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Methods and System for Siting Advanced Nuclear Reactors and Evaluating Energy Policy Concerns

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Abstract

There is a growing sociopolitical desire to develop cleaner energy sources in the United States and maintain energy security. Regardless of politics, many coal-fired electric plants have already been shut down and many utilities are vowing to retire their current coal-fired assets within the next two decades. Replacement power assets require consideration of appropriate siting. A geographic information system (GIS)-based multicriteria decision analysis approach is useful to assist utility and energy companies, as well as policymakers, to evaluate potential areas for siting new plants in the contiguous United States. A GIS-based framework is simply a database of location information that allows for mapping, querying, modeling, and analyzing data based on location. The spatial output can be structured to be visual, allowing for easier analysis of location data. The need to site additional power assets, including renewable resources and clean power sources, such as nuclear, led to the development of the Oak Ridge Siting Analysis for power Generation Expansion (OR-SAGE) tool discussed in this paper. The tool takes inputs such as population growth, water availability, environmental indicators, and tectonic and geological hazards to provide an in-depth visual analysis for siting options. Energy companies and other stakeholders can use OR-SAGE to procure feedback quickly and effectively on land suitability based on technology specific inputs. Policymakers can use OR-SAGE to analyze the impacts of future energy technology decisions, while balancing competing resource use. This paper discusses the recent use of OR-SAGE for these purposes and plans for future development.

Keywords: OR-SAGE, clean energy, siting, advanced reactors, GIS

1. Introduction

Most states require utilities to file integrated resource plans (IRPs) that detail how the utility is planning for new technology, aging infrastructure, the integration of distributed energy sources, the integration of renewable and clean energy sources, energy efficiency, and evolving environmental regulations. IRPs keep rate payers, investors, politicians, policy makers, environmentalists, and others informed of the near-term and long-term planning for generation and distribution of electricity to meet anticipated demand. Current utility IRPs indicate a move away from coal-fired electricity generation and a move toward cleaner technology (EIA, 2020a, 2020b). Many utilities are proposing to retire all coal-fired electricity generation in the next 15 years (Gearino, 2020).

At the same time, the U.S. Department of Energy (DOE) Energy Information Administration (EIA) projects that the total U.S. energy consumption will return to 2019 levels between 2029 and 2050, depending on the pace of post-COVID economic recovery (EIA, 2021). Therefore, in the near-term, new generation development will primarily be replacement power for those assets being retired per utility IRPs. This projection could be impacted by acceleration in the electrification of the transportation sector as proposed by the current administration's overall infrastructure proposal. In 2019, approximately 28% of all energy consumption in the US was required for transportation of goods and people (EIA, 2020c). Therefore, if a portion of transportation energy is transferred to the electricity sector, the demand for new generation could be increased further.

President Biden recently advocated for a 50% reduction in U.S. greenhouse gas emissions by 2030, which represents a 100% increase over the prior commitment under the 2015 Paris climate agreement. Regardless of the political debate on climate, there is bipartisan support for nuclear energy to be part of new clean energy supplies, including small modular reactors (SMRs) and advanced non-light-water reactors (non-LWRs). A key aspect of the expanded use of nuclear energy is power plant siting, including optimized siting of all aspects of the nuclear fuel cycle. The nuclear fuel cycle includes mining, milling, enrichment, and fuel production on the "front end" of the cycle prior to fuel use in a reactor. Subsequently, the fuel cycle includes cooling, onsite storage, and recycling or long-term storage in a surface facility or a geologic repository on the "back end" of the cycle after fuel use in a reactor. A geographic information system (GIS) based tool (Belles et al., 2012) called Oak Ridge Siting Analysis for power Generation Expansion (OR-SAGE) has been developed by Oak Ridge National Laboratory (ORNL) to inform owners, vendors, policymakers, regulators, and other stakeholders on nuclear fuel cycle siting issues, site availability, capacity availability, fuel cycle optimization, transport optimization, coal-fired plant backfits, and other matters. This paper discusses the flexible use of OR-SAGE for these purposes concluding in the development of a siting simulator.

The remainder of this paper is organized as follows. Section 2 presents some background information about OR-SAGE. Section 3 discusses the methodology used in OR-SAGE. Section 4 presents some of the applications of OR-SAGE for siting and policy analysis that led to initial development of a fuel cycle simulator tool. Section 5 discusses the simulator tool, and Section 6 presents some discussion points and a conclusion.

2. Background

Several years ago, the U.S. DOE Office of Nuclear Energy (DOE-NE) tasked ORNL to support evaluation of select sites for new SMR and advanced non-LWR power plants using the GIS based tool that ORNL had developed (Belles et al., 2012) for a broad range of power plant siting. The resulting OR-SAGE tool provides a flexible system to evaluate power plant siting options and considerations for a variety of power sources (Rodwell, 2002). The OR-SAGE tool is designed to provide insight on siting issues such as amenable locations, regional capacity, and population density.

While OR-SAGE does not replace the required detailed evaluation of candidate nuclear power plant sites, the tool is designed to use industry-accepted practices, based largely on the 2002 Electric Power Research Institute (EPRI) Siting Guide (Omitaomu et al., 2012) methodology, to screen regions and sites for nuclear power plant (NPP) siting opportunities. The tool employs an array of data sources through the considerable computational capabilities of GIS technology available at ORNL. The screening process divides the contiguous United States into 100 m x 100 m (1-hectare or ~2.5 acre) cells, applying successive exclusionary, avoidance, and suitability parameters from over 40 datasets (see Section 3 for detailed information about these datasets) to each of the 700 million individual land cells in the database.

Appropriate layered selection queries are generally associated with each siting criterion, including the application of recommended buffer zones. The result of any given set of query values is a static visual output reflecting the relational values stored in the database. Key parameters include population density, geologic considerations, water resources and limitations, proximity to hazards, and others.

Work on building the OR-SAGE tool began in 2008 and is ongoing. OR-SAGE has been used for a variety of applications, including an evaluation of the potential backfit of SMRs at coal-fired power plant sites (Belles et al., 2013); consideration for deep borehole disposal of spent nuclear fuel (Belles and Omitaomu, 2015); an evaluation of potential locations for siting SMRs near federal energy clusters to support federal clean energy goals (Belles and Omitaomu, 2014); input to the formation of the US Nuclear Regulatory Commission (NRC) advanced reactor siting policy (Belles et al., 2019); evaluation of fuel cycle sites; evaluation of cancelled reactor sites; development of a methodology to evaluate advanced nuclear reactor fleet and associated fuel cycle facilities given constraints over siting locations, material availability, and material movements; interface with University of Michigan Fastest Path to Zero project to provide reactor siting information integrated with socio-political factors; and support of the National Reactor Innovation Center (NRIC) to assess and propose demonstration reactor site ranking factors (Bucknor et al., 2021).

The DOE-NE SA&I campaign took notice of the various applications of OR-SAGE. Discussions on future analyses on the nuclear fuel cycle made it clear that OR-SAGE could play a role. The campaign subsequently funded the development of a fuel cycle simulator based on OR-SAGE.

3. Methodology

This section, first, describes the OR-SAGE methodology. Next, it discusses the regulatory guidelines that informed the data selection process as well as the individual datasets used for the modeling.

3.1. OR-SAGE Methodology

The basic OR-SAGE methodology and the potential for nuclear siting capacity is well documented (Belles et al., 2012; Omitaomu et al., 2012). The methodology is briefly summarized in this section.

Specifically, OR-SAGE uses a map algebra approach. This approach divides the contiguous U.S.A. into 100 m x 100 m grids for a total of 700 million cells. With K different types of siting criteria, a binary variable x_{ij}^{k} is defined for each cell, where x_{ij}^{k} equal 0 when siting criteria *k* for cell (*i,j*) satisfied the criteria threshold. Otherwise, x_{ij}^{k} equals 1. Therefore, the generation of suitable areas using map algebra formulation can be expressed as follows:

$$min\left\{z_{ij} = \sum_{k=1}^{K} x_{ij}^{k}\right\}$$

where $x_{ij}^{k} \in \{0,1\}, \forall k = 1,\ldots,K; i = 1,\ldots,N; j = 1,\ldots,M.$ Table 1 summarizes the threshold for each k^{th} factor for two technology options; that is, AP1000, developed by Westinghouse, as an example of a water-cooled technology (Oriani, 2018) and Xe-100, developed by X-energy, LLC., as an example of a helium cooled technology (IAEA, 2020).

Finally, z_{ij} is further classified as follows:

$$\begin{cases} if\ z_{ij} = 0 \xrightarrow{yields} \text{land area suitable for siting a reactor for } t \text{ technology option} \\ if\ z_{ij} > 0 \xrightarrow{yields} \text{land area not suitable for siting a reactor for } t \text{ technology option} \end{cases}$$

If $z_{ij} = 1$, one siting criterion is not satisfied. Similarly, $z_{ij} = 2$, two siting criteria are not satisfied, and so on. Section 3.2 describes how the siting criteria for the two technologies listed in Table 1 are selected.

Table 1: Summary of Criteria for Identifying Suitable Land Area

k	**Criteria Description**	**Condition for Cells Elimination**	
		AP1000	**Xe-100**
1	Population Density (PD)	PD ≥ 500 people per square mile within 20 miles	PD ≥ 500 people per square mile within 4 miles
2	Protected Land (PL)	Classified as a PL	Classified as a PL
3	Safe Shutdown Earthquake (SSE)	SSE > 0.3g	SSE > 0.5g
4	Landslide Hazard (LH)	Moderate or high LH	Moderate or high LH
5	Fault Lines (FL)	Close to FL	Close to FL
6	Hazardous Operations (HO)	Close to HO	Close to HO*
7	100-year Floodplain region (FPR)	In FPR	In FPR
8	Wetlands or Open water (WLOW)	Classified as WLOW	Classified as WLOW
9	Slope	Slope > 12%	Slope > 18%
10	Streamflow (SF)	SF ≤ 135,000 gallons per minute	Not Applicable
*HO may be classified differently for small, advanced reactors			

3.2. Choosing Datasets for the Siting Criteria

The NRC provides regulations for nuclear plant siting in 10 CFR 100 and provides well defined regulatory guidance for siting a nuclear power plant in Regulatory Guide (RG) 4.7 (NRC, 2014).

Review of RG 4.7 and the EPRI siting guide (Rodwell, 2002) led to selecting OR-SAGE nuclear power plant siting parameters that use readily available data, provide a high level of discrimination between sites, and offer a reasonable set of bounding criteria. A summary of the 40 datasets is presented in Table 2.

Table 2. Summary of OR-SAGE Datasets

S/N	Data Categories	Data Sub-categories
1.	Population	Current/Projected population
2.	Protected Areas	National parks, monuments, forests, and wilderness areas
		National, state, and local parks
		Wild and scenic rivers
		Wildlife refuges
		American Indian reservations
		Hospitals
		Correctional facilities
		Schools/Colleges
3.	Proximity to Hazardous Facilities	Major Airports
		Military Sites
		Chemical Facilities (up to 6 different plant types)
		Energy Facilities (up to 14 different plant types)
4.	Seismic Hazards	2% chance in 50 year return period
5.	Wetlands	Open-water or wetland areas
6.	Slope	Higher slope
7.	100-year Floodplain	Flood risk
8.	Landslide Hazard	Areas susceptible to moderate to high incidence
9.	Streamflow	Source of cooling water
10.	Fault Lines	Fault risk

3.2.1. Population Density

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

Since radiation dose is technology specific and closely held data, the NRC has established siting guidance in RG 4.7 which recommends an evaluation of population density of 500 people per square mile (ppsm) out to 20 miles from the site and to consider population density for 5 years following commissioning. OR-SAGE uses technology site footprint surrogates and an algorithm to calculate the population density in and around each database cell in successive 1-mile ring calculations. One way that the OR-SAGE evaluation has been adjusted to address smaller reactor technologies is to reduce the population cap calculation from 20 miles to a smaller value. This is in line with recent staff recommendations on alternative siting guidance for advanced non-LWRs in SECY 20-0045 (NRC, 2020).

Population densities of greater than 500 people per square mile begin to transition into an urban setting. One of the advantages of small modular reactors and advanced reactor technologies is the ability to replace smaller, aging electric plants located closer to population centers. Arguments for allowing SMRs to be closer to population centers typically include a reduced core damage frequency, elimination of large-break loss-of-coolant accident sequences, smaller source term, reduced early release fraction, reactor vessels and containment vessels that are located entirely underwater or below grade, and reactor buildings that are located partially or totally below grade.

3.2.2. Geologic Considerations

There are a few geologic considerations that must be considered for nuclear power plant siting. Parameters that are easily evaluated on a national basis include seismic restrictions, proximity to fault lines, steep slopes, and landslide risk.

The safe shutdown earthquake peak ground acceleration (2% chance in a 50-year return period) greater than a selected threshold parameter value is flagged by OR-SAGE. EPRI siting guidance recommends limiting large LWR technologies to less than 0.3 g safe shutdown earthquake peak ground acceleration. As small modular reactors and advanced reactor technologies allow for more seismic mitigation through design, the OR-SAGE threshold parameter for seismic activity has been set slightly higher at 0.5 g safe shutdown earthquake peak ground acceleration.

Land too close to any identified fault lines is flagged by the OR-SAGE tool. Table 1 in Appendix A of 10 CFR 100 provides a relationship between fault length and a standoff distance from the reactor site.

Steeper slopes are avoided based on the economic cost of preparing the site for construction. The 2002 EPRI siting guidance recommended limiting the slope to 12% for large reactor sites. Since small modular reactors and advanced reactor technologies tend to have smaller footprints compared to current large reactors, this value is relaxed to 18% as the baseline threshold value for advanced non-LWRs.

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

3.2.3. Water Considerations

Current large LWRs rely on cooling water for heat rejection. Therefore, plants that rely on makeup cooling water will need to be in proximity to a water source. For technologies that do not require water as the ultimate heat sink, the cooling water layer is pulled from the analysis.

Cells in the OR-SAGE model that are evaluated to fall within wetlands and open water are flagged and excluded. Likewise, cells that are evaluated to fall within an identified 100-year floodplain are flagged and excluded.

3.2.4. Other Considerations

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

Protected lands include national parks, national monuments, national forests, wilderness areas, wildlife refuges, wild and scenic rivers, state parks, county parks, American Indian lands, Bureau of Land Management, hospitals, colleges, schools, and correctional facilities.

Land in the vicinity of facilities that could pose a hazard to the safe operation of a reactor include commercial airports and military bases. In addition, missile, fire, and toxic gas hazards from certain energy and chemical industrial sites are flagged for further risk evaluation.

4. OR-SAGE Applications for Energy Security and Policy Initiating Simulator Development

This section presents some of the applications of OR-SAGE to support the analysis of coal-fired plants replacement, clean energy goals, and evaluating energy policies. Combining some of these unique OR-SAGE applications led to the development of a simulator for reactor placement to meet regional energy demand while optimizing reactor siting.

4.1. Siting Advanced Reactors at Former Coal-Fired Plant Sites

According to the EIA, in 2010, 31% of the total existing generating capacity in the US was available from coal. By 2020, just 20% of the total existing generating capacity in the US was available from coal. In late 2011, the Environmental Protection Agency (EPA) finalized the Mercury and Air Toxics Standards rule requiring maximum achievable control technology be applied to all power plants with capacities greater than 25 MW(e) to control emissions of mercury and other toxics. Since 2012, many utilities are opting to retire older, smaller coal-fired power plants rather than install relatively expensive emissions control equipment. Regardless of changing politics, these retirements will continue (EIA, 2020a, 2020b, Gearino, 2020) based on a combination of economics, clean energy goals, and environmental justice. This has piqued interest in replacing these small coal-fired plants with cleaner electrical power from SMRs.

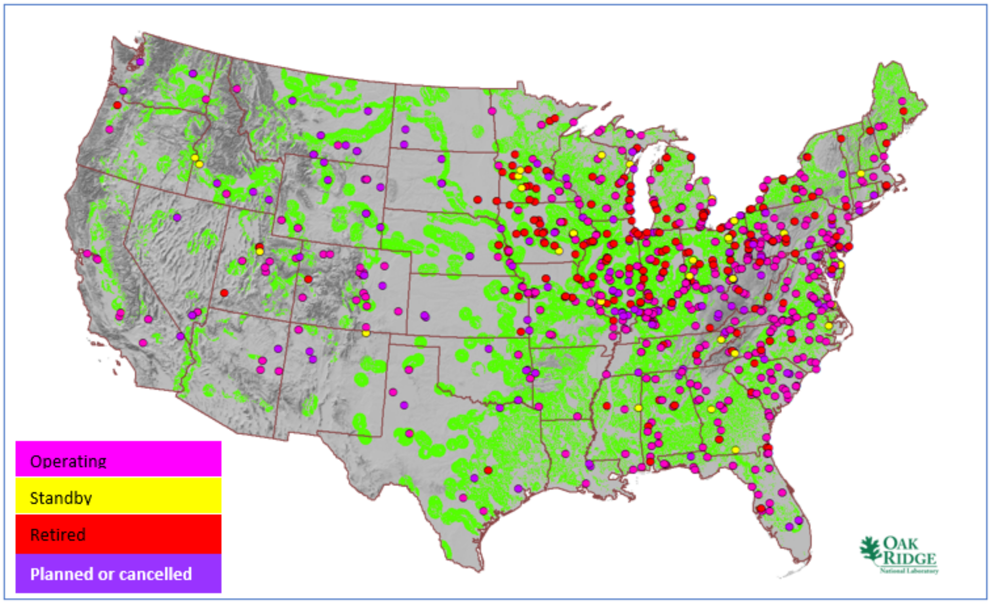


Figure 1. A map of 800 coal plant facilities (from EIA) in 2010 over OR-SAGE output of potential siting areas.

Figure 1 shows the approximately 800 locations of operating, standby, retired, and planned or cancelled coal-fired plant sites according to the EIA. Planned generators are those units that were still in a utility's integrated resource plan to be built to meet projected electricity demand. Cancelled generators are units that were planned and subsequently cancelled in favor of another generation source or in response to declining demand. The OR-SAGE tool was used to sample 34 coal-fired plants with an operating unit for the potential to backfit an SMR. The plants were selected to represent nuclear and non-nuclear utilities as well as a variety of states. The SMR siting criteria were applied to the specific sites of interest focusing on the area within a 0.5-mile radius (~500 acres) and a 1-mile radius (~2,000 acres) of the generator of interest.

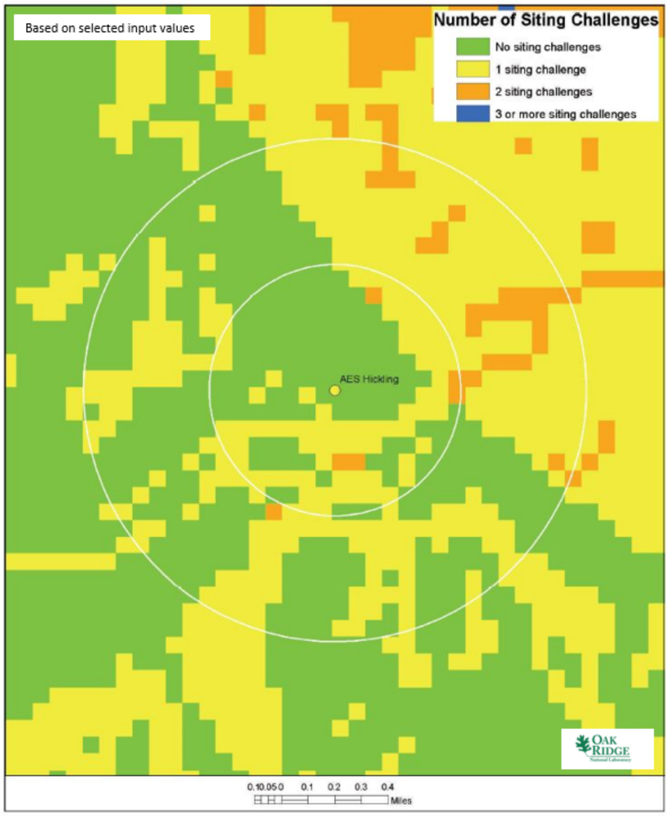


Figure 2. Sample siting criteria composite map for a plant of interest.

Results from the analyses of these 34 sites demonstrate that OR-SAGE provides useful insights for evaluating options and challenges related to repowering coal plant sites with SMRs. A sample result is shown in Figure 2 where green cells indicate that all selected siting criteria were met; yellow cells indicate all but one siting criterion were met; and orange cells indicate all but two siting criteria were met. Overall, 77% of the 34 sample plant sites met multiple conventional standards for consideration of siting an SMR at one of the randomly selected sample coal station sites.

This bottom-up site-specific approach using OR-SAGE is significant because it has become a mainstream use for the process tool. Many stakeholders now make use of the analysis tool to evaluate specific sites of interest. The most recent such use has been in the evaluation of specific demonstration reactor sites of interest for NRIC (Bucknor et al., 2021).

4.2. Support for Federal Clean Energy Goals

In accordance with Section 203 of the Energy Policy Act of 2005 (42 U.S.C. § 15852), each fiscal year the federal government must consume at least 7.5% of its total electricity from renewable sources—referred to as the renewable electricity requirement. SMRs and advanced non-LWRs are increasingly being considered as part of the necessary clean energy mix to meet climate energy goals. The National Defense Authorization Act for fiscal year (FY) 2019 directs the DOE to evaluate how micro-reactors can meet the needs for critical national security energy infrastructure and Executive Order 13972 promotes SMRs for national defense and space exploration.

"Federal agencies" include military and other agencies (e.g., Homeland Security, DOE, FBI, and Social Security Administration) that have missions of national critical importance. Historical Department of Defense (DoD) facility energy consumption data for FY 2010 and FY 2011 were averaged and analyzed. Likewise, historical DOE Federal Energy Management Program facility energy consumption data for all non-DoD federal facilities provided facility annual detail data for FYs 2009–2012 and were averaged and analyzed. This information was analyzed by postal ZIP code using spatial modeling and GIS.

The postal Zone Improvement Plan (ZIP) Code system breaks the country into 99 "mostly" contiguous areas. These areas are identified by the first two digits of the ZIP code. In an OR-SAGE report on siting SMRs in support of federal energy clusters (Belles and Omitaomu, 2014), the combined federal energy data were sorted by the first two digits of the ZIP code, binned, and plotted, as shown in Figure 3. The orange, dark blue, and red colored areas in Figure 3 have higher federal energy consumption. For clarity, the only dark blue areas are in Virginia, North Carolina, and Washington. This depiction allows clustered areas within state boundaries to be more visually obvious, as well as potential multi-state areas. Note that eastern Washington, which is dark blue, shares the same two-digit ZIP code area (99) as all of Alaska. The dark blue color in eastern Washington is a result of the power demand in Alaska. Much of the country shown in Figure 3 is binned into the lower energy consumption categories shown in light blue and purple.

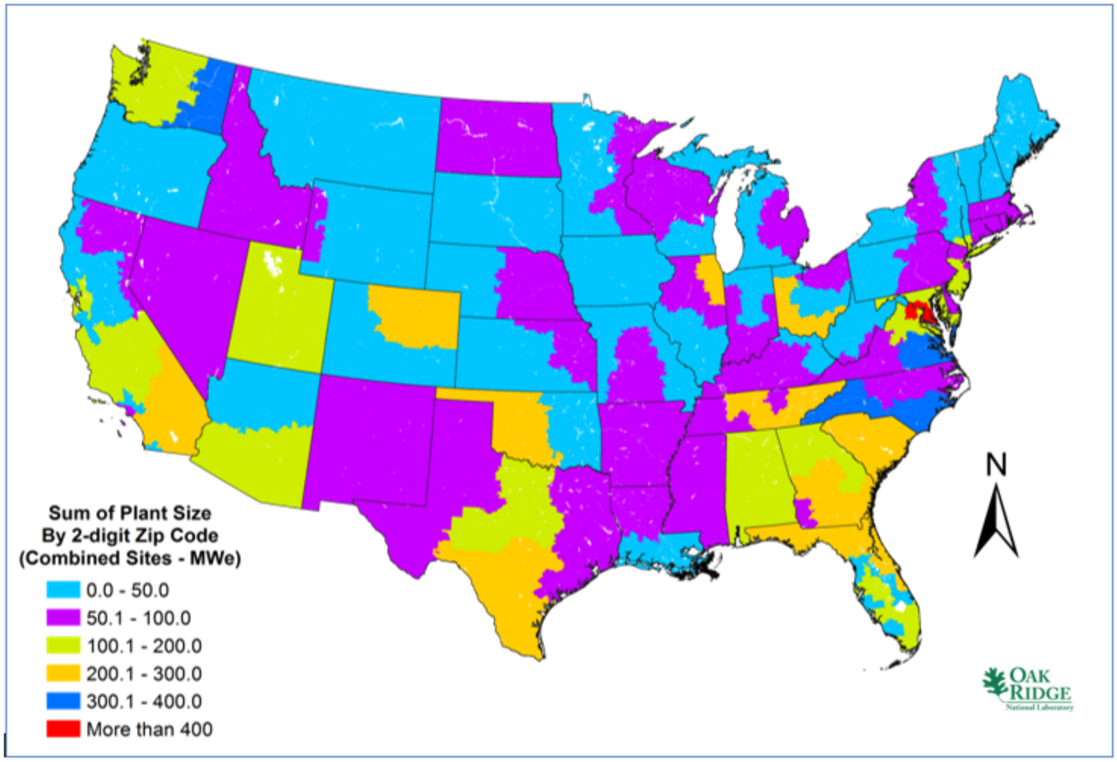


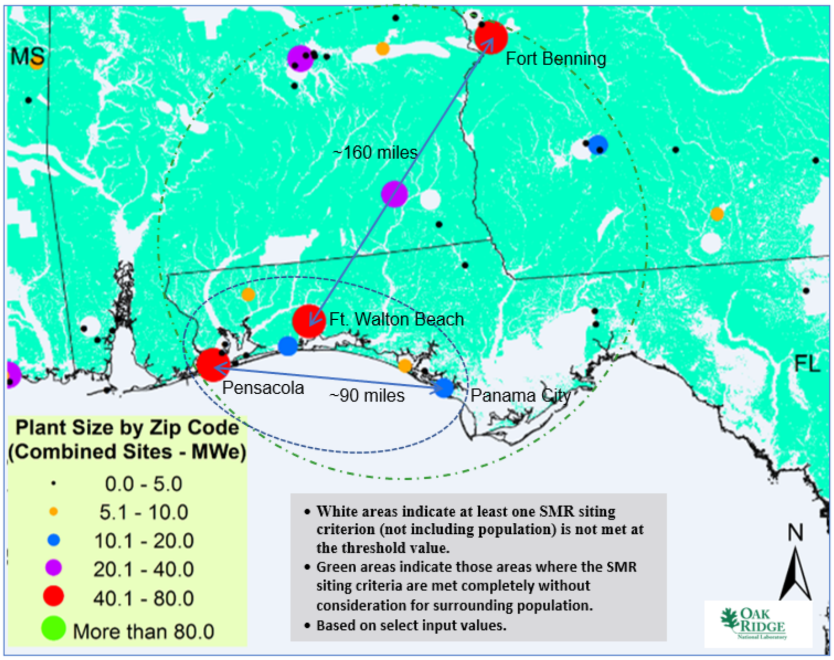
Figure 3. Combined federal energy consumption by two-digit ZIP code area.

The non-DoD and the DoD federal energy consumption datasets were combined and summed by ZIP code. Federal facilities were subsequently identified by a dot relative in size and color to the equivalent historical energy demand for the collective federal facilities in the given ZIP code area.

Regions with high federal energy demand were evaluated using an OR-SAGE top-down look for the potential siting of a central SMR facility to meet the federal green energy requirements.

For example, area in the Florida Panhandle, southeastern Alabama, and southwestern Georgia is shown in Figure 4 as a possible federal SMR region. The land mass is identified by black shoreline. For reference, Pensacola, Florida, is in the vicinity of the western-most red dot in Figure 4 along the Gulf Coast, and Fort Walton Beach is in the vicinity of the red dot on the Florida Panhandle just to the east of Pensacola. Areas in green on the map indicate those areas where SMR siting criteria are met completely without consideration for surrounding population. Areas in white on the map are those where at least one SMR siting criterion, excluding population, is not met at the threshold evaluated in the SMR siting report. For example, the large white area on the Gulf Coast, just east of Panama City, is excluded as wetlands, in the 100-year floodplain, or is protected land as part of the Apalachicola National Forest. The large white circles are commercial airports associated with larger cities. This provides a very basic go-no go evaluation of the potential for SMR siting over the entire region of interest. It is assumed that a federal SMR can be located on federal land away from population concerns.

The green areas indicate where SMR siting is favorable for servicing the numerous regional federal facilities. Approximately 160 miles separate Fort Walton Beach, Florida, and Fort Benning, Georgia, represented by the northern-most red dot.



- White areas indicate at least one SMR siting criterion (not including population) is not met at the threshold value.
- Green areas indicate those areas where the SMR siting criteria are met completely without consideration for surrounding population.
- Based on select input values.

Figure 4. Florida Panhandle, Alabama, and Georgia area relative to SMR siting criteria.

This analysis focused on solutions to meet federal energy demand. However, it also demonstrates the capability of the OR-SAGE siting tool to focus on the needs of select industries or other energy demand segments within the US.

4.3. Interfacing with Other Clean Energy Tools

Since performing the initial top-down national and regional siting analyses using the OR-SAGE tool power plant siting process, many additional uses of the process have been developed as noted in Section 2. As additional uses of the OR-SAGE tool are identified, interfaces with numerous other modeling and simulation tools as the tool have been developed. Some of these interfaces are summarized in this section.

A key interface tool for OR-SAGE since the initiation of the process tool has been LandScan^{TM}. LandScan^{TM} provides high-resolution global population distribution data representing an ambient population (average over 24 hours). The LandScan^{TM} algorithm uses spatial data and imagery analysis technologies and a multi-variable dasymetric modeling approach to disaggregate census counts within an administrative boundary. Each LandScan^{TM} database has two layers, a nighttime, and a daytime population distribution.

A subsequent use of the OR-SAGE tool required transportation modeling for spent nuclear fuel. The DOE Transportation Routing Analysis Geographic Information System (TRAGIS) model is designed for routing high-visibility shipments of spent nuclear fuel (SNF) and nuclear waste. OR-SAGE and TRAGIS outputs were interfaced to offer numerous options for spent nuclear fuel route calculation utilizing unique TRAGIS value-added network databases for highway, rail, and waterway infrastructures in the continental United States. Transportation scenarios were based on scenarios with data from the DOE-NE Integrated Waste Management Office Used Nuclear Fuel – Storage, Transportation & Disposal Analysis and Resource Data System (UNF-ST&DARDS). UNF-ST&DARDS is a comprehensive data and analysis system for the safe, secure and sustainable management of SNF.

The DOE Advanced Research Projects Agency - Energy (ARPA-E) Modeling-Enhanced Innovations Trailblazing Nuclear Energy Reinvigoration (MEITNER) project seeks to identify and develop innovative technologies that can enable designs for lower cost, safer advanced nuclear reactors. Under the ARPA-E MEITNER project, ORNL teamed with the University of Michigan Fastest Path to Zero carbon project to support a University of Michigan tool, “Janet,” on energy technology adoption. Decisions about energy technology adoption typically require the consideration of many different socio-political criteria and the cooperation and consent of many different stakeholders. The University of Michigan created an interface with OR-SAGE to create the Advanced Nuclear Site Locator (ANSL) tool to help identify, collect, and organize key geographic, political, economic, social, regulatory, and other siting attributes to aid in the decision-making process. ANSL is intended to be a geospatial tool that brings together climate-conscience communities and advanced nuclear companies.

DOE established NRIC to accelerate the deployment of advanced nuclear energy. NRIC subsequently tapped Argonne National Laboratory (ANL), the University of Michigan, and ORNL to use ANSL to evaluate selected sites for demonstration reactors. ANL developed a Multi-Objective Preference Model (MOPM) as a process to evaluate alternatives (advanced reactor demonstration site options, in this assessment), where there are multiple conflicting objectives to be achieved. The MOPM is a decision support framework that is based on rigorous decision analysis methods and techniques and was subsequently incorporated as an option in ANSL.

4.4. Evaluating Policy Issues

The NRC engaged ORNL staff to evaluate the considerations for and challenges to revising the Commission guidance regarding population for siting an advanced reactor (Belles et al., 2019). Current regulations in Title 10 Code of Federal Regulations Part 100, Reactor Site Criteria, and guidance support in Regulatory Guide (RG) 4.7, Revision 3, General Site Suitability Criteria for Nuclear Power Stations, are focused on large LWRs, addressing the distance that a nuclear reactor should be sited from a population center.

Some SMR and non-LWR vendors use a business plan that sites reactors close to an industrial partner to supply heat or to back-fit a reactor at a fossil plant site to take advantage of existing infrastructure. Factors such as smaller source terms (fission product release to the environment), passive safety systems, advances in barrier technology, advances in simulation and modeling, and improved understanding of societal risk may allow for siting these types of reactors closer to densely populated centers than has historically been accepted for large LWRs. OR-SAGE was used in one part of the study to evaluate the potential benefit to advanced reactor vendors of any population and density changes to siting guidance.

Using a single city as a proxy, the Landscan^{TM} interface (McKee et al., 2015) to OR-SAGE demonstrates the significance of reducing the distance required for making population density assessments at 500 people per square mile (ppsm) around a proposed advanced reactor site. As shown in Figure 5, noteworthy tracts of land around and occasionally within heavily populated cities become available for consideration as the population density calculation is capped at different distances. In Figure 5, the larger cyan area shows where population density exceeds 500 ppsm out to 20 miles distance per RG 4.7 siting guidance for large LWRs. The cyan color includes all smaller red-, green- and purple-colored areas within its boundary. The red area in the figure depicts a population density calculation of 500 ppsm capped at 10 miles and includes the smaller green- and purple-colored areas within its boundary. The green area in the figure depicts a population density calculation of 500 ppsm capped at 5 miles and includes the smaller, purple-colored areas within its boundary. The purple area in the figure depicts a population density calculation of 500 ppsm capped at 2 miles. So, as the population density calculation is capped at smaller radii, some coal-fired power plant sites (depicted by yellow dots in Figure 5) that would have been excluded by the current NRC RG 4.7 guidance on population density can subsequently be considered for SMR or advanced non-LWR siting.

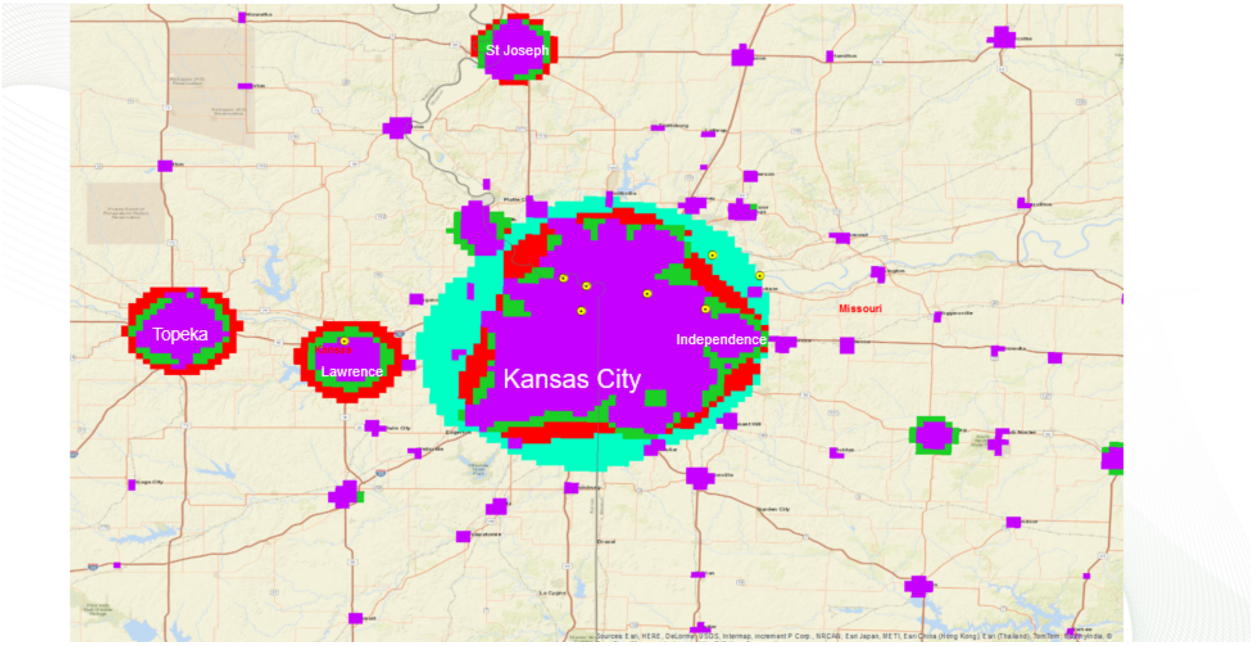


Figure 5. Population density comparison capped at various calculation distances. The 2030 population density comparison for 500 ppsm at 2- (purple), 5- (green), 10- (red), and 20-miles (cyan).

Similar reductions in the size of areas excluded by population will also be realized if higher population density values are used instead of simply reducing the area over which the population density must be assessed. This is because the population density trip threshold for any given point around a population center will become higher, resulting in less area being excluded by population density.

As areas on the outskirts of population centers become available for siting, the potential for siting advanced reactors closer to the populations they will serve will increase. This is in line with the goals of DOE and economic considerations of vendors and their financiers to enact business plans that include siting reactors close to an industrial partner to supply heat or backfitting a reactor at a fossil plant site to take advantage of existing infrastructure. The NRC staff has submitted SECY-20-0045 (NRC, 2020) to the Commission for their consideration of the staff recommendation to revise guidance to provide technology-inclusive, risk-informed, and performance-based criteria to assess population-related issues in siting advanced reactors. SECY-20-0045 was influenced by ORNL staff and the OR-SAGE tool.

5. Simulator for Virtual Placement of Reactors Based on Projected Energy Demand

The various uses of OR-SAGE discussed in Sections 4 culminated in visualization of a tool that could evaluate the entire nuclear fuel cycle, appraise regional energy demand, and optimize siting. This led to the development of a siting simulator supported by the DOE-NE SA&I campaign.

The objective of the simulator is to use the suitable areas obtained using the OR-SAGE tool to evaluate the feasibility of future nuclear energy development to meet regional energy demand. The simulator is also created to provide a picture of where future nuclear power plants may be placed in response to both the exclusion criteria and projected energy demand. An additional objective for the simulator is to allow the users to modify the simulation parameters to answer different policy questions.

5.1. Simulator Assumptions

The simulator assumes that the suitable areas are viable land for siting a nuclear plant. Therefore, the simulator will treat the cell size for the aggregated suitable land area as the minimum required land to create a nuclear plant. For example, if the suitable area has a resolution of 500 acres, the simulator will treat a single cell of that resolution as an acceptable footprint for that nuclear plant. This minimum aggregated area required for a given reactor technology is variable within the simulator. The simulator can take additional input such as the service boundaries of utilities which have invested in nuclear energy in the past. This makes the simulator favors these "nuclear friendly utility" areas over other areas when siting nuclear plants. The "nuclear friendly utility" input assumes that an existing nuclear plant being within the service area of a utility indicates that utility has a favorable opinion on nuclear energy development such that the utility would be more likely than other comparable areas within the same region to have future nuclear plants. Except for potentially favoring "nuclear friendly utilities", the simulator makes no distinction among all the potential land areas that are viable for nuclear plant siting. This means that no other criteria for nuclear plant development is accounted for other than those used to obtain the suitable land areas. This assumes that factors such as distance to transmission infrastructure and proximity to railway lines are not considered for the virtual placement.

Users provide the simulator with the capacity (in MW) of reactors of interest on a virgin land or as a replacement for an existing coal plants. This assumes that all future nuclear reactors which will be created to meet nuclear demand will be of the provided MW capacity, regardless of how much unmet demand exists in the region. For example, consider a scenario where the user inputs a default capacity of 1117 MW per reactor. In a region with 1200 MW unmet nuclear demand, 2 reactors would be created and produce an excess of 1034 MW in the region. The simulation treats the regions, which can be states or regional electric markets, as independent entities when it comes to electric power demand and production. That is to say that in the simulation, regions cannot generate electricity for another region. The required electricity to meet demand for nuclear energy in a region must be generated within that region. The ability for regions to import and/or export

5.2. Simulator Processing and Logic

This section describes the detailed logic of the simulator, the input data, and the results obtained from the simulator.

5.2.1. Simulator Input

The simulator takes input which informs the demand for nuclear energy, the placement of new nuclear plants, and the type of reactor and plant created. As is seen in Table 3, these parameters are meant to allow the user to provide regional demand information and exclusionary raster files of their own choosing, as well as specify the years they want to simulate for building nuclear reactors. Additionally, users can:

- Decide whether the simulator considers "nuclear friendly utilities" when siting plants
- Alter the capacity of reactors being created

- Alter the minimum allowable distance, or buffer, between nuclear plants
- Change the maximum number of reactors to place into a single plant
- Change how the simulator prioritizes construction of new plants versus placing additional reactors in existing plants

This is meant to provide flexibility to the users and allow for crafting multiple different scenarios of future nuclear supply and demand. All input raster datasets are in GeoTIFF (.tif) format and all vector data are in ESRI Shapefile (.shp) format.

Table 3. Required and Optional Parameters for the Simulator

Category	**Name**	**Description**	**Constraints**
Required	Years	List of years of interest for which to simulate the creation of nuclear plants	Must be years for which there is regional nuclear demand recorded in the Regional Nuclear Demand input
Required	Existing Nuclear Plants	Vector spatial data file recording the location and reactor capacity of existing plants	The spatial extent of the Existing Nuclear Plants must be within the Regional Nuclear Demand input and the attributes of the nuclear plants must include capacity for each reactor as well as the license year and closure year for each reactor
Required	Regional Nuclear Demand	Vector spatial data file of the regions of interest which contains attributes specifying the projected yearly regional nuclear demand (in MW) for the years of interest	Must have attributes for regional demand which line up with years of interest provided in the Years input list
Required	Suitable Areas	Raster spatial data file which records the aggregated potential suitable areas for the nuclear technology of interest	The spatial extent of the Exclusion Raster must be within the spatial extent of the Regional Nuclear Demand input
Required	Reactor Capacity	Capacity (in MW) which will be used to generate new reactors	N/A
Required	Maximum Reactors per Plant	Numerical limit on how many reactors can be placed in a single nuclear plant	Cannot exceed 8 (over 8 creates issues with shapefile field naming used in the simulator)
Required	Buffer Distance	Minimum allowable distance (in miles) between nuclear reactors	N/A
Required	Prioritization	Controls how the simulator prioritizes construction versus placing additional reactors in existing plants. If construction is prioritized, the simulator will first try to meet	Either TRUE or FALSE: - TRUE = additional reactors prioritized - FALSE = new construction prioritized

		demand by creating new plants before resorting to placing additional reactors in existing plants. If additional reactor placement is prioritized, the simulator will first try to site additional reactors in existing plants before resorting to creating new plants	
Optional	Nuclear Friendly Utility Raster	Raster spatial data file which records areas which are contained within nuclear friendly utility service areas with a value of 0 and areas not contained within nuclear friendly service areas with a value of 0.5	Must match the spatial extent and cell size of the Exclusion Criteria Raster layer

5.2.2. Simulator Logic

Figure 6 presents the flowchart for the simulator logic. The first step the simulator takes is isolating a single region from the input regional demand file. An example regional demand data, used in this study, is shown in Figure 7. This reduces the collection of regional demand features to a single regional demand feature with the attributes of both the geometric boundaries of the region and the projected demand for years of interest. The simulator then starts to loop through the years of interest provided as input and further filters the regional demand feature to specifically find the projected demand for a single year. The regional demand feature boundaries are then used in conjunction with the existing nuclear plants input and the year to isolate the existing nuclear plants which have not yet closed in that year that fall within the region boundaries. This results in both the projected demand for nuclear power as well as the simulated sites of supply of nuclear power to meet the projected demand for the respective region and year. The supply is subtracted from the demand to yield the unmet regional demand for nuclear power (in MW) of the year.

The simulator then uses the “maximum reactors per plant” input to filter the existing nuclear plants input into a list of plants which have fewer reactors than the maximum allowable reactor count. These plants are recorded as being viable for additional reactor placement.

The simulator then optionally accounts for nuclear friendly utilities by adding the “nuclear friendly utility raster” to the exclusion criteria raster. This affects the siting of plants by slightly increasing the exclusion value of areas not controlled by nuclear friendly utilities such that these areas, while still considered viable land by the simulator, are not seen as the most viable land and will be passed over in favor of areas controlled by nuclear friendly utilities.

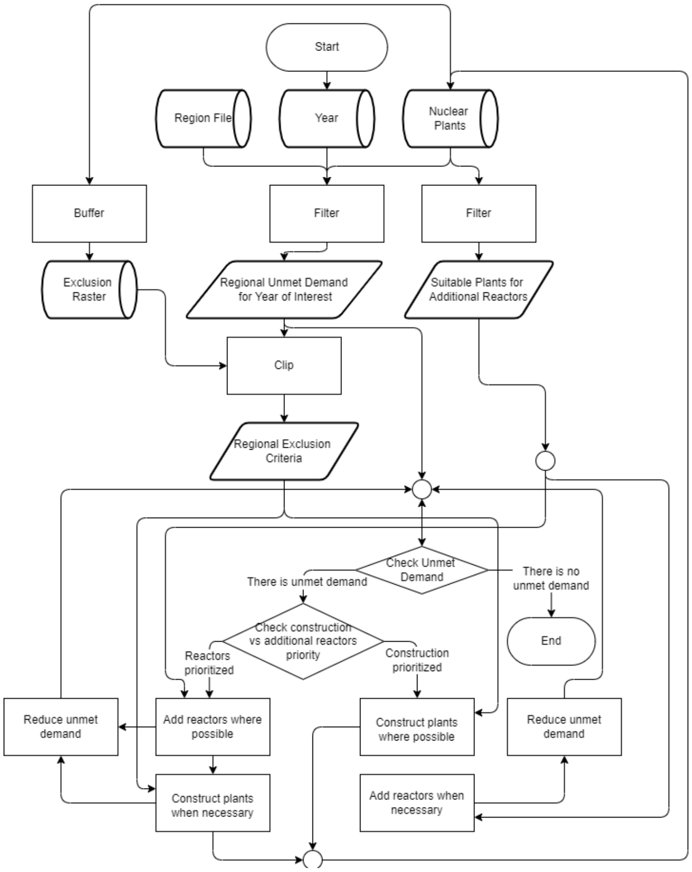


Figure 6. Nuclear Siting Simulator Logic Flowchart

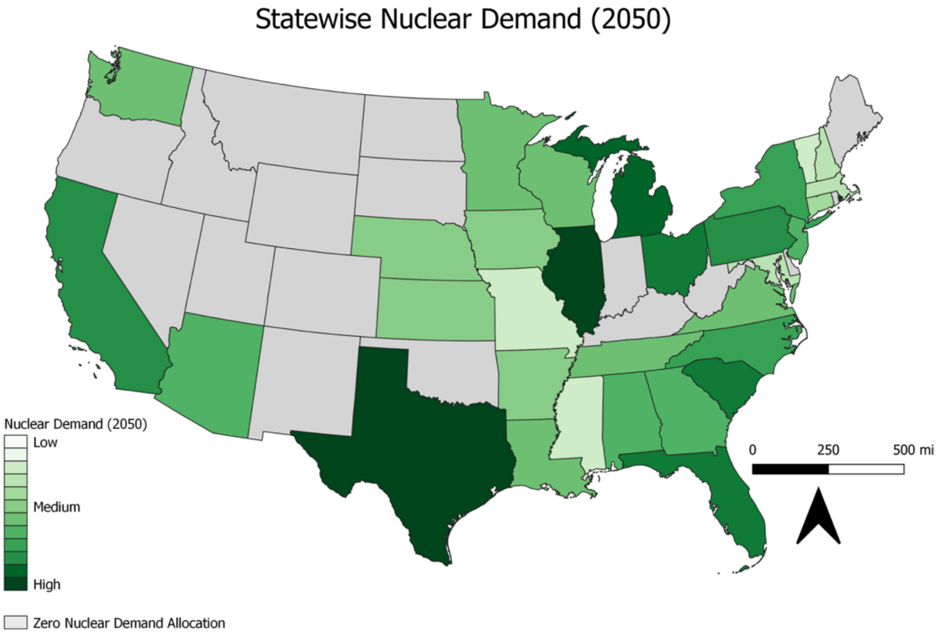


Figure 7. Nuclear energy contribution to the state-level projected energy demand for 2050. The nuclear energy contribution is based on Energy Information Administration's energy projection data.

The simulator then creates a buffer around existing nuclear plants, the size of which is controlled by the “buffer distance” input. The buffered nuclear plants are then converted to a raster format to be added to the exclusion criteria raster. Buffered areas are given a value over 1 to signify that they are to be excluded from consideration for siting nuclear plants. The exclusion criteria raster, now with nuclear plants buffered by an appropriate distance and optionally favoring nuclear friendly utilities, is clipped to the region to yield an exclusion criteria raster which only considers viable land within the boundaries of the region. The simulator then checks the regional unmet regional demand of the year. If the unmet demand is greater than 0, that indicates that there is additional nuclear power needed in the region. The simulator then checks the user provided priority.

If additional reactors are prioritized, then the list of plants suitable for additional reactors is used to identify plants which could house an additional reactor. The simulator will start placing additional reactors in viable plants, modifying the features of the existing nuclear plants affected and reducing unmet demand based on the user provided reactor capacity. The simulator will keep rechecking the unmet demand and housing new reactors in existing plants until either the unmet regional demand is reduced to 0 or there are no suitable plants for additional reactors. In the condition that there is still unmet regional demand after suitable plants for additional reactors are exhausted, the regional exclusion criteria are reviewed to find suitable land for a new nuclear plant. If viable land is found, a nuclear plant is then created with a single reactor which both reduces the unmet demand and creates a new feature in the nuclear plant input. This new nuclear plant then affects the regional exclusion raster by excluding areas within the provided buffer distance from consideration for development. The new plant also potentially becomes a suitable plant for additional reactor placement. This cycle of placing additional reactors in plants and creating new plants will continue until either all viable land is used, or unmet regional demand is reduced to 0.
If new construction is prioritized instead of additional reactors, the simulator reverses the order used in the additional reactor priority. That is to say that the simulator will respond to unmet regional demand by first trying to create new nuclear plants. If there is still unmet regional demand after all viable land is used, the simulator then starts placing additional reactors in plants suitable for additional reactors.

The simulator will reach its end for that region and year when either the demand for nuclear power for that region and year is met by supply or when both suitable land and suitable plants for housing additional reactors are exhausted.

At this point, the simulator will iterate to the next year of interest provided in the input list of years and start the process over with a new regional demand figure. When the input list of years is exhausted, the simulator will proceed to the next region feature in the input regional demand file and start the process over.

5.2.3. Simulator Outputs

The simulator outputs a modified version of the input “existing nuclear plants” file. The output includes both the existing plants as well as simulated plants. The attributes of this output file include the location of each plant, the number of reactors in each plant, the capacity of each reactor, and the license year and closure year of each reactor. As is seen when comparing simulator output in Figure 8, which models nuclear plants in 2050 using a reactor capacity of 1117 MW and prioritizing the placement of additional reactors, to simulator output in Figure 8, which models the same scenario but prioritizes new plant construction, the priority parameter affects how many nuclear plants are created as well as the reactor count in each plant. In Figure 8, 105 plants are shown as being sited to meet nuclear power demand, with 31 of those plants housing 4 reactors (the maximum reactor count per plant). In Figure 9, 203 plants are shown as being created to address the same level of nuclear power demand, with only 3 plants having 4 reactors and 160 plants having only one reactor. This is logical given that the construction priority will always prefer to create new plants over siting additional reactors in existing plants. It is also clear that reactor capacity has a large effect on the number of plants generated by the simulator when comparing Figure 8 to Figure 10, which uses a reactor capacity of 84.6 MW and increases the allowable reactors per plant to 8 but still prioritizes additional reactors. Compared to the 105 plants created in Figure 8, Figure 10 shows 258 plants created to meet nuclear demand. This is logical given that a much larger number of 84.6 MW reactors would be necessary to meet nuclear demand compared to 1117 MW reactors that are 13 times larger. However, the difference in the number of plants is not a factor of 13 as might be expected by the difference in capacities because less excess regional demand is generated using the smaller reactors.

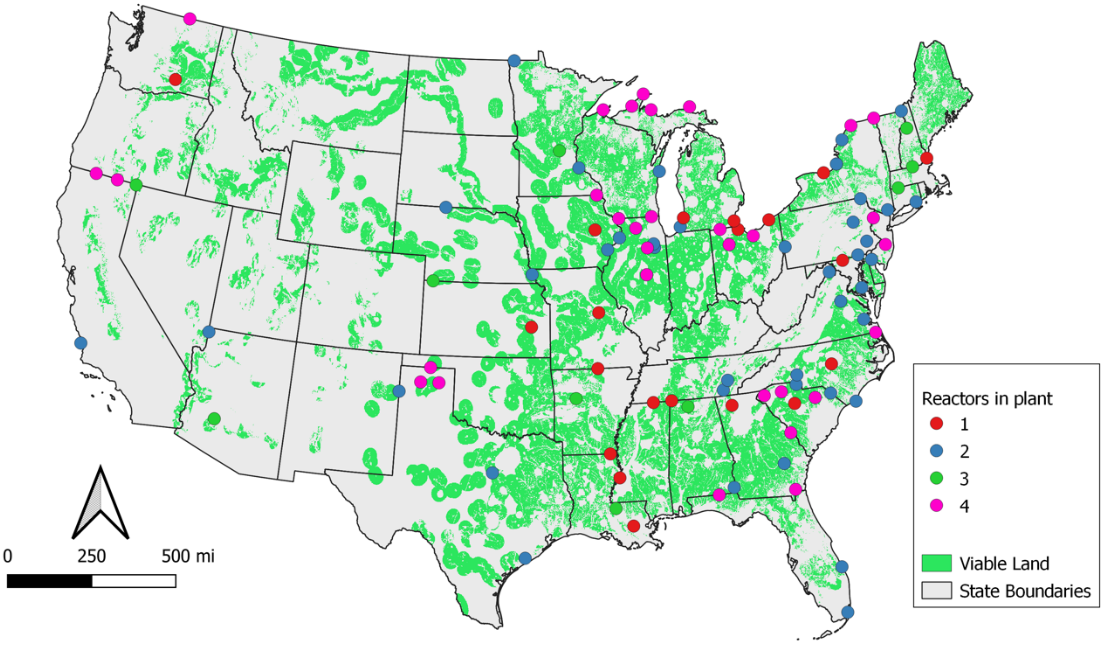


Figure 8. Simulator output with 1117 MW capacity reactors, 4 maximum reactors per plant, no utility preference, 50-mile buffer distance, and additional reactors prioritized. The green background is depiction of the suitable land area for AP1000.

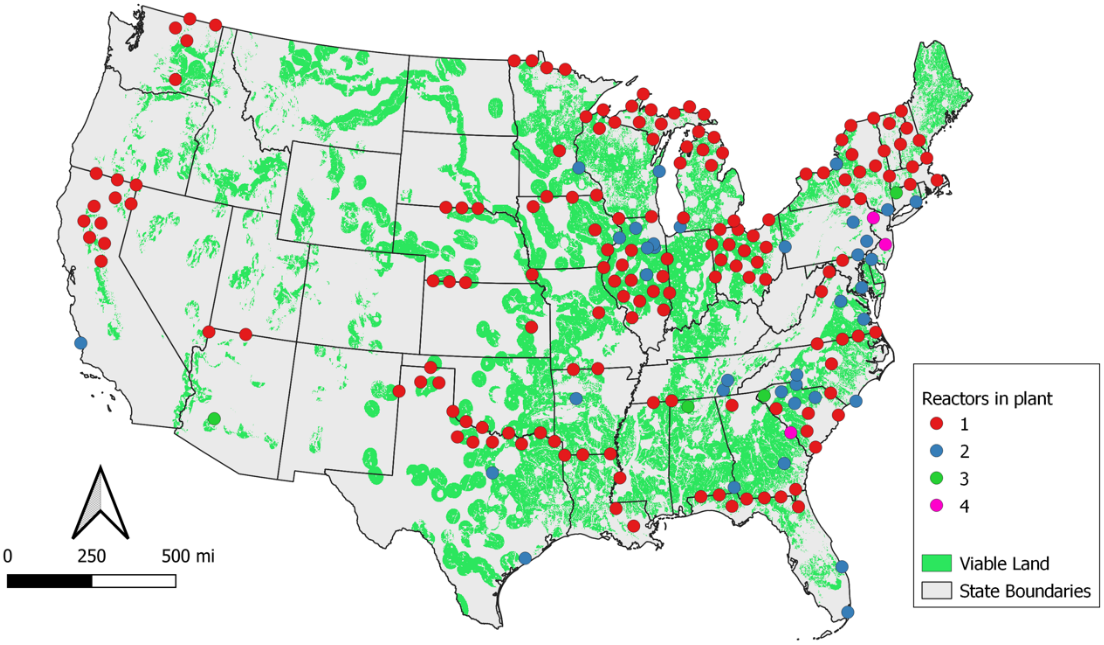


Figure 9. Simulator output with 1117 MW capacity reactors, 4 maximum reactors per plant, no utility preference, 50-mile buffer distance, and new construction prioritized. The green background is depiction of the suitable land area for AP-1000.

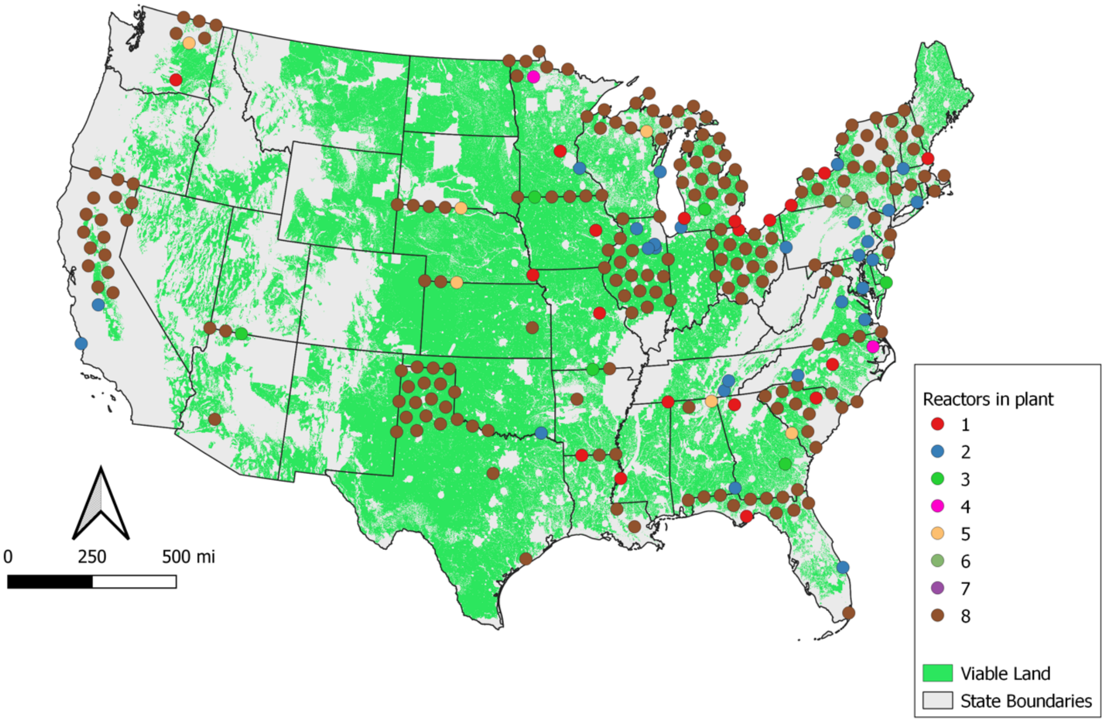


Figure 10. Simulator output with 84.6 MW capacity reactors, 8 maximum reactors per plant, no utility preference, 50-mile buffer distance, and additional reactors prioritized. The green background is depiction of the suitable land area for Xe-100.

6. Discussions and Conclusion

The OR-SAGE tool divides the entire contiguous United States into millions of 100 x 100 m cells for fine analyses related to energy siting. OR-SAGE can inform multiple industries on future energy generation technology questions. These questions range from impacts of national policy to the optimal site for an energy generation type. As documented previously (Omitaomu et al., 2012), OR-SAGE was fundamentally developed to inform energy stakeholders on locations and space for various sources of energy production. Eventually, the OR-SAGE siting focus came to be on nuclear energy and SMRs. Over time, the ability to apply geospatial knowledge and techniques to other aspects of the nuclear fuel cycle and nuclear policy were shown to be valuable.

OR-SAGE can provide a top-down geospatial look to provide a national, regional, or even local specific site evaluation of the potential for SMR, advanced non-LWR, or micro-reactor siting based on data queries appropriate to each reactor technology. The same data queries can be applied in a bottom-up approach to specific sites of interest such as retired coal-fired facilities or nuclear fuel cycle facilities to help inform specific siting alternatives.

In addition, the results of various OR-SAGE data queries can be used to supplement or interface with other clean energy data tools to further inform policymakers and other energy stakeholders e.g., fuel cycle modeling and analyses, economics etc. The OR-SAGE analysis has been shown that it can be tailored to specific energy sectors such as federal energy demand or to help optimize future reactor siting, nuclear fuel cycle, and the supporting nuclear supply chain.

The DOE-NE SA&I campaign has supported ORNL efforts to evolve the OR-SAGE tool to support total fuel cycle modeling and simulation, including front end locations, SMR, advanced reactor, and micro-reactor siting, and back-end connections. This effort is ongoing and continues to demonstrate the role of OR-SAGE in the decision-making process. This report documents initial efforts to prepare a simulator tool to meet future regional energy demand with varying nuclear technologies. Additional simulator efforts are planned to include the ability to bias placement toward retired or aging coal-fired generation and to optimize proposed reactor siting based on proximity to other fuel cycle facilities and operations.

It was originally envisioned that the OR-SAGE tool would be used by policymakers, industry, utilities, and other interested stakeholders to evaluate the impacts of policy, market development, technology enhancement, and optimizing the site selection and project planning process within a business. One way this vision is being accomplished is by interfacing OR-SAGE with energy diversity, economic, climate, public opinion, social and energy justice, and political tools and inputs to influence stakeholders on the appropriate energy mix to provide for energy security in the United States. Recent climatic events, such as the dramatic low temperatures and energy failures in Texas during February 2021 indicate that it is imperative for better energy policy and planning to optimize the location, use, and availability of all available energy technologies through the creation of an energy policy simulation tool. The plan is ultimately to make the OR-SAGE tool and simulator available online to users external to ORNL, and for use by all relevant stakeholders.

Future studies will consider sequential placement decision making under uncertainty; specifically, evaluate how global changes in environmental conditions and energy markets will impact placement of new nuclear power plants. The authors will also implement sensitivity analysis that will exclude the coastal areas to account for possible sea level rise. Furthermore, the results of the simulator will be compared with other global projections of energy production.

Author Contributions

Olufemi A. Omitaomu co-designed the study, co-designed the simulator, developed and implemented the algorithms, and contributed to the manuscript. Randy Belles co-designed the study, performed validation, and contributed to the manuscript. Nicholas Roberts co-designed the simulator, implemented the simulator, and contributed to the manuscript. Andrew Worrall co-designed the study and contributed to the manuscript.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Graphical Abstract