PSAM 18 (July 20, 2026)
SMR and Advanced Reactor Risk Assessment and Licensing - II

Combining GIS Spatial Analysis and PRA Concepts to Support Advanced Reactor Siting Decisions

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Background

- Growing interest in advanced reactors (ARs) and microreactors (MRs) to improve the safety, viability, and flexibility of nuclear energy.
- Unique characteristics of ARs and MRs, as compared to light-water reactors (LWRs), necessitate different siting considerations.
  - Smaller power outputs (SMRs ~ 70-350 MWe; MR ~ 1-20 MWe)
  - Colocation with loads (e.g., data centers)

➡ Multiple reactors (potentially dozens to 100) need to be distributed in a given geographical region.

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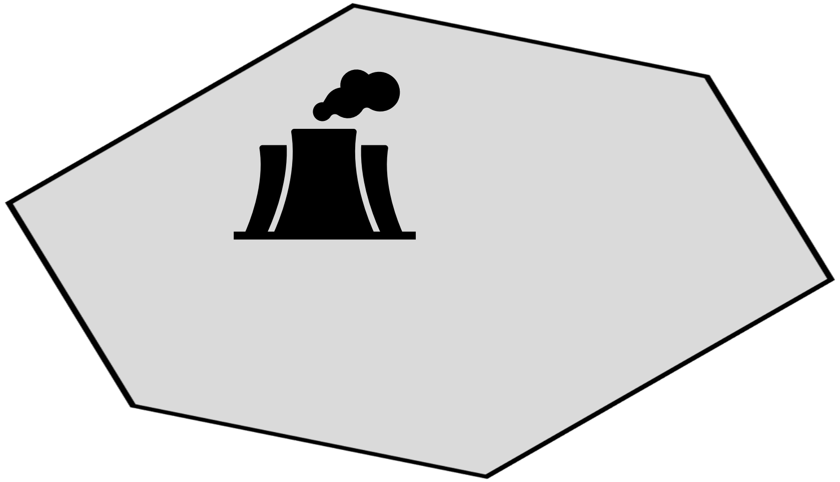
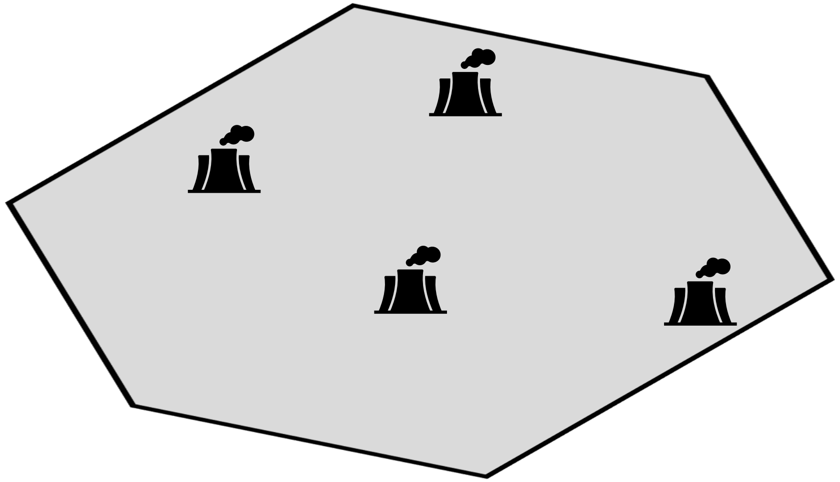
AR & MR Siting as a Portfolio Decision-Making

Traditional LWR Siting



- Select a single best alternative
- One-time decision-making

AR & MR Siting



- Select a subset of alternatives
- Sequential decision-making

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Methodological Gaps to Address

Insights from a literature review on AR and MR siting analysis:

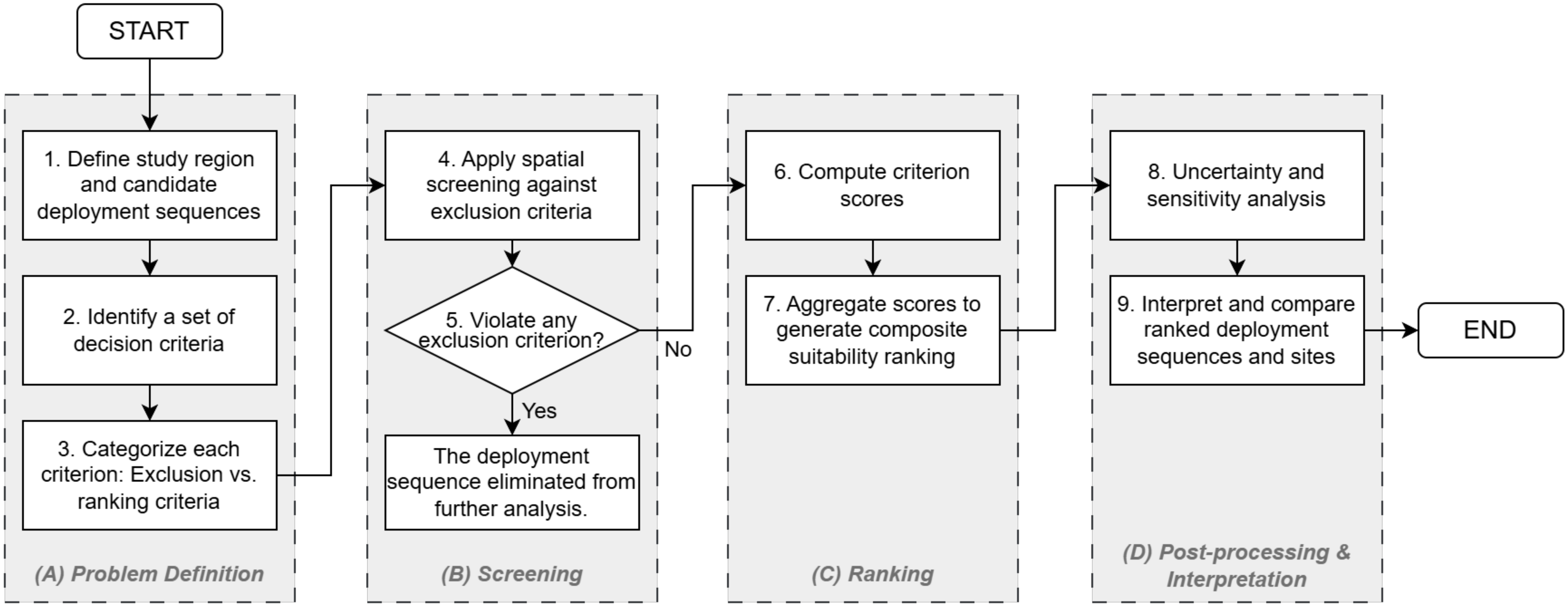
- No explicit consideration of the sequential deployment of multiple reactors and the spatial and operational correlations among multiple sites.
- Dependencies among decision criteria are not explicitly considered.
  - Example: Population distribution induces a common-cause influence on multiple criteria, such as labor availability, social vulnerability, etc.
  - In most cases, decision criteria are aggregated using a linear formula.

Research Objective

Develop a computational framework for AR/MR siting decision support.

- Multi-criteria portfolio decision analysis implemented in Geographic Information System (GIS).
- Explicit modeling of regional deployment sequences using dynamic decision tree analysis.
- Leverage nuclear PRA methods to enhance the generation of decision-relevant information.

Decision Analysis Workflow

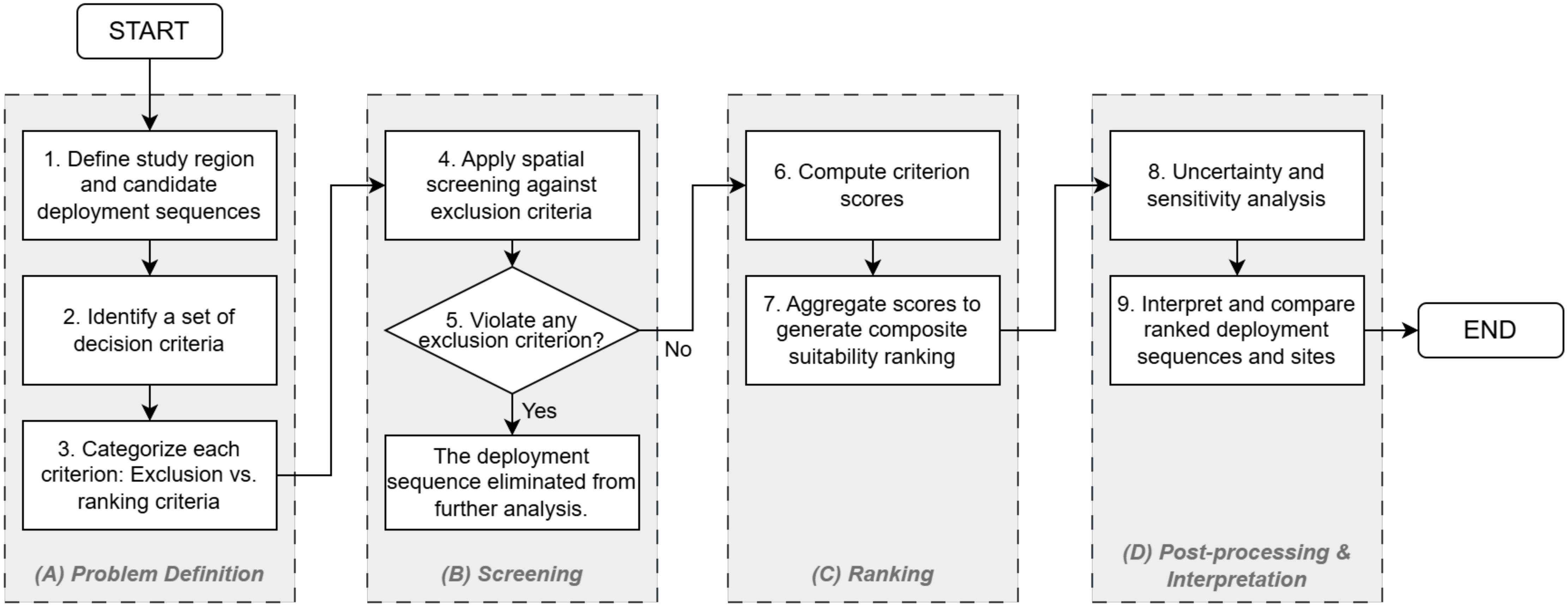


Identification of AR & MR Siting Criteria

Main Categories	Subcategories
Health and Safety	• Geological and seismological hazards • Nearby hazardous land uses • Accident consequences and emergency planning
Environmental	• Streamflow / Cooling water availability • Dewatering effects of adjacent wetlands • Climate change
Land Use and Socioeconomics	• Protected lands • Waste management • Social Vulnerability Index • Public acceptance (including nuclear sentiment)
Engineering and Cost-Related	• Site footprint and land availability • Transportation • Labor rates

- Health and Safety is the most commonly analyzed category.
- For ARs and MRs, socio-economic factors and additional engineering considerations (e.g., transportation) receive increased attention.

Decision Analysis Workflow (Cont.)



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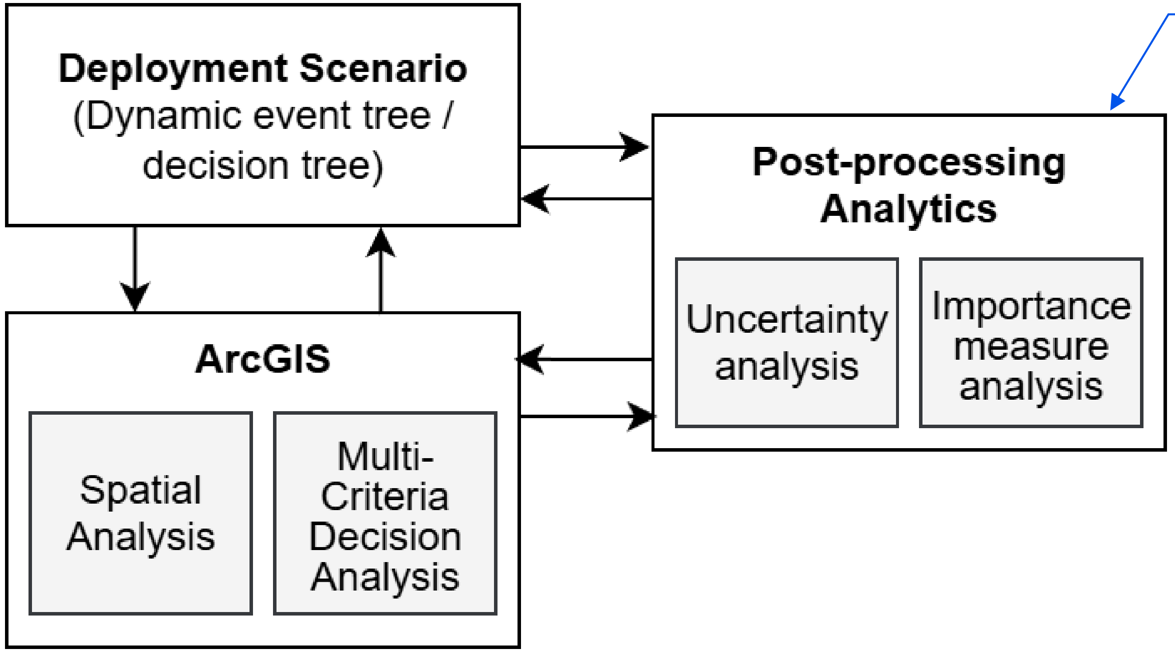
Computational Platform: Overarching Structure

- Generates deployment scenarios
- Iteratively runs ArcGIS
- Updates geospatial input data



- Conducts spatial analysis using ArcGIS
- Runs multi-criteria decision analysis
- Visualizes results

- Performs uncertainty and sensitivity analysis for ArcGIS with dynamic scenarios.
- Extracts key insights.

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ArcGIS Model Development

- A baseline ArcGIS model covers the western Pennsylvania region as an illustrative study area.
- A suitability analysis is conducted using the Raster Calculator in ArcGIS Pro 3.6.

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Preliminary Criteria & Data Sources in ArcGIS

Criterion	Description / Threshold	Data Sources
Population density	Exclude where ≥ 500 people/mi² within 2 miles	US Census (2023) [1]
Protected lands	Exclude all protected areas	USGS (2024) [2]
Seismic hazard	Exclude >4% chance of potentially damaging ground shaking in 100 years.	Petersen et al. (2023) [3]
Landslide hazard	Exclude moderate or high-risk zones: >40 of the 10-m cells exceeded the threshold of the slope-relief within a 90-m grid unit	Belair et al. (2022) [4]
Hazardous generator facilities	Exclude cells containing a place that creates hazardous waste	PA DEP (2016) [5]
Wetlands	Exclude wetlands and surface water	U.S. Fish & Wildlife Service (2026) [6]
Slope / terrain	Exclude slopes > 18%	USGS (2024) [7]

[1] U.S. Census Bureau, American Community Survey 5-Year Estimates, Table S0101, 2023.
[2] U.S. Geological Survey, Protected Areas Database of the United States (PAD-US) 4.1, data release.
[3] Petersen et al., USGS National Seismic Hazard Model (2023 update), seismic shaking probability data release.
[4] Belair et al., USGS Landslide Inventories Across the United States, v2, data release.
[5] PA Department of Environmental Protection, Captive Hazardous Waste Operation – Hazardous Generator Facilities dataset.
[6] U.S. Fish and Wildlife Service, National Wetlands Inventory, Wetlands by State geodatabase, 2026.
[7] U.S. Geological Survey, 3D Elevation Program, 1 Arc-Second Digital Elevation Model.

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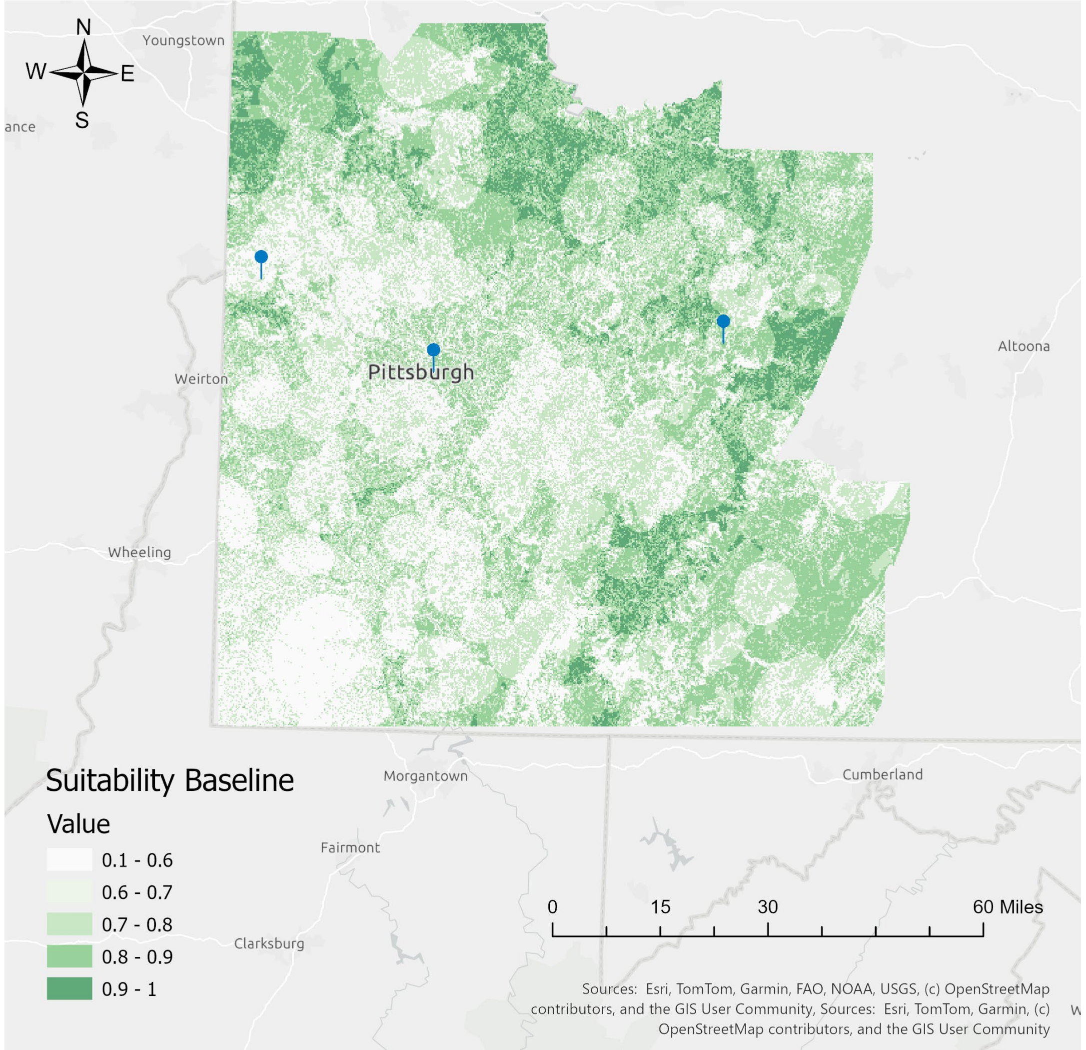
Preliminary Suitability Score



Darker green = More suitable

White = Excluded

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Interpretation of Results through Sensitivity Analysis

- **<u>Purpose</u>**: Rank the weights of decision criteria based on their contributions to the suitability score.

$$\underbrace{SS_l}_{\text{Suitability score for location } l} = \sum_i \underbrace{w_i}_{\text{Weight of criterion } i} \times \underbrace{C_{l,i}}_{\text{Score of criterion } i}$$

- For each location l, which decision criteria can most strongly affect the suitability score?

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Sensitivity Analysis for Siting Decision
Importance Measure-Like Approach

1) Identify a set of contextual change scenarios to evaluate.
2) For each scenario, identify the subset of decision criteria whose weights can be altered.

Contextual Changes	Impacted Criteria
Safety-Conservative	Population density, seismic hazard, landslide hazard
Infrastructure/Deployment-Driven	Wetlands, slope
Community/Land Use	Population density, protected lands, wetlands

Sensitivity Analysis for Siting Decision
Importance Measure-Like Approach (Cont.)

3) For each scenario, construct two sensitivity cases:

   R^+: The weights of the impacted criteria are <u>increased</u> by a factor of 2.

   R^-: The weights of the impacted criteria are <u>decreased</u> by a factor of 2.

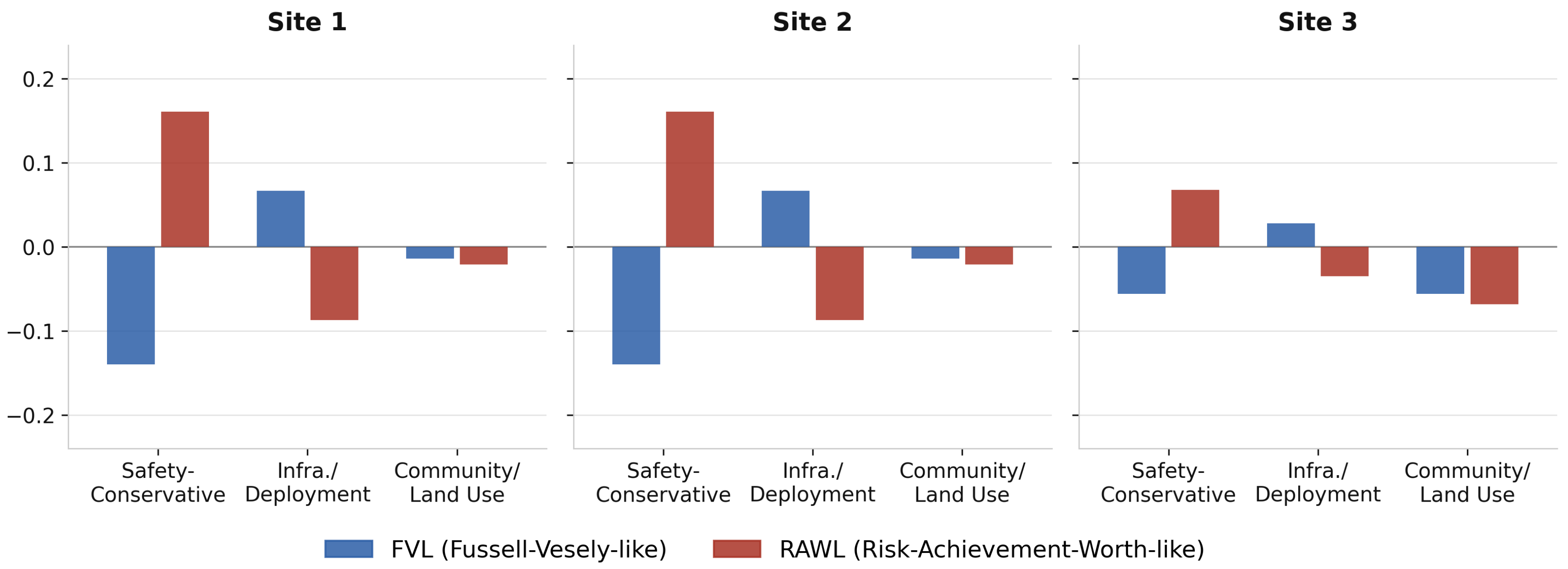
4) Execute the ArcGIS analysis for each sensitivity case.

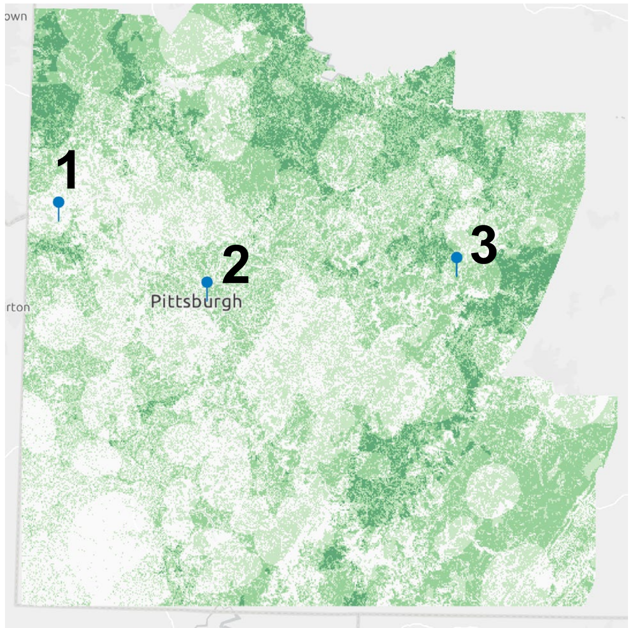
5) Calculate IM-like sensitivity indices:

   Fussell-Vesely-like index: $FVL_i = \left(R_0 - R_{i,-}\right)/R_0$

   Risk Achievement Worth-like index: $RAWL_i = \left(R_{i,+} - R_0\right)/R_0$

Importance Measure-Like Sensitivity Analysis: Illustrative Results





1. Beaver Valley Power Plant
2. University of Pittsburgh campus
3. Homer City Energy Campus

Note: The authors do not intend to propose these sites as actual candidates for future reactor siting. Instead, they are selected to illustrate how the tool developed in this study can characterize features across different sites within the studied region.

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Conclusion

- This research focuses on advancing the siting analysis of ARs and MRs by integrating portfolio decision analysis, GIS, and PRA methods.
- The current progress includes:
  - Establishing a literature-based criteria framework,
  - Developing a GIS-based computational platform, and
  - Conducting sensitivity analysis leveraging risk importance measures.
- Ongoing work:
  - Expanding the scope of the GIS data
  - Enhancing modeling capabilities for explicitly analyzing dynamic decision sequences

Thank you!

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