INL/RPT-22-67964
Revision 2

Investigating Benefits and Challenges of Converting Retiring Coal Plants into Nuclear Plants

Nuclear Fuel Cycle and Supply Chain

Prepared for
U.S. Department of Energy
Systems Analysis and Integration
J. Hansen, W. Jenson, A. Wrobel (INL)
N. Stauff, K. Biegel, T. Kim (ANL)
R. Belles, F. Omitaomu (ORNL)
September 13, 2022
INL/RPT-22-67964

ABSTRACT

A coal-to-nuclear (C2N) transition means siting a nuclear reactor at the site of a recently retired coal power plant. Three overarching questions from the C2N transition guide this research: where in the United States are retired coal facilities located and what factors make a site feasible for transition; what factors of technology, cost, and project timeline drive investor economics over such a decision; and how will C2N impact local communities?

The study team evaluated the siting characteristics of recently retired plants and those operating coal-fired power plant sites run by a utility or an independent power producer utilizing publicly available data to screen U.S. coal power plant sites to nuclear-feasible locations. After screening all retired coal sites to a set of 157 potential candidates and screening operating sites to a set of 237 candidates, the study team estimates that 80% of retired and operating coal power plant sites that were evaluated have the basic characteristics needed to be considered amenable to host an advanced nuclear reactor. For the recently retired plant sites evaluated, this represents a capacity potential of 64.8 GWe to be backfit at 125 sites. For the operating plant sites evaluated, this represents a capacity potential of 198.5 GWe to be backfit at 190 sites.

This report evaluates a case study for the detailed impacts and potential outcomes from a C2N transition. Based on the nuclear technology choices and sizes evaluated to replace a large coal plant of 1,200 MWe generation capacity at the case study site, nuclear overnight costs of capital could decrease by 15% to 35% when compared to a greenfield construction project, through the reuse of infrastructure from the coal facility. Nuclear replacement designs can have a lower capacity size because nuclear power plants run at higher capacity factors than coal power plants. In the case study replacing coal capacity with 924 MWe of nuclear capacity, the study team found regional economic activity could increase by as much as $275 million and add 650 new, permanent jobs to the region of analysis.

The evaluated site choice in the report is hypothetical for analysis purposes only and based on available data and documented assumptions. Consequently, the findings only inform at a general level. A community, investor, or other interested stakeholder can use these results to set up a detailed, in-depth analysis for a specific application of interest, such as evaluating a C2N transition of a specific coal power plant and a specific nuclear technology design. The report was subjected to independent peer reviews by experts in systems engineering and regional economic modeling to evaluate analysis and assumptions.

ACKNOWLEDGEMENT

The authors would like to thank Dr. Temitope Taiwo (ANL), William Halsey (ret. LLNL), and Bhupinder Singh (DOE) for suggesting analysis of the basic research question, "what is the potential for transitioning coal power plants in the United States to nuclear power plants?" The benefits and challenges pertaining to that question are remarkable, and the authors gratefully acknowledge the vision that led to this document. The authors would also like to thank George Griffith (GAIN and INL) and Greg Alward (University of Idaho and The Alward Institute), with expertise in systems engineering and economic modeling, respectively, for their helpful peer reviewer comments. The authors would also like to thank Ed Hoffman and Anton Moisseytsev (ANL), and Bhima Sastri (DOE), Christine King (GAIN and INL), analysts in the NETL systems, and Brent Dixon (INL) for valuable feedback on the report.

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IN-TEXT ACRONYMS AND ABBREVIATIONS

ANL	Argonne National Laboratory
ABCE	Agent-Based Capacity Expansion
A-LEAF	Argonne Low-Carbon Energy Framework
AR	Advanced Reactor
BLS	Bureau of Labor Statistics
CPP	coal power plant
DOE	Department of Energy
EAB	exclusion area boundary
EIA	Energy Information Administration
EEIO	Environmentally Extended Input-Output
FHR	Fluoride-salt cooled High-temperature Reactor
GAIN	Gateway for Accelerated Innovation in Nuclear
GDP	Gross Domestic Product
GHG	greenhouse gas emissions
GWe	Gigawatt electric
HTGR	high-temperature gas reactor
ICR	interest coverage ratio
IPP	independent power producer
INL	Idaho National Laboratory
IRP	integrated resource plan
Kg	kilograms
KP-FHR	Kairos Power Fluoride-salt-cooled High-Temperature Reactor
LCOE	levelized cost of electricity
LPZ	low-population zone
LWR	light-water reactor
MISO	Midcontinent Independent System Operator
MPa	Mega Pascals
MWe	Megawatts electric
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
OR-SAGE	Oak Ridge Siting Analysis tool for Power Generation Expansion
ppsm	people per square mile

PV	photovoltaic
PWR	pressurized water reactor
rem	roentgen equivalent man
SMRs	Small Modular Reactors
SSE	Safe shutdown earthquake
SC	Supercritical
SFR	sodium fast reactor
TVA	Tennessee Valley Authority
TES	Thermal Energy Storage
USC	Ultra-Supercritical
UZr	Uranium-Zircoloy Fuel
VHTR	Very High-Temperature Reactor
W/g	Watts per gram

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INVESTIGATING BENEFITS AND CHALLENGES OF CONVERTING RETIRING COAL PLANTS INTO NUCLEAR PLANTS

1. INTRODUCTION

The purpose of this study is to investigate the benefits and challenges associated with a coal-to-nuclear (C2N) transition in the United States. Benefits and challenges are complex and can be evaluated on many dimensions. Those evaluated here include (a) the potential for U.S. coal power plant (CPP) sites to be repurposed to sites with a nuclear power plant (NPP) measured at a national scale, (b) the cost and project timeline implications arising from infrastructure compatibility in repurposing equipment, and (c) regional economic and environmental impacts to communities where the C2N transition takes place. To this end, the study aims to answer these questions:

- In the United States, how many CPP sites are candidates for C2N transition?
- What are the risks/benefits associated with different C2N project types?
- How will C2N transition affect surrounding communities?

Environmental and climate change concerns place pressure on utility plant owners to retire CPPs. For example, greater emphasis on a decarbonized economy and increasing competitive economic pressure, such as the occurrence of negative prices in deregulated electricity markets, have caused utility owners across the United States to retire many CPPs and make plans to retire many more (EIA, 2020a; Omitaomu et al., 2022; U.S. CRS, 2021). Further, policy initiatives such as the "Good Neighbor Initiative" may accelerate the pace of retirements (U.S. EPA, 2022c). The C2N transition is a way to replace the retiring coal generation capacity while utilizing what would otherwise be stranded assets at CPPs and providing economic opportunity to site owners and surrounding communities. Further, the C2N transition may be an opportunity to deploy small modular reactors (SMRs) and advanced non-light-water reactors (ARs) via early adopter communities. SMRs and ARs have similar siting characteristics and are considered together in this report whenever the AR acronym is used. Large light-water reactors (LWRs) generally have a capacity of more than 1 GWe and are considered with a separate set of siting analyses in this report.[1]

This research, conducted by a multi-lab team of researchers from the Systems Analysis and Integration Campaign (SA&I) within the Department of Energy's (DOE's) Office of Nuclear Energy, assessed the benefits and challenges in three interrelated steps: siting analysis, techno-economic analysis (TEA) with decision modeling, and economic and environmental impact analyses. The siting analysis takes a national view of CPPs in the United States then quantifies the number of sites that meet the requirements for siting an NPP. The technical, decision-modeling, and economic analyses are carried out based on scenarios around a case study site. Using the siting analysis, researchers developed a representative CPP site in the Midwest, around which scenarios are set up for technical and economic evaluation. The test-case evaluation region for the case study is hypothetical only to facilitate the analysis. For it, study researchers leveraged publicly available data since no utility, municipality, power plant investor, cooperative, nor corporation is part of this study.

A summary of the study's component parts is listed in the subsections below.

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[1] Large LWRs that use passive safety systems are also often referred to as advanced reactors. However, due to capacity differences, siting is considered separately in this report from SMRs and ARs.

1.1 Siting Analysis

The siting analysis screened all U.S. CPP sites into a set of potential candidate sites composed of 157 retired sites and 237 operating sites. Of the candidate set of retired sites, the analysis shows that 80% are conducive for siting ARs, and 22% are amenable to siting large LWRs. For operating sites, the analysis also shows that 80% are amenable to siting ARs, and 40% are amenable to siting LWRs. This represents the potential for 125 recently retired sites (with 64.8 GWe coal capacity) and the potential for 190 operating sites (with 198.5 GWe coal capacity) if they were backfitted with AR technology. Differences between the capacity factor for CPPs and the various backfit reactor technologies are not considered for siting.

To conduct the evaluations, the OR-SAGE tool (Oak Ridge Siting Analysis tool for Power Generation Expansion) was applied to data obtained from the DOE-Energy Information Administration (EIA) (US EIA, n.d.). The siting analysis was instrumental in identifying a CPP location suitable for the study. Using criteria in OR-SAGE coupled with parameters from the EIA data, the siting analysis allowed the research team to develop a representative site based on characteristics of plants in the Midwest for a deeper case study. The composite CPP has a generator that was retired in the last 10 years and an operating generator announced for retirement in the coming decade. Each generator has a nameplate capacity of approximately 600 MWe for a combined coal capacity of 1,200 MWe. The review team developed the composite site to show the single CPP site generator could potentially be replaced by smaller AR technology, while the two CPP site generators could potentially be replaced by a large LWR. Thus, the composite, proxy location is a good case study of medium- to large-sized plants that have been or will be retired.

1.2 Technical Compatibility Analysis and Decision Modeling

This component of the study informs on the extent to which infrastructure at a CPP site might be repurposed for application in an NPP. The analysis leverages a database on costs for nuclear and coal facilities (EEDB, 1988). Based on data and cost accounting structure, this analysis suggests factors that will likely bear on repurposing infrastructure, focusing categorically on office buildings and electric switchyard components and transmission infrastructure, heat-sink components, and steam-cycle components. Based on compatibility (or lack thereof) across these systems, this analysis estimates a range of cost implications. The results suggest potential cost savings on the overnight capital cost (OCC) of an NPP in the range of 15% to 35% when compared with a greenfield project, depending on several factors. The compatibility analysis results in a technology mapping of factors to consider for evaluating future C2N transitions, which shows major decision-drivers. The study team developed a preliminary Agent-Based Capacity Expansion (ABCE) code as a plugin for the A-LEAF (Argonne Low-carbon Energy Framework) platform to evaluate investor economics of possible C2N transition projects. These results uncover the importance of timing a CPP decommissioning relative to an NPP start-up.

1.3 Regional Economic and Environmental Impact Study

This part of the study focuses on community impacts of the hypothetical Midwestern case study site. Applying the method of input-output (I-O) analysis and the software package IMPLAN (2022b), the study team evaluated the economic and environmental impacts of a C2N transition in the 1,200 MWe case study for coal and nuclear power plants of different sizes, one of which was a 924 MWe nuclear plant. Capacity factors for a CPP are less than those of an NPP—approximately 50% less for a CPP versus approximately 90% for an NPP (Statista, 2022). Consequently, smaller NPP alternatives (in MWe capacity) were evaluated in the case study. For the case of transitioning to a 924 MWe plant, the study results suggest that jobs in the region could increase by more than 650 permanent jobs, distributed across the NPP, the supply chain supporting the plant, and the community surrounding the plant. For reference, prior to the CPP closure, employment at the case study site was estimated at 150 jobs. Transitory effects (e.g., construction jobs) were excluded from this analysis because of the I-O approach to impact analysis.

Long-term job impacts translate to additional economic activity on the order of $275 million, implying a 92% tax revenue increase from the NPP for the local county when compared to a scenario of all coal to one of all nuclear. For the case of the 924 MWe plant, the environmental analysis suggests that greenhouse gas emissions (GHG) in the region could fall by as much as 86%; however, because transition effects were not modeled, the GHG impact of nuclear construction is not reflected. Moreover, this analysis addresses the implications for workforce transition as well as social and environmental justice. However, this study did not evaluate the impacts of fuel fabrication, spent nuclear fuel storage, or low-level and high-level wastes associated with operating an NPP because these services would take place outside the region of analysis. Similarly, environmental issues associated with ash ponds and other legacy CPP impacts were not a part of this study because they were outside the scope of analysis.

The report proceeds as follows: Section 2 provides an overview of the research effort on a C2N transition underway at other institutions; Section 3 presents the siting analysis, including a description of the geographic information system (GIS) capabilities for the study; Section 4 outlines the infrastructure compatibility issues, including the effect on the cost and project timeline, and shows how a decision-maker model can be used to evaluate C2N issues from an investment perspective; Section 5 describes the regional economic and environmental impact study with findings and implications; and Section 6 summarizes report findings and conclusions. A four-part appendix describes much of the technical detail and background information needed for each component of the study.

The reader is advised to keep in mind that this study is hypothetical for analysis purposes only, based on publicly available data and stated assumptions. It provides general information on siting, technical compatibility, and regional economics. A municipality, cooperative, utility, investor, or other interested stakeholder can use this study to identify the key factors in addressing a detailed and involved evaluation of a C2N transition.

2. BACKGROUND AND LITERATURE REVIEW

With the enthusiasm and interest for evaluating potential C2N transitions in the United States and the increasing push toward decarbonization, research on C2N transitions is increasingly important. While the subject of C2N is not new, it is still in its early stages. Not only has a C2N transition not yet occurred in the United States (although one such project is underway in Wyoming), but leading researchers on this topic are also still developing transition approaches and guidelines. This study aims to add insight to the existing body of C2N research.

This section summarizes publicly available literature. Recognizing that this study does not provide a comprehensive overview of *all* research in this area, the following summaries provide an overview of a subset of existing C2N research.

1. Belles et al. (2012) and Belles et al. (2013) are part of two Oak Ridge National Laboratory (ORNL) studies on an SMR site-screening study using the OR-SAGE tool. In the first part of the study, ORNL enhanced the OR-SAGE tool to specifically handle issues related to SMR siting. The second part of the SMR site-screening study, summarized in the 2013 paper, uses the enhanced OR-SAGE tool to screen a sample of a CPP site with the potential to be repowered with an SMR. The objective of the second part of the study is to demonstrate the capabilities of OR-SAGE in screening CPP sites for SMR repurposing, rather than to comment on the suitability of specific CPP sites. The sample of 34 CPP sites was chosen based on their nameplate capacity, which opted for older and smaller CPPs. The coal stations selected for screening were evaluated and assigned to a rating of "good," "better," or "best" based on their site selection and evaluation criteria.

2. Belles et al. (2021) evaluate 13 CPP sites in the Tennessee Valley Authority (TVA) service territory to determine the potential of these sites for SMR siting. The TVA CPP sites are a mix or existing and former sites and are evaluated using the OR-SAGE tool. OR-SAGE evaluates the sites based on established industry and regulatory criteria and available data. The results of the analysis conclude that most of the sites evaluated are suitable locations to site an SMR.

3. Bartela et al. (2021) investigate uncertainty surrounding the future of the Polish CPP fleet given economic challenges and increasingly ambitious climate targets and investigate the potential for SMRs to replace coal-fired boilers. Toward this aim, the authors perform a TEA of the replacement of the furnace and boiler in an existing Polish brownfield coal site with the Kairos Power Fluoride-salt-cool High-Temperature Reactor (KP-FHR). The results from the technical analysis suggest feasible integration of the steam-cycle and steam-turbine unit. The results from the economic assessment suggest an economic advantage of retrofitting an existing CPP site compared to a green field investment for each of the three investment pathways considered. The study also concludes that the price of coal, price of CO_2, and investment cost all significantly contribute to the viability of a C2N transition.

4. Qvist (2021) assesses retrofit decarbonization options of the Polish CPP fleet. Using the Polish CPP fleet as a case study, the authors compare the benefits of many retrofit decarbonization options including, adding carbon capture, converting to biomass feedstock, converting to natural gas and carbon capture, switching out coal boilers for nuclear reactors, wind turbines, solar photovoltaic panels, geothermal power, and more. After evaluating each option on many criteria including, ability to reutilize existing equipment, match thermal output, and ability to handle water scarcity issues, the authors find that the most attractive retrofit decarbonization option is using high-temperature SMRs.

With this option, overnight capital costs and LCOE are found to be lower than in a greenfield installation.

5. ScottMadden (2021) evaluate the potential of advanced reactors to revitalize post-coal communities. The focus of this paper is on the community impact of repurposing a CPP with an SMR, specifically analyzing the net changes in jobs, workforce retraining requirements, and broader economic impacts to the host community. The paper also examines why coal replacement with an SMR is favorable over other generation sources such as wind, solar, and natural gas. The findings of this report suggest SMRs are viable replacement options and would support the host community through economical and carbon-free electricity, more and better paying jobs, limited retraining required for CPP workers, and investment reductions through using existing site infrastructure and workforce.

6. NuScale (2021) discusses the impacts of coal plant closures on reliant communities and on the need to ensure a just economic transition. It also discusses the scale to which their research is relevant and timely, given that an estimated 145 GWe of coal capacity in the United States will retire if climate targets are met. NuScale presents the Centralia Coal Plant in Washington State as an example of a just economic transition plan that is in progress and suggests potential policies that the Department of Energy (DOE), state and local authorities, and power plant owners could support to facilitate a just transition. As a developer of SMR technology, the paper explains how the NuScale VOYGR plants could replace decommissioned CPP facilities while helping to maintain the economic vitality of the workers and their communities.

7. Toth et al. (2022) focuses on the frontline community impacts of transitioning away from coal. These are communities that have benefited economically from their proximity to coal plants, with employment, good paying jobs, tax revenue, and electricity. With the push to transition away from coal to cleaner sources, these communities need assistance with economic revitalization. Advanced nuclear may present a potential option for a CPP site transition while ensuring community longevity and economic security. Nuclear could use the existing transmission, transportation, and water infrastructure left behind from retired coal plants. This report also analyzes possible locations for C2N transitions based on community support and legal, environmental, and technical constraints. It concludes with a discussion of the ongoing policy efforts to support coal communities and transition efforts.

8. Griffith (2021) focuses on presenting near-term issues that need to be considered by utilities and stakeholders in replacing a CPP with an NPP. Some of the presented and discussed issues include decommissioning efforts of a CPP, siting conditions, the basics of generating energy, NPP and CPP matching, and other factors in replacing a CPP with an NPP. Griffith also discusses the potential options, each requiring varying levels of technical and socioeconomic considerations, of replacing coal power with nuclear power. To demonstrate how these considerations can be applied and how viability can be assessed, Griffith presents an example case study of a C2N transition at the Colstrip Plant in Montana. In addition to Griffith's study, the Gateway for Accelerated Innovation in Nuclear (GAIN) Initiative is leading an effort of community engagement to facilitate coal-community understanding of C2N impacts.

9. The Nuclear Energy Institute (NEI) works directly with state legislatures and policy makers to explore the potential of a C2N transition. In a presentation to the Montana State Legislature in January of 2022, Nichol (2022) discussed the advantages of SMR technology in terms of

environmental friendliness, system benefits, economic benefits to the region, and growing utility and state interest. Recognizing the negative impact of retiring a CPP on the local community and the value of repurposing existing infrastructure, NEI cites the findings of ScottMadden (2021), Griffith (2021) (the GAIN report), and Toth et al. (2022) (the report by The Good Energy Collective). With these presentations and interactions with state policy makers, NEI aims to promote a C2N transition. NEI has also established a working group to investigate strategies aimed at streamlining siting at coal stations.

10. TerraPower (2021) describes the C2N project underway in Kemmerer, Wyoming, to transition the Naughton CPP infrastructure for use in a Natrium NPP sited nearby. The remaining two units of the Naughton Power Plant are planned for retirement by 2025. TerraPower and its partners on the project evaluated many factors in determining the suitability of the site, such as access to existing infrastructure, grid demand, site characteristics, and the ability to obtain a license for the site from the Nuclear Regulatory Commission (NRC). According to TerraPower, the local community and communities across Wyoming have expressed their support for the demonstration project.

11. In this report, The Electric Power Research Institute (EPRI) (2019) considers the plant retirement and redevelopment process of coal sites from a wide range of topic areas, addressing key considerations, barriers, and potential actions to building a strategy or approach for site repurposing or redevelopment of retiring coal plants. To develop a comprehensive and holistic repurposing approach, EPRI seeks to assist its members by presenting and discussing case studies of repurposed sites, ongoing repurposing initiatives, funding benefits, and recommended next steps. While this study does not specifically focus on replacing retired coal plants with advanced nuclear, EPRI plans to complete a report on repowering coal-fired power plants for advanced nuclear by the end of 2022.

12. Ingersoll (2022) describes efforts at TerraPraxis to develop a repeatable, fast, and equitable strategy to repower coal plants. TerraPraxis is working with Bryden Wood, Microsoft, the Massachusetts Institute of Technology, and the University of Buffalo to develop different elements of this platform, including a standardized building system and a heat transfer and storage system. With this platform, TerraPraxis and its partners hope to contribute to decarbonization efforts while supporting the workforce employed today. In addition to helping accelerate decarbonization efforts, TerraPraxis and its partners see repowering coal plants with SMRs as an opportunity to maintain high-paying jobs while reducing the investments and efforts required with all new infrastructure. The final product of TerraPraxis and its partners will be an analytics tool that can quickly assess repowering options. Expected capabilities of the analytics tool include providing design outputs for manufacturing, using a design configurator to create initial concepts, and assessing the viability of a boiler replacement at a CPP.

13. Although not specifically related to a C2N transition, Louie and Pearce (2016) contribute to the broader conversation on transitioning the coal workforce and ensuring a just transition for coal communities. They investigate the costs of retraining the current coal workforce for vacant solar photovoltaic (PV) industry positions. The authors gather information on industry occupations, and the education, skills, and salary for each occupation in both industries. Using this information, authors determine the closest equivalent position in the solar PV workforce for each coal occupation. Finally, the authors quantify the expected retraining time and retraining investment. The results of this analysis show that most of the coal work would be able to transition into vacant solar PV positions with relatively minor investment in retraining required.

14. Shawhan (2017) and Shawhan and Picciano (2019) use a detailed power sector model to simulate the impacts of saving unprofitable generators from retiring. Evaluating variants of DOE's "Grid Resiliency Pricing Rule," which would guarantee coal and nuclear generator revenues sufficient to remain profitable, the authors of these papers investigate the net effects of preventing coal and nuclear retirements. The resulting effect of preventing the retirement of coal capacity is a negative net benefit, while applying the policy to preventing nuclear retirements produces positive net benefits.

15. In addition to the research and C2N efforts described above, additional international efforts are underway to promote a global C2N transition. For example, (1) a memorandum of understanding (MoU) was recently signed between a utility in Romania and NuScale (WNN, 2022b). Facilitated by U.S. involvement, the MoU outlines a path forward for NuScale to work with the the Nuclearelectrica to install an SMR at a decommissioned CPP; and (2) the International Atomic Energy Agency (IAEA) coordinates occasional webinars on the topic where researchers present on C2N initiatives underway within partner nations (IAEA, 2022).

3. SITING ANALYSIS

3.1 Coal-to-Nuclear Site Evaluations

Many utilities periodically file an integrated resource plan (IRP) detailing their plans for new generation technology deployment, aging infrastructure, integration of distributed energy resources, energy efficiency, and evolving state and federal regulations. IRPs inform rate payers, investors, regulators, policy makers, and other stakeholders about the near- and long-term planning for generating and distributing electricity to meet anticipated demand (Omitaomu et al., 2022). Many current utility IRPs indicate a move away from coal-fired electricity generation toward cleaner technology (EIA, 2020b, 2020c). Some utilities are proposing to retire all coal-fired electricity generation within the next 15 years (Gearino, 2020). As ARs and SMRs are licensed, these technologies will become available for consideration by a wider variety of utilities and independent power producers to replace retiring coal-fired assets. Because reactor licensing and siting is highly regulated, ORNL developed a GIS tool to assist in siting analysis known as OR-SAGE. Basically, the OR-SAGE database employs multiple GIS layers to establish evaluation parameters for siting. The parameters can each be assigned an acceptable threshold value depending on technology and user interest. Typical GIS output is visual, or map based. However, for this study, a numerical approach was utilized due to the number of sites included. The typical OR-SAGE methodology, visualizations, and the numerical approach are discussed in detail in Appendix A.

The operating and retired coal-plant data (US EIA, n.d.) was retrieved from the DOE-EIA website for August 2021. This was the latest data available at the initiation of the review.

The following subsections discuss the approach that the SA&I study team used to review the DOE-EIA data and identify a candidate set of recently retired coal facilities with an initial focus on plants in the Midwest using the OR-SAGE tool. The team settled on a site evaluation choice from the Midwest so that the case study results would be general in nature and not specific to any region or community where there are active C2N considerations or discussions. The team identified several Midwest sites for consideration by the team to be the focus of their economic analyses, then evaluated recently retired coal plants and operating plants throughout the United States on a regional basis. The siting portion of the study is intended to evaluate the nationwide C2N backfit potential. Therefore, there is no effort to exclude states with current restrictions on new nuclear construction.

3.1.1 Initial Review of Recently Retired Coal Facilities

As noted in 1.1, the EIA generator data for August 2021 are used for these analyses. As of that time, there were 841 retired coal-fired generators at 349 sites. This number includes all retired generators over time in the United States.

Many of these facilities will no longer have the infrastructure that make them attractive for a potential reactor backfit at the site. Older sites may have been totally remediated and used for other purposes or sold to another user. In addition, some sites will be owned by entities that are not ready to transition to nuclear energy. So, an effort was made to limit the retired generator set scope to address these concerns.

All CPP sites that were not owned and operated by a utility or an independent power producer were removed from the retired data set. Removed sites included industrial entities that produce their own energy, college and university energy facilities, and federal energy facilities. These types of facilities are not considered to be first movers for a power reactor backfit at a former CPP site. This reduced the retired CPP data set to 664 generators at 284 sites.

All remaining utility and IPP coal-fired generators retired prior to 2012 were also subsequently removed from the data set. It was assumed that the associated infrastructure at sites that have been retired for 10 years or more is deteriorated or removed. Likewise, older sites may already be used for an alternative purpose, or they were sold or could be sold to another entity. This would make these sites less favorable for a potential nuclear backfit. This further reduced the retired CPP data set to 505 generators at 229 sites.

At this point, OR-SAGE was used to provide a final quick screen of the sites. The EIA database provides the latitude and longitude for the center point of each CPP site. The OR-SAGE tool was used to evaluate the data cell containing the center point of each CPP site using preselected AR parameter thresholds. Thresholds are based on guidance provided by the NRC (NRC, 2014, 2020) and EPRI (Rodwell, 2002) as discussed in Appendix A. The site results for the center-point data cell were tabulated in a spreadsheet using a binary approach. Individual siting parameters that exceeded the OR-SAGE AR GIS thresholds were assigned a value of 1 in the spreadsheet and individual parameters that met the OR-SAGE AR thresholds were assigned a value of 0. The individual parameter binary values were summed across all the available GIS layers to produce a quick screen CPP site score. During this initial screen, sites with a score of 3 or less were retained for further study, while sites with a score of 4 or more were eliminated from further evaluation based on engineering judgment and prior application of the tool. The score is indicative of the number of siting parameter threshold values provided in the OR-SAGE tool that are exceeded and would roughly correspond to the degree of difficulty of using any particular site for siting a reactor. The initial screen of the EIA database provided a final retired CPP site data set reduction to 336 generators at 157 sites.

The goal of the final OR-SAGE quick screen was to manage the initial set of CPP locations selected for a more thorough analysis of larger areas around the plant sites. Subsequent evaluation revealed that 79% of the CPP sites with a score of 4 or higher in the quick screen were population limited (500 people per square mile [ppsm] at 4 miles for AR evaluation). These would have eventually been dropped from further investigation by this factor alone (NRC, 2020). As discussed in Section 3.1.3, the remaining 157 sites were evaluated individually across all the OR-SAGE siting factors, including population using a larger area analysis around the CPP site center point. Eventually, some of these sites were also judged to be “not amenable” to AR siting based on population density.

The 157 retired CPP sites selected for further evaluation were binned into one of five regional affiliations—Midwest, Northeast, Southeast, Southwest, and West. The states included in each region are shown in Table 3-1. By region, the 157 retired CPP sites were broken out as follows:

- Midwest – 60 sites
- Northeast – 18 sites
- Southeast – 50 sites
- Southwest – 13 sites
- West – 16 sites.

The number in parentheses in Table 3-1 identifies the number of CPP sites with utility or IPP generators retired in the last 10 years.

Table 3-1. List of states by region.

Midwest	Northeast	Southeast	Southwest	West
Illinois (7)	Connecticut (1)	Alabama (5)	Arizona (2)	Alaska (0)
Indiana (9)	Delaware (0)	Arkansas (0)	New Mexico (3)	California (4)
Iowa (4)	Maine (1)	Florida (5)	Oklahoma (1)	Colorado (5)
Kansas (2)	Maryland (4)	Georgia (5)	Texas (7)	Hawaii (0)
Michigan (10)	Massachusetts (0)	Kentucky (9)	–	Idaho (0)
Minnesota (5)	New Hampshire (0)	Louisiana (0)	–	Montana (2)
Missouri (7)	New Jersey (0)	Mississippi (1)	–	Nevada (1)
Nebraska (0)	New York (1)	North Carolina (7)	–	Oregon (1)
North Dakota (1)	Pennsylvania (11)	South Carolina (6)	–	Utah (1)
Ohio (10)	Rhode Island (0)	Tennessee (1)	–	Washington (0)
South Dakota (0)	Vermont (0)	Virginia (5)	–	Wyoming (2)
Wisconsin (5)	–	West Virginia (6)	–	–

The statistics shown in Table 3-2 summarize the scope of the utility and IPP coal-fired capacity that has been retired in the last 10 years.

Table 3-2. Summary of utility and IPP CPP capacity retired in last 10 years.

Region	Number of Sites	Number of Generators	Region Combined Generation Capacity (GWe)	Site Average Capacity (MWe)	Unit Average Capacity (MWe)
Midwest	60	131	22.3	371.4	170.1
Northeast	18	32	8.6	475.1	267.2
Southeast	50	125	24.9	498.0	199.2
Southwest	13	22	11.6	888.5	525.0
West	16	26	3.0	190.5	117.2

3.1.2 Population Density Analysis

The numerous siting parameters used by OR-SAGE, including population density, are presented in Appendix A. However, population density is a key parameter that differentiates AR siting from large LWR siting. Therefore, some discussion on population density is included here to clarify the calculation used for each reactor type.

Power reactor siting in the United States is based on limiting dose to individuals on the site exclusion area boundary (EAB) and on the boundary of a low-population zone (LPZ) as defined in Title 10 to the Code of Federal Regulations, Part 100 (10 CFR 100). There is also well-defined regulatory guidance for siting an NPP in NRC Regulatory Guide (RG) 4.7, “General Site Suitability Criteria for Nuclear Power Stations,” to assist a license applicant to meet the 10 CFR 100 requirements (NRC, 2014). Basically, RG 4.7 recommends excluding areas where there is a population density greater than 500 ppsm within 20 miles. This tends to promote remote siting of reactors and thereby provides an adequate margin to the dose requirements of 10 CFR 100. However, this conservative guidance is based on current large LWR technology.

Population densities of greater than 500 ppsm begin to transition into urban settings. One of the advantages of SMR and AR technologies is the ability to replace smaller, aging electric plants located closer to population centers. Arguments for allowing ARs and SMRs to be closer to population centers typically include a reduced core damage frequency, lower pressure operation, elimination of large-break loss-of-coolant accident sequences, smaller source term, reduced early release fraction, reactor vessels and containment vessels that are located entirely underwater or below grade, and reactor buildings that are located partially or totally below grade.

Based on these types of arguments, the NRC recently began taking a closer look at AR siting. The NRC staff has prepared SECY 20-0045 (NRC, 2020) for consideration by the commission with some alternative siting guidance options for ARs based on the Nuclear Energy and Innovation Modernization Act (NEIMA) definition. The NRC is not proposing any change in the 10 CFR 100 regulations for siting. Instead, they are looking at providing alternative siting guidance to be included in RG 4.7. The siting guidance option recommended by the NRC staff in SECY 20-0045 aligns the AR (NEIMA definition) siting guidance with proposed revisions to the emergency planning requirements and the radiological consequences calculated for design-specific events. The staff has recognized that the LPZ for a given reactor technology and the reactor EAB may be the same based on dose requirements as associated source terms diminish with size. Therefore, the staff recommended that if the LPZ remains larger than the EAB based on calculated dose from a design basis event or if a design basis event results in an offsite dose exceeding 1 roentgen equivalent man (rem) over the following 30 days, then siting guidance will exclude areas with greater than 500 ppsm out to a distance equal to twice the distance at which the 1 rem dose over 30 days is calculated. This will likely be a short distance for ARs. The TVA Clinch River Environmental Site Permit (ESP) Application had emergency planning calculations for 2 miles for the site EAB and for 2 miles around the site center point reflecting the anticipated short distance boundary. Under the same staff option, if there is no design basis event LBE dose exceeding 1 rem beyond the EAB, then the reactor can be sited right up to the edge of a population center of 25,000 people or more and within population centers smaller than 25,000 people. Therefore, for SMR and AR siting evaluations, the OR-SAGE population density calculation is capped at 4 miles to reflect the opportunity to site advanced demonstration power reactors much closer to population centers. The 4-mile value is based on the TVA Clinch River Environmental Site Permit, issued by the NRC. This value is conservative based on SECY-20-0045 recommended guidance. Actual population standoff distances will depend on the specific reactor technology selected.

The cap at 4 miles is based on vendors demonstrating small source terms that meet the 10 CFR 100 dose requirements at or near the reactor EAB. Otherwise, the cap per RG 4.7 guidance is set at 20 miles for large LWRs. Population density calculations are made for each data cell in the OR-SAGE database and their impact on each CPP site can be evaluated. Population density evaluations within a 4-mile radius and population density evaluations within a 20-mile radius of each data cell are demonstrated in this study and discussed in the following sections. More extensive discussion on these calculations is provided in Appendix A.

3.1.3 Expanded Review of Recently Retired Coal Facilities

As noted, the center-point analysis of the recently retired plants facilitated a reduction in the number of retired CPP sites to consider. However, the application of the OR-SAGE tool on a single data cell does not provide much discrimination among sites, nor does it provide a holistic look at the sites. Therefore, a more in-depth look at the remaining 157 recently retired CPP sites was undertaken. For this subsequent evaluation, OR-SAGE was applied to the area around the site center points to evaluate the area within a 0.5- and 1-mile radii (~500 acres and 2,000 acres). Often, a utility will own much of the land within a 0.5-mile radius; consequently, the AR siting parameters may not provide much discrimination. Therefore, a complementary look is applied to a 1.0-mile radius to ensure that siting parameters such as population density and land dedicated to public use are adequately reflected in the total site analysis. There is no connection to the establishment of an advanced reactor emergency planning zone (EPZ) to the siting analysis in this paper. Acceptance of a smaller advanced reactor EPZ by the NRC that differs from current practice is based on accident analyses, source term, and dose. Because such analyses are technology-specific, they are reviewed by the NRC on a case-by-case basis with respect to selected AR technologies, selected sites, and the EAB controlled by the utility.

For the 500-acre evaluation, OR-SAGE provides a visualization of approximately 208 data cells in the vicinity of the site center point listed by the EIA data for each CPP that passed the initial center point screen. The accompanying 2,000-acre evaluation provides a visualization of approximately 834 data cells in the vicinity of the site center point. The OR-SAGE analyses were performed using the base set of AR siting parameters and the base set of large LWR siting parameters. The base set of parameters for each are discussed in detail in Appendix A and are listed in Table 3-3 through Table 3-6. This was done to inform and facilitate the economic analyses.

For site analysis, the OR-SAGE tool is typically used to produce individual visual results that can be evaluated as discussed in Appendix A. The generation of individual visual results for each CPP site was not practical for this study due to the number of sites included. Therefore, the individual parameters were weighted regarding how many cells were necessary to flag a given parameter for the site area of interest (500 or 2,000 acres). The scoring relative to exceeding the parameter threshold value for each area and reactor type is discussed below. The scoring used for this phase of the evaluation is based on an evaluation of the OR-SAGE parameters as applied to the number of data cells within 0.5-mile radius or a 1-mile radius of the CPP site center point. The scoring is not the same as the initial screening evaluation on the CPP sites' center points. Engineering judgment and experience with the OR-SAGE tool was used to set the trip condition values in the following evaluations for the numerical evaluation of all the recently retired CPP sites that remained after the initial screening phase.

The numerical scoring system setup for this study involves a spreadsheet review of each CPP site based on the number of data cells within the 500-acre or 2,000-acre area that exceeded the AR or LWR parameter thresholds. The data cell count trip threshold was set at 50% of the included data cells for most of the individual siting parameters. A few parameters used a higher or lower data cell count threshold than 50% as discussed in the tables below. A binary score for that parameter is then assigned for that site. For example, each of the 208 data cells in a 500-acre area is evaluated individually for each of the siting parameters. If 105 or more cells are tripped for any given parameter set at 50% of the data cells present, then that parameter is scored with a value of 1; otherwise, it is scored with a value of 0. The binary score for each siting parameter is then summed to create a total score for that area at a CPP site. Higher scores imply more difficulty in siting a reactor at the CPP site. The score was then used to discriminate between CPP sites and was the basis for conclusions made about reactor siting in the study. Population density binary values were set at 20 and 0 so that population-limited sites could be eliminated from further consideration without regard to the other siting parameters. For large LWRs, site capacity was assigned a binary value of 10 if the current site capacity is less than 800 MWe. This implied that the existing infrastructure may not support a large LWR with a capacity more than 1 GWe. This provided quick discrimination of large-capacity CPP sites from smaller-capacity sites. One caveat to the numerical analysis is that it does not provide any insight on the distribution of tripped cells.

3.1.3.1 Advanced Reactor Evaluation Within a 0.5-Mile Radius

The OR-SAGE AR site evaluation parameters were evaluated and scored as shown in Table 3-3.

Table 3-3. AR 0.5-mile radius evaluation criteria.

Parameter	Trip Conditions
Population density > 500 people per square mile (ppsm) within 4 miles (NRC, 2020)	Flagged if >50% of the 208 cells exceed the threshold Tripped flag assigned a score of 20 (all other AR flags assigned a score of 1) Allows sites that are population limited to be readily identified
Safe shutdown earthquake (SSE)	Flagged if >50% of the 208 cells exceed the threshold
Faults	Flagged if >50% of the 208 cells exceed the threshold
Protected land	Flagged if >30% of the 208 cells exceed the threshold Provides a higher sensitivity to the proximity of protected land
Slope	Flagged if >50% of the 208 cells exceed the threshold
Landslide	Flagged if >50% of the 208 cells exceed the threshold
Wetlands and open water	Flagged if >60% of the 208 cells exceed the threshold Provides a lower sensitivity to the proximity of water because CPP sites typically have numerous ponds on-site in addition to the cooling source
Floodplain	Flagged if >40% of the 208 cells exceed the threshold Provides a higher sensitivity to the proximity of floodplains
Hazardous facilities	Flagged if >50% of the 208 cells exceed the threshold
Sum flag scores	Dismiss sites with a score of 20 or higher (reflects a population density trip) Rank remaining sites by score, presence of a dedicated cooling source (as opposed to once-through cooling from a river or lake), and years since retirement

The energy hazards and chemical hazards tracked by OR-SAGE identify risks within 5 miles of a site of interest (NRC, 2014). These are not included in the site score because they simply call for a risk assessment, but they are flagged for further discrimination between sites:

1. Energy hazard: flagged if >50% of the 208 cells exceed the threshold
1. Chemical hazard: flagged if >50% of the 208 cells exceed the threshold.

3.1.3.2 Advanced Non-Light-Water Reactor Evaluation Within a 1.0-Mile Radius

The OR-SAGE AR site evaluation parameters were evaluated like the process outlined above except that the total cell value is 834 cells. There were some differences in the way certain parameters were scored for the larger area evaluation as noted in Table 3-4.

Table 3-4. AR1.0-mile radius evaluation criteria.

Parameter	Trip Conditions
Population density > 500 ppsm within 4 miles (NRC, 2020)	Flagged if >40% of the 834 cells exceed the threshold Increased sensitivity to population encroachment on the broader area—possibly from multiple directions Tripped flag assigned a score of 20 (all other AR flags assigned a score of 1) Allows sites that are population limited to be readily identified
SSE	Flagged if >50% of the 834 cells exceed the threshold
Faults	Flagged if >50% of the 834 cells exceed the threshold
Protected land	Flagged if >25% of the 834 cells exceed the threshold Provides a higher sensitivity to the proximity of protected land in the larger area
Slope	Flagged if >50% of the 834 cells exceed the threshold
Landslide	Flagged if >50% of the 834 cells exceed the threshold
Wetlands and open water	Flagged if >60% of the 834 cells exceed the threshold Provides a lower sensitivity to the proximity of water because CPP sites typically have numerous ponds on-site in addition to the cooling source
Floodplain	Flagged if >30% of the 834 cells exceed the threshold Provides a higher sensitivity to the proximity of floodplains in larger area
Hazardous facilities	Flagged if >50% of the 834 cells exceed the threshold
Sum flag scores	Dismiss sites with a score of 20 or higher (reflects a population density trip) Rank remaining sites by score, presence of a dedicated cooling source (as opposed to once-through cooling from a river or lake), and years since retirement

The energy hazards and chemical hazards tracked by OR-SAGE identify risks within 5 miles of a site of interest. These are not included in the site score because they simply call for a risk assessment, but they are flagged for further discrimination between sites. They are given a slightly lower sensitivity for the larger analysis area:

2. Energy hazard: flagged if >60% of the 834 cells exceed the threshold
3. Chemical hazard: flagged if >60% of the 834 cells exceed the threshold.

3.1.3.3 Large Light-Water Reactor Evaluation Within a 0.5-Mile Radius

The OR-SAGE large LWR site evaluation parameters were evaluated like the process outlined above for an AR within a 0.5-mile radius. Population density is scored at a higher distance per RG 4.7 (NRC, 2014), and the need for makeup cooling water to the ultimate heat sink is evaluated. In addition, the capacity of the retired site is also evaluated. These differences are noted in Table 3-5.

Table 3-5. Large LWR 0.5-mile radius evaluation criteria.

Parameter	Trip Conditions
Population density > 500 ppsm within 20 miles (NRC, 2014)	Flagged if >50% of the 208 cells exceed the threshold Tripped flag assigned a score of 20 (all other AR flags assigned a score of 1) Allows sites that are population limited to be readily identified
SSE	Flagged if >50% of the 208 cells exceed the threshold
Faults	Flagged if >50% of the 208 cells exceed the threshold
Protected land	Flagged if >30% of the 208 cells exceed the threshold Provides a higher sensitivity to the proximity of protected land
Slope	Flagged if >50% of the 208 cells exceed the threshold
Landslide	Flagged if >50% of the 208 cells exceed the threshold
Wetlands and open water	Flagged if >60% of the 208 cells exceed the threshold Provides a lower sensitivity to the proximity of water because CPP sites typically have numerous ponds on-site in addition to the cooling source
Floodplain	Flagged if >40% of the 208 cells exceed the threshold Provides a higher sensitivity to the proximity of floodplains
Hazardous facilities	Flagged if >50% of the 208 cells exceed the threshold
Inadequate streamflow	Flagged if >80% of the 208 cells exceed the threshold Provides a lower sensitivity to the lack of available streamflow If adequate makeup cooling water is available anywhere within a 0.5-mile radius, it can be pumped the additional distance to the new reactor site
Site capacity	Flagged if total site capacity is less than 800 megawatts electric (MWe) Assumes site infrastructure is inadequate to support large LWR (>1 gigawatt electric (GWe) Tripped flag assigned a score of 10 (most other tripped flags assigned a score of 1) Allows sites that are capacity limited to be immediately identified (with or without a population limitation)
Sum flag scores	Dismiss sites with a score of 10 or higher (reflects limited site capacity) Dismiss sites with a score of 20 or higher (reflects a population density trip) Rank remaining sites by score, presence of a dedicated cooling source (as opposed to once-through cooling from a river or lake), and years since retirement

3.1.3.4 Large LWR Evaluation Within a 1.0-Mile Radius

The OR-SAGE large LWR site evaluation parameters were evaluated like the process outlined above for ARs within a 1.0-mile radius. There were some differences in the way certain parameters were scored for the larger analysis area are noted in Table 3-6.

Table 3-6. Large LWR 1.0-mile radius evaluation criteria.

Parameter	Trip Conditions
Population density > 500 ppsm within 20 miles (NRC, 2014)	Flagged if >40% of the 834 cells exceed the threshold Increased sensitivity to population encroachment on the broader area—possibly from multiple directions Tripped flag assigned a score of 20 (all other AR flags assigned a score of 1) Allows sites that are population limited to be readily identified
SSE	Flagged if >50% of the 834 cells exceed the threshold
Faults	Flagged if >50% of the 834 cells exceed the threshold
Protected land	Flagged if >25% of the 834 cells exceed the threshold Provides a higher sensitivity to the proximity of protected land in the larger area
Slope	Flagged if >50% of the 834 cells exceed the threshold
Landslide	Flagged if >50% of the 834 cells exceed the threshold
Wetlands and open water	Flagged if >60% of the 834 cells exceed the threshold Provides a lower sensitivity to the proximity of water because CPP sites typically have numerous ponds on-site in addition to the cooling source
Floodplain	Flagged if >30% of the 834 cells exceed the threshold Provides a higher sensitivity to the proximity of floodplains in larger area
Hazardous facilities	Flagged if >50% of the 834 cells exceed the threshold
Inadequate streamflow	Flagged if >70% of the 834 cells exceed the threshold Provides a lower sensitivity to the lack of available streamflow
Site capacity	Flagged if total site capacity is less than 800 MWe Assumes site infrastructure is inadequate to support large LWR (>1 GWe) Tripped flag assigned a score of 10 (most other tripped flags assigned a score of 1) Allows sites that are capacity limited to be immediately identified (with or without a population limitation)
Sum flag scores	Dismiss sites with a score of 20 or higher (reflects a population density trip) Rank remaining sites by score, presence of a dedicated cooling source (as opposed to once-through cooling from a river or lake), and years since retirement

3.1.3.5 Results of the Retired Plant Analyses

The retired sites were deemed to be amenable to further investigation for AR siting if they had a score of 5 or less[2]. As noted in Table 3-3 and Table 3-4, 20 points is assigned to retired CPP sites that are tripped by population density. Therefore, CPP sites with a score of 20 or higher stood out as being population limited based on the site evaluation parameter threshold of proximity of 500 ppsm within 4 miles. After

2 CPP site evaluations for this phase are based on a numerical review of tripped data cells surrounding the CPP site center point. Since no visual check of the site using the typical OR-SAGE output was applied in this case, the score threshold was set at 5 to avoid dropping sites unnecessarily. As noted in the text, no sites scored higher than 3 after removing CPP sites that were population limited (reflected by a score of 20 or higher).

removing the population limited sites from the total in each region, no remaining site had a score of more than 3, and all but one site had a score of 2 or less. So, population is clearly the discriminating parameter for backfit of an AR at a retired CPP.

Summaries of the analyses by region for retired CPP sites that may be amenable to siting an AR are shown in Table 3-7 and Table 3-8 based on the area analyzed (500- or 2,000-acre area). Each table shows the number of sites evaluated in each region, the number of sites evaluated as amenable to AR siting (AR amenable), the number of sites that remain viable with priority given to sites retired within the last 6 years, and the number of sites that remain viable with consideration given to the presence of a dedicated cooling source. Dedicated cooling sources can be a mechanical draft cooling system, a natural draft cooling tower, or a dedicated cooling pond or canal system. Because of the high value placed on water resources, a dedicated cooling source is an important economic factor in the consideration of a near-term reactor backfit at a coal-fired plant site. Each succeeding table column is relative to the number of units in the column to its left.

Table 3-7. Summary of retired sites evaluated for AR backfit within a 0.5-mile radius of the plant center.

Region	Sites	AR Amenable 0.5-mile	CPP Retired in Last 6 Years 0.5-mile	Dedicated Cooling Source
Midwest	60	41	27	13
Northeast	18	15	9	4
Southeast	50	45	17	11
Southwest	13	13	11	7
West	16	11	3	2
Total	157	125	67	37

Table 3-8. Summary of retired sites evaluated for AR backfit within a 1.0-mile radius of the plant center.

Region	Sites	AR Amenable 1.0-mile	CPP Retired in Last 6 Years 1.0-mile	Dedicated Cooling Source
Midwest	60	38	25	13
Northeast	18	14	8	3
Southeast	50	44	17	11
Southwest	13	13	11	7
West	16	10	2	1
Total	157	119	63	35

The Midwest and the Southeast have the largest number of AR amenable sites. For the 0.5-mile radius evaluation, 80% of the retired sites evaluated are amenable to AR siting. This is an exceptional outcome, and the results are consistent across the 0.5-mile radius (500 acres) analysis and the 1.0-mile radius (2,000 acres) analysis. There is only a loss of six AR-amenable sites when the site evaluations are expanded from 500 acres out to 2,000 acres.

As with the AR evaluations, the sites were deemed to be amenable to further investigation for large LWR siting if they had a score of 5 or less. As discussed previously, sites with a score of 20 or higher stood out as being population limited based on the site evaluation parameter threshold of proximity of 500 ppsm within 20 miles. In addition, for the large LWR evaluations, sites with a combined capacity of 800 MWe or less were assigned a score of 10 as shown in Table 3-5 and Table 3-6. Therefore, CPP sites with a score of 10–15 or 30 or more stood out as being capacity limited (<800 MWe) based on the current utilization of the site. After removing the population and capacity limited sites from the total in each region, no remaining site had a score of more than 2. So, population and site capacity are clearly the discriminating parameters for backfit of a large LWR at a retired CPP.

Summaries of the analyses by region for retired coal-fired sites that may be amenable to siting a large LWR are shown in Table 3-9 and

Table 3-10 based on the area analyzed (500- or 2,000-acre area). Each table shows the number of sites evaluated in each region, the number of sites evaluated as amenable to large LWR siting, the number of sites that remain viable with priority given to sites retired within the last 6 years, and the number of sites that remain viable with consideration given to the presence of a dedicated cooling source. Each succeeding column is relative to the number of units in the column to its left.

Far fewer CPP sites are amenable to siting a large LWR. This is expected because the larger area population density evaluation for an LWR is more limiting than the AR population density evaluation. In addition, many CPP sites have total site capacities of less than 800 MWe. The site capacity cutoff value is arbitrary, but with large LWR capacities typically more than 1 GWe and reactor capacity factors typically higher than the CPP to be replaced, this seemed to be a reasonable discriminator. In addition, many single-unit large LWRs struggle financially, so the site capacity cutoff could easily be considered at a higher value. There has not been a lot of interest expressed by industry to backfit large LWRs at former CPP sites, and this analysis may point to a core reason why. However, this analysis was undertaken to support an economic comparison of large LWR and AR backfits.

The Midwest and the Southeast have the largest number of large LWR-amenable sites. Overall, for the 0.5-mile radius evaluation, just 22% of the retired sites evaluated are amenable to large LWR siting. The results are consistent across the 0.5-mile radius analysis and the 1.0-mile radius analysis. There is only a loss of three LWR-amenable sites when the site evaluations are expanded from 500 acres out to 2,000 acres.

Table 3-9. Summary of retired sites evaluated for a large LWR backfit within a 0.5-mile radius of the plant center.

Region	Sites	LWR Amenable 0.5-mile	CPP Retired in Last 6 Years 0.5-mile	Dedicated Cooling Source
Midwest	60	12	8	7
Northeast	18	3	2	2
Southeast	50	11	4	2
Southwest	13	8	6	3
West	16	1	1	1
Total	157	35	21	15

Table 3-10. Summary of retired sites evaluated for large LWR backfit within a 1.0-mile radius of the plant center.

Region	Sites	LWR Amenable 1.0-mile	CPP Retired in Last 6 Years 1.0-mile	Dedicated Cooling Source
Midwest	60	10	7	6
Northeast	18	3	2	2
Southeast	50	11	4	2
Southwest	13	8	6	3
West	16	0	0	0
Total	157	32	19	13

3.1.4 Selection of the Case Study Site

The subsequent focus of the site evaluations was on the selection of representative sites to form a composite site for an economic case from among the 60 retired plant sites in the Midwest region. Based on the initial AR review described above over the 2,000-acre area surrounding the site center, 22 sites were removed from consideration based on population density. This left 38 sites to consider for the case study (see Table 3-8).

A literature review was conducted for these 38 sites to evaluate any ownership transfers that might limit future reactor backfits at the sites. In eight cases, the plant land has been sold, and a buyer was actively being sought in one additional case. A city municipality planned for bridge infrastructure at the site of another plant. This left 28 plant sites to consider further.

In-depth literature and aerial reviews were conducted on these 28 sites to further characterize their suitability for backfitting a reactor at the site. The plant infrastructure was demolished, except for a switchyard at five sites. This probably represents a neutral factor for reactor backfit, but these sites were removed from further consideration for the economic analysis. The coal-fired plants had been replaced by gas peaking units at three sites. Since an alternate generation source was used at these sites, they were removed from further consideration. One site had been converted to the use of synchronous condensers. Two sites are in sensitive locations—immediately across the Detroit River from Canada. Two additional sites include operational coal-fired generators with no announced retirement date. These two sites will ultimately be candidates for a reactor backfit, but they were removed from consideration as the case study site. This left 15 plant sites to consider further.

Twelve of the sites had excellent AR scores (0 using the weighted process described above for the 2,000-acre analysis).

Based on these 12 sites, the team developed a composite site for a proxy to apply the economic case studies.[3] The composite site reflects a retired generator and an operational generator, each with a nameplate capacity of approximately 600 MWe, rendering a composite site capacity of 1,200 MWe. The retired unit represents a unit removed from service within the last 10 years. The operating unit represents a unit slated for retirement within the coming decade. The total composite site capacity is favorable because the economic study includes analyses for the backfit of an AR and the backfit of large LWR. Therefore, the composite site was developed for analysis because each generator could potentially be replaced by a smaller AR technology while the two-generator composite could potentially be replaced by a large LWR. The existence of an operating coal-fired generator is considered advantageous because part of the focus of the economic analyses is on the active carbon generation that can be eliminated by a

[3] The authors are not aware of any actual plans for transitioning these sites.

reactor backfit. There was no collaboration with site ownership at any of the representative sites to develop the composite site. Nor is there any intent by the SA&I team to infer that any consideration is currently being given to siting any reactor technology at the site locations used to build the composite, proxy CPP site.

The composite site is amenable to the siting of an AR or a large LWR based on the OR-SAGE analysis. There is a dedicated cooling pond to provide plant cooling. The only siting parameter of note is the abundance of wetlands and open water. Much of this water is associated with various ponds associated with plant operation along with two streams that are near the plant site. There are no nearby chemical or energy facilities that may pose a fire, missile, or toxic gas risk factor. The concentric circles show the area within 0.5- and 1.0-mile radii of the plant center (~500 and 2,000 acres). The resulting favorable composite map is shown in Figure 3-1. It should be reemphasized that this selection is purely hypothetical for analysis purposes.

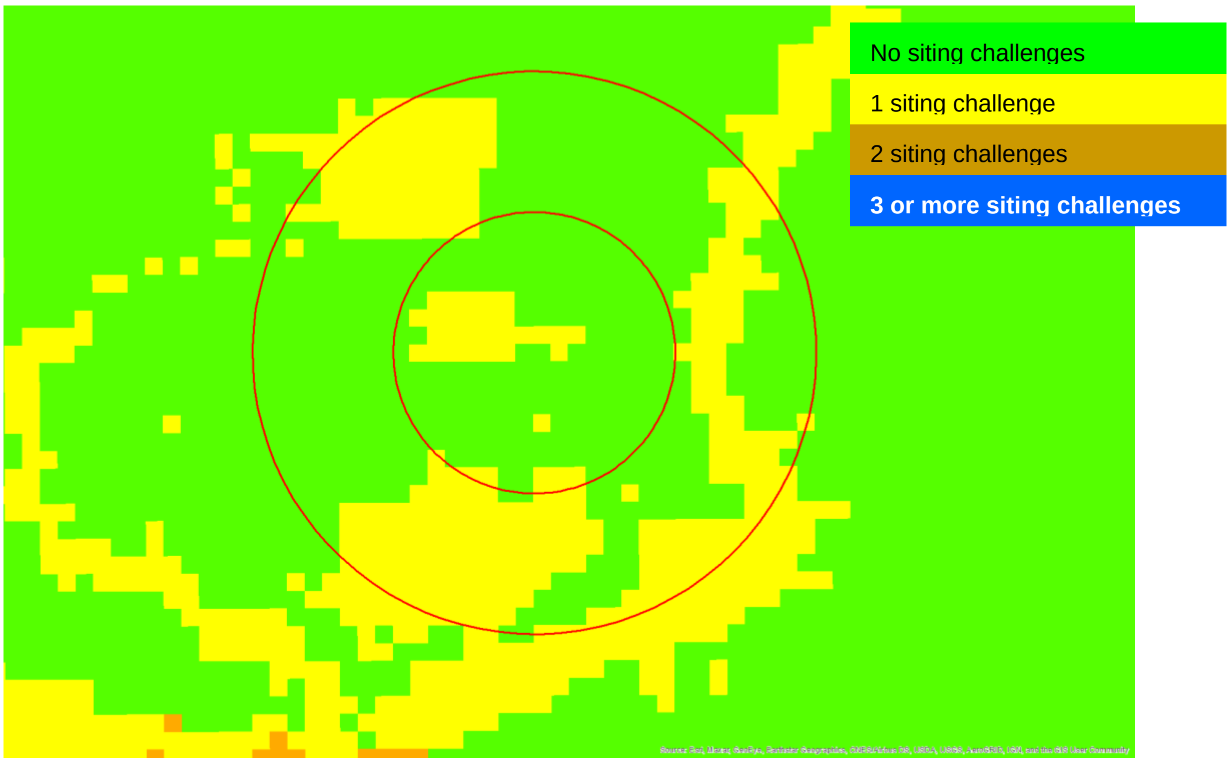

Figure 3-1. Case study site composite map.

3.1.5 Review of Operating Coal Facilities

The EIA generator data (US EIA, n.d.) for August 2021 are used for these analyses. As of that time, there were 581 operating coal-fired generators at 273 sites. The EIA data lists operating coal-fired generator status as operating, standby, or out-of-service and not expected to return in the next calendar year (2022). Most generators are listed as operating in the EIA data. Only 18 generators at 10 sites are not listed as operating. Among the generators categorized as operating, there is no further capacity factor data provided. Since there was a limited capacity to review each site individually using OR-SAGE visual results, an effort was made to limit the operating generator set scope.

As with the retired plant analyses, all CPP sites that were not owned and operated by a utility or an IPP were removed from the operating data set. Removed sites included industrial entities that produce their own energy, college and university energy facilities, and federal energy facilities. These types of facilities are not considered to be first movers with respect to nuclear backfit at a former CPP site. This reduced the retired coal-fired data set to 497 generators at 237 sites, including generators in all operating status categories. The remaining sites were binned into one of five regional affiliations—Northeast, Southeast, Midwest, Southwest, and West as shown in Table 3-1.

The same spreadsheet analyses were run on the operating plants as that described for the retired plants in the previous section. As before, the individual parameters were weighted regarding how many cells were necessary to flag a given parameter for the site area. The summed results were ranked by score and the presence of a dedicated cooling source (as opposed to once-through cooling from a river or lake). No effort was made to separate generators with an announced retirement date from those without a retirement forecast. Table 3-11 indicates the quantity of generators that are forecasted to be removed from service by region, and the latest forecast date included based on the August EIA data. Overall, 32% or just under one-third of the operating utility or IPP coal-fired generators (497 units) are scheduled for retirement by 2044. The average announced retirement date ranges from 2022 (Northeast) to 2033 (Southwest).

Table 3-11. CPP generators scheduled for retirement by region.

Region	Generators Scheduled for Retirement	Percentage of All Generators in the Region	Latest Year Scheduled	Retired Capacity (MWe)
Midwest	70	34%	2039	32,100
Northeast	5	14%	2024	2,620
Southeast	43	29%	2034	15,533
Southwest	23	44%	2044	13,576
West	18	31%	2033	7,142

Summaries of the analyses by region for operating coal-fired sites that may be amenable to siting an AR are shown in Table 3-12 based on the area analyzed (500- or 2,000-acre area).

Table 3-12. Summary of operational sites evaluated for AR backfit within 0.5-mile and 1.0-mile radii of the plant center.

Region	Sites	AR Amenable 0.5-mile	Dedicated Cooling Source	AR Amenable 1.0-mile	Dedicated Cooling Source
Midwest	91	65	32	60	30
Northeast	25	15	12	14	11
Southeast	62	52	38	51	36
Southwest	27	27	21	27	21
West	32	31	28	30	27
Total	237	190	131	182	125

The Midwest and the Southeast have the largest number of AR-amenable sites. For the 0.5-mile radius evaluation, 80% of the operating sites evaluated are amenable to AR siting. This is an impressive outcome and is consistent with the results seen for the retired CPP sites. The results are consistent across the 0.5-mile radius analysis and the 1.0-mile radius analysis. There is only a loss of eight AR-amenable sites when the site evaluations are expanded from 500 acres out to 2,000 acres. Only two of the 10 sites not categorized as operable in the EIA data are included as amenable to AR siting.

As with the AR evaluations, the operating coal-fired sites were deemed amenable to further investigation for large LWR siting if they had a score of 5 or less. Sites with a score of 20 or higher stood out as being population limited based on the site evaluation parameter threshold of proximity of 500 ppsm within 20 miles. In addition, sites with a score of 10–15 or 30 or more stood out as being capacity limited (<800 MWe) based on the current utilization of the site. After removing the population and capacity-limited sites from the total in each region, no remaining site had a score of more than 3. So, population and site capacity are clearly the discriminating parameters for backfit of a large LWR at an operating CPP site.

Summaries of the analyses by region for operating CPP sites that may be amenable to siting a large LWR are shown in Table 3-13 based on the area analyzed (500- or 2,000-acre area).

Far fewer CPP sites are amenable to siting a large LWR. This is expected because the larger area population density evaluation for LWRs is more limiting than the AR population density evaluation. In addition, many CPP sites have total site capacities of less than 800 MWe. The site capacity cutoff value is arbitrary, but with large LWR capacities typically more than 1 GWe, this seemed to be a reasonable discriminator. There has not been a lot of interest expressed by industry to backfit large LWRs at former CPP sites.

The Midwest and the Southeast have the largest number of large LWR-amenable sites. A full 40% of all operating sites evaluated are amenable to large LWR siting. This is a much larger percentage than that found for the retired plant sites. This is likely due to a trend for larger CPP sites built over time to meet electricity demand. Since these assets are younger, they tend to remain in operation. The results are consistent across the 0.5-mile radius analysis and the 1.0-mile radius analysis. There is only a loss of four LWR-amenable sites when the site evaluations are expanded from 500 acres out to 2,000 acres. None of the 10 sites categorized as other than operable in the EIA data are included as amenable to large LWR siting.

Table 3-13. Summary of operational sites evaluated for large LWR backfit within 0.5-mile and 1.0-mile radii of the plant center.

Region	Sites	LWR Amenable 0.5-mile	Dedicated Cooling Source	LWR Amenable 1.0-mile	Dedicated Cooling Source
Midwest	91	39	20	36	20
Northeast	25	5	4	5	4
Southeast	62	29	21	29	21
Southwest	27	15	12	15	12
West	32	8	8	7	7
Total	237	96	65	92	64

3.2 Site Evaluation Summary

There is some overlap among the retired CPP sites that were analyzed and the operating CPP set. There were 24 sites that had recently retired generators and operating generators across the five regions. Most of the overlap (11 sites) were in the Midwest. This was a factor in developing the case study proxy site.

Among the operating coal-fired utility and IPP generators, the opportunity for backfit of alternate energy sources to replace posted (advertised retirement date) and unposted (no advertised retirement date) retirements is summarized in Table 3-14. Review of currently retired coal-fired assets shows that these facilities tend to degrade quickly (demolition, land sale, land reuse, etc.) with respect to the future use of nuclear. So, the potential for backfit of advanced nuclear technologies at CPP sites would appear to strongly favor currently operating units. Capacity statistics on plants retired in the last 10 years are presented in Subsection 3.1.3.5.

Table 3-14. Summary of operating plant capacity.

Region	Utility/IPP Total Capacity (MWe)	Posted Retirement Capacity (MWe)	Percentage of Capacity to be Retired	Unposted Retirement Capacity (MWe)
Midwest	85,831	32,100	37%	53,731
Northeast	14,858	2,620	18%	12,238
Southeast	79,910	15,533	19%	64,377
Southwest	28,621	13,576	47%	15,045
West	19,956	7,142	36%	12,814
Total	229,176	70,971	31%	158,205

Another factor favoring backfit of near-term nuclear technology at operating coal-fired utility and IPP generators is the existence of a dedicated cooling source. Among the operating utility and IPP coal-fired sites, 68% have a dedicated cooling pond, a mechanical draft cooling system, or a natural draft cooling system. Only 43% of the recently retired sites evaluated have a dedicated cooling system. Operational Midwestern sites are the least likely to have a dedicated cooling system where just 48 of 91 sites were identified with a dedicated source through a visual analysis. Western sites were the most likely to have a dedicated cooling system where 29 of 32 sites were identified. Mechanical draft cooling systems were the most common nationwide, although 15 natural draft systems were identified in the Southeast. Of course, AR technologies that rely on the atmosphere as the ultimate heat sink are not limited by cooling water.

Sites with an OR-SAGE layer score of 5 or less were retained for further analysis. Among these sites, no operational coal-fired sites had a layer score of more than 2. Coal-fired sites with an OR-SAGE layer score of 0 should provide the easiest case for backfit of a nuclear plant. A summary of the 112 sites with an OR-SAGE score of 0, and an additional 54 sites with an OR-SAGE score of 1, is presented in the following tables by region. The presence of a dedicated cooling source is not reflected in the tables.

Thirty-six midwestern states with sites that have no OR-SAGE layers flagged are identified in Table 3-15. All 12 states in the region are represented. Eighteen additional sites had one OR-SAGE layer flagged and six sites had two OR-SAGE layers flagged (two in Illinois and four in Ohio).

Table 3-15. Midwestern states with few OR-SAGE layers flagged.

State	Sites with OR-SAGE Score of 0	Capacity Range (MWe)	Sites with OR-SAGE Score of 1	Capacity Range (MWe)
Iowa	2	725.9 – 811.9	3	212.0 – 1280.0
Illinois	3	681.7 – 1319.0	2	544.0 – 1099.8
Indiana	8	368.9 – 2600.0	2	530.4 – 3339.5
Kansas	2	348.7 – 2160.0	1	1598.9
Michigan	4	70.0 – 1547.0	1	1560.8
Minnesota	3	252.0 – 2469.3	0	-
Missouri	3	1099.4 – 1725.0	3	1242.0 – 2389.4
North Dakota	5	450.0 – 1209.6	0	-
Nebraska	2	228.7 – 1389.6	3	109.8 – 1362.6
Ohio	2	1086.5 – 2600.0	0	-
South Dakota	1	450.0	0	-
Wisconsin	1	1240.0	3	387.0 – 1402.6
Total	36		18	

OR-SAGE score relates to the number of site parameters that exceeded the threshold in the basic AR evaluation. Site parameters are identified in Section 3.1 and are further discussed in Appendix A.

There are six Northeastern states with sites that have no OR-SAGE layers flagged identified in Table 3-16. Only four of the 11 states in the region are represented. Eight additional sites in Pennsylvania had one OR-SAGE layer flagged, and no sites had two OR-SAGE layers flagged.

Table 3-16. Northeastern states with few OR-SAGE layers flagged.

State	Sites with OR-SAGE Score of 0	Capacity Range (MWe)	Sites with OR-SAGE Score of 1	Capacity Range (MWe)
Delaware	1	445.5	0	-
Maryland	2	495.0 – 1252.0	0	-
New Hampshire	1	100.0	0	-
Pennsylvania	2	94.0 – 1775.1	8	36.0 – 2012.0
Total	6		8	

OR-SAGE score relates to the number of site parameters that exceeded the threshold in the basic AR evaluation. Site parameters are identified in Section 3.1 and are further discussed in Appendix A.

There are 26 Southeastern states with sites that have no OR-SAGE layers flagged identified in Table 3-17. Eleven of the 12 states in the region are represented at this level. Nineteen additional sites had one OR-SAGE layer flagged, and five sites had two OR-SAGE layers flagged (one each in Florida, North Carolina, Tennessee, Virginia, and West Virginia).

Table 3-17. Southeastern states with few OR-SAGE layers flagged.

State	Sites with OR-SAGE Score of 0	Capacity Range (MWe)	Sites with OR-SAGE Score of 1	Capacity Range (MWe)
Alabama	2	952.0–2822.0	1	1390.5
Arkansas	2	558.0–609.0	3	720.0 – 1800.0
Florida	2	1429.2–2442.7	1	192.9
Georgia	3	1904.0–3564.0	0	-
Kentucky	5	509.4–2225.9	5	344.0 – 1608.5
Louisiana	4	558.0–1276.9	0	-
Mississippi	2	513.7–1096.6	0	-
North Carolina	2	2119.0–2491.2	2	763.2 – 1530.5
South Carolina	1	771.8	2	1260.0 – 2390.1
Tennessee	2	950.0–2600.0	1	1255.2
Virginia	1	848.0	0	-
West Virginia	0	-	4	95.7 – 1662.4
Total	26		19	

OR-SAGE score relates to the number of site parameters that exceeded the threshold in the basic AR evaluation. Site parameters are identified in Section 3.1 and are further discussed in Appendix A.

There are 23 southwestern states with sites that have no OR-SAGE layers flagged identified in Table 3-18. All four states in the region are represented. Four additional sites had one OR-SAGE layer flagged and no sites had two OR-SAGE layers flagged.

Table 3-18. Southwestern states with few OR-SAGE layers flagged.

State	Sites with OR-SAGE Score of 0	Capacity Range (MWe)	Sites with OR-SAGE Score of 1	Capacity Range (MWe)
Arizona	2	204.0–1765.8	2	821.8 – 1128.8
New Mexico	1	1848.0	1	2269.6
Oklahoma	6	350.0–1138.0	0	-
Texas	14	349.2–3736.8	1	1080.0
Total	23		4	

OR-SAGE score relates to the number of site parameters that exceeded the threshold in the basic AR evaluation. Site parameters are identified in Section 3.1 and are further discussed in Appendix A.

There are 21 Western states with sites that have no OR-SAGE layers flagged identified in Table 3-19. Only seven of the 11 states in the region are represented. Five additional sites had one OR-SAGE layer flagged, and four sites had two OR-SAGE layers flagged (one each in Colorado, Nevada, Utah, and Washington).

Table 3-19. Western states with few OR-SAGE layers flagged.

State	Sites with OR-SAGE Score of 0	Capacity Range (MWe)	Sites with OR-SAGE Score of 1	Capacity Range (MWe)
Alaska	3	10.3–90.0	0	-
Colorado	4	207.0–1635.3	1	1427.6
Hawaii	1	203.0	0	-
Montana	2	46.1–115.7	0	-
Nevada	1	567.0	0	-
Utah	3	58.1–1577.2	1	1640.0
Wyoming	7	95.0–2441.9	3	90.0–448.0
Total	21		5	

OR-SAGE score relates to the number of site parameters that exceeded the threshold in the basic AR evaluation. Site parameters are identified in Section 3.1 and are further discussed in Appendix A.

A full 80% of the 370[4] operational and retired sites evaluated are amenable to AR siting. This represents a 263.3 GWe capacity potential for reactor backfits at evaluated CPP sites. This exceptional outcome provides plenty of opportunity to consider AR backfits at existing coal-fired plants. However, plans need to be incorporated into IRPs because ad hoc literature reviews show that retired plants are frequently remediated or sold within 10 years, which represents a lost nuclear opportunity.

[4] Twenty-four evaluated sites had at least one retired generator and at least one operating generator. The sum of retired sites and operational sites is adjusted for this overlap.

4. TECHNO-ECONOMIC ANALYSIS OF C2N PROJECTS

This section of the report discusses the technical compatibility between CPP and nuclear reactor technologies. It informs on decision-drivers to consider different types of C2N projects. These drivers are useful for considering potential reuse of CPP components vis-à-vis compatibility with different reactor technologies.

As discussed in several publications (Bartela et al., 2021; ScottMadden, 2021), NPPs and CPPs share some important commonalities that bring potential for component reuse with corresponding capital costs and risks reduction. First, NPPs and CPPs are typically large-sized generators requiring a nontrivial overall physical site footprint and grid connection of significant size. CPPs and most NPPs rely on heating water to generate steam for power conversion cycles through coal combustion (for CPPs) and nuclear heating (for NPPs), to operate turbomachinery. Like all power plants, they need to evacuate waste heat, to transform and transmit electricity to the grid.

After considering the list of components that may be compatible between different CPP and NPP technologies in Section 4.1, several main types of C2N projects are defined as discussed in Griffith (2021):

> The potential reuse of CPP sites as locations for carbon-free nuclear power generation reveal a spectrum of potential options. There could be a variety of replacement options, from replacing only the heat source to replacing the entire plant. Three options are often discussed when considering a C2N transition (1) Reusing the electrical switchyard and grid connection (2) Direct connection and reuse of the steam system or (3) Indirect connection and reuse of the steam system.

Then in Section 4.2, characterization of different types of C2N projects are discussed. Based on these different C2N projects defined in our study, a costing and project timeline model is developed. The potential for reduction in OCC and several project timeline measures for different C2N projects are discussed. Finally, Section 4.3 presents an agent-based approach to assess the decision-drivers of different types of C2N projects.

4.1 C2N Technology Compatibility

The objective of this section is to provide a mapping of different CPP and NPP technologies and to discuss how different components from the CPP could be reused in a future NPP. This study builds upon previous reports on C2N technology discussed in Section 2, with the objective to inform on the compatibility between different CPP and NPP technologies. The compatibility mapping and costing is used in later sections to build out project planning and an economic model.

4.1.1 Introduction to Different CPP and NPP Technologies and Characteristics

Many different AR concepts are under development in the United States and could be considered for this study. In this report, the types of NPPs considered are limited to concepts with a high technology readiness level, and which are planned or proposed for relatively near-term deployments in the United States, as described in Table 4-1. This report considers several general reactor types to inform on paths toward C2N. The next step would be to consider specific technologies under development by industry; this approach would provide better resolution for a specific C2N project but should be completed by a nuclear vendor, such as those proposed by TerraPower (TerraPower, 2022b), Kairos Power (Bartela et al., 2021), and NuScale (NuScale, 2021). This study provides more general compatibility discussion that could be applied to different CPP and NPP technologies and will therefore rely on generic cost data with larger associated uncertainty.

Table 4-1. Description of various NPP concepts.

NPP Technology	Large PWR	Small PWR	SFR + Thermal Energy Storage (TES)	VHTR
Example reactor	AP1000	NuScale	Natrium	Xe-100
Electric power level	1117 MW	308 or 924 MW (4 or 12 packs)	345 MWe (nominal) Up to 500 MWe	80 MW

Among all the CPP in the United States, there are many different characteristics that may impact a C2N project, making specific CPPs better candidates than others. Table 4-2 summarizes the main CPP characteristics that would impact compatibility with specific NPP technology. Compatibility in terms of siting was discussed in Section 3.

Table 4-2. CPP characteristics to consider for a C2N project.

Characteristics	Range/options	Reason
Compatibility with site and electric components		
Site power	10 MW–3737 MW	Impacts the size of the total nuclear power generation without upgrading transmission line and of the amount of waste heat to release to the environment
Age of the CPP and environmental conditions	New to old and already retired	Impacts the level of cleanup required
Compatibility with steam-cycle components		
Coal steam-cycle	Subcritical (Sub) Supercritical (SC) Ultra-supercritical (USC)	Impacts potential for reutilizing steam-cycle components
Unit power	< 1.4 GW	Impacts the size of each nuclear power generator if we want to keep turbo-generator components
Compatibility with heat-sink components		
Cooling circuit	Mechanical draft cooling systems Dry cooling Natural draft cooling tower	Impacts whether nuclear unit will be readily able to reuse the heat-sink components, needs to build new one, or needs to use air-cooling technology

The following sections describe in more details the components from the CPP that could theoretically be reused in the NPP. They are categorized based on categories listed in the code of account (COA) identification system (EMWG, 2007). The potential value of reusing such components is discussed afterward in Section 4.2.

4.1.2 Reusing CPP Site, Office Buildings, and Electric Components

C2N projects can at a minimum reuse the land within the CPP boundaries, its connection to the grid, and its office buildings. This section provides a non-exhaustive list of components and facilities from CPP that could theoretically be reused in C2N projects, together with identified limitations.

The following list of siting and building elements common to both CPP and NPP installations was developed based on the Energy Economic Data Base (EEDB, 1988); each cost element is shown, here and in subsequent lists, with its COA identifier in parentheses and can be used to reproduce the analysis performed:

- Land and land rights – COA identifier: (20)
- Yard work (211)
- Administration and service building (218B)
- Electric switchyard buildings (218I)
- Transportation and lift equipment (251)
- Air and water steam service system (252)
- Communication equipment (253)
- Furnishing plus fixtures (254).

Other components that are not listed within the EEDB database, and referred as "owner's costs" in the *Advanced Fuel Cycle – Cost Basis Report* (Dixon et al., 2017) and that would account for up to 10% of the OCC, are:

- Substation, transmission facilities, generator step-up transformer, switchyard equipment. As stated in Griffith (2021), p. 12, "[t]he value of the original CPP switchyard would reach millions of dollars. The cost/mile of transmission lines can exceed $3M/mile and require multiple years of approval and construction."
- Roads and ancillary buildings (e.g., visitor's centers, cafeterias, and parking lots).

Reusing electric components from CPP site will typically require the total power of the new NPPs to be the same or less power than the existing CPPs. For instance, some of these components could not be reused if an AP1000 were to be sited at a former CPP site which was meant for <1000 MW without transmission upgrades. However, we could replace one CPP of 500 MW with 1 to 5 Xe-100 units and reutilize most of the electrical components. Common CPP and NPP electrical plant components (24) that are listed in the EEDB database include switchgear (241), switchboards (243), protective equipment (244), electric structure and wiring containers (245), power and control wiring (246).

For reactors that depend on active systems for reactor safety, class 1E electric components may be required, prompting upgrade of some components, in particular within accounts (241, 242, 243, 245, and 246) (Holcomb et al., 2011). However, none of the ARs under consideration in this study (Table 4-1) would likely require such 1E components as they all rely on passive safety.

4.1.3 Reusing CPP Heat-Sink Components

Both NPPs and CPPs require some type of ultimate heat sink typically via access to a cold source of water to dump the excess heat from the power conversion cycle. Reusing those would likely require reapproval and permitting but would provide significant value to a C2N project. Access to water supply and permits is one of the main benefits of C2N projects, especially for Western states applications.

For C2N projects where an upcoming NPP has different power or thermal efficiency than the CPP on site, the waste heat removal capacity of the site needs to be assessed. This is what is used to dimension the heat-sink components and water supply authorization. For instance, a 1 GWe CPP site where units have thermal efficiency of 45% would dump about 1.2 GW of heat to the environment. If replaced by a PWR with 33% thermal efficiency, the amount of heat that needs to be evacuated would be ~2 GW, which would likely be incompatible or require component upgrades and new permits.

Different ultimate heat-sink technology exists, such as natural draft cooling towers, mechanical draft cooling systems, and dry cooling. NPPs typically use natural draft cooling towers that are more expensive but provide better system efficiency (no power required to operate them). Some modern NPP designs consider using air-cooling technologies (e.g., NuScale). CPPs typically use mechanical draft cooling or direct cooling through dedicated channels. Still, the cooling through dedicated lake or rivers could be theoretically reused by NPP, avoiding some new investment costs but also resulting in reduced system efficiency. Some older heat-sink systems used in remaining CPPs may not be usable moving forward due to changes in regulations and requirements of use of "best technology available to minimize adverse environment impact" (Griffith, 2021). See also the FederalRegister (2022). The main heat-sink structures and mechanical equipment for the heat rejection for main condenser heat rejection system are listed under COA (26).

4.1.4 Reusing CPP Steam-Cycle Components

Reusing some of the CPP steam-cycle system components would provide both the largest challenge and opportunity for reducing OCC of the NPP. Here is a list of steam-cycle equipment listed in the EEDB that could potentially be reused in a C2N project: turbine room heater bay (Code of Accounts identifier: 213) and turbine plant equipment (23) that include turbine generator (231), condensing systems (233), feed heating system (234), other turbine plant equipment (235), and miscellaneous items (237). The steam generator is included in (222) for the NPP and (221) for the CPP.

Major compatibility and licensing challenges exist in reusing some of these components, and the decision of reusing components is technology-specific and site-dependent (depending on the estimated value remaining from the aged CPP steam-cycle component), as further discussed in (Griffith, 2021). Technology-specific compatibility is based on the steam-cycle types used in the CPP and NPP, as described in Table 4-3.

Table 4-3. Typical CPP and NPP steam-cycle characteristics.

Power plant	Steam-cycle type	Pressure (MPa)	Temperature (°C)
CPP	Subcritical (Sub)	16.5	538
CPP	Supercritical (SC)	22	600
CPP	Ultra-supercritical (USC)	32	610
NPP – PWR	Subcritical (Sub)	8	290
NPP – SFR	Subcritical (Sub)	15	500
NPP – VHTR	SC to USC	15-20	650

For PWRs, the steam-cycle components are unlikely to be reused because of the vastly different pressure and temperature operating conditions. This is especially true for turbine components, which require precise matching of steam characteristics (pressure, temperature, and flow). Other components could still theoretically be reused, since LWR operating conditions would not exceed their power and temperature specifications. It should be noted that CPPs operate at high temperature and pressure to achieve high thermal efficiency, while water usage as primary coolant of a PWR limits the temperature achievable.

For AR technologies such as SFR or VHTR, much higher operating temperatures are made possible using liquid metal or gas primary coolant, potentially enabling the reuse of some of these steam-cycle components. Here are the main components that would be involved: steam generator (SG), secondary pumps, turbine, generator, condenser, heaters, feedwater, and deaerator. For efficient reuse of all these components, the pressure/temperature operating conditions of the NPP cannot significantly differ from the original CPP conditions. CPPs using supercritical (SC), or ultra-supercritical (USC) operations are not typical for nuclear reactors because SGs would need to withstand high pressure. There are two main cases to consider:

- Direct coupling where the nuclear primary circuit is directly connected to the steam cycle through the SG. The SG would generally need to be replaced because it will be the reactor coolant pressure boundary and thus would need to be qualified as a nuclear safety component. Griffith concluded in regard to the prospect of directly connecting VHTR core to a CPP SG that "using an high-temperature gas reactor (HTGR) to replace combustion processes in a CPP boiler will require significant changes to the boiler design" (Griffith, 2021). Even though unlikely, such a scenario will not be disregarded in this report. The steam-handling system and turbine may still be reused in a direct coupling if the steam characteristics of the NPP are like those from the CPP. However, reusing some of the steam-cycle components will lead to unknown licensing requirements if these components play a role in the safety of the reactor. This will need to be assessed on a case-by-case basis.
- Indirect coupling where the nuclear primary circuit is separated from the steam cycle through an intermediate circuit such as TES, (like TerraPower's Natrium concept). In this case, the steam-cycle components may not need to be qualified as nuclear safety component, which may allow use of existing non-nuclear stamped SGs and steam-cycle components for all Sub, SC, and USC. As discussed in (Griffith, 2021), "[a] high-temperature reactor and heat storage system could enable reuse of the existing high-pressure secondary plant. Separation of nuclear- and coal-related equipment may also help in terms of licensing and design options. […] Such a disconnect could also allow for a simpler licensing analysis for the nuclear reactor, which could simplify licensing. A heat storage system could be used to separate the new safety- and nuclear-related systems from the legacy steam system of the pre-existing CPP." Some of the steam-cycle types may not be available depending on the pressure and temperature conditions allowed by the NPP and TES technologies.

The main points that would need to be considered with a full redesign analysis (beyond the scope of this report) are the potential cost opportunities and thermal-efficiency penalties of reusing CPP steam-cycle systems vs. components optimized for the NPP operating conditions. In Bartela et al. (2021), the authors went through the exercise of applying of FHR concept (from Kairos Power) to an existing CPP (SC), demonstrating that maintaining the thermal efficiency was feasible through careful reuse of its steam-cycle components and connection through TES.

4.1.5 Conclusions on Main C2N Projects

Based on this discussion, options focusing on four main types of C2N projects are described below. Those project types referenced as C2N#0-3 provide different potential for reusing different types of components and different project structures.

- Greenfield: This is a true greenfield NPP construction without any relation to any existing CPP. No CPP decommissioning costs are incurred; the only costs and schedule are directly due to the NPP construction project.
- C2N#0: Greenfield construction of NPP as a replacement to an existing CPP. The NPP could be completed near or far from a decommissioned CPP, but in this case, it is assumed that no site components are reused. In the context of this study, the linkage between the CPP and NPP is largely organizational rather than material or financial: the closure of the CPP motivates the construction of the NPP, but no infrastructure or resources are shared between them. In this case, the owner must pay to decommission the CPP in addition to the nuclear construction costs. It should be noted that a C2N#0 project where a new NPP is brought online close to decommissioned CPP may still bring benefits such as reuse of water rights, nearby transmission lines, and site workforce. However, the C2N#0 project cost estimates described in Section 4.2 do not consider any of these potential cost savings.
- C2N#1: Reuse of site, electrical and heat-sink components only. This is the type of C2N projects that would be used for LWR technology, or by any reactors that would replace one or several CPPs of

different sizes and would not reuse any of the steam-cycle components. This C2N#1 project will be applied to a PWR technology moving forward in the study.

- C2N#2 and C2N#3 both consider reuse of steam-cycle components, in addition to all the components reused in C2N#1. This is only possible if NPP units are replacing CPP units of similar power size and pressure/temperature operating regime. The differences in C2N#2 and C2N#3 projects are the following:
  - C2N#2 considers direct reuse of steam-cycle components, where the primary coolant of the reactor directly exchanges heat to the original CPP steam-cycle. An HTGR reactor technology could be applied for such transition and is used as an example technology for C2N#2 project moving forward in the study.
  - C2N#3 considers indirect reuse also of steam-cycle components, where the primary coolant of the reactor transfers heat to an intermediate circuit that is coupled with the CPP steam-cycle. This strategy enables separating the nuclear operation to the non-nuclear steam-cycle operation. An SFR technology that would use TES as buffer between primary circuit and steam-cycle (Natrium-type) is used as an example technology for C2N#3 project moving forward in the study.

A mapping between C2N types of projects based on some CPP and NPP technologies is proposed in Table 4-4. Many combinations could be considered and influence the type of C2N project considered as summarized in this table. The “NPP” column uses generic reactor-type categories rather than identifying specific reactor concepts, as many different individual designs could fill the general role indicated by each type of category.

Table 4-4. C2N project types considered for various scenarios.

Scenario description	CPP	NPP	Proposed C2N types (all could also use C2N#0 or C2N#1 if not specified)
1 NPP replaces 1 CPP unit (same or smaller size in terms of electrical power capacity and waste heat removal)	Any type	PWR	C2N#1
	Sub	SFR	C2N#2 (or C2N#1)
	SC or USC	SFR	C2N#1
	Any type	VHTR	C2N#2 (or C2N#1)
	Sub	SFR+TES	C2N#3 (or C2N#1)
	SC or USC	SFR+TES	C2N#1
	Any type	VHTR+TES	C2N#3 (or C2N#1)
1 NPP replaces 1 CPP unit (NPP has larger elec. Generation capacity and waste heat generation than original CPP unit)	Any	Any	C2N#0 (or modified C2N#1 requiring upgrade in transmission and potentially in heat-sink capacity)
1 NPP replaces 1 CPP unit (NPP has smaller elec. generation capacity and waste heat generation than original CPP unit)	Any	Any	C2N#1 (or C2N#2/3 depending on technology, with potential needs for upgrades)
1 large NPP replaces >12 smaller coal-fired units smaller collocated on same CPP (similar total power capacity)	Any type	Any type	C2N#1 or potentially C2N#3

One further aspect of technology-matching is the capacity of the nuclear reactor relative to the capacity of the CPP it replaces. The reactor capacity involves the electrical power level, which affects compatibility of turbomachinery, electrical systems, and transmission but also waste heat removal capability. CPPs vary considerably in size, from a few 10s of megawatts to over a gigawatt. ARs propose a variety of nameplate capacities, but each reactor (or module) typically has a predetermined nameplate capacity determined by the licensed design. Therefore, there likely will not be a perfect match between coal capacity and levels of nuclear capacity. The different C2N types of projects may provide some flexibility to enable compatibility with limited infrastructure upgrades.

Another important aspect in this discussion is the need to use an NPP that will be economically viable in the current market, which will likely involve different power level and flexibility requirements. Even though the CPP and NPP's role on the grid are mostly for baseload operation, a CPP typically operates at lower capacity factor to better match changing demand on the grid, and such a role may be better filled by a smaller NPP associated with TES. These aspects of market compatibility are considered in the analysis performed in Section 4.3.

The case study site considered in this study consists of two 600 MWe units for a combined site nameplate capacity of 1,200 MWe. For the scope of the current study, the modeled market was projected to experience low electricity demand growth, and extant heat-sink infrastructure of the site is sized to match this 1,200-MWe capacity. Therefore, in the context of this study, slightly smaller reactors were chosen over larger ones (e.g., the AP-1000) to account for the fact that PWRs have smaller thermal efficiency than CPPs, requiring higher heat-sink capacity per installed electrical power capacity, as discussed in Section 4.1.3. However, this study should not be construed as excluding the usefulness and compatibility of such larger reactors for C2N conversion projects. The 12-module NuScale plant PWR concept is considered with a total nameplate capacity of 924 MWe, and where each module provides 77 MWe of nameplate capacity. Likewise, consider the Natrium reactor, with a baseload nameplate capacity of 345 MWe that can ramp up to 500 MWe considering TES. Therefore, in addition to choosing a technology and a C2N project type, the owner must decide how much capacity to install with the new project.

For most of the cost estimates developed below, the specific capacity of the reactor replacing the CPP is not important. However, for distributing a few fixed costs on a per-kW basis, some assumptions were needed. The capacities used for the three reactor types are as shown in Table 4-5.

For the C2N#1 and C2N#3 projects, it is assumed that both units at the case study site are replaced by either a PWR (924 MWe, same power rating as 12-module NuScale) or two SFRs (1000 MWe total). For the C2N#2 project, the thermal output of the reactor must match the thermal output of the CPP, as the reactor is coupled directly to the pre-existing steam equipment. Therefore, C2N#2 project assumes the composite site with a scaled-down capacity of 1035 MWe, to match the 1035 MWe capacity of the example HTGR.

Table 4-5. Relative capacities of CPPs and replacement NPPs.

Reactor Type	NPP Nameplate Capacity (MWe)	Amount of Coal Capacity Replaced (MWe)
Example PWR	924	1200 (both units)
Example SFR	2x500	1200 (both units)
Example VHTR	1035	1035 *

* In this study, the VHTR is paired with the C2N#2 project, in which the reactor couples directly to the coal steam equipment of one CPP unit. Since no VHTR candidate from open literature would approximately match the power level of one case study unit (potentially required under C2N#2), it was decided to apply it in a C2N#2 type of project to an unassigned CPP site.

4.2 Characterization of C2N Projects Costs and Timeline

In this work, different types of C2N projects are considered. All involve the (eventual) closure of a CPP, and the construction and commissioning of a new NPP to replace the lost capacity. However, the costs, schedules, and economic characteristics of these projects vary widely, according to their differing purposes and technologies represented. The work in this section attempts to estimate and quantify how these different project types differ in terms of timelines and costing, which is required for modeling C2N projects in Section 4.3 and understanding decision-drivers.

The assumptions used to estimate variations in timeline and costing of different C2N projects are summarized in this section, especially in Table 4-9 and Table 4-10. Additional details and discussion are provided in Appendix C. Those discussions are kept in the Appendix C for brevity purposes, but they are especially important for the reader to understand the underlying assumptions used and the significant amount of uncertainty associated with these data. To account for such uncertainty, the results of the estimation process are provided for a “baseline” case and for a more “conservative” case.

4.2.1 C2N Projects Timeline

To understand in better detail and model these C2N projects, the sequence of project activities was broken out in Appendix C. The project activity flow sequences were developed for each C2N project to determine their associated timeline and requirements. The timeline involves pre-application activities, CPP Decommissioning and Demolition (D&D), C2N-related regulatory activity, NPP safety and non-safety components construction. Details about how activity duration estimates were developed are given in the Appendix C, Section C-2.

Table 4-8 summarizes the estimated activity durations for each major sub-activity in the project types described. The first three data columns of Table 4-8 show useful summary information about each project. The "Total NPP" column indicates the duration of the nuclear project alone without contributions related to any C2N activities. The "total critical path duration" is the required total duration to complete all project activities, measured as the longest possible path through the project activity directed graph. The "Required revenue gap" column shows the required span of time during which the utility receives no operating income from either the CPP or the NPP. This duration is determined largely by how early the CPP needs to be retired to perform refurbishment and regulatory activities.

For instance, the revenue gap of C2N#0 projects (greenfield) can be zero when the CPP is retired upon commissioning of the NPP, while the revenue gap is estimated as 2 to 9 years in other C2N projects where the CPP needs to be closed prior to some NPP construction activities. The C2N#3 type of project is especially interesting in this regard: the revenue gap is significantly reduced when compared to the C2N#2 project, since introduction of the TES means that most of the reused coal equipment falls outside of the "safety fence" (Griffith, 2021). This reduces the cost and time to analyze, refurbish, and receive NRC approval for these components and means that coal component refurbishment and licensing is no longer a prerequisite to receipt of the license.

4.2.2 C2N Projects Costing Estimation

For the different C2N project types considered in this report, one needs to determine the following components to the C2N projects. The following is a list of cost models that will affect the deployment perspective of a C2N projects. Only the ones highlighted are further discussed in Appendix C.

- OCC:
  - Reduction coming from site and components reutilization – this is the focus of estimate in Appendix C
  - Increase from refurbishment costs of CPP reused components
- Increase costs from site decontamination and D&D, as discussed in Appendix C
- Increased in fixed and variable operation and maintenance (FOM and VOM), discussed in Appendix C Section C-2, due to more frequent refurbishment of reused CPP components
- Potential reduction in system efficiency, leading to increased OCC and operating costs—this is due to reusing components that are potentially less optimized for NPP operating conditions (steam-cycle or heat-sink components)
- Financing costs:
  - Reduced financing costs if associated with reduced project risk and construction time as discussed in Section 4.2 and Appendix C
  - Transfer of the legacy debt of the CPP to the NPP
- Increase or decrease project construction time as discussed in Section 4.2.

The summary breakout of cost estimates for the various C2N project alternatives is shown in Table 4-9. The variations in OCC and O&M costs observed for C2N projects are due to different costs assumed for the reactor technologies considered for each C2N types of projects, and those are consistent with Dixon et al. (2017). It should be noted that this estimated OCC is much smaller than the value found for some existing NPP construction projects (such as the Vogtle power plant). This is because the OCC estimate in Dixon et al. (2017) assumes well-managed construction projects without costs overrun due to design changes throughout construction (Dixon et al., 2020). As mentioned previously, the example reactor types shown were selected from a variety of possible scenarios and should not be taken as definitive or as excluding alternatives. These technology types were chosen and matched with the given C2N project types for modeling purposes to allow more specific estimation of costs while still enabling an informative spread of possible project characteristics.

The approach used to estimate potential NPP construction savings from C2N projects was obtained by analyzing breakdown in OCC for various types of CPPs and NPPs from the EEDB Program from 1979 (EEDB, 1988). The NPP construction OCC savings estimated for several C2N projects are summarized in Table 4-6 with detailed assumptions discussed in Appendix C.

Table 4-6. Summary of upper bound NPP construction OCC savings associated to several C2N scenarios.

Reference	Example of nuclear technologies	PWR	SFR	VHTR	Min/Max reusing range in C2N projects	
	Components of OCC (greenfield construction)					
Estimate	Initial fuels inventory	7% s	11% s	6% s	0%	0%
CBR	Other costs (transmission, owner's, etc.)	10%	10%	10%	100%	100%
EEDB, 20	Land and land rights	0.3%	0.2%	0.3%	100%	100%
EEDB, 21	Structure and improvements	15%	12%	10%	0%	24%
EEDB, 22	Reactor plant equipment	18% s	29% s	30% s	0%	1%
EEDB, 23	Turbine plant equipment	15% s	10%	14% s	0%	99%
EEDB, 24	Electric plant equipment	5%	4%	5%	42%	78%
EEDB, 25	Miscellaneous plant equipment	2%	1%	1%	6%	91%
EEDB, 26	Main condenser and heat rejection system	3% s	2%	2% s	0%	100%
EEDB, 9	Total indirect costs	25%	21%	21%	16%	39%
CBR	$2020 – OCC for greenfield, $/kWe	4572	4912	5857		
	Savings on OCC from C2N#0	C2N#1	C2N#3	C2N#2		
	Baseline estimate (reject reuse of components of CPP that cost 30% less than in NPP)					
Estimate	$2020 – OCC for C2N, $/kWe	3371	3167	3621		
	Conservative estimate (reject reuse of components of CPP that cost less than in NPP)					
Estimate	$2020 – OCC for C2N, $/kWe	3806	3925	4279		

Note: Components with safety requirements, needs to be constructed after licensing (discussed in Section 4.2).

This analysis shows that the C2N#1 project type still provides large potential savings through reusing of site, offices, heat sink, and electrical components. Our conservative estimate show ~17% of savings on the OCC for the NPP project only (without considering any of the CPP D&D costs),), while the optimistic estimate would be up to 26%. The CN#2 and #3 project types would provide even larger potential for savings through reusing the steam-cycle components by 20% to 38%. For a 500 MWe SFR, the total assumed NPP construction OCC would be $2.46 billion for a greenfield project, and potential savings could achieve $493 million to $872 million. These "optimistic" estimates compare well with estimates from TerraPraxis: "Converting these plants to run on Advanced Modular Reactors (AMRs) will deliver a capital cost saving of 28%-35% (compared with a new nuclear plant) and a 9%-28% reduction in the levelized cost of energy." (WNN, 2022a). This estimate is also consistent (or comes from) analysis based on Kairos Power LLC SMR design (Bartela et al., 2021), and is consistent with C2N#3 approach.

After accounting for added costs from CPP removal and requalification shown in Table 4-9, the estimated project savings are summarized in Table 4-7. The expected project OCC reduction associated with a

C2N#1 project is 15–25%, and for C2N#2-3 projects is 17–35% when compared with a greenfield project. The different between greenfield and C2N#0 accounts for added costs of D&D for the CPP, which represent about 2-4% of OCC for the different scenarios considered in this study.

Table 4-7. Estimated project savings for different C2N projects when compared to greenfield or C2N#0.

		C2N#0	Greenfield
C2N#1	Baseline	-21%	-25%
C2N#1	Conservative	-11%	-15%
C2N#2	Baseline	-33%	-35%
C2N#2	Conservative	-19%	-22%
C2N#3	Baseline	-31%	-34%
C2N#3	Conservative	-14%	-17%

Table 4-8. Estimated activity durations (in years) for each major activity type, for all modeled projects.

						NPP Construction Activities			CPP Removal and Requalification Activities		
Project Type	Example Reactor Type	Assumption set	Total NPP	Total Critical Path Duration	Required Revenue Gap	NPP Non-safety	NPP Safety	NPP Commis-sioning	CPP D&D	CPP Ash Removal	CPP NRC Licensing
				years		years	years	years	years	years	years
C2N#0	PWR	Baseline	5	5.5	0	1	3	1	1	1.5	0
C2N#1	PWR	Baseline	5.25	6.75	6.75	1	3	1.25	1	1.5	1
C2N#1	PWR	Conservative	6.25	8.75	8.75	1	4	1.25	1	2	1.5
C2N#0	HTGR	Baseline	5	5.5	0	1	3	1	1	1.5	0
C2N#2	HTGR	Baseline	5.5	6.5	6.5	1	3	1.5	1	2	2
C2N#2	HTGR	Conservative	6.5	8	8	1	4	1.5	1	2.5	2.5
C2N#0	SFR	Baseline	5	5.5	0	1	3	1	1	1.5	0
C2N#3	SFR	Baseline	5.25	5.5	2.75	1	3	1.25	1	1.5	1.5
C2N#3	SFR	Conservative	6.25	7	3.25	1	4	1.25	1	2	2

Note: See Figures C-1 to C-4 in Appendix C for the derivation of the total critical path duration and the required revenue gap. These durations depend on the project activity dependency trees, which are different for each of the C2N project types.

Table 4-9. Cost assumptions for all C2N project alternatives in 2022 USD.

			Operating Costs			Total OCC	NPP Construction Costs		CPP Removal and Requalification		
Project Type	Example Reactor Type	Assumption Set	VOM	FOM	Fuel Cost	Sum of All →	NPP Non-safety	NPP Safety	CPP D&D	CPP Ash Removal	CPP NRC Licensing
			$/MWh	$/kw-yr	$/MWh	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW
Greenfield	PWR	Baseline	$2.00	$80.00	$10.52	$4,572	$1,940	$2,632	$0	$0	$0
C2N#0	PWR	Baseline	$2.00	$80.00	$10.52	$4,799	$1,940	$2,632	$194	$33	$0
C2N#1	PWR	Baseline	$2.00	$92.61	$10.52	$3,598	$1,430	$1,941	$194	$33	$0
C2N#1	PWR	Conservative	$2.50	$110.05	$13.15	$4,066	$1,615	$2,191	$194	$66	$0
Greenfield	HTGR	Baseline	$2.07	$96.64	$11.46	$5,859	$1,977	$3,882	$0	$0	$0
C2N#0	HTGR	Baseline	$2.07	$96.64	$11.46	$6,028	$1,977	$3,882	$145	$25	$0
C2N#2	HTGR	Baseline	$2.07	$118.78	$11.46	$3,951	$1,222	$2,400	$145	$123	$61
C2N#2	HTGR	Conservative	$2.59	$140.33	$14.33	$4,732	$1,444	$2,836	$145	$246	$61
Greenfield	SFR	Baseline	$2.00	$86.00	$15.38	$4,912	$2,415	$2,497	$0	$0	$0
C2N#0	SFR	Baseline	$2.00	$86.00	$15.38	$5,121	$2,415	$2,497	$179	$30	$0
C2N#3	SFR	Baseline	$2.00	$104.33	$15.38	$3,398	$1,557	$1,610	$179	$30	$21
C2N#3	SFR	Conservative	$2.50	$120.46	$19.23	$4,228	$1,929	$1,996	$179	$61	$63

4.3 C2N Decision-Modeling Methodology

This section presents a novel approach that is developed to help assess the decision-drivers for different energy production projects, focused on C2N projects in this report. It relies on the ABCE code under active development by SA&I since FY-21, and only preliminary results can be provided in this report that will rather focus on describing the methodology developed.

4.3.1 Agent-Decision-Modeling Code

The Argonne Low-carbon Energy Framework (A-LEAF) is a unit commitment, economic dispatch, and capacity expansion code, which uses explicit high-granularity time-series to solve real-time dispatch for a wide scope of user-specifiable electricity market systems. The A-LEAF dispatch module generates least-cost solutions for hourly or 5-minute dispatch and co-optimizes electricity with ancillary services.

The main A-LEAF capacity expansion module is like most electricity generation capacity expansion models in that it uses least-cost optimization methods to determine optimal system-wide generation portfolio mixes given user inputs about some future state of the system—total demand, wind and solar availability patterns, and unit cost data. This centralized planning-based approach, however, does not incorporate many economic decision-making factors employed by real firms interacting in a market, such as limited firm resources and limited local information. It also does not represent organic system evolution over time, instead interpolating directly to a prespecified future point in time. For the purposes of this study, an alternate capacity investment simulation code was developed as a plugin for A-LEAF, using agent-based simulation methods.

The agent-based ABCE code accepts the same inputs as A-LEAF, in addition to user-specified information about supply-side “utility agents” which exist in the system of interest, including the portfolio of units owned by each agent, the agents’ cost of securing debt and equity finance, and the agents’ starting levels of outstanding debt, equity, and undepreciated capital assets. The goal of each agent is to maximize the discounted profitability of their own portfolio, which they make projections based on information they have on the current and expected future composition of the market. They can use the cash flow at their disposal from operating power plants to finance new construction projects or retire uneconomical plants which are currently operating.

The agent-based code allows the observation of behavior patterns from different types of agents given different system starting conditions and assumptions about unit costs.

4.3.2 Composite Electricity Market Model

The representative, composite CPP used as a C2N case study is in the Midwestern United States. To describe the site’s grid-operations and market environment, an appropriate electricity market and system model was developed.

The composite case study serves multiple electricity markets, so the team developed a composite state model reflecting demand, wind and solar availability, ancillary services, and market rules across both jurisdictions.

Details of this composite model are presented in Appendix B. The peak demand in the system for the starting year is 30,000 MWe, and the installed portfolio in the starting year is shown in Table 4-10. A subsidy for NPPs and a production subsidy for wind units, like the federal wind production tax credit (PTC), were assumed to exist.

Table 4-10. Case study model installed capacity by generator type.

Generator Type	Installed Capacity (MWe)
Wind	7,000
Solar PV	600
Nuclear	12,000
Coal	9,000
NGCC	9,000
NGCT	11,700

4.3.3 Analysis Methods and Results

4.3.3.1 Modeling Setup

For this preliminary analysis work, a system with two hypothetical decision-making agents was created. The agents were created to represent two possible types of utility firms operating in the electricity market described above and generate differentiated behavior.

The overall goal of each agent is to optimize its projected financial return from the portfolio of generation units it owns and operates. The objective function of each agent has two differently weighted terms:

- **Maximize return (high weight)**: maximize the expected net present value of its portfolio over a 60-year horizon
- **Maximize firm liquidity (lower weight):** maintain a high firm interest coverage ratio (ICR).[5]

The ICR is a proxy for firm liquidity, or the amount of financial "headroom" it has available to invest in new projects or accommodate temporary reductions in cash flows. High ICR values indicate a high level of flexibility and financial resources available; as the firm engages in more new projects, it effectively exchanges this headroom for the prospect of improved future cash flows. The model prevents the ICR from falling below certain thresholds with a hard constraint, and its presence in the objective function also softly incentivizes maintenance of a high ICR (i.e., higher liquidity).

The first objective term tends to incentivize higher levels of activity, including both new construction and retirements. The second objective term tends to incentivize conservatism, or lower levels of firm activity. The first agent is a large generation owner, which owns a diversified portfolio of different generation technologies including fossil, renewables, and nuclear units. This agent has a relatively high level of cash flow due to its large portfolio, and its levels of pre-existing outstanding debt and equity were tuned to create an agent with a moderate-high level of liquidity. This agent was intended to have relatively strong flexibility in financing new construction projects and retiring uneconomical generation units.

The second agent is a smaller, legacy fossil generation owner with a mix of natural gas combined cycle and coal units. Due to the unprofitability of the coal units, as well as the manual tuning of the agent's level of outstanding debt and equity, this agent has a lower liquidity level than the large agent. It is far from financial distress, but it has less flexibility in financing costly new projects and has less ability to tolerate lapses in revenue streams.

The summary characteristics of these agents are shown in Table 4-11. Some capacity values may not exactly match Table 4-10 due to underlying generation unit capacity levels in the model (e.g., each Wind generator is 100 MW, so 6,700 MW is the closest possible match to 6,695 MW without undercounting).

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[5] The ICR is calculated for each year as (Forecasted FCF + Forecasted Interest Obligation) / (Forecasted Interest Obligation).

These agents are not intended to represent specific operators, nor is this simulation intended to reproduce expected outcomes for the composite market model.

Table 4-11. Summary characteristics of the two representative system agents.

Factor	Large agent	Smaller agent
Installed generation capacity:		
Wind (MWe)	7,000	0
Solar (MWe)	600	0
NGCC (MWe)	5,000	4,000
NGCT (MWe)	11,700	0
Coal (MWe)	3,000	6,000
Nuclear (MWe)	12,000	0
Total (MWe)	39,000	10,000
Initial indicative credit rating	A3	Baa3

For the preliminary analysis, the agents were permitted to choose from among the following types of behaviors during each year's decision round. Agents can choose combinations of behaviors/activities and multiple instances of each activity in the same round if economically favorable and permitted by constraints.

- Begin a "large" C2N construction project, replacing two coal units (around 600 MWe each) with two nuclear units, as described in Table 4-5 (including the greenfield C2N#0 project type)
- Begin a "small" C2N construction project, replacing one coal unit (around 600 MWe) with a nuclear unit of similar size, as described in Table 4-5 (including the greenfield C2N#0 project type)
- Build a modest number of wind generation units per turn
- Retire any currently operating unit (even without a corresponding C2N project).

Demand was modeled as flat for the first 5 years of the simulation, increasing at about 1% per year after that point. A $20/MWh production tax credit was available for both nuclear and wind generation; this value was a compromise between the 2020 federal wind PTC value of $19/MWh, the proposed range of wind and solar PTCs from the Build Back Better Bill capped at $25/MWh, and varying emissions credits between $10/MWh and $20/MWh. Agents are constrained to avoid reducing certain financial performance metrics below certain targets, which were developed using the Moody's Investors Service ratings methodology for unregulated electric power utilities. This analysis used the "baseline" assumption set for the C2N projects rather than the "conservative" case. As the nuclear plant costs are not assumed to evolve over time, this simulation implicitly assumes n^{th}-of-a-kind type project costing.

4.3.3.2 Modeling Results

With this basic setup, it was observed that the large agent chose to repower three of its existing coal units using C2N#3 conversion projects where each CPP unit is replaced with one SFR unit of similar power rating, starting one such project per year across the first 3 years of the simulation. The C2N#3 project type was chosen over the other C2N options due to its low cost, shorter overall schedule, and shorter mandatory revenue gap. The large agent began the simulation owning five total coal units; the remaining two coal units owned by this agent were retired in the first simulation period. This agent also consistently built new wind generation units. These decisions are shown in Figure 4-1.

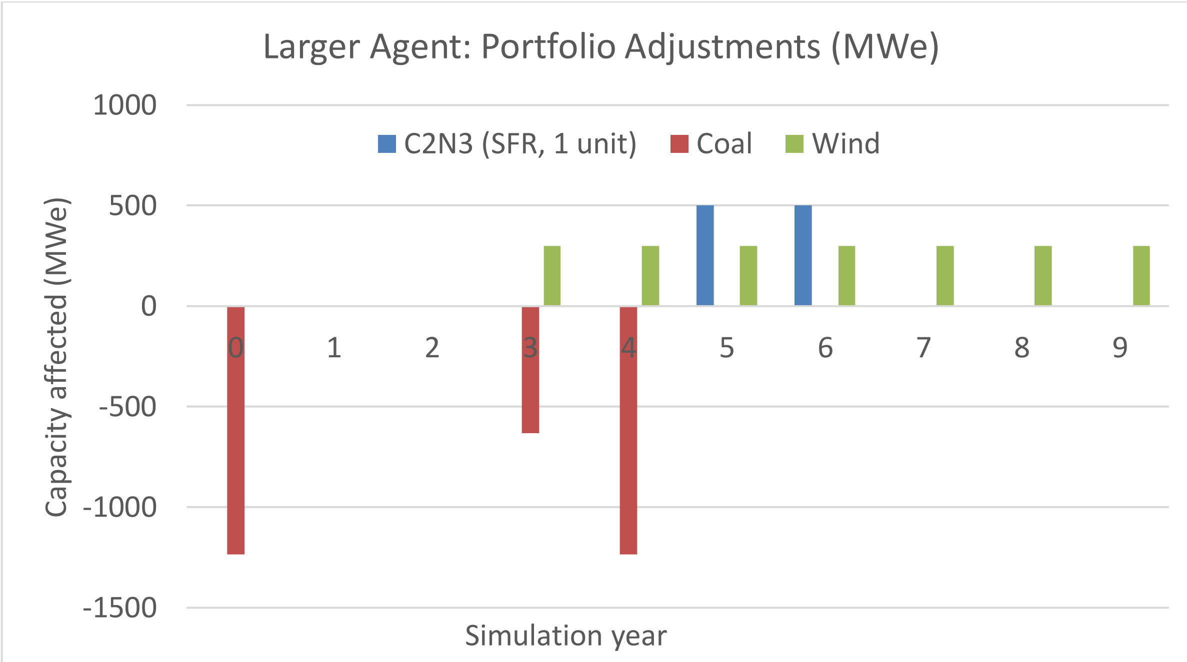

Figure 4-1. Portfolio changes (in MWe) for the larger agent.

Note in Figure 4-1 that both capacity additions and retirements are shown in the period during which the capacity change takes place. Retirements can be scheduled on the spot or years in advance. All capacity additions require construction time; for example, the two C2N projects were started in years 0 and 1, respectively. The larger agent did not begin any new construction projects after year 6.

The smaller agent evaluated the C2N#1 and C2N#3 projects to be economically viable in an absolute sense (positive net present value (NPV)) but was unable to engage in even the smaller-scale types of these projects (converting one coal unit into one nuclear unit) due to a lack of financial resources. Its base of free cash flow was too small to support enough new financing to invest in any nuclear energy option. Instead, the smaller agent invested in 200 MWe of wind units in the first period, to partially offset the lost capacity from retiring one coal unit. This limited activity is shown in Figure 4-2.

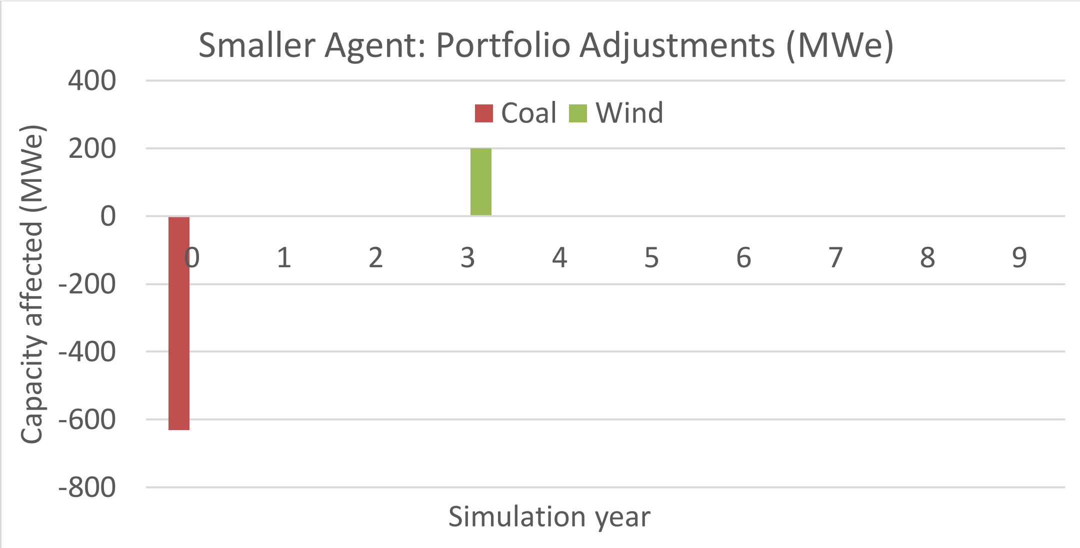

Figure 4-2. New construction and asset retirement activity for the smaller agent.

To explore these behavioral differences in more depth, the financial evolution of both agents are explored. The larger agent used its higher degree of financial flexibility to support the temporary decline in free cash flow caused by the capital expenditure outlay to build the nuclear plant, whereas the smaller agent was unable to do this, even though it evaluated several of the C2N project types as beneficial in absolute-dollar terms. The impacts of these decisions on the larger agent's projected financial levels of free cash flow (FCF) are shown in Figure 4-3.

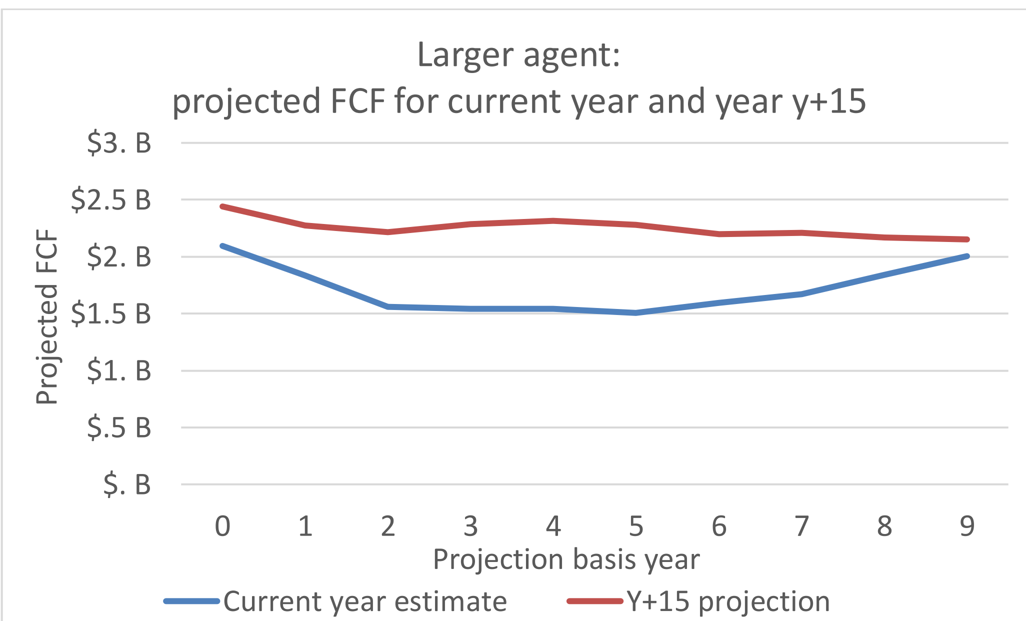

Figure 4-3. FCF projections for the larger utility agent, for simulation years 0 through 9.

During each simulation period, the agent projects its expected financial results for a rolling horizon of 60 years. Figure 4-4 shows the evolution of the larger agent's projections about its own financial outlook. Across the horizonal axis are simulation time-steps, showing from which period the agent is making the projection. The blue line ("current year estimate") shows the agent's estimate of its FCF for the upcoming fiscal year based on the basis year. The red line ("Y+15 projection") shows the agent's estimate of its FCF 15 years after the basis year (i.e., its expectations about its medium-to-long-term future).

During the first 2 years of the simulation, the agent's total level of projected next-year FCF decreases by 25.5%, as the agent begins a substantial program of capital investment. However, FCF projections quickly reach an equilibrium; as the agent successfully retires all its coal units and its new nuclear and wind units come online, its FCF values begin to increase again, indicating that it has located a new relatively stable competitive position. Despite this initial decrease, long-term FCF projections remain relatively constant throughout the simulation: the agent accommodates short-term decreases in FCF, but its capital investments result in relatively stable cash flow levels expected in the long term.

It is of interest to examine how this larger agent's ICR evolves over time. The constraint prohibiting the agents from reducing their financial performance metrics below certain levels is often binding in the decision algorithm. Figure 4-4 shows the evolution of the larger agent's current ICR across 10 years. This interest coverage constraint requires this value to always remain above 4.2 to avoid the agents falling into the "speculative grade" (i.e., "junk bonds") indicative rating range.

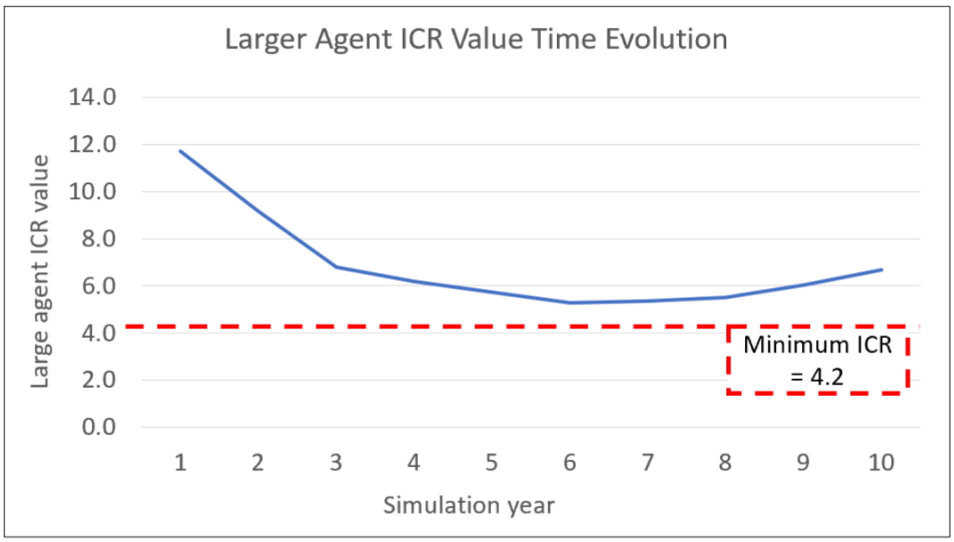

Figure 4-4. Evolution of the larger agent's ICR value over a 10-year simulation.

At the beginning of the simulation, the agent begins with a high ICR value of 11.7. Starting in that period, the agent begins to invest in new projects using this available "headroom." In subsequent years, the agent makes capital investments, and overall profit levels in the system decline slightly as the generation mix shifts, further reducing this value. After year 6, the agent's ICR value begins to increase again. This reflects the fact that its capital expenditure program is slowing as the agent and system reach a new equilibrium state—once many of the original coal units have been retired through C2N projects or stand-alone retirements.

Note how the large agent uses its large amount of "investment headroom" to finance the chosen C2N#3 and wind investment projects. The agent relatively quickly chooses to make investments which earmark its ICR headroom to drive FCF stability in its changing market, as shown in the previous figure. The smaller agent is unable to tolerate this drop in ICR and can only make marginal adjustments to its portfolio.

In contrast, Figure 4-5 shows the smaller agent's expectations about the change in its ICR if it were to build a smaller C2N#3 type project starting in the first simulation year.

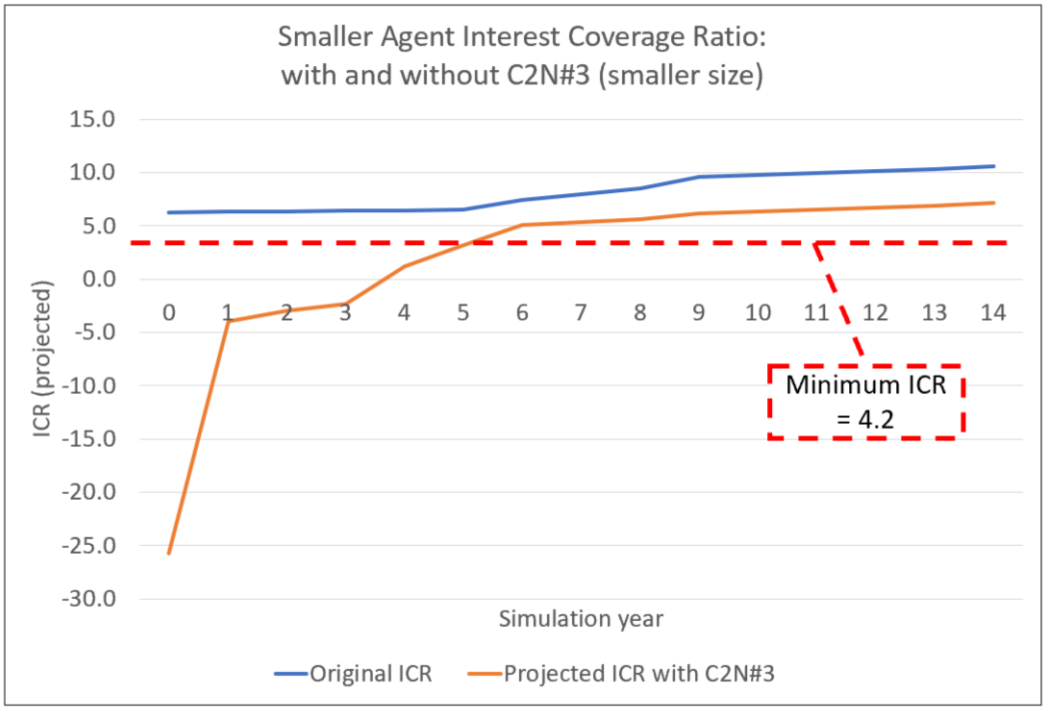

Figure 4-5. Smaller agent's projected interest coverage ratio with and without investment in a C2N#3 project.

The smaller agent could support the increased interest expense within its FCF, but the severe degradation of its ICR metric prohibits this investment.

4.3.3.3 Notes and Ongoing Work

The C2N#3 project was chosen by the larger utility agent using the current decision model and set of inputs, but that does not rule out the possibility of other C2N project types becoming viable in other situations. C2N#3 would likely involve more schedule and cost escalation risk than C2N#1 as it reuses more components; in an expanded model where risk is explicitly evaluated, the C2N#1 project may become more favorable. The C2N#1 project also has comparable construction costs and lower operating costs than the C2N#3 project.

When compared to the greenfield projects, the C2N#3 project has lower capital costs, but it also has a slightly longer overall construction schedule, including a mandatory revenue gap of at least 2.75 years, whereas the greenfield C2N#0 projects have no gap. The greenfield projects may be more attractive to the smaller in some situations, as the agent does not need to tolerate a revenue gap.

The C2N#2 project may require some specific circumstances to become favorable, as its costs are higher and its schedule longer than for the other projects. However, this type of project should still be studied, as it may have situational benefits which outweigh the nominal cost and schedule differences outlined here.

Ongoing simulation work is expanding the initial set of agent representations which are tested using this modeling capability. Having demonstrated the lower-bound case of an agent whose financial resources are too limited to participate in C2N projects, it is of interest to scan across agent financial parameters and portfolio size to determine when and how agents begin to select C2N type projects. In general, allowing for agent co-ownership of generation assets would also increase the scope of agents for which these projects are feasible, and could provide an interesting model for consortium NPP projects. Understanding the scenarios under which agents begin to choose larger-capacity replacements over smaller-capacity replacements is also of interest. The analysis will also be expanded to consider the conservative as well as baseline assumption sets described in Table 4-9. The agent-based approach also supports simulation of cost and schedule escalation, as the differing timelines of the C2N project may become even more important when cost and schedule risk is considered.

The analysis performed here considered C2N projects focusing on a relatively large CPP site (either at full 1,200-MWe capacity or half 600-MWe capacity). Similar study needs to be completed on other sites, such as smaller site in the ~100MWe power range, to assess viability of nuclear considering different cost scaling assumptions, as considered in Stauff et al. (2021). It would be important to assess if the cost savings associated with CPP component reuse added to other NPP cost reduction potentially obtained through factory manufacturing, etc. would be sufficient to offset likely increase in operating costs (O&M, fuels, etc.).

4.4 Summary for NPP/CPP Compatibility Study and Decision-Modeling Study

This section investigates compatibility between different CPP technologies that would be repowered with various types of NPP. The C2N projects were sorted into three main categories depending on the type of CPP components that could be reused in the NPP: C2N#1 considers only reuse of site, electrical components, and heat sink; C2N#2 also considers direct reuse of steam-cycle components, while C2N#3 considers indirect (through coupling with TES) reuse of steam-cycle components.

From this mapping, a simple economic model and project layout was built for each C2N project type based on representative NPP types. For this, the cost parameters of different NPP projects were estimated based on potential reuse of CPP components and assumed cost for D&D and cleanup activities. Such simple approach was used to quantify the potential benefits associated with different types of C2N project showing potential project cost reduction up to 25% in C2N#1 projects and up to 35% in C2N#2 and #3 projects, when compared to a greenfield project. Additional study would be needed to verify compatibility, assess refurbishment, and understand licensing costs associated with reuse of specific components in the various types of C2N project. The plan for each C2N projects was also estimated to quantify the duration of critical path and required revenue gap.

This C2N projects model was applied in a novel agent-based market modeling approach, which is currently under active development. The preliminary results obtained confirm that a C2N project is more attractive than greenfield deployment of an NPP under the assumptions derived in this section. A wide range of additional agent-decision analyses are enabled by this modeling tool, which is further applied to understand better utility drivers to pursue different types of C2N projects.

5. REGIONAL ECONOMIC STUDY

The purpose of this section is to study the economic impacts to the region wherein a CPP transitions to an NPP. Specifically, the research questions of interest to answer here are:

- What is the contribution to the regional economy of the CPP?
- What is the potential contribution to the regional economy from an NPP?

This section draws on the methodology of regional economic I-O analysis and the software IMPLAN, and yields answers to these questions in terms of jobs, taxes, economic growth—and because of the relationship between the economy and the environment—emissions (see Appendix D for additional details on I-O analysis). This analysis compares two possible states of the world: one where a CPP is in a community and another where an NPP replaces the CPP. Notionally, this is like the OCC in nuclear economics. The OCC measures the cost to build an NPP as if it was built in a day, estimating the resource needs for the project absent many of the transitionary impacts such as financing or delays. Similarly, I-O aims to measure the economic differences in a region between two possible states of the world. Like the OCC, some transition effects are intentionally not captured in this I-O, such as interim construction impacts, the way people redistribute across sectors of the economy while in transition, or possibly other factors. What the analysis yields instead is a differential in terms of jobs and other economic impacts between a community with a CPP that transitions to an NPP. That is, the analysis reflects the steady state equilibrium where a CPP is in place, then a separate steady state equilibrium where an NPP operates in place of the CPP.

There are two points to note here. First, the economic study in this section pertains to the regional economy surrounding the case study site. That is, this section concerns itself with regional impacts rather than the impacts to the utility that owns the CPP. This section also does not provide economic data on C2N profitability. Those considerations are addressed in Section 4.3. Second, this is a stylized, hypothetical analysis in that researchers leverage publicly available data; no municipality, utility, nor investor are partnered in this study.

This section proceeds with a description of the regional study site. Section 3.2 described the logic in developing the case study site. Section 5.1 provides a regional economic profile of the CPP community and the surrounding area that make up the region of analysis. Then the section provides background detail on the CPP itself. Section 5.2 describes the alternatives in the regional economic study. Section 5.2 describes the technical characteristics of scenario alternatives. In Section 5.2, these link to the alternatives evaluated based on regional economics. Section 5.3 details the regional economic study and provides the results. Then Section 5.4 summarizes and concludes the section.

5.1 Regional Case Study Site

5.1.1 Case Study Counties

The case study site is modeled based on the composite CPP site introduced in Section 3. For reasons discussed there, the case study serves as the basis of analysis for the regional economic impacts. But the region of impact is larger than the study site. This is true for any CPP. So, for the case study site, a four-county area is assumed for the region of analysis where economic impacts are evaluated. The determination to include additional counties is based on a labor shed approach to regional economic modeling. That is, the region of analysis is based on data from people in adjacent counties commuting to the CPP. The U.S. Census Bureau collects data on commuter flows from place of residence to place of work (U.S. Census Bureau, 2022). The region of analysis was established based on analysis of these data for commuter inflows to a representative Midwestern county.

The U.S. Environmental Protection Agency (EPA) (2022b) developed an online user interface for characterizing communities in the United States based on parameters of social and environmental justice.

It is a useful resource to understand characteristics of the region. These data, combined with data from the U.S. Census Bureau, enable a detailed socioeconomic summary of the region. Table 5-1 shows the summary data for the region with corresponding data for the United States listed for comparison. These data elucidate the social justice implications for the region.

Table 5-1. Socioeconomic summary of the region.

	Region	United States
	Demographics	
Population	78,000	331,893,745
People of Color	11%	40%
Low Income	34%	31%
Demographic Index	22%	
	Income and Employment	
Median Housing Value	$119,000	$229,800
Median Household Income	$56,000	$64,994
Civilian Labor Force	62%	63%
Unemployment Rate	4%	5%
Persons in Poverty	10%	11%
	Education	
High School Diploma	91%	89%
Bachelor's or Greater	21%	33%

Note: Summary data are for Census published year 2020. Data represent Census year of acquisition (U.S. Census Bureau).

The EPA defines the Demographic Index as the average of the share of the population that identify as people of color and the share of the population in low-income status. A person is considered a person of color if, on the census questionnaire, they do not select "white alone" when reporting racial and ethnic identification. A household is considered low income if the income level is less than twice the federal poverty level. Comparing the demographic data of the region to the state and nation, the region shows that there is less demographic diversity than the comparison. However, it also shows that there are more low-income households in the region than the state or nation.

The income and employment data for the region show, by comparison to state and national data, somewhat of an economic disadvantage. Housing values, an approximated for household wealth, are at about half that of the comparison. Household income shows a slightly better picture in comparison. In terms of the regional labor force, the region is approximately as well off as the comparison, although the unemployment rate is a bit lower, as is the rate of persons in poverty. Not to be confused with the low-income category noted above, the poverty level is the fraction of people who live below the established poverty level while low income reflects the total number of people living below a threshold of two times the poverty level.

The education profile shows that the region has roughly the same amount of people graduating from high school as the comparison. But the fraction of people with a college degree is considerably less than the comparison.

Turning now to parameters characterizing the environmental justice of the region, Table 5-2 shows the indicator value of the environmental parameter for the region, an adjusted environmental justice (EJ) index, and the region's ranking relative to the state. EPA defines the EJ index as follows (U.S. EPA, 2022a): EJ Index = (Environmental Indicator) X (Demographic Index for Block Group – Demographic Index for the United States) X (Population Count for Block Group).

Table 5-2. EJ index of the region.

Environmental Indicator Category	Value	EJ Index (adj.)	State Percentile
Superfund Proximity (site count/km distance)	0.02	-0.71	50
2017 Diesel Particulate Matter (ug/m3)	0.17	-0.82	49
2017 Air Toxic Cancer Risk (risk per MM)	21.91	-0.37	45
2017 Air Toxics Respiratory HI	0.30	-0.47	43
Particulate Matter 2.5 (ug/m3)	9.33	-0.87	42
Ozone (ppb)	44.12	-1.17	41
Hazardous Waste Proximity (facility count/km distance)	0.72	-0.42	41
Wastewater Discharge (toxicity-weighted concentration/m distance)	0.21	-0.90	39
Traffic Proximity (daily traffic count/distance to road)	242.89	-0.80	38
Lead Paint (%pre-1960s housing)	0.37	-0.75	28
Underground Storage Tanks	5.17	-1.13	25
Risks Management Plan Facility Proximity (facility count/km distance)	1.47	-0.80	22

Note: Author calculations using data from U.S. EPA (2022b).

A limitation of EJ in this format is that the resulting index is not comparable across indicators. To resolve this problem, the adjusted EJ in the table is based on the following: The indicator value is normalized to a 0 to 1 scale. This enables a comparison of impact from one indicator to the next. The value of the indicator by itself is not indicative of the severity of the issue in the region, rather its purpose is for comparison to other indicators only. Then the natural log of the listed population is computed. Then substituting in the normalized indicator value and the natural log of population, the adjusted EJ index results. A negative value results because of the demographic diversity of the region relative to the national comparison. Noted above, there is more demographic diversity across the nation than in the region. The greater the index value, the more of an issue the listed environmental category. The data are sorted based on the state percentile ranking. They show that, in the region, the proximity to a superfund site is in the 50th percentile for the state. In addition to proximity to a superfund site, the EPA indicators show high levels of air pollutants relative to the state ranking.

In terms of a regional summary of industries, Table 5-3 shows the industries in the region and the employment in each. Health care and manufacturing are the leading industries. Utilities, where electricity generation is categorized, is a small component of the industries in the region.

Table 5-3. Regional employment summary by industry.

Industry	Jobs	(%)
Health Care and Social Assistance	5,461	10.7
Manufacturing	5,394	10.5
Retail Trade	4,976	9.7
Public Administration	4,373	8.5
Accommodation and Food Services	3,783	7.4
Transportation and Warehousing	3,517	6.9
Other Services (except Public Administration)	3,475	6.8
Agriculture, Forestry, and Farming	3,104	6.1
Professional, Scientific, and Technical Services	2,990	5.8
Construction	2,913	5.7
Finance and Insurance	2,259	4.4
Wholesale Trade	1,826	3.6
Real Estate Rental and Leasing	1,627	3.2
Administrative and Support and Waste	1,487	2.9
Arts, Entertainment, and Recreation	1,314	2.6
Information	794	1.5
Mining	771	1.5
Management of Companies	574	1.1
Utilities	381	0.7
Educational Services	251	0.5

Note: Source data (IMPLAN, 2022b; U.S. BEA, 2022).

Based on the socioeconomics, the environmental indicators, and the industrial summary, one can begin to get an idea of the type of community in the region. The next section turns to the region's CPP.

5.1.2 CPP Site

As noted in Section 3, the case study composite CPP has a nameplate capacity of approximately 1,200 MWe. In the composite case, one unit shut down in the last 10 years and another unit is scheduled for shutdown within the next 10 years.

Recent data on CPP capacity factors in the United States show that, on average, a CPP operated in 2021 at 49.3% (Statista, 2022). An EPA analysis based on modeling with eGRID (Emissions and Generation Resource Integrated Database) shows that CO_2 emissions at a CPP averages 2,180 lbs/MWh (U.S. EPA, 2019). Applied to the case study, estimates suggest that a facility like that in the composite example emits approximately 3 million tons of CO_2 per year. The case study composite facility would account for about

5.1% of statewide CO_2 emissions. A CPP produces more than CO_2 only—SO_2, NOx, and mercury emissions are not reflected in these calculations.

The case study region has a lot of coal deposits, but many of them have been mined out leaving only a few as active mines today. Data show that the case study facility sourced its coal from the Western U.S. In the early 2010s, nearly 5 million tons were used, and by the late 2010s, the number dropped below 2 million tons. Although economic impacts to the coal mining sector are beyond the scope of this study, it is worth noting that the demand reduction from shuttering a facility is an economic impact to another region of the country.

Based on the characteristics of the case study CPP and based on cost estimates discussed in Section 4, the next section introduces the alternatives evaluated in the regional economic impact study.

5.1.3 Input-Output Model Study Area

The region described above constitutes the study area for I-O analysis. It should be noted that no nuclear generating facilities exist in the region. The I-O model was customized to include the nuclear electric power generation sector using a representative, state nuclear utility industry production function within IMPLAN. The I-O model estimates economic impact while simultaneously allowing economic leakage (economic flows out of the study region) to occur when supporting industries are not geographically available to meet industry supply-chain needs. It is likely that the results of the I-O model will understate the full impact of economic activity because some of the business activity and jobs created could be located outside of the defined four-county region. For example, an economic leakage is the economic flow between the region and the location of where coal feedstock is sourced in the Western United States. If the entire United States, or case study state, were modeled as the region of analysis then the multiplier effect of economic activity would change as the opportunity for economic leakage is reduced.

Although the scenarios presented in this study are specifically modeled using the four counties surrounding the case study facility, the results would likely be similar in other communities around the United States, especially for communities where the socioeconomic characteristics are closely matched.

5.2 Analysis of Alternatives

5.2.1 Description of Closure and Development Scenarios

Economic impacts were calculated to reflect four possible scenarios faced by a coal-fired generating facility in the case study location. (See Section 5.1.2.) The case study facility consisted of two generating facilities that each have a nameplate generating capacity of approximately 600 MWe for a total of 1,200 MWe. The facility closed one generating unit in the last 10 years and has plans to close the second unit in the coming decade (US EIA, n.d.). For the coal-fired generating facility, employment estimates used in this report were based on industry averages derived from an Iowa study that provided detailed employment and electricity production characteristics for nine different facilities (Christianson et al., 2021). These facilities had nameplate generating capacities ranging from 212 to 923 MWe and 30 to 97 employees. The average generating facility in the Iowa study had a generating capacity of 8.4 MWe per worker. Employment figures are not being reported in full-time equivalence. This electric output per worker calculation was used to estimate employment for future and past coal-plant-operating scenarios. Economic impacts of these actual and anticipated events are based on the following scenarios.

5.2.2 Pre-Closure

In the “Pre-Closure” scenario, the I-O model is used to show the economic impact of two generating units operating under relatively normal conditions prior to the closure that occurred in the last 10 years. For this study, a pre-closure general estimate of 75 workers per generating unit was used, for a combined total of 150 employees based on a total nameplate capacity of approximately 1,200 MWe. This employment estimate was based on the findings of the Iowa study mentioned previously.

5.2.3 Half Closure

In the "Half Closure" scenario, the model estimates the economic impact of a single generating unit operating with a nameplate capacity of approximately 600 MWe and 75 employees. This is analogous to the situation in the composite case study location today; one of the units at the CPP shutdown in the last 10 years.

5.2.4 Coal and Nuclear

The purpose of the "Coal and Nuclear" scenario is to demonstrate the estimated economic impact that would occur if one coal-fired generating unit was replaced with a small nuclear facility like the Natrium reactor being developed by TerraPower (TerraPower, 2022b) or the NuScale Power Module (NuScale, 2021). The TerraPower reactor produces 345 MWe of electricity and would employ 250 workers based on information provided though company press releases (TerraPower, 2022b). The six-module NuScale facility would produce an estimated 462 MWe with 193 employees (Black & Peterson, 2018). Each of these reactor design concepts were used to model the nuclear operations portion of the economic impacts. The coal-fired facility impacts used the same assumptions as the "half closure" scenario, with 75 employees at the facility. It was assumed the coal and nuclear facility would operate in tandem. An actual example of this type of scenario took place in Florida with the Crystal River Nuclear Plant, which had a nuclear side nameplate capacity of 860 MWe and four coal facilities with capacities ranging from 373 to 717 MWe (IAEA-PRIS, 2022). When this scenario is evaluated using the TerraPower design, it is analogous to C2N#3 from Section 4.2.

5.2.5 All Nuclear

The "All Nuclear" scenario assumes both generating facilities would be replaced with a 12-module SMR facility under the NuScale Power design configuration. As outlined, this scenario is analogous to C2N#1 from Section 4.2. This reactor design selection would provide 924 MWe of electric capacity with expected employment of 360 workers based on estimates available in Black and Peterson (2018). Even though the SMR electric capacity is less than the previous CPP, the capacity factor for the CPP was only 49.3% compared to 92% at the nuclear facility. Therefore, the nuclear replacement will produce more electricity annually than the existing plants.

The economic impact model is designed to permit employment estimate fluctuations. It should also be noted that the underlying production functions in the I-O model do not change depending on the brand of small modular reactor that is being used. As a result, if impact results differ from one rector brand to another, it is simply a factor of labor inputs changing, at least until proprietary operations expenses can be incorporated into the model. In the SMR impact study, performed by Black and Peterson (2018), an estimate of 360 jobs was used for the 12-pack version of the NuScale generating facility. A later marketing study by NuScale (2021) estimated the facility would employ 270 workers, closer to the estimated 250 jobs at the TerraPower plant. Based on a desire to allow for sensitivity, the 360 NuScale jobs estimate was used in this study for the larger NuScale plant. If actual employment at the NuScale plant ends up closer to 270 jobs, then economic impact results would closely match the impact estimates for the TerraPower reactor as outlined in the impact results of the "Coal and Nuclear" scenario.

5.3 Regional Economic Impact Analysis

This section presents the results of the impact analysis. They are separated into economic impacts, environmental impacts, and impacts to workforce transition. All economic impacts are in 2022-dollar years and are represented in annual amounts.

5.3.1 Economic Impacts

Results of the I-O model are displayed in sequence, progressing from pre-closure to complete replacement of the coal-fired generating facilities with nuclear. Additional figures were added to show the net change in impact from pre-closure to all nuclear. All these impacts are identified as totals as well as individual impacts stemming from direct, indirect, and induced categories of economic activity. A more detailed discussion of these impact categories is in Appendix D.

5.3.1.1 Employment Impact

The number of annual jobs either created or sustained by electric power generation ranged from 399 under the pre-closure scenario to 1,053 in the "all nuclear" scenario. This report does not provide an analysis of economic impacts related to construction of new facilities. These counts include direct jobs associated with the generating facility as well as the indirect and induced jobs that result from supply-chain sources and typical employee household spending.

The coal and nuclear scenarios had a total employment impact of 764 jobs for the NuScale designed reactor and 931 jobs for the TerraPower reactor. The difference in employment impacts between these two reactor designs is purely reflective of how many direct jobs were associated with these facilities. The TerraPower design suggested a need for 250 workers to run the reactor facility while NuScale estimated only 193; in both cases, these are counted as direct employment in the I-O model. With input from both SMR developers, adjustments could be made to increase the accuracy of the I-O model. Under both scenarios, it was assumed the coal generating facility would use 75 direct employees.

The impact of moving from a CPP to an NPP reveals a net increase of 653 jobs. In a later section of this report, additional analysis was performed on the transferability of knowledge, skills, and abilities from C2N facilities. Job transferability is not limited to the two types of generating facilities, but would also include the supply chain and other jobs within the community.

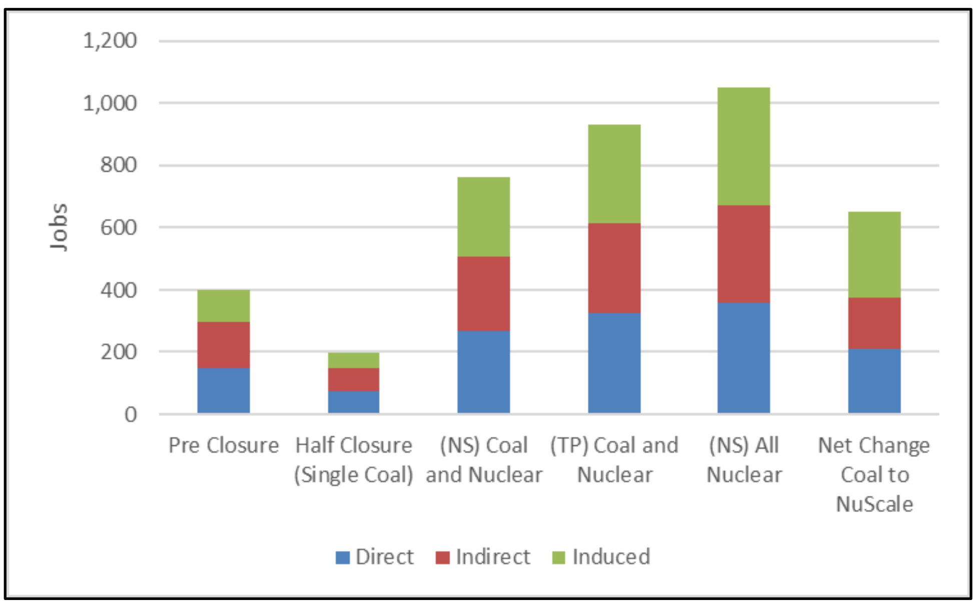

Figure 5-1. Economic impact – employment.

5.3.1.2 Output Impact

The value of annual industry production constitutes the output impact in this model. These output-impact results are estimated based on industry per worker production statistics obtained by IMPLAN. Described in Appendix D, the approach used in this report was to introduce coal and nuclear facility employment estimates into the model as direct impacts and let the model estimate the other components which include industry output. Actual industry output figures are often proprietary and are usually not disclosed unless a company is willing to provide the information or if the company is publicly held. Attempts were made to forecast plant revenues. Using wholesale electric prices for the region, the plant is combined with actual production statistics for the plant as reported through EIA. After this process was completed, it was determined that IMPLAN's estimates would be used.

Annual output impacts for the study area ranged from $284.8 million during the pre-closure period to $552.7 million once the plant is fully converted to nuclear using the NuScale Power 12-module configuration with the highest employment estimate. In the "Coal and Nuclear" scenario, the output impacts ranged from $438.7 million using the NuScale six-module configuration and $526.2 million if the TerraPower reactor design was used. The difference in output impact between the two reactor designs is tied to TerraPower estimating the need for more employees. This leads to increased labor income and higher overall output. Even though electric production is similar between the coal and nuclear options, total output will differ for several reasons. One reason for the difference is the increased need for employees at a nuclear facility versus a coal facility. As more company earnings are directed to local employees, those dollars have a higher likelihood of being spent locally rather than directed to non-labor inputs like coal or other materials required for CPP production that are sourced outside the region. As proprietary revenue and employment information is shared by plant operators, the I-O model can be adjusted, and total output impacts would likely change.

While employment impacts are distributed quite evenly between direct, indirect, and induced effects, the other impact categories show much more impact concentrated in the direct effect. This is caused by higher wages being paid to employees working for direct-impact companies. It should also be noted that employment impacts are displayed as a count of jobs rather than full-time equivalents. Employers in the indirect and induced effect categories are more likely to pay lower wages and have more part-time employees.

The net increase of transitioning from C2N yields a total output impact of $267.8 million, with 64% of that impact coming from the net increase in direct effects and 36% from indirect and induced effects.

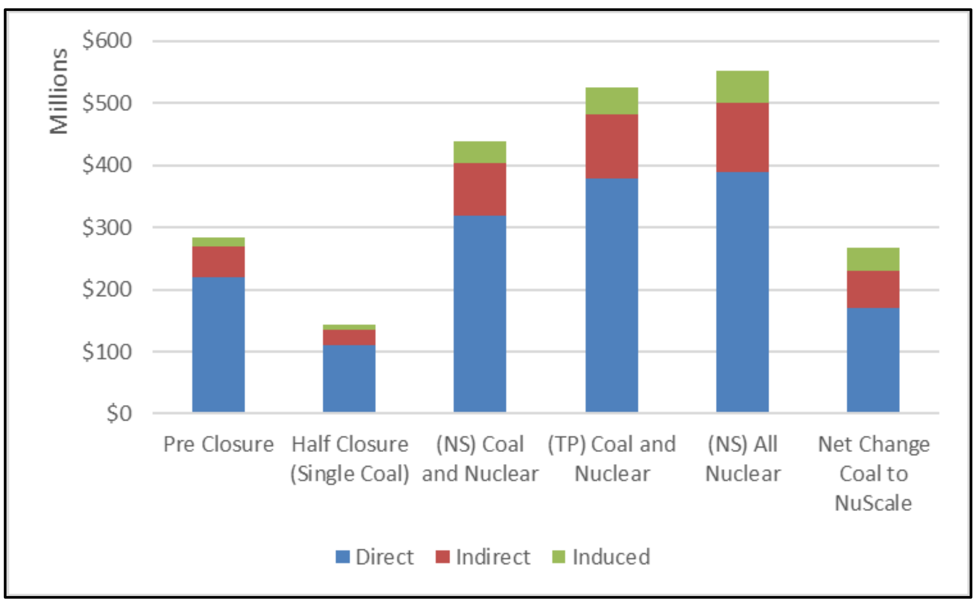

Figure 5-2. Economic impact – output.

5.3.1.3 Labor Income Impact

The labor income component of the impact model includes benefits, all forms of income employees would receive, proprietor income, as well as required state and local employer taxes. IMPLAN estimates for labor income were compared with Bureau of Labor Statistics reports to ensure these costs were accurate. The I-O model was determined not to require any additional adjustment. The I-O model estimates the pre-closure CPP facility would create or sustain $40.5 million in total labor income, $25.5 million of that coming directly from the facility. Total labor income impacts would increase to $142.6 million if the facility was converted completely to an NPP, a net increase of $102.1 million. The net change includes $22.8 million of labor income resulting from indirect and induced effects.

If the facility was dually powered by coal and nuclear the labor income impacts would range from $96.7 million if using the NuScale six-module reactor design and $119.3 million under the TerraPower design.

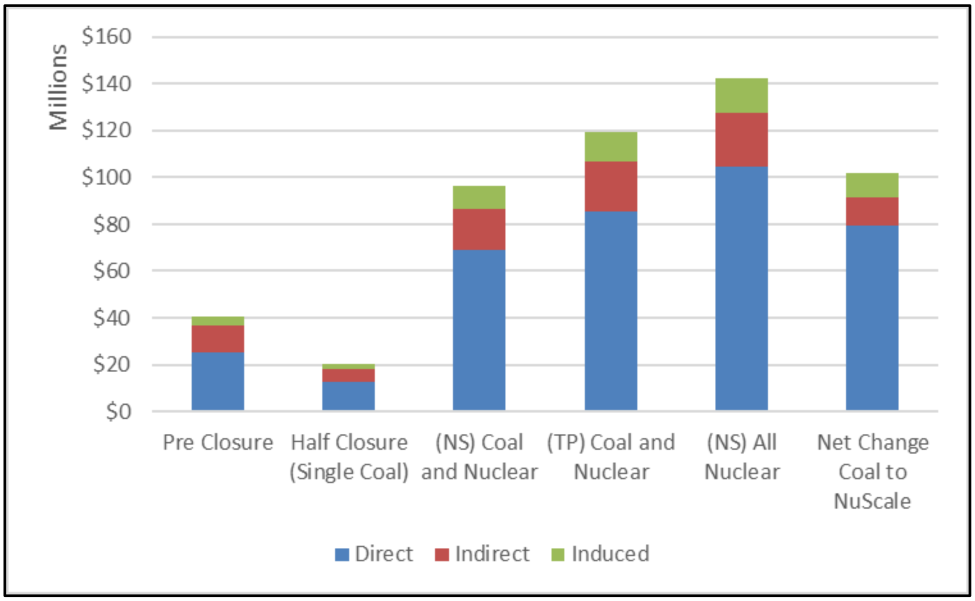

Figure 5-3. Economic impact – labor income.

5.3.1.4 Value-Added Impacts

The value-added category of impacts shows the electricity generating industry contribution toward gross domestic product in the defined four-county region. As intermediate goods are transformed through production methods into final goods, the value that is created is captured in this impact category. At each step in the supply chain, additional economic value is added, and that is what this impact captures. Pre-closure value-added impacts reach $131.8 million, with 63% of that impact coming directly from the CPP. If converted completely to an NPP, the value-added impacts would increase by more than $161 million to $293.4 million. This net change brings an additional $50 million of economic activity to local businesses through indirect and induced effects.

The combination of coal and nuclear facilities offered a range of $223.2 million and $269.7 million for the NuScale and TerraPower reactor concepts respectively. Again, these impacts are different only because the TerraPower facility expects to employ 250 workers compared to 193 at the NuScale facility.

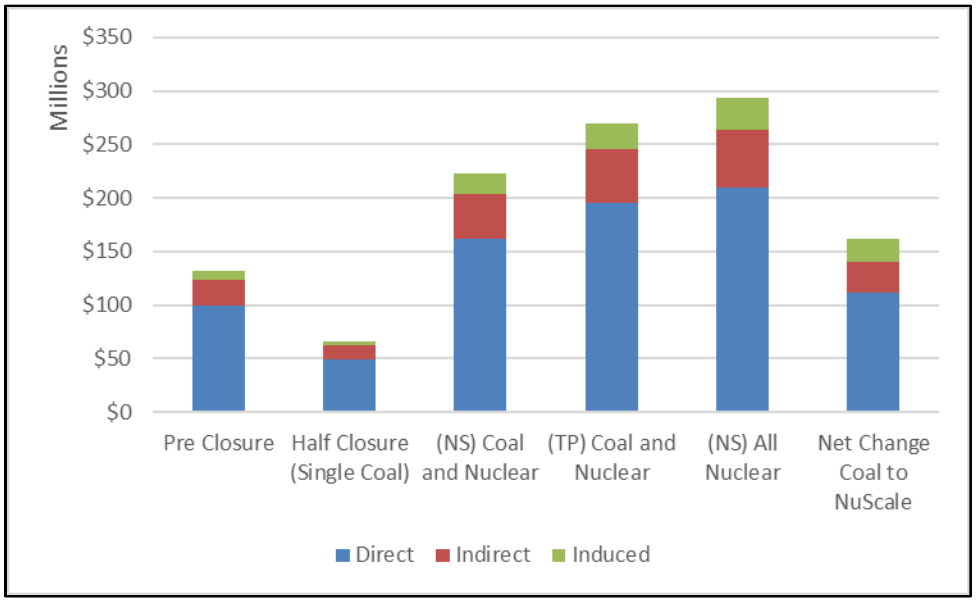

Figure 5-4. Economic impact – value added.

5.3.1.5 County Tax Impact

The model results include estimated taxes at a county level. Historical tax records show where CPP plants made significant tax payments. The tax data below reflect the aggregation of tax information based on the developed case study site described in Section 3. The peak tax paying year occurred when the combined effect contributed more than $7 million in taxes to the stylized county, with nearly $4.5 million, the largest portion, going to the local school tax district. In tax year 9, tax payments began to fall with the sharpest decline after the closure of a generating unit. Over a 10-year period, tax contributions from the plant decreased by 80.3%. Although this study did not investigate the drivers for the changes in tax payments, it is worth noting the decline associated with the plant closure of the shuttered generating unit. It closed in tax year 14.

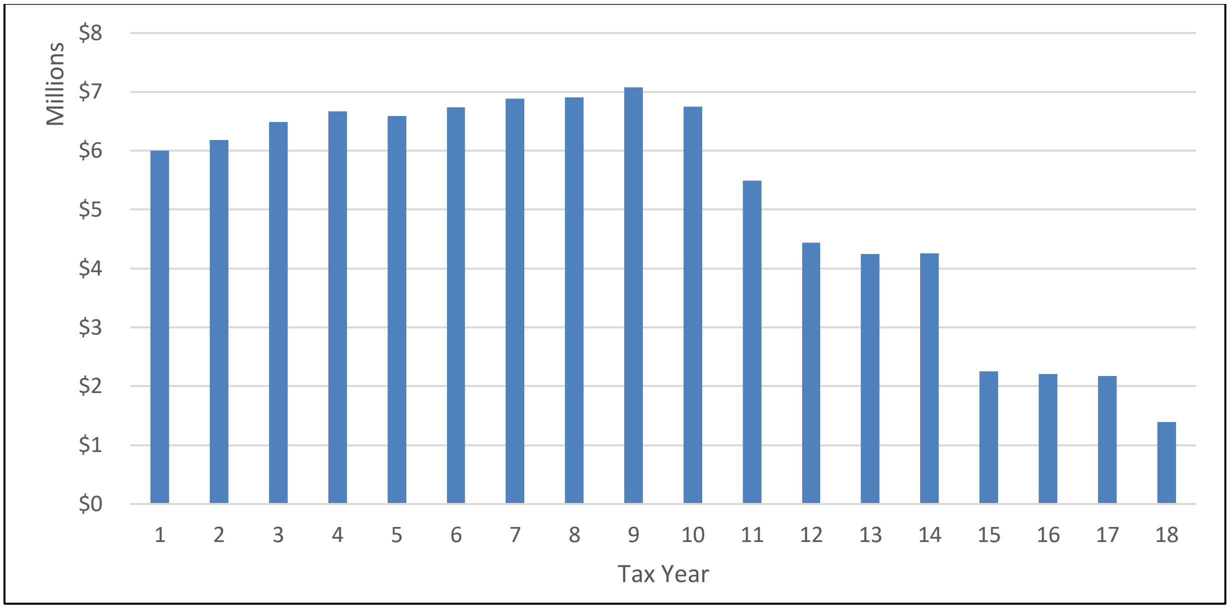

Figure 5-5. Economic impact – tax revenues from case study site.

Table 5-4. Representative CPP site county tax data (1 of 2).

Year "9" Plant Property Tax Details		
District	Tax Rate	Extension
School	3.638	$4,354,000
Case Study County	1.405	$1,681,000
MISC.	0.445	$532,000
Township	0.162	$194,000
Library	0.150	$180,000
Fire	0.085	$102,000
County Extension Service	0.027	$32,000
Multi-Township Asmt	0.007	$8,600
TOTAL	5.919	$7,082,000

Table 5-5. Representative CPP site county tax data (2 of 2).

Year "18" Plant Property Tax Details		
District	Tax Rate	Extension
School	4.376	$820,000
Case Study County	1.738	$326,000
MISC.	0.432	$81,000
Road District	0.372	$70,000
Library	0.184	$35,000
Fire	0.163	$31,000
Township	0.126	$24,000
County Extension Service	0.031	$5,700
Multi-Township Asmt	0.013	$2,500
TOTAL	7.435	$1,394,000

IMPLAN provides a report that estimates federal, state, and local taxes. It should be noted that actual taxes are likely different from what IMPLAN estimates provide. Individual taxes at a county level are complicated by depreciation and special exemptions. Further research would need to be done to explain all the reasons why the IMPLAN tax impacts are different from county tax records. For this study, the aggregated tax impact report is used with the main goal of showing the percent difference in tax implications between the "pre-closure" scenario and the "all nuclear" scenario.

Based on model inputs, IMPLAN shows a total tax impact increase of $46.5 million by moving from the pre-closure, all coal scenario to an all-nuclear scenario—a 92% increase. More than 72% of the increase is a result of taxes paid by the plant, and the remaining 28% is divided between suppliers and community spending. The net change to county and state taxes was $13.6 million and $20.5 million respectively. County level taxes increased by 59% while state taxes increased by 64%. In the model, federal taxes for the pre-closure scenario began with a negative $4.6 million. IMPLAN explains that negative taxes are the result of rebates or subsidies from government that can include various types of social assistance programs, that more than offset actual tax payments.

Table 5-6. Economic impact – tax revenue.

Economic Impact Results ($ Millions)				
	Tax Impacts			
Impact Scenario	County	State	Federal	Total Tax
Pre-Closure	$23.2	$32.1	-$4.6	$50.7
1 – Direct	$20.4	$27.8	-$6.1	$42.0
2 – Indirect	$2.3	$3.5	$0.9	$6.8
3 – Induced	$0.5	$0.8	$0.6	$1.8
All Nuclear	$36.8	$52.6	$7.7	$97.2
1 – Direct	$29.7	$42.1	$3.8	$75.6
2 – Indirect	$5.2	$7.7	$1.8	$14.8
3 – Induced	$1.8	$2.8	$2.0	$6.7
Net Change Coal to NuScale	$13.6	$20.5	$12.3	$46.5
1 – Direct	$9.4	$14.3	$9.9	$33.6
2 – Indirect	$2.9	$4.2	$0.9	$8.0
3 – Induced	$1.3	$2.1	$1.5	$4.8

Note: All results are rounded, as a result the sum of direct, indirect, and induced impacts may not equal the grand total.

5.3.2 Environmental Impacts

IMPLAN uses underlying data provided by EPA's Environmentally Extended Input-Output model (EEIO). Once a given dollar amount of industry output is introduced, the impacts are applied to industry specific environmental factors. Air-related environmental impacts are measured in kilograms, land-related impacts are measured in square meters, and water-related impacts are measured in cubic meters. Environmental impacts can be broken down into 589 different "tags" representing specific contributors to the overall impact (IMPLAN, 2022a).

Transitioning from C2N only results in increased environmental impacts once the employment levels of the NPP reach well beyond employment levels of the original CPP. That is, if employment levels at the NPP remain the same or become less than those at the CPP, then there is no change in environmental indicators. Comparing the pre-closure scenario (150 employees at the CPP) to the highest expected employment levels of the NPP (360 employees at the NPP), greenhouse gas emissions decrease by 99% when looking at the direct impacts and are reduced by 86% when looking at total impacts. In the direct category of impact, greenhouse gases were reduced by nearly 2.6 billion kilograms per year. Once indirect and induced impacts are included, total greenhouse gas impacts fell by 2.4 billion kilograms. These reductions in greenhouse gases are the equivalent to annual emissions created by more than 500,000 gasoline-powered passenger vehicles.

The environmental impact increase observed in other categories in the net change from a C2N transition is tied to additional economic activity that comes from a higher number of workers (150 at the CPP vs. 360 at the NPP) and not from plant operations. If equal employment counts were used for CPP and NPP operations (see Table 5-7 for 150 CPP jobs compared to 150 NPP jobs), IMPLAN's estimated total environmental impact decreases for nuclear plants across all categories except pesticide use in the induced (household spending) portion of the impact. The modeled increase in pesticide use could be explained by higher wages at the nuclear plant and increased disposable income being diverted to typical household spending like pest control services.

As employment opportunities expand following the C2N transition, population would increase as well. Some of the impacts estimated by the I-O model are the result of that population increase and are not directly associated with power production. These effects can be seen in Table 5-7 as the difference between the direct impacts (at both the CPP and NPP) with total impacts (power plant impacts plus impacts in the community). In this analysis, the IMPLAN model does not account for coal or nuclear environmental impacts of front-end feedstocks which are produced outside the study area. For example, economic and environmental impacts in mining coal or uranium elsewhere in the country are not reflected here.

Other environmental impacts are available in Table 5-7. It shows three different levels of employment at nuclear facilities to facilitate understanding of environmental impacts of additional workers. A jobs level of 150 is a direct comparison to the number of workers employed pre-closure. The next two alternatives, jobs of 270 and 360, reflect employment at the same nuclear facility and show how environmental indicators change with increasing levels of employment. The impact of C2N transition is observed in the comparison of 150 pre-closure jobs to 150 nuclear jobs.

Table 5-7. Environmental impacts.

Impact Type	Scenario (Jobs)	Kg/Year	Kg/Year	Sq Meters	Kg/Year	Kg/Year	Kg/Year	Kg/Year	Cubic Meters
		Criteria Pollutants	Greenhouse Gases	Land Use	Mineral Use	Nitrogen and Phosphorus Release to Water	Pesticide Emissions	Toxic Chemical Releases	Water Use
Direct	Pre-Closure (150)	5,406,176	2,595,982,880	1,833,454	0	36,656	0	28,790	297,446,454
	Nuclear (150)	4,006,213	7,977,364	1,358,670	0	27,167	0	21,335	220,420,840
	Nuclear (270)	7,211.183	14,359,256	2,445,606	0	48,894	0	38,402	396,757,512
	Nuclear (360)	9,614,911	19,145,674	3,260,808	0	65,192	0	51,203	529,010,016
Total	Pre-Closure (150)	6,222,468	2,744,173,698	3,211,800	774,813	135,989	5	32,379	334,603,463
	Nuclear (150)	4,776,462	157,455,878	2,029,567	677,238	129,434	7	25,005	258,428,602
	Nuclear 270	8,597,632	285,220,581	3,653,221	1,219,028	232,981	13	45,009	465,171,484
	Nuclear (360)	11,463,509	380,294,108	4,870,961	1,625,370	310,641	17	60,012	620,228,645

A limitation of the IMPLAN-based environmental impact analysis is that it does not capture two significant impacts associated with a C2N transition. First, legacy ash ponds and other environmental impacts at the coal facility are not reflected in these data because ash ponds are not in the available data set of analysis and are thus beyond the scope of the current analysis. Although to some extent, the impacts on particulate matter in the air are reflected in the GHG data, direct effects of cleaning up legacy ash ponds is not reflected here. A detailed study on this would be warranted if evaluating a site for an actual C2N transition. The IMPLAN data do account for emissions impacts in the supply chain, but the second limitation is that this study does not reflect long-term waste storage implications of low-level or high-level nuclear waste.

5.3.3 Workforce Transition

This section examines the workforce transition potential for displaced coal workers using industry staffing patterns by comparing the general knowledge, skills, education, and work experience (later referred to as core competencies) of the coal and nuclear workforce. Exploring the potential for a C2N workforce transition informs on workforce impacts in the coal community. Unlike the economic impact analysis, this analysis approaches this transition by identifying specific impacts to each occupation class. This enables interested stakeholders to evaluate investments in retraining and transition assistance. An important dimension not reflected in this analysis is that of labor unions. Recognizing that unions make up a large share of the nuclear workforce, addressing how union jobs are impacted is not addressed.

This section presents the workforce transition results. The data and methodology supporting this analysis are discussed in Appendix D. The results give insight on the potential for coal workers to transition to a position in a new nuclear facility. After the results, a brief discussion examines the impacts of construction time on a successful workforce transition. Given the large share of union labor at nuclear facilities, there may be an opportunity to leverage union training programs in a C2N transition, but that is beyond the scope of this analysis.

5.3.3.1 Workforce Transition Analysis Results

This section discusses the results of the workforce transition analysis using two main data sources. First, a discussion gives an overview of the results of the analysis using the Bureau of Labor Statistics (BLS) employment matrices (U.S. BLS, 2022). Next, the discussion turns to the results of the analysis using the IMPLAN Occupation Data (Clouse, 2022; IMPLAN, 2022b). Then, a brief comparison of the results of the two data sources follows.

The data from BLS and IMPLAN are applied to a scenario based on a decrease of 150 jobs in the fossil fuel sector, of which coal jobs are a part, and an increase of 360 jobs in the nuclear sector, following the scenarios evaluated in Section 5.3.1. Based on the staffing pattern from the BLS, Table 5-8 presents the impact on specific occupations in both industries. The top portion of the table displays the ten fossil fuel occupations that incur the largest losses, and the bottom portion of the table displays the ten nuclear occupations that gain the most jobs. The table also includes a column displaying the net changes in jobs (i.e., the sum of lost fossil fuel jobs and gained nuclear jobs) for those occupations. The column for fossil jobs is ordered smallest to largest, to show the occupations impacted the greatest by retirement in the case study CPP facility. See Section D-1 in Appendix D for the full list of occupational impacts.

Table 5-8. BLS staffing patterns (abbreviated).

Largest Losses in Fossil Fuel Jobs (Top 10)				
Occupation Code	Occupation Title	Fossil Jobs	Nuclear Jobs	Net Change
51-8013	Power plant operators	-25.35	2.16	-23.19
49-9051	Electrical power-line installers and repairers	-10.2	2.52	-7.68
49-2095	Electrical and electronics repairers, powerhouse, substation, and relay	-7.8	10.44	2.64
17-2071	Electrical engineers	-6.75	9.72	2.97
51-1011	First-line supervisors of production and operating workers	-6.3	17.28	10.98
43-4051	Customer service representatives	-5.25	0	-5.25
49-9041	Industrial machinery mechanics	-4.65	9.36	4.71
49-1011	First-line supervisors of mechanics, installers, and repairers	-4.5	8.64	4.14
49-9012	Control and valve installers and repairers, except mechanical door	-3.45	0.72	-2.73
47-2111	Electricians	-3	5.76	2.76
Total		-77.25	66.6	-10.65
Largest Gains in Nuclear Jobs (Top 10)				
Occupation Code	Occupation Title	Fossil Jobs	Nuclear Jobs	Net Change
17-2161	Nuclear engineers	-0.45	44.64	44.19
51-8011	Nuclear power reactor operators	-0.45	37.44	36.99
33-9032	Security guards	-0.75	37.44	36.69
19-4051	Nuclear technicians	-0.9	24.48	23.58
51-1011	First-line supervisors of production and operating workers	-6.3	17.28	10.98
49-2095	Electrical and electronics repairers, powerhouse, substation, and relay	-7.8	10.44	2.64
13-1151	Training and development specialists	-0.75	9.72	8.97
17-2071	Electrical engineers	-6.75	9.72	2.97
11-9041	Architectural and engineering managers	-1.2	9.36	8.16
49-9041	Industrial machinery mechanics	-4.65	9.36	4.71
Total		-30	209.88	179.88

Note: See Appendix D for the unabbreviated list of occupations.

The results show that power plant operators are impacted the greatest by the closure of the last unit of the case study facility with a loss of about 25 jobs. Looking at the occupations that incur the largest fossil fuel job losses, the 10 occupations impacted the most lose roughly 77 jobs in total. Out of the 360 nuclear jobs added by replacing the coal facility with a nuclear facility, nearly 210 of those jobs are gained in only 10 occupations. The important point to consider with an analysis like this is that these impacts are aimed at direct impacts only—that is, jobs at the CPP and the NPP, respectively.

Changes across occupations show how workers may be able to directly transition between the coal and nuclear workforces while staying in the same occupation although the day-to-day activities and knowledge required may differ.

Table 5-8 shows, by occupation, there is not a perfect match from C2N workforces. Some occupations experience a negative net change while others experience a positive net change. For those occupations that experience a negative net change, exploring the underlying core competencies may highlight how these workers may fill the new or vacant occupational positions created in the nuclear facility and what retraining investment is required. A further extension of this analysis using data on core competencies is further discussed in Appendix D.

Some occupations are employed only in the fossil fuel industry, some only in the nuclear industry, and some occupations are employed in both industries. These occupations total 131 across both industries. Figure 5-6 shows the impacts to all 131 occupations across the two industries. That is, using the BLS approach, a loss in 150 fossil fuel jobs and a gain of 360 nuclear jobs results in a net gain in 196.29 direct jobs.[6]

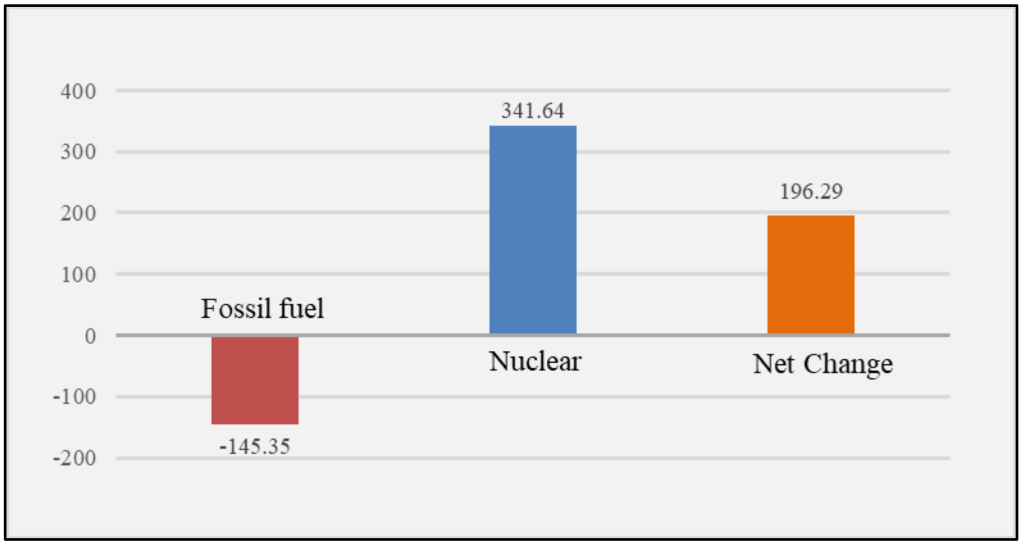

Figure 5-6. Scenario results from BLS.

Like the BLS method, IMPLAN Occupation Data results show the direct impact of a loss in 150 fossil fuel jobs and a gain in 360 nuclear jobs on the occupations employed in both industries.

Table 5-9 displays the IMPLAN Occupational Data results and shows which occupations added employment in the region and which lost employment. These are direct impact jobs, meaning these are changes at the coal and nuclear facilities. In addition to direct impacts, IMPLAN also generates results for indirect, induced, and total impacts. The table shows the results of the coal-nuclear (150 jobs vs. 360 jobs) scenario evaluated using IMPLAN data. Comparing the two methods of calculating direct occupational impacts, 196.29 (Figure 5-6) vs. 198.78 (Table 5-9), reveals both methods approach the same answer.

6 This represents the direct impact only. The BLS data reports the percent of industry values for each occupation at 1 decimal place so rounding error leads to summing differences.

Table 5-9. Scenario results from IMPLAN.

	Employment	Wages and Salaries	Compensation
Direct	198.78	$43,875,506.15	$60,221,532.38
Indirect	198.43	$17,411,258.49	$22,089,968.71
Induced	399.39	$24,438,178.53	$29,143,558.78
Total	796.62	$85,724,943.22	$111,455,059.80

Looking deeper at the results presented here, Table 5-10 shows which occupations added employment in the region and which lost employment. These are direct impact jobs, meaning these are changes at the CPP and NPP facilities.

In a C2N workforce transition, investment and transition plans for the workforce must consider the impact of the required revenue gap, discussed in Section 4. In other words, plans must consider how to (a) support workers through the time between employment at the coal facility to employment at the new nuclear facility and (b) use the time between employment for worker retraining or educational investment. Note that this only applies to direct employees at an operational plant and does not apply to temporary employment created by construction or demolition efforts. A smooth transition from a coal position to a nuclear position may depend on many factors such as:

- Can the worker directly transition into the same role at the new nuclear facility? If not, is there another role can they fill? If the required revenue gap is greater than zero, what will they do in the meantime?
- What kind of training/education is required for the transition? How long is that expected to take?
- How will the worker and their family be supported financially through this transition?

This section briefly discusses the potential challenge of the required revenue gap in C2N scenarios on workforce transitions. This discussion is presented to highlight the importance of considering the impact of the required revenue gap on transition success and smoothness. Furthermore, this section provides examples of the kind of questions to consider for each individual. Although there will likely be no one-size-fits-all solution to these workforce transition challenges, this type of thought process will help ensure a just transition.

Table 5-10. Top ten list of occupation gains and losses.

Employment Gains by Occupation (top 10)	
Occupation Title	Impacts to Employment
Nuclear Engineers	46.42
Security Guards and Gambling Surveillance Officers	36.86
Nuclear Technicians	25.92
Power Plant Operators, Distributors, and Dispatchers	11.49
First-line Supervisors of Production and Operating Workers	9.77
Training and Development Specialists	8.32
Architectural and Engineering Managers	7.13
Miscellaneous First-line Supervisors, Protective Service Workers	5.44
Industrial Engineers, including Health and Safety	5.35
Electrical and Electronics Engineers	4.5
Miscellaneous Business Operations Specialists	4.46
Employment Losses by Occupation (top 10)	
Occupation Title	Impact to Employment
Line Installers and Repairers	-8.75
Customer Service Representatives	-5.58
Control and Valve Installers and Repairers	-2.32
Construction Equipment Operators	-1.87
Miscellaneous Plant and System Operators	-1.52
Welding, Soldering, and Brazing Workers	-0.88
General and Operations Managers	-0.87
Meter Readers, Utilities	-0.86
Stationary Engineers and Boiler Operators	-0.86
Pipelayers, Plumbers, Pipefitters, and Steamfitters	-0.75

Figure 5-7 presents the percent of employees by education level achieved in the fossil fuel industry and the nuclear industry. In 2020, the most common educational achievement in the fossil fuel workforce was a high school diploma. The second and third most common educational achievements in the fossil workforce were post-secondary certificates and bachelor’s degrees, respectively. The three most common educational achievements in the nuclear workforce in 2020 were (1) bachelor’s degree, (2) high school diploma, and (3) post-secondary certificate. Although more than 80% of both workforces have educational levels between a high school diploma and bachelor’s degree, the data in the figure show that, on average, the nuclear workforce is more educated than the coal workforce. More analysis on the core competencies of these two workforces is presented in Appendix D.

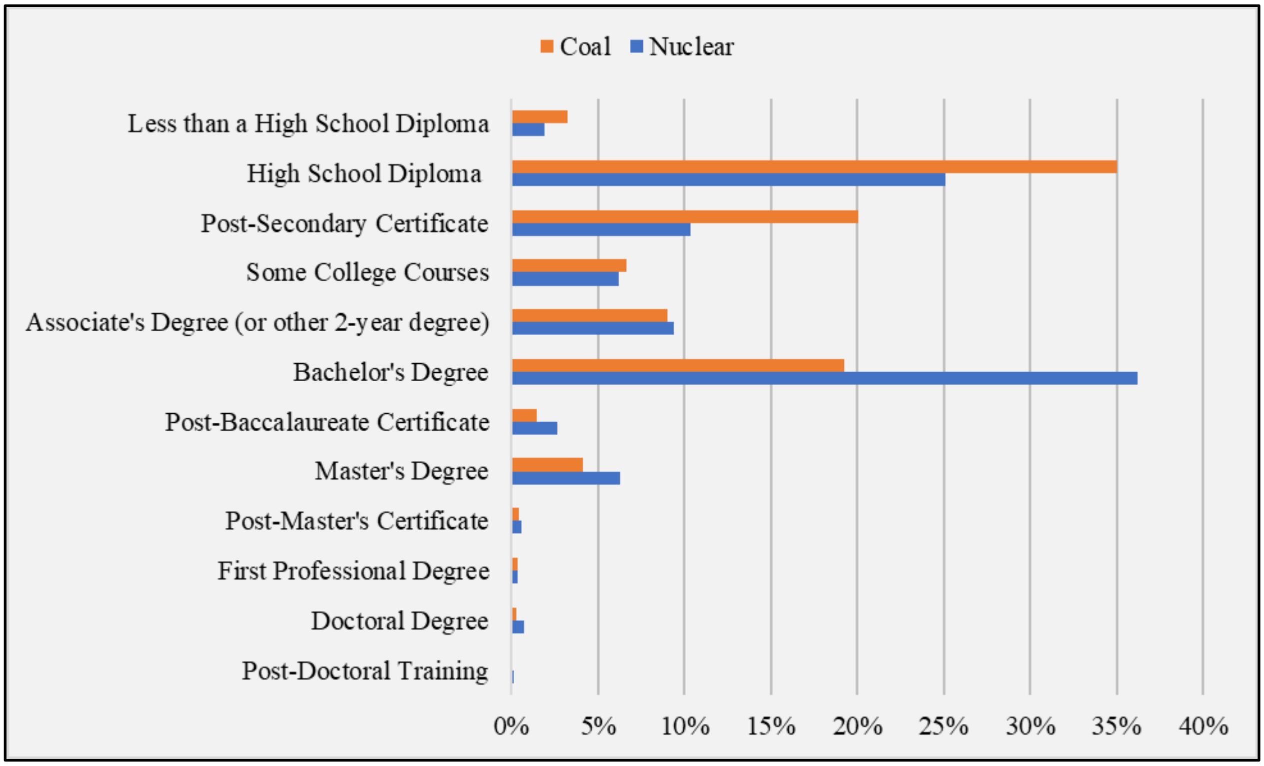

Figure 5-7. Educational attainment by workforce.

5.4 Social and Environmental Justice

The economic impacts in the community have social and EJ impacts. Noted above is a scenario where the case study composite CPP is replaced with all nuclear of equivalent size results in about 653 new jobs to the region, distributed across the NPP, the supply chain, and the local community. Table 5-1 shows data on the poverty rate in the representative region, which is low relative to the comparison. But the table also shows that the relative wealth of households in the region, approximated by median income and housing values, are low relative to the comparison. Table 5-10 shows the occupations where a net gain would likely take place in the region. Occupations with the largest gains include nuclear engineers, security guards, and nuclear technicians. Industry average wages for these occupations are $110,000 for engineers, $87,000 for security forces, and $90,000 for technicians (ScottMadden, 2021). This context, coupled with the economic impacts of increased output, wages across the community, and value added in the supply chain, suggests positive economic impacts to the region. The median income of $56,000 and median housing value of $119,000 will experience upward pressure, thereby increasing the economic well-being of members of the community.

An additional social justice impact will likely affect taxes. At the height of CPP operations in the case study composite site in year 9, compared to operations in year 18, county tax revenue fell by nearly 80%

(see

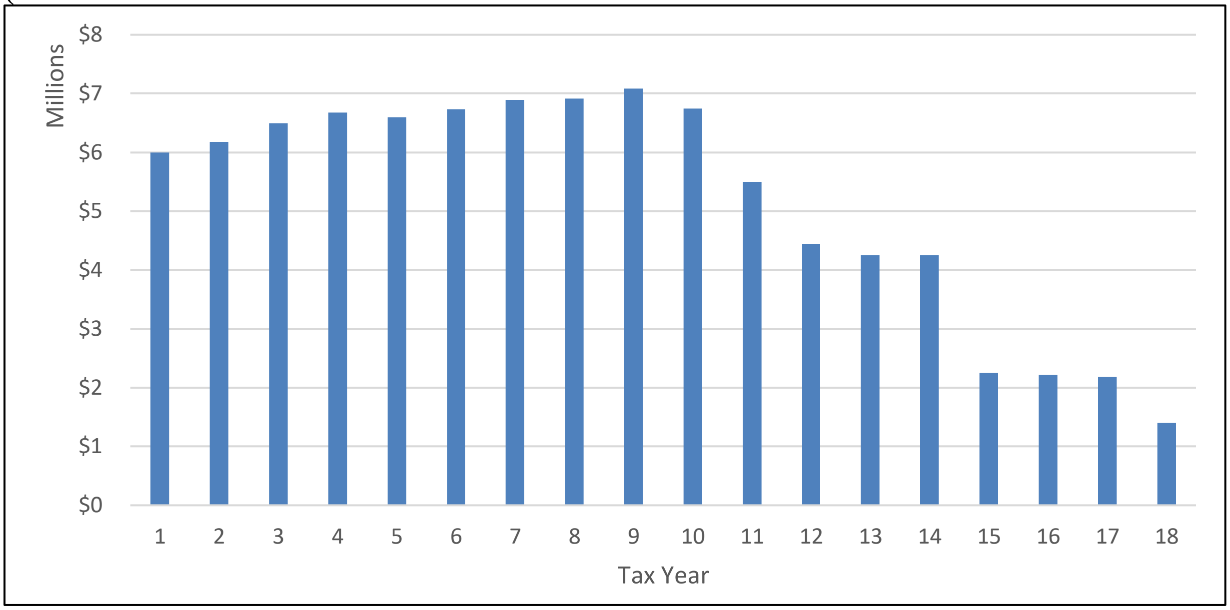

Figure 5-5). To place this in context, consider the changes in tax revenue received across entities in the county from the case study composite site. Table 5-4 and Table 5-5 show how the local school district, the county itself, and other entities were impacted. Tax revenue for schools fell from around $4.5 million in year 9 to $820 thousand in year 18. Similar reductions can be seen in the categories of the tables. Further, from Table 5-6, anticipated changes in tax revenue show that tax revenue across the region would increase from $51 million to $97 million, an increase of 92%. A change in tax revenue will have an impact on many sectors of the community beyond impacts evaluated in this study. For example, Table 5-1 shows that, whereas the region compares favorably to the comparison in terms of high school graduates, it fairs much lower in terms of the prevalence of people with college degrees. A financial boost to regional schools would likely impact this educational statistic. The analysis on workforce transition in Section 5.3.3, coupled with the impact of an increase in tax revenue in the regional economy, suggest that a financial boost to education would provide helpful support in facilitating labor force readiness.

With respect to EJ, the top indicators in Table 5-2 show that the composite region experiences a good deal of air pollution relative to the state ranking. Several of the indicators measure parameters on air quality. From the environmental impact analysis in Section 5.3.2, Table 5-7 shows how a change from a CPP to an NPP impacts environmental attributes. Particularly, note the impact on greenhouse gases. The direct impact on GHG shows a reduction of about 99%, and the total impact shows a reduction of about 86%. Discussed above, the direct impact reduction is because the NPP produces no greenhouse gas emissions, but the CPP does. The 86% reduction (2.7 billion kg/year to 380 million kg/year of GHG) is because of increased economic activity that generates GHG, hence 86% instead of 99%. Notwithstanding, an 86% reduction in GHG, although not measured in this study, suggests favorable impacts on EJ indicators, especially on those indicators measuring air quality.

6. SUMMARY AND CONCLUSIONS

The C2N transition will create benefits and challenges in a variety of domains, and such a variety requires the need for multiple ways of evaluating the transition. Three primary questions about the transition guided the research in this study: How many CPP sites in the United States are good candidates? What are the benefits and challenges of transition? How will it affect local communities? To answer these questions, the SA&I research team carried out a three-pronged approach to the study: a siting analysis, a TEA, and an economic and environmental impact analysis. The short answers to these questions are that advanced reactors smaller than a gigawatt scale are amenable to siting at 80% of the CPP sites that passed the first round of screening; repurposing CPP infrastructure may lead to savings on overnight capital costs that range from 15% to 35%; and depending on the nuclear design under consideration, job growth could increase by over 650 new, permanent jobs leading to nearly $270 million in new economic activity, and GHG emissions in a community could fall by as much as 86%.

Context for these results is important. The economic and environmental impact results are based on a case study evaluation of a composite, four-county region surrounding a representative CPP site in the Midwest. The case study is hypothetical because it is based on a composite of sites described in Section 3, and to the knowledge of the study team, none of the representatives in the composite are under consideration for a C2N transition. Further, the team conducted the study without any utility, investor, cooperative, or corporation partnering on the analysis. Findings are based on the analysis of publicly available data and documented assumptions. With respect to the TEA, the nuclear designs considered are based on published design concepts. Consideration of capacity factor adjustments (nuclear plants operate at higher capacity factors than coal plants) did not bear on the choice of nuclear designs, but discrete sizes available in the literature did have a bearing. Consequently, evaluated designs could produce more megawatt hours per year than the coal plants they are modeled to replace. Finally, the study team uses the term advanced reactors in reference to SMRs and advanced, non-light-water reactors because the siting requirements are similar. The term LWRs refers to gigawatt scale reactors because their siting requirements are different from for smaller reactors.

6.1 Siting Analysis Summary

The siting analysis was instrumental to understand the CPPs locations in the United States and to evaluate which of these could be repurposed for siting an NPP. This evaluation leveraged the OR-SAGE tool, which is a GIS-modeling platform fitted with the NRC's criteria for siting nuclear reactors. The siting evaluation takes input data from the U.S. DOE's EIA, as of August 2021, that records the status of CPPs across the country. At the time the study got underway, in August of 2021, the EIA data listed 814 retired CPP generators at 349 sites. After an initial screening of the sites (e.g., age of retirement and ownership type), the set of candidates retired sites reduced to 157. The EIA data showed that there were 581 operating generators at 273 sites. After screening these sites (e.g., those not likely to engage in a C2N transition), the set of candidate operating sites reduced to 237.

With the candidate set of retired and operating sites identified, a more involved evaluation took place where the OR-SAGE tool was applied to filter out sites that did not meet the NRC siting requirements. The results of this evaluation are differentiated on two dimensions: operating vs. retired sites and advanced reactors vs. large LWRs. The results show that of the candidate set of retired sites, 80% (125 sites) are amenable to siting an advanced reactor, and 22% (35 sites) are amenable to siting a large LWR. For the candidate set of operating sites, again, 80% are amenable to siting an advanced reactor (190 sites), and 40% are amenable to siting a large LWR (35 sites). Based on the results of the analysis, for both advanced reactors and large LWRs, population density is clearly the discriminating parameter for backfit feasibility. Using advanced reactors to replace coal capacity, across retired and operating sites, could potentially amount to about 263 GWe of coal capacity.

6.2 Techno-Economic Analysis Summary

The study team engaged in a TEA to investigate the factors driving a decision to pursue a C2N transition from the perspective of a notional investor, which could be a utility or some other interested party. The TEA took place in three parts. The compatibility analysis compared NPP design alternatives with features of CPP, such as steam and heat requirements. In the second step, the project model was used to evaluate cost and timeline implications. Then the dynamic aspect of a transition decision was evaluated using an agent-based model. In the compatibility analysis, the team generated four scenarios whereby a transition could take place. The scenarios varied the amount of infrastructure that could be repurposed based on nuclear-to-coal technology compatibility. For example, scenarios varied from limited repurposing, such as office buildings, up to more involved repurposing of the heat sink and electrical components. Then the team evaluated the intersection of transition scenarios with nuclear technology alternatives (e.g., PWR, SFR, and VHTR). The project modeling component leveraged the Energy Economic Data Base, which is a rich data set containing capital and operating costs for nuclear and coal generators. Based on the compatibility results, the team estimated the extent of cost savings by comparing systems within a CPP to systems within an NPP. Then the team used a newly developed agent-based code to evaluate how projected cost savings interacted with factors such as firm liquidity, the time gap of revenue generation, and electricity market characteristics.

Based on the three components of the TEA portion of the study, the results suggest that for a project where an NPP is sited at a former CPP site, the overnight cost of capital could decrease by as much as 15% to 35% when compared to siting an NPP at a greenfield site. On NPP projects where the total costs of the project are measured in billions of dollars, 15% to 35% represents a substantial, potential cost savings. The results also show a C2N project generates revenue profiles that reduce the gap time of revenue generation when compared to projects sited at greenfield locations.

6.3 Regional Economic and Environmental Impact Summary

To evaluate the impacts to local communities where a C2N transition might take place, the study team employed the methodology of I-O modeling, using the software platform IMPLAN. This approach leverages data gathered by the U.S. Bureau of Economic Analysis and Bureau of Labor Statistics and Environmental Protection Agency. IMPLAN collates data from these sources so that an analyst can evaluate an economic “shock.” In this study, those shocks are the scenarios evaluated, which include closing one of the generators at the CPP, closing both generators at the CPP, and then alternatively implementing nuclear designs as replacements. These are modeled after the TerraPower concept and the NuScale concept because of published data on these concepts. The I-O modeling requires data on staffing requirements, and the study team found these data for the listed nuclear designs. A feature that IMPLAN enables is that of modeling environmental impacts based on economic outcomes. The team leveraged this capability to perform the environmental impact analysis in the study region. Because the analysis was set up to address local impacts, issues such as impacts to the coal mining industry or long-term storage of nuclear waste were not part of the analysis. The coal mine in the case study sources coal feedstock from the Powder River Basin (outside the region of analysis), and similarly, long-term nuclear storage would take place outside the region.

In the scenario where both coal generators shut down at the CPP and 924 MWe of nuclear capacity replaces it, the economic impact results suggest that over 650 new, permanent, long-term jobs would be created in the community. These jobs are distributed across positions at the power plant, the supply chain, and in the community. These are net jobs, so this means that over 650 new positions are created after displaced coal workers are redistributed into new occupations in the economy. New jobs mean new economic activity in the region. The results suggest that economic activity could increase by as much as $275 million, of which $102 million is new labor income (i.e., wages). The economic impact analysis digs into what this workforce transition might look like, based on educational attainment versus requirements at the new NPP. The environmental impact portion of the analysis found that in the case where employment is held constant, all measured environmental indicators could decrease. In the scenario of 924 MWe of nuclear capacity, GHG emissions in the region could fall by as much as 86%. Because this scenario generates the growth in population and economic activity, some of the environmental indicators increase, such as land and water use. Two issues related to environmental impacts are those of legacy ash ponds at CPPs and long-term, high-level, and low-level nuclear waste. The environmental data available for this study does not reflect these two issues. Consequently, deep analysis on these is beyond the scope of the current study. However, they do represent issues to investigate further in extensions to the environmental impact analysis initiated in this study.

6.4 Conclusions

Based on the results of the study at least four key, high-level conclusions can be drawn.

1. Economic potential exists for owners of CPPs and communities where such plants are located.

The study results suggest tangible, economic value in C2N transition for entities that own CPPs. The cost savings estimated for the overnight capital cost are significant, especially when considering the total value of nuclear projects. The study looked at the transition decision from the perspective of owning CPP assets. One extension of this line of inquiry is to evaluate how purchasing a CPP site for the intent of C2N transition bears on investor economics. Notwithstanding, the results reported here imply cost savings from repurposing coal infrastructure. Given this finding, coupled with the reality that 32% of operating CPP sites have announced retirement dates in the EIA data, economic potential exists for the remaining 68% of CPP sites. This is underscored once again with the study result that C2N projects appear to perform better economically than stand-alone, greenfield nuclear projects.

The second takeaway with respect to economic potential is that C2N transitions may be an economic boost for disadvantaged communities. Noted earlier, the economic impacts in the case study show noticeable economic opportunity for communities. Through the lens of social and environmental justice—review of the case study site showed economic disadvantages relative to the state and national comparison—job growth and increased economic activity suggest an improved quality of life in the region. This implication is balanced on the environmental side with the study finding that GHG emissions in the region can decrease by as much as 86%.

2. Opportunities likely exist for first-mover projects.

Building on the last point, the study results suggest economic potential for communities and firms that pursue C2N transitions. An implication of this is that there is a potential advantage for interested coal communities to be first movers in what could be a series of many C2N transitions across the United States. Working with local ownership of the CPPs, early adopter communities can "get ahead" of the transition by working with utility management to update integrated resource plans with a focus on C2N transitions. This may be especially important for a utility ownership that does not currently have nuclear as part of their energy generation portfolio. The utility stands to save on capital costs from repurposed infrastructure, and the community stands to mitigate negative outcomes from shutdown of the local power plant.

3. Extensions of this analysis.

This study looks at a single strategy for decarbonizing the U.S. economy: C2N transition where the modeled transition is CPP sites to NPP sites. A limitation of the study is it does not evaluate impacts to the coal mining sector and other upstream (beyond the region of analysis) supply-chain issues. Related to supply-chain analysis is the assessment of life cycle GHGs. Recognizing that constructing NPPs creates emissions is also not reflected in this study. This leaves open the opportunity in a broader, supply-chain analysis to evaluate this impact. Also, related to supply chain is the unions' role in facilitating workforce transition. The study also does not consider transitioning other energy assets to clean energy, such as retired steel facilities or petro-chemical plants. There may also be an economic opportunity for communities and owners of emitting assets like natural gas turbines or refineries. A logical extension is to expand the analysis to consider broader supply-chain implications. In the study, displaced CPP workers in the region are offset with job gains at the new nuclear plant. Displaced coal miners are not represented in this study. Broader supply-chain analyses should investigate impacts like these. The implications of this study suggest that analysis of these additional transition opportunities is warranted.

The study results touched on the importance of ownership position in the C2N transition. Extending ownership structure to reflect CPP purchase options to facilitate C2N transition should also be addressed. The timing aspect of cost burden and revenue generation will likely factor into purchase options. The agent-based model used in this study could facilitate additional factors that will impact investor economics.

4. How can this study be used to set up site-specific analysis?

Finally, this is a study with general-level findings which are informative for case-specific applications. Below are a few examples of how the findings could be used to set up a more in-depth analysis of C2N transition.

The findings in the TEA portion of the study can be used to compare alternative nuclear designs with plant specific characteristics at a CPP. The following system-by-system analysis is an informative approach for analyzing in robust detail the extent of how CPP infrastructure that can be repurposed at an NPP site. Results of such an approach could then be used to refine the extent of cost savings. The TEA also dealt with many of the project planning and implementation aspects of a transition that should be considered. For example, results are informative with respect to the time gap, and therefore, the revenue gap, between shutting down a CPP and the point where revenue is generated, begins at the NPP.

The economic impact results suggest that many of the job functions at a CPP match up with the job functions at an NPP. Some do not. These results could be used to refine the types of job transition programs that a community or utility may want to consider in implementing a C2N transition. Further, the economic impact study evaluated options for nuclear capacity that in some cases would generate more megawatt hours than the replaced coal capacity. This suggests that case-specific applications could investigate the potential for expanded market opportunity from nuclear capacity.

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Appendix A

Summary Overview of OR-SAGE and Additional Site Considerations

The OR-SAGE tool is designed to use industry-accepted practices in screening sites and then employ the proper array of data sources through the considerable computational capabilities of GIS technology available at ORNL. Detailed discussions of the OR-SAGE development and application are available in several sources (Belles et al., 2013; Belles et al., 2012; Omitaomu et al., 2012). Initially, ORNL staff adapted and extended the 2002 EPRI Siting Guide (Rodwell, 2002) methodology, developed to support early site permit applications, for the purpose of screening potential sites on a national and regional basis. However, because of the tool granularity, it is often focused specifically on user sites of interest. This is possible because the screening process divides the contiguous United States into 100-by-100-m (1-hectare) squares (cells), applying successive suitability criterion to each cell. If a cell meets the user-specified thresholds for the siting parameter values for each criterion, the individual data cell is deemed a candidate area for siting a power plant. In this manner, a collection of data cells that make up a site of a given size can be evaluated. This is known as a database query.

The available guiding concepts were used to develop exclusionary, avoidance, and suitability criteria for screening sites for a variety of power generation types, including NPPs. For a given technology application, it is necessary to develop evaluation parameters that encompass several key screening criteria that essentially provide for a basic site characterization for that application. Available evaluation parameters include population density, slope, seismic activity, proximity to cooling-water sources, proximity to hazard facilities, avoidance of protected lands and floodplains, susceptibility to landslide hazards, and others. Some siting parameters recommend against siting a plant because of an environmental, regulatory, or land-use constraint. Other parameters assist in identifying less favorable areas such as proximity to hazardous operations. All the parameters should be considered flags to inform siting decisions and should not be used to rule in or rule out any site.

The OR-SAGE process is very versatile, and ORNL staff have used the OR-SAGE tool to evaluate site-screening criteria for large and small NPPs, advanced coal plants with carbon sequestration, wet and dry solar power technologies (excluding photovoltaic cells), compressed air energy storage, nuclear fuel cycle component siting, spent nuclear fuel storage siting, and borehole waste storage siting. Principal differences between various NPP technologies are population density calculations, cooling-water demand, and plant footprint.

A-1. Approach and Methodology

Essentially, OR-SAGE is a visual, relational database. The database partitions the contiguous United States, a total of 7.2E8 hectares (~1.8 billion acres), into 100- by 100-m (1 hectare or ~2.5 acre) cells. Therefore, the database is tracking just under 700 million individual land cells.

There is well-defined regulatory guidance for siting an NPP in the United States (NRC, 2014), although some of the existing guidance, developed with large LWRs in mind, may be less applicable to AR designs. Approximately 50 potential siting criteria were identified in various sources related to health and safety, environment, socioeconomic, and engineering factors. The study team developed a subset of parameters for nuclear plant siting that were considered to have the most impact on the viability of any given site and were directly amenable to application of GIS techniques. The selected AR parameters are based on providing a high level of discrimination and readily available data. The default AR parameters are provided here, and a more detailed discussion of each individual parameter layer is provided in Section 3.1.

- Land with a population density greater than 500 people per square mile (including a 4-mile buffer) is excluded. The cap at 4 miles is based on vendors demonstrating small source terms that meet the 10 CFR 100 dose requirements at or near the NPP EAB. Otherwise, the cap per RG 4.7 guidance (NRC, 2014) is set at 20 miles for large LWRs.
- Land with SSE peak ground acceleration (2% chance in a 50-year return period) greater than 0.5 g is excluded. This can be adjusted based on individual technology design specifications.
- Land too close to the identified fault lines is excluded; the length of the fault line determines the required standoff distance per 10 CFR 100, Appendix A.
- Land with a moderate or high landslide hazard susceptibility is excluded. This is a flag based on broad-based risk assessments by the U.S. Geological Survey (USGS) and is not a substitute for in-depth geological evaluations at the site.
- Land with a slope greater than 18% (~10°) is excluded. This is an economic consideration regarding site preparation.
- Wetlands and open water are excluded.
- Land that lies within a 100-year floodplain is excluded.
- Land areas that are more than 20 miles from cooling-water makeup sources with at least 135,000 gallons per minute are excluded for nominal LWR plant applications. This layer is removed for ARs under the assumption that they may use air-cooled ultimate heat-sink applications or the current water rights at the CPP are sufficient for the much smaller cooling-water requirements.
- Protected lands (e.g., national parks, historic areas, and wildlife refuges) are excluded.
- Land located in proximity to hazardous facilities (airports, military facilities, missile generating, or toxic gas generating facilities) is avoided. This is a flag based on a broad consideration for risk and RG 4.7 guidance (NRC, 2014). Meeting this avoidance criterion is not a substitute for an in-depth risk assessment.

Based on preliminary data available from various AR technologies and expert judgment, it is assumed that an AR can easily be accommodated on a 50-acre footprint. Many proposed AR NPP technologies have even smaller proposed footprints. Microreactors may require a footprint of only a few acres. An overview of the OR-SAGE tool application is detailed in Figure A-1.

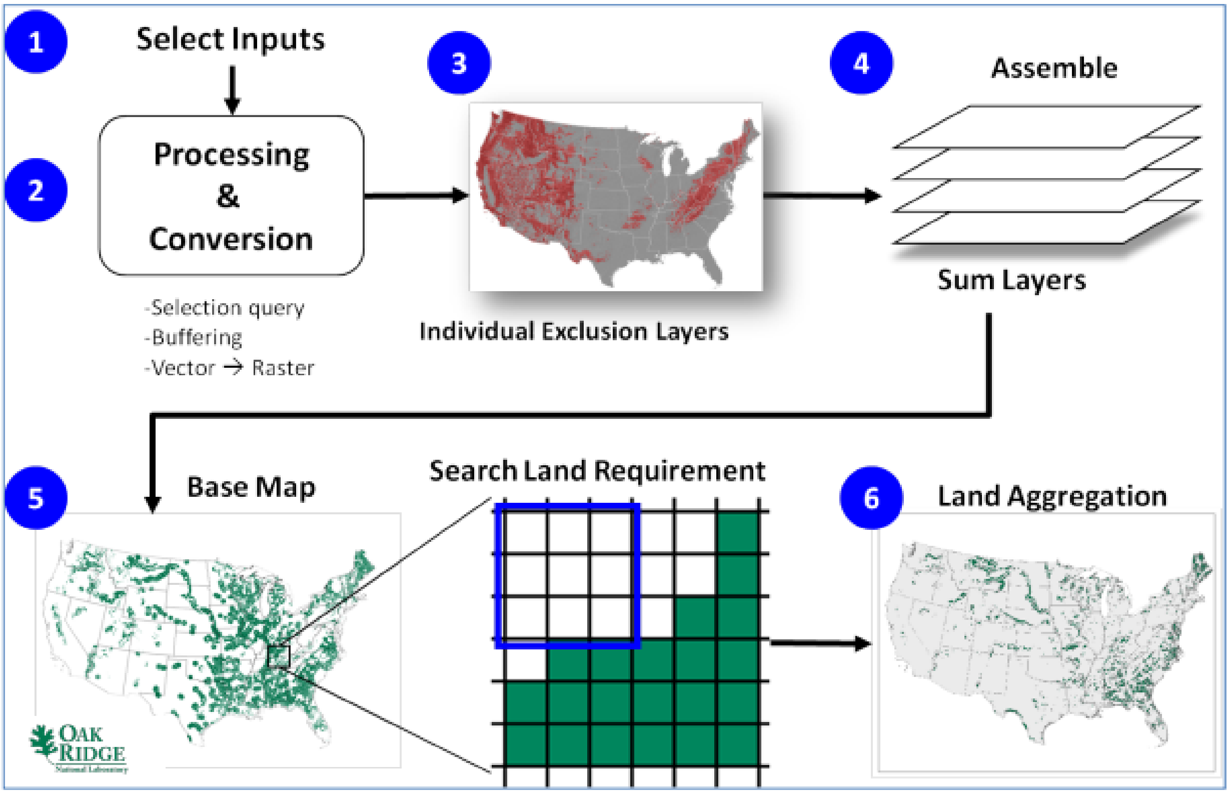

Figure A-1. Overview of the OR-SAGE analysis processes.

The first step shown in Figure A-1 is to select input data sets and then process and convert the input data sets. This involves vector to raster conversion and raster reclassification. The data sets are typically not to the same scale. The conversion process allows all the data sets to be represented to the same scale on a common map. Appropriate layered selection queries are generated associated with each siting criterion, including the application of any buffer zones. The application of a buffer zone can be a complex process such as evaluating population density in the vicinity of each cell, or it can be a simple standoff distance such as is applied to fault lines. Then, the parameter layers are assembled into a single output. Essentially, the applicable layers are summed cell-by-cell. The result is a highlighted U.S. contiguous map of all the areas that do not meet one or more of the threshold criteria for the static query under consideration, typically highlighted in red. During this step, individual layers can be moved in and out of the study to conduct sensitivity analyses. The limits associated with any given parameter layer can also be adjusted to conduct sensitivity analyses.

Since the desired result is to identify cells where a given power source is viable, the highlighted portions of the map are inverted to reveal all the areas that have no siting challenges based on the user-selected siting parameter values. Each individual cell that meets every site parameter threshold is typically highlighted in green on the base map. Given that a single cell represents approximately 2.5 acres of land, a land search must be conducted to identify realistically sized, connected plots of land that can support the typical size of a given power source. Typically, 50-acre plots are determined to be acceptable, and the cells are evaluated in 5x5 arrays with a requirement that 90% of the cells in each array meet the threshold siting parameter values.

More than 50 different data sets are used to build the parameter layers and populate each cell. Data sets that provide national or greater coverage with attributes matching the desired site evaluation parameters are selected. The specific parameters identified for each power source are detailed as part of the results discussion for each power source. Greater than national coverage is preferred to prevent map "edge-effects." Appropriate scaling and resolution of each data set must be considered before using a data set in the study. The data set sources include:

- U.S. Geological Survey (USGS), U.S. National Park Service
- U.S. Forest Service
- U.S. Fish and Wildlife Service
- U.S. Department of Transportation
- Federal Emergency Management Agency
- Federal Aviation Administration
- U.S. Census Bureau
- ORNL LandScan™ data (a high-resolution population distribution database developed by ORNL)
- ORNL 7-day, 10-year low flow calculated data
- Many other commercial sources.

Because OR-SAGE tracks the query parameters for each cell, the output can be used not only to visually identify the data cells clear of all the user-specified parameters, but it can also identify data cells that are tripped by one, two, or three or more parameter values. The result is known as the composite map. A sample national composite map for an AR database query is shown in Figure A-2. A similar map can be prepared for the detailed area around a site of interest, such as a coal plant. The composite feature is a powerful feature, because it allows areas with a limited number of siting challenges to also be identified. Engineering solutions may be available for areas with limited siting challenges.

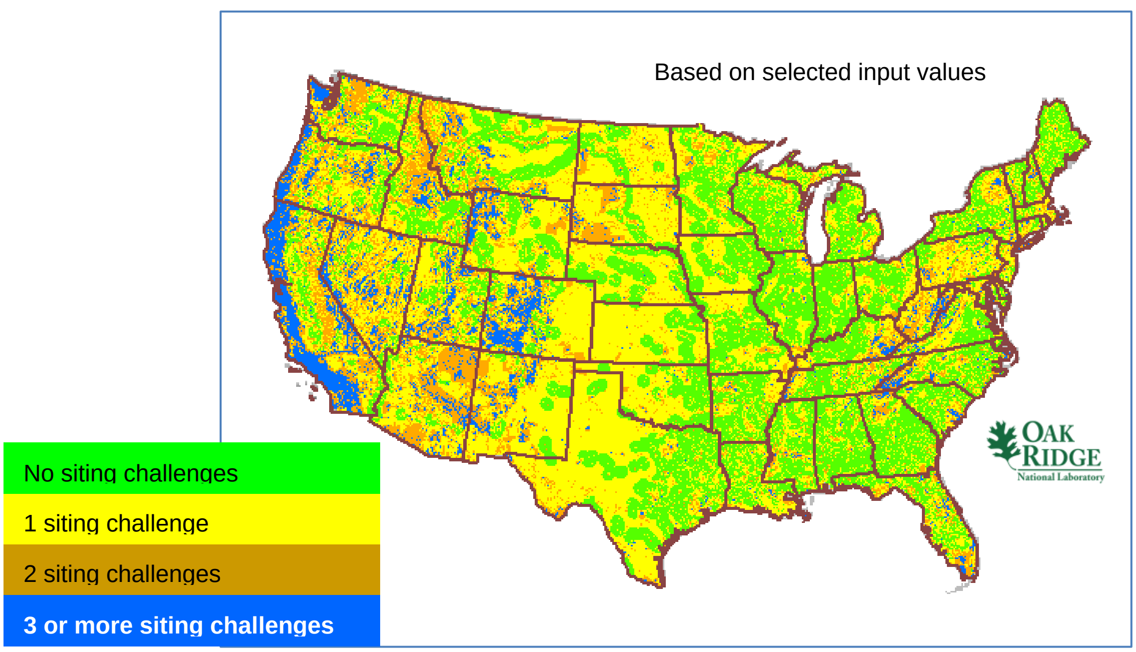

Figure A-2. Nominal, bounding SMR composite map detailing siting challenges.

A-2. Nominal Reactor Siting Criteria

The NRC provides regulations for nuclear plant siting in 10 CFR 100—Reactor Site Criteria and provides well-defined regulatory guidance for siting an NPP in NRC RG 4.7, General Site Suitability Criteria for Nuclear Power Stations (NRC, 2014). The EPRI siting guide (Rodwell, 2002) also provides siting considerations. The selected NPP siting parameters in OR-SAGE are based on providing a high level of discrimination and using readily available data while providing a reasonable set of bounding criteria. A discussion of each nuclear siting parameter is provided below under four broad categories of population density, geologic considerations, water considerations, and other considerations.

A-2.1 Population Density

The regulatory requirements in 10 CFR 100 for population have to do with potential radiation dose at the site boundary (EAB) and in the low-population zone (LPZ) surrounding the site, as well as the distance to a population center of 25,000 residents or more. In addition, 10 CFR 100 states that reactor sites should be located away from very densely populated centers. Areas of low-population density are, generally, preferred.

Specifically, NRC RG 4.7 (NRC, 2014) indicates that:

> …a reactor should preferably be located such that, at the time of initial site approval and within about 5 years thereafter, the population density, including weighted transient population, averaged over any radial distance out to 20 miles (cumulative population at a distance divided by the circular area at that distance), does not exceed 500 persons per square mile.

To meet the guidance, each of the 700 million cells in the OR-SAGE database is queried for the nearby population, taking into consideration the weighted transient population. If a cell population is greater than 500 ppsm, it is immediately excluded. If a cell population is less than 500 people per square mile, the surrounding area is evaluated by calculating the population density in an expanding set of 1-mile rings out to a maximum of 20 miles (in simple terms, a buffer zone). If any ring is determined to have a population density above 500 people per square mile, then the center cell is excluded. If no ring around the central cell exceeds a population density of 500 people per square mile, then the cell remains viable regarding population. This calculation is repeated for every cell in the database. Figure A-3 shows a representative result of a population data set query with a buffer distance considered. The maximum search radii can be set at a value less than 20 miles to create alternate buffer distances.

Smaller reactor technologies can evaluate the impact on siting with population density caps of less than 20 miles. One of the advantages of SMRs and AR technologies is the ability to replace smaller, aging electric plants located closer to population centers. Arguments for allowing ARs to be closer to population centers typically include a reduced core damage frequency, elimination of large-break loss-of-coolant accident sequences, smaller source term, reduced early release fraction, reactor vessels and containment vessels that are located entirely underwater or below grade, and reactor buildings that are located partially or totally below grade.

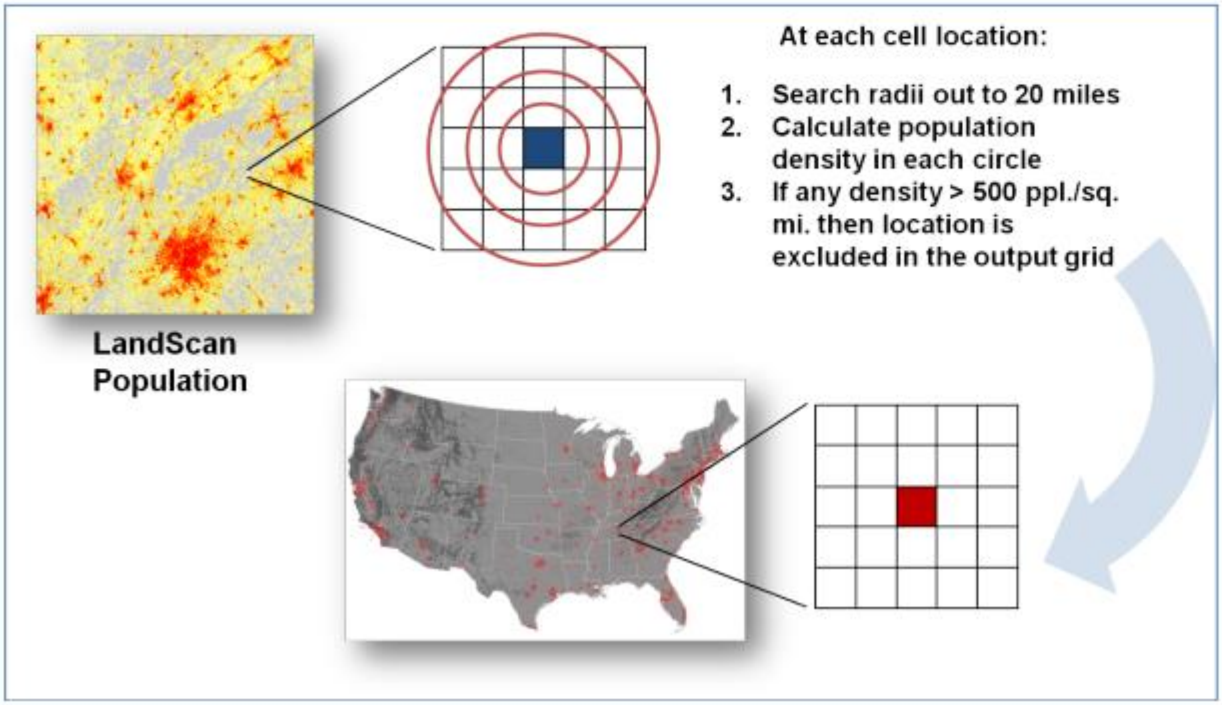

Figure A-3. Sample population calculation for each grid cell.

Past OR-SAGE studies have used a population calculation cap value of 10 miles for SMR evaluations assuming that they could be sited closer to population centers, although this adjustment had no regulatory or guidance basis. However, the NRC has recently begun taking a closer look at advanced reactor siting.

The NRC staff has prepared SECY 20-0045 (NRC, 2020) for consideration by the commission with some alternative siting guidance options for ARs based on the Nuclear Energy and Innovation Modernization Act (NEIMA) definition. The NRC is not proposing any change in the 10 CFR 100 regulations for siting. Instead, they are looking at providing alternative siting guidance. The siting guidance option recommended by the staff in SECY 20-0045 aligns the advanced reactor (NEIMA definition) siting guidance with proposed revisions to the emergency planning requirements and the radiological consequences calculated for design-specific events. The staff has recognized that the LPZ for a given reactor technology and the reactor EAB may be the same based on dose requirements as associated source terms diminish with size. Therefore, the staff has recommended that if the LPZ remains larger than the EAB based on calculated dose from a design basis event or if a design basis event results in an offsite dose exceeding 1 rem over the following 30 days, then siting guidance will exclude areas with greater than 500 people per square mile (ppsm) out to a distance equal to twice the distance at which the 1 rem dose over 30 days is calculated. This will likely be a short distance. The TVA Clinch River Environmental Site Permit Application had emergency planning calculations for 2 miles and for the site boundary. Under the same staff option, if there is no licensing basis event dose exceeding 1 rem beyond the EAB, then the reactor EAB can be situated right up to the edge of a population center of 25,000 people or more and within population centers smaller than 25,000 people. If the reactor technology produces calculated offsite doses that exceed 1 rem, then the standoff distance must be increased. Using the TVA ESP 2-mile EPZ as a basis, the OR-SAGE population density calculation is conservatively capped at 4 miles (twice the emergency planning distance) to reflect the opportunity to site ARs much closer to population centers. The population density calculation for very small reactors could potentially be capped at even smaller values in accordance with the SECY 20-0045 recommendations and the discussion above.

Even with provisions for AR siting closer to population centers, many of the coal plants failed the revised advanced reactor population evaluation. Population limited coal plants, using AR calculation caps at 4 miles, were eliminated from further consideration for backfit. This is because of the direct link of the population density parameter to the 10 CFR 100 reactor siting requirements.

A-2.2 Geologic Considerations

There are several geologic considerations that must be considered for NPP siting. Parameters that are easily evaluated on a national basis include seismic restrictions, proximity to fault lines, steep slopes, and landslide risk. These parameters are incorporated into the OR-SAGE tool.

The SSE peak ground acceleration (2% chance in a 50-year return period) greater than a selected threshold parameter value is flagged by OR-SAGE. The 2002 EPRI siting guidance recommended limiting large reactor technologies to less than 0.3 g SSE peak ground acceleration. As AR technologies allow for more seismic mitigation through design, the OR-SAGE threshold parameter for seismic activity has been set slightly higher at 0.5 g SSE peak ground acceleration. Mitigating design features may include smaller footprints, smaller piping systems, passive safety systems, underground installation, and improved seismic isolation. As noted, this value is variable within the database and can be adjusted based on technology.

Land too close to identified fault lines is flagged by the OR-SAGE tool. Table 1 in Appendix A to 10 CFR 100 provides a relationship between fault length and a standoff distance from the reactor site. This table is embedded in the OR-SAGE evaluation of faults. If a cell is too close to a fault of a given length per the table, then the cell is flagged. The fault evaluation in OR-SAGE is fixed and cannot be adjusted.

Steeper slopes are avoided based on the economic cost of preparing the site for construction. The 2002 EPRI siting guidance recommended limiting the slope to 12% for large reactor sites. Since SMRs and AR technologies tend to have smaller footprints compared to current large reactors, this value is relaxed to 18% as the baseline threshold value in OR-SAGE for these technologies recognizing that more extensive site work to prepare a relatively small site may be justifiable. This threshold value is variable within the database and can be adjusted based on technology and site economics.

The USGS provides broad landslide risk based on generic geological data for land regions. OR-SAGE flags cells falling within areas of moderate or high risk. This does not imply that a site is unusable; it is merely a flag to indicate the need for further localized geologic evaluation for landslide risk.

A-2.3 Water Considerations

Current large LWRs rely on cooling water for heat rejection. Therefore, plants that rely on makeup cooling water will need to be in proximity to a water source. Conflicting water considerations for siting include wetlands and open water as well as areas that lie within a designated 100-year flood plain. These parameters are easily evaluated on a national basis and are incorporated into the OR-SAGE tool.

For those reactor technologies that require a water-based ultimate heat sink, the OR-SAGE tool assumes a closed-cycle cooling system with freshwater makeup water requirements. Cooling-water makeup requirements are based on rules of thumb for cooling-water makeup required per megawatt of generation. These rules of thumb are consistent with environmental analyses supporting site evaluations submitted to the NRC. A subset of reactor technologies can be bounded by a threshold makeup need and a siting assessment for a makeup cooling-water need can be evaluated. In this case, the threshold parameter value is selected based on the largest MWe rating of the nominal reactor technology configuration (single plant, multi-module, etc.). Additionally, based on the EPRI siting guidance, it was assumed that cooling-water makeup should be limited to taking no more than 10% of the available stream flow. This limits the siting of reactor plants to the vicinity of streams with sufficient flow volumes. The EPRI guidance further recommends that the cooling source be within 20 miles to provide reasonable proximity to a cooling-water source, allowing for piping and pumps. The OR-SAGE tool has several preset makeup water values for selection as the threshold value of interest. Other methods for providing the plant ultimate heat sink include saltwater, aquifers, grey (sanitized) water, and air-cooling. Alternate cooling-water sources are not directly modeled. This layer is not modeled for AR technologies under the assumption that they can use the atmosphere for their ultimate heat sink or that the current water use at the site is sufficient. So, this OR-SAGE layer does not exclude any coal plant analyses for ARs. However, the backfit of large LWRs at certain coal plant sites was considered in this report. Therefore, the discussion on a cooling-water evaluation layer is valid.

Data cells in the OR-SAGE model that are evaluated to fall within wetlands and open water are flagged and excluded. In general, the tool will identify all areas containing surface water, including engineered-cooling ponds near a site of interest. Follow-up consideration of a site can determine any limitations associated with such features. Likewise, data cells that are evaluated to fall within an identified 100-year floodplain are flagged and excluded.

A-2.4 Other Considerations

Proximity of a data cell to other land uses or risks are also evaluated by the OR-SAGE tool. Areas considered include a large class of land that is considered protected for other public uses and data cells that may be excluded based on their proximity to facilities that could provide a hazard to nearby reactor operation.

Protected lands include national parks, national monuments, national forests, wilderness areas, wildlife refuges, wild and scenic rivers, state parks, county parks, American Indian lands, Bureau of Land Management, hospitals, colleges, schools, and correctional facilities. These lands are excluded based on their public nature or their special use. Exclusions based on the individual data sets are fixed; however, any given protected land data set can be turned off for special consideration. For example, the American Indian lands layer could be turned off if there were interest in siting a facility on American Indian land.

Land in the vicinity of facilities that could pose a hazard to the safe operation of a reactor include commercial airports, chemical facilities such as oil refineries, certain energy facilities such as natural-gas compressor stations, and military bases. The vapor plume from any associated reactor cooling-water tower could also pose a risk to a nearby commercial airport. Commercial airports are identified with a 10-mile buffer in the OR-SAGE database. Chemical and energy facilities are pinpointed with a 5-mile buffer, and military facilities are outlined with a 1-mile buffer. Cells that fall inside the buffer zone for one of these facilities are flagged for further analysis. In the case of airports, this could be a risk assessment to further evaluate the runway orientation and the operations tempo. Military bases may be considering siting a reactor on the facility. In this case, the exclusion layer for military bases can be removed.

A-2.5 Evaluating Specific Sites

The typical application of OR-SAGE is focused on a top-down evaluation of national or regional siting evaluations. However, building on the top-down fundamentals, it is also possible to apply OR-SAGE in a bottom-up fashion by focusing the tool on specific sites. For this type of evaluation, concentric circles are projected around a selected site center point at a 0.5-mile radius (500 acres) and a 1-mile radius (2,000 acres). In this type of evaluation, the individual 100- by 100-m OR-SAGE data cells become more visually apparent. An example of a site-specific evaluation is shown in Figure A-4.

An evaluation of the data cell containing the site center point can be conducted for a quick screen of the site. This was done for this study for the initial list of recently retired plants to manage the scope of plants to review for the selection of a case study site. However, the application of the OR-SAGE tool on a single point does not provide much discrimination among sites nor does it provide a wholistic look at the sites. Therefore, a more in-depth site evaluation was applied to the area around the site center points to evaluate the area within a 0.5- and 1-mile radii (~500 acres and 2,000 acres). Often, a utility will own much of the land within a 0.5-mile radius; consequently, the AR or LWR siting parameters may not provide much discrimination. Therefore, a complimentary look is also applied to a 1.0-mile radius to ensure that siting parameters such as population density and land dedicated to public use are adequately reflected in the total site analysis.

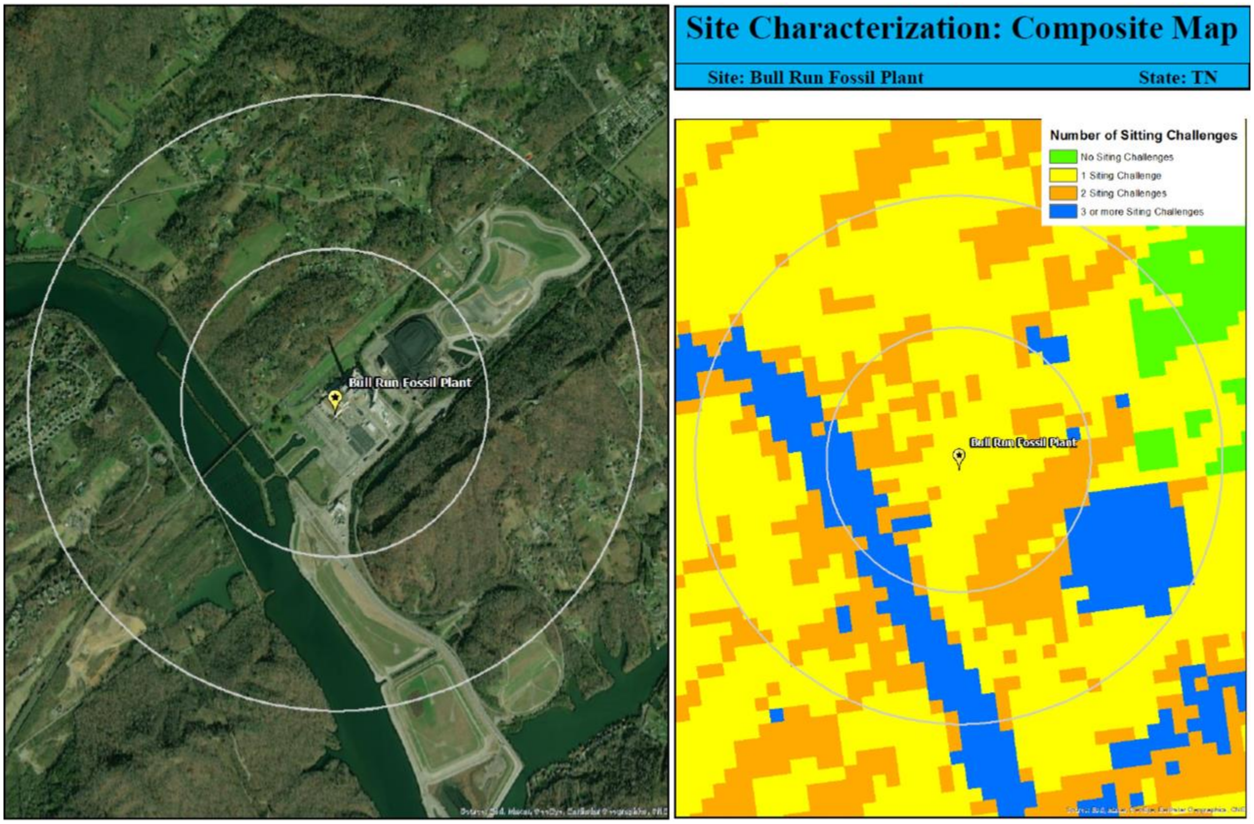

Figure A-4. Example site evaluation.

For the 500-acre evaluation, OR-SAGE provides a visualization of approximately 208 data cells in the vicinity of the site center point listed by the EIA data for each CPP that passed the initial center point screen. The accompanying 2,000-acre evaluation provides a visualization of approximately 834 data cells in the vicinity of the site center point. Visual evaluations, such as that demonstrated in Figure A-4, require construction of the site map and an individual evaluation of each site. This was not a practical approach for the hundreds of recently retired and operational CPP sites to be evaluated in this study.

Therefore, a numerical scoring system was setup for this study as discussed in Section 3.1.3 and Section 3.1.5. The spreadsheet review of each CPP site was based on the number of data cells within the 500-acre or 2,000-acre area that exceeded the AR or LWR parameter thresholds. The data cell count trip threshold was set at 50% of the included data cells for most of the individual siting parameters. A few parameters used a higher or lower data cell count threshold than 50% as discussed in the tables in Section 3.1.3. A binary score for that parameter is then assigned for that site. For example, each of the 208 data cells in a 500-acre area is evaluated individually for each of the siting parameters. If 105 or more cells are tripped for any given parameter set at 50% of the data cells present, then that parameter is scored with a value of 1; otherwise, it is scored with a value of 0. The binary score for each siting parameter is then summed to create a total score for that area at a CPP site. Higher scores imply more difficulty in siting a reactor at the CPP site. The score was then used to discriminate between CPP sites and was the basis for conclusions made about reactor siting in the study. Population density binary values were set at 20 and 0 so that population limited sites could be eliminated from further consideration without regard to the other siting parameters. For large LWRs, site capacity was assigned a binary value of 10 if the current site capacity is less than 800 MWe. This implied that the existing infrastructure may not support a large LWR with a capacity more than 1 GWe. This provided quick discrimination of large capacity CPP sites from smaller-capacity sites.

Appendix B

Derivation of Case Study Electricity Market Model Portfolio of Installed Capacity by Generator Type

B-1. Case Study State Generation Portfolio

The portfolio of installed capacity was taken from the National Renewable Energy Laboratory's Cambium data retrieval tool. Installed capacity for the case study for the year 2020 is shown in Table B-1. This table also shows total annual generation for these unit types for illustrative purposes only; this generation data is not used directly in the ABCE/A-LEAF model and is included only to provide the reader with a sense of the overall characteristics of the system.

Table B-1. Original portfolio data (National Renewable Energy Laboratory [NREL], Cambium data tool).

Generation Technology	Rounded Installed Capacity (MW)
Battery (2 hr)	300
Battery (4 hr)	<10
Biopower	<10
Coal	9,000
Hydro	<50
Wind	7,000
NGCC	9,000
NGCT	11,000
Nuclear	12,000
Oil-Gas-Steam	700
Rooftop PV	100
Utility PV	500

To slightly simplify the system model, technologies representing less than 0.5% of total annual generation were not included in the final model. Where possible, these technologies' capacity was rolled into the most similar extant alternative:

- Rooftop solar PV to utility PV
- Oil-gas-steam to natural-gas combustion turbine
- Biopower to coal.[7]

The hydropower (0.08% of installed capacity) and battery (0.61% of installed capacity) resources were excluded. A-LEAF currently does not model hydroelectric dispatch, and the very small installation base of hydro made it reasonable to exclude. ABCE does not yet model battery storage, and its small capacity renders its expected impact small as well. Battery storage will likely become an important factor in future

[7] Biopower and coal both (generally) use solid fuel-powered boilers to generate electricity. Biopower differs from coal in other respects, especially carbon emissions, but as emissions are not a studied factor and the overall biopower capacity in the case study is extremely small, this should not impact the results.

U.S. electricity grids, but as this study's focus is more near-term, this assumption should not impact the validity of the analysis.

After accounting for these adjustments, the final portfolio for the model is shown in Table 4-10 in the main report body.

B-2. Electricity Demand and Renewables Availability

Hourly data for statewide electricity demand, total wind generation, and total solar generation were taken from the National Renewable Energy Laboratory's Cambium data retrieval tool.

A-LEAF and ABCE use normalized time-series to represent demand and renewables availability over time, so that the time-series can be easily scaled as demand and installed renewables capacities change. The demand time-series is divided by its maximum value in the baseline year to produce a series normalized between 0 and 1. The wind and solar time-series are divided by the total installed capacity of each respective technology to produce series which may have values between 0 and 1 (but which are not necessarily guaranteed to reach either extreme).

B-3. Ancillary Services

A-LEAF co-optimizes ancillary services alongside electricity generation. This modeling process takes as an input the total amount of each ancillary service product procured each hour of the year.

The two ISOs have separate processes for determining ancillary service requirements and procuring reserve products, although the products themselves are similar between the two markets: a rapid-response frequency reserve service, a spinning reserve, and a longer term reserve.

One ISO does not publish ancillary service time-series data. The other ISO does publish such data, but only for broad sub-regions of its service footprint. As a stand-in for statewide ancillary service requirement data, the data for the ISO zone containing the case study state was scaled down by the ratio between the overall zonal peak demand and the total state peak demand for 2020. The accuracy of this data series would be greatly improved by locating more specific data on ancillary services requirements for the ISO regions or by developing more sophisticated scaling procedures for the ISO data. However, as ancillary services are not the primary determinant of economic outcomes in the state, these approximations should not excessively impact the simulation results.

B-4. Locational Transmission Effects

The version of A-LEAF used in this analysis does not represent physically distinct transmission lines or buses. Therefore, in the outputs of this model, there are no local variations in electricity price due to congestion. The agent-decision code also does not yet support transmission representation. The most up-to-date version of A-LEAF available does have transmission representation available, so expanding this work to consider the effects of transmission would be an interesting item of future work.

B-5. Policies and Market Rules

Various U.S. states have enacted zero-emissions credit or PPA programs designed to support nuclear generation within those states. Values range from approximately $10/MWh to over $25/MWh and expire between 2025 and 2031. It is assumed here that such programs extend so that new generation built in a similar state would qualify for such support. The federal wind subsidy is likewise assumed to be extended. The scenarios modeled in this study use a value for production tax credits based around the $10–25/MWh extant values for the case study state program and the federal wind subsidy, as well as the $25/MWh maximum renewable PTC proposed in the Build Back Better Bill. Both ISOs feature separate capacity auction mechanisms. However, as the agent-decision code is currently not able to model capacity auctions, the impact of these mechanisms is currently not considered.

Appendix C

C2N Project Descriptions and Costing Assumptions

This appendix provides additional details on the scheduling and costing assumptions used to characterize the different types of C2N projects considered in Section 4 of this report.

C-1. Project Descriptions and Timelines

For dynamic modeling of C2N projects using ABCE code, assumptions in terms of project planning were derived. This section describes and justifies these assumptions for all C2N types of projects considered in Section 4.2 of the main report.

C-1.1 License Approval: The Key Project Stage-gate

In our representation of each project under consideration, the key stage-gate—a point beyond which the project cannot progress until all prerequisites are met—is the issuance of the NRC license for the nuclear plant under construction. No safety-related construction can be performed on the nuclear plant until the license has been issued. As safety-related work comprises the most costly, complex, and expensive activities on the project schedule, the license approval therefore constitutes an important process bottleneck.

C-1.2 Assumptions Applying to all Project Alternatives

The project activity flow sequences developed below are based on the authors' best judgment. As they are very simplified, they will not reflect the true complexity and multi-layered processes involved in an NPP construction project. However, it is hoped that these process flows are representative enough to be useful for the purposes of this study.

It is assumed for all projects that the coal plant must be demolished. This ensures comparisons are made on an equivalent basis. However, radiological remediation requirements are significantly reduced for some project types, and timelines may be shifted.

For all projects, it is also assumed that the nuclear-only portion of the license application proceeds on schedule and on budget. It is further assumed that this portion of the license application begins several years in advance of the start of the project. Exploring situations where these assumptions do not hold would be an interesting item for future work, given the significant impact of licensing time variability on the assessment of nuclear projects. However, this effect is external to the C2N conversion process, so this factor is omitted from this study.

All projects have a "CPP Decommissioning and Demolition (D&D) (blocking)" and a "CPP D&D (non-blocking)" project activity. The blocking D&D type is the subset of demolition and disposal activities which are strictly required before nuclear construction can be completed (not including coal waste/ash-related activities).

For simplicity, it is assumed that NPP non-safety construction is completed prior to the start of the NPP safety-related construction. In a real project, some of these activities will be parallelized. However, in the absence of more specific schedule data for typical nuclear construction projects on the temporal distribution of these general activity categories, non-safety construction was made a strict prerequisite for safety work. A more generalized expansion of the agents' constrained resource optimization problem with partial activity ordering would be methodologically interesting, but also complex, and is left as an item of potential future work.

C-1.3 Greenfield Nuclear Projects

The simplest type of project alternative considered in this study is the greenfi4-6)eld project. In this project alternative, the utility builds a new nuclear plant on a separate site from the existing CPP. The utility must still shut down and demolish the coal plant. The only linkage between the two is that the nuclear plant operationally replaces the coal plant's lost capacity: the utility waits to shut down the coal plant until the nuclear plant is ready to begin operations. This means that there is no period of lost revenues.

The assumed structure for this type of project is shown in Figure C-1. This structure applies to any of the nuclear reactor concepts—the three reactor types, when built from greenfield rather than brownfield, differ in their construction cost and schedule but not in very general structure.

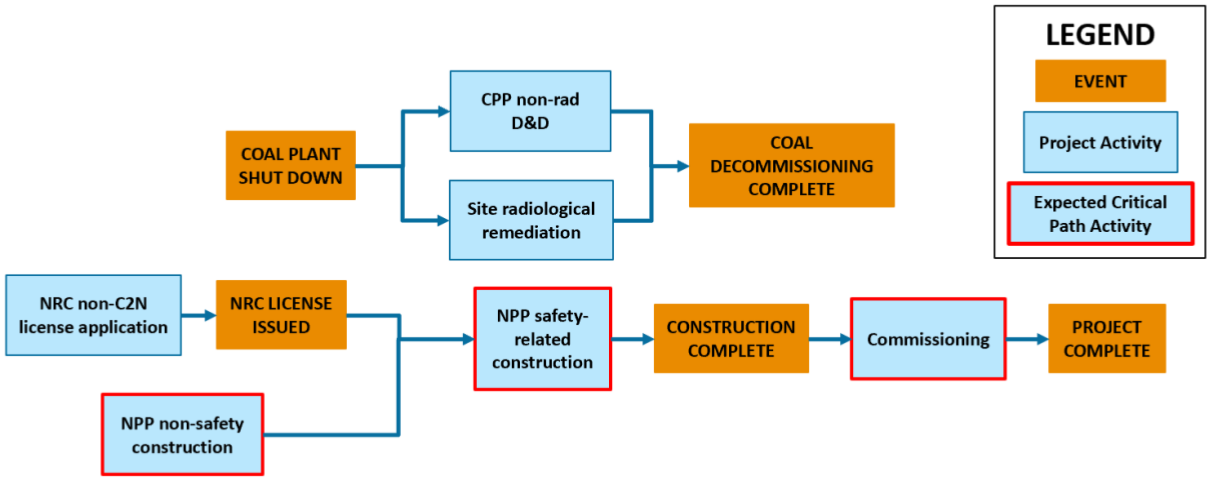

Figure C-1. Project activity flow for a (C2N#0) greenfield project.

There is no direct linkage between the nuclear construction project and the coal demolition project. In real-world terms, the demolition of the coal plant could be put off indefinitely (and in fact, many utilities choose to mothball rather than truly demolish and rehabilitate former coal plant sites). For the purposes of this study, it is assumed that the agent will always wait until after the nuclear plant comes online, and then immediately begin the demolition or remediation work on the coal site.

C-1.4 C2N#1: Reusing the Site, Electrical Equipment, and Office Buildings Only

The simplest C2N project alternative is to reuse only the electrical equipment (transmission connection, switchyard, etc.) and some civil infrastructure such as office space. The project flow graph for this project alternative is shown in Figure C-2.

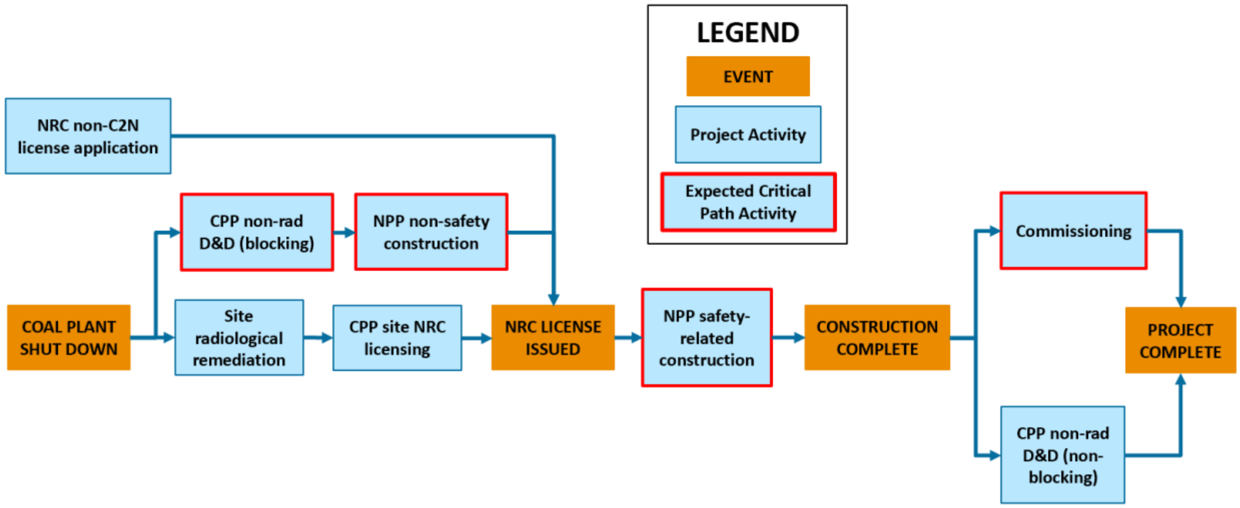

Figure C-2. Project activities flow graph for a C2N #1 project.

By comparison with the greenfield nuclear diagram, it can be observed that some coal D&D and remediation activities have been moved into the pre-licensing stage. Also, the coal plant must be shut down prior to the start of the nuclear project: some of the existing plant will need to be dismantled, and the electrical equipment being reused in-situ will need to be tested and refurbished.

Unlike the greenfield nuclear project, this project is at risk of schedule slippage due to unexpectedly protracted demolition or radiological remediation work.

C-1.5 C2N#2: Direct Coupling to CPP Steam-Cycle Equipment

This project is the most complex of all projects considered in this study. The direct coupling means that the steam plant equipment will likely be considered safety related. Therefore, reanalysis and refurbishment of these components becomes a strict prerequisite for the issuance of the license. Non-safety work can still proceed before the requalification of the steam-cycle equipment, but safety-related work must be delayed until after the full licensing process is complete. The actual cost and time to perform this analysis also increases, due to the increased regulatory scrutiny and operational performance required for safety-related systems.

The project flow graph for this project alternative is shown in Figure C-3.

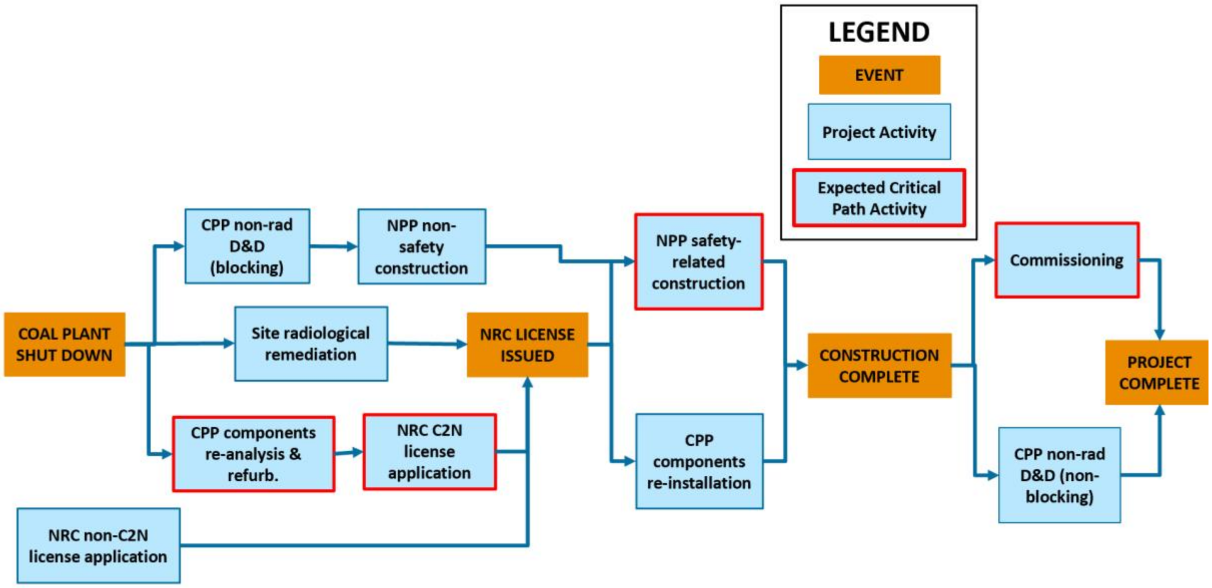

Figure C-3. Project activities flow graph for a C2N#2 project.

The introduction of the coal components into the conceptual “safety fence,” as well as the increased need for pre-construction demolition and remediation, introduces a significant risk of schedule slippage in the pre-license stage of the project, on top of increased baseline cost for these activities.

C-1.6 C2N#3: Indirect Coupling to CPP Steam-Cycle Equipment via Intermediary TES

This project alternative is more complex than the electrical-only site conversion option but is less complex than the direct steam coupling option. The introduction of the TES means that most of the reused coal equipment falls outside of the “safety fence” (Griffith, 2021). This reduces the cost and time to analyze, refurbish, and receive NRC approval for these components and means that coal component refurbishment and licensing is no longer a prerequisite to receipt of the license. However, there is still a possibility that the coal components reanalysis and relicensing activity may become critical path if significant delays are encountered during the process.

The project flow graph for this project alternative is shown in Figure C-4.

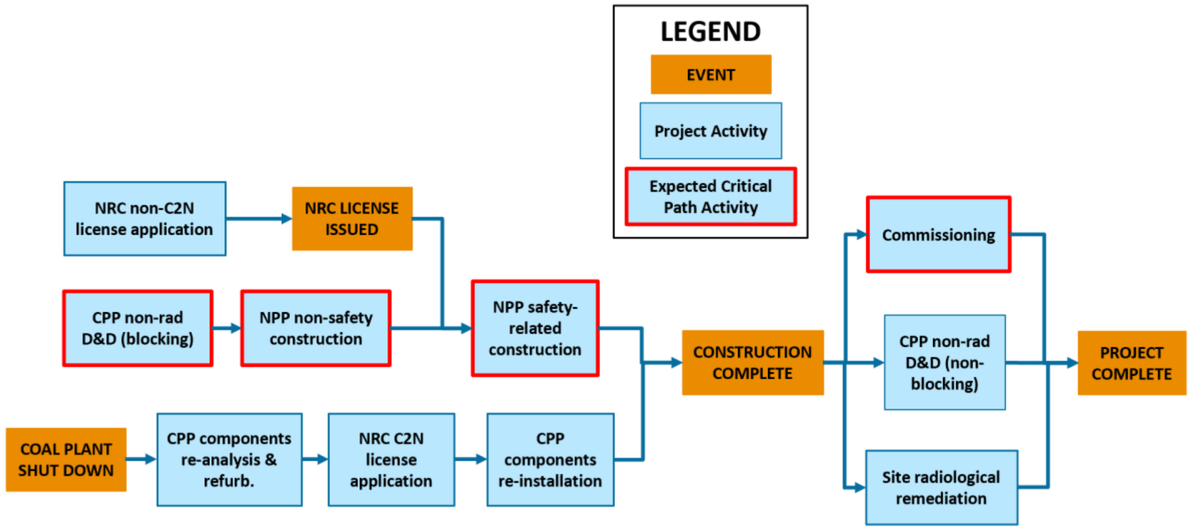

Figure C-4. Project activities flow graph for a C2N #3 project.

C-2. C2N Project Timelines

The project timelines of different C2N projects are summarized in Table 4-8 of the main report. Details about how these durations were estimated are given in the subsections below.

C-2.1 NPP Non-safety and Safety Construction

These time spans were estimated using publicly available information from NuScale (for the PWR) (NuScale, 2019) and TerraPower (for the SFR) (TerraPower, 2022a). HTGR data on construction duration was not readily available, but as the NuScale and TerraPower estimates for nuclear construction duration were like one another, it was assumed that the HTGR would require a comparable span of time for its nuclear construction work as well. NuScale and TerraPower both provide estimates of the construction time allocated to non-safety construction activities versus post-license-approval safety-related construction work. In the conservative case, it is assumed that safety-related construction takes 25% longer than anticipated.

C-2.2 NPP Commissioning

The baseline estimate for nuclear commissioning in a greenfield project is 1 year, taken from an example given in (IAEA, 2012). For brownfield projects, it is assumed that commissioning will require slightly more time: 25% longer for the simpler C2N#1 and C2N#3 projects and 50% longer for the more complex C2N#2 project.

C-2.3 CPP D&D and Ash Remediation

Representative estimates for CPP D&D and ash removal were taken from Henson (2004). Two to 3 years appear to be a typical duration for all demolition and remediation at sites of comparable size to the case study site, with longer durations corresponding to more stringent environmental remediation requirements. A baseline estimate of 1 year for D&D and 1.5 years for ash handling was used, as most sources cite ash remediation as the more expensive and time-consuming portion of the process.

D&D requirements should be roughly comparable across all project options. The time involved in ash removal is assumed to scale roughly comparably to its cost.

C-2.4 CPP Component Reanalysis, Refurbishment, and Licensing

According to US NRC (2016), the average time required for an existing NPP to navigate the life-extension relicensing process is 22 months. This figure is rounded to 2 years for the purposes of this study.

For all greenfield projects, this process does not exist and therefore has a duration of 0.

For the C2N#1 project, which reuses a smaller amount of equipment which is all non-safety in nature, it is assumed that the C2N portion of the license development and approval takes half that long or 1 year. The C2N#3 project ensures that all reused equipment is non-safety, so 75% of the nominal value (1.5 years) is used as the baseline. The C2N#2 project reuses significant amounts of equipment which must be safety-rated, so the full 2 years is used as the baseline. For the conservative cases, an additional 6 months is added to each estimate.

C-3. Costing Assumptions for C2N Projects

This section summarizes the assumptions used to estimate the cost components of various C2N projects, as used in Section 4.2. The summary of the project costs for each C2N project is provided in Table 4-9 of the main report.

C-3.1 Overnight Capital Costs

The objective of this section is to estimate the potential reduction in OCC that could be obtained when reusing CPP components listed in Section 4.1. The approach used for this estimate relies on data from the EEDB Program from 1979 (EEDB, 1988) that published OCC breakdown for various types of CPPs and NPPs, including PWRs, SFR, and VHTR. From this report, we could estimate in Table 4-6 of the main report, which components are shared within different NPPs and CPPs, and get an estimate of the upper bound of cost saving available when considering that similar components would be reused in C2N projects.

A simple compatibility check between CPP and NPP components is done based on the costs (in $/MW) of the CPP and NPP components. In the “optimistic” estimate of Table 4-6, one reuses CPP components that would cost at least 70% of the cost of the equivalent NPP components, while the "conservative" estimate disregards any CPP components that are cheaper than in the NPP. Cost is used as a proxy for component complexity and suitability, as components for nuclear applications must be manufactured to higher quality standards; coal components which are very inexpensive relative to their nuclear equivalents are assumed to be unsuitable for nuclear use. Additional study would be needed to verify compatibility and assess refurbishment and licensing costs associated with reuse of these components in specific C2N project.

The EEDB data does not provide a complete estimate of the OCC, missing the initial core inventory and some of the “other” costs (transmission, etc.). Here are a few additional important notes and assumptions:

- The “other” costs were estimated at 10% of OCC for all NPPs based on (Dixon et al., 2017), which including transmission, step-up transformers, roads and ancillary buildings, etc. The most expensive components are assumed to be reutilized in every C2N project.
- The initial fuel inventory of the NPP is a significant fraction of the OCC and could be estimated for standard PWR, SFR and VHTR concepts, accounting for mining, enrichment (tails enrichment of 0.25%), fabrication, and disposal of the fuel, and their contribution to overall OCC is reported in Table 4-6. In PWRs, we are assuming UOX fuel with a specific power density of 34 W/g (Watts per gram) with average enrichment of 4.2% (initial load), average discharged burnup of 50 GWd/ton, and thermal efficiency of 33%. In SFRs, we are considering UZr fuel with a specific power density of 68 W/g, average enrichment of 15%, average discharged burnup of 100GWd/ton, and thermal efficiency of 40%. In VHTR, we are assuming tri-structural isotropic (TRISO) fuel with specific

power density of 67 W/g, enrichment of 10%, average discharged burnup of 120 GWd/ton, and thermal efficiency of 50%.

- The SFR cost estimates is based on EEDB data, which is not meant to be representative of a Natrium cost, since it includes the cost of an intermediate sodium loop and does not include the cost of TES. More detailed costing modeling for a Natrium-type project goes beyond the work scope of this project.
- The VHTR estimate is currently missing the cost of the initial helium inventory.
- In C2N#2 and #3, the SG cost from the CPP is simply deduced from the NPP reactor plant equipment.
- For PWR cost estimates from the EEDB 1979 report, it was found that very similar results would be obtained when using more recent cost information (Ganda et al., 2019). For consistency purposes with other technologies, only the PWR cost information from the EEDB 1979 report are summarized here.
- The indirect costs account for 20–25% of the total OCC, including construction services and engineering work, temporary offices, etc. As a first-order approximation, one assumes the indirect costs are reduced in the C2N project in proportional amount to the direct costs. This assumption is justified as less construction and engineering work would be required from reusing more CPP components, and less temporary offices would need to be installed with the availability of existing CPP office buildings, etc.

The main results from Table 4-6 show that the C2N#1 project type still provides large potential savings through reusing of site, offices, heat sink, and electrical components. Our conservative estimate shows ~17% of savings, while the optimistic estimate would be up to 26%. The CN#2 and #3 project types would provide even larger potential for savings through reusing the steam-cycle components, by 20% to 38%.

In Table 4-6, the breakdown between safety and non-safety costs was done at the two-digit cost code level, using the authors' judgment based on subject matter expertise. Each two-digit cost category (e.g., land and land rights, and electric plant equipment) was allocated in its entirety to either safety or non-safety construction. Nearly all categories will include some elements which are attributable to both safety and non-safety work, but this first-order approximation was sufficient for present purposes. Further work could refine the allocation of costs between these two categories.

C-3.2 Operating Costs

C-3.2.1 VOM and Fuel Cost

For the C2N#1 and C2N#3, costs are taken from the *SA&I Cost Basis Report*.

For the C2N#3, the fuel costs are taken from the *SA&I Cost Basis Report*. The VOM and cost is taken from the Gas-Cooled Reactor Associates report, "Projection of O&M and Owner's Costs for GT-MHR Plants" (1994). These values were escalated from 1994 USD to 2022 USD using escalation data from the *2017 Cost Basis Report*.[8].

For all projects, the baseline cost assumption case uses the baseline values from these sources. The conservative case applies a 25% increase to each value.

[8] Dixon et al. (2017) compiles nuclear cost escalation data from the Handy-Whitman Index (1965–1995), U.S. Department of Energy (1995–2000), IHS North American Power Capital Costs Index (2000–2015), and the GDP Implicit Price Deflator (2016–2017). To escalate from 2017 to 2022 values, the U.S. Bureau of Labor Statistics Producer Price Index series 2211: electric power generation, transmission, and distribution was used.

C-3.2.2 FOM Cost

The underlying values for FOM costs were taken from the same sources as listed above for the three representative reactor types. As for the VOM and fuel costs, in the conservative case a 25% cost increase was applied to each of the underlying values.

However, a reactor which reuses some coal components will likely experience increased maintenance costs, due to using older components which were not designed for use in a nuclear plant, and which may be run at slightly off-optimal temperatures and pressures.

To simulate these increased costs, each project type's FOM cost was broken out into maintenance and non-maintenance portions. EIA (1995) reports cost breakdowns for nuclear reactors between 1974 and 1993, and the proportion attributable to maintenance labor and materials remains relatively consistent at about 60% of total operations and maintenance cost.

Therefore, it was assumed that 60% of the FOM cost for each non-greenfield project type would be subject to some degree of cost increase due to the use of repurposed coal components. To determine the degree of cost increase, it was assumed that any decrease in nuclear OCC would be 1%-to-1% proportional to the increase in maintenance FOM. That is, a 10% reduction in nuclear OCC would cause the maintenance FOM figure (60% of total FOM) to increase by 10%. The non-maintenance portion of FOM was assumed to be unaffected. The 1-to-1 correspondence was used as an assumption due to lack of more specific data to provide a more specific estimate.

C-3.3 CPP Removal and Requalification

These columns quantify the cost to demolish any unneeded coal plant infrastructure, deal with waste capping or removal, and reanalyze/relicense any coal components for use in the nuclear plant.

The coal-related demolition and remediation costs do not actually scale per kW of replacement reactor since they are related to the characteristics of the coal site as it exists at the plant's date of retirement. These costs are only converted into a $/kW basis here to allow easier comparison by the reader in Table 4-9. In the underlying model, they are fixed lump-sum costs per overall project, not per kW. The capacity assumptions for the CPP installation and NPP replacement are shown in Table 4-5.

C-3.3.1 CPP D&D

Data on coal-plant demolition and disposal were taken from Raimi (2017). The study's mean D&D cost ($/kW coal) for a coal plant was scaled from 2017 USD to 2022 USD using the BLS data mentioned previously. The $/kW value was converted to dollars using the capacity of the case study plant (1,200 MWe), and then scaled to $/kW by the capacity of each nuclear replacement facility.

C-3.3.2 CPP Ash Removal

Dealing with coal ash is a complex, costly process, and the amount of work involved can vary significantly even between plants of approximately the same capacity. The age, physical layout, and total ash contents of the ash ponds can have a significant impact on the cost to manage the waste. Furthermore, depending on environmental regulations, specific regulatory intervention, and desired use case for the site, the actual process for managing the ash varies significantly. The least-expensive option is to leave the ash in-situ and simply seal the entire pond in place with some impermeable material. More expensive is the complete removal of all ash from the site: this process can cost an order of magnitude more than the "cap-in-place" option and take many years to complete (Morehouse, 2020).

Coal ash tends to contain a non-negligible number of radionuclides, due to the composition of coal used as fuel. If the coal plant's site is to be reused for an NPP, the requirements for sealing or removing ash will be significantly more stringent, due to the need to meet NRC site radiological limits. Specific data or maps of typical coal site radiological contamination were not found, so further data on this topic would improve understanding of specific needs for remediation work. The level of such work required may vary widely depending on the age, size, and prior management practices of the coal facility, as well as on the specifics of the C2N project.

In all cases, it is assumed that the ash must be dealt with somehow (i.e., the owner cannot abandon the ash ponds uncapped). For projects which will not use the site directly or where the nuclear plant can be sited away from the contaminated coal areas, a lower cost is derived. For projects where the nuclear plant must be sited close to the coal-ash contaminated areas, a higher cost is assumed.

The baseline cost is based on estimates of the total ash extant at the case study site: 3.3 million cubic yards, per the Global Energy Monitor. Raimi (2017) provides data on ash management costs for a few U.S. coal plant case studies. The average cost for all six case studies, $8/cubic yards, is used as the baseline cost. The case study site's 3.3 million cubic yards of waste is used as the baseline ash quantity, resulting in a baseline total ash remediation cost of $26.4 million. The RFF report also notes a 15% contingency and indirect cost multiplier for this type of project, so that value is scaled by 115% to result in a final cost estimate of $30.3 million. This value is used directly for all greenfield projects, where the level of ash management required is lowest.

For the brownfield C2N#1 and C2N#3 projects, this baseline estimate was multiplied by 2. These projects involve reuse of the site but assume that the nuclear installation is far away from the coal-ash facilities, so that ash management needs are lower than would be required for the C2N#2 project type.

For the brownfield C2N#2 project where the NPP is directly coupled to initial CPP steam cycle, some additional assumptions were required, as the nuclear island will likely need to be in contaminated areas of the CPP. The "upper bound" for ash remediation costs is not well-defined; for example, Duke Energy is required by regulation to fully close and rehabilitate all its ash ponds in North and South Carolina, with estimated costs reaching as high as $4.2 billion. This value is roughly an order of magnitude higher than our baseline cost estimate, when converted to equivalent units. However, little detail is currently publicly available about this cost estimate. As a starting point, the baseline ash remediation cost estimate was multiplied by 5 to arrive at the "high-cost" estimate. This higher estimate approximates the increased cost, complexity, and time involved in physically removing ash from the site. This higher figure also provides scope for the cost of possible wholesale removal of surface material from highly contaminated areas, as detailed cost estimates for this type of activity could not be located. As more information about Duke Energy and other utilities' ash removal processes becomes available, this estimate can be updated with more precise data.

C-3.3.3 CPP NRC Licensing

No coal-plant components or systems have ever been relicensed by the NRC for use in a nuclear plant. Therefore, the true cost and time involved in this process is very uncertain. As a possible analog, the cost required to extend an NPP's operating license by 20 years has been used to estimate the cost of this process. The 2010 NEI report, "Status and Outlook for Nuclear Energy in the United States," cites an average cost of $10–15 million to "prepare the necessary regulatory filings and navigate the NRC's license renewal process," specifically excluding "any major capital expenditures necessary to upgrade the plant"

Taking the upper bound of $15 million as a baseline and using the BLS data described above to escalate to current dollars produces an estimated baseline relicensing cost of $17.5 million. The C2N#2 project involves direct coupling to the coal plant's steam equipment, which is likely to be a highly complex process. As a conservative estimate, the relicensing cost for this project was assumed to be three times as large as the baseline relicensing cost or $52.5 million. These costs were then scaled by the size of the replacement nuclear plants to achieve a $/kW basis.

Appendix D

Input-Output Model Overview and Methodology

This study implements an input-output (I-O) modeling software program called IMPLAN®. IMPLAN is widely accepted as a reliable choice for estimating economic impacts. The core of the model is built around a matrix derived from industry-based spending patterns for 546 different sectors and the commodities they produce. The matrix makes it possible to show how economic activity in a specific sector is distributed throughout the remaining sectors. All results in the model are annual. The following terminology identifies the different types of electric generating facility operations-based economic impacts displayed in this report:

Direct Effect: These effects are derived from the generating facility’s operations data and measure output associated with industry employment estimates. Once multipliers are applied to these initial employment estimates, the region’s economic response becomes visible.

Indirect Effect: Electric generating facilities create indirect impacts through the purchases of goods and services from other industries or businesses in their supply chain. In turn, these businesses will purchase a wide array of goods and services necessary to operate. Multipliers for these effects are based on characteristics of the region’s economy and typical industry spending patterns. Spending patterns are based on U.S. Bureau of Economic Analysis research.

Induced Effect: To fully understand the generating facility’s impact on the overall economy, one must account for the direct and indirect increases in employment and income on household purchasing. These consumption-driven impacts occur through the re-spending of income received directly and indirectly through estimated employee compensation and proprietor income. The income is circulated through the regional economy based on household spending patterns that are adjusted by income level, which then cause additional economic activity. Household spending patterns are based on U.S. BLS research.

The IMPLAN model demonstrates the following impact measures:

Output Impact: Represents the value of industry production of goods and services for 1 year.

Employment Impact: The total number of full and part-time jobs created or sustained throughout the defined region.

Labor Income Impact: Includes all forms of income including wages, taxes, benefits, and proprietor income.

Value-Added Impact: The difference between an industry or establishment's total output and the cost of its intermediate inputs; it is a measure of contributions to Gross Domestic Product (GDP). Value added is a large portion of output, as it encompasses labor income (LI), other property income, and taxes on production and imports.

Tax Impact: These impacts include all payments to government (excise, sales, property taxes, fees, fines, licenses, and permits). Employer and employee payroll taxes, which include social security, Medicare, and unemployment insurance, are also included in the model. In some instances, the resulting tax impact may be negative. This occurs when government subsidies are expected based on the industries included in the model, or based on the household income brackets associated with wages and salaries associated with those industries. Tax impacts are estimated at county (local), state, and federal level.

Multiplier: Total impact divided by direct impact. This illustrates the ripple effect of generating facility operations as it stimulates new economic activity throughout the defined region.

Input-output (I-O) modeling experts measure the impacts, or contributions, of companies or industries on defined geographic regions using several different approaches which depend on the type of industry information that is available. If the dollar value of production for an industry or individual business is known, it is possible to begin estimating impacts by introducing that dollar amount into the model. If industry output or business volume is unknown or not publicly available, it is possible to use employment figures as a base for the economic impact model. Input-output models utilize extensive databases of industry standards and statistics to accurately predict industry output based on employment estimates or vice versa. This employment approach accounts for how business or industry spending directly influences the economy and begins a ripple effect of additional spending.

D-1. WORKFORCE TRANSITION DATA AND METHODOLOGY

D-1.1 Data and Methodology

This section outlines the methodology used in analyzing the workforce transition potential in a hypothetical C2N scenario and the data used for the analysis discussed in Section 5.3.3.

Two main data sources are utilized in this analysis. The first is the U.S. BLS (U.S. BLS, 2022) national employment matrices for the fossil fuel electric power generation and the nuclear power generation industries. The BLS classifies workers into occupational categories using the Standard Occupational Classification (SOC) system. Under this federal statistical standard, at the highest level of specification, workers are classified into one of 867 occupations. Each of those 867 occupations have a corresponding code, generally referred to as the occupation's SOC code. The SOC system classifies workers into an occupation by considering job duties, and the knowledge skills, abilities, education, and training required to perform those job duties. SOC codes are six digits (Bureau of Labor Statistics (BLS), 2018).

The BLS employment matrices provide a national-scale representation of the staffing pattern in an industry. As mentioned above, the BLS breaks down industry employment matrices occupation-by-occupation. Only direct employment in an industry is displayed in these matrices. Once in an occupation-by-occupation format, these matrices also report on statistics such as the total employment by industry occupations for the data year, the percent of the industry employed in each occupation, among others. For the purposes of the study, the parameter used to conduct this analysis is the percent of the industry employed by occupation. Note that the BLS employment matrices do not provide information on the staffing patterns in specific plants or on differences in staffing patterns in different regions. Furthermore, the staffing pattern of coal versus other fossil fuel generation plants are not differentiated. Given that no data on staffing patterns at case study site is available, a national representation of the average staffing pattern at a nuclear and fossil-fired facility is the next best alternative.

Data in Table D-1 is from the 2020 BLS employment matrices and displays the top 15 occupations employed in the fossil fuel electric power generation and nuclear power generation industries. Out of the 118 total occupations employed in the fossil fuel industry, power plant operators comprise almost 17% of the industry, followed by electrical and electronics repairers, powerhouse, substation, and relay employees at about 5%. Out the 80 total occupations employed in the nuclear industry, 12.4% are nuclear engineers, and 10.4% are nuclear power reactor operators. The losses experienced by occupation in the fossil fuel industry are calculated by multiplying the total expected losses by each occupation's percent of industry value. The same method is used for calculating the gains to occupations in the nuclear industry. The net impacts to occupations in both industries is calculated by summing the losses and gains.

Table D-1. BLS data on staffing patterns.

Fossil Fuel		Nuclear	
Occupation Title	Percent of Industry	Occupation Title	Percent of Industry
Power plant operator	16.90%	Nuclear engineers	12.40%
Electrical and electronics repairers, powerhouse, substation, and relay	5.20%	Nuclear power reactor operators	10.40%
Power distributors and dispatchers	2.00%	Security guards	10.40%
Nuclear technicians	0.60%	Nuclear technicians	6.80%
Electrical power-line installers and repairers	6.80%	First-line supervisors of production and operating workers	4.80%
Nuclear power reactor operators	0.30%	Electrical and electronics repairers, powerhouse, substation, and relay	2.90%
Control and valve installers and repairers, except mechanical door	2.30%	Electrical engineers	2.70%
Gas plant operators	0.50%	Training and development specialists	2.70%
Wind turbine service technicians	0.20%	Architectural and engineering managers	2.60%
Electrical engineers	4.50%	Industry machinery mechanics	2.60%
Plant and system operators, all other	0.30%	First-line supervisors of mechanics, installers, and repairers	2.40%
Stationary engineers and boiler operators	0.60%	Project management specialists and business operation specialists, all other	2.00%
Tank car, truck, and ship loaders	0.20%	Electricians	1.60%
Meter readers, utilities	0.40%	Miscellaneous first-line supervisors, protective service workers	1.30%

The second main source of data is the IMPLAN Occupation Data (IMPLAN® model, [2020] Data). IMPLAN creates occupational data by pulling from four main publicly available sources. These data sources include (1) BLS Occupational Employment Survey (OES), (2) BLS National Employment Matrices by Industry (described above), (3) Census Bureau American Community Survey Public Use Microdata Sample (PUMS), and (4) the Occupation Information Network (O*NET). The OES data provides information on the wages and employment of an occupation in an industry. PUMS data provides information on the hours worked by occupation, industry, and by employer type. Last, O*NET data outlines the underlying knowledge, skills, abilities, education, work experience, and on-the-job training, collectively referred to as core competencies, for each occupation. Clouse (2022) provides more detailed information and methods used to create the IMPLAN Occupation Data and for more information on the underlying data sources.

IMPLAN Occupational Data provides greater detail than the BLS employment matrices data. Like the BLS data, the IMPLAN data also generates the direct occupational impact results from a loss in fossil fuel jobs and a gain in nuclear jobs. However, in addition to the direct occupational impacts, IMPLAN also provides the indirect, induced, and total occupational impacts. Furthermore, IMPLAN also generates data on the core competencies of the two workforces.

This analysis is conducted using two data sources to highlight two possible avenues to consider using in future work. Although the BLS employment matrices provide less insight, the BLS employment matrices are publicly available. Using IMPLAN is not free; however, the advantage of IMPLAN is that it generates a lot of valuable information with little work. While all the data used to generate the IMPLAN data is also publicly available, manual collection and analysis would be required to replicate the results.

D-1.2 Occupational Impacts and Core Competencies Analysis

The full list of occupational impacts using the BLS method is presented in Table D-2 below.

Table D-2. Unabbreviated table of BLS occupational impacts.

Occupation Code	Occupation Title	Fossil Fuel Jobs	Nuclear Jobs	Net Change
13-2011	Accountants and auditors	-1.35	1.44	0.09
11-3010	Administrative services and facilities managers	-1.05	2.88	1.83
11-9041	Architectural and engineering managers	-1.2	9.36	8.16
49-3023	Automotive service technicians and mechanics	-0.3	0	-0.3
43-3011	Bill and account collectors	-0.3	0	-0.3
43-3021	Billing and posting clerks	-0.15	0	-0.15
43-3031	Bookkeeping, accounting, and auditing clerks	-0.6	0	-0.6
13-2031	Budget analysts	-0.15	0	-0.15
49-3031	Bus and truck mechanics and diesel engine specialists	-0.6	0	-0.6
13-1020	Buyers and purchasing agents	-1.2	2.16	0.96
17-3098	Calibration technologists and technicians and engineering technologists and technicians, except drafters, all other	-0.6	0	-0.6
17-2041	Chemical engineers	0	1.08	1.08
19-4031	Chemical technicians	-0.6	2.52	1.92
19-2031	Chemists	-0.45	2.52	2.07
11-1011	Chief executives	-0.15	0	-0.15
17-2051	Civil engineers	-0.3	0	-0.3
13-1041	Compliance officers	-0.75	2.16	1.41
11-3021	Computer and information systems managers	-0.75	1.08	0.33
15-1241	Computer network architects	-0.3	0	-0.3
15-1231	Computer network support specialists	-0.3	0.72	0.42
15-1299	Computer occupations, all other	-0.15	1.08	0.93
15-1251	Computer programmers	-0.15	0	-0.15
15-1211	Computer systems analysts	-1.35	2.16	0.81
15-1232	Computer user support specialists	-0.75	0.72	-0.03
47-2061	Construction laborers	-0.15	0	-0.15
11-9021	Construction managers	-0.6	0	-0.6
49-9012	Control and valve installers and repairers, except mechanical door	-3.45	0.72	-2.73
51-9021	Crushing, grinding, and polishing machine setters, operators, and tenders	-0.3	0	-0.3
43-4051	Customer service representatives	-5.25	0	-5.25
15-1245	Database administrators and architects	-0.15	0	-0.15
43-5032	Dispatchers, except police, fire, and ambulance	-0.45	0	-0.45
17-3023	Electrical and electronic engineering technologists and technicians	-1.95	2.16	0.21
17-3012	Electrical and electronics drafters	-0.45	0	-0.45
49-2094	Electrical and electronics repairers, commercial and industrial equipment	-0.75	0.72	-0.03
49-2095	Electrical and electronics repairers, powerhouse, substation, and relay	-7.8	10.44	2.64
17-2071	Electrical engineers	-6.75	9.72	2.97
49-9051	Electrical power-line installers and repairers	-10.2	2.52	-7.68
47-2111	Electricians	-3	5.76	2.76
17-2072	Electronics engineers, except computer	-0.15	0.72	0.57
11-9161	Emergency management directors	0	1.08	1.08
17-2199	Engineers, all other	-0.6	2.16	1.56
17-2081	Environmental engineers	-0.15	0.72	0.57
19-4042	Environmental science and protection technicians, including health	0	1.08	1.08
19-2041	Environmental scientists and specialists, including health	-0.45	1.08	0.63
47-5022	Excavating and loading machine and dragline operators, surface mining	-0.15	0	-0.15
43-6011	Executive secretaries and executive administrative assistants	-0.9	2.52	1.62
43-4071	File clerks	0	0.72	0.72
13-2098	Financial and investment analysts, financial risk specialists, and financial specialists, all other	-1.05	1.44	0.39
11-3031	Financial managers	-0.6	0.72	0.12
47-1011	First-line supervisors of construction trades and extraction workers	-0.75	0.72	-0.03
49-1011	First-line supervisors of mechanics, installers, and repairers	-4.5	8.64	4.14
43-1011	First-line supervisors of office and administrative support workers	-1.2	1.8	0.6
51-1011	First-line supervisors of production and operating workers	-6.3	17.28	10.98
53-1047	First-line supervisors of transportation and material-moving workers, except aircraft cargo handling supervisors	-0.3	0	-0.3
19-1032	Foresters	-0.15	0	-0.15
51-8092	Gas plant operators	-0.75	0	-0.75
11-1021	General and operations managers	-2.7	2.52	-0.18
47-4041	Hazardous materials removal workers	0	0.72	0.72
17-2111	Health and safety engineers, except mining safety engineers and inspectors	-0.15	0.72	0.57
53-3032	Heavy and tractor-trailer truck drivers	-0.15	0	-0.15
49-9098	Helpers--installation, maintenance, and repair workers	-0.45	0	-0.45
51-9198	Helpers--production workers	-0.3	0	-0.3
11-3121	Human resources managers	-0.3	0.72	0.42
13-1071	Human resources specialists	-0.6	1.08	0.48
17-3026	Industrial engineering technologists and technicians	-0.15	1.44	1.29

17-2112	Industrial engineers	-0.3	4.32	4.02
49-9041	Industrial machinery mechanics	-4.65	9.36	4.71
11-3051	Industrial production managers	-1.2	3.96	2.76
53-7051	Industrial truck and tractor operators	-0.6	0	-0.6
43-4199	Information and record clerks, all other	0	0.72	0.72
15-1212	Information security analysts	-0.45	1.8	1.35
51-9061	Inspectors, testers, sorters, samplers, and weighers	-0.3	1.44	1.14
49-9099	Installation, maintenance, and repair workers, all other	-0.15	0	-0.15
25-9031	Instructional coordinators	0	0.72	0.72
37-2011	Janitors and cleaners, except maids and housekeeping cleaners	-0.15	0	-0.15
53-7062	Laborers and freight, stock, and material movers, hand	-0.9	1.08	0.18
23-1011	Lawyers	-0.45	0	-0.45
13-1081	Logisticians	-0.75	0.72	-0.03
51-4041	Machinists	-0.6	0.72	0.12
49-9071	Maintenance and repair workers, general	-1.8	2.16	0.36
49-9043	Maintenance workers, machinery	-0.45	0	-0.45
13-1111	Management analysts	-2.1	2.16	0.06
13-1161	Market research analysts and marketing specialists	-0.15	0	-0.15
11-2021	Marketing managers	-0.15	0	-0.15
17-2131	Materials engineers	0	0.72	0.72
17-2141	Mechanical engineers	-0.3	2.16	1.86
43-5041	Meter readers, utilities	-0.6	0	-0.6
49-9044	Millwrights	-0.3	0	-0.3
33-1090	Miscellaneous first-line supervisors, protective service workers	-0.15	4.68	4.53
49-3042	Mobile heavy equipment mechanics, except engines	-0.6	0	-0.6
11-9121	Natural sciences managers	0	0.72	0.72
15-1244	Network and computer systems administrators	-0.45	1.44	0.99
17-2161	Nuclear engineers	-0.45	44.64	44.19
51-8011	Nuclear power reactor operators	-0.45	37.44	36.99
19-4051	Nuclear technicians	-0.9	24.48	23.58
19-5011	Occupational health and safety specialists	-0.75	4.32	3.57
19-5012	Occupational health and safety technicians	0	0.72	0.72
43-9061	Office clerks, general	-1.05	3.96	2.91
47-2073	Operating engineers and other construction equipment operators	-1.8	0	-1.8
15-2031	Operations research analysts	-0.15	0	-0.15
23-2011	Paralegals and legal assistants	-0.15	0	-0.15
11-9198	Personal service managers, all other; entertainment and recreation managers, except gambling; and managers, all other	-0.9	4.32	3.42
19-2012	Physicists	0	0.72	0.72
51-8099	Plant and system operators, all other	-0.45	0	-0.45
47-2152	Plumbers, pipefitters, and steamfitters	-0.6	0	-0.6
51-8012	Power distributors and dispatchers	-3	1.08	-1.92
51-8013	Power plant operators	-25.35	2.16	-23.19
43-3061	Procurement clerks	0	0.72	0.72
51-9199	Production workers, all other	-0.15	0	-0.15
43-5061	Production, planning, and expediting clerks	-1.2	3.96	2.76
13-1198	Project management specialists and business operations specialists, all other	-2.55	7.2	4.65
11-2030	Public relations and fundraising managers	-0.3	0	-0.3
27-3031	Public relations specialists	-0.3	0	-0.3
11-3061	Purchasing managers	-0.15	0.36	0.21
11-2022	Sales managers	-0.15	0	-0.15
41-3091	Sales representatives of services, except advertising, insurance, financial services, and travel	-0.3	0	-0.3
43-6014	Secretaries and administrative assistants, except legal, medical, and executive	-1.65	2.52	0.87
33-9032	Security guards	-0.75	37.44	36.69
43-5071	Shipping, receiving, and inventory clerks	-0.15	0	-0.15
15-1256	Software developers and software quality assurance analysts and testers	-0.45	0.72	0.27
51-8021	Stationary engineers and boiler operators	-0.9	0	-0.9
53-7065	Stockers and order fillers	-0.9	1.08	0.18
17-3031	Surveying and mapping technicians	-0.15	0	-0.15
53-7121	Tank car, truck, and ship loaders	-0.3	0	-0.3
27-3042	Technical writers	0	1.44	1.44
11-3131	Training and development managers	-0.15	2.52	2.37
13-1151	Training and development specialists	-0.75	9.72	8.97
11-3071	Transportation, storage, and distribution managers	-0.15	0.72	0.57
51-8031	Water and wastewater treatment plant and system operators	-1.05	0	-1.05
51-4121	Welders, cutters, solderers, and brazers	-1.5	0.72	-0.78
49-9081	Wind turbine service technicians	-0.3	0	-0.3
	Total	-145.35	341.64	196.29

According to the IMPLAN Occupational Data, a loss of 150 fossil fuel jobs and a gain of 360 nuclear jobs result in a gain of 198.43 indirect jobs and 399.39 induced jobs. Combining the three levels of impacts results in a net gain of almost 800 jobs. Although the total gain in direct jobs is similar between the two methods of calculations, note that the SOC codes reported in the IMPLAN results are different from those shown above in the BLS employment matrix data. SOC codes are broken into four levels. The highest level of categorization is major groups (e.g., 49–000), followed by minor groups (e.g., 49–900), broad occupations (e.g.,49–9010), and finally detailed occupations (e.g., 49–9012). For more information on SOC codes (BLS, 2018).The BLS employment matrix reports detailed occupations, the highest level of granularity. IMPLAN reports occupations at the minor group level as shown in Figure D-1. Given the two different levels of reporting, no comparison is conducted on changes in specific occupations across the two methods. However, the total change in direct jobs across the two methods is comparable, and the results are consistent. While comparison across the two methods is not possible, Figure D-1 presents the 10 minor occupations that lose the most jobs and the 10 minor occupations that gain the most jobs for reference.

Occupation Code	Occupation	Net Change in Employment by Occupation
49-9000	Other Installation, Maintenance, and Repair Occupations	(6.78)
43-4000	Information and Record Clerks	(4.92)
49-3000	Vehicle and Mobile Equipment Mechanics, Installers, and Repairers	(1.17)
11-1000	Top Executives	(1.09)
43-3000	Financial Clerks	(0.72)
11-2000	Advertising, Marketing, Promotions, Public Relations, and Sales Managers	(0.68)
51-4000	Metal Workers and Plastic Workers	(0.57)
13-2000	Financial Specialists	(0.44)
23-1000	Lawyers, Judges, and Related Workers	(0.41)
41-3000	Sales Representatives, Services	(0.30)
37-2000	Building Cleaning and Pest Control Workers	(0.24)
53-1000	Supervisors of Transportation and Material Moving Workers	(0.24)
47-1000	Supervisors of Construction and Extraction Workers	(0.20)
53-3000	Motor Vehicle Operators	(0.19)
47-5000	Extraction Workers	(0.18)
41-9000	Other Sales and Related Workers	(0.17)
15-2000	Mathematical Science Occupations	(0.11)
19-1000	Life Scientists	(0.11)
19-3000	Social Scientists and Related Workers	(0.09)
41-4000	Sales Representatives, Wholesale and Manufacturing	(0.09)
53-7000	Material Moving Workers	(0.09)
27-1000	Art and Design Workers	(0.07)
41-1000	Supervisors of Sales Workers	(0.06)
23-2000	Legal Support Workers	(0.05)
43-1000	Supervisors of Office and Administrative Support Workers	0.19
29-1000	Healthcare Diagnosing or Treating Practitioners	0.41
51-9000	Other Production Occupations	0.59
47-2000	Construction Trades Workers	0.62
25-9000	Other Educational Instruction and Library Occupations	0.74
47-4000	Other Construction and Related Workers	0.82
43-5000	Material Recording, Scheduling, Dispatching, and Distributing Workers	1.33
27-3000	Media and Communication Workers	1.79
43-9000	Other Office and Administrative Support Workers	2.12
43-6000	Secretaries and Administrative Assistants	2.34
17-3000	Drafters, Engineering Technicians, and Mapping Technicians	2.91
49-2000	Electrical and Electronic Equipment Mechanics, Installers, and Repairers	3.00
15-1200	Computer Occupations	3.47
19-2000	Physical Scientists	3.83
19-5000	Occupational Health and Safety Specialists and Technicians	4.39
49-1000	Supervisors of Installation, Maintenance, and Repair Workers	4.39
33-1000	Supervisors of Protective Service Workers	5.44
11-3000	Operations Specialties Managers	7.61
51-8000	Plant and System Operators	8.54
51-1000	Supervisors of Production Workers	9.77
11-9000	Other Management Occupations	12.37
13-1000	Business Operations Specialists	15.65
19-4000	Life, Physical, and Social Science Technicians	28.76
33-9000	Other Protective Service Workers	37.26
17-2000	Engineers	59.41
	Total	198.78

Occupation Code	Occupation	Net Change in Employment by Occupation
49-9000	Other Installation, Maintenance, and Repair Occupations	(6.78)
43-4000	Information and Record Clerks	(4.92)
49-3000	Vehicle and Mobile Equipment Mechanics, Installers, and Repairers	(1.17)
11-1000	Top Executives	(1.09)
43-3000	Financial Clerks	(0.72)
11-2000	Advertising, Marketing, Promotions, Public Relations, and Sales Managers	(0.68)
51-4000	Metal Workers and Plastic Workers	(0.57)
13-2000	Financial Specialists	(0.44)
23-1000	Lawyers, Judges, and Related Workers	(0.41)
41-3000	Sales Representatives, Services	(0.30)

49-1000	Supervisors of Installation, Maintenance, and Repair Workers	4.39
33-1000	Supervisors of Protective Service Workers	5.44
11-3000	Operations Specialties Managers	7.61
51-8000	Plant and System Operators	8.54
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17-2000	Engineers	59.41
	Total	198.78

Figure D-1. Direct occupational impacts from IMPLAN.

As mentioned previously, jobs in the nuclear industry are higher paying than jobs in the fossil fuel section. As shown Table 5-10 in the body of the test, IMPLAN calculates an increase in almost 44 million dollars in direct employment wages and salaries, a result expected in a C2N transition. Furthermore, the impact of the lost coal jobs and gained nuclear jobs results in an increase in almost 86 million dollars in total employment wages and salaries.

Next this section discusses the how the fossil fuel and nuclear industries compare in terms of education and worker skills and knowledge requirements. To create a detailed and successful workforce transition plan, policy makers need to consider what education, skills, and knowledge the current workforce already possess versus what education, skills, and knowledge the workforce lacks that would be required in a nuclear workforce.

Table D-3 and Table D-4 present the top 10 most important skills and knowledge requirements in the two workforces, according to the O*NET database. Although they are ranked differently, critical thinking, active listening, and reading comprehension are ranked the top three most important skills in both workforces. Comparing all 10 most important skills, only the skills ranked number 10 are different between the fossil fuel and nuclear workforce. Like the top three skills, the top three knowledge requirements in both work forces are the same. Furthermore, English language, mathematics, and computer and electronics are ranked the same in terms of importance across the two workforces. Of the top 10 knowledge requirements, clerical is the only unique knowledge requirement in the fossil fuel workforce, and physics is the only unique knowledge requirement in the nuclear workforce.

Table D-3. Top 10 skills for the fossil fuel and nuclear industries.

	Skills	
Rank	Fossil Fuel	Nuclear
1	Critical Thinking	Reading Comprehension
2	Active Listening	Active Listening
3	Reading Comprehension	Critical Thinking
4	Speaking	Monitoring
5	Monitoring	Speaking
6	Judgment and Decision-Making	Writing
7	Complex Problem Solving	Complex Problem Solving
8	Coordination	Judgment and Decision-Making
9	Writing	Coordination
10	Time Management	Active Learning

Table D-4. Top 10 knowledge for the fossil fuel and nuclear industries.

	Knowledge	
Rank	Fossil Fuel	Nuclear
1	English Language	English Language
2	Mathematics	Mathematics
3	Computers and Electronics	Computers and Electronics
4	Customer and Personal Service	Engineering and Technology
5	Mechanical	Public Safety and Security
6	Administration and Management	Education and Training
7	Education and Training	Customer and Personal Service
8	Clerical	Mechanical
9	Engineering and Technology	Physics
10	Public Safety and Security	Administration and Management

The breakdown in Table D-3 and Table D-4 suggests a comparable set of skills and knowledge requirements between the two workforces. Table D-5 below displays the most common duration of on-the-job training in the fossil fuel and nuclear industries. The most common on-the-job duration for the fossil fuel industry is between 6 months to 1 year. The most common on-the-job duration for the nuclear industry is comparatively shorter, with “anything beyond a short demonstration to one month” ranked number one. In the fossil fuel industry, the most common on-the-job training duration is one year or less for about 61% of employees. In the nuclear industry, 2 years or less if the most common duration of on-the-job training for roughly the same share of employees. Longer term (2+ years) on-the-job training durations are ranked last in both industries.

Table D-5. On-the-job training durations in the fossil fuel and nuclear industries.

On-the-job Training	Fossil Fuel Share of Total	Nuclear Share of Total
None or short demonstration	3.00%	3.95%
Anything beyond short demonstration, up to and including 1 month	13.88%	17.38%
Over 1 month, up to and including 3 months	15.36%	13.80%
Over 3 months, up to and including 6 months	15.07%	14.47%
Over 6 months, up to and including 1 year	16.75%	17.18%
Over 1 year, up to and including 2 years	13.79%	15.77%
Over 2 years, up to and including 4 years	12.39%	10.44%
Over 4 years, up to and including 10 years	8.95%	5.66%
Over 10 years	0.81%	1.35%

Figure D-2 displays the required work experience for the fossil fuel and nuclear workforces. For both industries, a duration between 2–4 years of work experience is the most common. Roughly 16% and 20% of the fossil fuel and nuclear workforces require no experience, respectively. Over 50% of both workforces require between 1–6 years of work experience. Data from both industries show comparable divisions among the durations of work experience required.

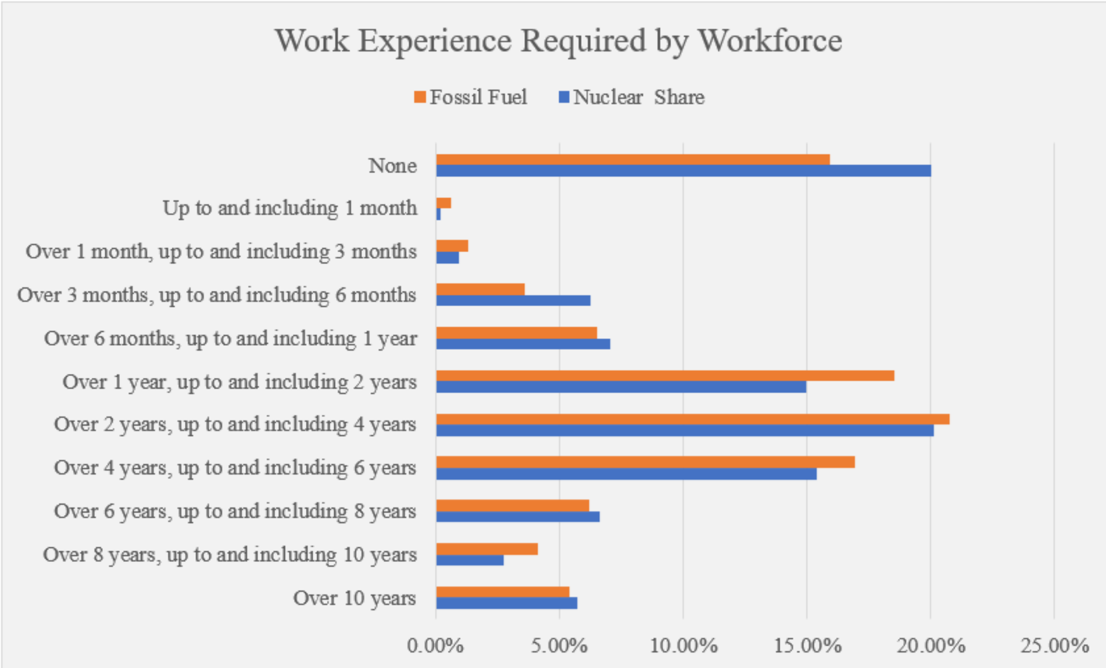

Figure D-2. Duration of work experience required by workforce.

IMPLAN Occupational data also provides insight into the abilities in the two industries. Since the abilities of the two workforces are evenly spread across all 52 abilities, not much distinguishable or interesting information can be gleaned from comparison. Table D-6 displays the top 10 abilities of the two workforces.

Table D-6. Top 10 abilities as a share of total by workforce.

Ability Description	Competency Share of Total - Fossil Fuel	Competency Share of Total - Nuclear
Oral Comprehension	4.37%	4.51%
Written Comprehension	3.75%	4.22%
Oral Expression	4.17%	4.43%
Written Expression	3.35%	3.76%
Fluency of Ideas	2.52%	2.70%
Originality	2.43%	2.54%
Problem Sensitivity	3.87%	4.33%
Deductive Reasoning	3.66%	3.97%
Inductive Reasoning	3.40%	3.77%
Information Ordering	3.44%	3.70%

This analysis is conducted from a workforce-to-workforce perspective, rather than an occupation-to-occupation perspective. In other words, it does not compare the core competencies of two specific occupations or comment on the likelihood a displaced coal plant operator will be able to fill a specific job in the new nuclear workforce. Although such an analysis is possible, it is outside the scope of this analysis given time constraints. At its most detailed level, the O*NET data used to create the IMPLAN Occupation Data enables such an analysis. Like what is listed for the fossil fuel and nuclear industries above, the O*NET website lists the top (in terms of importance) knowledge, skills, and education required for each occupation.

For example, Table D-7 below displays the top 10 most important skills of a nuclear power reactor operator. The O*NET website provides this information and other occupation specific information for each occupation (O*NET). The workforce transition analysis performed in this section compares the core competencies of the two workforces, which aggregates the core competencies of each occupation employed in each industry. Access to the detailed core competencies by occupation enables, however, enables direct comparison of occupation-by-occupation core competencies. For those occupational mismatches between the two workforces, those tasked with developing workforce transition plans can use the information from the table below to explore how a displaced worker can best be utilized in the new workforce.

Table D-7. Top 10 most important skills for a nuclear power reactor operator.

51-8011.00 - Nuclear Power Reactor Operators		
Importance	Skill	Skill Description
75	Reading Comprehension	Understanding written sentences and paragraphs in work-related documents.
75	Operations Monitoring	Watching gauges, dials, or other indicators to make sure a machine is working properly.
75	Operation and Control	Controlling operations of equipment or systems.
72	Active Listening	Giving full attention to what other people are saying, taking time to understand the points being made, asking questions as appropriate, and not interrupting at inappropriate times.
72	Critical Thinking	Using logic and reasoning to identify the strengths and weaknesses of alternative solutions, conclusions, or approaches to problems.
72	Monitoring	Monitoring/Assessing performance of yourself, other individuals, or organizations to make improvements or take corrective action.
69	Complex Problem Solving	Identifying complex problems and reviewing related information to develop and evaluate options and implement solutions.
63	Writing	Communicating effectively in writing as appropriate for the needs of the audience.
63	Judgment and Decision-Making	Considering the relative costs and benefits of potential actions to choose the most appropriate one.
60	Time Management	Managing one's own time and the time of others.

Source: (O*NET).