobs being created.

Global, cultural, and social:

- Nuclear power plants specifically, are somewhat unpopular in the United States because of misconceptions surrounding their safety. The installation of a nuclear power plant may be unpopular without data and more information showing the multitude of safety systems.

Environmental:

- Environmentally, this power plant would be beneficial because of the intent to use it to supplement renewable forms of energy like wind and solar. With the projected power output, nuclear power plants would likely start to replace non-renewable methods of power production. The overall carbon emissions of the new systems implemented would be less than the current coal and natural gas plants currently in use.

Economic:

- There are significant economic benefits that can come from the potential cost of energy from these new nuclear plants. The ability to supplement the renewable forms of energy would also help to reduce the cost of energy during peak loads, as well as times when the renewable production is lower. Conversely, the up-front cost of the development and construction of a reactor of this type may be quite high for initial constructions.

6 Conclusions

6.1 Progress Overview

As Detail in this report, we did this project in two broad phases. The first phase was primarily research, where we looked for promising advanced nuclear reactors, primarily SMRs, that could meet our projects requirements and were mature enough to gather enough data for evaluation. We completed primary research to compare and present our findings. After presenting the data to our advisor, Dr. McCalley, we made our decision as a group to narrow our reactor pool down to the six most promising reactors. We then compiled important data about these six, and noted their unique features that might be interesting for our discission making and analysis.

After our research phase we moved on to the second phase where we used the software CST and a benefit to cost ratio to analytically test and compare each of the remaining six designs. Using the results of these testing scenarios we had enough data to decide what aspects of a reactor are the most economically feasible. Using this data alongside our research, we provided a design with recommended features.

6.2 Value of Design

Every year many of the governments of the world push harder and harder for "green” energy production. Replacing the fossil fuel-based energy infrastructure with new very low carbon emitting technologies such as solar and wind. However, one of the issues that currently causes wariness for complete adoption of such technologies is lack of assured production during all demand times. Wind farms only generate when there is enough wind to spin the turbines and solar only generates during sunny hours of the day. Some other technology must be there to take on the load during high demand times and when the other "green" technologies are not available. One of the available options that we believe should be considered is nuclear, particularly new nuclear SMRs.

Nuclear power can fit into the same "spot" that fossil fuels are in by providing power during all hours of the day. Which helps the primary green sources with base load production and filling in any production gaps that occur from the variability that comes with wind and solar. However, unlike fossil fuels, nuclear produces no greenhouse gases, thus working with the goal of having a very low carbon emitting power grid, but also not affecting the lifestyles of average citizens by having unreliable electricity availability.

6.3 Potential Future Steps

Given more time to there would be several things we would like to look more in depth into to make sure this design fills the void left by fossil fuels and demonstrates safe and economically sound practices to sooth any concerns that may be brought up citizens and potentials buyers.

Safety:

As stated in previous sections of the document nuclear energy isn't particularly favored by the general public. Many view it as a safety concern or worry about its potential Enviromental impact if something went wrong or the waste is improperly disposed. Some ways we could progress with the design in this aspect are:

- Poll the public on their thoughts on nuclear power and understand their primary concerns so we can possibly implement components into the design that will alleviate the safety concerns while keeping the design economically feasible.
- Advanced Fuels – such as TRISO (Tri-structural Isotropic) particle fuel which are more stable at higher temperatures but are currently costly.

Economic:

Another major concern with nuclear power is the immense capital that is needed to build a plant and keep it maintained compared to other methods of generation. Many of these SMR designs already made great headway into lowering the cost compared to old school large reactors however, there is still a hurdle in justifying building a SMR, over a traditional fossil fuel plant. Nuclear's main ally in this endeavor is carbon taxes and the desire to become completely green. However, there are still things we would like to research, such as factory-built components and lower concrete needs that might be able to decrease the cost of a nth build reactor that would make the design more attractive.

Reserves:

One of the things that we wanted to get to but was put on the back burner in favor of more important research design steps was reserve benefits. We used reserves in our benefit to cost ratio calculator, however the numbers, we based on MISO data, though every reactor was using the same reserve numbers. However, some reactors, such as the Natrium, have better reserve capabilities, than the others. We kept this information in mind when we made our decisions, but it would be nice to get reliable numbers from each reactor to see if the Benefit to Cost shows a clearer winner for the researched designs.

7 Appendices

7.1 Appendix 1 – Operation Manual

Interpreting Data Reported by Co-optimized Expansion Planning (CEP) Software

CEP software results are returned to the user via a GAMS file. To analyze the results provided, the user can follow along with these simple steps:

1) Open the GAMS file returned by the CEP software.

2) Navigate in GAMS to the tab titled "pv_GenInvYear".

3) Locate the desired bus number by scrolling through the data set. Additionally, users can isolate specific buses by right clicking the bus number column header.

4) Once the desired bus is located, analyze the column titled "Level". This column repeats in six year increments, so ensure the to view the column associated with the desired time interval. The level column for the years 2032 and 2038 are shown in the following image:

				2032					2038				
				Level	Marginal	Lower	Upper	Scale	Level	Marginal	Lower	Upper	Scale
1	249516	CoalST	2	0	37.6557	0	+INF	1	0	37.7145	0	+INF	1
		CC	1	0	0	0	+INF	1	0	173.412	0	+INF	1
		CCNew	626	0	0	0	+INF	1	0	269.294	0	+INF	1
		GasGT	3	0	0	0	+INF	1	0	60.9011	0	+INF	1
		GasST	4	0	0	0	+INF	1	0	60.8621	0	+INF	1
		GTNew	788	0	322.733	0	+INF	1	0	246.142	0	+INF	1
		DPVNew	1436	0	29.9011	0	+INF	1	500	0	0	+INF	1
		CCCCSNew	1922	0	166.717	0	+INF	1	1825.7	0	0	+INF	1
		Natrium	1	0	475.127	0	+INF	1	0	1264.99	0	+INF	1
	249521	CoalST	8	0	37.6557	0	+INF	1	0	37.7145	0	+INF	1
		CC	7	0	0	0	+INF	1	0	173.412	0	+INF	1
		CCNew	627	0	0	0	+INF	1	0	269.294	0	+INF	1
		GasGT	9	0	0	0	+INF	1	0	60.9011	0	+INF	1
		GTNew	789	0	322.733	0	+INF	1	0	246.142	0	+INF	1
		DPVNew	1437	0	30.2978	0	+INF	1	500	0	0	+INF	1
		CCCCSNew	1923	0	166.717	0	+INF	1	0	0	0	+INF	1
		Natrium	1	345	0	0	+INF	1	0	360.444	0	+INF	1
	249532	CoalST	10	0	37.6557	0	+INF	1	0	37.7145	0	+INF	1
		CCNew	628	0	0	0	+INF	1	0	269.294	0	+INF	1
		GasGT	11	0	0	0	+INF	1	0	60.9011	0	+INF	1
		GTNew	790	0	322.733	0	+INF	1	0	246.142	0	+INF	1
		DPVNew	1438	0	32.7258	0	+INF	1	500	0	0	+INF	1
		Hydro	12	0	424.895	0	+INF	1	0	925.338	0	+INF	1
		CCCCSNew	1924	0	166.717	0	+INF	1	681.9	0	0	+INF	1
		Natrium	1	345	0	0	+INF	1	0	360.444	0	+INF	1

Looking at the image above, note that in the year 2032, for example, the CEP software recommends investing 345 MW of Natrium power technology on bus #'s 249521 and 249532. This is how to interpret power technology investment data from CEP software.

5) Next, navigate in GAMS to the tab titled "pv_PG".

6) Right click the column corresponding to power technologies and isolate the technology you wish to view. Continuing in our example, we will isolate Natrium.

7) In the column labeled "Level", users will be able to see the MW output the software recommends running the power technology at. In the image below, the level column is boxed in red. Notice the 6-year increments to the left of the level column are further separated into seasons.

			1				
			Level	Marginal	Lower	Upper	Scale
		Peak	345	0	0	+INF	1
		PR	345	0	0	+INF	10
249532	2020	Summer	345	0	0	+INF	1
		Winter	345	0	0	+INF	1
		Spring	345	0	0	+INF	1
		Fall	345	0	0	+INF	1
		Peak	345	0	0	+INF	1
		PR	345	0	0	+INF	10
	2026	Summer	345	0	0	+INF	1
		Winter	345	0	0	+INF	1
		Spring	345	0	0	+INF	1
		Fall	345	0	0	+INF	1
		Peak	345	0	0	+INF	1
		PR	345	0	0	+INF	10
	2032	Summer	690	0	0	+INF	1
		Winter	690	0	0	+INF	1
		Spring	690	0	0	+INF	1
		Fall	690	0	0	+INF	1
		Peak	690	0	0	+INF	1
		PR	690	0	0	+INF	10
	2038	Summer	690	0	0	+INF	1
		Winter	690	0	0	+INF	1
		Spring	690	0	0	+INF	1
		Fall	690	0	0	+INF	1
		Peak	690	0	0	+INF	1
		PR	690	0	0	+INF	10

Interpreting the image above, we see that the CEP software recommends running the Natrium plant at maximum capacity all 18 years (345 MW per plant). Note that the level jumps from 345 to 690 MW in the year 2032. This is due to the investment made in Natrium in that year, doubling the capacity of the power technology on the bus shown above.

7.2 Appendices 2 – Alternative/initial version of design

During the navigation process of our original project, we were unsure of how many nuclear reactor designs we should be evaluating in-depth. Initially, we were going to do an in-depth analysis of the 18 reactor designs we all had come up with. This number was reduced down too 15 due to some overlap. However, upon consideration with our advisor, this was deemed too many and most likely a waste of resources/time due to some reactor designs outshining others.

An additional consideration of our design we had from our advisor is from a testing perspective. For our project, if we had time we were asked to find a piece of software that could be used as a testing element for our reactor designs. Our advisor had heard things about a software called ASPEN possibly being used for developing and evaluating reactor designs. Needed a testing element for our project we first looked into this recommendation as a starting point. Upon, further inspection we learned that ASPEN wasn't capable of what we were looking for. ASPEN as a software is more for creating the steam cycles that the reactor outputs. However, in our case, we were looking at something to demonstrate the benefit of the plant in correlation to it's cost. For this reason, we looked for additional software and ended up using the Co-Optimized Expansion Planning (CEP) tool for this.

7.3 Appendices 3 – Other considerations

Throughout this entire project, our group as a whole learned a lot about nuclear reactors. We all came from an electrical engineering background. Our studies only mentioned the immense cost and safety risks associated with nuclear plants. In addition to how much power the plants can output compared to other generation methods. This project made us look at how we could reduce the overall cost of nuclear energy and how beneficial it will be in the future for our grid. As we move to a more renewable energy grid wind and solar are being pushed very heavily. What most people don't consider is that these energy sources have many variables and can't supply the entire country's load. This means we will either have to heavily improve our storage capacity to store the excess renewable energy for peak load times. Or have fossil fuel plants such as natural gas or coal be used in conjunction with renewable energy. Otherwise, use nuclear as the other option which isn't carbon emitting. That's where these small modular reactors could really make a difference. These plants are designed to be less expensive and output a large amount of power while not releasing CO_2. If we want to have a cleaner earth it will be vital to further develop our nuclear research and resources.

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