Framing a New Nuclear Renaissance Through Environmental Competitiveness, Community Characteristics, and Cost Mitigation Through Passive Safety

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For Angella Clarke, the strongest person I will ever know

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Abstract

The nuclear power sector has a history of challenges with its relative competitiveness against other forms of electricity generation. The availability of low cost low natural gas, the Fukushima accident, and the cancellation of the AP1000 V.C. Summer project has caused a considerable role in ending the short lived "Nuclear Renaissance." Historically, the nuclear industry has focused on direct cost reduction through construction, increasing installed capacity, and improving efficiencies to capacity factors in the 1990s and 2000s as ways to maintain competitiveness against other forms of energy generation. With renewables serving as an emerging low-carbon competitor, an added focus needs to be placed on indirect methods to increase the competitiveness of nuclear power. This thesis focuses on establishing pathways where nuclear power can be competitive with other forms of electricity generation given its advantages environmentally with Small Modular Reactors (SMRs), socioeconomically with legacy nuclear power plants, and through passive safety with SMRs.

In Chapter 2, I estimate the life cycle GHG emissions and examine the cost of carbon abatement when nuclear is used to replace fossil fuels for the Westinghouse SMR (W-SMR) and AP1000. I created LCA models using past literature and Monte Carlo simulation to estimate the mean (and 90% confidence interval) life cycle GHG emissions of the W-SMR to be 7.4 g of CO_2-eq/kwh (4.5 to 11.3 g of CO_2-eq/kwh) and the AP1000 to be 7.6 g of CO_2-eq/kwh (5.0 to 11.3 g of CO_2-eq/kwh). Within the analysis I find that the estimated cost of carbon abatement with an AP1000 against coal and natural gas is \$2/tonne of CO2-eq (-\$13 to \$26/tonne of CO_2-eq) and \$35/tonne of CO_2-eq (\$3 to \$86/tonne of CO_2-eq), respectively. In comparison, a W-SMR the cost of carbon abatement against coal and natural gas is \$3/tonne of CO_2-eq (-\$15 to \$28/tonne of CO_2-eq) and \$37/tonne of CO_2-eq (-\$1 to \$90/tonne of CO_2-eq), respectively. I conclude, with the exception of hydropower, the Westinghouse SMR design and the AP1000 have a smaller footprint than all other generation technologies including renewables. Assigning a cost to carbon for natural gas plant or implementing zero-emission incentives can improve the economic competitiveness of nuclear power through environmental competitiveness. The retirement of small and medium-scale coal power plants due the availability of natural gas can provide an opportunity for SMRs to replace that missing capacity. This trade-off between higher costs but lower GHG emissions demonstrates that depending on the value placed on carbon, SMR technology could be economically competitive with fossil fuel technologies

Following my environmental competitiveness analysis, I shift towards investigating socioeconomic competitiveness of legacy large scale nuclear power plants compared to baseload coal and natural gas plants. In Chapter 3, I utilize ANOVA models, Tukey's, and t-tests to explore the socioeconomic characteristics and disparities that exist within counties and communities that contain baseload power plants. My results

indicate, relative to the home counties of nuclear plants, communities closer to nuclear plants have higher home values and incomes than those further away. Conversely, communities near coal and natural gas have incomes and home values that increase with distance from the plant. Communities near coal plants are typically either in less wealthy parts of the county or have a similar socioeconomic makeup as county. It can be suggested that equity issues regarding the community characteristics could be included in the discussion of converting existing power plants to use other fuel sources. Communities near power plants are not created equally and have different needs. While communities near nuclear power plants may benefit from the added tax base and absence of emissions, this is not the case for communities near coal and natural gas. With the impending retirement of large scale coal plants, the conversion of these plants to natural gas or small modular reactors presents an opportunity where negative environmental externalities can be reduced while also retaining some of the economic benefits.

In Chapter 4, I present a model for estimating environmental dose exposure in a post-accident scenario to support scalable emergency planning zones (EPZs). The model includes calculating radionuclide inventory; estimating the impact decontamination factors from the AP1000, NUREG-6189, and EPRI's Experimental Verification of Post-Accident iPWR Aerosol Behavior test will have on radioactivity within containment; and estimate dose exposure using atmospheric dispersion models. This work aims to compare historical decontamination factors with updated decontamination factors to outline the impact on containment radioactivity and dose exposure relative to the Environmental Protection Agency's Protective Action Guide (PAG) limits. On average, I have found the AP1000, Surry, and iPWR produces 139, 153, and 104 curies/ft^3 75 minutes after a LOCA. The iPWR produces less radioactivity per volume in containment than the AP1000 and Surry 84% and 96% of the time, respectively. The AP1000 produces less radioactivity per volume than Surry 68% of the time. On average, the AP1000, Surry, and iPWR produces 84,000, 106,000, and 7,000 curies/MW$_{\mathrm{th}}$ 75 minutes after a LOCA. The lower bound 5 rem PAG limit is never exceeded for and does not exceeds the 1 rem lower PAG limit for whole body exposure at the 5-mile EPZ using the mean value. Considering this analysis uses a simple worst case Gaussian Plume model for atmospheric dispersion, the findings can be used to in conjunction with the State-of-the-Art Reactor Consequence Analyses (SOARCA) to provide accurate and realistic estimates for exposure. I believe this analysis can help to develop a regulatory basis for technology-neutral, risk-based approach to EPZs for iPWRs.

Finally, in Chapter 5 I discuss historical challenges facing the nuclear industry, policy implications, and recommendations. These policy implications and recommendations serve as pathways to frame an new nuclear renaissance. I also recommend future work where I details opportunities for improvements to nuclear competitiveness. Ultimately, this thesis can help policy and decision makers that can improve competitiveness and minimize risk as it relates to the expansion of nuclear power sector.

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Chapter 1

Introduction

1.1 General Motivation

The early and mid-2000s ushered in a new era of optimism within the nuclear industry with what was dubbed as "the Nuclear Renaissance." This optimism was driven by increased concerns over greenhouse gas (GHG) emissions, the rising costs of fossil fuels, increasing electricity demands, and financial incentives from the Energy Policy Act of 2005. These financial incentives along with a new streamlined licensing process[1] prompted utilities to submit 28 applications for combined construction and operating licenses (COL) to the Nuclear Regulatory Commission (NRC) [2]. However, the optimism within the nuclear industry ended with the abundance of economically recoverable shale natural gas, the Fukushima Daiichi nuclear disaster, and the bankruptcy of Westinghouse [3]. This resulted in all but two AP1000 construction projects in the US being cancelled and have stifled hopes of a nuclear revival. In the past, "the Nuclear Renaissance" was focused soley on the promise of a new generation of reactors that would be economically competitive than fossil fuel plants, renewables, and the previous generation of nuclear power plants. Assessing the success of nuclear energy should expand beyond direct economic competitiveness. This thesis focuses on several analyses that measure the competitiveness of nuclear based on environmental, socioeconomic, equitable, and risk-based indicators. Understanding these indicators would aid in identifying attributes, trade-offs, and risk-mitigation opportunities that would allow nuclear power plants to compete with fossil fuel plants economically.

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[1] The Nuclear regulatory Commission (NRC) previously issued licenses under a two-step process via construction permits and operating licenses. In 1989 to promote standardization in reactor designs, the NRC established combined construction and operating licenses (COLs). These COLs served as an alternative licensing process that combined construction and operating licensing processes [1].

1.1.1 Historical Challenges

Historically, the nuclear industry has been plagued by numerous cost overruns on nuclear power plant construction projects. The largest expansion of nuclear construction projects began in the late 1960s with the inception of Generation II[2] class of commercial nuclear power plants. Prior to Generation II, Generation I plants served as non-commercial, early prototype or research reactors. The expansion of nuclear power plants was largely driven by an enthusiasm in this new technology, a projected increased demand for electricity, and the high price of coal [4]. Lovering et al. (2016) notes that for constructions that began between 1967 and 1972, 48 nuclear power plants were completed prior to the Three Mile Island accident (TMI) in 1979. Pre-TMI the overnight construction cost ranged between $600-$2500/kW. During the construction period between 1968 and 1978, only 51 nuclear power plants were completed post-TMI. Their overnight construction cost were estimated to range between $1,800-$11,000/kW, with 38 reactors falling between $3,000/kW and $6,000/kW [5]. Figure 1.1 shows the overnight capital costs and construction duration for US nuclear power plants pre and post-TMI. Completed constructions pre-TMI typically took less than 10 years and most plants had overnight construction costs of less than $3,000/kW. However, constructions post-TMI would routinely take between 10 and 15 years, with overnight construction more than doubling. These delays and cost overruns are due to larger, more complex reactor designs, and post-TMI safety requirements.

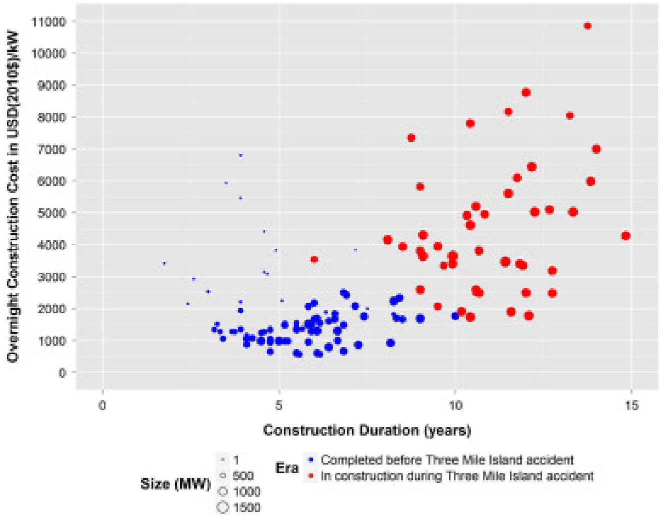

Figure 1.1: Overnight capital costs and construction duration for US nuclear power plants pre and post-TMI [5].

By the late 1970s, the US began to move towards energy conservation and efficiency as part of its overall

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[2] Generation I reactors are non-commercial, early prototype or research reactors. Generation II reactors are current nuclear power plants in commercial operation built between 1965-1996. Generation III+ reactors are evolutionary improvements in standardization, fuel technology, thermal efficiency, and passive safety systems over Generation II plants. Generation IV reactors are designs generally not expected to achieve commercial maturity until 2030.

energy strategy instead of building new capacity [6]. This strategy towards conservation and efficiency in conjunction with TMI, an anti-nuclear movement, and lower than expected electricity demand resulted in the cancellation of 120 new nuclear power plants. Figure 1.2 from Hultman and Koomey (2013) [7] shows 40% of these cancellations occurred pre-TMI indicating this new energy strategy curbed the need for new nuclear capacity.

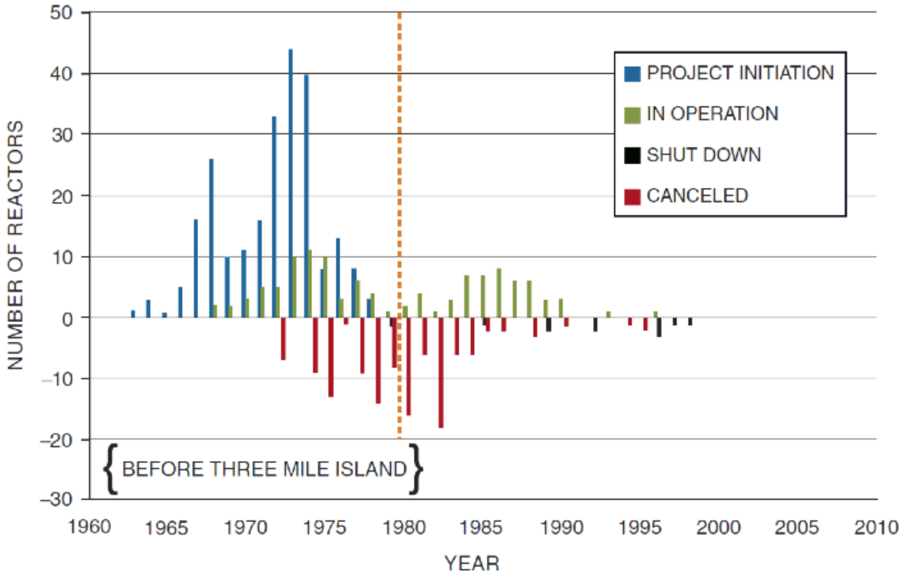

Figure 1.2: Reactor projects initiated, cancelled, in operation, and shut down (1960-2010) [7].

In addition to TMI, the cancellation of nuclear projects between 1972 to 1990 could be attributed to a rapidly changing regulatory environment, reduced energy demands, environmental activism, and a shift in the US energy strategy via the Public Utility Regulatory Policies Act of 1978 (PURPA). These factors made investments in nuclear power plants politically challenging, cost prohibitive, and a financial risk. Many Public Utility Commissions (PUCs) believed it was not justifiable to have ratepayers cover the cost of a stranded asset, such as a failed nuclear project [8]. Regulatory hurdles and the lack of standardization plant designs were viewed as a contributing factors for the large capital cost of nuclear power.

Despite the expansion of nuclear power in the 1960s and 1970s, the industry did not benefit from learning-by-doing because each project was considered a one-of-a-kind design. These non-standardized construction project may have contributed to negative learning rates [5, 9]. As part of the overall regulatory structure, the Atomic Energy Act of 1954 originally outlined a two-step process for granting licenses [10]. Under these provisions, utilities were required to apply for licenses to construct and operate nuclear power plants. First, utilities would perform a safety analysis as part of their application for a construction permit, following project completion, utilities would then apply for an operating license to generate electricity.

Post-TMI this created additional challenges for utilities, for example, projects that had already started construction were faced with new regulatory design requirements. These design changes were required in order for utilities to obtain operating licenses; causing rework and delays in construction. As a result, cost overruns began to increase and interest in nuclear power began to dwindle. For the better part of 30 years there were no new nuclear construction projects. While construction stagnated, the operating fleet became increasingly efficient with capacity factors increasing from 56% in 1980 to 92% in 2015 [11] as utilities began to consolidate their fleets and operational experience improved.

1.1.2 Renewed Optimism in Emerging Technologies

Post-TMI, nuclear construction projects have been considered a financial risk because or regulatory hurdles and lack of design standardization. The emergence of Generation III+ designs hoped to solve the problem of standardization, while the advent of COLs would streamline the application process and would alleviate some of the regulatory hurdles that caused long construction times. Cooper (2014) [12] believes cost escalation also stemmed from the inherent complexity in executing nuclear projects and the high bar for nuclear safety. Standardization and COLs were perceived as vehicles to control capital cost of new plant construction. Large light water Generation III+ reactors, such as the AP1000 featured modular construction, passive safety systems, plant simplification, and standardized designs that were perceived to reduce the capital cost of construction. The AP1000 was the first Generation III+ reactor to receive final design approval from the NRC. The Southern Company and SCANA were expected to be the first utilities to construct and operate an AP1000. With AP1000 COLs issued by the NRC, it was expected that V.C. Summer Units 2&3 from SCANA would be fully operational by 2017 and 2018. However, numerous delays and cost overruns revised the project's completion date to 2020. After billions of dollars in cost overruns, SCANA abandoned the construction effort in 2017.

Despite being a Generation III+ nuclear power plant and having a seemingly streamlined regulatory process with COLs, the AP1000 construction projects are the most recent example of large-scale nuclear projects that faced the same historical challenges of large capital costs and financial risks associated with nuclear power. However, proponents view the deployment of Small Modular Reactors (SMRs) as a strategy to control the high capital costs and long construction durations that have plagued older Generation II and recent Generation III+ construction projects. The development and deployment of SMRs are driven by their potential for higher levels of safety, siting and grid flexibility, reductions in construction duration, minimizing cost overruns, and lower overall capital costs. Generation IV SMRs have added benefits, such as higher fuel burnup rates, longer refueling cycles, enhanced safety features, and higher thermal efficiencies. Typically, most LWRs achieve a thermal efficiency of 33%, while Generation IV plants, such as sodium cooled fast reactors and high temperature gas cooled reactors can achieve efficienes between 40-50% [13].

Light water and advanced SMRs can be utilized for commercial functions outside of electricity generation. Light water SMRs can be used for desalination in areas with limited access to drinking water and provide district heating in remote locations. Advanced SMRs are able to operate at temperatures above 700°C. This allows them to supply heat for oil refineries, chemical, and hydrogen production; reducing the need to use natural gas plants for these processes [13]. NuScale has issued a series of white papers indicating the potential applications for their design, including desalination via Multi-stage flash distillation (MSF), Multiple-effect distillation (MED), and Reverse osmosis (RO) as well as the ability to load-follow intermittent renewables [14, 15, 16]. While SMR development in the US, with the exception of NuScale's design, has stagnated; the perceived advantages of SMRs have prompted their construction in other countries. NuScale's design is the only SMR that has it design certification[3] pending by the NRC [17]. Despite this, China's HTR-PM and Argentina's CAREM SMRs will be deployed in 2018 [18] and 2019 [19], respectively, while no COL has been issued to NuScale's SMR. While SMRs have electrical outputs of 300 $\mathrm{MW_e}$, many vendors are exploring the deployment potential of Very Small Modular Reactors (vSMRs). With an electrical output of $\leq$25 $\mathrm{MW_e}$ and the capability generate electricity for 10 years without refueling using >5% enriched fuel, vSMRs are designed to provide electricity and heat for decentralized energy systems and markets.

With large cost overruns and numerous delays during the construction of the AP1000, new commercial plants are not seen as economically viable in the US. In the short term it is difficult for large-scale Generation III+ economically competitive with fossil fuel plants in deregulated markets [20]. This is due the large capital costs, the regulatory environment, and construction delays typically associated with nuclear power plant projects [20, 21]. Ideally, the best and most cost effective option for utilities are to maintain the existing nuclear fleet. However, this is not a long term solution. Of the 99 nuclear power plants currently in operation, 86% are over the age of 30 and 45% are over the age of 40 [22]. Generation II nuclear power plants were originally designed to operate for 40 years. However, as more plants reach the end of their lifetime, utilities are requesting licenses to extend the operating lifetime of their plants to 60 years from the NRC. With nuclear power supplying 20% of the electricity in the US in 2015 and an aging nuclear fleet, a large portion of low-carbon baseload installed capacity is at risk of being lost if they are not replaced. It is estimated that if license renewals are not extended beyond 60 years, then 30% of the current nuclear fleet is estimated to face retirement by 2035 [23]. Currently, the existing fleet is facing difficulty remaining economically competitive against natural gas plants without the aid of zero-emission tax credits in some markets. SMRs present an opportunity to replace aging units and expand nuclear capacity, while also reducing captial

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[3] NRC design certification indicates the NRC staff has reviewed safety issues related to the proposed plant design.

costs and minimizing financial risk. In 2015, nuclear power generated about 20% of electricity within the US and was responsible for 62% of emission-free electricity [24]. Without the construction of new nuclear power plants, this low-carbon installed capacity will be replaced with natural gas generation, resulting in increased GHG emissions [25]. The survival of the nuclear industry largely depends on its ability to compete with baseload fossil fuel plants. While nuclear energy is not suited to compete economically with its fossil fuel counter parts, competitiveness can be measured with to other metrics. Competitiveness based on environmental, socioeconomic, safety, and other risk-based indicators would aid in identifying attributes, trade-offs, and risk-mitigation opportunities that would allow nuclear power plants to compete with fossil fuel plants economically.

1.2 Research Aims and Questions

The aim of this research is to frame and develop new pathways for a new nuclear renaissance through environmental competitiveness, community characteristics, and cost mitigation through passive safety using SMRs, Generation II, and Generation III+ nuclear power plants. Nuclear power plays a vital role in the future of reliable, low-carbon, baseload electricity generation in the US. These studies investigate pathways where nuclear power can be competitive with other forms of electricity generation given its advantages environmentally, socioeconomically, and through utilizing SMRs the cost of nuclear power plants can be further managed. To develop this new framing, the research aims and questions for each chapter are outlined here.

1. **Estimate the environmental competitiveness of SMRs, Generation II, and Generation III+ nuclear power plants.** The research objective of this study is to estimate the life cycle GHG emissions produced by SMRs, Generation II, and Generation III+ nuclear power plants. This work is, to the best of my knowledge, the first study to perform a prospective attributional life cycle assessment of an SMR and investigate if generational improvements in nuclear power plant designs and the key features of SMRs result in a reduction in life cycle GHG emissions. These emissions results are compared to the life cycle GHG emissions from fossil fuel plants and renewables. The GHG emissions from each nuclear power plant type is used to estimate the cost of carbon abatement for SMRs and Generation III+ nuclear power plants to compete with fossil-fuel power plants. The research questions for this study are listed below:

    (a) What are the life cycle GHG emissions for an SMRs, Generation II, and Generation III+ nuclear power plants? How do they compare?

   (b) How do the life cycle GHG emissions compare to fossil fuel plants and renewables?
   (c) What is the cost of carbon abatement for SMRs and Generation III+ nuclear power plants?
   (d) What are the policy implications of the emission results?

2. **Estimate and compare the socioeconomic characteristics of communities surrounding baseload power plants.** The research objective of this study is to understand the characteristics associated with communities near baseload nuclear, coal, and natural gas power plants. This study explores utilizing socioeconomic indicators (population density, the percentage of black residents, the percentage of residents with Bachelor's degrees or above, household income, poverty rate, and home value) as a metric, outside of cost and emissions, to explore the socioeconomic disparities (i) at the county level, (ii) at the community level relative to the sited power plant county, and (iii) the evolution of socioeconomic characteristics over time. This study will be used to understand the relationships between power plant type, distance, and time using a set of census variables. The findings can be used to suggest equity issues regarding the community characteristics should be included in the discussion of the siting and conversion existing power plants to use cleaner fuel sources. The research questions for this study are listed below:
   (a) What types of socioeconomic disparities exist within counties and communities associated with nuclear, natural gas, and coal power plants?
   (b) Are negative externalities associated with community characteristics based on power plant type?
   (c) How have socioeconomic indicators changed over time for communities near operating baseload power plants?

3. **Estimate the environmental dose exposure in a post-accident SMR scenario using decontamination factors to support scalable emergency planning zones (EPZs).** The research objective of this study is to quantify the risk of radioactive material being released into the environment relative to a representative Generation II PWR and a Generation III+ large light water reactor in a post-accident scenario. This study will estimate the radioactive activity inside containment in a post-accident scenario using decontamination factors produced from EPRI's Experimental Verification of Post-Accident iPWR Aerosol Behavior test, the AP1000, and NUREG-6189 to estimate the dose exposure after a simulated core melt. The containment radioactivity can be used to calculate the dose exposure after the radioactive material is released into the environment. The performance of the decontamination factors can be used to establish regulatory considerations in establishing scalable EPZs for SMRs via dose-based, risk-informed methods. The quantification of these risks can be used

in conjunction with analytical methods presented in the NRC's State-of-the-Art Reactor Consequence Analyses to develop a basis for risk-based approach to establishing scalable EPZs for SMRs. The research questions for this study are listed below:

(a) How do the decontamination factors from the AP1000, the iPWR aerosol behavior test, and NUREG-6189 compare?

(b) How much radioactivity is present in containment after the decontamination factors have been applied in a post-accident scenario?

(c) What is the dose exposure after radioactive material is released into the environment?

(d) What are the policy implications?

Chapter 2

The environmental competitiveness of SMRs, Generation II, and Generation III+ nuclear power plants[1]

This work conducts a prospective attribution life cycle assessment of an SMR. Monte Carlo simulation and sensitivity analyses are used to account for the uncertainties in the analysis. The analysis finds that the mean (and 90% confidence interval) life cycle GHG emissions of the Westinghouse SMR (W-SMR) to be 9.1 g of CO_2-eq/kwh (5.9 to 13.2 g of CO_2-eq/kwh) and the Westinghouse AP1000 to be 8.4 g of CO_2-eq/kwh (5.5 to 12.1 g of CO_2-eq/kwh). The GHG emissions of the AP1000 are 9% less than the W-SMR. However, when the nuclear fuel cycle is not included in the analysis the GHG emissions for the W-SMR and the AP1000 are effectively the same given the inherent uncertainties in the analysis. However, the analysis finds that both types of plants stochastically dominate the Generation II 4 loop SNUPPS. The mean (and 90% confidence interval) life cycle GHG emissions of the SNUPPS is 13.6 g of CO_2-eq/kwh (10.5 to 17.3 g of CO_2-eq/kwh). While the AP1000 has the benefits of economies of scale, the W-SMR's modular ability enables it to make up some of the difference through efficiencies in construction, operation and maintenance, and decommissioning.

2.1 Introduction

In an effort to mitigate climate change, the United States (US) pledged to reduce their greenhouse gas (GHG) emissions over the next 10 years by 26%-28% below 2005 levels [26]. To meet this goal the

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[1] This work has been published in *Energy* as shown in the reference below:
Carless, T.S., Griffin, W.M., Fischbeck, P.S. (2016). "The Environmental Competitiveness of Small Modular Reactors: A Life Cycle Study." Energy 114:84-99

US Environmental Protection Agency (EPA) finalized the Clean Power Plan regulation to reduce carbon pollution by establishing GHG emission guidelines for existing fossil-fuel power plants [27, 28]. In 2013, the EPA estimated that electricity generation accounted for 37% of all CO_2 emissions in the United States [29]. In this calculation the EPA accounted for an additional 5.5 GW_e of nuclear capacity that is currently under construction in Georgia, South Carolina, and Tennessee [30]. With the early retirement of Vermont Yankee, Crystal River, San Onofre, Kewaunee, FitzPatrick, and Pilgrim nuclear power facilities, there will roughly be no net gain of installed nuclear capacity. It is estimated that if license renewals are not extended beyond a 60-year lifetime, 30% of installed capacity will be lost by 2035 [23]. In the Clean Power Plan regulation, the EPA assumes that nuclear power plants will continue to run and does not account for any early retirements due to low natural gas prices and large maintenance costs.

The US Energy Information Administration (EIA) estimates that the demand for electricity in the United States will increase by 29% between 2012 and 2040 [31]. While the EIA estimates that the natural gas (NG) share of total generation will increase [31], NG plants are not well suited to reduce GHG emissions as a bridge fuel. Though NG plants produce roughly half the GHG emissions as a coal-fired plant, fugitive emissions from upstream operations may negate the GHG emission reductions gained [32, 33]. It is estimated that renewables will contribute 16% of total US electrical generation by 2040 [31]. However, though wind and solar produce no GHG emissions during operation, their intermittency and capacity factors, 35% and 25% [34], respectively are unable to provide reliable baseload energy. NG power plants often times serve as backup to intermittent renewable energy sources, such as wind and solar. To meet the estimated 29% increase in electricity demand, an increase in nuclear power using small modular reactors (SMRs) may help meet future energy needs and provide affordable low-carbon electricity.

The capital cost associated with nuclear power is a major deterrent in the expansion of nuclear capacity. Federal loan guarantees authorized by the Energy Policy Act of 2005 can be allocated to projects that help reduce greenhouse gases by employing new technologies [35]. These loan guarantees can save utilities billions in financing charges. The lower capital cost of SMRs allows federal loan guarantees to be spread across more utilities or may provide options for firms to find financing options outside of the US federal government. The intermittency of renewables, their significant land use needed per MW, and their reliance on fossil fuels as backups or energy-storage technology that is still in its infancy make SMRs a viable option. To help accelerate development of SMRs, the US Department of Energy has appropriated $452 million for the Small Modular Reactor Licensing Technical Support program over a six-year period. To date, funding has been provided to mPower American and NuScale Power in support of this goal.

There has been work in estimating the levelized cost of electricity (LCOE) of SMRs [36], to date there are no studies that estimate their life cycle GHG emissions. This study estimates the life cycle GHG emissions of SMRs. SMRs have the potential to be competitive with renewables and fossil fuels as the "middle option" if SMRs can be shown to be (i) more available and cost effective than renewables and (ii) generate less GHGs than fossil fuels. Estimates indicate that large gigawatt scale Generation III+ nuclear power plants will have a lower LCOE than solar, offshore wind, and biomass [34].

When considering the GHG emissions produced over the lifetime of a nuclear power plant (NPP), nuclear power generally falls between renewables (e.g. wind and solar) and fossil fuels (e.g. natural gas and coal) [37]. In the past there have been several LCAs [38, 37, 39] on the GHG emissions from generation II 1,000 MW_e NPPs. Warner and Heath (2012) performed a harmonization of life cycle assessments (LCAs) for light water reactors to find that the median life cycle emissions could be 9 to 110 g of CO_2-eq/kwh. The wide variation in estimates are attributed to the primary energy mix, the uranium ore grade used during mining, the LCA method, and assumptions made by each author, such as including an alternate scenario where global decrease in the availability of current average uranium ore grades. These studies do not give a clear indication to where SMRs will fall in terms of cost and life cycle GHG emissions relative to other sources of electricity.

While there are many commonalities between Generation II and III+ nuclear plants and SMRs, there are key differences inherent in the design of SMRs, such as:

- Longer refueling cycles
- Increased thermal efficiency
- Improved construction efficiency through modularity
- Shorter, more efficient supply chain
- Lower operation and maintenance costs
- Reduction in construction time and mass production
- Simpler decommissioning

The costs and benefits of these differences are explained in further detail in Appendix A.1. The operating licenses of the current nuclear fleet are expected to begin expiring in 2029. Nuclear power plants that cannot compete economically or too expensive to maintain will face early retirement. Some NPPs incur the added risk of early retirement because of the sheer age of these plants and inability to compete financially with NG plants. Additional investments in new capacity can explored to replace the capacity that maybe lost, meet future energy demand, and reduce GHG emissions.

This paper estimates the life cycle GHG emissions of a Westinghouse iPWR SMR (W-SMR), an AP1000, and a 4-Loop Standardized Nuclear Unit Power Plant System (SNUPPS) across the nuclear fuel cycle, construction, operation and maintenance, and decommissioning stages of each plant. These estimates are used to show generational improvements in NPPs and to determine if the key features of an SMR result in a reduction in life cycle GHG emissions. These findings are used to estimate the cost of carbon abatement needed for SMRs to compete with fossil fuel power plants.

2.2 Methods

The guidelines and framework presented in ISO 14044 provide a basis for our life cycle assessment. Process chain analysis (PCA) was primarily used when inventory data was available for each stage, such as mining and milling, conversion, fuel fabrication and enrichment. In the event that inventory data was not available, an environmentally extended economic input output method (EIOLCA) [40] was utilized. It is common practice to utilize the EIOLCA method for the operation and maintenance stage [41, 42]. The construction stage utilized a combination of methods from PCA and EIOLCA. A PCA was used to calculate the production of materials, equipment use, and employee transportation. The EIOLCA method was used to calculate the emissions generated from the production of the Instrumentation and Control system (I&C). Inventory data for the I&C system of an NPP was not available; therefore, the cost of the system was used to determine emissions. The combination of PCA and EIO has been discussed in several LCA review papers (e.g., Sovacool (2008) [37], Beerten et al. (2009) [38], Warner and Heath (2012) [39]). The input data for this study were sourced from literature on the nuclear fuel cycle, modular construction methods, and LCA on Generation II NPPs.

2.2.1 Goals and Scope Definition

The goal of this study is to estimate the cradle-to-grave US-centric life cycle GHG emissions of an nth of a kind SMR for comparison to Generation II and III+ NPPs. This study encompasses mining, milling, conversion, enrichment, fuel fabrication, construction, operation, maintenance, and decommissioning of each NPP. Currently, the US does not recycle or reprocess spent nuclear fuel; as a result, a once-through nuclear fuel cycle is assumed. There are uncertainties in each stage of our LCA. To account for this, Monte Carlo simulations and sensitivity analysis were implemented. While the stages related to the nuclear fuel cycle are similar in each reactor,[2] there are differences in the construction, operation, maintenance, and

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[2] In this study the Generation II, Generation III+, and SMR are enriched to 3.60%, 4.55%, and 4.95% respectively. Lower enrichment levels produces additional uranium needed for fuel fabrication, which produces additional emissions.

decommissioning stages. Many Generation II NPPs in the US were constructed in the 1970s and are non-standardized products. Generation III+ NPPs benefit greatly by the introduction of standardization and modularity. While proposed SMRs are designed to provide around 20% of the power of a 1,000 MW_e unit plant and on the surface may seem to lose economic leverage on the basis of economies of scale [43], SMRs are based on the idea of modularity by allowing for 100% of the plant to be built in factories and assembled onsite. Because of this added modularity, SMRs can offset the loss in economies of scale and for some metrics may perform better than 1,000 MW_e units. This study aims to determine the environmental competitiveness of SMRs when including the value of modularity, size, standardization, and their ability to be fully fabricated in a factory and assembled on-site.

Within the US, there are two types of commercial NPPs, Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs). PWRs are the most common type of commercial reactor operating in the US, making up 66% of the total fleet and represent the 5.5 GW_e future installed capacity. Most generation III+ designs including the Advanced CANDU Reactor, the AP1000, the European Pressurized Reactor, the APR-1400, and the VVER-1200/1300 are PWRs. Because PWRs are more common and are the technology of choice for most generation III+ reactors, the SNUPPS, AP1000, and W-SMR PWRs were analyzed here.

The Westinghouse designed Sizewell B NPP (SNUPPS) sited in Suffolk, England, UK was selected as the representative Generation II reactor because of data availability. The Westinghouse AP1000 was selected as the base model for the Generation III+ reactor because of data availability on construction (i.e., four reactors under construction in Georgia and South Carolina).

The SMR modeled is an integrated PWR (iPWR). An iPWR SMR is considered a Generation III+ plant based on its evolutionary design and technological maturity. However, Generation IV SMR designs do not use water as a neutron moderator and are not expected to achieve commercial maturity until 2030. By definition SMRs produce an electrical output of 300 MW_e. The iPWR design was selected because it is generally accepted that it will be the SMR technology that will face the least amount of regulatory hurdles [44], as it is based on current technology, which reduces uncertainty in a conservative nuclear industry. The Westinghouse designed 225 MW_e SMR (W-SMR) was selected as the base model for SMRs because its design is based on the AP1000, reducing the complexity in estimating construction methods and material needed during construction; however, this similarity to the AP1000 may reduce differences between the two designs.

2.2.2 Functional Unit

A functional unit of kwh of electricity generated by each NPP was used. The life cycle inventory results are reported in g of CO_2-eq/kwh for NPP comparison.

2.2.3 System Boundary

The system boundary defines the stages and components as well as flows of energy, waste and materials within the NPP life cycle in this analysis (Figure 2.1). Each stage, process, and flow is common among all three power plants. The life cycle stages and sub-processes include:

- Nuclear Fuel Cycle
  - Uranium mining and milling
  - Conversion
  - Enrichment
  - Fuel fabrication
- Construction
  - Construction material production
  - Construction worker travel
  - Equipment use
- Operation and Maintenance
  - Power plant employee travel
  - Repair, replacement, and refurbishment
- Decommissioning
  - Facility and building deconstruction
  - Radioactivity measurements
  - Cutting and decontamination
  - Interim storage

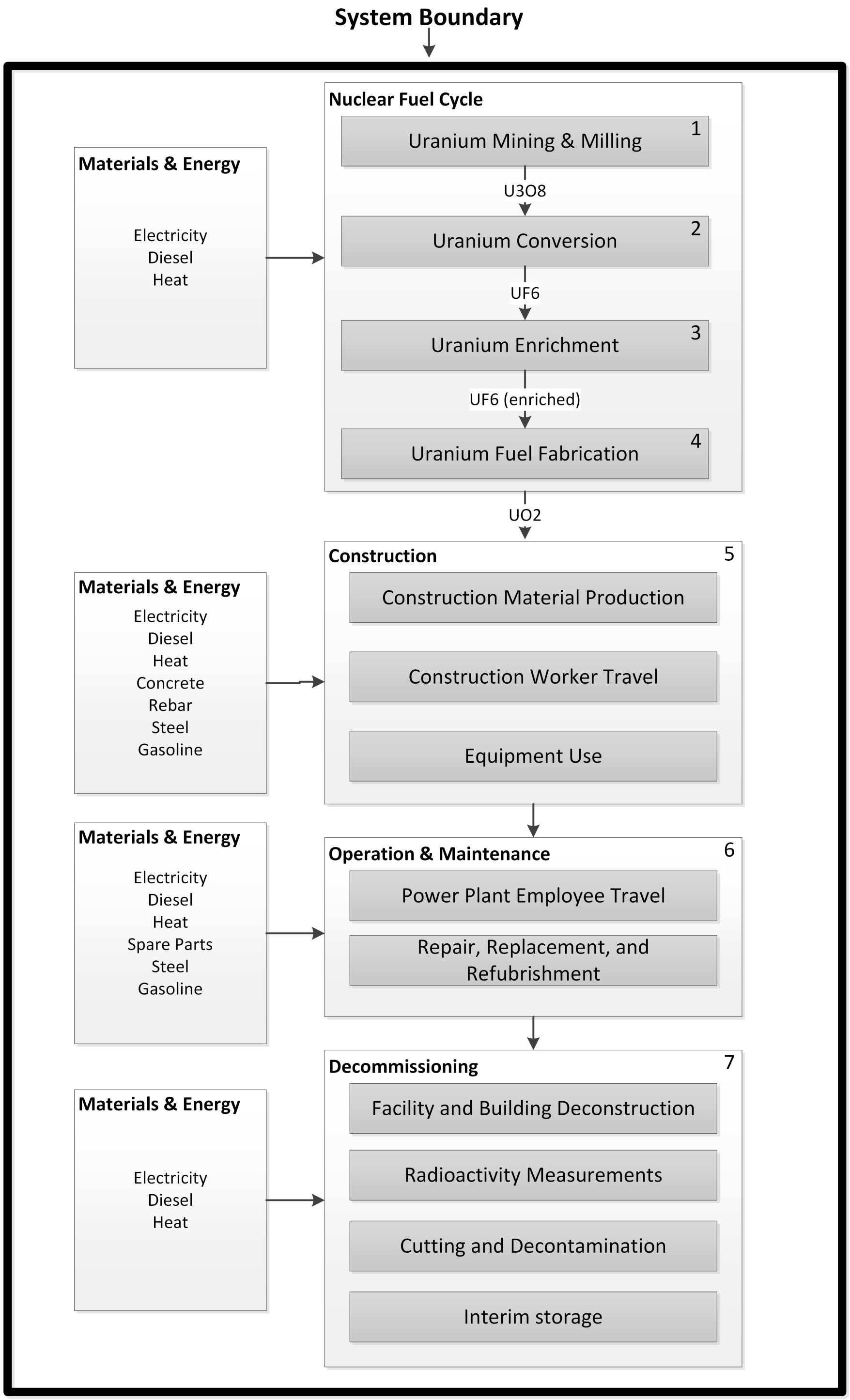

Figure 2.1: Life cycle Process and Material Flow of the Modeled Nuclear Power Plants.

2.2.4 Assumptions

As with any LCA, assumptions of plant performance and input data are necessary. The assumptions for each power plant, the uranium fuel needed per year, and the associated nuclear fuel cycle are shown in Table 2.1. Gas centrifugation is assumed to be the only enrichment method used (see Appendix A.2). The W-SMR capacity factor, construction duration, and lifetime electricity produced are uncertain parameters. The capacity factor is estimated using the W-SMR refueling outage duration distribution. As such, the W-SMR uranium mass balance parameters vary based on the W-SMR refueling outage distribution duration outlined in Table 2.3.

Table 2.1: Nuclear Power Plant Specification Parameters.

Description	**SNUPPS**	**AP1000**	**W-SMR**
Current Status	Existing	Under Construction	Proposed
Reactor Type	PWR	PWR	iPWR
Electrical Output (MW_e)	1,200	1,117	225
Thermal Output (MW_t)	3,500	3,415	800
Thermal Efficiency	34%	33%	28%
Core Power Density (MW_t/t U)[3]	39.3	40.4	30.4
Total Core Load (tonnes U)	89.1	84.5	26.3
Fuel Assemblies	193	157	89
Feed Assemblies	80	64	36
Lifetime (years)	60	60	60
Capacity Factor	90%	90%	97%
Refueling Cycle (months)	18	18	24
Construction Duration (months)	96	60	24
Lifetime Electricity Produced (TWh)	568	520	114
Concrete (million tonnes)	1.24	0.24	0.08
Rebar (thousand tonnes)	65	12	4

Note: The capacity factor, construction duration, and the amount of concrete and rebar for the W-SMR are the reported means from Monte Carlo simulation. The parameters for the distributions used are defined in Table 2.3.

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[3] The core power density of the Westinghouse AP1000 and W-SMR is assumed to be 40.4 and 30.4 MW_t/t U, respectively [45].

Table 2.2: Uranium Mass Balance.

Description	SNUPPS	AP1000	W-SMR
Average Discharge Fuel Burnup (GWd/t U)	49	51	51
Required Uranium (tonnes/year)	296	274	75
Uranium Enrichment (Product Assay)[45]	4.60%	4.50%	4.90%
Tails Assay %	0.30%	0.30%	0.30%
Uranium Mill (tonnes of U_3O_8)	296	274	75
Uranium Mill (tonnes of U)	251	233	63
Conversion Uranium Loss	0.50%	0.50%	0.50%
Conversion (tonnes UF_6 natural)	369	342	93
Conversion (tonnes U natural)	250	231	63
Enrichment Energy Consumption (GWh_e)	7.2	7.3	2.5
Enrichment Separative Work Units[4] (thousand SWUs)	153	141	39
Enrichment (tonnes UF_6 enriched)	35.1	33.2	8.3
Enrichment (tonnes UF_6 depleted)	334	309	84.9
Enrichment (tonnes U)	23.8	22.4	5.6
Fuel Fabrication Uranium Loss	1%	1%	1%
Fuel Fabrication (tonnes UO_2)	26.7	25.2	6.3
Fuel Fabrication (tonnes U)	23.5	22.2	5.6

Note: The gas centrifuge enrichment energy consumption is based on mean of 63 kwh/SWU derived from a triangular distribution (40, 50, 100 kwh/SWU). The uranium mass balance of the W-SMR is based on a capacity factor of 97%.

2.2.4.1 W-SMR Capacity Factor and Construction Duration

Recently, capacity factors for NPPs in the U.S. have improved to 90% [47], from an average of 55% in the 1980s. This is due to a reduction in the amount of days required for a refueling outage. Today, typical regular maintenance runs concurrently with refueling for NPPs. Based on data from 2000-2013 (see Table A.1), the average refueling outage duration for a 1,000 MW_e NPP is 40 days. A linear extrapolation of refueling outage duration of the 1,000 MW_e plant based on the electrical output of a 225 MW_e W-SMR is 9 days. The historical and linear extrapolated estimates for each year can be seen in Appendix A.2.1.

Normal distribution statistics from Table A.1 are used to model refueling uncertainty for the W-SMR. As an upper bound, it is assumed that the refueling of a W-SMR will not take longer than a traditional 1,000 MW_e NPP. As a lower bound, it is assumed, at minimum, on average, 9 days will be needed to refuel a W-SMR regardless of the plant size. In comparison, it is estimated that at minimum, 7 to 10 days are needed to refuel a large NPP [48]. This is because it is estimated that SMRs use about 20% of the fuel of a large NPP. The refueling duration can also be reduced based on a reduction in maintenance requirements for factory-fabricated modules. To account for the W-SMR refueling outage duration uncertainty, a uniform

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[4] Separative work units (SWUs) are "The standard measure of enrichment services. The effort expended in separating a mass F of feed of assay x_f into a mass P of product assay x_p and waste of mass W and assay x_w is expressed in terms of the number of separative work units needed, given by the expression $\mathrm{SWU} = \mathrm{W} \times \mathrm{V}(\mathrm{x_w}) + \mathrm{P} \times \mathrm{V}(\mathrm{x_p}) - \mathrm{F} \times \mathrm{V}(\mathrm{x_f})$, where V(x) is the value function, defined as $\mathrm{V}(\mathrm{x}) = (1 - 2\mathrm{x}) \times \ln((1 - \mathrm{x})/\mathrm{x})$ [46]."

distribution was implemented using the normal distribution of linearly extrapolated values of the W-SMR as the minimum and the normal distribution of the historical values of the 1,000 $\mathrm{MW_e}$ plant as the maximum. Table 2.3 outlines the parameters for the W-SMR refueling outage duration uniform distribution.

Table 2.3: Nuclear Power Plant Life Cycle Uncertainty Distributions. The minimum, best estimate, maximum, μ (mean), and σ (standard deviation) are parameters used for their respective distributions.

Description	**Unit**	**Distribution**	**Minimum**	**Best Estimate**	**Maximum**	μ	σ
W-SMR Construction Duration	Year(s)	Uniform	18	-	30	-	-
Historical Refueling Outage Duration	Day(s)	Normal	-	-	-	40.3	3.4
W-SMR Extrapolated Refueling Outage Duration	Day(s)	Normal	-	-	-	9.1	0.8
W-SMR Refueling Outage Duration	Day(s)	Uniform	9.1	-	40.3	-	-
Mining & Milling	tonnes CO_2/tonnes U_30_8	Triangular	7.2	18.9	63.4	-	-
Uranium Conversion Electrical Energy	MWhe/t U	Triangular	7	13.1	15.9	-	-
Uranium Conversion Thermal Energy	GJth/t U	Triangular	18.3	149.7	1425	-	-
Enrichment Gas Centrifuge	kwh/SWU	Triangular	40	50	100	-	-
Fuel Fabrication Electrical Energy	MWhe/t U	Triangular	49.2	105.3	303	-	-
Fuel Fabrication Thermal Energy	GJth/t U	Triangular	0	1,101	6,169	-	-
AP1000 Total Metal	tonnes	Uniform	35,711	-	37,222	-	-
Concrete Modular Reduction Factor	%	Uniform	21	-	54	-	-
Rebar Modular Reduction Factor	%	Uniform	21	-	57	-	-
Steel Modular Reduction Factor	%	Uniform	21	-	71	-	-
W-SMR Concrete	million kg	Triangular	52.3	71.2	114.5	-	-
W-SMR Rebar	million kg	Triangular	2.5	3.5	5.7	-	-
W-SMR Steel	million kg	Triangular	5.1	9.6	17.8	-	-
W-SMR Construction Workforce Reduction	%	Uniform	0	-	73	-	-
Construction Equipment Use Reduction	%	Uniform	0	-	20	-	-
I&C EIOLCA Emissions	million kg CO_2-eq	Uniform	7.1	-	28.4	-	-
W-SMR Operational Workforce Reduction	%	Uniform	0	-	73	-	-
Standard Maintenance, Repair, and Refurbishment	kg CO_2-eq/kwh	Triangular	0.0022	0.0039	0.0108	-	-
AP100 Steel / SNUPPS Steel	%	Uniform	19*	-	100	-	-
W-SMR Steel / SNUPPS Steel	%	Uniform	6*	-	100	-	-
100% Recycling Scenario Emissions	%	Uniform	87	-	100	-	-
W-SMR Decommissioning Duration	Year(s)	Uniform	4*	-	10	-	-

2.2.5 Uranium Mining and Milling

The uranium mining and milling stage is where uranium ore is extracted from the earth and processed into triuranium octoxide (U_3O_8) or "yellowcake." (see Appendix A.3) Three primary methods of mining are considered: in situ leaching, underground, and open pit mining. The World Nuclear Association estimates that 46%, 37%, and 17% of uranium mining is done by in situ leaching, underground, and open pit, respectively [49].

The ore grade of a uranium deposit has a large impact on energy use in the mining and milling stage of the uranium fuel cycle. The grade indicates the concentration of uranium within the ore. Lower ore grades require more material ore to be mined and processed to get the desired amount of uranium resulting in higher GHG emissions (see Appendix A.3). Table 2.4 outlines the mines, ore grades and emissions per tonne of (U_3O_8) recovered from the mining and milling process [50, 51, 52].

Table 2.4: Mining & Milling Ore Grades and Emissions [50, 51, 52].

Uranium Mine	**Mining Method**	**Ore Grade ($\%U_3O_8$)**	**% of World Uranium Production**	**Emissions (t CO_2/t U_3O_8)**	**Standard Deviation (+/-t CO_2/t U_3O_8)**
Ranger	Open Pit	0.28 - 0.42	4%	14.1	2.3
Olympic Dam	Underground	0.064 - 0.114	6%	50.4	13
Rossing	Open Pit	0.034 - 0.041	3%	45.7	4.2
Beverley	In-Situ Leaching	0.18	1%	10.3	3
McArthur River	Underground	14.24	14%	9.6	N/A

The Ranger, Olympic Dam, Rossing, Beverley, and McArthur River uranium mines represent 28% of the world's total uranium production. The lack of data for other mining operations resulted in the use of these mines as a representative sample of total uranium production. Table 2.3 provides the mining and milling triangular distribution using the lowest available estimate from the Beverly mine (+/- 3 t CO_2/t U_3O_8 standard deviation) and the Olympic Dam (+/- 13 t CO_2/t U_3O_8 standard deviation) mine for the highest available estimate. A weighted average of the GHG emissions from mining calculated by emissions from each mine, the world uranium production, and the mining method distributions (see Equation A.2) was used as the best estimate.

2.2.6 Conversion

The uranium conversion stage is where the U_30_8 is stripped of all remaining impurities and converted to hexafluoride (UF_6). This three-step phase is detailed in Appendix A.4. Table 2.3 provides the parameters used in the electrical and thermal energy requirement triangular distributions to account for uncertainty among the estimates in Table A.2. An emission factor of 560 g CO_2-eq/kwh was assumed for the US electrical grid [53]. This is used to convert the electrical energy needed during the conversion process to kg CO_2-eq. A high-efficiency boiler running at 80% efficiency is assumed for the thermal energy requirements to calculate the amount of CO_2-eq/tonnes U.

2.2.7 Enrichment

The enrichment stage is where the uranium in UF_6 from the conversion stage becomes enriched to 3 to 5%. There are two methods of enriching uranium, gaseous diffusion and gas centrifuge with the former being 40 times more energy intensive than the latter. Warner (2012) outlines previous studies where a combination of diffusion and centrifuge methods were used to enrich the uranium. Energy requirements for each enrichment method can be found in Appendix A.5. This study only includes the centrifuge method, because sole diffusion plant in Paducah, KY closed in May 2013. Table 2.3 provides the parameters in a gas centrifuge triangular distribution to account for the energy requirement uncertainty. Table 2.2 outlines annual enriched uranium needed by each NPP. This is calculated from the UF_6 obtained from the conversion stage and an assumed product (enrichment %) and tails assay. Typically, the higher the product assay, the less enriched UF_6 is produced during the nuclear fuel cycle. The amount of enriched UF_6 is used to calculate the Separative Work Units (SWUs) needed in the enrichment process. The total lifetime emissions are calculated by multiplying the lifetime SWUs by the energy requirements of the centrifuge method.

2.2.8 Fuel Fabrication

The final stage in the nuclear fuel cycle is fuel fabrication where the enriched UF_6 is converted to uranium dioxide (UO_2) in a powder form. The UO_2 powder is then processed into pellets. Table 2.3 provides the parameters used in the electrical and thermal energy fuel fabrication triangular distributions[5] among the estimates in Table A.3. Like the conversion process, the U.S. electrical grid emissions and 80% efficiency is assumed for the thermal energy requirements to calculate the amount of CO_2-eq/t U.

2.2.9 Construction[6]

The construction of each successive generation of 1,000 MW_e NPP has become increasingly more efficient, using less concrete and less steel without sacrificing safety. Generation III+ plants, such as the AP1000, employ modular construction methods that can lead to additional reduced construction time, materials, and waste generation. The AP1000 is estimated to use about 20% of the amount of concrete and

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[5] The reported mean is used as the best estimate for the triangular distribution.

[6] Emission factors of 0.4 kg CO_2-eq/kg of concrete, 4.4 kg CO_2-eq/kg of rebar, and 3.3 kg CO_2-eq/kg of steel were assumed. Steel is assumed to be non-structural steel. Rebar is assumed to be structural steel.

rebar as a SNUPPS given the about the same electrical output. The AP1000 is able to use "60% fewer valves, 75% less piping, 80% less control cable, 35% fewer pumps, and 50% less seismic building volume than in a conventional reactor [54]," because it utilizes advanced modular construction methods with about 350 modular components. This reduces the total amount of construction material required to build the AP1000. While the W-SMR is considered 100% modular, there are no SMRs under construction or in commercial operation. As such, there is no data on the amount of concrete and steel required to build an SMR so these values were estimated by calculating the volume of concrete and steel in AP1000 containment building and scaling to the size of a W-SMR for the upper bound. Peterson et al. (2005) [55] estimated the physical dimensions and the amount of steel and concrete needed to construct a General Atomics 286 MW_e Gas Turbine Modular Helium Reactor (GT-MHR) SMR. A lower bound was calculated by scaling the containment volume to the size of a W-SMR (see Appendix A.7).

There are no data available on the benefits of modularity to a NPP. In a case study, Quale et al. [56] estimates the emissions from the construction of modular homes and traditional homes built on-site (see Appendix A.7.1). The modularity reduction from the SNUPPS in concrete, rebar, and steel was used to set the minimum of the modular reduction factor uniform distribution in Table 2.3. The maximum was set based on the percent change from the scaled W-SMR estimate from the AP1000 to the scaled up estimate from the GT-MHR (see Appendix A.7.1).

These modularity reductions were factored into the scaled W-SMR estimates from the AP1000 for a best estimate. Table 2.5 outlines the utilization of a triangular distribution to account for uncertainty among the amount of concrete, rebar, and steel needed for a W-SMR.

Table 2.5: W-SMR Material Distribution.

Desciption	**Scaled From GT-MHR (Min)**	**Modular Reduction (Best Estimate)**	**Scaled From AP1000 (Max)**
Concrete Triangular Distribution (Million kg)	52.3	71.2	114.5
Rebar Triangular Distribution (Million kg)	2.5	3.5	5.7
Steel Triangular Distribution (Million kg)	5.1	9.5	17.8

Note: The modular reduction column contains the reported mean values from Monte Carlo simulation. The parameters are uncertain variables based on random draws from uniform distributions defined in Table 2.3.

Chapman et al. (2012) [57] provides estimates for the emissions from the construction workforce and equipment usage for a 1,000 MW_e reactor. Table A.8 outlines the carbon emissions generated from transportation of the workers over the period of construction for each type of power plant. Additional details can be found in Table A.9. Table 2.3 outlines the W-SMR construction workforce emissions reduction from a typical 1,000 MW_e NPP using a uniform distribution. The minimum is 0% assuming there is no additional reduction from the estimate in Table A.8. The maximum is 73% based on the worker reduction in Table A.6.

The estimated annual carbon emissions generated from equipment usage during construction for a traditional 1,000 MW_e NPP [57] and a scaled estimate of a W-SMR are 3.34 and 0.64 million kg CO_2-eq respectively (see Table A.9). Table 2.3 outlines the W-SMR construction equipment emissions reduction uniform distribution. The minimum is 0% assuming there is no additional reduction from the scaled estimate from equipment usage. The maximum is 20% based on the worker reduction in Table A.6.

The GHG emissions generated from the production of I&C equipment for each NPP was estimated using EIOLCA [40]. Assuming low-end and high-end cost estimates of $25 million and $100 million [58] and all equipment falls in sector 334111[7] for electronic computer manufacturing, the estimated GHG emissions from I&C production for a SNUPPS is between 7.1 and 28.4 million kg of CO_2-eq. Table 2.3 outlines the uniform distribution used to estimate the emissions from SNUPPS I&C production. The AP1000 and W-SMR GHG emissions are estimated by multiplying the percentage of component steel in an AP1000 and W-SMR compared to a SNUPPS (See Section 2.2.10).

2.2.10 Operation and Maintenance

The operation and maintenance (O&M) is the stage where the GHG emissions from tasks, such as operating diesel generators during an outage, employee travel to work, and repair, replacement, refurbishment, or upgrades that take place during each plant's lifetime are captured. A PCA analysis was used to estimate employee travel based on the methodology in Chapman et al. (2012) [57], whereas an EIOLCA was implemented for the other tasks [42, 59]. Chapman et al. (2012) [57] provides estimates for the emissions from employees traveling to work during the operation of a 1,000 MW_e NPP. Table A.10 outlines the carbon emissions generated from transportation from the employees over the lifetime for each power plant. The commuting trips for the W-SMR were scaled based on the electrical output. To account for staffing uncertainty, a uniform distribution is used with the same parameters as the workforce reduction uniform distribution in Table 2.3[8].

A triangular distribution is used to estimate the GHG emissions from maintenance, repair, and refurbishment for the SNUPPS. White and Kulcinski's (2000) [42] estimate of 0.0022 kg CO_2-eq/kwh is used as

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[7] Sector 334111 of the North American Industry Classification System (NAICS) is used to classify economic activity of electronic computer manufacturing.

[8] Current regulations and staffing requirement ensure that one reactor operator and one senior reactor operator are required for the operation of one nuclear unit. The inherent simplicity of a W-SMR could reduce the support staff significantly.[60]

the minimum, Fthenakis and Kim's (2007) [59] estimates of the average and maximum, 0.0039 and 0.0108 kg CO_2-eq/kwh, are used as the best estimate and maximum respectively. Table 2.3 outlines the parameters for the standard maintenance, repair, and refurbishment triangular distribution.

The AP1000 uses about 20% of the non-structural steel as a SNUPPS. It is assumed components in NPPs, such as the reactor vessel, steam generator, and other equipment use non-structural steel in their production. Because these components generally require standard maintenance over time, the reduction in the amount of non-structural steel needed was used to estimate a reduction in maintenance, repair, and refurbishment. Table 2.3 shows a uniform distribution where the minimum is the fraction of non-structural steel in an AP1000 and a W-SMR compared to a SNUPPS, respectively. The maximum value is 100%, and assumes the AP1000 or W-SMR requires the same maintenance as a SNUPPS. The values from the standard maintenance, repair, and refurbishment triangular distribution were multiplied by the "AP100 Steel / SNUPPS Steel" and a "W-SMR / SNUPPS Steel" uniform distributions in Table 2.3 resulting in an estimate for kg of CO_2-eq/kwh needed for maintenance, repair, and refurbishment of the AP1000 and W-SMR.

2.2.11 Decommissioning

The decommissioning stage involves dismantling, decontaminating, and removing the NPP. Additional details on decommissioning can be found in Appendix A.9. There is little data available on GHG emissions from NPPs in the U.S. Seier and Zimmerman (2014) [61] is used as the basis for estimating GHG emissions from decommissioning of the Greifswald nuclear power station (KGR) in Germany because of the transparency and availability of data. For decommissioning stage, Seier and Zimmerman (2014) [61] estimated KGR produced 11.27 g CO_2-eq/kWh. The reported GHG emissions are higher than other studies primarily because KGR operated for about 17 years with a capacity factor of about 77%. While Seier and Zimmerman's (2014) [61] analysis contained final storage, this was not included in our study because there is uncertainty with long-term storage solutions in the US. Typically, dry interim storage casks are housed in an outdoor storage area requiring a minimal amount of electricity compared to the electricity generated by the host NPP over its lifetime.

The KGR 1,760 MW_e NPP required 1.5 million tonnes of concrete during construction, and a SAFSTOR strategy was utilized for the decommissioning. The energy required to decommission a SNUPPS, AP1000, and a W-SMR are scaled relative to each reactor's concrete use compared to the KGR. The majority of parts and components of an NPP are not radioactive and as a result most parts can be recycled [62]. Seier and Zimmerman's (2014) [61] estimate for 100% recycling of residual materials results in a 13% reduction in GHG emissions. Table 2.3 outlines the recycling emissions uniform distribution. The minimum is a 100% recycling scenario where 87% of the emissions are produced from the 0% recycling scenario. The maximum is a 0% recycling scenario during decommissioning. Table 2.6 outlines the emissions for the decommissioning process for each plant for the 0% recycling scenario.

Table 2.6: Facility Decommissioning Emissions.

	KGR	**SNUPPS**	**AP1000**	**W-SMR**
			(Million kg CO_2-eq)	
Facility and Building Deconstruction	728	589	113	34
Radioactivity Measurements	44	36	7	2
Cutting and Decontamination	111	90	17	5
Interim storage	979	3	3	1
Total	1,861	718	140	42

SMRs are designed with simplicity in mind therefore, the equipment used in the decommissioning phase will use less energy compared to a 1,000 MW_e NPP. The GHG emissions generated from equipment use of a W-SMR scaled by the electrical output from a 1,000 MW_e NPP. A uniform distribution representing the reduction in GHG emissions due to a reduction in equipment use with a lower bound of 0% and a higher bound of 20% is utilized. The lower bound parameter assumes there are no additional GHG emissions reductions from the modularity of SMRs, while the higher bound assumes a 20% reduction based on modularity (see Appendix A.7.1). This is applied by multiplying the W-SMR total facility decommissioning emissions with the difference between 100% and the Construction Equipment Use Reduction distribution.

Chapman et al. (2012) [57] estimates emissions from employees traveling to work during decommissioning at 1,000 MW_e NPP. Table A.12 outlines the carbon emissions generated from transportation for these employees. Commuting trips for the W-SMR were scaled down based on the plants' electrical outputs. The decommissioning duration for the W-SMR is a uniform distribution where the minimum is scaled down based on the construction time of the AP1000 and the maximum is 10 years based on decommissioning workforce duration in (see Appendix A.9).

2.3 Results

A Monte Carlo simulation of 100,000 samples using the risk analysis software package @Risk was used with a chi-square binning arrangement of equal intervals to estimate the stochastic mean GHG emissions per kwh for each NPP. Figure 2.2 outlines the mean and 90% confidence interval emissions for the nuclear fuel cycle, construction, O&M, decommissioning, and non-fuel related (construction, O&M, and decommissioning) stages for each type of plant. The error bars in Figure 2.2 represent the 90% confidence interval.

Figure A.3 identifies the distributions that have the most influence on the life cycle GHG emissions for the W-SMR.

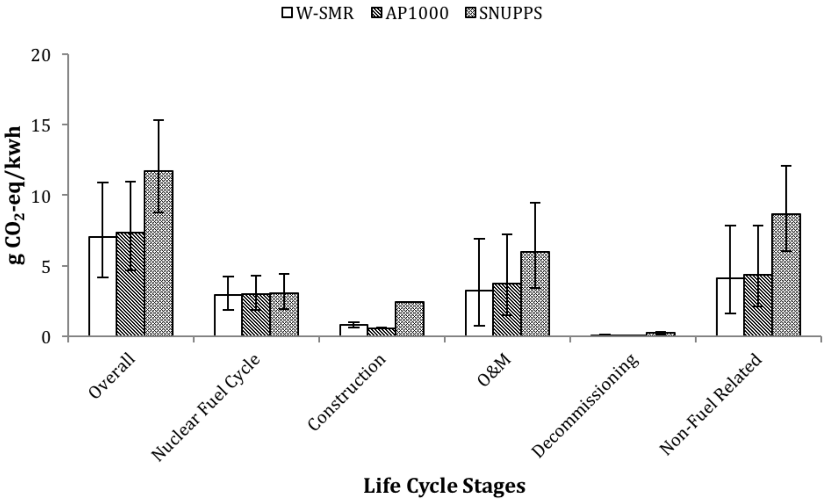

Figure 2.2: Mean and 90% confidence interval CO_2-eq emissions for W-SMR, AP1000, and SNUPPS from Monte Carlo sampling.

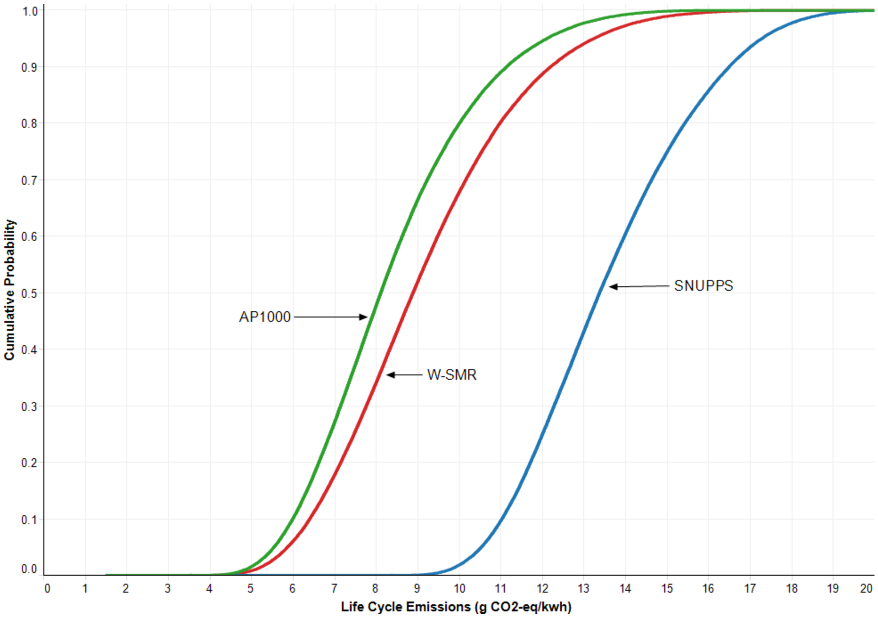

Figure 2.3: W-SMR, AP1000, and SNUPPS Cumulative Distribution Function Life Cycle Emissions.

Figure 2.3 shows the cumulative distribution function produced by @Risk. The stochastic means, standard deviations, 90% confidence intervals of the distributions, and coefficient of variations (COVs) are shown for each power plant in Table 2.7. COVs are used as an important metric in this analysis because it illustrates the extent of variability in relation to the sample mean.

The W-SMR produces 9% more life cycle GHG emissions than the AP1000. Because there is less than a 20% difference between the means and 90% confidence intervals, the difference is not significant in the real world [63]. As a result, their estimated life cycle GHG essentially the same. The differences between the Generation II and Generation III+ power plants are due to the construction, operation and maintenance, and decommissioning stages. The AP1000 and W-SMR, the SNUPPS and W-SMR, and the SNUPPS and AP1000 have a mean difference of -0.8, 4.5, and 5.2 g of CO_2-eq/kwh, respectively. Given the added estimated modularity, the W-SMR produces less GHG emissions than the AP1000 (AP1000 emissions - W-SMR emissions) 34% of the time. On average the AP1000 and W-SMR produces 61% and 67% of the lifetime GHG emissions, respectively, compared to the SNUPPS. AppendixA.10 outlines the contribution each stage makes toward the total emissions. The SNUPPS generates the most GHG emissions per kwh of all the power plants within the construction, O&M, and decommissioning stages. On average, the W-SMR produces less GHG emissions per kwh than the AP1000 in the O&M stage while the AP1000 produces less GHG emissions per kwh during the construction and decommissioning stages.

When examining the non-fuel related stages, on average the W-SMR produces about the same GHG emissions per kwh as the AP1000 and less than the SNUPPS. In the scenario where the nuclear fuel is not considered, the AP1000 and the W-SMR, have a mean difference of 0.2 g of CO_2-eq/kwh while the SNUPPS and W-SMR have a mean difference of 5.4 g of CO_2-eq/kwh. The W-SMR is estimated to produce less GHG emissions per kwh than the AP1000 50% of the time. On average the AP1000 and W-SMR is estimated to produce 47% and 45% of the non-fuel related GHG emissions, respectively, of the SNUPPS. The W-SMR can reduce its life cycle GHG emissions by improving its thermal efficiency. By increasing its installed capacity to 260 MW_e, matching the thermal efficiency of the AP1000, the W-SMR improves its life cycle GHG emissions to a mean (and 90% confidence interval) of 8.3 g of CO_2-eq/kwh (5.2 to 12.3 g of CO_2-eq/kwh).

In a low-carbon scenario where the emission factor of the U.S. electrical grid is 10 g of CO_2-eq/kwh, the life cycle GHG emissions of the W-SMR and AP1000 shifts to 7.6 and 7.2 g of CO_2-eq/kwh, respectively. Using a high-carbon scenario of coal only at about 980 g of CO_2-eq/kwh we see the life cycle GHG emissions of the W-SMR and AP1000 shifts to 10.3 and 9.3 g of CO_2-eq/kwh, respectively.

2.3.1 Nuclear Fuel Cycle

The nuclear fuel cycle calculations are common to all three designs. Table 2.7 shows a similar COV amongst all three NPPs because the distributions for the nuclear fuel cycle for all three plants are similar. Typically, the higher the enrichment percentage, the less enriched UF_6 is produced during the nuclear fuel

Table 2.7: Summary Statistics for Life Cycle GHG Emissions for W-SMR, AP1000, and SNUPPS. The COV is the σ/μ. The summary statistics contain rounded values.

Stage	**W-SMR**					**AP1000**					**SNUPPS**				
	(g of CO_2-eq/kwh)														
	μ	σ	**COV**	**5%**	**95%**	μ	σ	**COV**	**5%**	**95%**	μ	σ	**COV**	**5%**	**95%**
Overall	9.1	2.2	0.3	5.9	13.2	8.4	2.0	0.2	5.5	12.1	13.6	2.1	0.2	10.5	17.3
Nuclear Fuel Cycle	4.6	1.1	0.2	3.0	6.7	3.7	0.9	0.2	2.4	5.4	3.7	0.9	0.2	2.4	5.4
Construction	0.9	0.1	0.1	0.7	1.1	0.6	0.0	0.0	0.6	0.6	2.6	0.0	0.0	2.6	2.7
O&M	3.2	1.9	0.6	0.8	6.9	3.7	1.8	0.5	1.5	7.2	6.0	1.9	0.3	3.4	9.4
Decommissioning	0.4	0.1	0.2	0.3	0.5	0.3	0.0	0.0	0.3	0.3	1.2	0.1	0.0	1.1	1.3
Non-Fuel Related	4.5	1.9	0.4	1.9	8.2	4.6	1.8	0.4	2.3	8.1	9.8	1.9	0.2	7.3	13.3

cycle (See Table 2.2 and Section 2.2.7). The AP1000 is estimated to have a burnup rate (fuel utilization) of around 50 GWd/ tonnes of U. It is assumed the W-SMR will have a similar burnup rate as the AP1000. This is possible due to the lower power density of the W-SMR. As a result, the W-SMR does not have as many safety related core design constraints as larger NPPs. Though the W-SMR and the AP1000 are estimated to have similar burnup rates, a lower thermal efficiency requires additional uranium to produce electricity. This results in the W-SMR producing more GHG emissions per kwh than the AP1000 and SNUPPS in the nuclear fuel cycle.

2.3.2 Construction

The amount of concrete and rebar in the SNUPPS and AP1000 is fairly certain based on the assumptions made in Table 2.1. The non-structural steel in an AP1000 was estimated from the distribution in Table 2.3. The non-structural steel of the SNUPPS was calculated by multiplying the non-structural steel in an AP1000 by 5. This is based on the ratio of about 5:1 when comparing the amount of rebar and concrete in a SNUPPS to AP1000 (See Table 2.1). As such the uncertainty represented by the COV shown in Table 2.7 for the AP1000 and SNUPPS is small compared to the W-SMR. The AP1000 and W-SMR achieve first order stochastic dominance over the SNUPPS with lower construction emissions. Although the construction duration for AP1000 Unit 2 and 3 in South Carolina is expected to be, on average, about 6.5 years, the overall results are relatively insensitive to this parameter (See Appendix A.10).

2.3.3 Operation and Maintenance

The estimates for operation and maintenance share the same initial uncertainty of the distributions found in White and Kulcinski (2000) [42] and Fthenakis and Kim (2007) [59]. Though the reduction in non-structural steel reduces the mean emissions, the uncertainty around the amount of steel produces a larger COV for the W-SMR and AP1000 compared to the SNUPPS. Figure A.3 identifies the Standard Maintenance, Repair and Refurbishment and the ratio of W-SMR:SNUPPS steel distributions as the most influential for the W-SMR. The SMR / SNUPPS uniform distribution feeds directly into the Standard Maintenance, Repair and Refurbishment modularity factor.

2.3.4 Decommissioning

The energy needed to decommission each plant is scaled by total concrete of the KGR plant. Because the amount of concrete in W-SMR is uncertain, the emissions generated during decommissioning are also uncertain. The emission estimates for decommissioning are assumed to have minimal uncertainty for the

AP1000 and SNUPPS based on the assumptions in Seier and Zimmerman (2014) [61] and Chapman et al. (2012) [57]. Though the 100% recycling scenario distribution is the same for each plant, the uncertainty surrounding the amount of construction materials needed for the W-SMR contributes to the larger COV compared to the AP1000 and SNUPPS. The AP1000 outperforms the W-SMR in this stage because there is less uncertainty for the AP1000 than the W-SMR and the AP1000 generates more electricity over its lifetime than the W-SMR.

2.3.5 Non-Fuel Related (Construction, O&M, and Decommissioning)

The non-fuel related emissions are estimated by removing nuclear fuel cycle stages for the three types of NPPs. The COVs for the SNUPPS, AP1000, and W-SMR are 0.19, 0.38, and 0.43. It is during the operation and maintenance stage where the W-SMR achieves its marginal superiority over the AP1000.

2.4 Discussion

To illustrate the overall competitiveness of the W-SMR, LCOE estimates from Abdulla and Azevedo (Revised and Resubmitted) [36] and the EIA [34] are combined with life cycle GHG emissions estimates presented here to determine if the W-SMR can be utilized as the best “middle option” for current PWR technologies. LCOE estimates for the nth of a kind W-SMR and AP1000 sited in the southeastern US are from Abdulla and Azevedo (Revised and Resubmitted) [36] using expert elicitation with a 3% discount rate [36]. The LCOE estimates for the nth of a kind W-SMR and AP1000 exclude owner’s costs for site-work, transmission upgrades, etc. The EIA estimates transmission investment cost of \$1.1/MWh (2012\$) for advanced nuclear power plants [34]. GHG emission estimates for the SNUPPS falls within the estimated range of 9 to 110 g CO_2-eq/kwh for Generation II PWRs in the Warner and Heath (2012) [39] harmonization study. Because of this, the SNUPPS is used to represent Generation II PWRs. Warner and Heath (2012) [39] attributes the large variation in estimates to the primary source energy mix, the uranium enrichment method, the LCA method, and the future of uranium ore grade markets. LCOE estimates for the SNUPPS are based on the assumption that typically existing plants have paid off their initial capital cost [64]. Figure 2.4 shows that on average, the W-SMR and AP1000 outperform Generation II NPPs in life cycle emissions. All LCOE estimates are in 2012 dollars.

Figure 2.5 compares the NPPs outlined in Figure 2.4 to other types of power plants. The life cycle GHG emission estimates are shown in log scale. Non-nuclear power plant GHG emission data points are sourced from the Intergovernmental Panel on Climate Change (IPCC) special report on renewable energy

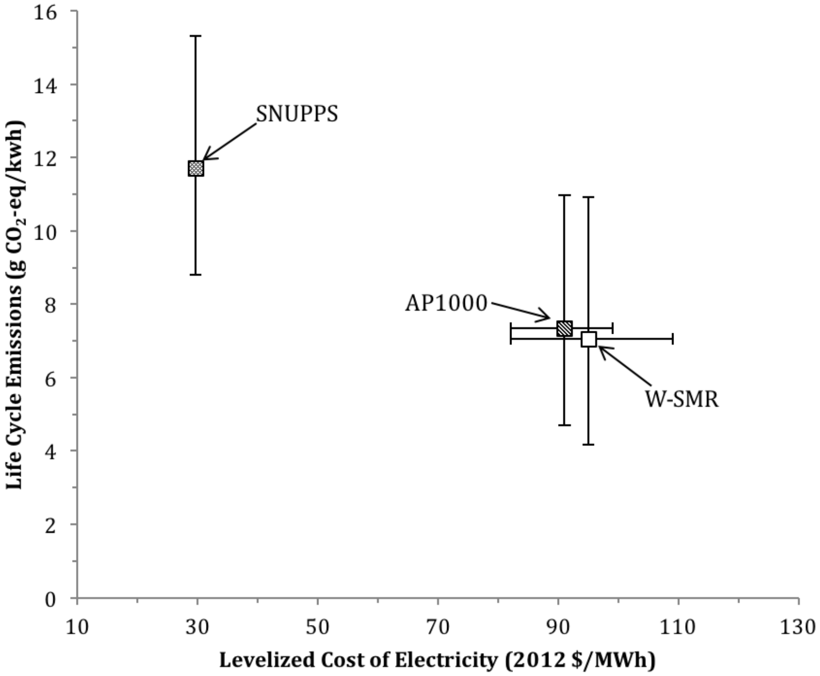

Figure 2.4: Nuclear Power Life Cycle GHG Emissions and LCOE Comparison. AP1000 and nth of a kind W-SMR LCOE estimates (estimates are adjusted to 2012$ using the US Bureau of Labor Statistics CPI Inflation calculator) exclude owner's costs for site-work, transmission upgrades, and etc. [36]. SNUPPS LCOE estimates cost [64].

sources and climate change mitigation [65]. The LCOE estimates for the other non-nuclear energy sources entering service in 2019 are from the EIA's annual energy outlook [31].

The W-SMR and the AP1000 on average perform the best for life cycle GHG emissions against all forms of energy generation except for hydropower plants. The AP1000 on average performs better than the W-SMR for LCOE and slightly for life cycle GHG emissions.

Using the data presented in Figure 2.4 and Figure 2.5; it is possible to estimate the cost of carbon abatement by substituting coal and natural gas generation with nuclear generation. Assuming that coal and natural gas fired power plants produce lifetime GHG emissions of 1001 and 469 g of CO_2-eq per kwh [65], the cost of carbon abatement with an AP1000 against coal and natural gas is \$2/tonne of CO_2-eq (-\$13 to \$26/tonne of CO_2-eq) and \$35/tonne of CO_2-eq (\$3 to \$86/tonne of CO_2-eq), respectively. In comparison, a W-SMR the cost of carbon abatement against coal and natural gas is \$3/tonne of CO_2-eq (-\$15 to \$28/tonne of CO_2-eq) and \$37/tonne of CO_2-eq (-\$1 to \$90/tonne of CO_2-eq), respectively. To put these into perspective, the EPA estimates the social cost of carbon to be between \$16 and \$73/tonne of CO_2 by 2030 using a 5% and 2.5% discount rate in 2007 dollars, respectively [67].

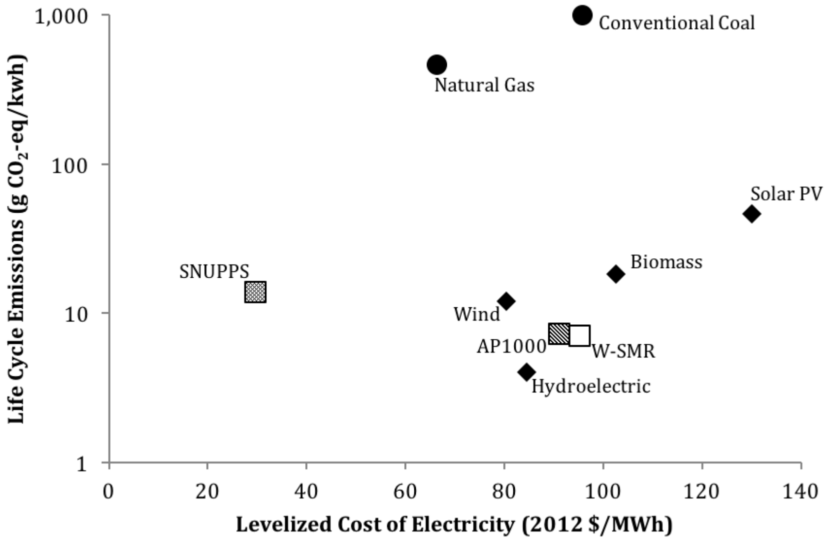

Figure 2.5: Electricity Generation Life Cycle GHG Emissions and LCOE Comparison. Non-nuclear LCOE data [31]. Non-nuclear Emission data [65]. The LCOE for non-nuclear power sources represent plants entering service in 2019. The LCOE for conventional coal does not include a $15 adder. This adder represents the cost of financing new coal plants without carbon capture technology to reflect the uncertainty of greenhouse gas legislation. A 3-percentage point adder is similar to a $15 per metric ton emissions fee [66]. AP1000 and nth of a kind W-SMR LCOE estimates (estimates are adjusted to 2012$ using the US Bureau of Labor Statistics CPI Inflation calculator) exclude owner's costs for site-work, transmission upgrades, and etc. [36]. SNUPPS LCOE estimates cost [64].

2.5 Conclusions and Policy Implications

Nuclear power is a critical part of the US medium-term plan to reduce future carbon emission. To inform this discussion, this research is the first to complete LCAs for two designs of future nuclear power plants, the Generation III+ (AP1000) and the SMR (W-SMR). In terms of life cycle GHG emissions, both new designs have smaller footprints than existing SNUPPS. These benefits are achieved by the reduction in building materials and the extensive use of factory-fabricated components.

Differences between the two new designs result in similar footprints. While the AP1000 has the benefits of economies of scale, the W-SMR's modular ability enables it to make up some of the difference through efficiencies in construction, operation and maintenance, and decommissioning. Compared to the AP1000, the relatively low thermal efficiency of the W-SMR is a major contributor to its life cycle GHG emissions. The strength of the case for the W-SMR achieving similar life cycle GHG emissions as the AP1000 depends on the resolution of uncertainties in the construction, operation and maintenance, and decommissioning phases of the plants. With the exception of hydropower, the W-SMR and the AP1000 have a smaller footprint than all other generation technologies including renewables.

Estimates from the EIA [31] and expert elicitation show that the AP1000 and W-SMR have a higher

LCOE than natural gas and conventional coal. This trade-off between higher costs but lower GHG emissions demonstrates that depending on the value placed on carbon, SMR technology could be economically competitive with fossil fuel technologies (i.e., Generation III+ plants and SMRs can be viewed as a suitable middle option for climate-mitigation strategies).

Though this study does not include a long-term solution for final storage of spent nuclear fuel, nuclear power can be viewed as a reliable, low-carbon, baseload energy solution. With the early retirement of four nuclear power plants since 2012, the eventual retirement of older units in the nuclear fleet, and the United States pledging to reduce GHG emissions by 26%-28% over the next decade, installing new capacity using Generation III+ plants and SMRs creates an alternative for states and firms looking to comply with GHG emission regulation while providing baseload power to customers.

Chapter 3

The socioeconomic characteristics of communities surrounding baseload power generation facilities[1]

This work estimates and compares the socioeconomic characteristics that exist within counties and communities 0-5, 5-10, and 10-15 miles away from nuclear, coal, natural gas power plants. This work explores the socioeconomic disparities (i) at the county level, (ii) at the community level relative to the sited power plant county, and (iii) the evolution of socioeconomic characteristics over time. These estimates provide evidence that socioeconomic characteristics of home counties and communities near power plants differ by generating technology. The findings can be used to suggest equity issues regarding the community characteristics should be included in the discussion of the siting and conversion existing power plants to use cleaner fuel sources.

3.1 Introduction

In 2015 energy from coal, natural gas, and nuclear power plants produced approximately 3,500 TW_h of electricity and accounted for 85% of total net generation in the US [68]. Coal and natural gas power plants each contributed about 33% of all generation in the US, while Generation II nuclear power plants accounted for about 19% and produced 62% of the emission-free electricity [24]. Communities surrounding power plants are exposed to different and varying levels of environmental hazards. As a byproduct of

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[1] An early version of his work has been published in *Transactions of the American Nuclear Society* as shown in the reference below:
Carless, T.S. and Fischbeck, P.S. (2016). "The Economic and Societal Impact of Baseload Power Generation on Local Communities." Transactions of the American Nuclear Society, Vol. 115, Las Vegas, NV November 6-10, 2016. A full version of this work has been submitted to Risk Analysis in March 2018.

electricity, combustion fossil fuel plants release emissions, such as CO_2, N_2O, NO_x, SO_2, and particulate matter. The compounds CO_2, CH_4, and N_2O are major greenhouse gases (GHGs) that have been linked to global climate change. The release of NO_x and SO_2 has been shown to have a negative impacts on human health and contribute to smog and acid rain [69]. Communities near power plants are often subjected to negative externalities, such as pollution, noise, undesirable visuals, and safety concerns. Though nuclear power plants do not produce air emissions, there are concerns of nuclear waste, radiation leaks into the environment [70], and Fukushima-level accidents. Residents living within 10 miles of a nuclear power plant are also within the plume exposure pathway Emergency Planning Zone (EPZ).

With electricity generation, there are economic, safety, and environmental trade-offs between nuclear, coal, and natural gas power plants. Comparisons between power plants are typically made using the levelized cost of electricity (LCOE) and life cycle GHG emissions; however, the presence of power plants can have both positive and negative impacts on surrounding communities. There have been several works published on hedonic pricing methods, health effects, housing and labor markets on communities near power plants. Davis (2011) [71] found that communities living within 2 miles of fossil fuel power plants experience a 3-7% decrease in housing values using a hedonic pricing method. There is further evidence that those that live closer experience larger decreases [71].

Bezdek and Wendling (2006) [72] analyzed the effects that nuclear waste disposal facilities and power plants have on property values, economic growth, tax revenues, public services, community development, employment, and schools. Their analysis inferred nuclear facilities are responsible for as much as 20-30% of the total employment within their counties and up to 35% of the local incomes. Taxes and fees from nuclear facilities fund about half of county and school district budgets. Bezdek and Wendling (2006) also reviewed the work done by Nelson (1981) [73], Gamble and Downing (1982) [74], and Galster (1986) [75]. Nelson (1981) [73] investigated the impact on property values following the Three Mile Island accident in 1979 with a hedonic price model[2] and found there was no statistically significant decrease in homes near Three Mile Island.

Within the environmental justice space, Bullard (2000) [76] explored pollution and stressors from industrial expansion on black communities in the South. Similarly, Pastor et al. (2004) [77] and Mohai et al. (2009) [78] investigate socioeconomic disparities in communities near industrial facilities. Both found communities of color significantly more likely to live within a mile of a polluting facility. While past studies have investigated the effects, disparities, and the siting related to power plants and industrial sites on surrounding communities, this study investigates the socioeconomic characteristics and disparities that exist within counties and communities that have nuclear, coal, natural gas power plants. This explores the so-

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[2] A hedonic price model is a method for determining the price or value of a good based on internal or external factors.

cioeconomic disparities (i) at the county level, (ii) at the community level relative to the sited power plant county, and (iii) the evolution of socioeconomic characteristics over time.

Outside of the typical cost and emissions metrics, this work serves as an extension by investigating and comparing the socioeconomic disparities of counties and communities 0-5, 5-10, and 10-15 miles within baseload nuclear, coal, or natural gas power plants at a national level over time using census data. To accomplish this, the study is divided into two analyses.

Socioeconomic Analysis

(i) County-level analysis: Investigate the socioeconomic differences that currently exist in counties with nuclear, coal, and natural gas power plants.

(ii) Community-level analysis: Investigate the socioeconomic differences that currently exist in communities 0-5, 5-10, and 10-15 miles away from nuclear, coal, and natural gas power plants as well as examining the relationship between the communities near these power plants and their home counties.

Socioeconomic Trend Analysis

(i) Community-level analysis: Investigate the evolution of the socioeconomic differences in communities 0-5, 5-10, and 10-15 miles away from nuclear, coal, and natural gas power plants over time after the power plants begin generating electricity.

The socioeconomic indicators examined are population density, the percentage of black residents, the percentage of residents with Bachelor's degrees or above, household income, poverty rate, and home value.

3.2 Methods

3.2.1 General Data Sources

The Emissions & Generation Resource Integrated Database (eGrid) 9th edition [53] is used to capture detailed power plant data and characteristics, such as county, state, geographic coordinates, nameplate capacity, and capacity factor. US Census county-level data are from the US Census Bureau [79] and The Social Explorer [80]. Community data are from the US Census 2007-2011 American Community Survey (ACS) block group-level data [81] and 1970-2010 US Census tract-level data from Geolytic's Neighborhood Change Database (NCDB). While many variables in the ACS and NCDB are the same, there are differences. The ACS block group level data uses median household income and median home values, while the NCDB uses average household income and average home values.

3.2.2 Spatial Data Management

Spatial analysis is performed using ArcGIS in conjunction with eGrid, Census, and NCDB data with the "WGS_1984_Web_Mercator_Auxiliary_Sphere projected coordinate system and Mercator_Auxiliary_Sphere" projection. Figure 3.1 shows an example of the three primary investigation areas (0-5, 5-10, and 10-15 miles) for each nuclear, coal, and natural gas plant created in ArcGIS. Each power plant is located at the centroid of each investigation area.

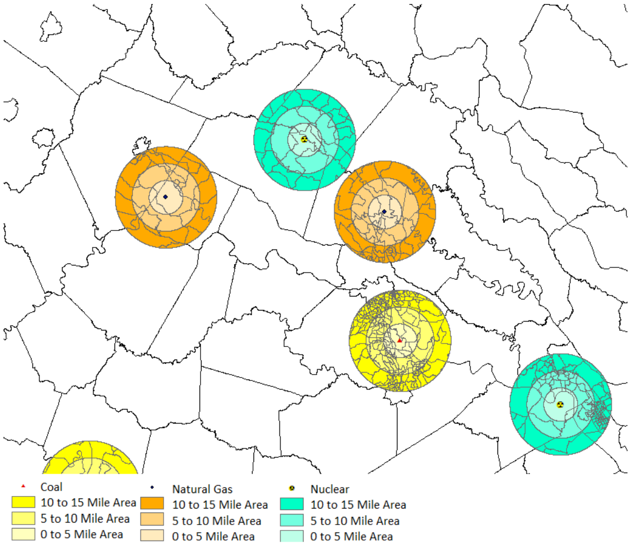

Figure 3.1: Sample image of the three investigation areas for each power plant type. Block groups contain the highest level of socioeconomic data resolution.

The classification for each power plant is based on the "Plant Primary Fuel Generation" category from eGrid. In total, there are over 2,000 power plant sites. These studies focus on larger operating plants with nameplate capacities ≥500 MW_e and capacity factor ≥20%. Overall, 490 power plants (235 coal, 190 natural gas, and 65 nuclear power plants) meet these constraints. To eliminate community overlap between technologies, power plant sites that are within 30 miles of each other (i.e., overlapping 15-mile circles) are removed from the analysis. With these restrictions, there are 184 coal, 137 natural gas, and 35 nuclear power plant sites. Figure 3.2 shows the location of the power plants included in the study. Because of data limitations in historical censuses (e.g., lack tract-level data in the 1970 and 1980 census), some of the analysis in this paper use a subset of the power plant data.

3.2.3 Socioeconomic Analysis

This analysis provides an indication of the socioeconomic conditions of communities near power plants using descriptive statistics and cross-sectional 2007-2011 ACS census data. As shown in Figure 3.2 there are

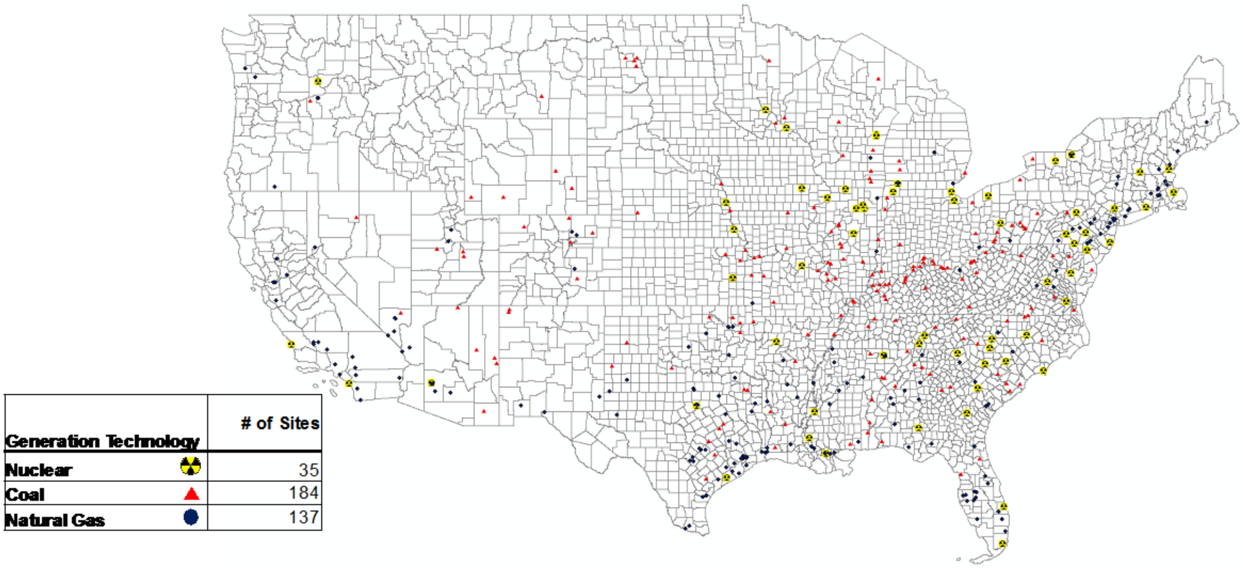

Figure 3.2: Locations of nuclear, coal, and natural gas power plants within the continental United States.

184, 137, and 35 communities investigated near coal, natural gas, and nuclear power plant sites, respectively. This study analyzes characteristics at the county-level and community-level using their socioeconomic indicators. The county-level analysis uses one-way ANOVA models to estimate the statistical significant differences between counties with nuclear, natural gas, and coal power plants for each socioeconomic indicator. Tukey's tests are used to compare their socioeconomic indicators. The Community-level analysis uses a two-way ANOVA models to estimate the statistical significant differences by power plant type and distance from the baseload power plant for each socioeconomic indicators. Tukey's tests are used to compare their socioeconomic indicators by power plant type and distance. A paired t-test is also used examine the relationship communities near power plants have with their home counties.

3.2.3.1 County-level Analysis

3.2.3.1.1 County-level Data Sources and Methods

County-level socioeconomic data on population density, percent of black residents, percent of residents with Bachelor's degrees or above, median household income, poverty rate, and median home value are sourced from the 2007-2011 ACS [81]. For the county-level analysis, one-way ANOVA tests by power plant type are used to quantify significant differences between power plant types for the home county-level values. The independent variable, Plant Type, is a categorical variable, while the socioeconomic indicators are dependent variables for separate ANOVA models. As a follow on, a post-hoc Tukey test is used to identify statistical significant differences in pairwise comparisons.

3.2.3.1.2 County-level Results

Table 3.1 shows the results from the one-way ANOVA models. There are power plant type main effects at the 0.001 significance level for all county-level socioeconomic indicators with the exception of %poverty at the 0.05 significance level.

Table 3.1: County-level one-way ANOVA tests of plant type effects summary statistics for the six socioeconomic indicators.

	term	df	Sum of Squares	Mean Square	F Statistic	p value
Population Density	Plant Type	2	7.13E+06	3.28E+01	32.85	0.000***
	Residuals	1065	1.16E+08			
%Black	Plant Type	2	3.95E-01	1.05E+01	10.53	0.000***
	Residuals	1065	1.99E+01			
%Bachelor's Degree or Above	Plant Type	2	6.93E-02	3.10E+01	31.03	0.000***
	Residuals	1065	1.19E+00			
%Poverty	Plant Type	2	1.75E-02	3.26E+00	3.26	0.039*
	Residuals	1065	2.86E+00			
Average Median Income	Plant Type	2	4.77E+09	1.84E+01	18.43	0.000***
	Residuals	1065	1.38E+11			
Average Median Home Values	Plant Type	2	6.58E+11	4.75E+01	47.47	0.000***
	Residuals	1065	7.38E+12			

Follow-on post-hoc Tukey pair-wise comparison tests are utilized to outline the specific differences for each indicator and power plant type (see Table 3.2). Figure 3.3 shows boxplots for each socioeconomic indicator at the county level for each power plant type with the numeric values representing the means. The means provided in Figure 3.3 can be used to calculate the mean differences shown in Table 3.2.

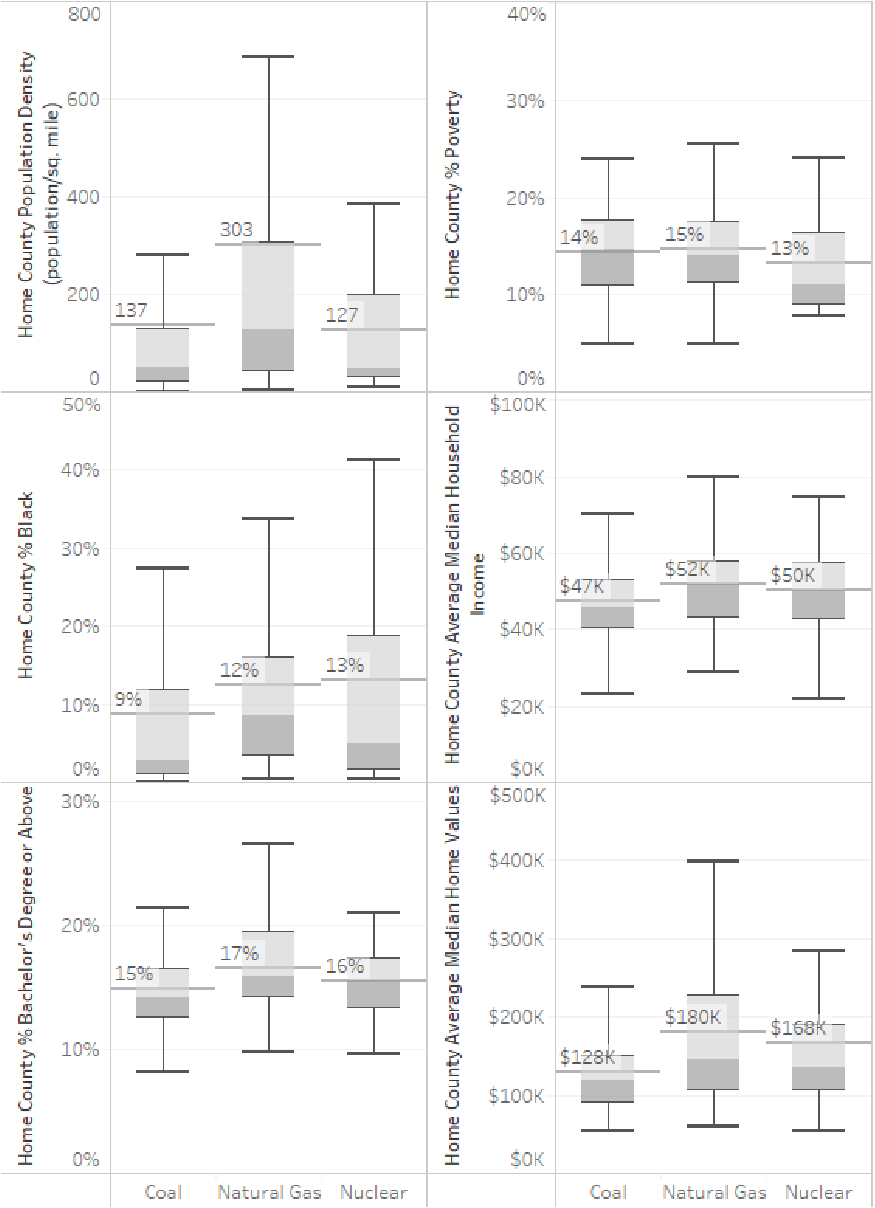

Figure 3.3: Current county-level boxplots for the six socioeconomic indicators with the numeric values representing the means.

Counties with natural gas power plants have significantly larger population density compared to counties with nuclear *(mean difference = 176 pop./sq. mile, adjusted p < 0.001)* and coal *(mean difference = 166 pop./sq. mile, adjusted p < 0.001)* power plants. The average share of black residents at the county level is significantly larger at the in counties with nuclear *(mean difference = 4.4%, adjusted p = 0.008)* and natural gas *(mean difference = 3.7%, adjusted p < 0.001)* power plants compared to coal plants. Counties with natural gas power plant have a significantly larger share of residents with Bachelor's degrees or above than counties with coal *(mean difference = 1.2%, adjusted p < 0.001)* and nuclear power plants *(mean difference*

Table 3.2: County-level post-hoc Tukey's tests for plant type for the six socioeconomic indicators.

	term	**Comparison**	**mean difference**	**2.5% level**	**97.5% level**	**adjusted p value**
Population Density (pop./sq. mile)	Plant Type	Natural Gas-Coal	166	116	217	0.000***
	Plant Type	Nuclear-Coal	-9	-92	73	0.961
	Plant Type	Nuclear-Natural Gas	-176	-260	-91	0.000***
%Black	Plant Type	Natural Gas-Coal	3.70%	1.60%	5.80%	0.000***
	Plant Type	Nuclear-Coal	4.40%	0.90%	7.80%	0.008**
	Plant Type	Nuclear-Natural Gas	0.70%	-2.80%	4.20%	0.897
%Bachelor's Degree or Above	Plant Type	Natural Gas-Coal	1.70%	1.20%	2.20%	0.000***
	Plant Type	Nuclear-Coal	0.70%	-0.10%	1.50%	0.117
	Plant Type	Nuclear-Natural Gas	-1.00%	-1.90%	-0.20%	0.016*
%Poverty	Plant Type	Natural Gas-Coal	0.20%	-0.60%	1.00%	0.82
	Plant Type	Nuclear-Coal	-1.20%	-2.50%	0.10%	0.065
	Plant Type	Nuclear-Natural Gas	-1.40%	-2.80%	-0.10%	0.030*
Average Median Income	Plant Type	Natural Gas-Coal	$4,469	$2,729	$6,209	0.000***
	Plant Type	Nuclear-Coal	$2,744	-$100	$5,587	0.061
	Plant Type	Nuclear-Natural Gas	-$1,725	-$4,646	$1,195	0.348
Average Median Home Values	Plant Type	Natural Gas-Coal	$51,724	$38,995	$64,453	0.000***
	Plant Type	Nuclear-Coal	$39,161	$18,360	$59,962	0.000***
	Plant Type	Nuclear-Natural Gas	-$12,563	-$33,927	$8,800	0.352

= 1%, adjusted p = 0.016). The average median household income is significantly larger for counties with natural gas plants than coal plants *(mean difference = $4,469, adjusted p < 0.001).* Average median home values are also significantly larger in counties with natural gas *(mean difference = $51,724, adjusted p < 0.001)* and nuclear power plants *(mean difference = $39,161, adjusted p < 0.001)* than for counties with coal plants.

3.2.3.2 Community-level Analysis

3.2.3.2.1 Community-level Data Sources and Methods

The 2007-2011 ACS block group level data [81] is utilized to measure and identify various socioeconomic indicators from communities 0-5, 5-10, and 10-15 miles from each generating station. The ACS block group data are used to represent the current community. The 2007-2011 ACS block group dataset was selected for this study because block groups provide the most detailed publicly available information from the US Census surveys at the highest resolution. Community-level analyses uses two-way ANOVA tests to measure the statistical significance of the power plant type and distance main effects of the nominal community values and community-to-power plant county ratios for the six socioeconomic indicators. The ratio between the community and the respective county the power plant is located serves as way to control for regional differences for each socioeconomic indicator (e.g., if the average home value for communities 0-5 miles away from a nuclear power plant is \$110,000 and the associated average county home value is \$100,000; then the community-to-power plant county ratio is 1.1. This indicates the average home value the community 0-5 miles away from this nuclear power plant is 10% higher than its associated county). Following the two-way ANOVA test, a post-hoc Tukey's test is used to identify where the statistical significant differences lie in a pairwise comparison. Tukey's tests correct for Type I errors during multiple comparisons by requiring a more conservative significance threshold. The current community ANOVA model is presented in Equation 3.1.

$$Y_{s,3,3} = \mu_s + PlantType_{s,3} + Distance_{s,3} + (PlantType \times Distance)_{s,3,3} + \varepsilon_{s,3,3} \tag{3.1}$$

Where Y is the dependent variable, s refers to the socioeconomic indicator of interest, *Plant Type* is an independent categorical variable with 3 levels that denotes the type of power plant (nuclear, coal, and natural gas) and *Distance* is an independent categorical variable with 3 levels used to describe the investigation area (0-5 miles, 5-10 miles, and 10-15 miles).

For comparisons between each community and the power plant home county, paired t-tests are used to measure the statistical significance. Paired t-tests are used to reduce intersubject variability since the objective is to make the comparison between the same subjects.

3.2.3.2.2 Community-level Results

The community-level two-way ANOVA statistical analysis provides comparative descriptive statistics for the current societal and economic demographics of communities near nuclear, coal, and natural gas power. The power plant type and distance main effects and interaction effects using nominal values for each community socioeconomic indicator are shown in Table 3.3 (See Table for full summary statistics). Table 3.3 contains the degrees of freedom, p-values, sum of square and mean square values, residuals, and F-statistics of each socioeconomic indicator from the two-way ANOVA model shown in Equation 1. Table 3.3 shows power plant main effects for all socioeconomic indicators and distance main effects for percentage of residents with Bachelor's degrees or above. There are no significant interactions effects.

Figure 3.4 shows boxplots and means for each socioeconomic indicator at the county and community level for each power plant type using the nominal socioeconomic values. Table 3.4 and Figure 3.4 provides an indication of the community socioeconomic indicators based on power plant type and distance. Post-hoc Tukey pair-wise comparison tests are used to determine the statistical significant differences between groups (e.g., 0-5 miles Nuclear vs 0-5 miles Coal) in the current community analysis to determine where specific differences lie. Table 3.4 shows the mean differences, adjusted p-values, and the 95% confidence interval

Table 3.3: Community-level two-way ANOVA tests of plant type effects summary statistics with nominal values for the six socioeconomic indicators.

	term	df	Sum of Squares	Mean Square	F Statistic	p value
Population Density	Plant Type	2	1.37E+07	6.87E+06	29.54	0.000***
	Residuals	1059	2.46E+08	2.33E+05		
%Black	Plant Type	2	3.12E-01	1.56E-01	8.06	0.000***
	Residuals	1059	2.05E+01	1.93E-02		
%Bachelor's Degree or Above	Plant Type	2	2.93E-01	1.47E-01	16.5	0.000***
	Distance	2	1.46E-01	7.28E-02	8.18	0.000***
	Residuals	1059	9.42E+00	8.89E-03		
%Poverty	Plant Type	2	9.17E-02	4.58E-02	11.62	0.000***
	Residuals	1059	4.18E+00	3.95E-03		
Average Median Income	Plant Type	2	1.03E+10	5.14E+09	27.1	0.000***
	Residuals	1059	2.01E+11	1.90E+08		
Average Median Home Values	Plant Type	2	8.68E+11	4.34E+11	50.95	0.000***
	Residuals	1059	9.02E+12	8.52E+09		

from the post-hoc Tukey's test for each socioeconomic indicator. The means provided in Figure 3.4 can be used to verify the mean differences shown in Table 3.4.

Nominally, communities near natural gas plants have overall have a statistically significantly larger population densities than communities near coal *(mean difference = 221, adjusted $p < 0.001$)* and nuclear *(mean difference = 281, adjusted $p < 0.001$)* power plants. The mean difference between for populations densities increases within closer distances. Overall, the percentage of black residents near natural gas plants are significantly larger than coal *(mean difference = 3.5%, adjusted $p < 0.001$)* plants. The percentage of residents with Bachelor's degrees or above for communities near nuclear *(mean difference 4.8%, adjusted $p < 0.001$)* and natural gas *(mean difference 2.7%, adjusted $p < 0.001$)* power plants generally are higher than communities near coal plants. The poverty rates for communities near nuclear power plants generally are significantly lower than communities near coal *(mean difference = 2.8%, adjusted $p < 0.001$)* and natural gas *(mean difference = 3.3%, adjusted $p < 0.001$)* plants. With the 0-5 mile comparison, the mean difference in poverty rates increases for coal *(4.2%)* natural gas *(4.9%)*. The average median incomes for communities near nuclear *(mean difference $8,000, adjusted p < 0.001)* and natural gas *(mean difference $5,000, adjusted p < 0.001)* power plants are generally larger than communities near coal plants. While at all distance the mean difference between natural gas and coal are around the $5,000 range, at the 0-5 mile range the mean difference between communities near nuclear and coal increases to $10,000. Overall, the average median home values for communities near nuclear *(mean difference $71,000, adjusted p < 0.001)* and natural gas *(mean difference $52,000, adjusted p < 0.001)* power plants are larger than communities near coal plants. Within the natural gas-coal comparison, with an increase in distance the mean difference increases from $48,000 to $57,000. However, with the nuclear-coal comparison with an increase in distance the mean difference decreases from $86,000 to $62,000.

While the nominal ANOVA and post-hoc Tukey's test investigates whether there are significant differences between communities associated with specific types of power plants, the paired t-test can provide a measurable indication for the difference that exist between the communities and counties. Table 3.5 shows the results of a paired t-test and correlation coefficients between the community and county by power plant type and distance for each socioeconomic indicator. Figures 3.5-3.7 shows scatter plots of the percentage of black residents, average median household income, and average median home value by community and home county. Figures B.1-AB.3 show the scatter plots of population density, educational attainment, and poverty rates. The x-axis represents the home county socioeconomic indicator values and the y-axis represents the communities 0-5, 5-10, and 10-15 miles away from each respective power plant. The solid line and the dashed line represents the reference line and the best fit line, respectively.

The power plant community-to-home county paired t-test shows communities near nuclear power plants are significantly different compared to their home counties relative to natural gas and coal plants. Table 3.5 shows there are significant differences for every socioeconomic indicator for every distance associated with nuclear power plants except population density at 5-10 and 10-15 miles; and percentage of black residents and poverty rates at 10-15 miles. All communities around coal have significantly higher rates of educational attainment that their counties. At 5-10 and 10-15 miles, communities around coal have significantly larger average median incomes and home values than their counties. Similar to communities near coal plants, communities at all distances near natural gas plants have higher rates of educational attainment compared to their home counties. Communities 0-5 miles from natural gas plants have significantly larger population densities than their home counties. At all distances, communities near natural gas plants have significantly larger average median incomes than their home counties. However, there are only significantly larger average median home values for communities 10-15 miles from natural gas plants when compared against their home counties.

It can be seen in Figure 3.5 that between 71% and 97% of communities near nuclear power plants have a lower percentage of black residents than their home counties, while communities near fossil fuel plants range between 44% and 66%. Table 3.5 shows the percentage of black residents are significantly less than the home counties for communities 0-5 *(mean difference = -5.7%, p value < 0.001)* and 5-10 *(mean difference = -4.4%, p value < 0.001)* miles away from nuclear power plants. In comparison there are no significant differences in the between the communities and counties for natural gas and coal power plants. The percentage of black residents in communities near coal and natural gas plants are similar to their counties. However, for

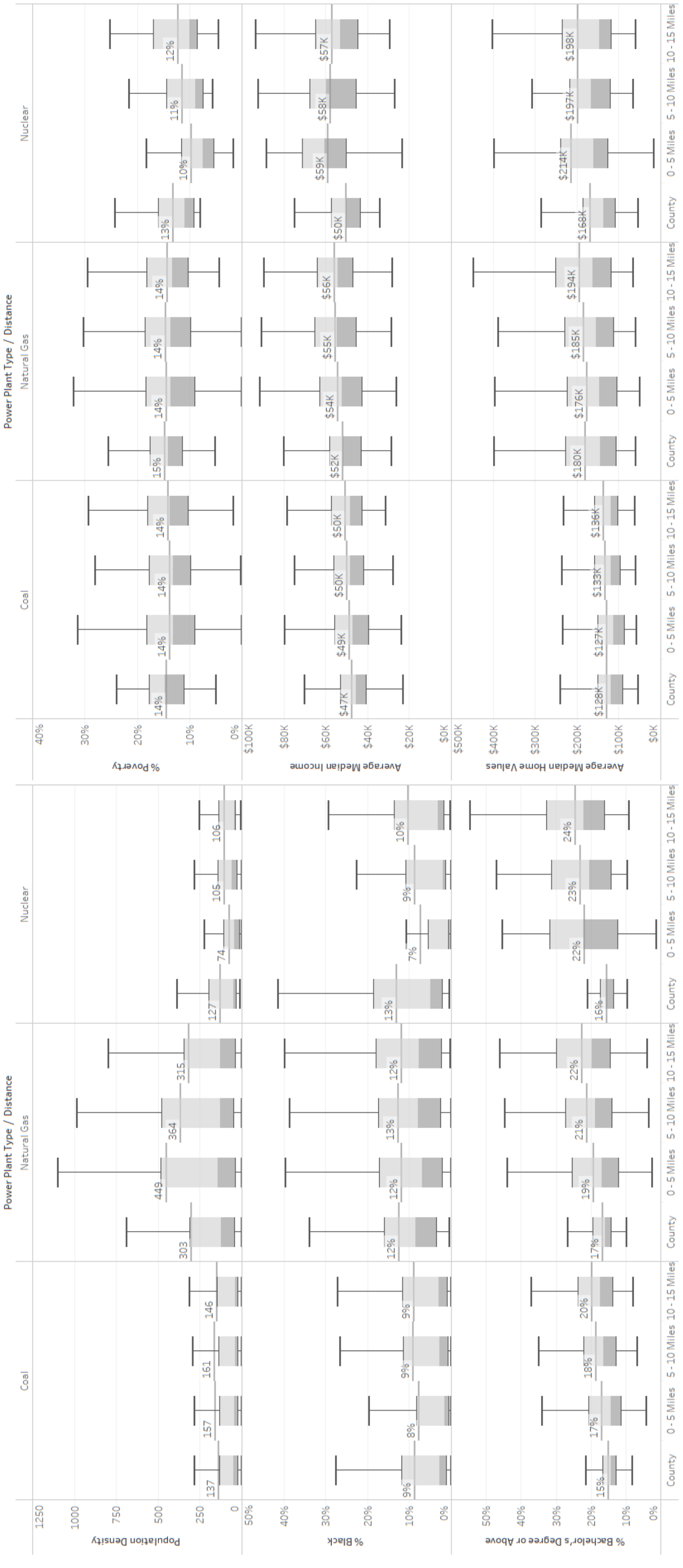

Figure 3.4: Community-level boxplots of home counties and communities 0-5, 5-10, and 10-15 miles from nuclear, coal, and natural gas power plants for the six socioeconomic indicators with the numeric values representing the means.

Table 3.4: Community-level post-hoc Tukey's tests for plant type and distance with nominal values for the six socioeconomic indicators.

	term	**Comparison**	**mean difference**	**2.5% level**	**97.5% level**	**adjusted p value**
Population Density (pop./sq. mile)	Plant Type	Natural Gas - Coal	221	147	295	0.000***
	Plant Type	Nuclear - Natural Gas	-281	-404	-157	0.000***
	Plant Type × Distance	Natural Gas × 0-5 Miles - Coal × 0-5 Miles	291	122	461	0.000***
	Plant Type × Distance	Nuclear × 0-5 Miles - Natural Gas × 0-5 Miles	-375	-659	-91	0.001**
	Plant Type × Distance	Natural Gas × 5-10 Miles - Coal × 5-10 Miles	203	33	372	0.006**
%Black	Plant Type	Natural Gas - Coal	3.5%	1.40%	5.7%	0.000***
%Bachelor's Degree or Above	Plant Type	Natural Gas - Coal	2.7%	1.2%	4.1%	0.000***
	Plant Type	Nuclear - Coal	4.8%	2.4%	7.2%	0.000***
	Distance	10-15 Miles - 0-5 Miles	2.9%	1.2%	4.5%	0.000***
%Poverty	Plant Type	Nuclear - Coal	-2.8%	-4.4%	-1.2%	0.000***
	Plant Type	Nuclear - Natural Gas	-3.30%	-4.90%	-1.70%	0.000***
	Plant Type × Distance	Nuclear × 0-5 Miles - Coal × 0-5 Miles	-4.2%	-7.8%	-0.6%	0.010**
	Plant Type × Distance	Nuclear × 0-5 Miles - Natural Gas × 0-5 Miles	-4.9%	-8.6%	-1.2%	0.002**
Average Median Income	Plant Type	Natural Gas - Coal	$5,451	$3,345	$7,558	0.000***
	Plant Type	Nuclear - Coal	$8,219	$4,776	$11,661	0.000***
	Plant Type × Distance	Natural Gas × 0-5 Miles - Coal × 0-5 Miles	$5,620	$788	$10,452	0.010**
	Plant Type × Distance	Nuclear × 0-5 Miles - Coal × 0-5 Miles	$10,397	$2,501	$18,293	0.002**
	Plant Type × Distance	Natural Gas × 5-10 Miles - Coal × 5-10 Miles	$5,445	$613	$10,277	0.014*
	Plant Type × Distance	Natural Gas × 10-15 Miles - Coal × 10-15 Miles	$5,288	$456	$10,120	0.020*
Average Median Home Values	Plant Type	Natural Gas - Coal	$52,310	$38,198	$66,422	0.000***
	Plant Type	Nuclear - Coal	$70,891	$47,830	$93,953	0.000***
	Plant Type × Distance	Natural Gas × 0-5 Miles - Coal × 0-5 Miles	$48,262	$15,892	$80,632	0.000***
	Plant Type × Distance	Nuclear × 0-5 Miles - Coal × 0-5 Miles	$86,466	$33,568	$139,364	0.000***
	Plant Type × Distance	Natural Gas × 5-10 Miles - Coal × 5-10 Miles	$51,577	$19,207	$83,947	0.000***
	Plant Type × Distance	Nuclear × 5-10 Miles - Coal × 5-10 Miles	$64,280	$11,382	$117,178	0.005**
	Plant Type × Distance	Natural Gas × 10-15 Miles - Coal × 10-15 Miles	$57,092	$24,722	$89,462	0.000***
	Plant Type × Distance	Nuclear × 10-15 Miles - Coal × 10-15 Miles	$61,928	$9,030	$114,826	0.009**

Table 3.5: Paired t-test Summary Statistics and correlation coefficients of each power plant community and home county.

		mean difference	**2.5% level**	**97.5% level**	**p value**	**corr.**
	0 - 5 Miles					
Nuclear	Population Density (pop./sq. mile)	-53	-100	-7	0.024*	0.52
	% Black	-5.7%	-8.3%	-3.2%	0.000***	0.92
	% Bachelor's Degree or Above	6.4%	2.6%	10.1%	0.001**	0.36
	% Poverty	-3.6%	-4.6%	-2.6%	0.000***	0.9
	Average Median Household Income	$8,831	$3,057	$14,606	0.004**	0.53
	Average Median Home Value	$46,348	$11,743	$80,953	0.010*	0.91
Coal	Population Density (pop./sq. mile)	20	-17	58	0.279	0.55
	% Black	-1.0%	-2.5%	0.4%	0.174	0.7
	% Bachelor's Degree or Above	2.1%	1.0%	3.2%	0.000***	0.49
	% Poverty	-0.7%	-1.5%	0.1%	0.104	0.55
	Average Median Household Income	$1,179	-$174	$2,532	0.087	0.68
	Average Median Home Value	-$957	-$5,796	$3,882	0.697	0.83
Natural Gas	Population Density (pop./sq. mile)	145	21	270	0.023*	0.54
	% Black	-0.5%	-2.0%	1.1%	0.539	0.81
	% Bachelor's Degree or Above	2.8%	1.2%	4.3%	0.001***	0.49
	% Poverty	-0.2%	-1.3%	0.9%	0.732	0.5
	Average Median Household Income	$2,329	$28	$4,630	0.047*	0.56
	Average Median Home Value	-$4,419	-$14,701	$5,863	0.397	0.84
	5 - 10 Miles					
Nuclear	Population Density (pop./sq. mile)	-22	-67	23	0.334	0.57
	% Black	-4.4%	-6.7%	-2.0%	0.001***	0.94
	% Bachelor's Degree or Above	7.4%	4.5%	10.4%	0.000***	0.66
	% Poverty	-1.8%	-2.9%	-0.6%	0.003**	0.85
	Average Median Household Income	$7,428	$4,326	$10,531	0.000***	0.77
	Average Median Home Value	$29,679	$7,315	$52,043	0.011*	0.89
Coal	Population Density (pop./sq. mile)	24	-16	65	0.233	0.58
	% Black	0.4%	-0.8%	1.6%	0.537	0.79
	% Bachelor's Degree or Above	3.6%	2.6%	4.6%	0.000***	0.62
	% Poverty	-0.6%	-1.3%	0.1%	0.092	0.61
	Average Median Household Income	$2,310	$1,136	$3,484	0.000***	0.77
	Average Median Home Value	$4,560	$321	$8,799	0.035*	0.87
Natural Gas	Population Density (pop./sq. mile)	61	-24	145	0.157	0.62
	% Black	0.2%	-1.0%	1.3%	0.799	0.88
	% Bachelor's Degree or Above	4.6%	3.3%	6.0%	0.000***	0.6
	% Poverty	-0.2%	-1.0%	0.7%	0.717	0.7
	Average Median Household Income	$3,286	$1,491	$5,081	0.000***	0.69
	Average Median Home Value	$4,413	-$3,793	$12,619	0.289	0.9
	10 - 15 Miles					
Nuclear	Population Density (pop./sq. mile)	-22	-60	17	0.263	0.69
	% Black	-2.7%	-5.6%	0.1%	0.061	0.9
	% Bachelor's Degree or Above	8.9%	5.7%	12.2%	0.000***	0.65
	% Poverty	-1.0%	-2.3%	0.4%	0.16	0.8
	Average Median Household Income	$6,717	$3,289	$10,145	0.000***	0.81
	Average Median Home Value	$30,811	$12,316	$49,306	0.002**	0.95
Coal	Population Density (pop./sq. mile)	9	-23	41	0.569	0.65
	% Black	0.2%	-0.9%	1.4%	0.685	0.79
	% Bachelor's Degree or Above	4.8%	3.7%	5.8%	0.000***	0.57
	% Poverty	-0.4%	-1.1%	0.3%	0.242	0.58
	Average Median Household Income	$3,064	$1,787	$4,340	0.000***	0.71
	Average Median Home Value	$8,044	$3,047	$13,040	0.002**	0.81
Natural Gas	Population Density (pop./sq. mile)	12	-55	78	0.733	0.68
	% Black	-0.5%	-1.9%	0.9%	0.469	0.82
	% Bachelor's Degree or Above	5.9%	4.5%	7.3%	0.000***	0.64
	% Poverty	-0.4%	-1.2%	0.4%	0.313	0.67
	Average Median Household Income	$3,883	$2,140	$5,626	0.000***	0.7
	Average Median Home Value	$13,411	$5,613	$21,210	0.001***	0.91

communities 0-5 and 5-10 miles from a nuclear power plant there are smaller shares of black residents. There is some selection bias present for the share of black residents as nuclear power plants are typically sited in more rural and less diverse areas compared natural gas and coal power plants.

Figure 3.5: Scatter plot of Home County percentage of Black residents vs 0-5, 5-10, and 10-15 mile Community percentage of Black residents with solid reference line and dotted best fit line.

Figure 3.6 shows between 20%-26% of communities near nuclear power plants have lower average median household incomes than their counties. In comparison communities near fossil fuel plants range between 30% and 50%. Table 3.5 shows average median household income are significantly larger for communities 0-5 *(mean difference = $8,800, p value = 0.004)*, 5-10 *(mean difference = $7,400, p value < 0.001)*, and 10-15 *(mean difference = $6,700, p value < 0.001)* miles from nuclear power plants relative to their counties. Similarly for natural gas plants, communities 0-5 *(mean difference = $2,300, p value = 0.047)*, 5-10 *(mean difference = $3,300, p value < 0.001)*, and 10-15 *(mean difference = $3,900, p value < 0.001)* miles have significantly larger average median household incomes than their counties. There are significantly larger average median household incomes for communities 5-10 *(mean difference = $2,300, p value < 0.001)* and 10-15 *(mean difference = $3,000, p value < 0.001)* miles from coal plants relative to their counties. At the 0-5 miles, the income of the community is similar to the county. With an increase in distance, statistically significant mean differences in incomes for coal and natural gas plants can increase from $2,300 and $3,900.

Conversely, incomes from communities near nuclear power plants decrease from $8,800 to $6,700 with an increase in distance.

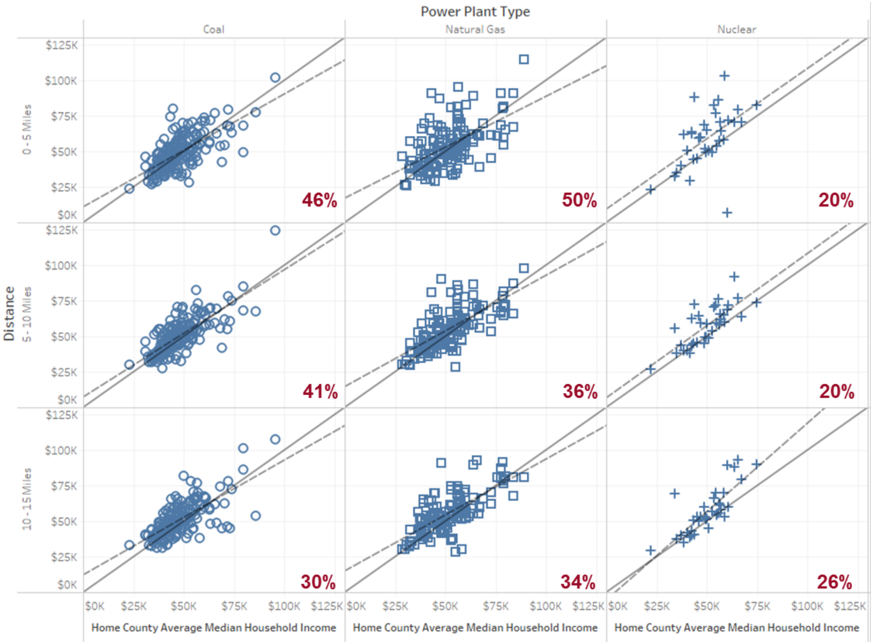

Figure 3.6: Scatter plot of Home County Average Median Household Income vs 0-5, 5-10, and 10-15 mile Community Average Median Household Income with solid reference line and dotted best fit line.

Figure 3.7 shows between 20% and 26% of communities near nuclear power have lower average median home values than their counties. Fossil fuel plants typically range between 33% and 55%. Table 3.5 shows average median home values are significantly larger for communities 0-5 *(mean difference = $46,000, p value = 0.010)*, 5-10 *(mean difference = $30,000, p value < 0.011)*, and 10-15 *(mean difference = $31,000, p value = 0.002)* miles from nuclear power plants compared to their counties. There are significantly larger average median home values for communities 5-10 *(mean difference = $5,000, p value = 0.035)* and 10-15 *(mean difference = $8,000, p value = 0.002)* miles from coal plants relative to their counties. There are significantly larger home values for communities 10-15 *(mean difference = $13,000, p value = 0.001)* miles from natural gas plants relative to their counties. Average median home values for communities 0-5 miles from coal plants; and communities 0-5 miles and 5-10 miles from natural gas plants are similar to their counties.

As a follow-on, the community-level two-way ANOVA model, specified in Equation 3.1, is also used to perform a comparative analysis using the ratio between communities around power plants with the county the power plant is located to control for regional differences. Table 3.6 shows power plant main effects for all socioeconomic indicators and distance main effects for population density, %Bachelor's degrees or above, and average median home values. There are no significant interactions.

Figure 3.7: Scatter plot of Home County Average Median Home Value vs 0-5, 5-10, and 10-15 mile Community Average Median Home Value with solid reference line and dotted best fit line.

Figure 3.8 is similar to Figure 3.4; however, the socioeconomic indicators presented by the boxplot are the ratios of communities 0-5, 5-10, and 10-15 miles to the home county for each power plant type. The relationship between Figure 3.8 and Table 3.7 is similar to the relationship between Figure 3.4 and Table 3.4.

Communities near nuclear power plants tend to have a lower average population density compared to communities near fossil fuel plants. While moving to investigation areas further from the power plant, the population density trends upwards for communities around nuclear power plants while the opposite is true for fossil fuel plants. The plant type *($F(2,2) = 4.82$, $p = 0.008$, $\eta^2 = 0.009$)* and distance *($F(2,2) = 3.13$, $p = 0.044$, $\eta^2 = 0.006$)* main effects show a statistical significant difference, however there is a weak effect size. A Tukey's test shows statistical significant differences between the natural gas-coal *(mean difference = 0.52, adjusted $p = 0.023$)* and nuclear-natural gas *(mean difference = -0.82, adjusted $p = 0.039$)*. The average share of black residents with respect to distance is fairly flat for communities near natural gas and coal plants, while communities near nuclear power plants see an increasing share of black residents over distance. There are statistically significant differences in main effects for the plant type *($F(2,2) = 5.73$, $p = 0.003$, $\eta^2 = 0.011$)*, though there is a small effect size for distance. A Tukey's test shows statistically significant differences in the overall nuclear-coal *(mean difference = -0.70, adjusted $p = 0.003$)* comparison.

Table 3.6: Community-level two-way ANOVA Tests of plant type and distance effects summary statistics using the ratios of communities-to-power plant counties for the six socioeconomic indicators.

	term	**df**	**Sum of Squares**	**Mean Square**	**F Statistic**	**p value**	η^2
Population Density	Plant Type	2	88.8	44.40	4.82	0.008**	0.01
	Distance	2	57.56	28.78	3.13	0.044*	0.01
	Residuals	1059	9,751	9.21			
%Black	Plant Type	2	45.58	22.79	5.73	0.003**	0.01
	Residuals	1053	4,189	3.98			
%Bachelor's Degree or Above	Plant Type	2	5.27	2.64	11.05	0.000***	0.02
	Distance	2	5.59	2.80	11.72	0.000***	0.02
	Residuals	1059	253	0.24			
%Poverty	Plant Type	2	2.81	1.41	9.05	0.000***	0.02
	Residuals	1059	165	0.16			
Average Median Income	Plant Type	2	0.93	0.46	10.72	0.000***	0.02
	Residuals	1059	46	0.04			
Average Median Home Values	Plant Type	2	1.66	0.83	12.07	0.000***	0.02
	Distance	2	0.84	0.42	6.07	0.002**	0.01
	Residuals	1059	73	0.07			

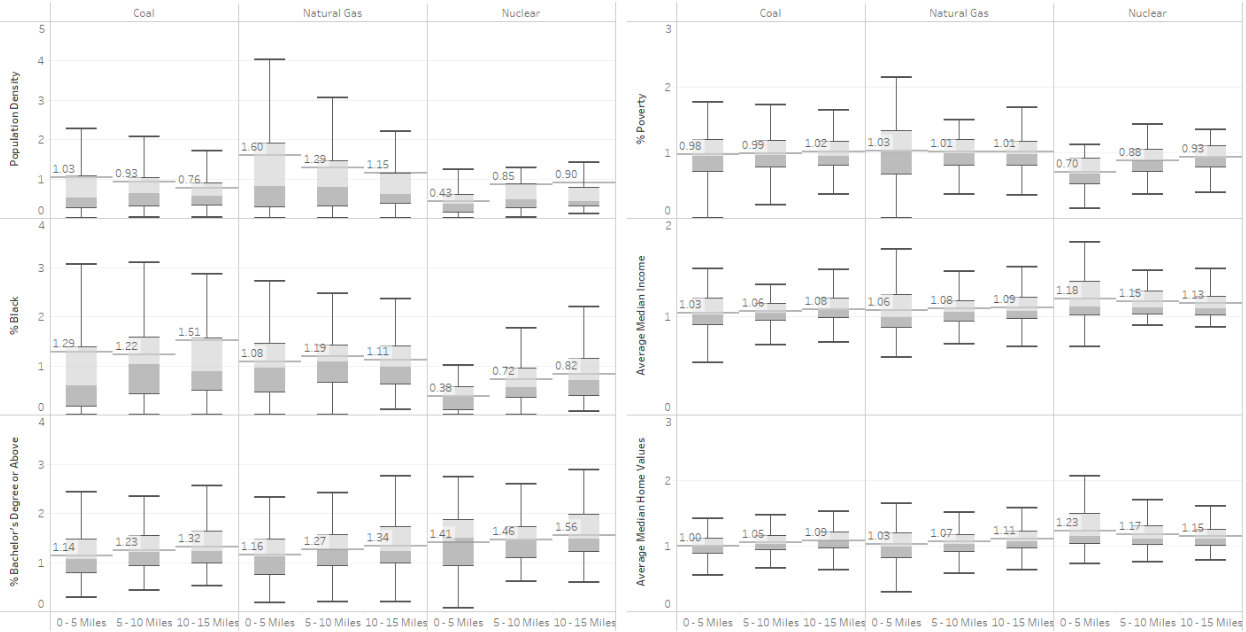

Figure 3.8: Community-level boxplots and means of 0-5, 5-10, and 10-15 community-to-power plant county ratios for the six socioeconomic indicators with the numeric values representing the means.

Table 3.7: Community-level post-hoc Tukey's tests for plant type and distance using the ratios of communities-to-power plant counties for the six socioeconomic indicators.

	term	**Comparison**	**mean difference**	**2.5% level**	**97.5% level**	**adjusted p value**
Population Density	Plant Type	Natural Gas - Coal	0.52	0.06	0.99	0.023*
	Plant Type	Nuclear - Natural Gas	-0.82	-1.59	-0.03	0.039*
	Distance	10-15 Miles - 0-5 Miles	-0.57	-1.1	-0.03	0.034*
%Black	Plant Type	Nuclear - Coal	-0.7	-1.2	-0.2	0.003**
%Bachelor's Degree or Above	Plant Type	Nuclear - Coal	0.24	0.12	0.37	0.000***
	Plant Type	Nuclear - Natural Gas	0.22	0.09	0.34	0.000***
	Distance	10-15 Miles - 0-5 Miles	0.18	0.09	0.26	0.000***
	Distance	5-10 Miles - 0-5 Miles	0.1	0.01	0.18	0.024*
	Plant Type × Distance	Coal × 10-15 Miles - Coal × 0-5 Miles	0.18	0.02	0.34	0.013*
% Poverty	Plant Type	Nuclear - Coal	-0.16	-0.26	-0.06	0.000***
	Plant Type	Nuclear - Natural Gas	-0.18	-0.28	-0.08	0.000***
	Plant Type × Distance	Nuclear × 0-5 Miles - Coal × 0-5 Miles	-0.28	-0.5	-0.05	0.004**
	Plant Type × Distance	Nuclear × 0-5 Miles - Natural Gas × 0-5 Miles	-0.33	-0.56	-0.1	0.000***
Average Median Income	Plant Type	Nuclear - Coal	0.1	0.05	0.15	0.000***
	Plant Type	Nuclear - Natural Gas	0.08	0.03	0.13	0.001**
	Plant Type × Distance	Nuclear × 0-5 Miles - Coal × 0-5 Miles	0.15	0.03	0.27	0.004**
Average Median Home Values	Plant Type	Nuclear - Coal	0.14	0.07	0.2	0.000***
	Plant Type	Nuclear - Natural Gas	0.12	0.05	0.18	0.000***
	Distance	10-15 Miles - 0-5 Miles	0.07	0.02	0.11	0.001**
	Plant Type × Distance	Nuclear × 0-5 Miles - Coal × 0-5 Miles	0.22	0.07	0.37	0.000***
	Plant Type × Distance	Nuclear × 0-5 Miles - Natural Gas × 0-5 Miles	0.2	0.05	0.36	0.002**

Communities near all power plants, with respect to distance, trend upwards in average share of population with Bachelor's degrees or higher. There are statistically significant differences in main effects for the plant type *(F(2,2) = 11.05, p = 0.000, η^2 = 0.020)* and distance *(F(2,2) = 11.72, p = 0.000, η^2 = 0.022)*. A Tukey's test shows statistically significant differences in the overall nuclear-coal *(mean difference = 0.24, adjusted p = 0.000)*, nuclear-natural gas *(mean difference = 0.22, adjusted p = 0.000)*, 10-15 vs. 0-5 mile *(mean difference = 0.18, adjusted p = 0.000)*, and 5-10 vs. 0-5 mile *(mean difference = 0.10, adjusted p = 0.024)* comparisons as well as the interaction between coal 10-15 mile and 0-5 miles *(mean difference = 0.18, adjusted p = 0.013)*. Average poverty rates for communities near fossil fuel plant remain fairly flat and around the county average with respect to distance, however poverty rates for communities near nuclear power plants trend upwards. There are statistically significant differences in main effects for the plant type *(F(2,2) = 9.05, p = 0.000, η^2 = 0.017)*. A Tukey's test shows statistically significant differences in the overall nuclear-coal *(mean difference = -0.16, adjusted p = 0.000)* and nuclear-natural gas *(mean difference = -0.18, adjusted p = 0.000)* comparison. There are statistical significant differences in interactions between the nuclear-coal *(mean difference = -0.28, adjusted p = 0.004)* and the nuclear-natural gas *(mean difference = -0.33, adjusted p = 0.000)* comparison within the 0-5 mile investigation area.

While average median household incomes increase steadily for communities near fossil fuel plants with added distance from the plant, the opposite is shown for communities near nuclear power plants. The plant type (F(2,2) = 10.72, p = 0.000, η^2 = 0.020) main effects show a statistical significant difference, however there is a weak effect size. A Tukey's test shows statistical significant differences between the overall nuclear-coal *(mean difference = 0.10, adjusted p = 0.000)* and nuclear-natural gas *(mean difference = 0.08, adjusted p = 0.001)* comparisons as well as the interaction between nuclear and coal plants at the 0 - 5 mile investigation area *(mean difference = 0.15, adjusted p = 0.004)*.

The average median home values increase has a similar relationship with the power plant types and distances. As distance increases, the home values of communities near nuclear power plants decreases, while communities near fossil fuels experience an increase in home values. The plant type *(F(2,2) = 12.07, p = 0.000, η^2 = 0.022)* and distance *(F(2,2) = 6.07, p = 0.002, η^2 = 0.011)* main effects show a statistical significant difference, however there are small effect sizes for plant type and distance. A Tukey's test shows statistical significant differences between the overall nuclear-coal *(mean difference = 0.14, adjusted p = 0.000)*, nuclear-natural gas *(mean difference = 0.12, adjusted p = 0.000)*, and the 10-15 vs. 0-5 mile *(mean difference = 0.07, adjusted p = 0.001)* comparisons. There are also statistical significant differences in interactions between the nuclear-coal *(mean difference = 0.22, adjusted p = 0.000)* and the nuclear-natural gas *(mean difference = 0.20, adjusted p = 0.002)* comparison within the 0-5 mile investigation area.

3.2.4 Socioeconomic Trend Analysis

The socioeconomic trend analysis uses three (nuclear, coal, and natural gas) two-way ANOVA and post-hoc Tukey tests to understand the relationship between distance and generation technology over time from 1990-2010. This analysis is used to show the how socioeconomic indicators evolve over time with respect to distance and power plant type. The trend ANOVA study only includes power plants built before 1990 limiting the power plant sites to 176 coal, 26 natural gas, and 34 nuclear power plants.

3.2.4.1 Community-level Socioeconomic Trend Data Sources

US Census 1990-2010 tract level data from the NCDB are utilized in analysis of socioeconomic indicators from communities 0-5, 5-10, and 10-15 miles from each generating station over time. While the NCDB does not have the same data resolution as the ACS, the NCDB normalizes historical tracts to 2010 boundaries. This normalization of boundaries allow the comparison of community socioeconomic indicators over time. Past studies from Davis (2011) [71] and Olsen (2014) [82] have also used the NCDB as a data source.

3.2.4.2 Community-level Socioeconomic Trend Methods

The trend socioeconomic analysis examines the evolution in socioeconomic indicators over time. Two-way ANOVA models for each power plant type are used to measure main and interaction effects of distance and the census decade, while a post-hoc Tukey test is used for distance and census decade comparisons. The trend ANOVA is expressed in Equation 3.2.

$$Y_{s,p,3,3} = \mu_{s,p} + Distance_{s,p,3} + Year_{s,p,3} + (Distance \times Year)_{s,p,3,3} + \varepsilon_{s,p,3,3} \tag{3.2}$$

Where *p* refers to the power plant type if interest, *Year* is an independent categorical variable with 3 levels used to describe the census decade (1990, 2000, and 2010). *Distance* maintains the same definition outlined in section 3.2.3.2.

3.2.4.3 Community-level Socioeconomic Trend Results

The socioeconomic trend analysis is used to determine if there are measurable differences after operating across 3 decades. By 1990 the US became fully tracted and as a result the socioeconomic indicators are more representative of each community. Figure 3.9 shows the means and 95% confidence interval overall (distances collapsed) trends for each power plant type and socioeconomic indicator between 1990 and 2010. Figure B.4 shows the means and 95% confidence interval for all socioeconomic indicators by distance, power plant type, and decade. There are wide 95% confidence interval bands in Figure 3.9 and Figure B.4 for population density, %black, and %poverty wide. These wide bands are caused by the home county of a power plants having low or high population densities, %black, and % poverty while the pre-normalized rates for communities near these power plants have high rates (or vice-versa). Figure 3.9 and Figure B.4 visualizes the pairwise comparison shown in Table B.6.

The distance and year main and interaction effects for each community socioeconomic indicator are quantified for each power plant type to investigate the relationship between distance and time for each respective community near coal, natural gas, and nuclear power plants. For the trend analysis, the Year main effects is the variable of interest as many of the previous relationships between distance and power plant type remain consistent. The two-way ANOVA shows there are only Year main effects for poverty rates. Table 3.8 shows the summary statistics of the two-way ANOVA model presented in Equation 3.2 for poverty rates.

Table 3.8: Community-level two-way ANOVA 1990-2010 socioeconomic trend summary statistics by power plant type.

	%Poverty					
	term	**df**	**Sum of Squares**	**Mean Square**	**F Statistic**	**p value**
Nuclear	Year	2	8.22	4.11	26.02	0.000***
	Residuals	297	47	0.16		
Coal	Year	2	55.3	27.65	102.19	0.000***
	Residuals	1,575	426	0.27		
Natural Gas	Year	2	38.03	19.02	11.6	0.000***
	Residuals	225	369	1.64		

Table 3.9 contains the mean differences, adjusted p-values, and the 95% confidence interval from the post-hoc Tukey's test poverty rates by power plant type. Poverty rates are statistically significantly larger during the 2010 census compared to the 2000 and 1999 census. This can be seen further within the pairwise comparisons for distance and year. As shown in Table 3.8 there are year main effects for poverty rates in communities near natural gas and nuclear power plants. Specifically, within Table 3.9 there are statistically significantly larger poverty rates during the 2010 census compared to the 2000 and 1990 census. This can be seen further within the pairwise comparisons for distance and year for communities near nuclear power plants. Within communities near nuclear power plants there are statistically significantly larger rates of poverty with communities 10-15 miles compared to those within 0-5 miles.

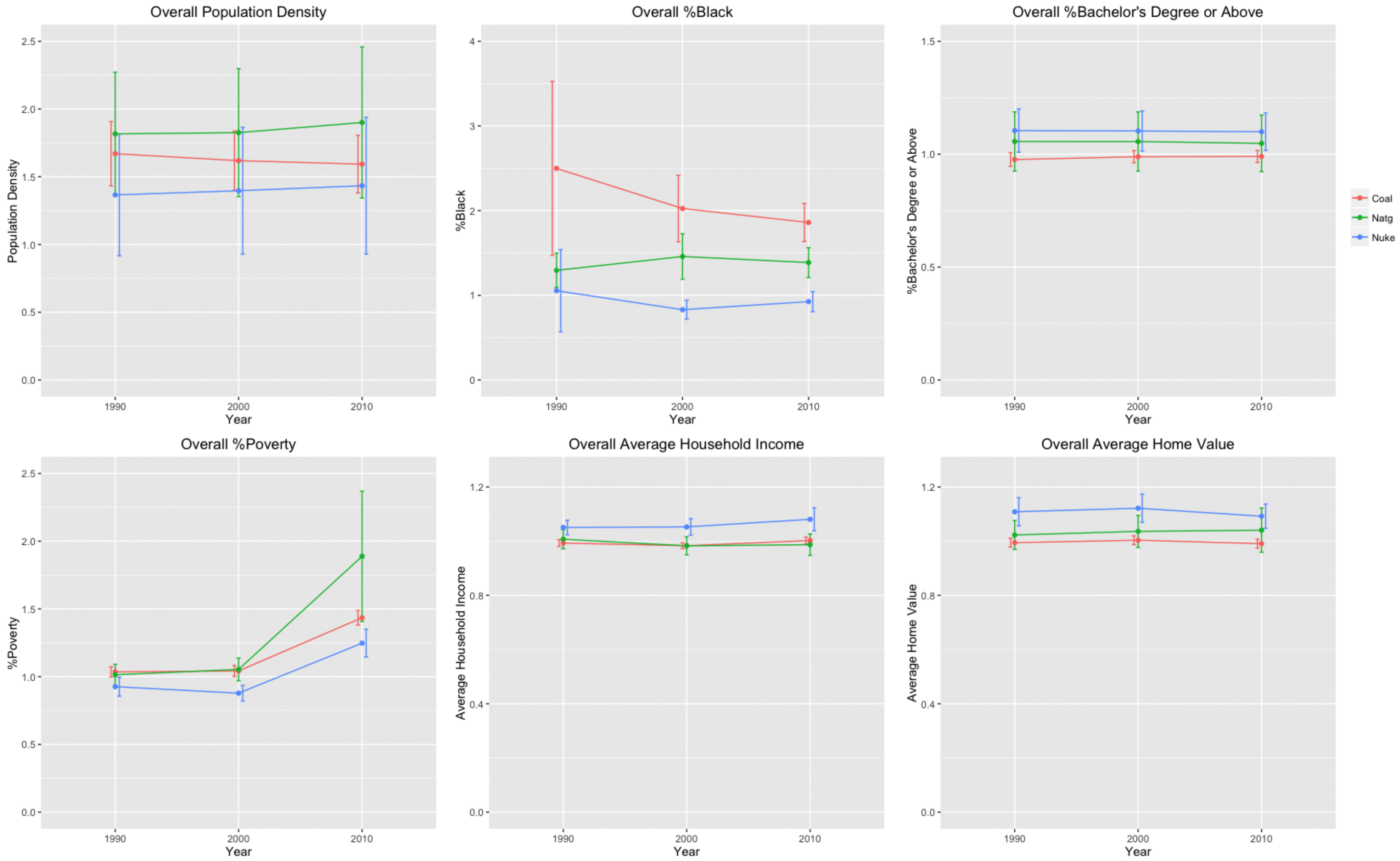

Figure 3.9: Mean and 95% confidence interval trends of the six socioeconomic indicators of communities near coal, natural gas, and nuclear power plants with distance collapsed.

Table 3.9: Post-hoc 1990-2010 socioeconomic trend Tukey's tests for distance and year by power plant type.

%Poverty

	term	**comparison**	**mean difference**	**2.5% level**	**97.5% level**	**adjusted p value**
Nuclear	Distance × Year	0-5 Miles × 2010 - 0-5 Miles × 1990	0.15	-0.15	0.45	0.819
	Distance × Year	0-5 Miles × 2010 - 0-5 Miles × 2000	0.29	-0.01	0.59	0.070
	Distance × Year	5-10 Miles × 2010 - 5-10 Miles × 1990	0.37	0.07	0.67	0.005**
	Distance × Year	5-10 Miles × 2010 - 5-10 Miles × 2000	0.37	0.07	0.68	0.004**
	Distance × Year	10-15 Miles × 2010 - 10-15 Miles × 1990	0.44	0.14	0.75	0.000***
	Distance × Year	10-15 Miles × 2010 - 10-15 Miles × 2000	0.44	0.14	0.74	0.000***
Coal	Distance × Year	0-5 Miles × 2010 - 0-5 Miles × 1990	0.37	0.2	0.54	0.000***
	Distance × Year	0-5 Miles × 2010 - 0-5 Miles × 2000	0.36	0.19	0.53	0.000***
	Distance × Year	5-10 Miles × 2010 - 5-10 Miles × 1990	0.42	0.24	0.59	0.000***
	Distance × Year	5-10 Miles × 2010 - 5-10 Miles × 2000	0.41	0.24	0.58	0.000***
	Distance × Year	10-15 Miles × 2010 - 10-15 Miles × 1990	0.41	0.24	0.59	0.000***
	Distance × Year	10-15 Miles × 2010 - 10-15 Miles × 2000	0.41	0.23	0.58	0.000***
Natural Gas	Distance × Year	0-5 Miles × 2010 - 0-5 Miles × 1990	0.95	-0.16	2.06	0.165
	Distance × Year	0-5 Miles × 2010 - 0-5 Miles × 2000	0.92	-0.19	2.03	0.199
	Distance × Year	5-10 Miles × 2010 - 5-10 Miles × 1990	0.78	-0.34	1.89	0.417
	Distance × Year	5-10 Miles × 2010 - 5-10 Miles × 2000	0.73	-0.39	1.84	0.515
	Distance × Year	10-15 Miles × 2010 - 10-15 Miles × 1990	0.90	-0.21	2.01	0.224
	Distance × Year	10-15 Miles × 2010 - 10-15 Miles × 2000	0.86	-0.25	1.97	0.276

3.3 Discussion

There are benefits to having a power plant in a region. While, they can promote economic activity and create a larger tax base for both the local community and county; power plants have also produce negative externalities. This analysis provides evidence that based on Census data, the home county and surrounding communities of power plants differ by the technology of the plant. The reasons for these differences are varied, but they can be related to the availability of fuel, cooling water, externalities, and age of plant.

Nuclear power plants were typically constructed on rural sites with low population densities and with direct access to major water sources needed for plant cooling. Nearby waterfront locations have been sought after by high-income residents with high-end homes. Compared to their home counties, immediate nuclear plant communities are wealthier than those further away. This has led to immediate communities having the highest income and home values. This is dramatically different than the coal and natural gas, where income and home values increase with distance from the plant. This is despite the fact that nuclear power plants have specific regulatory constraints that other generating technologies are not subject to. These constraints can play a factor in socioeconomic characteristics for these communities. Specifically, the 10-mile EPZ surrounding all nuclear power plants would be expected to create negative externalities for communities especially for those states, such as California, that require realtors to disclose the immediacy of the power plant [83]. However, this research shows an association between communities near nuclear power with higher household incomes, home values, and levels of educational attainment despite safety concerns from potential nuclear accidents.

Coal plants require access to major transportation networks, such as 120 rail cars supplying 10,000 tons of coal per day and cooling water. Coal plants have the largest and visible impacts on local communities; coal plants have a large footprint with pollution-emitting smokestacks towering hundreds of feet and acres of coal piles. While communities that are not in the immediate area and the county can benefits from the economic activity and tax base created by coal plants, the highest negative externalities and are generally not sited in wealthy parts of the county. Typically, these communities are in the less wealthy parts of the county or have a similar socioeconomic makeup as the county receive most of the negative externalities that are common with industrial facilities that generates pollution. Relative to their counties, communities near coal power plants contain vulnerable populations that have lowest average household incomes, home values, and highest percentages of black residents compared to nuclear and natural gas plants. These findings are similar to those of Mohai and Saha (2015) [84] who find that communities near hazardous waste facilities are lower-income and communities of color. Their findings also show these communities have less political power to resist siting which can explain the reason behind the disparity between the siting coal power plants compared to nuclear and natural gas.

Unlike coal and nuclear power plants, natural gas plants do not have an aging fleet and their facility has the smallest footprint. While they require access to natural gas pipelines, these can be underground with minimal visible impact. The small footprint, allows them to be built in counties with higher population densities. From a siting perspective, natural gas plants do not have the same environmental and safety concerns as nuclear (accidents) and coal (pollution from SO_x, NO_x, and $PM_{2.5}$) power plants. Without these concerns, natural gas plants have more flexibility in siting, construction, and operations relative to coal and nuclear power plants.

There are significant differences for population density, percentage of Black residents, percentages of residents with Bachelor's degrees or above, poverty rates, household income, and home values in counties and communities with nuclear, coal, and natural gas power plants based on the findings from the county and community-level analysis. It is expected that natural gas power plants are associated with communities with large population densities because they are located in densely populated counties and are near large population centers, such as cities and metropolitan statistical areas. Conversely, coal and nuclear power plants are located in more rural areas. Comparatively, coal and nuclear power plants have similar siting and population characteristics. Both generating technologies are in close proximity to large bodies of water and have similar population densities at the county and community level. While it is typical that homes near large bodies of water see an increase in home values, this is only true for homes near nuclear power plants.

At the community-level between 1990-2010, there were no significant changes in population density, the percentage of black residents, the percentage of residents with Bachelor's degrees or above, household income, and home value for each power plant type. After power plants begin operation, the associated socioeconomic indicators stay relatively the same. While this study does not infer causality, the community-level relationships and differences between power plants persist over three decades. Further analysis is needed to determine if the county and community-level relationships existed before the operation of these power plants and whether they differ based on power plant type.

With an aging fleet of nuclear and coal power plants, it is expected many will face retirement in the near future. The average ages of nuclear and coal power plants in the socioeconomic analysis are 32 and 41 years, respectively, while the average age of natural gas power plants are 14 years. Rode et al. (2017) [85] finds 86% of all power plants ever built were still in operation in 2014. This rapidly aging fleet will likely lead to a growth in power plant retirements after 2030. Regulatory emissions uncertainty, economic factors, and license renewals are the largest factors for determining the timing of the retirements. About 30% of installed nuclear capacity will be lost by 2035 if the operating licenses for nuclear power plants are not extended beyond 60 years [23]. Industry has largely replaced its retiring capacity with natural gas due to it availability and low price. Utilities are moving towards converting coal plants to use natural gas as a primary fuel. For example, AEP's Clinch River coal power plant completed its conversion to natural gas in 2016 [86]. Communities and counties that dealt with the externalities of large coal facility in the past are now the site of smaller capacity natural gas plants.

Moving forward, many large baseload coal and nuclear power plants have the potential to be replaced with smaller capacity natural gas plants or small modular reactors. There is a legacy of older plant technologies and surrounding communities that most likely will not hold going forward. During this conversion it will be important to understand the change in relationships that will occur between power plants and their communities in the future. With the conversion from coal to natural gas, communities with existing coal plants have the opportunity to reduce the worst of the negative externalities and yet retain some of the economic benefits. The worst outcome for a community surrounding a large coal plant is retirement. The community is left with the environmental stigma, loss of jobs, and loss of tax revenue.

It can be seen that there are disparities in communities surrounding power plants. The relationship between power plant types and their respective home counties are explored and the risks related to the current demographics associated with power plants and their power plant siting are quantified. However, Davis (2017) [87] finds that US residential consumption of electricity significantly decreased in 2012 and has remained flat. Should this trend continue, the replacement of large gigawatt scale coal and nuclear power plants with smaller capacity natural gas plants and small modular reactors can result in the preservation of economic activity, reduce negative externalities, and ultimately change the relationships and risks between socioeconomic indicators.

Chapter 4

Risk and regulatory considerations for SMR emergency planning zones based on passive decontamination potential

This work estimates and compares the environmental dose exposure in a post-accident scenario using decontamination factors from EPRI's Experimental Verification of Post-Accident iPWR Aerosol Behavior test to the AP1000 and historical decontamination factors derived from NUREG-6189. On average, the AP1000, Surry, and iPWR produces 139, 153, and 104 curies/ft^3 75 minutes after a LOCA. The iPWR produces less radioactivity per volume in containment than the AP1000 and Surry 84% and 96% of the time, respectively. The AP1000 produces less radioactivity per volume than Surry 68% of the time. On average, the AP1000, Surry, and iPWR produces 84,000, 106,000, and 7,000 curies/MW$_{\mathrm{th}}$ 75 minutes after a LOCA. The iPWR has stochastically less radioactivity per unit of thermal power than the AP1000 and Surry. The lower bound 5 rem PAG limit is exceeded between 2 to 3 miles for thyroid exposure using the dose exposure means for the AP1000 and Surry. In comparison, the 5 rem PAG thyroid limit is never exceeded for the iPWR. The 1 to 5 rem PAG limit for whole body exposure is not exceeded at the 10-mile EPZ using the mean estimates for the AP1000 and Surry. The iPWR does not exceeds the 1 rem lower PAG limit for whole body exposure at the 5-mile EPZ using the mean value. These findings can be used in conjunction with the improved analytical methods, found in the SOARCA study, to provide accurate and realistic estimates for exposure. This will help create a pathway to develop a regulatory basis for technology-neutral, risk-based approach to EPZs for iPWRs.

4.1 Introduction

The relative uncertainty of new construction in the US has called into question the economic viability and competitiveness of large-scale nuclear power plants [88, 89]. Construction of the two V.C. Summer AP1000 units in South Carolina have ceased as a result of numerous delays and cost overruns [89]. The development and deployment of SMRs are driven by their potential for higher levels of safety, reduction in construction time, improved construction efficiency through modular construction methods, minimizing cost overruns, and lower overall capital cost. Ultimately within the nuclear industry, the goal for the deployment of SMRs is to maintain a high level of safety, reduce the financial risks that have burdened large-scale nuclear power plants, and provide flexibility for installed capacity.

There are a variety of designs and types of Generation III+ and Generation IV SMRs. Thermal reactors rely on neutron moderators to reduce the speed of fast neutrons to maintain the nuclear chain reaction. Fast reactors rely on fast neutrons to maintain the nuclear chain reaction and do not require a neutron moderator. SMR classifications are listed below:

- Thermal Rectors
  - Pressurized Water Reactors (PWRs)
    - Integrated PWRs (iPWRs)
  - High Temperature Gas-cooled Reactors (HTGRs)
  - Molten Salt fueled Reactors (MSRs)
  - Fuel fabrication
- Fast Reactors
  - Liquid Metal Fast Reactors (LMFRs)
  - Gas-cooled Fast Reactors (GFRs)
  - Equipment use

Within these classifications, PWRs and iPWRs are considered generation III+ reactors, while HTGRs, MSRs, LMFRs, and GFRs are considered generation IV reactors. As a subset of PWRs, iPWRs differ because all major components are located inside the reactor vessel. While there are many types of conceptual SMR designs from many vendors around the world, the NuScale iPWR design is the only SMR to submit an Nuclear Regulatory Commission (NRC) design certification. Based on this, the near term deployment of commercial iPWR SMRs in the US are more likely than the generation IV designs. With the NRC accepting the Tennessee Valley Authority's application for an early site permit, there have been questions regarding tying SMRs to the same regulatory framework as large-scale nuclear power plants. This includes staffing and security requirements, the size of emergency planning zones (EPZs), and the licensing process [90].

It has been argued that a risk and performance-based approach to licensing would be appropriate for SMRs because they have a much different risk profile than large-scale reactors [91, 92]. This is based on several factors including their limited electrical capacity of 300 $\mathrm{MW_e}$, the below grade reactor vessel, and passive safety features, and lower radioactive material on-site. One design feature that can significantly reduce accident severity is the larger lateral surface area-to-volume (A/V) ratio of SMRs [93, 94]. This larger A/V ratio can increase the removal of particles due to natural phenomena compared to traditional LWRs [93, 94].

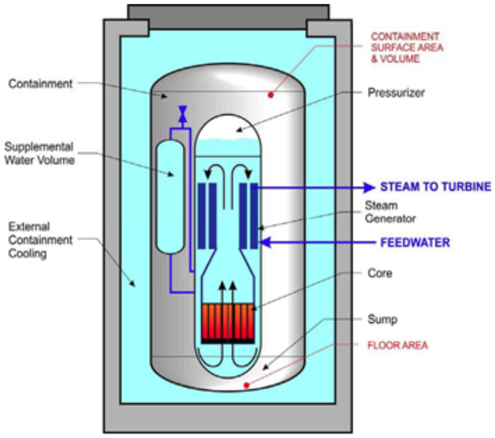

Figure 4.1: Diagram of generic iPWR SMR [93].

The size of EPZs for SMRs are viewed as one of the most pressing issues regarding the regulatory framework for SMRs. EPZs are currently 10 and 50-mile buffer zones around nuclear power plants. They are designed to facilitate protective actions in the event of a nuclear incident. Protective actions, such as sheltering, evacuation, and using potassium iodide within the 10-mile buffer plume exposure pathway EPZ is designed to reduce exposure of radioactive material through inhalation [95]. Protective actions, such as prohibiting the consumption of contaminated food and liquid within the 50-mile ingestion exposure pathway EPZ is designed to reduce the ingestion of radioactive materials [95]. EPZs can be determined on a case-by-case basis for gas-cooled reactors or reactors with thermal power of <250 $\mathrm{MW_{th}}$ [96], however they are still governed by emergency response guidance in NUREG-0396 [97].

One of the first protective measures implemented to protect the public in the event of an accident was the establishment of a low population zone in 1962 as part 10 CFR Part 100. Though emergency preparedness had been a requirement for nuclear facilities, previous guidance was not specified for the distance of planning zones until 1970 with 10 CFR 50 Appendix E. Despite these efforts, there were still questions regarding emergency planning recommendations based on the characteristics and the magnitude of nuclear accidents. In response, a task force made up of NRC and EPA representatives in 1976 were assembled to determine the appropriate level of emergency planning at the local, state, and federal levels. In 1978 the task force produced a report in the form of NUREG-0396 [97]. This report established the concept of a generic EPZ to protect the public and environment in the event of an accident.

As part of the NRC licensing process for any nuclear facility, emergency response plans must be developed in coordination with state and local agencies to protect the public health end environment in the event of the release of radioactive material. Other forms of power generation are not required to establish and maintain EPZs. As a result, they are not subject to their associated costs. Figure 4.2 shows the estimated cost for establishing and maintaining a 10-mile, 5-mile, 2-mile, and site boundary EPZ. On average, it is estimated that it costs approximately $10 million to establish an EPZ and an additional $2.25 million per year to maintain. This estimation assumes the EPZ is for a single unit plant with a nominal 40-year lifetime [98]. Reducing the 10-mile plume exposure pathway EPZ can reduce offsite emergency preparedness lifetime costs by between 68% - 84% for a 5-mile EPZ, 89% - 92% for a 2-mile EPZ, and 94% at the site boundary EPZ with a 3% discount rate.

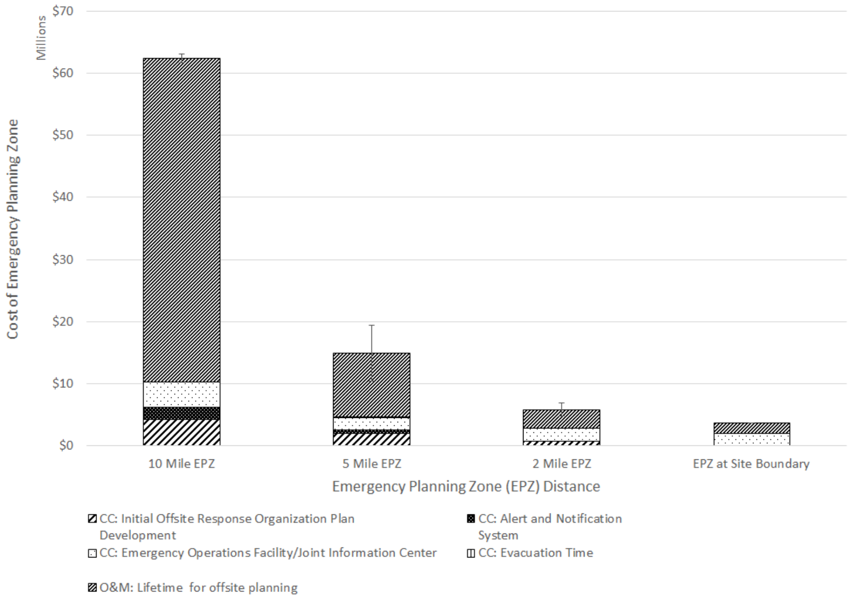

Figure 4.2: Estimated lifetime costs of emergency planning zones [98].

With a relatively strong safety record and the high costs of maintaining EPZs, the nuclear industry is lobbying the NRC to move towards using more risk-informed approaches when establishing EPZs for iPWR SMRs. From a cost perspective, there are opportunities to reduce the financial risk based on the inherent attributes of iPWR SMRs compared to large-scale Light Water Reactors (LWRs). Typically, a large emphasis is placed on the capital cost and the LCOE for iPWR SMRs [99, 100, 101, 102, 103]. Instead of focusing on costs related to overnight construction and the LCOE, shifting the focus to safety can create opportunities to reduce cost. Specifically, using dose exposure in a post-accident scenario as a risk and performance-based metric that can be used to reduce the size of EPZs for iPWR SMRs.

In 2011 the NRC concluded EPZ designation could employ a technology-neutral, dose-based, risk-informed approach for SMRs [104]. In response the NEI produced a white paper on methods and criteria for establishing a technical basis for risk-informed scaling EPZs for SMRs based on associated dose characteristics [105]. NRC Regulatory Guide 1.183 [106] permits the use of natural deposition correlations to determine nuclear containment decontamination factors (DFs) after an accident for large-scale nuclear power plants. Specifically, natural processes, such as gravitational settling,[1] diffusiophoresis,[2] and thermophoresis[3] during accident conditions for large-scale LWRs developed in Powers et al. (1996) [107]. However, these correlations have not been quantified for iPWRs. In the past Sandia National Laboratories produced a report [93] that evaluated aerosol deposition experimental data since 1993. These could prove relevant to iPWRs and assist in developing the experimental framework needed to evaluate aerosol depositions for an iPWR given their A/V ratios and post-accident transient containment conditions. In their analysis, two iPWR accident containment conditions were considered; An early release, within 1 hour of an accident with a pressure of 45-700 psig and temperature of 290°F-500°F. As well as a late release, within an hour to 7 days of an accident with a pressure of 20-190 psig and 230°F-380°F. A nuclear power plant assessment tool, MELCOR (typically used to model the progression of accidents in LWRs) was used to model the aerosol deposition rates for gravitational settling, diffusiophoresis, and thermophoresis. The Sandia National Laboratories report found deposition velocity for gravitational settling is important for dry environments and diffusiophoresis is the dominant process in determining DFs for iPWR expected containment conditions. Thermophoresis was shown to be an unimportant factor for iPWR in expected conditions.

While the report by Sandia National Laboratories identified phenomena significant during post-accident scenarios, there is a research gap in quantifying DFs for iPWR designs. The Electric Power Research Institute (EPRI) with support from Department of Energy (DOE) has funded a research program to fill this research gap by conducting a set of experiments and developing a Computational Fluid Dynamics (CFD) model to estimate the aerosol behavior for an iPWR under accident conditions [94, 108]. EPRI's Experimental Verification of Post-Accident iPWR Aerosol Behavior test simulated the release of particles ranging from 2

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[1] A phenomena where particles settle to the bottom of containment due to gravity.

[2] The process where particles travel from a higher to a lower steam concentration due to the movement of steam to the walls.

[3] A phenomenon where a high to low temperature gradient causes particles within containment to move towards the surface.

to 10 μm in size into the containment environment following an assumed pipe break to better understand aerosol behavior inside containment in a post-accident scenario for iPWRs. The technical report indicates the inclusion of convective flow significantly increases the decontamination (reduction in airborne radioactive particles within containment) in the CFD models. The report also indicates an increase in lateral A/V results in faster deposition rates. The goal of this work is to uses the DFs found in EPRI's iPWR Aerosol Behavior test to estimate dose exposure rates to the public after an accident. From a regulatory standpoint, reduced exposure to radionuclides in the environment can be credited towards dose savings in support of a Level 3 Probabilistic Risk Assessment (PRAs)[4] during licensing.

To establish scalable EPZs for iPWR SMRs; a dose-based, risk-informed approach can be incorporated by estimating the environmental dose exposure in a post-accident scenario with the DFs produced from EPRI's Experimental Verification of Post-Accident iPWR Aerosol Behavior test. The estimated dose exposure can be used as a metric for risk-informed EPZ scaling decisions. RASCAL is used to estimate the radioactivity present after a simulated core melt of the reactor vessel where radionuclides are released into the containment structure (ex-vessel release phase). The estimated DFs are used to estimate radioactivity within containment and dose exposure in the enviornment. The calculated dose and DFs will be compared to the AP1000 and Surry Unit 1. The AP1000 was selected to represent Generation III+ nuclear power plants because Vogtle units 3&4 are currently under construction in Georgia and its aerosol removal coefficients are well documented. Surry was selected because it was used to model a typical PWR in safety studies NUREG-1150 and the State-of-the-Art Reactor Consequence Analyses (SOARCA). With this comparison, the risks of radioactive material being released into the environment relative to large LWR can be quantified. The calculated dose of the AP1000 and the iPWR Aerosol Behavior test will be evaluated against the EPA Protective Action Guide (PAG) limits of 1 to 5 rem for whole body dose and 5 to 25 rem for thyroid dose [109] at the proposed site boundary, 2 mile, 5 mile, and 10 mile EPZ. Regulatory framework decisions made by the NRC regarding reactor safety can be influenced by the advice of subject matter experts on the Advisory Council on Reactor Safeguards (ACRS). The recommendations that the ACRS provides to the NRC includes initiating reviews of nuclear facility safety-related items. The comparative results can be used to quantify the risks to regulatory acceptance by including additional considerations to the Level 3 PRA based on recent research in aerosol behavior for iPWRs. This approach includes the inherent passive safety features present in iPWR SMRs that were not present in legacy PWRs. NRC regulations and design certifications are considered the international "gold standard" in nuclear safety [90], however organizations feel the regulatory burden may have a negative economic impact on growth for a fragile industry. This work

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[4] Level 1 PRAs estimate the frequency of accidents that cause core damage. Level 2 PRAs estimates the frequency of accidents that release radionuclides into the environment. Level 3 PRAs estimate the consequences related exposure to the public after the release of radionuclides into the environment.

can ultimately be used to quantify the risks related to the release of radionuclides into the environment and offsite consequences to support Level 3 PRAs for iPWRs.

4.2 Methods

To estimate the dose from the release of radionuclides following a LOCA, a collection of methods are used to estimate the core inventory of radionuclides, calculate the DFs, and estimate the dispersion of radionuclides after the containment vessel leaks material or fails. The current regulatory basis for EPZ are based on atmospheric dispersion models and methodology that is over 40 year old [110]. This analysis uses updated aerosol behavior methodology for iPWRs and simple atmospheric dispersion models. Figure 4.3 outlines a simplified diagram of the major steps in this study. First, the inventory of the radionuclides are assumed using the values presented in NUREG-1940 [111]. NUREG-1465 [112] is used to estimate the radioactivity during each release phase. Second, to account for inherent uncertainties, Monte Carlo simulations are used in instances with multiple DF estimates. The DFs will be applied to the radionuclide inventory while in containment before an assumed containment vessel failure or leakage. DFs are sourced from the natural process described in Powers et al. 1996 [107], the AP1000 passive containment cooling via the natural process as described in the AP1000 Design Control Document (DCD) Appendix 15B[5] [113], and EPRI's iPWR Aerosol Behavior technical report [108]. Finally, a straight-line Gaussian plume model is used to estimate the dispersion of material over a proposed site boundary, 2 mile, 5 mile, and 10 mile EPZ to determine if the dose falls within PAG limits. Because of limited iPWR DF data, the dose estimation is limited to 80 minutes following a LOCA.

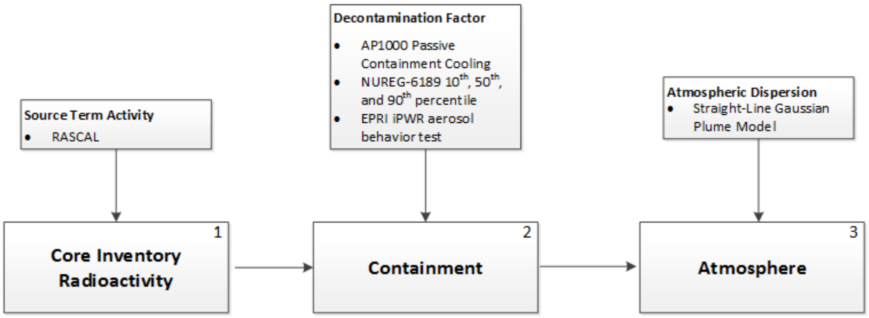

Figure 4.3: Core Inventory, Containment Decontamination, and Atmospheric Process Flow. Core inventory radioactivity is estimated using the NRC code, RASCAL. Then decontamination factors from the AP1000 Design Control Document Appendix 15B, NUREG-6189, and EPRI's aerosol behavior test is used to estimate the containment radioactivity. Finally, a straight-line Gaussian Plume model is used to estimate the dose exposure from the radioactive material exiting containment.

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[5] It is assumed that the AP1000 does not apply convective flows as an in-containment vessel aerosol removal natural process [108].

4.2.1 Radionuclide Inventory and Plant Specifications

The AP1000, Surry, and a hypothetical 160 $\mathrm{MW_{th}}$ iPWR are used as test cases to evaluate the performance of DFs in relation to dose rates following a post-accident scenario. Table 4.1 shows key plant parameters for the AP1000, Surry, and the hypothetical 160 $\mathrm{MW_{th}}$ iPWR are used as input for RASCAL[6] to establish the radionuclide inventory for each model.

Table 4.1: AP1000, Surry, and iPWR Plant Parameters.[7]

Parameters	**AP1000**	**Surry**	**iPWR**
Thermal power ($\mathrm{MW_{th}}$)	3,415	2,587	160
Average burnup (MWd/MTU)	30,000	30,000	30,000
Containment Volume ($\mathrm{ft^3}$)	2,060,000	1,800,000	10,537
Surface area-to-volume ratio ($\mathrm{ft^{-1}}$)	0.04	0.03	0.60 0.67 0.75
Design leak rate (%/d)	0.1	0.1	0.1
Assemblies in core	157	157	37
Assumed stack height (m)[8]	10	10	0-10

Table 4.2 shows the initial core inventory and the percentage of each radionuclide group for each power plant. Table 4.3 shows the fraction of radionuclides that are released for each phase following a LOCA [111] and the percentage of radioactivity attributed to each radionuclide group after the ex-vessel stage. While a majority of the radioactivity is attributed to the Cerium group and Lanthanides in Table 4.2, noble gases and halogens make up a combined 86% of the radioactivity by the ex-vessel stage in Table 4.3. This is due to 100% of the nobles gases, 40% of halogens, 30% of alkali metals, and 5% of the tellurium's group's inventory are released into containment by the end of the in-vessel stage. NUREG-0396 [97] considers I-131, I-132, I-133, I-134, I-135, Te-132, Kr-88, Xe-133, Xe-135, Cs-134, and Cs-137 to have significant contributions to whole body and thyroid exposure to the public. Within the ex-vessel phase, 100% and 65% of the initial inventory of noble gases, Halogens and Alkali metals will be released into containment, respectively. While in containment, the natural process is expected remove the fission products with the exception of noble gases via natural convective flows, gravitational settling, diffusiophoresis, and thermophoresis. The DFs are used to quantify how well the natural process can remove the fission materials.

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[6] NUREG-1940 [111] outlines the core inventory of radionuclide during operation by thermal capacity

[7] The iPWR is assumed to have the same thermal power as the NuScale SMR. The PWR surface area-to-volume ratio presented in Rochau et al. (2014) [93] is the assumed value for Surry

[8] Typically, the nuclear island and containment vessel are below grade for SMRs. A uniform distribution is used to model the stack height range. The stack height for Surry and the AP1000 are based on Regulatory Guide 1.145 [114]

Table 4.2: Power Plant Initial Core Radioactivity.

Total Radioactivity	**AP1000**	**Surry**	**iPWR**	**% of Total Radioactivity**
	(Million Curies)			
Noble Gases (Kr, Xe)	568	431	27	9%
Halogens (I, Br)	790	598	37	12%
Alkali Metals (Cs, Rb)	26	20	1	0%
Tellurium group (Te, Sb, Se)	230	174	11	3%
Barium, Strontium (Ba, Sr)	544	412	25	8%
Noble metals (Ru, Rh, Pd, Mo, Tc, Co)	732	554	34	11%
Cerium group (Ce, Pu, Np)	2,362	1,789	111	35%
Lanthanides (La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Cm, Am)	1,421	1,077	67	21%
Total Radioactivity	6,674	5,055	313	100%

Table 4.3: Fraction of Core Radioactivity Inventory Released for PWRs. [111, 112]

	Gap 0.5 Hours	**Early In-Vessel** 1.3 Hours	**Ex-Vessel** 2 Hours	**Late In-Vessel** 10 Hours	**Ex-vessel Radioactivity**
Noble Gases (Kr, Xe)	0.05	0.95	0	0	45%
Halogens (I, Br)	0.05	0.35	0.25	0.1	41%
Alkali Metals (Cs, Rb)	0.05	0.25	0.35	0.1	1%
Tellurium group (Te, Sb, Se)	0	0.05	0.25	0.005	5%
Barium, Strontium (Ba, Sr)	0	0.02	0.1	0	5%
Noble metals (Ru, Rh, Pd, Mo, Tc, Co)	0	0.0025	0.0025	0	0%
Cerium group (Ce, Pu, Np)	0	0.0005	0.005	0	1%
Lanthanides (La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Cm, Am)	0	0.0002	0.005	0	1%

4.2.2 iPWR Aerosol Behavior Test and CFD Model Design

The iPWR Aerosol Behavior test [94, 108] estimates the deposition rates for convective flows, gravitational settling, diffusiophoresis, and thermophoresis inside a iPWR containment using Phase Doppler Particle Analyzers (PDPAs). PDPAs are used to measure particle size, velocity, density and volume flux. The iPWR Aerosol Behavior test containment structure contains three vertical locations with 3 pairs of sample points for the PDPAs to measure particle behavior. Sample points 1&2, 3&4, and 5&6 are 24 inches, 28 inches, and 72 inches from the top of the containment vessel, respectively.

For each A/V scenario the iPWR Aerosol Behavior test is run three times with a temperature range between 250°F and 500°F to capture the early and late release scenarios in the Sandia National Laboratories study. The iPWR Aerosol Behavior test assumes the ex-vessel release phase because it is representative of the post-pressurization aerosol depletion period. This will allow the two PDPAs to capture the aerosol behavior data for each pair of sample points. The deposition velocities are outlined by Friedlander (2000) [115] and Powers et al. (1996) [107]. Figure 3 shows the physical containment structure has cylindrical inserts with diameters of 4 inches, 26 inches, and 36 inches that correspond to A/V ratios of 0.60 ft^{-1}, 0.67 ft^{-1}, and 0.75 ft^{-1} with containment vessel diameters of 80 inches and a reactor vessel height of 8 ft. The CFD

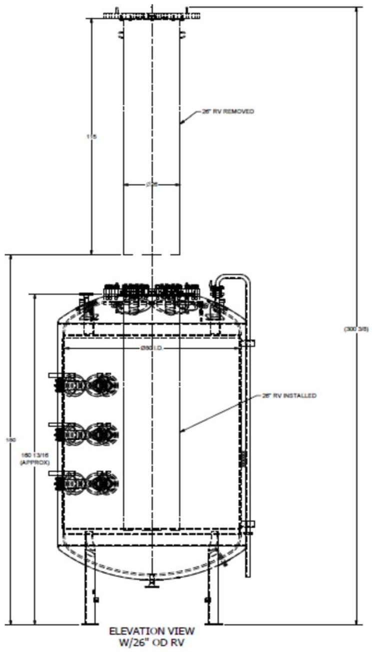

Figure 4.4: iPWR Containment Structure with Reactor Vessel Cylindrical Inserts [94].

model, developed by Biwalker and Satbir (2017) [116], performs simulations using CONVERGE CFD codes with user defined functions while transient flow simulations are performed with Reynolds-Averaged Navier-Stokes (RANS). The model is made up of a condensation, deposition velocity, and drift-flux models [116]. The CFD model was verified against the Sandia National Laboratories report for deposition velocities and literature for prediction of condensation and phoretic phenomena [116]. A two-dimensional (2D) slice of the containment vessel is simulated during a post-accident scenario. A verified CFD model is created by using corresponding locations from the iPWR Aerosol Behavior test to calibrate the CFD model. Other locations will be used to determine the accuracy in estimating the deposition velocities from the corresponding CFD 2D slice inside the containment vessel.

4.2.3 Decontamination Factors in Containment

Globally, there are a diversity of SMR designs from many different vendors [117]. Each SMR design will have varying A/V ratios that will ultimately impact their ability to remove radioactive particles in post-accident scenario within containment via natural process. DFs are defined as the ratio between the initial aerosol mass and the aerosol mass after a decontamination mechanism, such as natural process or sprays are initiated. This work will focus on the DFs from the natural process within the containment vessel for representative legacy large LWRs (Surry), Generation III+ large LWRs (AP1000), and hypothetical Generation III+ iPWRs (160 MW_{th}). Historically, a simplified method developed by Powers et al. (1996)

has been used to derive DFs using aerosol removal coefficients outlined in Table 4.4. Aerosol reduction factors (RDF) are the inverse of DFs as shown in Equation 4.1.

Table 4.4: Aerosol Removal Correlation Coefficients for Gap and Early In-vessel Release Stages [107].

Release Stage	Time Interval (s)	Percentile	Aerosol Removal Coefficients
Gap	0 - 1800	90	$\lambda(90) = 0.0349 + 3.76 \times 10^{-6}$ P
Gap	0 - 1800	50	$\lambda(50) = 0.0256 + 3.90 \times 10^{-6}$ P
Gap	0 - 1800	10	$\lambda(10) = 0.0167 + 3.25 \times 10^{-6}$ P
Early In-vessel	1800 - 5400	90	$\lambda(90) = 0.0505 + 0.94 \times 10^{-6}$ P
Early In-vessel	1800 - 5400	50	$\lambda(50) = 0.0257 + 3.87 \times 10^{-6}$ P
Early In-vessel	1800 - 5400	10	$\lambda(10) = 0.0166 + 3.49 \times 10^{-6}$ P

Where P is the thermal reactor power (MW).

$$DF(t) = \frac{1}{RDF} = \frac{M_0}{M_t}, \tag{4.1}$$

Where:

M_0 : is the initial aerosol mass

M_t : is the aerosol mass at time t

DFs can also be derived from the aerosol removal coefficients shown in Table 4.4 using Equation 4.2 from Zhao et al. (2015) [118].

$$DF(T) = \frac{1}{e^{-\int_0^T}\lambda(t)dt}, \tag{4.2}$$

Where:

$\lambda(t)$: is the aerosol removal coefficient, as a function of time

T : is the time after aerosol removal

Studies in the past have typically investigated post-accident scenarios for least 24-hours [118, 119]. Zhao et al. (2015) [118] shows the AP1000 PCC has the most dominant DF within a 24 hour period compared to the 10th, 50th, and 90th percentile DFs from Powers et al. (1996) [107]. The DFs outlined NUREG-1228 and RASCAL are only dominant during the first 6 hours post-accident. However, Zhao et al. (2015) [118] considers the DFs from RASCAL and NUREG-1228 to be unrealistic. As a result, the DFs from RASCAL and NUREG-1228 are not in the Monte Carlo simulation. The iPWR Aerosol Behavior test used 7 test cases with varying parameters for reactor vessel wall temperature, containment vessel wall temperature, pressure, A/V ratio, and steam mass fraction to calculate their associated DFs. Table 4.5 shows the varying parameters for each test case. Figure 4.5 shows a reproduced plot of the DFs from each respective test case. Based on the on the iPWR Aerosol Behavior test, test case 7 has the lowest DF (15), while test case 5 and 13 have the highest (28 and 27, respectively).

Table 4.5: iPWR Aerosol Behavior Decontamination Factor Test Case Parameters [108].

Test Case	Test Type	Reactor Vessel Wall Temperature (°F)	Containment Vessel Wall Temperature (°F)	Pressure (psi)	Surface Area to Volume Ratio (ft^{-1})	Steam Mass Fraction
5	TGCD	500	220	200	0.67	0.7
6	TGCD	450	220	200	0.67	0.7
7	TGCD	400	220	200	0.67	0.7
10	TGCD	500	220	200	0.60	0.7
11	TGCD	500	220	200	0.75	0.7
13	TGCD	500	220	65	0.67	0.7
15	TGCD	500	220	20	0.67	0.7

Note: T - Thermophoresis, G - Gravitational settling, C - Convective flow, and D - Diffusiophoresis

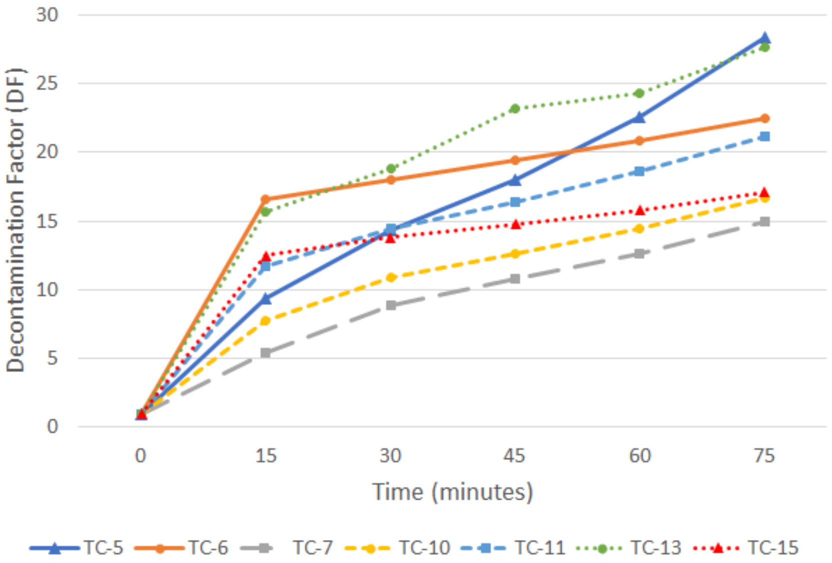

Figure 4.5: Reproduced Decontamination Factor Curve Fit for Test Cases [108].

Figure 4.6 shows the DFs during the first 75 minutes following a LOCA for the AP1000 and the 160 MW$_{th}$ iPWR using DFs from Powers et al. (1996) [107], the AP1000 PCC, and iPWR Aerosol Behavior test. Because the iPWR Aerosol Behavior test has 7 test cases, Monte Carlo simulation is used to account for uncertainty. The error bars for the iPWR represent the 90% confidence interval to reflect the same interval used in Powers et al. (1996).[9]

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[9] Error bars are included in Figure 4.6 to represent the 10th and 90th percentile using the Powers et al. (1996) method for the AP1000 and iPWR. Because there is no significant difference in DF at 75 minutes they do not appear in the log scale.

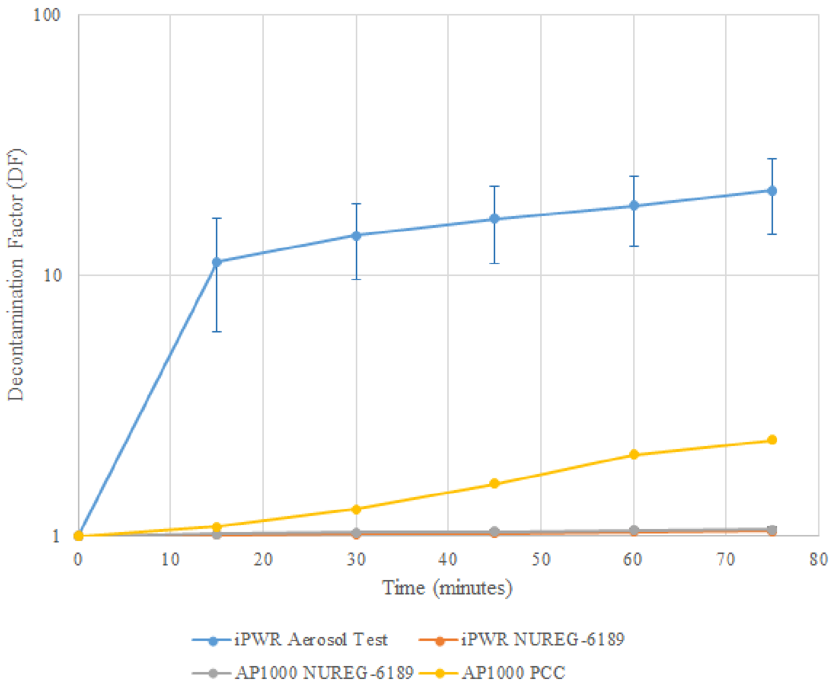

Figure 4.6: Comparison of decontamination factors for the AP1000 and the iPWR.

The DFs are slightly above 1 (<1% of particles are removed) during the first 75 minutes for the AP1000 and 160 MW_{th} iPWR assuming the Powers et al. (1996) method. The AP1000 PCC achieves a DF of 2 (50% of particles are removed) after 75 minutes and it takes about 5 hours to reach a DF of 10. Zhao et al. (2015) [118] shows it takes about 8 hours for the AP1000 to reach a DF of 10 using the 90^{th} percentile correlation coefficients. In comparison, the 160 MW_{th} iPWR approaches a DF of 10 within the first 15 minutes and a DF of 21 (95% of particles are removed) in 75 minutes using the DFs from EPRI's Aerosol Behavior test.

4.2.4 Atmospheric Dispersion

After containment failure, the radionuclides within the containment vessel are leaked into the atmosphere. The atmospheric dispersion of radionuclides are modeled using straight-line Gaussian Plume models. Within this analysis, Gaussian plume models are used to estimate the concentration of radioactivity from point sources assuming conditions are at steady state, the concentration of radioactivity is time-averaged, and the terrain is flat. Historically, Gaussian plume models are a simplified method for modeling atmospheric dispersion of air pollutants, particles, and radionuclides at ground level based on a given distance. Inputs typically consist of the wind speed, the wind stability category, point source stack height, and emissions rate. While simple, straight-line Gaussian plume models tend to have conservative tendencies and they produce conservative dose estimates for preliminary safety analyses [120]. Based on the distance and sector, Gaussian plume models can have a relative concentration of up to 14 times higher than Lagrangian plume models [120]. Lutman et al. (2004) [121] also finds that Lagrangian dispersion models can provide more realistic atmospheric dispersion estimates than Gaussian plume models. Based on the its relative simplicity and conservative tendencies, Gaussian plume models will be used to represent the higher bound estimate for dose exposure within this analysis. A generic Gaussian Point Source Plume model is shown in Equation 4.3. The Gaussian plume model is reduced to Equation 4.4 to estimate downwind centerline ground-level exposure.

$$\chi(x,y,z) = \frac{Q}{2\pi u \sigma_z \sigma_y}\left[\exp\left(\frac{-(z-h)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z+h)^2}{2\sigma_z^2}\right)\right] \times \left[\exp\frac{-(y)^2}{2\sigma_y^2}\right], \tag{4.3}$$

Where:

χ : is the concentration of radioactivity at position x, y, z within the Cartesian coordinate system (meters)

Q : is the contaminant emission rate of all radionuclides (curies/second)

u : is the wind speed at the stack release height in (meters/second)

σ_y : is the lateral plume spread based on Pasquill-Gifford stability categories

σ_z : is the vertical plume spread based on Pasquill-Gifford stability categories

$$\chi(x,0,0) = \frac{Q}{\pi u \sigma_z \sigma_y}\left[\exp\left(\frac{-(h)^2}{2\sigma_z^2}\right)\right] \tag{4.4}$$

Understanding the impact atmospheric dispersion and radionuclide transport plays an important role in estimating dose exposure. RASCAL and several studies in the past utilizes straight-line Gaussian plume models to estimate the concentration of radionuclides. The calculated concentrations from Gaussian plume models are used in Equation 4.5 [122, 123] to estimate the total thyroid dose exposure for the AP1000, Surry, and the 160 MW_{th} iPWR. The sum of the whole body inhalation (CEDE) and immersion (EDE) doses using Equation 4.5 and 4.6 are used to calculate the total effective dose equivalent (TEDE) [123].

$$D_{CEDE} = \sum_i DCF \times B \times \frac{\chi}{Q} \times ST_i, \tag{4.5}$$

Where:

D_{CEDE} : is the is inhalation dose (Committed Effective Dose Equivalent) (rem)

DCF : is the dose conversion factor for radionuclide i (rems/curies)

B : is the assumed breathing rate of 2.66×10^{-4} m^3/second

$\frac{\chi}{Q}$: is the relative concentration

ST_i : is the source term for radionuclide i (curies)

$$D_{im} = \sum_i DCF \times \frac{\chi}{Q} \times ST_i, \tag{4.6}$$

Where:

D_{im} : is the is immersion dose (Effective Dose Equivalent) (rem)

Inhalation and immersion DCFs are sourced from Federal Guidance Report No. 11 [124]. Table 4.6 outlines the DCF for each radionuclide in this analysis.

Table 4.6: Radionuclide Dose Conversion Factors [124].

Radionuclide	**Thyroid Inhalation**	**Whole Body Inhalation**	**Whole Body Immersion**
	(rem/curies)		(rem-m^3/seconds-curies)
I-131	1,080,400	32,893	-
I-132	6,438	381	-
I-133	179,820	5,846	-
I-134	1,066	131	-
I-135	31,302	1,228	-
Te-132	217,190	8,362	-
Cs-134	41,070	46,250	-
Cs-137	29,341	31,931	-
Kr-88	-	-	3,700
Xe-133	-	-	62
Xe-135	-	-	481

4.3 Results

4.3.1 Containment Deposition

A Monte Carlo simulation of 100,000 samples is used to estimate the radioactive activity for the AP1000, Surry, and the 160 MW$_{\text{th}}$ iPWR. The DFs presented in Figure 4.6 are applied to the AP1000, Surry, and the iPWR. To account for uncertainty, a uniform distribution using the AP1000 DCD and the NUREG-6189 DFs as parameters are used to estimate the containment radioactivity for the AP1000. Figure 4.7 shows the mean and 90% confidence interval of the radioactive activity for I-131, I-132, I-133, I-134, I-135, Te-132, Cs-134, and Cs-137 inside containment normalized to the volume and thermal power for each power plant. Panel 1 shows the total radioactivity per volume, Panel 2 shows the total radioactivity per unit of thermal power, Panel 3 shows the cumulative radioactivity per volume, and Panel 4 shows the cumulative radioactivity per unit of thermal power. Panel 1 of Figure 4.7 shows, on average, the AP1000, Surry, and iPWR produces 139, 153, and 104 curies/ft^3 75 minutes after a LOCA. The iPWR stochastically dominates Surry and on average, has less radioactivity per volume in containment than the AP1000. The Monte Carlo simulation shows the iPWR will produce less radioactivity per volume in containment than the AP1000 and Surry 84% and 96% of the time, respectively. The AP1000 produces less radioactivity per volume than Surry 68% of the time. On average, Panel 2 of Figure 4.7 shows the AP1000, Surry, and iPWR produces 84,000, 106,000, and 7,000 curies/MW$_{\mathrm{th}}$ 75 minutes after a LOCA. The iPWR has stochastically less radioactivity per unit of thermal power than the AP1000 and Surry. Based on the comparisons of DFs in Figure 4.6, it can be seen within 75 minutes, the iPWR DFs plays a substantial role in reducing the radioactivity. While it is expected that the iPWR would have a lower radioactivity level than the AP1000 and Surry, the iPWR continues to have lower radioactivity levels after normalizing by thermal reactor power and volume. Panels 3 and 4 shows the average radioactivity per volume and thermal power of Surry increases 18% faster than the AP1000 and 46% faster than the iPWR between minute 30 and 75. The AP1000's radioactivity by volume and thermal power increase 23% faster than the iPWR. Appendix C shows the estimated radioactivity from each iPWR Aerosol Behavior test case.

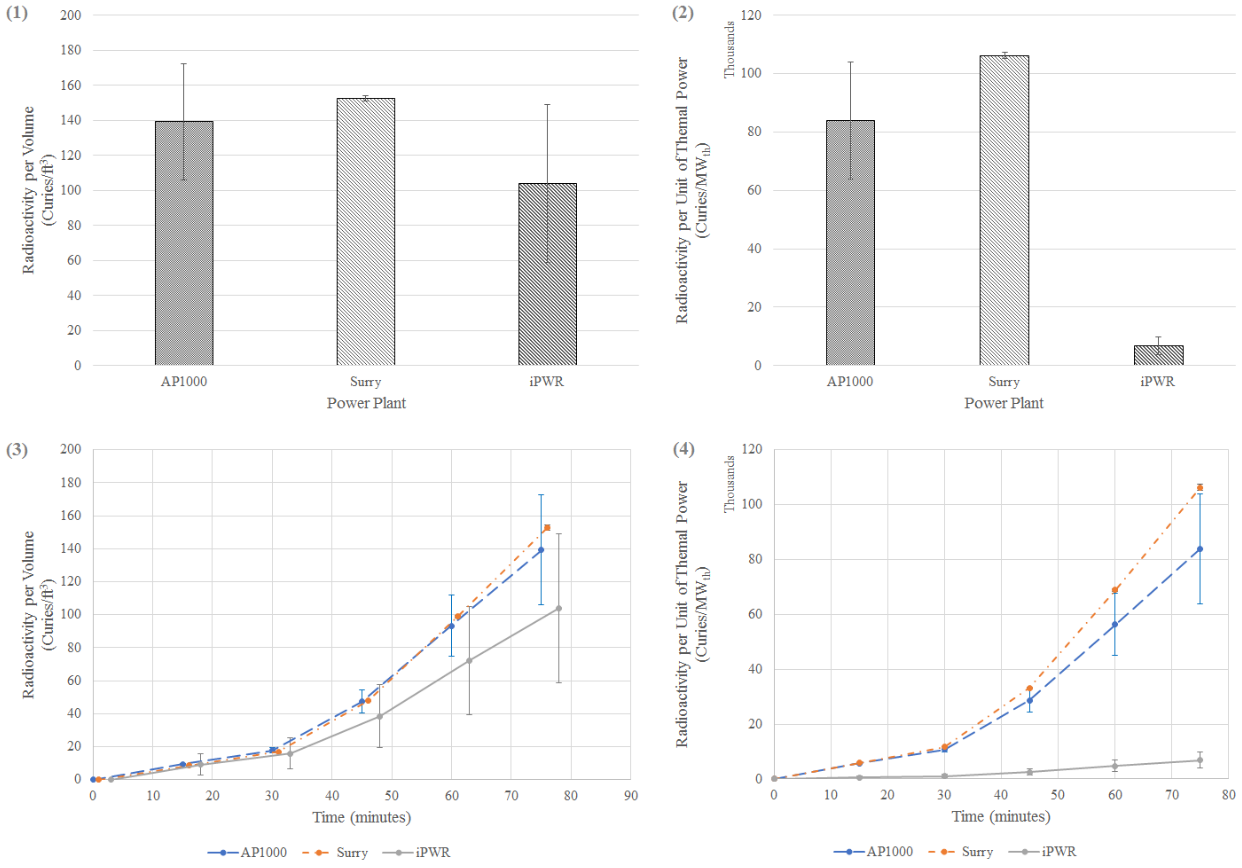

Figure 4.7: Panel 1: Radioactivity per Volume in Containment. Panel 2: Radioactivity per Thermal Power in Containment. Panel 3: Cumulative Radioactivity per Volume in Containment. Panel 4: Cumulative Radioactivity per Thermal Power in Containment.

4.3.2 Off-site Consequence Analysis

Straight-line Gaussian Plume models are used to estimate dose exposure within the EPZ for the AP1000, Surry, and the iPWR. The behavior of atmospheric dispersion is in part governed by the Pasquill-Gifford stability classes via horizontal (σ_y) and vertical (σ_z) dispersion coefficients at a given distance from the point release. Monte Carlo simulation is used to incorporate stability classes B, D, and F to represent moderately unstable, neutrally stable, and stable conditions, respectively, with winds speeds between 1-3 meters/second. Figure 4.8 and Table 4.7 shows the mean and 90% confidence interval for the thyroid and whole body[10] dose exposure by distance. Panel 1 of Figure 4.8 shows the lower bound 5 rem PAG limit is exceeded between 2 to 3 miles for thyroid exposure using the mean value for the AP1000 and Surry. That same limit is violated at 5 mile range for the AP1000 and Surry using the 95th percentile. In comparison, the 5 rem PAG thyroid limit is never exceeded for the mean and 95th percentile value for the iPWR.

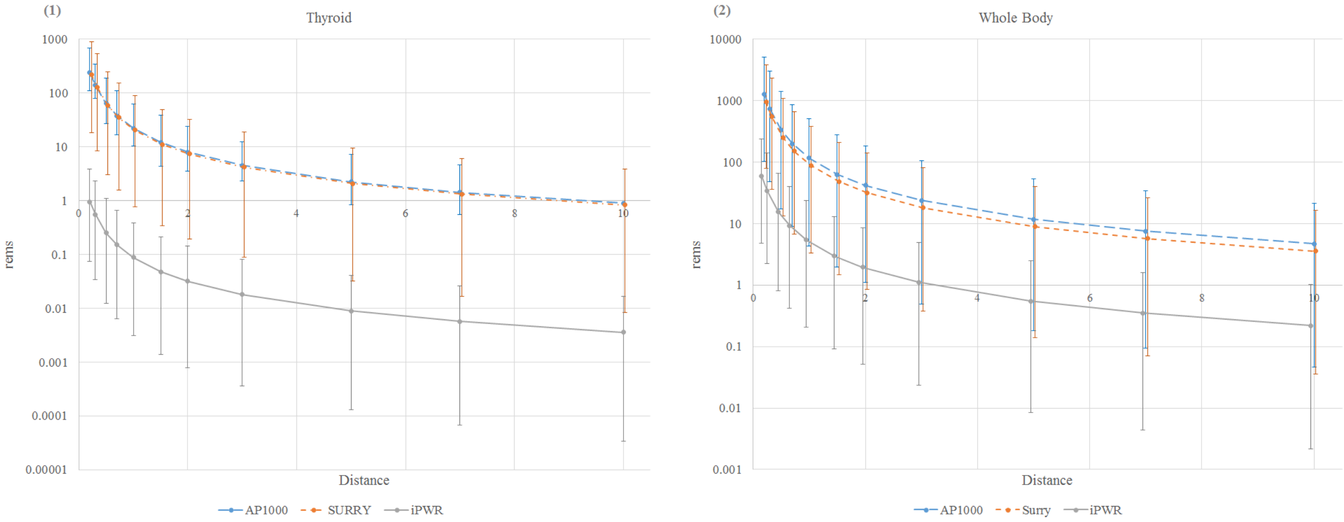

Figure 4.8: Thyroid and Whole Body Dose Exposure for AP1000, Surry, and iPWR.

Panel 2 of Figure 4.8 shows the 1 to 5 rem PAG limit for whole body exposure is not exceeded at the 10-mile EPZ using the mean estimates for the AP1000 and Surry. However, these limits are exceeds using the 95th percentile. On average, the iPWR meets the lower bound 1 rem PAG limit for whole body exposure at the 5-mile EPZ. The iPWR exceeds the 1 to 5 rem PAG limit for whole body exposure at the 1.5-mile range using the mean value. The limit is not exceed when using the 95th percentile at the 2-mile EPZ. A major source of the lower dose exposure of the iPWR compared to the large LWRs is due to the higher deposition rates present in the iPWR and the lower overall radioactivity within containment.

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[10] The whole body dose includes the immersion dose from the noble gas radionuclides.

Table 4.7: Mean and 90% confidence interval for thyroid and whole body dose exposure for the AP1000, Surry, and the iPWR.

	AP1000						**Surry**						**iPWR**					
Distance	**Thyroid**			**Whole Body**			**Thyroid**			**Whole Body**			**Thyroid**			**Whole Body**		
	Mean	5%	95%	Mean	5%	95%	Mean	5%	95%	Mean	5%	95%	Mean	5%	95%	Mean	5%	95%
(miles)									(rem)									
0.2	241	221	506	1,259	1,156	2,643	223	204	468	959	880	2,012	0.96	0.88	2.05	58.8	53.9	123.4
0.3	139	130	310	728	680	1,621	129	120	287	554	518	1,234	0.55	0.52	1.26	34.0	31.7	75.7
0.5	64	60	148	333	316	772	59	56	137	254	240	588	0.25	0.24	0.60	15.5	14.7	36.0
1.0	22	21	53	116	112	276	21	20	49	88	85	210	0.09	0.09	0.21	5.4	5.2	12.9
1.5	12	12	29	63	61	152	11	11	27	48	47	116	0.05	0.05	0.12	3.0	2.9	7.1
2.0	8	8	19	42	41	102	7	7	18	32	31	77	0.03	0.03	0.08	1.9	1.9	4.7
3.0	5	4	11	24	23	59	4	4	10	18	18	45	0.02	0.02	0.05	1.1	1.1	2.8
5.0	2	2	6	12	12	30	2	2	5	9	9	23	0.01	0.01	0.02	0.5	0.5	1.4
10.0	1	1	2	5	5	12	1	1	2	4	4	9	0.00	0.00	0.01	0.2	0.2	0.6

4.4 Conclusions and Policy Implications

As an increasing number of coal and nuclear plants begin to retire due to age and the inability to compete economically with natural gas plants in deregulated markets, iPWRs can be viewed as a viable option to can replace aging plants and can be viewed as economically competitive. While there are large uncertainties related to the capital cost of iPWRs, the cost reduction can be achieved through added safety and higher capacity factors with longer periods between refueling. Over the 40 year lifetime of a nuclear power plant as much as $80 million can be saved by reducing the EPZ to 5 miles. Using simple straight-line Gaussian Plume models from the past and with historical DF estimates, AP1000 DF estimates, and updated DF estimates from EPRI's Experimental Verification of Post-Accident iPWR Aerosol Behavior test to estimate offsite consequence techniques, this analysis has shown that iPWRs can meet the EPA specified PAG lower limits at 5 miles for whole body exposure and at site boundary for thyroid. Under the higher PAG limit of 5-rems, the iPWR can meet the whole body dose exposure limit at 1.5 miles. Comparing the past DF estimates (NUREG-6189 and the AP1000) against updated iPWR DFs based on an increased understanding of aerosol behavior can serve as a step to support Level 3 PRAs and estimate off-site consequences in conjunction with historical methods for modeling atmospheric dispersion (NUREG-1940, NUREG-1140, and NUREG-2260). Putting it in perspective, accident analysis is performed over the course of at least 24 hours post-accident. Zhao et al. (2015) [118] investigated the DFs of the AP1000 PCC during a 24 hour period and the Surry SOARCA study investigated the release of iodine during a 48 hour period. Though this study is limited to the first 75 minutes, the DFs for iPWRs will only substantially increase over time. At 14 hours the AP1000 PCC achieves a DF of about 1,000 [118]. It is conceivable that the iPWR can achieve that DF in a fraction of the time. The EPRI also estimates decontamination for lateral A/V ratios outside of the experimental test range using CFD simulations. Under the lower bound 0.14 ft^{-1} A/V ratio, decontamination occurs 9 times slower at minute 20 compared to 0.75 ft^{-1} A/V ratio. Though the 0.14 ft^{-1} A/V ratio decontaminates much slower than a iPWR A/V ratio, the 0.14 ft^{-1} A/V ratio is much closer to that of a large LWR. This can start a discussion for A/V ratios and convective flows being included as a parameter for estimating DFs for large LWRs.

The basis of the 10-mile EPZ is based on methodology and consequence analyses that is over 40 years. The consequence analyses for nuclear power plants have evolved from WASH-740 (1957), WASH-1400 (1975), CRAC-II (1982), and NUREG-1150 (1991) to SOARCA (2012). The newest consequence analyses study, SOARCA, uses improved and realistic methods to model risk associated with severe accidents, such as incorporating emergency operating procedures, loss of infrastructure due to seismic events, improved modeling capability in MELCOR and MACCS2. The SOARCA also included emergency response programs. Specifically timing of decisions, infrastructure analysis, modeling infrastructure failure locations, the utilization of potassium iodide, adverse weather, modeling evacuation time estimates, shielding factors, communication, population distribution, and population attributes that can range from the general public to populations within schools or special facilities (hospitals, prisons, nursing homes, and etc.). For radiological releases, the SOARCA study found the amount of radioactive material released is much smaller than previously estimated in prior studies [125]. For off-site consequences, the SOARCA study estimated the core damage frequency (CDF) to be 3×10^{-8} for a interfacing systems loss-of-coolant accident (ISLOCA) compared to 1×10^{-5} in the estimated CDF in NUREG-2239 [125]. Compared to the SOARCA, NUREG-2239's integral release fraction estimate of Iodine and Cesium is 3 and 34 times larger, respectively. Similarly, within this analysis the DFs from past studies are compared against updated DF estimates for iPWRs with lateral S/A ratios of 0.60 ft^{-1}, 0.67 ft^{-1}, and 0.75 ft^{-1}. Using more robust atmospheric dispersion models, such as MACCS2 or EPA's AERMOD will provide more accurate and improved estimation for dose exposure. Because straight-line Gaussian Plume models have conservative tendencies, MACCS2 and AERMOD is expected estimate more realistic and lower dose exposure rates.

NRC's SOARCA study incorporates new modeling and realistic methods to accurately estimate off-site consequences for PRAs. More importantly, the SOARCA study also compares its finding against previous NRC sponsored safety studies and shows with improved modeling and emergency preparedness, the risk of off-site consequences and the release of radioactive material is substantially reduced. However, the SOARCA findings does not support a new regulatory basis for EPZs and is not its intended purpose. This analysis, shows DFs of iPWRs substantially reduces off-site exposure compared to its large LWR counterparts without using the advanced dispersion, emergency response, and estimated time to evacuation models presented in the SOARCA. Incorporating the results from this work with the improved analytical methods of severe accident progression and off-site consequences found in the SOARCA study in conjunction with emerging communication technologies, such as the Intelligent Alarm Systems and FEMA's Integrated Public Alert and Warning System can accurately estimate and reduce the risk off-site consequences. With regards to large LWRs, the AP1000 PCC decontamination does not take into account convective flows. An argument can be made where CFD models using A/V ratios similar to that of large LWRs can be used to estimate their DFs and also investigate off-site exposure in a post-accident scenario as well. This approach in estimating off-site exposure in a post-accident scenario would ultimately create a pathway to develop a regulatory basis for technology-neutral, risk-based approach to EPZs for iPWRs and to a lesser extent Generation III+ power plants.

Chapter 5

Conclusions

The demand for electricity in the US is expected to increase by 29% between 2012 and 2040. With an increasing shift towards a low-carbon energy sector, renewable are often viewed as the primary catalyst for this transition. In 2015, wind represented 6% of the installed capacity [126] and produced of 5% the total net generation in the US [68]. The DOE expects the installed capacity of wind to increase threefold by 2030. Despite the estimated rapid increase in installed wind capacity, nuclear produced 4 times the amount of electricity with 9% of total US capacity. Since 2010, utilities have announced the planned closure of 10 nuclear power plant citing challenging economic conditions. Previously, early retirements have been announced for 5 nuclear power plants in Illinois and New York, however these plans were canceled after the introduction of economic incentives via zero emission credits for nuclear power. With regulatory uncertainty concerning the clean power plan, the nuclear industry may not receive regulatory relief and other intensives at a national level to help mitigate climate change. By 2035 it 30% of the installed nuclear capacity will be lost if licenses are not extended to a 80-year lifetime [23]. Facing economic competition due to low natural gas prices it is possible for a larger loss in installed capacity.

Throughout the history of the nuclear power sector has always been plagued with issues related to its competitiveness. Typically, the focus has always been cost relative to other forms of electricity generation, in the early history of the nuclear power sector it was coal. Today, it is low natural gas prices and increasingly renewables. During the anti-nuclear movement in the 1960s and 1970s, nuclear power was viewed as being dangerous and not environmentally palatable because of TMI, association with nuclear weapons, and concerns surrounding nuclear waste. Today, there are still concerns regarding nuclear waste, but nuclear energy is getting a second look because of its potential to produce low-carbon baseload electricity. The major barrier to achieving the large-scale expansion of nuclear power has always been cost and concerns about safety. The demise of each iteration of a nuclear renaissance revolves around safety, the regulatory response, energy strategy, and cost competitiveness. The rapid expansion of nuclear capacity during the 1960s and 1970s came to a halt after TMI and the subsequent regulatory response and a shift in the national energy strategy. The "Nuclear Renaissance" ended after the Fukushima Daiichi nuclear accident and the following regulatory review of the safety of all nuclear power plants. The shift in energy strategy was driven by the market with the availability of affordable natural gas.

5.1 Summary of Results and Policy Implications

This section summarizes the results from the previous chapters and discusses policy implications.

1. Chapter 2 — The environmental competitiveness of SMRs, Generation II, and Generation III+ nuclear power plants:

   (a) *What are the life cycle GHG emissions for an SMRs, Generation II, and Generation III+ nuclear power plants? How do they compare?*

   The mean (and 90% confidence interval) life cycle GHG emissions of the W-SMR to be 7.4 g of CO_2-eq/kwh (4.5 to 11.3 g of CO_2-eq/kwh) and the AP1000 to be 7.6 g of CO_2-eq/kwh (5.0 to 11.3 g of CO_2-eq/kwh). The GHG emissions of the W-SMR and AP1000 are effectively the same given the inherent uncertainties in the analysis. While, the AP1000 has the benefits of economies of scale, the W-SMR's modular ability enables it to make up some of the difference through efficiencies in construction, operation and maintenance, and decommissioning.

   (b) *How do the life cycle GHG emissions compare to fossil fuel plants and renewables?*

   In comparison with other energy sources, the W-SMR and the AP1000 on average perform the best for life cycle GHG emissions against all forms of energy generation except for hydropower plants.

   (c) *What is the cost of carbon abatement for SMRs and Generation III+ nuclear power plants?*

   The estimated cost of carbon abatement with an AP1000 against coal and natural gas is $2/tonne of CO2-eq (-$13 to $26/tonne of CO_2-eq) and $35/tonne of CO_2-eq ($3 to $86/tonne of CO_2-eq), respectively. In comparison, a W-SMR the cost of carbon abatement against coal and natural gas is $3/tonne of CO_2-eq (-$15 to $28/tonne of CO_2-eq) and $37/tonne of CO_2-eq (-$1 to $90/tonne of CO_2-eq), respectively.

   (d) *What are the policy implications of the emission results?*

   The retirement of small and medium-scale coal power plants due the availability of natural gas can provide an opportunity for SMRs to replace that missing capacity. Assigning a cost to carbon for natural gas plant or implementing zero-emission incentives can improve the economic competitiveness of nuclear power through environmental competitiveness. With the large uncertainty surrounding the capital cost of an SMR, a majority of the economic benefits would have to come on the backend though the cost of carbon or other incentives. The major difference between this approach is there is less of a perceived financial risk for a NOAK SMR compared to an AP1000.

2. Chapter 3 — The socioeconomic characteristics of communities surrounding baseload power generation facilities:

   (a) *What types of socioeconomic disparities exist within counties and communities associated with nuclear, natural gas, and coal power plants?*

   Relative to the home counties of nuclear plants, communities closer to nuclear plants have higher home values and incomes than those further away. Conversely, communities near coal and natural gas have incomes and home values that increase with distance from the plant. Relative to their counties, communities near coal plants have the lowest incomes, home values, and the highest percentages of Black residents compared to nuclear and natural gas plants. Communities near coal plants are in less wealthy parts of the county or have a similar socioeconomic makeup as county.

   (b) *Are negative externalities associated with community characteristics based on power plant type?*

   Communities around coal and nuclear power plants are associated with negative externalities related to pollution and nuclear accidents, respectively. These differing negative externalities for each power plant type are associated with differing community characteristics. Communities near coal plants are associated with vulnerable populations that have lowest average household incomes, home values, and highest percentages of black residents compared to nuclear and natural gas plants. Nuclear power plants are shown not to be bad neighbors, given their associations with higher incomes and home values.

   (c) *How have socioeconomic indicators changed over time for communities near operating baseload power plants?*

   At the community-level between 1990-2010, there were no significant changes in population density, the percentage of black residents, the percentage of residents with Bachelor's degrees or above, household income, and home value for each power plant type. After power plants begin operation, the associated socioeconomic indicators stay relatively the same. While this study does not infer causality, the community-level relationships and differences between power plants persist over three decades.

3. Chapter 4 — Risk and regulatory considerations for SMR emergency planning zones based on passive decontamination potential:

   (a) *How do the decontamination factors from the AP1000, the iPWR aerosol behavior test, and NUREG-6189 compare?*

   The DFs are slightly above 1 (<1% of particles are removed) assuming the Powers et al. (1996) method. The AP1000 PCC achieves a DF of 2 (50% of particles are removed) after 75 minutes and it takes about 5 hours to reach a DF of 10. It takes about 8 hours for the AP1000 to reach a DF of 10 using the 90th percentile correlation coefficients. In comparison, the 160 $\mathrm{MW_{th}}$ iPWR approaches a DF of 10 within the first 15 minutes and a DF of 21 (95% of particles are removed) in 75 minutes using the DFs from EPRI's Aerosol Behavior test.

   (b) *How much radioactivity is present in containment after the decontamination factors have been applied in a post-accident scenario?*

   Seventy-five minutes after a LOCA the AP1000, Surry, and iPWR produces 139, 153, and 104 curies/ft^3 when normalized by containment volume. The AP1000, Surry, and iPWR produces 84,000, 106,000, and 7,000 curies/$\mathrm{MW_{th}}$ when normalized by reactor power.

   (c) *What is the dose exposure after radioactive material is released into the environment?* The mean thyroid dose exposure is estimated to be 4.5 and 4.2 rems at 3 miles for the AP1000 and Surry, respectively. The 5 rem PAG limits for the AP1000 and Surry are not violated after 3 miles using the mean; the 5 rem PAG limit is not violated after 7 miles using the 95th percentile. The mean thyroid dose exposure is estimated to be 0.02 rem at 3 miles for the iPWR. The 5 rem PAG limit is never violated using the mean or the 95th percentile for the iPWR. The mean whole body dose exposure is estimated to be 4.7 and 3.5 rems at 10 miles for the AP1000 and Surry, respectively. The 5 rem PAG limits for the AP1000 and Surry are not violated at 10 miles using the mean. The mean whole body dose exposure is estimated to be 1.1 rem at 3 miles for the iPWR. The 5 rem PAG limit is not violated at after mile 2 using the 95th percentile for the iPWR.

   (d) *What are the policy implications?*

   Reducing the EPZ from 10 miles to 5 miles can save between $40-$50 million for iPWR SMRs over their lifetimes. The findings can be used to in conjunction with the improved analytical methods to provide accurate and realistic estimates for exposure. This can pave a way for the creation of a pathway to develop a regulatory basis for technology-neutral, risk-based approach to EPZs for iPWRs. Further research needs to be performed to used improved atmospheric dispersion models and estimate the impact convective flows can have the DFs for large-scale LWRs to develop a similar technology-neutral risk-based approach to scaling EPZs for BWRs and PWRs.

Ultimately, this latest attempt at a “Nuclear Renaissance” ended with the cancellation of the V.C. Summer Units 2&3 and the bankruptcy of Westinghouse Electric Company. Ideally, the approach that poses the least amount of risk is to continue to keep the current fleet of power plants operating. However, eventually these power plants will face retirement. Coal plants are also facing early retirements due to regulatory changes and economic challenges from natural gas. While previous attempts at starting a nuclear renaissance focused primarily on increasing the installed capacity and direct cost reduction, this work focuses on indirect methods and insight on framing the next nuclear renaissance that encompasses SMRs, legacy, and Generation III+ nuclear power plants. This work specifies indirect methods related to environmental competitiveness where I compare the life cycle GHG emissions of nuclear power plants against renewables and fossil fuels; compare community socioeconomic characteristics of legacy nuclear power plants to fossil fuel plants to help identify equity issues related to power plant siting and provide an indication how communities can change after power plant generating technologies are converted; and through safety by estimating off-site dose exposure following an accident to develop a regulator basis related to scalable EPZs for SMRs.

5.2 Future Work

The work presented in this dissertation has answered many questions regarding indirect methods to improve the competitiveness of nuclear power. Based on this work, additional questions have been posed that can be addressed in future work.

1. Chapter 2 shows that emissions savings from economies of scale for an AP1000 can be attained by through the modularity benefits inherent in SMR designs. The benefits of modularity can be used to disaggregate the concept of economies in the nuclear industry. Additional research is needed to quantify the utility of the modularity of an SMR compared to economies of scale of a larger Generation III+ nuclear power plant.

2. With the construction of the Generation IV HTR-PM reactor in China, additional research is needed to quantify the value on an on-time and on-budget Generation III+ nuclear power plant compared to the perceived benefits from a Generation IV nuclear power plant.

3. As the nuclear industry continues to lobby state governments to provide subsidies for struggling units through zero emission credits, additional research is needed to explore economic benefits for SMRs to load-follow renewables during intermittent periods. Within a load-following regime, integrated SMRs

and renewables may have the potential to be more cost competitive with natural gas together rather than separately without subsidies.

4. Chapter 3 shows differing negative externalities for communities near coal (pollution) and nuclear power plants (nuclear accidents) are associated with differing community characteristics. As many baseload coal power plants are converted to natural gas plants, additional research is needed to identify the changes in community characteristics following the conversion.

5. As an increasing amount of nuclear and coal power plant being to retire, additional research is needed to investigate the effects these retirements have on the local economy and associated communities. This can be extended further to explore if these retirements have differing impacts based on the power plant type.

6. Assess differences in the labor force and employment opportunities based on power plant type using Census data.

7. Chapter 4 shows the decontamination factors from iPWRs produce lower containment radioactivity and environmental dose exposure compared to the decontamination factors for the AP1000 and Surry plants. Additional research is need to explore using more robust atmospheric dispersion models, such as the augmented straight-line Gaussian plume model in the NRC code MACCS2 and the AERMOD steady-state plume model to determine if further reductions in dose exposure can be achieved.

Appendix A

The environmental competitiveness of SMRs, Generation II, and Generation III+ nuclear power plants

A.1 SMR Key Features

SMRs are designed with flexibility and reduced cost in mind. Below are some key features that may reduce the life-cycle GHG emissions:

- **Longer refueling cycles.** Generation II NPPs are typically refueled every 12-18 months, whereas it is expected that SMRs will need to be refueled at a minimum of every 24 months. There are some SMR designs that never have to be refueled during their lifetime. Within this design after the fuel is depleted, the core is removed for decommissioning.
- **Increased thermal efficiency.** Generation II and III+ NPPs typically have a thermal efficiency of 30% to 33%. While this is also true for most SMR designs, the EM^2 SMR is claimed to achieve a thermal efficiency of around 48% [62]. This higher efficiency increases the amount of energy you receive per unit of fuel.
- **Improved construction efficiency through modularity.** Generation II NPPs are typically built on site. Generation III+ plants, such as the Westinghouse AP1000 have introduced modularity into the design; as a result several structural and mechanical components are built in a factory and shipped to site where it is assembled. SMRs are designed to be totally modular in their design.

- **Shorter, more efficient supply chain.** SMRs are a fraction of the size of Generation II and III+ plants. Typically Generation II and III+ plant components are large leaving only a few vendors with the resources available to manufacture these components. SMRs will utilize smaller components meaning additional vendors can be included in the supply chain.

- **Lower operation and maintenance cost.** The simpler design of SMRs will employ fewer materials as well as have a majority if not all of their components fabricated in a factory. The benefits of having a simpler design will allow for fewer pumps, valves, and components. This will increase the quality and therefore reduce the amount of maintenance required during the lifetime of the plant.

- **Reduction in construction time and mass production.** Typically 7 years were needed to construct a Generation II NPPs. Generation III+ plants reduced this time to 5 years. SMRs have the ability to be mass produced reducing overall construction time. It is expected that some SMRs can be fully constructed in 18 months.

- **Simpler decommissioning.** Simpler methods of disassembly that will can involve disconnection of transportable modules that can be reused.

A.2 Assumptions

In 2012, 38% of enriched uranium came from foreign suppliers [127]. Prior to May 2013, the U.S. was the only country that used gaseous diffusion to enrich uranium. After the United States Enrichment Corporation ceased operation of its Paducah, Kentucky gaseous diffusion plant, the U.S. has relied on gas centrifugation for uranium enrichment. Currently, Urenco's National Enrichment Facility in Eunice, New Mexico, provides domestic enrichment services.

A.2.1 Historical and Scaled Estimates of Refueling Outage Duration

Table A.1 outlines the historical average length of time each refueling period each year from 2000-2013. A scaled estimate for the refueling period was calculated for the W-SMR based on the electrical output.

A.3 Mining & Milling

Uranium mining is the primary means for which NPPs are supplied with fuel. A majority of the world's known recoverable uranium is sourced from Australia, Kazakhstan, and Canada with 31%, 12%, and 9% of the total fuel mined, respectively [37]. The process of open pit mining consists of drilling and using explosives

Table A.1: Historical and Scaled Estimates of Refueling Outage Duration.

Year	**1,000 MWe (Days)** [128]	**W-SMR (Days)***
2000	44	9.9
2001	37	8.3
2002	33	7.4
2003	40	9
2004	42	9.5
2005	38	8.6
2006	39	8.8
2007	40	9
2008	38	8.6
2009	41	9.2
2010	40	9
2011	45	10.1
2012	46	10.4
2013	41	9.2
Sample Mean	40.29	9.06
Sample Standard Deviation	3.38	0.76

Note: The asterisk* indicates an extrapolated estimate based on the historical average of the 1,000 MWe plant.

in large open pits to remove rock covering the uranium ore. Underground shafts and excavation techniques are utilized when ore deposits are deeper. The in situ leaching process involves dissolving uranium ore in sulfuric acid.

The uranium milling operation typically takes place near the location of the mining operation. The mined uranium ore is crushed and leached in sulfuric acid to remove the impurities within the ore. The product of this process is a 70% to 90% uranium concentrate of U_3O_8 or "yellowcake."

Figure A.1 is a recreated plot from Norgate et al. (2014) [41] that outlines the relationship between uranium ore grade and emissions for NPPs.

The best estimate for the triangular distribution in table was calculated using the following equations:

$$RT = WPU_{RGM} + WPU_{ODM} + WPU_{RSM} + WPU_{BVM} + WPU_{MRM} \tag{A.1}$$

Where RT is the representative total of the world production of uranium, WPU_j is the world production of uranium as a percentage from mine j *(RGM=Ranger Mine, ODM=Olympic Dam Mine, RSM=Rossing Mine, BVM=Beverly Mine, and MRM=McArthur River Mine)*

$$\begin{aligned} BE = MM_{UG}(ME_{ODM} \times \frac{WPU_{ODM}}{RT} + ME_{MRM} \times \frac{WPU_{MRM}}{RT}) \\ +MM_{OP}(ME_{RGM} \times \frac{WPU_{RGM}}{RT} + ME_{RSM} \times \frac{WPU_{RSM}}{RT}) \\ +MM_{ISL}(ME_{BVM}(\frac{WPU_{BVM}}{RT})) \end{aligned} \tag{A.2}$$

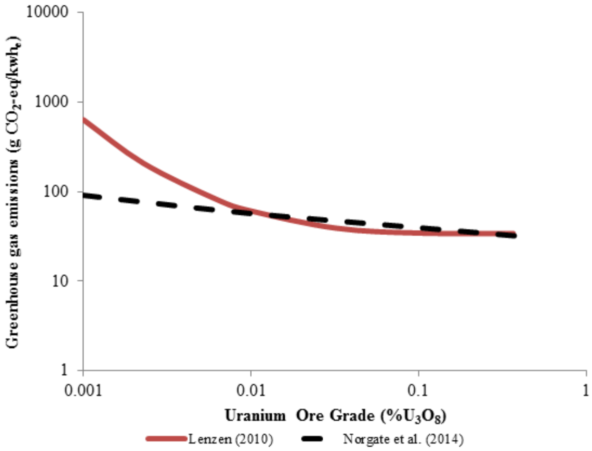

Figure A.1: Effect of Uranium Ore Grade on Emissions [41].

Where MM_i is the mining method percentage, i is the mining method *(UG=Underground, OP=Open pit, and ISL=In situ leaching)*, and ME_j is the median estimate for mining emissions in t CO_2/ t U_3O_8.

A.4 Conversion

The uranium conversion stage begins by feeding U_3O_8 into a 1,200°F fluidized-bed reactor where it reacts with hydrogen to form uranium dioxide (UO_2). The UO_2 is fed into a fluidized-bed reactor at 1,000°F where it reacts with hydrogen fluoride (HF) to create uranium tetrafluoride (UF_4). The UF_4 reacts with fluorine gas (F_2) to create UF_6 [46]. The reaction is shown below:

$U_3O_8 + 2H_2 \longrightarrow 3UO_2 + 2H_2O$

$UO_2 + 4HF \longrightarrow UF_4 + 2H_2O$

$UF_4 + F_2 \longrightarrow UF_6$

Table A.2 [129] outlines the energy consumption estimates for uranium conversion from previous studies.

Table A.2: Uranium Conversion Energy Consumption [129].

Reference Study	Year	Electrical Energy (MWh_e/t U)	Thermal Energy (GJ_{th}/t U)
Areva	2008	7.0	18.3
Franklin et al.	1971	11.0	131
Rombough & Koen	1974	15.1	234
Rotty et al.	1975	14.6	1425
SRI	1975	10.3	1313
Chapman	1975	15.9	195
Mortimer	1977	12.1	235
Torf et al.	1998	10.3	700
Mean	-	12.0	531

A.5 Enrichment

Typically, when uranium is mined the natural uranium is comprised of mainly 2 isotopes, 99.284% U-238 and 0.711% U-235. Within this enrichment process the amount of U-235 in UF_6 increases to $\leq$ 5%. Typically diffusion requires between 2,400 and 3,000 kwh/SWUs with a best estimate of 2,500 kwh/SWU [130], whereas centrifuges require between 40 and 100 kwh/SWUs [59] with a best estimate of 50 kwh/SWU [130].

A.6 Fuel Fabrication

Table A.3 [129] outlines the energy consumption estimates for uranium fuel fabrication from previous studies.

Table A.3: Fuel Fabrication Energy Consumption [129].

Reference Study	Year	Electrical Energy (MWh_{el}/t U)	Thermal Energy (GJ_{th}/t U)
Franklin et al.	1971	109	0
USAEC	1972	53.5	137
Rombough & Koen	1974	168.8	6,169
Rotty et al.	1975	303	2,720
SRI	1975	98	262
Chapman	1975	49.2	142
Mortimer	1977	65	341
Orita	1995	56.3	120
Australian Coal Association	2001	54.3	154
Reported Mean	-	105.3	1,101

Note: This table contains reproduced from data from Norgate et al. (2010) [41].

A.7 Construction

The dimensions of the AP1000, W-SMR, and GT-MHR containment building, reactor pressure vessel, and steel liner seen in Table A.4. The estimated mass of concrete and steel in each structure is detailed in Table A.4. A steel density of was assumed 7,850 kg/m^3. The total plant concrete of the W-SMR is scaled from the volume of concrete in an AP1000. The AP1000 and W-SMR steel liner volume were calculated assuming a cylindrical shape. The AP1000 and the GT-MHR shield building volume were calculated assuming a cylindrical shape, while the W-SMR was assumed to be cubic. The AP1000, W-SMR, and GT-MHR reactor vessel volume were calculated assuming a cylindrical shape.

Table A.4: Concrete and Steel Mass Material Estimates [131, 132, 133, 134, 135, 136, 102, 137].

Structure	Description	AP1000	W-SMR	GT-MHR
Steel Liner	Diameter (m)	39.62	9.75	N/A
	Height (m)	65.63	27.13	
	Thickness (m)	0.044	0.044	
	Total Steel Volume* (m3)	471.9	43.3	
	Total Steel Liner* (million kg)	3.7	0.34	
Shield Building(Nuclear Island)	Diameter (m)	44.2	N/A	32
	Base (m)	N/A	33.53	N/A
	Width (m)	N/A	33.53	N/A
	Height (m)	81.76	33.53	46
	Concrete (m)	0.876	0.914	0.914
	Plate thickness x2 (m)	0.019	0	0
	Total Thickness (m)	0.914	0.914	0.914
	Volume* (thousand m3)	12.7	5.8	5.4
	Total Concrete Volume* (thousand m3)	12.2	5.8	5.4
	Total Steel Volume* m3	514	0	0
	Total plate Steel* (million kg)	4	0	0
	Total Plant Concrete (Million kg)	240	115*	52
Reactor Vessel	Diameter (m)	4.1	3.5	7.7
	Height (m)	12	24.6	23.7
	Thickness (m)	0.038	0.038	0.22
	Volume* (m3)	6.75	10.95	140
	Total Steel Vessel* (tonnes)	53	85.9	1,098
Rebar	Weight (thousand tonnes)	12	5.7	2.5*

There are little data available on the total steel used in other areas of an AP1000. Peterson et al. (2005) estimated the amount of metal in a 1,500 MW$_e$ Economic Simplified Boiling Water Reactor (ESBWR). It is assumed that the unidentified metal has the same emissions factor as steel. The AP1000 has a total concrete volume of 100,000 m^3, whereas the ESBWR has a total concrete volume of 104,000 m^3 [55]. The similarity in concrete volume is used as justification for scaling the tonnage of metal used in the AP1000. The amount of metal for the W-SMR is scaled using the concrete volume of the AP1000. Table A.5 outlines the estimated tonnes of metal in the AP1000 and W-SMR.

Table A.5: Additional Mass from Metal.

	ESBWR	**AP1000**	**W-SMR**	**GT-MHR**
Concrete (thousand m^3)	104	100	48	21
Turbine Building (tonnes)	8,214	7,881	3,761	N/A
Fuel Storage (tonnes)	835	801	382	89
Misc Buildings (tonnes)	3,952	3,792	1,810	N/A
Non-I&C Reactor Equipment (tonnes)	6,526	6,261	2,988	4,050
Turbine Plant Equipment (tonnes)	16,519	15,848	7,564	N/A
Miscellaneous Equipment (tonnes)	1,176	1,128	538	617
Total Metal (tonnes)	37,222	35,711	17,404	4,756

Note: The total metal in the W-SMR is the reported mean from Monte Carlo simulation. This uncertain variable based on scaling the random draw from the AP1000 total metal uniform distribution by the volume of concrete. ESBWR and GT-MHR materials are sourced from Peterson et al. (2005) [55].

The amount total metal outlined in the AP1000 is uncertain, to account for this a uniform distribution using a minimum of 35,711 tonnes and a maximum of 37,222 tonnes. Table 2.3 outlines parameters for the AP1000 total metal uniform distribution. The total metal for the W-SMR is scaled down based on the result from the uniform distribution of the AP1000.

A.7.1 Modularity Reduction

There is no data available on the benefits of modularity to a NPP. In addition to this, there is little data on the emission benefits of modular construction for any structure. Quale et al. (2012) [56] performs a case study where the emissions from the construction of modular homes and traditional homes built on site. Based on the data provided in Quale et al. (2012) [56]. Table A.6 shows the reductions in GHG emissions from using modular construction methods.

Table A.6: Modularity Reduction Factors Uniform Distribution (kg CO_2-eq/2,000 ft^2 home).

Description	**On-Site Average** (kg CO_2-eq)	**Modular Average** (kg CO_2-eq)	**% Reduction**
Materials Production	780	613	21%
Construction Energy Use	11,500	9,230	20%
Worker Transportation	7,160	1,941	73%

The modularity reduction of a W-SMR is highly uncertain, to estimate this, the GHG reduction factor for materials was used as the minimum for concrete, rebar, and steel considering a modular home is far less complex than a NPP. Table A.7 outlines a modularity reduction maximum of a W-SMR for material use was estimated on the percent change from the scaled W-SMR estimate from the AP1000 to the scaled up estimate from the GT-MHR.

Table A.7: Modularity Reduction Factors Uniform Distribution Maximum.

Description	**Scaled From AP1000** (Million kg)	**Scaled From GT-MHR** (Million kg)	**% Reduction**
W-SMR Concrete	114.5	52.3	54%
W-SMR Rebar	5.7	2.5	57%
W-SMR Steel	17.8	5.1	71%

A.7.2 Construction Workforce and Equipment Use

Table A.8: Construction Workforce CO_2-eq Emissions.

	SNUPPS	**AP1000**	**W-SMR**
Electrical output (MW_e)	1,200	1,117	225
Commuting Trips (round trips/day)	1,000	1,000	1,000
Commuting Distance (miles/round trip)	40	40	40
Commuting days (days/year)	365	365	365
Construction duration (years)	8	5	2
Total lifetime distance traveled (million miles)	116.8	73	29
Fuel Economy (miles/gallon)	22	22	22
Total fuel used (million gallons)	5.4	3.4	1.4
CO_2 per gallon (tonnes)	0.00892	0.00892	0.00892
Total CO_2 (thousand tonnes)	48.2	30.1	12.4
CO_2 equivalent factor	0.985	0.985	0.985
Total (million kg of CO_2-eq)	49	30.6	12.6

Note: The construction duration, total lifetime distance traveled, total fuel used, total CO_2 and CO_2-eq produced for the W-SMR are the reported means from Monte Carlo simulation. The parameters for the distributions used are defined in Table 2.3.

Table A.9: Annual Construction Equipment Use Emissions.

Description	**1,000 MW_e**	**W-SMR**
Earthwork and Dewatering (tonnes of CO_2-eq)	1,714	386
Batch Plant Operations (tonnes of CO_2-eq)	486	0
Lifting and Rigging (tonnes of CO_2-eq)	800	180
Warehouse Operations (tonnes of CO_2-eq)	200	45
Equipment Maintenance (tonnes of CO_2-eq)	143	32
Total (tonnes of CO_2-eq)	3,343	643
Total (million kg of CO_2-eq)	3.34	0.64

A.8 Operation, Maintenance, Repair, and Refurbishment

It should be noted that fuel economy should improve over the next 60 years. An estimate of 22 mpg is a conservative estimate.

Table A.10: Operational Workforce CO_2-eq emissions.

Description	1,000 MW_e	W-SMR
Commuting Trips (round trips/day)	550	124
Commuting Distance (miles/round trip)	40	40
Commuting days (days/year)	365	365
Lifetime (years)	60	60
Total lifetime distance traveled (million miles)	482	108
Fuel Economy (miles/gallon)	22	22
Total fuel used (million gallons)	22.3	5
CO_2 per gallon (tonnes)	0.00892	0.00892
CO_2 (thousand tonnes)	199	45
CO_2 equivalent factor	0.985	0.985
Total (million kg of CO_2-eq)	202	45

A.9 Decommissioning

NPPs are decommissioned when they reach their end of life, are too expensive to operate because of external economic factors, their licenses are terminated or are too expensive to repair. There are currently 11 NPPs in the U.S. that have been fully decommissioned [138]. The Nuclear Regulatory Commission (NRC) allows for three types of decommissioning, DECON or immediate dismantling, SAFSTOR or a deferred dismantling, and ENTOMB where the site is encased in concrete. This study will primarily focus on the SAFSTOR method. In the U.S., spent uranium fuel is contained inside concrete dry cask structures within range of the NPP. After the power plant is decommissioned the casks remain there until a permanent nuclear repository is developed. Table A.11 shows the GHG emissions generated from the construction of the concrete dry casks. These estimates assume the use of MAGNASTOR dry storage casks designed by NAC International [139]. The MAGNASTOR design was selected because it has the most recent certificate of compliance issue date [140].

Table A.11: Interim Dry Cask Storage Emissions.

Description	**SNUPPS**	**AP1000**	**W-SMR**
Core Fuel Assemblies	193	157	89
Replaced Fuel Assemblies per Refueling Cycle	64	52	30
Lifetime Refueling Outages	40	40	30
Lifetime Total Fuel Assemblies	2,573	2,093	890
MAGNASTOR Assembly Capacity	37	37	37
Max Dry Cask Weight (tonnes)	145	145	145
Lifetime Casks	70	57	24
Fuel Assembly Weight (tonnes)	0.66	0.66	0.66
Total Fuel Assembly Weight (tonnes)	1,693	1,377	585
Total Max Dry Cask Weight (tonnes)	10,095	8,212	3,491
Empty Dry Cask Weight (tonnes)	8,403	6,835	2,906
Total (tonnes)	3,361	2,734	1,162
Total (million kg CO_2-eq)	3.4	2.7	1.2

Table A.12 shows the GHG emissions generated from the decommissioning workforce.

Table A.12: Decommissioning Workforce.

	1,000 MWe	**W-SMR**
Commuting Trips (round trips/day)	200	45
Commuting Distance (miles/round trip)	40	40
Commuting days (days/year)	250	250
Decommissioning duration (years)	10	7
Total lifetime distance traveled (million miles)	20	3
Fuel Economy (miles/gallon)	22	22
Total fuel used (thousand gallons)	926	146
CO_2 per gallon (tonnes)	0.00892	0.00892
Total CO_2 (tonnes)	8,259	1,300
CO_2 equivalent factor	0.985	0.985
Total million kg CO_2-eq	8.4	1.3

Note: The decommissioning duration of the W-SMR is the reported mean from Monte Carlo simulation. The W-SMR decommissioning duration is an uncertain variable based on random draws from the uniform distribution from Table 2.3.

A.10 Results

Figure A.2 outlines the allocation each stage contributes to total emissions. There is a percentage reduction in the construction and decommissioning in the W-SMR and AP1000 when compared to the SNUPPS. This reduction is shifted over to the nuclear fuel cycle. This indicates that there is a GHG emission reduction from W-SMRs and AP1000s. If it is assumed the refueling outage duration for the W-SMR is the same as a large scale LWR (40 days) the life cycle GHG emissions would increase by 0.7% to 9.17 g of CO_2-eq/kwh. In the extreme case where the refueling outage takes 500 days resulting in a capacity factor of 32%, the life cycle GHG emissions would increase to the estimate of wind at about 12 g of CO_2-eq/kwh. At 700 days with a capacity factor of 4%, the life cycle GHG emissions would increase to the estimate of solar PV at about 45 g of CO_2-eq/kwh.

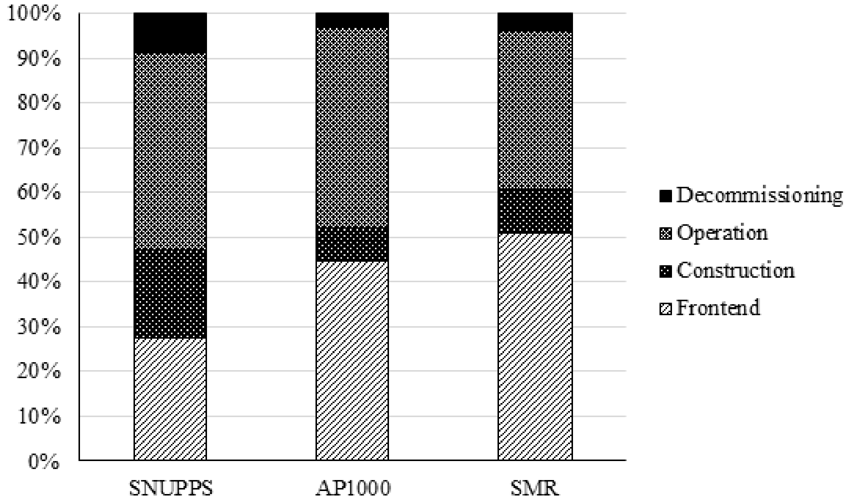

Figure A.2: Mean Share of Emissions.

Assuming a worst-case scenario where the construction duration of a W-SMR is 6.5 years, the mean (and the 90% confidence interval) is shifted to 9.3 g of CO_2-eq/kwh (6.0 and 13.1 of g CO_2-eq/kwh). This represents a 2% increase from the original estimate of 9.1 g of CO_2-eq/kwh. Based on this analysis, construction would have to take 75 years to produce the same life cycle GHG emissions as wind at about 12 g of CO_2-eq/kwh. To produce the same life cycle GHG emissions as solar PV at about 46 g of CO_2-eq/kwh the construction duration would be about 950 years. Figure A.3 shows the ten most influential distributions on the emissions from the W-SMR life cycle. Three variables are sourced from the nuclear fuel cycle while the others are from uncertainties in the construction and decommissioning duration, maintenance and operations, and modularity reduction rates from steel.

Figure A.4 outlines the correlation coefficients on influential distributions to the mean output emissions for the W-SMR.

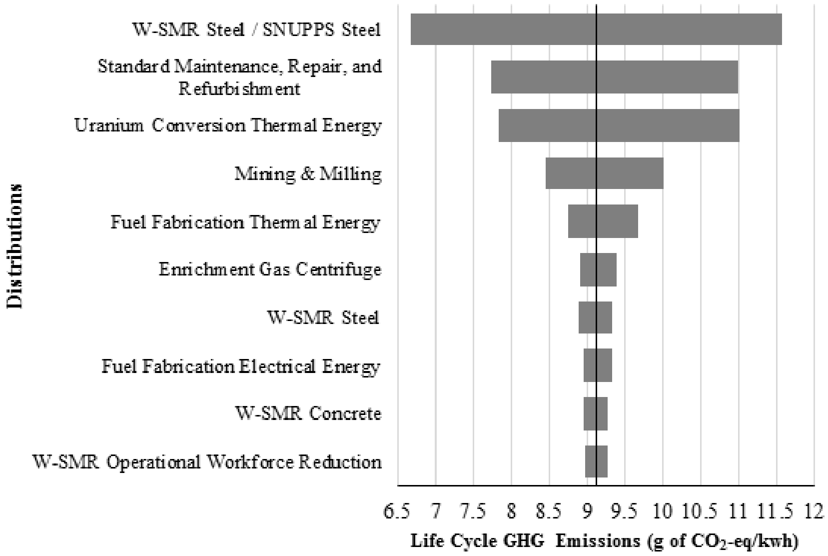

Figure A.3: Influential Distributions on W-SMR Emissions. Inputs ranked by effect on output mean. The baseline is 9.12 g of CO_2-eq/kwh.

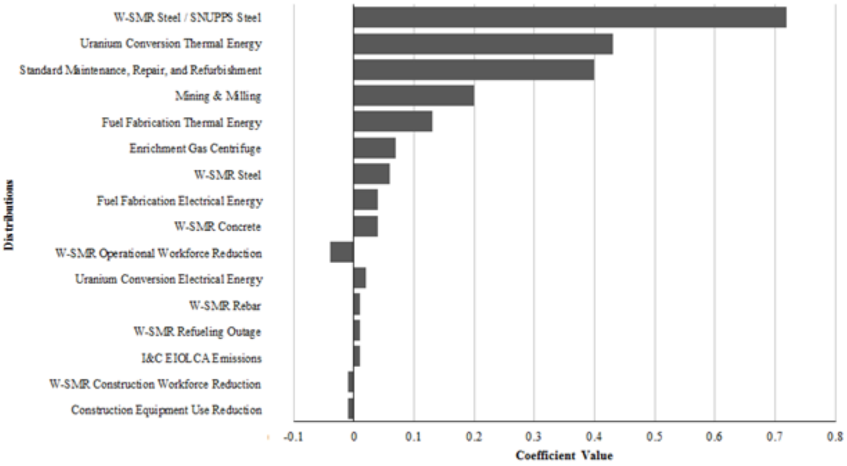

Figure A.4: Correlation Coefficients (Spearman Rank) on Influential Distributions on W-SMR Emissions.

Appendix B

The Socioeconomic Characteristics of Communities Surrounding Baseload Power Generation Facilities

B.1 Full Summary Statistics and Detailed Figures

The tables presented in this Appendix are the full versions of the abridged tables in Sections 3.2.3.1, 3.2.3.2, and 3.2.4.

Table B.1: Community-level two-way ANOVA tests of plant type effects summary statistics for the six socioeconomic indicators (Table 3.3).

	term	**df**	**Sum of Squares**	**Mean Square**	**F Statistic**	**p value**
Population Density	Plant Type	2	1.37E+07	6.87E+06	29.54	0.000***
	Distance	2	5.24E+05	2.62E+05	1.13	0.325
	Plant Type × Distance	4	7.80E+05	1.95E+05	0.84	0.501
	Residuals	1059	2.46E+08	2.33E+05		
%Black	Plant Type	2	3.12E-01	1.56E-01	8.06	0.000***
	Distance	2	2.52E-02	1.26E-02	0.65	0.521
	Plant Type × Distance	4	1.63E-02	4.07E-03	0.21	0.933
	Residuals	1059	2.05E+01	1.93E-02		
%Bachelor's Degree or Above	Plant Type	2	2.93E-01	1.47E-01	16.5	0.000***
	Distance	2	1.46E-01	7.28E-02	8.18	0.000***
	Plant Type × Distance	4	1.44E-03	3.60E-04	0.04	0.997
	Residuals	1059	9.42E+00	8.89E-03		
%Poverty	Plant Type	2	9.17E-02	4.58E-02	11.62	0.000***
	Distance	2	1.98E-03	9.90E-04	0.25	0.778
	Plant Type × Distance	4	1.22E-02	3.06E-03	0.78	0.541
	Residuals	1059	4.18E+00	3.95E-03		
Average Median Income	Plant Type	2	1.03E+10	5.14E+09	27.1	0.000***
	Distance	2	3.36E+08	1.68E+08	0.88	0.413
	Plant Type × Distance	4	2.45E+08	6.13E+07	0.32	0.863
	Residuals	1059	2.01E+11	1.90E+08		
Average Median Home Values	Plant Type	2	8.68E+11	4.34E+11	50.95	0.000***
	Distance	2	1.78E+10	8.89E+09	1.04	0.352
	Plant Type × Distance	4	1.76E+10	4.41E+09	0.52	0.723
	Residuals	1059	9.02E+12	8.52E+09		

Table B.2: Community-level post-hoc Tukey's tests for plant type and distance with nominal values for the six socioeconomic indicators (Table 3.4).

	term	**Comparison**	**mean difference**	**2.5% level**	**97.5% level**	**adjusted p value**
Population Density (pop./sq. Mile)	Plant Type	Natural Gas - Coal	221	147	295	0.000***
	Plant Type	Nuclear - Coal	-60	-180	61	0.475
	Plant Type	Nuclear - Natural Gas	-281	-404	-157	0.000***
	Distance	10-15 Miles - 5-10 Miles	-27	-112	58	0.739
	Distance	10-15 Miles - 0-5 Miles	-54	-139	31	0.291
	Distance	5-10 Miles - 0-5 Miles	-27	-112	57	0.728
	Plant Type × Distance	Natural Gas × 0-5 Miles - Coal × 0-5 Miles	291	122	461	0.000***
	Plant Type × Distance	Nuclear × 0-5 Miles - Natural Gas × 0-5 Miles	-375	-659	-91	0.001**
	Plant Type × Distance	Natural Gas × 5-10 Miles - Coal × 5-10 Miles	203	33	372	0.006**
%Black	Plant Type	Natural Gas - Coal	3.5%	1.4%	5.7%	0.000***
	Plant Type	Nuclear - Coal	0.2%	-3.3%	3.7%	0.989
	Plant Type	Nuclear - Natural Gas	-3.3%	-6.9%	0.2%	0.073
	Distance	10-15 Miles - 5-10 Miles	-0.2%	-2.6%	2.3%	0.987
	Distance	10-15 Miles - 0-5 Miles	0.9%	-1.5%	3.4%	0.64
	Distance	5-10 Miles - 0-5 Miles	1.1%	-1.3%	3.5%	0.541
%Bachelor's Degree or Above	Plant Type	Natural Gas - Coal	2.7%	1.2%	4.1%	0.000***
	Plant Type	Nuclear - Coal	4.8%	2.4%	7.2%	0.000***
	Plant Type	Nuclear - Natural Gas	2.1%	-0.3%	4.6%	0.095
	Distance	10-15 Miles - 5-10 Miles	1.2%	-0.4%	2.9%	0.185
	Distance	10-15 Miles - 0-5 Miles	2.9%	1.2%	4.5%	0.000***
	Distance	5-10 Miles - 0-5 Miles	1.6%	0.0%	3.3%	0.06
%Poverty	Plant Type	Natural Gas - Coal	0.5%	-0.5%	1.5%	0.428
	Plant Type	Nuclear - Coal	-2.8%	-4.4%	-1.2%	0.000***
	Plant Type	Nuclear - Natural Gas	-3.3%	-4.9%	-1.7%	0.000***
	Distance	10-15 Miles - 5-10 Miles	0.1%	-1.0%	1.2%	0.983
	Distance	10-15 Miles - 0-5 Miles	0.3%	-0.8%	1.4%	0.774
	Distance	5-10 Miles - 0-5 Miles	0.2%	-0.9%	1.3%	0.868
	Plant Type × Distance	Nuclear × 0-5 Miles - Coal × 0-5 Miles	-4.2%	-7.8%	-0.6%	0.010**
	Plant Type × Distance	Nuclear × 0-5 Miles - Natural Gas × 0-5 Miles	-4.9%	-8.6%	-1.2%	0.002**
Average Median Income	Plant Type	Natural Gas - Coal	$5,451	$3,345	$7,558	0.000***
	Plant Type	Nuclear - Coal	$8,219	$4,776	$11,661	0.000***
	Plant Type	Nuclear - Natural Gas	$2,768	-$768	$6,303	0.158
	Distance	10-15 Miles - 5-10 Miles	$549	-$1,874	$2,973	0.856
	Distance	10-15 Miles - 0-5 Miles	$1,364	-$1,059	$3,788	0.383
	Distance	5-10 Miles - 0-5 Miles	$815	-$1,608	$3,239	0.71
	Plant Type × Distance	Natural Gas × 0-5 Miles - Coal × 0-5 Miles	$5,620	$788	$10,452	0.010**
	Plant Type × Distance	Nuclear × 0-5 Miles - Coal × 0-5 Miles	$10,397	$2,501	$18,293	0.002**
	Plant Type × Distance	Natural Gas × 5-10 Miles - Coal × 5-10 Miles	$5,445	$613	$10,277	0.014*
	Plant Type × Distance	Natural Gas × 10 - 15 Miles - Coal × 10 - 15 Miles	$5,288	$456	$10,120	0.020*
	Plant Type × Distance	Nuclear × 10 - 15 Miles - Coal × 10 - 15 Miles	$6,397	-$1,499	$14,293	0.224
	Plant Type × Distance	Nuclear × 10 - 15 Miles - Natural Gas × 10 - 15 Miles	$1,109	-$7,001	$9,218	1
Average Median Home Values	Plant Type	Natural Gas - Coal	$52,310	$38,198	$66,422	0.000***
	Plant Type	Nuclear - Coal	$70,891	$47,830	$93,953	0.000***
	Plant Type	Nuclear - Natural Gas	$18,581	-$5,104	$42,266	0.157
	Distance	10-15 Miles - 5-10 Miles	$5,375	-$10,860	$21,610	0.717
	Distance	10-15 Miles - 0-5 Miles	$9,986	-$6,249	$26,221	0.319
	Distance	5-10 Miles - 0-5 Miles	$4,612	-$11,623	$20,847	0.783
	Plant Type × Distance	Natural Gas × 0-5 Miles - Coal × 0-5 Miles	$48,262	$15,892	$80,632	0.000***
	Plant Type × Distance	Nuclear × 0-5 Miles - Coal × 0-5 Miles	$86,466	$33,568	$139,364	0.000***
	Plant Type × Distance	Natural Gas × 5-10 Miles - Coal × 5-10 Miles	$51,577	$19,207	$83,947	0.000***
	Plant Type × Distance	Nuclear × 5-10 Miles - Coal × 5-10 Miles	$64,280	$11,382	$117,178	0.005**
	Plant Type × Distance	Natural Gas × 10 - 15 Miles - Coal × 10 - 15 Miles	$57,092	$24,722	$89,462	0.000***
	Plant Type × Distance	Nuclear × 10 - 15 Miles - Coal × 10 - 15 Miles	$61,928	$9,030	$114,826	0.009**

Figure B.1 shows between 51% and 69% of communities near nuclear power have lower population densities than their counties. Fossil fuel plants typically range between 43% and 55%. Table 3.5 shows population densities are significantly lower for communities 0-5 miles *(mean difference = 53 pop./sq. mile, p value = 0.024)* from nuclear power plants compared to their counties. Conversely, population densities are significantly larger for communities 0-5 miles *(mean difference = 145 pop./sq. mile, p value = 0.023)* natural gas plants relative to their counties.

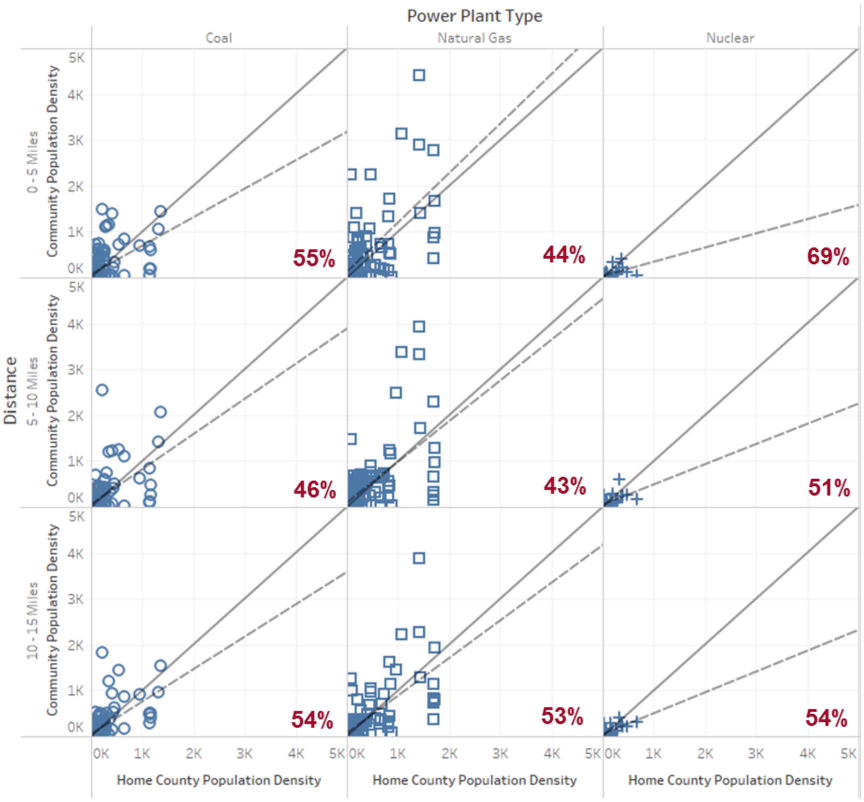

Figure B.1: Scatter plot of Home County Population Density vs 0-5, 5-10, and 10-15 mile Community Population Density with solid reference line and dotted best fit line.

Figure B.2 shows between 14% and 37% of communities near nuclear power have lower educational attainment rates than their counties. Fossil fuel plants typically range between 27% and 55%. Table 3.5 shows educational attainment rates are significantly larger for all communities across all technologies.

Figure B.2: Scatter plot of Home County Bachelor's degree or above vs 0-5, 5-10, and 10-15 mile Community Bachelor's degree or above with solid reference line and dotted best fit line.

Figure B.3 shows between 60% and 86% of communities near nuclear power have lower poverty rates than their counties. Communities near coal and natural gas plants range between 55% and 58%; and 49% and 55%, respectively. Table 3.5 shows that poverty rates are significantly lower for communities 0-5 (mean difference = 3.6%, p value < 0.001) and 5-10 (mean difference = 1.8%, p value = 0.003) from nuclear power plants compared to their counties. With an increase in distance, the mean difference between the community and the county decrease to insignificant mean differences. There are no significant differences between the community and county for fossil fuel plants.

Figure B.3: Scatter plot of Home County poverty rates vs 0-5, 5-10, and 10-15 mile Community poverty rates with solid reference line and dotted best fit line.

Table B.3: Community-level two-way ANOVA Tests of plant type and distance effects summary statistics using the ratios of communities-to-power plant counties for the six socioeconomic indicators (Table 3.6).

	term	**df**	**Sum of Squares**	**Mean Square**	**F Statistic**	**p value**	**Èă2**
Population Density	Plant Type	2	88.8	44.40	4.82	0.008**	0.009
	Distance	2	57.56	28.78	3.13	0.044*	0.006
	Plant Type × Distance	4	42.67	10.67	1.16	0.328	0.000
	Residuals	1059	9,751	9.21			
%Black	Plant Type	2	45.58	22.79	5.73	0.003**	0.011
	Distance	2	5.76	2.88	0.72	0.485	0.001
	Plant Type × Distance	4	7.19	1.80	0.45	0.771	0.002
	Residuals	1053	4,189	3.98			
%Bachelor's Degree or Above	Plant Type	2	5.27	2.64	11.05	0.000***	0.020
	Distance	2	5.59	2.80	11.72	0.000***	0.022
	Plant Type × Distance	4	0.07	0.02	0.07	0.991	0.000
	Residuals	1059	253	0.24			
%Poverty	Plant Type	2	2.81	1.41	9.05	0.000***	0.017
	Distance	2	0.26	0.13	0.83	0.435	0.002
	Plant Type × Distance	4	0.98	0.24	1.58	0.178	0.006
	Residuals	1059	165	0.16			
Average Median Income	Plant Type	2	0.93	0.46	10.72	0.000***	0.020
	Distance	2	0.13	0.07	1.51	0.221	0.003
	Plant Type × Distance	4	0.12	0.03	0.67	0.611	0.003
	Residuals	1059	46	0.04			
Average Median Home Values	Plant Type	2	1.66	0.83	12.07	0.000***	0.022
	Distance	2	0.84	0.42	6.07	0.002**	0.011
	Plant Type × Distance	4	0.4	0.10	1.44	0.218	0.005
	Residuals	1059	73	0.07			

Table B.4: Community-level post-hoc Tukey's tests for plant type and distance using the ratios of communities-to-power plant counties for the six socioeconomic indicators (Table 3.7.)

	term	**Comparison**	**mean difference**	**2.5% level**	**97.5% level**	**adjusted p value**
Population Density	Plant Type	Natural Gas - Coal	0.44	0.07	0.99	0.020*
	Plant Type	Nuclear - Coal	-0.18	-1.04	0.48	0.663
	Plant Type	Nuclear - Natural Gas	-0.62	-1.59	-0.03	0.039*
	Distance	10-15 Miles - 5-10 Miles	-0.13	-1.10	-0.03	0.034*
	Distance	10-15 Miles - 0-5 Miles	-0.26	-0.83	0.23	0.385
	Distance	5-10 Miles - 0-5 Miles	0.13	-0.27	0.80	0.467
	Plant Type × Distance	Nuclear × 0-5 Miles - Natural Gas × 0-5 Miles	-1.17	-2.18	-0.15	0.012*
%Black	Plant Type	Natural Gas - Coal	-0.21	-0.52	0.09	0.241
	Plant Type	Nuclear - Coal	-0.70	-1.20	-0.20	0.003**
	Plant Type	Nuclear - Natural Gas	-0.49	-1.00	0.03	0.067
	Distance	10-15 Miles - 5-10 Miles	0.13	-0.22	0.48	0.658
	Distance	10-15 Miles - 0-5 Miles	0.17	-0.18	0.52	0.481
	Distance	5-10 Miles - 0-5 Miles	0.04	-0.31	0.39	0.957
%Bachelor's Degree or Above	Plant Type	Natural Gas - Coal	0.02	-0.05	0.10	0.738
	Plant Type	Nuclear - Coal	0.24	0.12	0.37	0.000***
	Plant Type	Nuclear - Natural Gas	0.22	0.09	0.34	0.000***
	Distance	10-15 Miles - 5-10 Miles	0.08	0.00	0.17	0.07
	Distance	10-15 Miles - 0-5 Miles	0.18	0.09	0.26	0.000***
	Distance	5-10 Miles - 0-5 Miles	0.10	0.01	0.18	0.024*
	Plant Type × Distance	Coal × 10-15 Miles - Coal × 0-5 Miles	0.18	0.02	0.34	0.013*
%Poverty	Plant Type	Natural Gas - Coal	0.02	-0.04	0.08	0.669
	Plant Type	Nuclear - Coal	-0.16	-0.26	-0.06	0.000***
	Plant Type	Nuclear - Natural Gas	-0.18	-0.28	-0.08	0.000***
	Distance	10-15 Miles - 5-10 Miles	0.02	-0.05	0.09	0.754
	Distance	10-15 Miles - 0-5 Miles	0.04	-0.03	0.11	0.402
	Distance	5-10 Miles - 0-5 Miles	0.02	-0.05	0.09	0.835
	Plant Type × Distance	Nuclear × 0-5 Miles - Coal × 0-5 Miles	-0.28	-0.50	-0.05	0.004**
	Plant Type × Distance	Nuclear × 0-5 Miles - Natural Gas × 0-5 Miles	-0.33	-0.56	-0.10	0.000***
Average Median Income	Plant Type	Natural Gas - Coal	0.02	-0.01	0.05	0.221
	Plant Type	Nuclear - Coal	0.10	0.05	0.15	0.000***
	Plant Type	Nuclear - Natural Gas	0.08	0.03	0.13	0.001**
	Distance	10-15 Miles - 5-10 Miles	0.01	-0.02	0.05	0.668
	Distance	10-15 Miles - 0-5 Miles	0.03	-0.01	0.06	0.191
	Distance	5-10 Miles - 0-5 Miles	0.01	-0.02	0.05	0.651
	Plant Type × Distance	Nuclear × 0-5 Miles - Coal × 0-5 Miles	0.15	0.03	0.27	0.004**
Average Median Home Values	Plant Type	Natural Gas - Coal	0.02	-0.02	0.06	0.407
	Plant Type	Nuclear - Coal	0.14	0.07	0.20	0.000***
	Plant Type	Nuclear - Natural Gas	0.12	0.05	0.18	0.000***
	Distance	10-15 Miles - 5-10 Miles	0.04	-0.01	0.08	0.161
	Distance	10-15 Miles - 0-5 Miles	0.07	0.02	0.11	0.001**
	Distance	5-10 Miles - 0-5 Miles	0.03	-0.01	0.08	0.223
	Plant Type × Distance	Nuclear × 0-5 Miles - Coal × 0-5 Miles	0.22	0.07	0.37	0.000***
	Plant Type × Distance	Nuclear × 0-5 Miles - Natural Gas × 0-5 Miles	0.20	0.05	0.36	0.002**

Table B.5: Community-level two-way ANOVA 1990-2010 socioeconomic trend summary statistics by power plant type for the six socioeconomic indicators (Table 3.8).

	term	**df**	**Sum of Squares**	**Mean Square**	**F Statistic**	**p value**
			Nuclear			
Population Density	Distance	2	27.34	13.67	2.33	0.099
	Year	2	0.24	0.12	0.02	0.980
	Distance × Year	4	0.18	0.04	0.01	1.000
	Residuals	297	1,743	5.87		
	Distance	2	0.98	0.49	0.21	0.807
%Black	Year	2	2.58	1.29	0.57	0.567
	Distance × Year	4	7.16	1.79	0.79	0.534
	Residuals	297	675	2.27		
%Bachelor's Degree or Above	Distance	2	0.55	0.27	1.31	0.270
	Year	2	0	0.00	0.00	0.997
	Distance × Year	4	0.01	0.00	0.02	1.000
	Residuals	297	62	0.21		
%Poverty	Distance	2	0.97	0.48	3.06	0.049*
	Year	2	8.22	4.11	26.02	0.000***
	Distance × Year	4	0.79	0.20	1.26	0.288
	Residuals	297	47	0.16		
Average Median Income	Distance	2	0.01	0.00	0.10	0.904
	Year	2	0.06	0.03	0.95	0.388
	Distance × Year	4	0.01	0.00	0.10	0.983
	Residuals	297	9	0.03		
Average Median Home Values	Distance	2	0	0.00	0.00	0.997
	Year	2	0.04	0.02	0.34	0.711
	Distance × Year	4	0.04	0.01	0.17	0.952
	Residuals	297	19	0.06		
			Coal			
Population Density	Distance	2	113.57	56.78	8.41	0.000***
	Year	2	1.62	0.81	0.12	0.887
	Distance × Year	4	0.62	0.15	0.02	0.999
	Residuals	1,575	10,640	6.76		
%Black	Distance	2	153.9	76.95	1.35	0.26
	Year	2	115.74	57.87	1.01	0.363
	Distance × Year	4	43	10.75	0.19	0.944
	Residuals	1,572	89665	57.04		
%Bachelor's Degree or Above	Distance	2	5.39	2.70	26.24	0.000***
	Year	2	0.06	0.03	0.30	0.742
	Distance × Year	4	0.05	0.01	0.13	0.972
	Residuals	1,575	162	0.10		
%Poverty	Distance	2	0.39	0.19	0.71	0.491
	Year	2	55.3	27.65	102.19	0.000***
	Distance × Year	4	0.17	0.04	0.16	0.959
	Residuals	1,575	426	0.27		
Average Median Income	Distance	2	0.14	0.07	3.57	0.028***
	Year	2	0.1	0.05	2.47	0.085
	Distance × Year	4	0	0.00	0.05	0.995
	Residuals	1,575	31	0.02		
Average Median Home Values	Distance	2	0.87	0.43	12.05	0.000***
	Year	2	0.04	0.02	0.62	0.539
	Distance × Year	4	0.01	0.00	0.05	0.996
	Residuals	1,575	57	0.04		
			Natural Gas			
Population Density	Distance	2	0.4	0.20	0.04	0.960
	Year	2	0.33	0.17	0.03	0.967
	Distance × Year	4	0.25	0.06	0.01	1.000
	Residuals	225	1123	4.99		
	Distance	2	0.3	0.15	0.16	0.856
%Black	Year	2	1.05	0.53	0.55	0.580
	Distance × Year	4	0.52	0.13	0.14	0.969
	Residuals	225	217	0.96		
%Bachelor's Degree or Above	Distance	2	0.26	0.13	0.38	0.681
	Year	2	0	0.00	0.01	0.995
	Distance × Year	4	0.02	0.01	0.01	1.000
	Residuals	225	76	0.34		
%Poverty	Distance	2	0.62	0.31	0.19	0.827
	Year	2	38.03	19.02	11.60	0.000***
	Distance × Year	4	0.3	0.08	0.05	0.996
	Residuals	225	369	1.64		
Average Median Income	Distance	2	0.05	0.02	0.88	0.415
	Year	2	0.03	0.01	0.51	0.604
	Distance × Year	4	0.03	0.01	0.28	0.888
	Residuals	225	6	0.03		
Average Median Home Values	Distance	2	0.09	0.04	0.52	0.597
	Year	2	0.01	0.01	0.08	0.927
	Distance × Year	4	0.04	0.01	0.10	0.982
	Residuals	225	20	0.09		

Table B.6: Post-hoc 1990-2010 socioeconomic trend Tukey's tests for Distance and year by power plant type for six socioeconomic indicators (Table 3.9).

			Nuclear				**Coal**				**Natural Gas**			
	term	**comparison**	**mean diff.**	**2.5% level**	**97.5% level**	**adj. p val.**	**mean diff.**	**2.5% level**	**97.5% level**	**adj. p val.**	**mean diff.**	**2.5% level**	**97.5% level**	**adj. p val.**
Population Density	Dist.	10-15 Miles - 0-5 Miles	0.70	-0.10	1.50	0.100	-0.66	-1.03	-0.28	0.000***	-0.07	-0.92	0.77	0.977
	Dist.	10-15 Miles - 5-10 Miles	0.16	-0.64	0.96	0.883	-0.31	-0.69	0.06	0.124	0.03	-0.82	0.87	0.997
	Dist.	5-10 Miles - 0-5 Miles	0.54	-0.26	1.34	0.253	-0.34	-0.72	0.03	0.082	-0.10	-0.94	0.75	0.959
	Year	2010 - 1990	0.07	-0.73	0.87	0.978	-0.08	-0.45	0.30	0.88	0.08	-0.76	0.93	0.970
	Year	2010 - 2000	0.04	-0.76	0.84	0.993	-0.03	-0.40	0.35	0.986	0.07	-0.77	0.92	0.976
	Year	2000 - 1990	0.03	-0.77	0.83	0.996	-0.05	-0.43	0.32	0.945	0.01	-0.83	0.85	1.000
%Black	Dist.	10-15 Miles - 0-5 Miles	0.12	-0.38	0.61	0.846	0.76	-0.33	1.85	0.229	0.06	-0.32	0.43	0.933
	Dist.	10-15 Miles - 5-10 Miles	0.12	-0.37	0.62	0.829	0.42	-0.68	1.51	0.643	-0.03	-0.40	0.34	0.979
	Dist.	5-10 Miles - 0-5 Miles	-0.01	-0.50	0.49	0.999	0.35	-0.74	1.44	0.737	0.09	-0.28	0.46	0.846
	Year	2010 - 1990	-0.13	-0.63	0.37	0.814	-0.64	-1.73	0.45	0.356	0.09	-0.28	0.46	0.827
	Year	2010 - 2000	0.10	-0.40	0.59	0.894	-0.16	-1.26	0.93	0.933	-0.07	-0.44	0.30	0.893
	Year	2000 - 1990	-0.22	-0.72	0.27	0.538	-0.47	-1.57	0.62	0.565	0.16	-0.21	0.53	0.551
%Bach. Degree or Above	Dist.	10-15 Miles - 0-5 Miles	0.10	-0.05	0.25	0.252	0.14	0.10	0.19	0.000***	0.00	-0.22	0.22	1.000
	Dist.	10-15 Miles - 5-10 Miles	0.07	-0.08	0.22	0.535	0.07	0.02	0.12	0.001**	-0.07	-0.29	0.15	0.733
	Dist.	5-10 Miles - 0-5 Miles	0.03	-0.12	0.18	0.860	0.07	0.03	0.12	0.001**	0.07	-0.15	0.29	0.724
	Year	2010 - 1990	-0.01	-0.16	0.15	0.997	0.01	-0.03	0.06	0.766	-0.01	-0.23	0.21	0.995
	Year	2010 - 2000	0.00	-0.15	0.15	0.999	0.00	-0.05	0.05	0.998	-0.01	-0.23	0.21	0.996
	Year	2000 - 1990	0.00	-0.15	0.15	1.000	0.01	-0.03	0.06	0.799	0.00	-0.22	0.22	1.000
	Dist. × Year	5-10 Miles × 1990 - 0-5 Miles × 1990	0.04	-0.31	0.38	1.000	0.09	-0.02	0.19	0.199	0.09	-0.42	0.59	1.000
	Dist. × Year	10-15 Miles × 1990 - 0-5 Miles × 1990	0.11	-0.23	0.46	0.984	0.16	0.05	0.27	0.000***	0.00	-0.50	0.50	1.000
	Dist. × Year	10-15 Miles × 2000 - 0-5 Miles × 2000	0.11	-0.23	0.46	0.984	0.13	0.02	0.24	0.005**	0.00	-0.50	0.51	1.000
	Dist. × Year	10-15 Miles × 2010 - 0-5 Miles × 2010	0.08	-0.27	0.43	0.998	0.14	0.03	0.25	0.001**	0.00	-0.50	0.50	1.000
%Poverty	Dist.	10-15 Miles - 0-5 Miles	0.13	0.00	0.27	0.044*	0.04	-0.04	0.11	0.512	-0.13	-0.61	0.36	0.812
	Dist.	10-15 Miles - 5-10 Miles	0.04	-0.09	0.17	0.746	0.01	-0.07	0.08	0.986	-0.05	-0.54	0.43	0.961
	Dist.	5-10 Miles - 0-5 Miles	0.09	-0.04	0.22	0.214	0.03	-0.04	0.11	0.612	-0.07	-0.55	0.41	0.936
	Year	2010 - 2000	0.37	0.24	0.50	0.000***	0.39	0.32	0.47	0.000***	0.83	0.35	1.32	0.000***
	Year	2010 - 1990	0.32	0.19	0.45	0.000***	0.40	0.32	0.48	0.000***	0.87	0.39	1.36	0.000***
	Year	2000 - 1990	-0.05	-0.18	0.08	0.660	0.01	-0.07	0.08	0.971	0.04	-0.44	0.52	0.980
	Dist. × Year	0-5 Miles × 2010 - 0-5 Miles × 1990	0.15	-0.15	0.45	0.819	0.37	0.20	0.54	0.000***	0.95	-0.16	2.06	0.165
	Dist. × Year	0-5 Miles × 2010 - 0-5 Miles × 2000	0.29	-0.01	0.59	0.070	0.36	0.19	0.53	0.000***	0.92	-0.19	2.03	0.199
	Dist. × Year	5-10 Miles × 2010 - 5-10 Miles × 1990	0.37	0.07	0.67	0.005**	0.42	0.24	0.59	0.000***	0.78	-0.34	1.89	0.417
	Dist. × Year	5-10 Miles × 2010 - 5-10 Miles × 2000	0.37	0.07	0.68	0.004**	0.41	0.24	0.58	0.000***	0.73	-0.39	1.84	0.515
	Dist. × Year	10-15 Miles × 2010 - 10-15 Miles × 1990	0.44	0.14	0.75	0.000***	0.41	0.24	0.59	0.000***	0.90	-0.21	2.01	0.224
	Dist. × Year	10-15 Miles × 2010 - 10-15 Miles × 2000	0.44	0.14	0.74	0.000***	0.41	0.23	0.58	0.000***	0.86	-0.25	1.97	0.276
Average Household Income	Dist.	10-15 Miles - 0-5 Miles	0.01	-0.05	0.07	0.928	0.02	0.00	0.04	0.038*	0.03	-0.03	0.09	0.564
	Dist.	10-15 Miles - 5-10 Miles	0.01	-0.05	0.07	0.913	0.02	0.00	0.04	0.082	0.03	-0.03	0.09	0.427
	Dist.	5-10 Miles - 0-5 Miles	0.00	-0.06	0.06	0.999	0.00	-0.02	0.02	0.947	-0.01	-0.07	0.06	0.973
	Year	2010 - 1990	0.03	-0.03	0.09	0.432	0.01	-0.01	0.03	0.538	-0.02	-0.08	0.04	0.718
	Year	2010 - 2000	0.03	-0.03	0.09	0.487	0.02	0.00	0.04	0.068	0.00	-0.06	0.07	0.985
	Year	2000 - 1990	0.00	-0.06	0.06	0.995	-0.01	-0.03	0.01	0.479	-0.02	-0.09	0.04	0.614
Average Home Value	Dist.	10-15 Miles - 0-5 Miles	0.00	-0.08	0.08	1.000	0.06	0.03	0.08	0.000***	0.04	-0.08	0.15	0.729
	Dist.	10-15 Miles - 5-10 Miles	0.00	-0.09	0.08	0.998	0.03	0.01	0.06	0.014*	0.05	-0.07	0.16	0.599
	Dist.	5-10 Miles - 0-5 Miles	0.00	-0.08	0.09	0.998	0.02	0.00	0.05	0.095	-0.01	-0.12	0.10	0.976
	Year	2010 - 1990	-0.02	-0.10	0.07	0.891	0.00	-0.03	0.02	0.944	0.02	-0.09	0.13	0.926
	Year	2010 - 2000	-0.03	-0.11	0.05	0.688	-0.01	-0.04	0.01	0.525	0.00	-0.11	0.12	0.995
	Year	2000 - 1990	0.01	-0.07	0.10	0.929	0.01	-0.02	0.04	0.727	0.01	-0.10	0.12	0.958

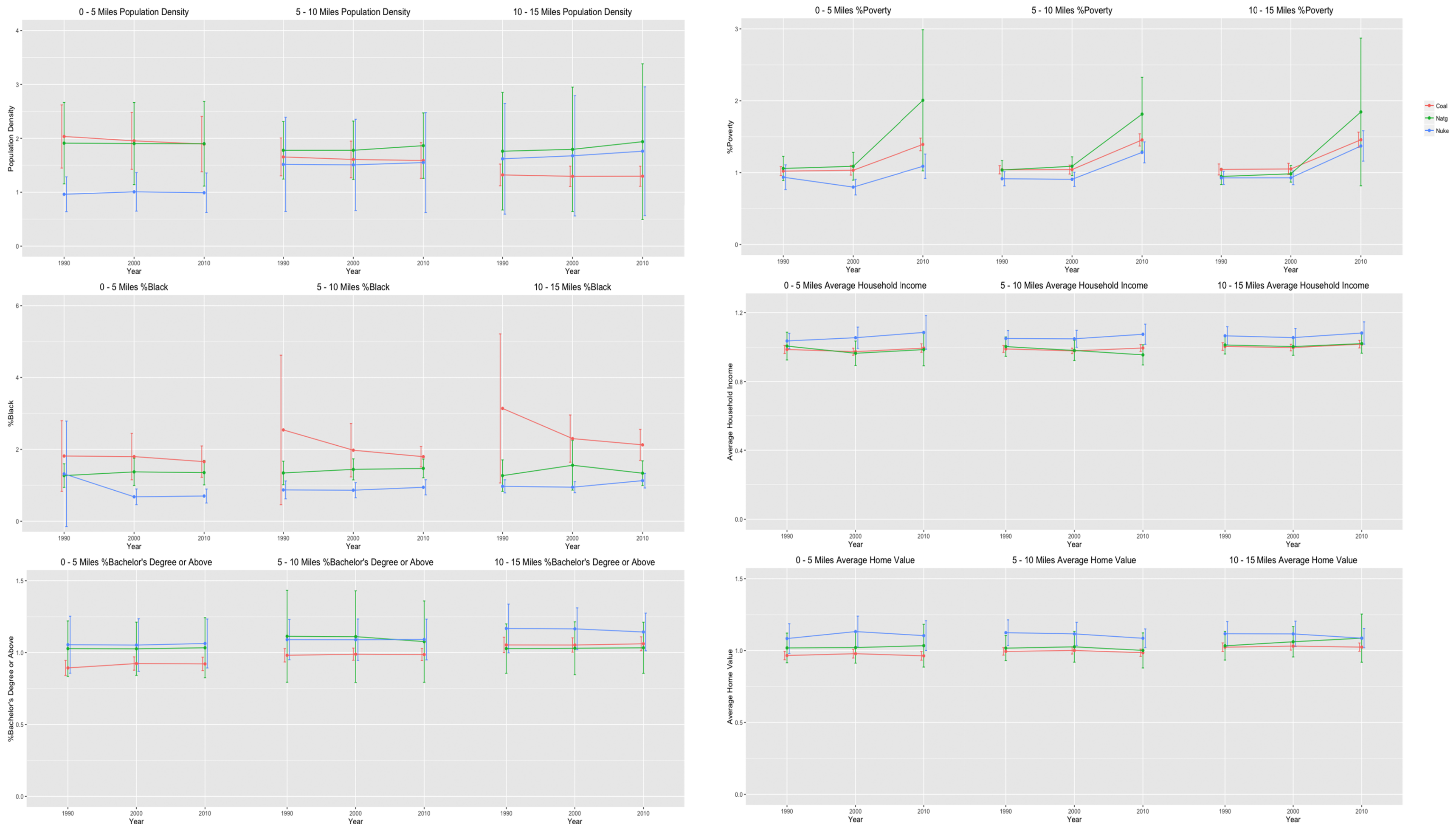

Figure B.4: Mean and 95% confidence interval trends of the six socioeconomic indicators of communities near coal, natural gas, and nuclear power plants for each distance.

B.2 Pre-operation Logistic Regression Analysis

The pre-operation logistic regression study is used quantify the relationship between socioeconomic indicators prior to the plant generating electricity. Similarly, Pastor et al. (2004) [77] and Mohai et al. (2009) [78] utilizes logistic regression models to show disparities with placement of industrial facilities. However, this study investigates socioeconomic disparities in counties and communities given the eventual siting of a baseload nuclear, natural gas or coal power plant. At the county-level and community-level this analysis quantifies the odds of a county or community receiving a nuclear, natural gas, or coal power plant based socioeconomic indicators before plant operation.

B.2.1 Pre-operation County-level Analysis

B.2.1.1 Pre-operation County-level Data Sources

The pre-operation logistic regression analysis uses 1970-2010 county-level data for the counties with nuclear, natural gas, or coal power plants from the US Census Bureau and the Social Explorer.

B.2.1.2 Pre-operation County-level Methods

Based on several socioeconomic indicators, the county-level pre-operation logistic regression study uses Census data to predict the counties that will receive a coal, natural gas, or nuclear power plant given the eventual siting of a power plant. The county-level pre-operation logistic regression study uses 85 coal, 119 natural gas, and 31 nuclear power plant sites. Three logistic regressions (coal, nuclear, natural gas) are performed in this study. Equation B.1 expresses the county-level pre-operation logistic regression.

$$\begin{gathered} Y_p = \beta_{0p} + \beta_{1p}(PopulationDensity)_p + \beta_{2p}(\%Black)_p + \beta_{3p}(\%Bachelor'sDegreeandAbove)_p + \\ \beta_{4p}(\%Poverty)_p + \beta_{5p}log(AverageHouseholdIncome)_p + \beta_{6p}log(HomeValue)_p + \epsilon_p \end{gathered} \tag{B.1}$$

where Yp is a binary variable for power plant type p (coal, natural gas, nuclear). For example, the binary variable $Ycoal$ is 1 when a county will eventually get a coal power plant, if $Ycoal$ is 0 then that county will either get a nuclear or natural gas power plant. All counties in this analysis will eventually get one type of power plant. The pre-operation logistic regression study treats each power plant during each decennial census as an observation.

B.2.1.3 Pre-operation County-level Results

Given the eventual placement of a baseload nuclear, coal, or natural gas power plant, the county-level analysis finds counties near nuclear power plants are associated with less population densities, higher home values and incomes. Table B.7 shows the abridged county-level summary statistics of the nuclear, coal, and natural gas logistic regression models. The results from Equation B.1 in Table B.7 show counties that receive coal plants are associated with lower rates of Black residents, lower percentage of residents with Bachelor's degrees or above, lower poverty rates, and lower average household incomes. Counties that receive nuclear power plants are associated with higher rates of Black residents, lower poverty rates, and lower average household incomes. Counties that receive natural gas plants are associated with higher percentage of residents with Bachelor's degrees or above, higher poverty rates, and higher household income.

Table B.7: County-level pre-operation logistic regression summary statistics.

		Equation B.7				**Equation B.7 w/Census Decade Fixed Effects**			
	term	**coeff.**	**std.error**	**z value**	**p value**	**coeff.**	**std.error**	**z value**	**p value**
Nuclear	Population Density	0.00	0.00	-0.26	0.796	0.00	0.00	-1.13	0.2580
	%Black	4.10	1.39	2.94	0.003**	6.13	1.76	3.49	0.000***
	%Bachelor's Degree or Above	-4.33	5.15	-0.84	0.400	3.55	5.32	0.67	0.5050
	%Poverty	-16.49	4.76	-3.46	0.001***	-20.55	6.15	-3.34	0.000***
	log(Average Household Income)	-5.77	2.07	-2.78	0.005**	-7.63	2.86	-2.67	0.008**
	log(Average Home Value)	0.40	0.85	0.47	0.635	1.53	1.08	1.42	0.1560
	1980	-	-	-	-	-1.40	0.54	-2.60	0.009**
	1990	-	-	-	-	-3.09	1.08	-2.87	0.004**
Coal	%Black	-3.10	1.02	-3.04	0.002**	-2.97	1.05	-2.84	0.005**
	%Bachelor's Degree or Above	-13.07	4.66	-2.81	0.005**	-7.05	4.75	-1.48	0.1380
	%Poverty	-5.08	2.29	-2.22	0.027*	-3.46	2.43	-1.43	0.1540
	log(Average Household Income)	-4.01	1.42	-2.83	0.005**	-2.97	1.57	-1.89	0.0590
	1980	-	-	-	-	-0.08	0.33	-0.25	0.8000
	1990	-	-	-	-	-2.11	0.63	-3.34	0.000***
	2000	-	-	-	-	-2.46	1.05	-2.35	0.019*
Natural Gas	Population Density	0.00	0.00	0.11	0.912	0.00	0.00	1.40	0.1620
	%Black	1.17	0.88	1.33	0.183	0.88	0.93	0.95	0.3420
	%Bachelor's Degree or Above	10.23	3.87	2.65	0.008**	3.02	3.95	0.76	0.4450
	%Poverty	9.11	2.29	3.97	0.000***	7.80	2.47	3.16	0.002**
	log(Average Household Income)	5.47	1.31	4.18	0.000***	4.73	1.51	3.13	0.002**
	1980	-	-	-	-	0.50	0.30	1.66	0.0970
	1990	-	-	-	-	2.60	0.55	4.71	0.000***
	2000	-	-	-	-	3.24	1.04	3.12	0.002**

B.2.2 Pre-operation Community-level Analysis

B.2.2.1 Community-level Data Sources

The pre-operation logistic regression analysis uses 1970-2010 NCDB tract-level data. While NCDB contains normalized and historical tract-level data, the US did not have complete tract-level information until the 1990 Census. This creates a number of data quality issues. First, about 90% of power plants in this analysis were constructed during the 1970s and 1980s. Second, the 1970 and 1980 Census contain up to 70% and 54% of missing tract data, respectively. Because a lack of data availability, only complete tracts are used to represent the community surrounding the power plant for analysis using 1970s and 1980s tract level data.

B.2.2.2 Pre-operation Community-level Methods

The pre-operation logistic regression study, expressed in Equation B.2, uses pre-operation data via the NCDB to estimate the socioeconomic indicators that will best predict the location of a coal, natural gas, or nuclear power plant given a power plant will be placed in the community. Equation B.2 is a modified version of Equation B.1 .

$$\begin{aligned} Y_p = \beta_{0p} + \beta_{1p}(Distance)_p + \beta_{2p}(PopulationDensity)_p + \\ \beta_{3p}(\%Black)_p + \beta_{4p}(\%Bachelor'sDegreeandAbove)_p + \\ \beta_{5p}(\%Poverty)_p + \beta_{6p}log(AverageHouseholdIncome)_p + \\ \beta_{7p}log(HomeValue)_p + \epsilon_p \end{aligned} \tag{B.2}$$

where *Distance* is a categorical fixed effects variable used to indicate the distance a community is from a power plant (0-5, 5-10, and 10-15 miles). The variables correspond to the community-to-power plant socioeconomic indicators ratios. All communities in this analysis will eventually get one type of power plant. Table B.8 outlines the number of power plant sites used for the pre-operation logistic regression study. The pre-operation logistic regression study treats each power plant during each decennial census as an observation.

Table B.8: Baseload Power plant communities for pre-operation logistic regression and event study regression models. Each power plant during each decennial census is treated as an observation.

Power Plant Type	Distance	Population Density	%Black	%Bachelor's Degree or Above	%Poverty	Average Income	Average Home Values
Nuclear	0-5 Miles	14	13	14	14	14	13
Nuclear	5-10 Miles	16	14	16	16	16	15
Nuclear	10-15 Miles	18	16	18	18	18	17
Coal	0-5 Miles	34	25	34	34	34	33
Coal	5-10 Miles	36	30	36	36	36	33
Coal	10-15 Miles	41	34	41	41	40	36
Natural Gas	0-5 Miles	85	75	85	85	85	83
Natural Gas	5-10 Miles	97	93	97	97	97	92
Natural Gas	10-15 Miles	102	99	102	102	102	94

B.2.2.3 Pre-operation Community-level Results

Given the eventual placement of a baseload nuclear, coal, or natural gas power plant, the community-level analysis finds communities near nuclear power plants are associated with less population densities, higher home values and incomes. Table B.9 shows the abridged community-level summary statistics of the nuclear, coal, and natural gas logistic regression models. Results using Equation B.2 presented in Table B.9 show, communities that receive coal plants are associated with higher population of black residents and lower percentages of residents with Bachelor's degrees or above (Equation B.2 results), while communities that will receive a nuclear power plants are associated with lower population density, higher average household incomes, and higher home values. Communities that will receive natural gas plants are associated with higher population density, lower percentage of Black residents, and lower household income.

Table B.9: Community-level pre-operation logistic regression summary statistics.

		Equation B.2				**Equation B.2 w/Census Decade Fixed Effects**			
	term	**coeff.**	**std.error**	**z value**	**p value**	**coeff.**	**std.error**	**z value**	**p value**
Nuclear	Population Density	-0.22	0.08	-2.74	0.006**	-0.19	0.07	-2.60	0.009**
	%Black	0.00	0.01	0.06	0.954	-0.01	0.01	-0.39	0.696
	%Bachelor's Degree or Above	0.34	0.20	1.70	0.088	0.14	0.20	0.71	0.479
	%Poverty	0.87	0.53	1.65	0.100	1.18	0.58	2.02	0.043*
	log(Average Household Income)	2.74	1.11	2.46	0.014*	2.60	1.11	2.33	0.020*
	log(Average Home Value)	1.62	0.67	2.42	0.016*	2.57	0.66	3.90	0.000***
	1980	-	-	-	-	-0.93	0.36	-2.58	0.010**
	1990	-	-	-	-	-18.36	1081.34	-0.02	0.986
Coal	%Black	0.10	0.02	4.42	0.000***	0.09	0.02	3.86	0.000***
	%Bachelor's Degree or Above	-0.63	0.32	-1.97	0.049*	-0.49	0.28	-1.76	0.079
	%Poverty	-0.12	0.36	-0.33	0.745	-0.25	0.39	-0.65	0.518
	log(Average Household Income)	1.65	0.95	1.74	0.083	0.26	1.00	0.26	0.793
	1980	-	-	-	-	-1.03	0.26	-4.05	0.000***
	1990	-	-	-	-	-2.28	0.44	-5.23	0.000***
	2000	-	-	-	-	-2.84	0.60	-4.75	0.000***
Natural Gas	Population Density	0.11	0.03	3.19	0.001**	0.10	0.03	2.89	0.004**
	%Black	-0.12	0.03	-4.46	0.000***	-0.11	0.03	-3.75	0.000***
	%Bachelor's Degree or Above	-0.14	0.16	-0.86	0.389	-0.06	0.16	-0.40	0.691
	%Poverty	0.00	0.33	0.01	0.993	0.02	0.36	0.05	0.961
	log(Average Household Income)	-1.97	0.80	-2.48	0.013*	-0.94	0.86	-1.10	0.273
	1980	-	-	-	-	1.08	0.22	4.98	0.000***
	1990	-	-	-	-	2.84	0.43	6.58	0.000***
	2000	-	-	-	-	3.42	0.60	5.74	0.000***

B.2.3 Pre-operation Discussion

Based on the analysis, it can be seen there are instances of differing likelihood of plant placement at the county-level compared to community-level. Nuclear power plants have a significantly higher likelihood of plant placement in counties with a higher percentage of black residents, lower poverty rates, and lower average household incomes. However, within counties at the community-level, nuclear power plants they are significantly more likely to be sited in areas with lower population densities, higher household incomes, and higher home values. Coal power plants have a significantly higher likelihood of plant placement in counties with a lower percentage of black residents, a lower percentage of residents with Bachelor's degrees or above, lower poverty rates, and lower average household incomes. Within counties at the community-level, coal power plants are significantly more likely to be sited in areas with a higher percentage of black residents and lower rates of residents with Bachelor's degrees or above. Natural gas power plants are significantly more likely to be sited in counties with higher percentage of residents with Bachelor's degrees or above, poverty rates, and average household incomes. At the community-level within these counties, natural gas power plants are sited in areas with higher population density, a lower rate of black residents, and lower average household incomes.

B.2.4 Pre-operation Future Work

Additional research is need to identify counties that are likely to receive any power plant with an installed capacity of >500 $\mathrm{MW_e}$ based on their socioeconomic indicators. Pastor et al. (2004) [77] utilizes similar methods to illustrate disproportionate exposures to TRI sites based on race based in California using tract-level data. This analysis focuses on power plants as opposed to TRI sites and is expanded to the continental US using county-level data. Equation B.3 expresses the logistic regression model.

$$\begin{aligned} Y = \beta_0 + \beta_1(PopulationDensity) + \beta_2(\%Black) + \beta_3(\%Bachelor'sDegreeandAbove) + \\ \beta_p(\%Poverty) + \beta_5 log(AverageHouseholdIncome) + \beta_6 log(HomeValue) + \epsilon \end{aligned} \tag{B.3}$$

Where Y is a binary variable for a power plant sited within the county. County-level 1970 census data, power plants that began operation after 1970, and power plant within 30 miles of each other will be used in the analysis. In total, 326 power plants (104 coal, 165 natural gas, and 57 nuclear power plants) will be included in the logistic regression.

B.3 Socioeconomic Impact Analysis

This analysis provides an indication of the changes experienced by communities near baseload power plants before and after operation. The difference-in-difference event study regression framework is used estimate the influence power plants may have on surrounding communities. Similarly, Currie et al. (2015) [141] utilized an event study regression model to measure the impact of the opening and closing of toxic plants with respect to infant health and housing values within 2 miles. Table B.10 shows plant openings by decade from 1971 to 2010.

Table B.10: Power Plant Openings by Decade.

	1971 to 1980	**1981 to 1990**	**1991 to 2000**	**2001 to 2010**
Nuclear	17	13	1	0
Coal	52	30	2	4
Natural Gas	7	3	15	96

B.3.1 Event Study Difference-in-Difference Data Sources and Quality

The event study difference-in-difference model uses the same data subset as the pre-operation logistic regression analysis outlined in Section B.2.1.1. Table B.8 outlines the number of power plant sites used as observations in the event study difference-in-difference regression models.

B.3.2 Difference-in-Difference Event Study Methods

The difference-in-difference event study framework is used to provide some indication of the influence fossil fuel and low-carbon baseload power plants have on surrounding communities. Typically, this framework is used when several years of observational data change over time in different locations to measure the effect of a policy or an event. The difference-in-difference event study regression model, expressed in Equation B.4, measures the differences within each power plant type while using the 0-5 and 5-10 mile investigation areas as treatment groups. The socioeconomic indicators for each community around power plants are estimated using the following econometric model:

$$\begin{aligned} Y_{ipdt} = \beta_{0i} + \beta_{1i}(Distance)_{ipd} + \beta_{2i}(Operating)_{ipt} + \beta_{3i}(PlantID)_d + \beta_{4i}(Year)_t + \\ \beta_{5i}\Big[(Distance)_{ipd} \times (Operating)_{ipt}\Big] + \epsilon_{ipdt} \end{aligned} \tag{B.4}$$

where Y_{ipdt} denotes the output variable of socioeconomic indicator i, near power plant site p, within investigation area d, for census t. Following the framework specified in Curie et al. (2015) [141], the independent dummy variable, *Operating*, indicates if power plant p is generating electricity during decennial census t. *Year* is a categorical variable used to indicate the decennial census (1970, 1980, 1990, 2000, and 2010) fixed effects. A power plant site level fixed effects variable, *Plant ID*, is utilized to control for unobservable factors for each community around a power plant that are time-invariant. Nuclear power plants and the 10-15 mile distances are the baseline. The event study difference-in-difference model uses historical data to indicate if there is evidence to suggest the operation of baseload power plant impacted the community.

B.3.2.1 Difference-in-Difference Event Study Results and Discussion

Table B.11 shows the coefficient estimates, standard errors, t-statistic, and p values from the difference-in-difference regression models outlined in Equation B.4. The baseline are communities that 10-15 miles away from the respective power plant type. The results indicate there are no significant changes within the 0-5, and 5-10 mile treatment groups.

Table B.11: Event study difference-in-difference regression model summary statistics.

		Nuclear				**Coal**				**Natural Gas**			
	term	**coeff.**	**std.error**	**t stat.**	**p val.**	**coeff.**	**std.error**	**t stat.**	**p val.**	**coeff.**	**std.error**	**t stat.**	**p val.**
Population Density	Operating	0.19	0.75	0.25	0.805	0.31	0.53	0.59	0.556	0.09	0.52	0.18	0.859
	0-5 Miles × Operating	-0.61	0.71	-0.87	0.387	-0.64	0.50	-1.28	0.202	-0.42	0.47	-0.90	0.368
	5-10 Miles × Operating	-0.44	0.68	-0.64	0.525	-0.71	0.50	-1.44	0.151	0.13	0.45	0.28	0.779
%Black	Operating	-0.49	1.18	-0.42	0.677	-7.53	5.81	-1.30	0.196	-0.16	0.25	-0.63	0.532
	0-5 Miles × Operating	2.16	1.09	1.97	0.050	8.28	5.66	1.46	0.144	0.29	0.23	1.29	0.198
	5-10 Miles × Operating	2.03	1.08	1.88	0.061	4.34	5.43	0.80	0.425	-0.02	0.21	-0.09	0.925
% Bachelor's Degree or Above	Operating	0.21	0.20	1.06	0.291	-0.01	0.07	-0.20	0.838	0.08	0.06	1.33	0.185
	0-5 Miles × Operating	0.07	0.19	0.39	0.696	0.04	0.07	0.57	0.567	0.01	0.05	0.17	0.863
	5-10 Miles × Operating	-0.03	0.18	-0.18	0.856	0.05	0.07	0.77	0.445	0.01	0.05	0.27	0.790
%Poverty	Operating	-0.14	0.15	-0.93	0.354	0.02	0.10	0.17	0.868	0.02	0.06	0.30	0.767
	0-5 Miles × Operating	-0.01	0.14	-0.09	0.929	-0.12	0.09	-1.32	0.188	-0.07	0.06	-1.29	0.197
	5-10 Miles × Operating	0.00	0.13	0.04	0.971	-0.06	0.09	-0.64	0.524	-0.02	0.05	-0.32	0.747
Average Household Income	Operating	-0.14	0.15	-0.93	0.354	0.02	0.10	0.17	0.868	0.06	0.03	1.62	0.105
	0-5 Miles × Operating	-0.01	0.14	-0.09	0.929	-0.12	0.09	-1.32	0.188	-0.03	0.03	-1.13	0.257
	5-10 Miles × Operating	0.00	0.13	0.04	0.971	-0.06	0.09	-0.64	0.524	-0.02	0.03	-0.51	0.609
Average Home Value	Operating	-0.02	0.09	-0.18	0.860	-0.02	0.04	-0.50	0.617	0.06	0.05	1.22	0.222
	0-5 Miles × Operating	0.11	0.08	1.41	0.161	0.04	0.04	0.96	0.336	-0.03	0.04	-0.67	0.505
	5-10 Miles × Operating	0.04	0.08	0.57	0.571	0.01	0.04	0.33	0.743	0.00	0.04	-0.03	0.974

B.3.3 Discussion and Future Work

There are no changes that can be attributed to the operation of the types of power plants at the ranges specified in this using the event study difference-in-difference framework. Impacts have been found in previous studies that investigated effects of coal plants and toxic facilities on home values in Davis et al. (2011) [71] and Currie et al. (2015) [141] when using distances of 1-2 miles. Limited data availability of tracts in 1970 and 1980 decennial census records may have contribute to the overall results of this difference-in-difference. Additional research is needed at the county level. County-level event study difference-in-differences regression models can be used to as an additional layer of analysis to quantify significant impacts power plants can have on counties after operation. While the community-level event study difference-in-difference regression models use higher resolution data, the county-level analysis uses complete and reliable count-level data from 1970-2010. In a past study, de Faria et al. (2017) [**?**] investigates the socioeconomic impacts of large hydropower plants in Brazil at the county-level from 1991 to 2010 using the event study difference-in-difference framework. The socioeconomic indicators of interest relate to an economic indicator (total GDP, industry GDP, services GDO, agriculture GDP, public revenue, services tax, state transfer, and federal transfer) and the human development index (income, longevity, education, access to electricity and piped water, teenage pregnancy rates, and HIV rates). The analysis found counties with hydropower plats had a greater GDP and tax revenues during the first few years of development. However, the positive economic effect lasted less than 15 years. The county-level study will use a modified version of Equation B.4, where the Distance independent categorical variable is replaced with a County independent binary variable (0=control county, 1=treatment county) in Equation B.5.

$$\begin{aligned} Y_{ipt} = \beta_{0i} + \beta_{1i}(County)_{ip} + \beta_{2i}(Operating)_{ipt} + \beta_{3i}(PlantID) + \beta_{4i}(Year)_t + \\ \beta_{5i}\Big[(County)_{ip} \times (Operating)_{ipt}\Big] + \epsilon_{ipt} \end{aligned} \tag{B.5}$$

Appendix C

Risk and regulatory considerations for SMR emergency planning zones based on passive decontamination potential

C.1 iPWR Aerosol Behavior Test Case Radioactivity

Figure C.1 shows the cumulative radioactivity for each iPWR Aerosol Behavior test case DF inside containment.

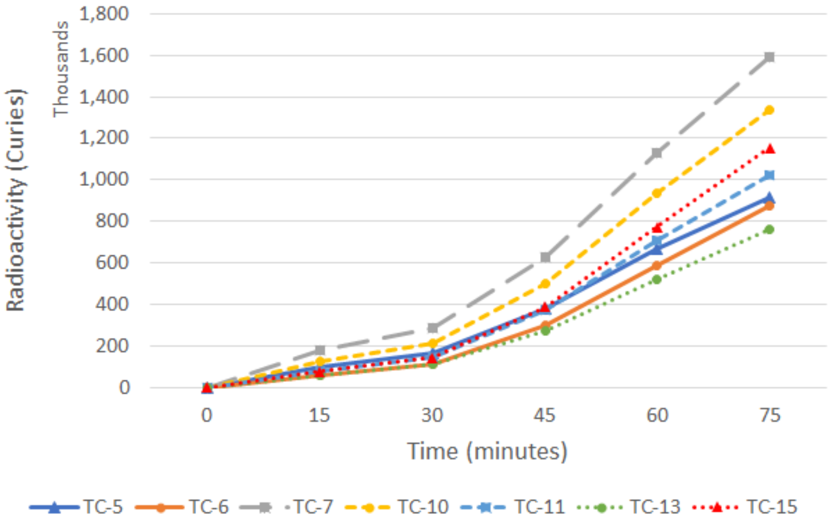

Figure C.1: Cumulative radioactivity for each iPWR Aerosol Behavior test case decontamination factor inside containment.

Figure C.2 shows the cumulative radioactive activity in containment for each iPWR Aerosol Behavior test case DF normalized by volume in Panel 1 and normalized by thermal power in Panel 2.

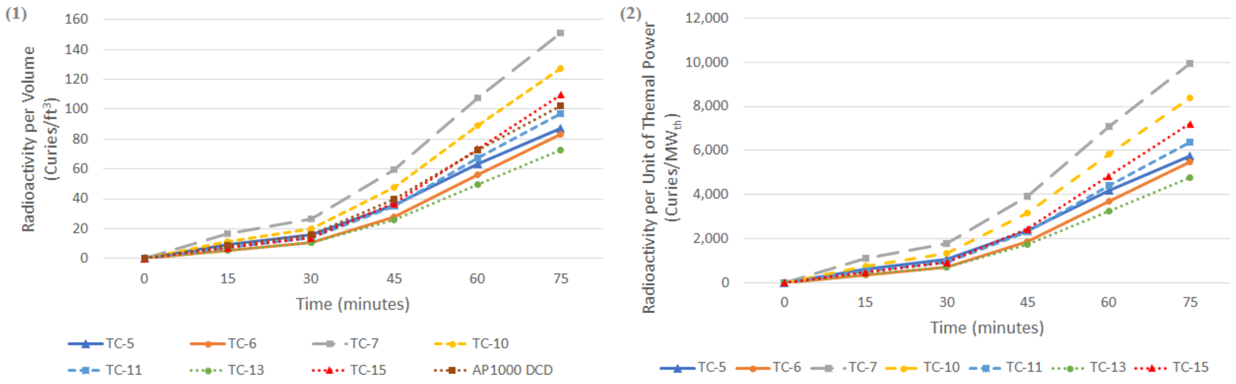

Figure C.2: Panel 1: Radioactivity per Volume for iPWR Aerosol Behavior test case decontamination factors and the AP1000 DCD decontamination factor. Panel 2: Radioactivity per Unit of Thermal Power for iPWR Aerosol Behavior test case decontamination factors.

Panel 2 shows the radioactivity per volume for the AP1000 is 102 curies/ft^3 using the AP1000 DCD DF at minute 75. The AP1000 radioactivity per volume is between test case 11 (97 curies/ft^3) and 15 (110 curies/ft^3).

Bibliography

[1] Nuclear regulatory Commission, "Nuclear power plant licensing process (nureg/br-0298, revision 2)," Jul. 2009. [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/nuregs/brochures/br0298/

[2] Nuclear Regulatory Commission, "Combined license applications for new reactors," 2017, accessed 01-10-2018. [Online]. Available: https://www.nrc.gov/reactors/new-reactors/col.html

[3] D. C. Soble and Jonathan. (2017) Westinghouse files for bankruptcy, in blow to nuclear power. [Online]. Available: https://www.nytimes.com/2017/03/29/business/westinghouse-toshiba-nuclear-bankruptcy.html

[4] L. Parker and M. Holt, "Nuclear power: Outlook for new us reactors." LIBRARY OF CONGRESS WASHINGTON DC CONGRESSIONAL RESEARCH SERVICE, Conference Proceedings.

[5] J. R. Lovering, A. Yip, and T. Nordhaus, "Historical construction costs of global nuclear power reactors," *Energy Policy*, vol. 91, pp. 371–382, 2016.

[6] R. F. Hirsh, *Power Loss: The Origins of Deregulation and Restructuring in the American Electric Utility System*. THE OXFORD INSTITUTE FOR ENERGY STUDIES, 2003.

[7] N. Hultman and J. Koomey, "Three mile island: The driver of us nuclear power's decline?" *Bulletin of the Atomic Scientists*, vol. 69, no. 3, pp. 63–70, 2013. [Online]. Available: https://www.tandfonline.com/doi/pdf/10.1177/0096340213485949?needAccess=true

[8] L. W. Davis, "Prospects for nuclear power," *Journal of Economic Perspectives*, vol. 26, no. 1, pp. 49–66, 2012. [Online]. Available: https://pubs.aeaweb.org/doi/pdfplus/10.1257/jep.26.1.49

[9] E. S. Rubin, I. M. Azevedo, P. Jaramillo, and S. Yeh, "A review of learning rates for electricity supply technologies," *Energy Policy*, vol. 86, pp. 198–218, 2015.

[10] J. S. Walker and T. R. Wellock, *A Short History of Nuclear Regulation, 1946-2009.* US Nuclear Regulatory Commission, 2010. [Online]. Available: https://www.nrc.gov/docs/ML1029/ML102980443.pdf

[11] Nuclear Energy Institute, "Us nuclear generating statistics 1971-2015," April, 2016 2016. [Online]. Available: https://www.nei.org/Knowledge-Center/Nuclear-Statistics/US-Nuclear-Power-Plants/US-Nuclear-Generating-Statistics

[12] M. Cooper, "Small modular reactors and the future of nuclear power in the united states," *Energy Research and Social Science*, vol. 3, pp. 161–177, 2014.

[13] T. M. Persons and F. Rusco, "Nuclear reactors: Status and challenges in development and deployment of new commercial concepts," United States Government Accountability OfceCenter for Science, Technology, and Engineering, Tech. Rep. GAO-15-652, July 2015.

[14] D. Ingersoll, Z. Houghton, R. Bromm, C. Desportes, M. McKellar, and R. Boardman, "Extending nuclear energy to non-electrical applications," in *19th Pacific Basin Nuclear Conference, Vancouver, BC, Canada, Aug*, 2014, pp. 24–28.

[15] D. Ingersoll, Z. Houghton, R. Bromm, and C. Desportes, "Nuscale small modular reactor for co-generation of electricity and water," *Desalination*, vol. 340, pp. 84–93, 2014.

[16] D. Ingersoll, C. Colbert, Z. Houghton, R. Snuggerud, J. Gaston, and M. Empey, "Can nuclear power and renewables be friends?" in *Proceedings of ICAPP*, 2015, pp. 3–6.

[17] Nuclear Regulatory Commission, "Design certification application - nuscale," Oct. 2017. [Online]. Available: https://www.nrc.gov/reactors/new-reactors/design-cert/nuscale.html

[18] World Nuclear News, "First htr-pm vessel head in place," Jan. 2018. [Online]. Available: http://www.world-nuclear-news.org/NN-First-HTR-PM-vessel-head-in-place-0401185.html

[19] World Nuclear News, "Contract for prototype carem balance of plant," Sep. 2016. [Online]. Available: http://www.world-nuclear-news.org/NN-Contract-for-Contract-for-prototype-CAREM-balance-of-plant-0609164.html

[20] J. Deutch, E. Moniz, S. Ansolabehere, M. Driscoll, P. Gray, J. Holdren, P. Joskow, R. Lester, and N. Todreas, "The future of nuclear power," *an MIT Interdisciplinary Study, http://web.mit.edu/nuclearpower*, 2003. [Online]. Available: http://130.88.20.21/uknuclear/pdfs/MIT_nuclearpower-update2009.pdf

[21] N. E. Hultman, J. G. Koomey, and D. M. Kammen, "What history can teach us about the future costs of us nuclear power," 2007.

[22] Nuclear Regulatory Commission, "Information digest, 2017âĂŞ2018 (nureg-1350, volume 29, revision 1)," Office of Public Affairs, U.S. Nuclear Regulatory Commission, Tech. Rep., Dec. 2017.

[23] R. Schwitters, T. AllenIdaho, C. Back, W. Barletta, J. Dahlburg, P. Hosemann, J. Remer, R. Rosner, D. Teter, G. Was, R. Yang, and S. Zinkle, "Renewing licenses for the nation's nuclear power plants," American Physical Society, Report, December 2013.

[24] Nuclear Energy Institute, "Environment: Emissions prevented," 2016. [Online]. Available: http://www.nei.org/Knowledge-Center/Nuclear-Statistics/Environment-Emissions-Prevented

[25] R. Martin, "Nuclear shutdowns could ramp up u.s. carbon emissions," Accessed 5/1/2018, May 2016, https://www.technologyreview.com/s/601533/nuclear-shutdowns-could-ramp-up-us-carbon-emissions/.

[26] The White House, Office of the Press Secretary, "Fact sheet: U.s. reports its 2025 emissions target to the unfccc," March 2015. [Online]. Available: https://obamawhitehouse.archives.gov/the-press-office/2015/03/31/fact-sheet-us-reports-its-2025-emissions-target-unfccc

[27] U.S. Environmental Protection Agency, "Carbon pollution emission guidelines for existing stationary sources: Electric utility generating units; final rule. in: Agency ep, editor. federal register: Federal register; 2015. p. 64661-5120."

[28] U.S. Environmental Protection Agency, "Clean power plan for existing power plants," Dec. 2015. [Online]. Available: http://www2.epa.gov/cleanpowerplan/clean-power-plan-existing-power-plants

[29] U.S. Environmental Protection Agency, "Overview of greenhouse gases carbon dioxide emissions," Jun. 2015. [Online]. Available: http://www.epa.gov/climatechange/ghgemissions/gases/co2.html

[30] U.S. Environmental Protection Agency, "Technical support document (tsd) for the caa section 111(d) emission guidelines for existing power plants," 2014. [Online]. Available: http://www2.epa.gov/sites/production/files/2014-06/documents/20140602tsd-goal-computation.pdf

[31] U.S. Energy Information Administration, "Annual energy outlook 2014 with projections to 2040," U.S. Energy Information Administration, Report, Apr. 2014. [Online]. Available: https://www.eia.gov/outlooks/aeo/pdf/0383(2014).pdf

[32] M. Jiang, W. M. Griffin, C. Hendrickson, P. Jaramillo, J. VanBriesen, and A. Venkatesh, “Life cycle greenhouse gas emissions of marcellus shale gas,” *Environmental Research Letters*, vol. 6, no. 3, 2011.

[33] A. Venkatesh, P. Jaramillo, W. M. Griffin, and H. S. Matthews, “Uncertainty in life cycle greenhouse gas emissions from united states natural gas end-uses and its effects on policy,” *Environmental Science & Technology*, vol. 45, no. 19, pp. 8182–8189, 2011.

[34] U.S. Energy Information Administration, “Levelized cost and levelized avoided cost of new generation resources in the annual energy outlook 2014,” 2014. [Online]. Available: http://www.eia.gov/forecasts/archive/aeo14/electricity_generation.cfm

[35] U.S. Energy Information Administration, “Energy policy act of 2005 summary,” Jul. 2005. [Online]. Available: http://www.eia.gov/oiaf/aeo/otheranalysis/aeo_2006analysispapers/epa2005_summary.html

[36] A. Abdulla and I. L. Azevedo, “Developing a range of levelized cost estimates for integral light water small modular reactors,” *Energy Economics*, Revised and Resubmitted.

[37] B. K. Sovacool, “Valuing the greenhouse gas emissions from nuclear power: A critical survey,” *Energy Policy*, vol. 36, no. 8, pp. 2950–2963, 2008.

[38] J. Beerten, E. Laes, G. Meskens, and W. D’haeseleer, “Greenhouse gas emissions in the nuclear life cycle: A balanced appraisal,” *Energy Policy*, vol. 37, no. 12, pp. 5056–5068, 2009.

[39] E. S. Warner and G. A. Heath, “Life cycle greenhouse gas emissions of nuclear electricity generation,” *Journal of Industrial Ecology*, vol. 16, pp. S73–S92, 2012.

[40] Carnegie Mellon University Green Design Institute, “Economic input-output life cycle assessment (eio-lca),” http://www.eiolca.net, 2008, "Accessed 1 January, 2008". [Online]. Available: http://www.eiolca.net

[41] T. Norgate, N. Haque, and P. Koltun, “The impact of uranium ore grade on the greenhouse gas footprint of nuclear power,” *Journal of Cleaner Production*, vol. 84, pp. 360–367, 2014.

[42] S. W. White and G. L. Kulcinski, “Birth to death analysis of the energy payback ratio and co2 gas emission rates from coal, fission, wind, and dt-fusion electrical power plants,” *Fusion Engineering and Design*, 2000.

[43] A. Makhijani, “Light water designs of small modular reactors: Facts and analysis,” Institute for Energy and Environmental Research, Report, 2013.

[44] A. Y. Abdulla, "Exploring the deployment potential of small modular reactors," Thesis, 2014.

[45] J. A. Brown, "Comparison of 4-loop, ap100, smr equilibrium cycle fuel requirements, personal communication 5/10/2016," p. 1, 2016.

[46] N. Tsoulfanidis, *The Nuclear Fuel Cycle.* American Nuclear Society, 2013.

[47] Nuclear Energy Institute, "Us nuclear capacity factors," 2015. [Online]. Available: http://www.nei.org/Knowledge-Center/Nuclear-Statistics/US-Nuclear-Power-Plants/US-Nuclear-Capacity-Factors

[48] J. S. Miller, B. Stakenborghs, and R. Tsai, "Improving nuclear power plant's operational efficiences in the usa," 2012.

[49] World Nuclear Association, "World uranium mining production," Dec. 2014. [Online]. Available: http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Mining-of-Uranium/World-Uranium-Mining-Production/

[50] G. M. Mudd and M. Diesendorf, "Sustainability of uranium mining and milling: Toward quantifying resources and eco-efficiency," *Environmental Science & Technology*, vol. 42, no. 7, pp. 2624–2630, 2008. [Online]. Available: http://dx.doi.org/10.1021/es702249vhttp://pubs.acs.org/doi/pdfplus/10.1021/es702249v

[51] J.-A. Nilsson and J. Randhem, "Environmental impacts and health aspects in the mining industry-a comparative study of the mining and extraction of uranium, copper and gold," Thesis, 2008.

[52] World Nuclear Association, "Uranium mining overview," Nov. 2012. [Online]. Available: http://www.world-nuclear.org/info/nuclear-fuel-cycle/mining-of-uranium/uranium-mining-overview/

[53] U.S. Environmental Protection Agency, "egrid 9th edition version 1.0 year 2010 summary tables," Enviornmental Protection Agency, Report, 2014.

[54] T. L. Schulz, "Westinghouse ap1000 advanced passive plant," *Nuclear Engineering and Design*, vol. 236, no. 14-6, pp. 1547–1557, 2006, 062JZ Times Cited:58 Cited References Count:7. [Online]. Available: <GotoISI>://WOS:000238941700013

[55] P. Peterson, H. Zhao, and R. Petroski, "Metal and concrete inputs for several nuclear power plants," University of California Berkeley, Report UCBTH-05-001, 2005. [Online]. Available: http://fhr.nuc.berkeley.edu/wp-content/uploads/2014/10/05-001-A_Material_input.pdf

[56] J. Quale, M. J. Eckelman, K. W. Williams, G. Sloditskie, and J. B. Zimmerman, "Construction matters: Comparing environmental impacts of building modular and conventional homes in the united states," *Journal of Industrial Ecology*, vol. 16, no. 2, pp. 243–253, 2012.

[57] E. Chapman, J. Rishel, J. Niemeyer, K. Cort, and S. Gulley, "Assumptions, calculations, and recommendations related to a proposed guidance update on greenhouse gases and climate change," Pacific Northwest National Laboratory, Report, 2012.

[58] Nuclear Engineering International, "Digital switch," May 2012. [Online]. Available: http://www.neimagazine.com/features/featuredigital-switch/

[59] V. M. Fthenakis and H. C. Kim, "Greenhouse-gas emissions from solar electric- and nuclear power: A life-cycle study," *Energy Policy*, vol. 35, no. 4, pp. 2549–2557, 2007.

[60] Nuclear Regulatory Commission, "50.54 conditions of licenses," Dec. 2014. [Online]. Available: http://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0054.html

[61] M. Seier and T. Zimmermann, "Environmental impacts of decommissioning nuclear power plants: methodical challenges, case study, and implications," *The International Journal of Life Cycle Assessment*, vol. 19, no. 12, pp. 1919–1932, 2014.

[62] World Nuclear Association, "Small nuclear power reactors," Dec. 2014. [Online]. Available: http://www.world-nuclear.org/info/nuclear-fuel-cycle/power-reactors/small-nuclear-power-reactors

[63] H. S. Matthews, C. Hendrickson, and D. H. Matthews, *Life Cycle Assessment: Quantitative Approaches for Decisions That Matter*, 2015. [Online]. Available: http://www.lcatextbook.com

[64] T. F. Stacy and G. S. Taylor, "The levelized cost of electricity from existing generation resources," Institute for Energy Research, Report, June 2015 2015. [Online]. Available: http://instituteforenergyresearch.org/wp-content/uploads/2015/06/ier_lcoe_2015.pdf

[65] Intergovernmental Panel on Climate Change, *Special Report on Renewable Energy Sources and Climate Change Mitigation*. United Kingdom and New York, NY, USA: Cambridge University Press, 2011.

[66] U.S. Energy Information Administration, "Market trends: Emissions concerns about future ghg policies affect builds of new coal-fired generating capacity," Jun. 2014. [Online]. Available: http://www.eia.gov/forecasts/archive/aeo14/MT_emissions.cfm#ghg_coalfired

[67] U.S. Environmental Protection Agency, "The social cost of carbon," Feb. 2015. [Online]. Available: http://www3.epa.gov/climatechange/EPAactivities/economics/scc.html

[68] U.S. Energy Information Administration, “Table 1.1. net generation by energy source: Total (all sectors), 2006-june 2016,” 2016. [Online]. Available: http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_1_01

[69] U.S. Environmental Protection Agency, “Effects of acid rain,” Aug. 2016. [Online]. Available: https://www.epa.gov/acidrain/effects-acid-rain

[70] US News & World Report, “Nuclear plants leak radiation, and regulator faces scrutiny,” Aug. 2016. [Online]. Available: http://www.usnews.com/news/articles/2016-03-15/nuclear-plants-leak-radiation-and-regulator-faces-scrutiny

[71] L. W. Davis, “The effect of power plants on local housing values and rents,” *Review of Economics and Statistics*, vol. 93, no. 4, pp. 1391–1402, 2011.

[72] R. H. Bezdek and R. M. Wendling, “The impacts of nuclear facilities on property values and other factors in the surrounding communities,” *International Journal of Nuclear Governance, Economy and Ecology*, vol. 1, no. 1, pp. 122–144, 2005.

[73] J. P. Nelson, “Three mile island and residential property values: Empirical analysis and policy implications,” *Land Economics*, vol. 57, no. 3, pp. 363–372, 1981.

[74] H. B. Gamble and R. H. Downing, “Effects of nuclear power plants on residential property values,” *Journal of Regional Science*, vol. 22, no. 4, pp. 457–478, 1982.

[75] G. C. Galster, “Nuclear power plants and residential property values: A comment on short–run vs. long–run considerations,” *Journal of Regional Science*, vol. 26, no. 4, pp. 803–805, 1986.

[76] R. D. Bullard, *Dumping in Dixie: Race, class, and environmental quality.* Westview Press, 2008.

[77] M. Pastor, J. L. Sadd, and R. Morello-Frosch, “Waiting to inhale: the demographics of toxic air release facilities in 21st century california,” *Social Science Quarterly*, vol. 85, no. 2, pp. 420–440, 2004.

[78] P. Mohai, P. M. Lantz, J. Morenoff, J. S. House, and R. P. Mero, “Racial and socioeconomic disparities in residential proximity to polluting industrial facilities: evidence from the americans’ changing lives study,” *American Journal of Public Health*, vol. 99, no. S3, pp. S649–S656, 2009.

[79] US Census Bureau, “Usa counties data file downloads,” Jun. 2017. [Online]. Available: https://www.census.gov/support/USACdataDownloads.html

[80] US Census Bureau, “Census 1970, census 1980, census 1990, census 2000,” Jun. 2017. [Online]. Available: https://www.socialexplorer.com/explore/tables

[81] US Census Bureau, “Tiger/line with selected demographic and economic data, 2007 - 2011 block group data,” Jun. 2016. [Online]. Available: https://www.census.gov/geo/maps-data/data/tiger-data.html

[82] S. Olsen, “Essays on water and energy economics,” Thesis, 2014. [Online]. Available: https://digital.lib.washington.edu/researchworks/handle/1773/26372

[83] National Association for Realtors, “Homes near nuclear plants face new challenges,” Feb. 2011. [Online]. Available: https://www.nar.realtor/RMODaily.nsf/pages/News2011032302?OpenDocument

[84] P. Mohai and R. Saha, “Which came first, people or pollution? assessing the disparate siting and post-siting demographic change hypotheses of environmental injustice,” *Environmental Research Letters*, vol. 10, no. 11, p. 115008, 2015.

[85] D. C. Rode, P. S. Fischbeck, and A. R. Páez, “The retirement cliff: Power plant lives and their policy implications,” *Energy Policy*, vol. 106, pp. 222–232, 2017.

[86] S. Gossard, “Coal-to-gas plant conversions in the u.s.” Feb. 2015. [Online]. Available: http://www.power-eng.com/articles/print/volume-119/issue-6/features/coal-to-gas-plant-conversions-in-the-u-s.html

[87] L. W. Davis, “Evidence of a decline in electricity use by us households,” *Economics Bulletin*, vol. 37, no. 2, pp. 1098–1105, 2017.

[88] S. Mufson, “Georgia regulatory staff calls the last u.s. nuclear construction project uneconomic,” Dec. 2017, "Accessed 4/13/2018". [Online]. Available: https://www.washingtonpost.com/business/economy/georgia-regulatory-staff-calls-the-last-us-nuclear-construction-project-uneconomic/2017/12/05/84086788-d9d4-11e7-b1a8-62589434a581_story.html?utm_term=.2546ea0e2167

[89] S. Mufson, “S.c. utilities halt work on new nuclear reactors, dimming the prospects for a nuclear energy revival,” Jul. 2017, "Accessed 4/13/2018". [Online]. Available: https://www.washingtonpost.com/business/economy/sc-utilities-halt-work-on-new-nuclear-reactors-dimming-the-prospects-for-a-nuclear-energy-revival/2017/07/31/5c8ec4a0-7614-11e7-8f39-eeb7d3a2d304_story.html?utm_term=.1bd8d613ede6

[90] M. Ramana, L. B. Hopkins, and A. Glaser, “Licensing small modular reactors,” *Energy*, vol. 61, pp. 555–564, 2013.

[91] Nuclear Regulatory Commission, “Rulemaking for emergency preparedness for small modular reactors and other new technologies - srm-secy-16-0069,” 2017. [Online]. Available: https://adamswebsearch2.nrc.gov/wba/view

[92] Nuclear Energy Institute, “Industry proposes ep framework for small modular reactors,” Jun. 2014, https://www.nei.org/News-Media/News/News-Archives/Industry-Proposes-EP-Framework-for-Small-Modular-R. [Online]. Available: https://www.nei.org/News-Media/News/News-Archives/Industry-Proposes-EP-Framework-for-Small-Modular-R

[93] G. Rochau, F. Gelbard, and T. Lewis, “Advanced nuclear technology: Integrated pressurized water reactor (ipwr) containment aerosol deposition behavior phase 1 - test plan development,” Sandia National Laboratories, Report, 2014. [Online]. Available: https://www.epri.com/#/pages/product/000000003002004218/

[94] Electric Power Research Institute, “Advanced nuclear technology: Integrated pressurized water reactor (ipwr) containment aerosol deposition behavior - phase 2a: Technical basis and test plan for experimental testing and computational fluid dynamics analysis,” Electric Power Research Institute, Report, 2018. [Online]. Available: https://www.epri.com/#/pages/summary/000000003002010491/

[95] Nuclear Regulatory Commission, “Emergency planning zones,” 2014, https://www.nrc.gov/about-nrc/emerg-preparedness/about-emerg-preparedness/planning-zones.html. [Online]. Available: https://www.nrc.gov/about-nrc/emerg-preparedness/about-emerg-preparedness/planning-zones.html

[96] Nuclear Regulatory Commission, “50.47 emergency plans,” Aug. 2017. [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0047.html

[97] H. E. Collins, B. K. Grimes, and F. Galpin, “Planning basis for the development of state and local government radiological emergency response plans in support of light water nuclear power plants,” Nuclear Regulatory Commission, Washington, DC (USA). Office of Nuclear Reactor Regulation; Environmental Protection Agency, Washington, DC (USA). Office of Radiation Programs, Tech. Rep., 1978.

[98] W. L. Moe, “Opportunities in smr emergency planning,” Advanced Reactor Technologies Program, Idaho National Lab. (INL), Idaho Falls, ID (United States), Report INL/EXT–14-33137 United States 10.2172/1168629 INL English, 2014. [Online]. Available: http://www.osti.gov/scitech/servlets/purl/1168629

[99] A. Abdulla, I. L. Azevedo, and M. G. Morgan, “Expert assessments of the cost of light water small modular reactors,” *Proceedings of the National Academy of sciences*, vol. 110, no. 24, pp. 9686–9691, 2013. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3683777/pdf/pnas.201300195.pdf

[100] G. Rothwell and F. Ganda, “Electricity generating portfolios with small modular reactors,” Tech. Rep., 2014. [Online]. Available: https://www.energy.gov/sites/prod/files/2014/06/f16/Electricity%20Generating%20Portfolios%20with%20SMRs.pdf

[101] B. K. Sovacool and M. Ramana, “Back to the future: Small modular reactors, nuclear fantasies, and symbolic convergence,” *Science, Technology, & Human Values*, vol. 40, no. 1, pp. 96–125, 2015.

[102] J. Vujić, R. M. Bergmann, R. Škoda, and M. Miletić, “Small modular reactors: Simpler, safer, cheaper?” *Energy*, vol. 45, no. 1, pp. 288–295, 2012.

[103] G. Locatelli, C. Bingham, and M. Mancini, “Small modular reactors: A comprehensive overview of their economics and strategic aspects,” *Progress in Nuclear Energy*, vol. 73, pp. 75–85, 2014.

[104] Nuclear Regulatory Commission, “Development of an emergency planning and preparedness framework for small modular reactors,” Nuclear Regulatory Commission, Report, 2011.

[105] Nuclear Energy Institute, “White paper on proposed methodology and criteria for establishing the technical basis for small modular reactor emergency planning zone,” Nuclear Energy Institute, Report, 2013.

[106] Nuclear Regulatory Commission, “Regulatory guide 1.183 - alternative radiological source terms for evaluating design basis accidents at nuclear power reactors,” 2000. [Online]. Available: https://www.nrc.gov/docs/ML0037/ML003716792.pdf

[107] D. Powers, K. Washington, J. Sprung, and S. Burson, “A simplified model of aerosol removal by natural processes in reactor containments,” Nuclear Regulatory Commission, Washington, DC (United States). Div. of Systems Technology; Sandia National Labs., Albuquerque, NM (United States), Tech. Rep., 1996.

[108] Electric Power Research Institute, “Advanced nuclear technology: Integrated pressurized water reactor (ipwr) containment aerosol deposition behavior - phase 2b: Experimental data and simulated results for ipwr containment aerosol decontamination technical report,” Electric Power Research Institute, Report, 2018. [Online]. Available: https://www.epri.com/#/pages/summary/000000003002010491/

[109] Nuclear Regulatory Commission, “Emergency preparedness rulemaking with regard to small modular reactors and other new technologies (rin: 3150-aj68; nrc docket id: Nrc-2015-0225),” Nov. 2017, "Accessed 4/12/2018". [Online]. Available: https://www.nrc.gov/reactors/new-reactors/regs-guides-comm/ep-smr-other.html

[110] Nuclear Regulatory Commission, "Reactor safety study. an assessment of accident risks in us commercial nuclear power plants. appendices iii and iv nureg-75/014 (wash-1400)," Nuclear Regulatory Commission, Tech. Rep., 1975.

[111] J. Ramsdell, G. Athey, and J. Rishel, *RASCAL 4: Description of models and methods.* United States Nuclear Regulatory Commission, Office of Nuclear Security and Incident Response, 2012.

[112] L. Soffer, S. Burson, C. Ferrell, R. Lee, and J. Ridgely, "Accident source terms for light-water nuclear power plants. final report," Nuclear Regulatory Commission, Washington, DC (United States). Div. of Systems Technology, Tech. Rep., 1995.

[113] Westinghouse Electric Company, LLC, "Ap1000 design control document rev. 19 - accident analyses - appendix 15b - removal of airborne activity from the containment atmosphere following a loca," Westinghouse Electric Company, Report, 2011.

[114] W. Snell and R. Jubach, *Technical Basis for Regulatory Guide 1.145," Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants".* Division of Health, Siting and Waste Management, Office of Nuclear Regulatory Research, US Nuclear Regulatory Research, 1981.

[115] S. K. Friedlander, *Smoke, Dust, and Haze*, 2nd ed. Oxford, 2000.

[116] R. Biwalker and S. Singh, "Cfd simulations to predict aerosol deposition losses to walls of smr containment vessels," 2017.

[117] International Atomic Energy Agency, "Advances in small modular reactor technology developments," 2016.

[118] Y. Zhao, L. Zhang, and J. Tong, "Development of rapid atmospheric source term estimation system for ap1000 nuclear power plant," *Progress in Nuclear Energy*, vol. 81, pp. 264–275, 2015.

[119] X. Sun, X. Cao, X. Shi, and J. Yan, "Comparative study on aerosol removal by natural processes in containment in severe accident for ap1000 reactor," *Annals of Nuclear Energy*, vol. 99, pp. 216–226, 2017.

[120] G.-S. Choi, J.-M. Lim, K.-S. S. Lim, K.-H. Kim, and J.-H. Lee, "Characteristics of regional scale atmospheric dispersion around ki-jang research reactor using the lagrangian gaussian puff dispersion model," *Nuclear Engineering and Technology*, 2017.

[121] E. Lutman, S. Jones, R. Hill, P. McDonald, and B. Lambers, "Comparison between the predictions of a gaussian plume model and a lagrangian particle dispersion model for annual average calculations of long-range dispersion of radionuclides," *Journal of environmental radioactivity*, vol. 75, no. 3, pp. 339–355, 2004.

[122] S. A. McGuire, "A regulatory analysis on emergency preparedness for fuel cycle and other radioactive material licensees nureg-1140," Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Division of Reactor Accident Analysis, Washington, DC 20555, Tech. Rep., Jan. 1988.

[123] Westinghouse Electric Company, LLC, "Ap1000 design control document rev. 19 - accident analyses - appendix 15a - evaluation models and parameters for analysis of radiological consequences of accidents," Westinghouse Electric Company, Report.

[124] K. F. Eckerman, A. B. Wolbarst, and A. C. Richardson, "Limiting values of radionuclide intake and air concentration and dose conversion factors for inhalation, submersion, and ingestion: Federal guidance report no. 11," Environmental Protection Agency, Washington, DC (USA). Office of Radiation Programs; Oak Ridge National Lab., TN (USA), Tech. Rep., 1988.

[125] Nuclear Regulatory Commission, "State-of-the-art reactor consequence analyses project; volume 1: Peach bottom integrated analysis, volume 2: Surry integrated analysis - nureg/cr-7110, vol. 2, rev. 1," Nuclear Regulatory Commission, Tech. Rep., 2012.

[126] U.S. Energy Information Administration, "Electric power annual 2015," U.S. Energy Information Administration, Tech. Rep., Nov. 2016.

[127] U.S. Energy Information Administration, "The u.s. relies on foreign uranium, enrichment services to fuel its nuclear power plants," Dec. 2013. [Online]. Available: http://www.eia.gov/todayinenergy/detail.cfm?id=12731

[128] Nuclear Energy Institute, "Us nuclear refueling outage days," Dec. 2014. [Online]. Available: http://www.nei.org/Knowledge-Center/Nuclear-Statistics/US-Nuclear-Power-Plants/US-Nuclear-Refueling-Outage-Days

[129] T. Norgate, N. Haque, P. Koltun, and A. Tharumarajah, "Life cycle assessment of the uranium nuclear power cycle: Part 1 once-through cycle with current technologies," Tech. Rep., 2010.

[130] World Nuclear Association, "Uranium enrichment," Oct. 2014. [Online]. Available: http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Uranium-Enrichment/

[131] Westinghouse Electric Company, LLC, "Ap1000 design control document: Design of structures, components, equipment and systems rev. 14," Government Document December 29, Dec. 2008. [Online]. Available: http://www.nrc.gov/reactors/new-reactors/design-cert/ap1000/dcd/Tier%202/Chapter%203/3-8_r14.pdf

[132] T. Meneely, "Ap1000 design overview," 2009. [Online]. Available: http://www.atomeromu.hu/download/1676/AP%201000%20reaktor.pdf

[133] General Atomics, "Gas turbine-modular helium reactor conceptual design description report rev. 1," 1996. [Online]. Available: http://pbadupws.nrc.gov/docs/ML0224/ML022470282.pdf

[134] Office for Nuclear Regulation, "Generic design assessment – new civil reactor build step 4 civil engineering and external hazards assessment of the westinghouse ap1000® reactor," 2011. [Online]. Available: http://www.onr.org.uk/new-reactors/reports/step-four/technical-assessment/ap1000-ceeh-onr-gda-ar-11-002-r-rev-0.pdf

[135] Westinghouse Electric Company, LLC, "The westinghouse ap1000 advanced nuclear plant," Dec. 2003. [Online]. Available: http://www.apcnean.org.ar/arch/3e139fc91ebe2e675db2194460badc7c.pdf

[136] Westinghouse Electric Company, LLC, "Ap1000 design control document: Design of structures, components, equipment and systems rev. 19," Government Document, 2011. [Online]. Available: http://pbadupws.nrc.gov/docs/ML1117/ML11171A430.pdf

[137] R. Bowser, "Nuclear power a journey of continuous improvement," 2013. [Online]. Available: https://engineering.tamu.edu/media/948603/bowser_ppt.pdf

[138] Nuclear Regulatory Commission, "Backgrounder on decommissioning nuclear power plants," Dec. 2014. [Online]. Available: http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/decommissioning.html

[139] J. C. Subiry, "The evolution to ultra-high capacity dry storage casks an update on magnastor® technology," in *IAEA Meeting TM-45455*. NAC International, 2013, Conference Proceedings. [Online]. Available: https://www.iaea.org/OurWork/ST/NE/NEFW/Technical-Areas/NFC/documents/spent-fuel/TM-45455/Agenda-24-USA-Evolution_to_ultra-high_capacity_spent_fuel_storage_systems.pdf

[140] Nuclear Regulatory Commission, "Dry spent fuel storage designs: Nrc approved for general use," Feb. 2015. [Online]. Available: http://www.nrc.gov/waste/spent-fuel-storage/designs.html

[141] J. Currie, L. Davis, M. Greenstone, and R. Walker, “Environmental health risks and housing values: evidence from 1,600 toxic plant openings and closings,” *The American economic review*, vol. 105, no. 2, pp. 678–709, 2015. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4847734/pdf/nihms766662.pdf