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Zonal Global Sensitivity Analysis for Policy-Constrained Capacity Expansion Planning in New York

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Abstract

Long-term power system planning is increasingly affected by uncertainty in electricity demand growth, technology costs, transmission expansion, and policy implementation. While capacity expansion models are widely used to explore future planning scenarios, few studies systematically identify which uncertainties most influence system-wide and zonally resolved planning outcomes. This paper presents a Morris-based global sensitivity analysis framework integrated with the GenX capacity expansion model for the New York 2040 planning system. The framework evaluates uncertainty across policy, technology, transmission, and demand assumptions while preserving zonal structure within a multi-region planning environment. Results show that electrification-driven demand growth remains the dominant driver of statewide planning cost sensitivity across all policy cases, while policy activation shifts zonal sensitivities in downstate regions from thermal retirement dependence toward demand-driven behavior. These results demonstrate the value of zonally resolved global sensitivity analysis for identifying regional planning risks and uncertainty interactions within large-scale capacity expansion planning models. The proposed framework provides a scalable approach for evaluating uncertainty propagation across policy-constrained multi-zone power system planning environments.

Keywords
Global Sensitivity Analysis, Morris Method, Capacity Expansion Planning, GenX, Energy System Optimization.

1. Introduction
Long-term electric power system planning is becoming increasingly complex due to growing electrification, renewable energy integration, transmission expansion needs, and evolving decarbonization policies. New York electricity demand is projected to increase significantly through 2040 due to electrification, including EV adoption, heat pumps, and new large electrical loads. Future energy demand and clean energy deployment remain uncertain due to policy changes, economic conditions, technology adoption rates, and infrastructure development constraints. System operators and planners must maintain reliability while adapting to evolving policy, transmission, and clean energy deployment conditions. These interacting uncertainties create a large and complex planning space in which small changes in assumptions can substantially alter optimal investment pathways, system costs, and regional

infrastructure requirements. Planning strategies must remain adaptable across a broad range of future system conditions and policy scenarios (New York State Energy Planning Board 2025).

These challenges are particularly relevant in New York State, where ambitious decarbonization targets established under the Climate Leadership and Community Protection Act require 70% renewable electricity by 2030 and a zero-emission electricity system by 2040. Achieving these targets requires coordinated expansion of generation, storage, and transmission infrastructure across eleven geographically diverse load zones, each with distinct resource availability, demand characteristics, transmission dependencies, and policy constraints. Uncertainty in electrification demand, natural gas retirement schedules, clean energy deployment, transmission siting, and policy implementation creates significant planning risk, particularly in downstate regions where reliability and transmission congestion are already major concerns.

1.1 Objectives

This study presents a Morris-based global sensitivity analysis framework integrated with a multi-zone New York State 2040 capacity expansion model developed using a PowerGenome-to-GenX workflow. The framework evaluates uncertainty across policy, technology, transmission, and demand assumptions while preserving zonal structure across the eleven-zone planning system. Multiple policy activation configurations—including carbon emissions caps, reserve margin constraints, and renewable energy share requirements—are evaluated to examine how uncertainty sensitivities evolve under progressively constrained policy environments. Both system-wide and zonally resolved outputs are analyzed to identify the uncertain parameters that most strongly influence statewide planning costs, regional infrastructure dependencies, and spatial planning risk.

The contributions of this work are threefold:

- Development of a zonal Morris-based uncertainty framework for large-scale capacity expansion planning;
- Integration of dynamic policy activation to evaluate sensitivity under progressively constrained policy environments; and
- Identification of system-wide and region-specific planning drivers across New York's 2040 decarbonization pathway.

2. Literature Review

Existing energy system planning studies have increasingly incorporated global sensitivity analysis (GSA) methods to evaluate uncertainty in technology costs, policy assumptions, demand growth, and infrastructure planning decisions within large-scale optimization models. The Morris screening method has been widely applied due to its computational efficiency for high-dimensional uncertainty analysis and large-scale energy system optimization problems (Morris 1991; Campolongo et al. 2007).

Usher et al. (2023) demonstrated the application of GSA within the OSeMOSYS energy system optimization framework using open-source tools to identify influential uncertain input parameters affecting model outcomes. Urbano et al. (2022) applied uncertainty and sensitivity analysis methods to energy system design and operational optimization problems, including industrial energy investment applications. However, comparatively fewer studies, have examined zonally resolved uncertainty propagation within large-scale multi-region capacity expansion planning models.

3. Methods

3.1 Overview

This study employs a global sensitivity analysis framework integrated with a multi-zone power system capacity expansion optimization model to measure the influence of uncertain input parameters on long-term system planning outcomes. The framework combines policy-constrained optimization using the GenX capacity expansion model with zonal uncertainty parameterization, trajectory-based global sensitivity analysis, and post-processing aggregation techniques.

The analytical workflow as shown in Figure 1, consists of five major stages:

1. Policy Setup: Model and scenario configuration,
2. Morris Parameter Setup: Uncertainty parameters and sampling design,
3. GenX Capacity Expansion Optimization: Optimization-based capacity expansion,
4. Morris Elementary Effect: Trajectory-Morris based elementary effect computation, and
5. Visualization and Analysis: Sensitivity aggregation and visualization.

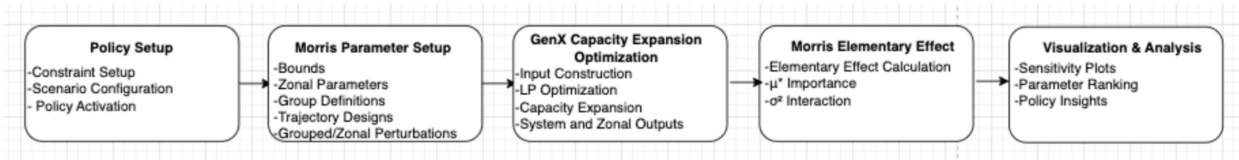


Figure 1: Framework constructed to perform Policy and Parameter uncertainty analysis using the Morris Method using the NY State Current Policy 2040 Capacity Expansion model

For each sampled uncertainty input, the GenX optimization model determines the least-cost system expansion pathway subject to operational, policy, reliability, and infrastructure constraints. The resulting optimized system and zonal outputs are subsequently evaluated using Morris-based global sensitivity analysis.

3.2 Policy Setup: Model and Scenario Configuration

The analysis is conducted using a multi-zone capacity expansion framework implemented in GenX. GenX is a linear programming-based optimization model designed to determine cost-optimal generation, storage, and transmission investment decisions while satisfying system operational and policy requirements over long-term planning horizons. Each simulation case represents a fully specified system environment composed of:

- Policy constraints,
- Resource and technology definitions,
- Operational system configuration, and
- Optimization outputs.

The present study focuses exclusively on a baseline NY State Model Current Policy scenario for the P3 (2040) High Electrification planning period to evaluate uncertainty propagation under progressively constrained policy environments. The NY State 2040 planning case used in this study was developed using a Power Genome-to-GenX workflow and provided the baseline system representation, technology assumptions, and policy constraint structure used for capacity expansion analysis.

3.2.1 GenX Model Configuration

The GenX framework was configured as a linear programming-based capacity expansion model with generation, storage, and transmission investment planning decisions for the New York State 2040 system. Optimization simulations were solved using the Gurobi/HiGHS solver framework with transmission expansion enabled under a transport-model formulation ($\mathrm{DC\_OPF} = 0$). Time-domain reduction was implemented using k-means clustering with representative periods to reduce computational burden associated with large Morris trajectory ensembles.

The model incorporated natural gas retirement options, new nuclear expansion eligibility, and policy-driven transmission reinforcement constraints. Unless otherwise specified, default GenX preprocessing and configuration settings were retained.

3.2.2 Policy Constraint Configurations

To evaluate the sensitivity of system planning outcomes under progressively constrained policy environments, multiple policy activation configurations were evaluated within the NY State baseline Current Policy scenario for planning period 2040 (P3).

Each configuration selectively activates combinations of policy constraints within the GenX framework, including:

- CO_2 emissions caps (CO2Cap),
- Capacity reserve margin requirements (CapacityReserveMargin),
- Renewable energy share requirements (EnergyShareRequirement)

The evaluated policy case scenarios are shown in Table 1:

Table 1: Policy setup in the NY State Current Policy 2040 Capacity Expansion model used for parameter uncertainty analysis using the Morris Method.

Policy Configuration	Active Constraints
inputs_p3	No active policy constraints
inputs_p3_CO2Cap	CO_2 cap only
inputs_p3_CapResMar	Capacity reserve margin only
inputs_p3_ESR	Energy share requirement only
inputs_p3_CO2Cap_CapResMar	CO_2 cap + reserve margin
inputs_p3_CO2Cap_CapResMar_ESR	CO_2 cap + reserve margin + energy share requirement

Policy modules were activated dynamically within the GenX optimization framework according to the selected policy configuration for each Morris ensemble. This incremental policy activation structure enables controlled evaluation of how uncertainty sensitivities evolve as additional policy and reliability constraints are imposed on the system optimization problem.

3.3 Morris Parameter Setup: Parameter uncertainty representation and sampling design

Uncertain input parameters represent major sources of long-term planning uncertainty, including technology costs, fuel and retirement assumptions, electricity demand growth, hydrogen deployment, renewable siting constraints, transmission reinforcement limits, and policy constraints.

Each parameter was defined over a bounded interval and discretized into finite Morris sampling levels. A trajectory-based Morris sampling strategy was used to explore the uncertainty space through one-at-a-time (OAT) perturbations, enabling computationally efficient screening of high-dimensional parameter interactions.

The framework also supports grouped and zonal perturbations, allowing uncertainty parameters to be evaluated across technology classes, policy categories, and spatial regions within the multi-zone GenX environment. Grouped perturbations allow related regional uncertainty parameters to vary together during Morris trajectory generation.

3.3.1 Uncertain Parameter Definitions

Uncertain parameters were defined using bounded ranges applied to selected GenX inputs representing technology costs, policy constraints, transmission expansion, and demand conditions. Table 2 shows parameters discretized using fixed Morris sampling levels, with some implemented at zonal resolution to capture regional uncertainty variations.

Table 2: Uncertain parameter definitions and bounds used for Morris sensitivity analysis

Morris Parameter Name	Definition	Lower Bound	Upper Bound
`CO2Cap_Multiplier`	Scaling factor applied to the baseline CO_2 emissions cap constraint. Lower values represent more stringent decarbonization requirements, while higher values relax allowable system emissions.	-25	25
`Gas_Retirement`	Controls retirement eligibility for existing natural gas generation resources using the `Can_Retire` flag. This parameter evaluates the sensitivity of system outcomes to thermal fleet retirement flexibility.	0	1
`Nuclear_Availability`	Controls whether new nuclear resources are eligible for capacity expansion through the `New_Build` flag. This parameter captures uncertainty associated with nuclear deployment feasibility and policy acceptance.	0	1
`IRA_InvCost_Multiplier`	Multiplier applied to clean energy investment costs representing continuation or rollback of IRA-style federal subsidies. Lower values correspond to stronger policy support and reduced capital costs for solar and storage technologies.	0	1
`OffshoreWind_Cost_Multiplier`	Scaling factor applied to offshore wind investment costs to represent uncertainty in supply chains, financing conditions, and technology maturation. Lower values reflect successful industry scaling, while higher values represent cost overruns and deployment challenges.	0.7	1.3
`OnshoreWind_Cost_Multiplier`	Scaling factor applied to onshore wind investment costs representing uncertainty in manufacturing, installation, and technology learning rates. Higher values reflect increased project costs and supply chain constraints.	0.7	1.3
`Battery_Cost_Multiplier`	Scaling factor applied to battery storage investment costs reflecting uncertainty in technology learning curves and critical mineral price volatility. Lower values represent strong manufacturing scale-up and declining storage costs.	0.8	1.2
`Solar_Cost_Multiplier`	Scaling factor applied to solar photovoltaic investment costs representing uncertainty in commodity pricing, tariffs, and supply chain conditions. Lower values correspond to continued solar cost declines, while higher values represent elevated deployment costs.	0.8	1.2
`Hydrogen`	Parameter representing uncertainty in hydrogen technology deployment, infrastructure expansion, and system integration costs. Lower values reflect rapid electrolyzer innovation and infrastructure scaling.	-50	80
`Line_Max_Reinforcement_MW`	Controls the maximum allowable transmission reinforcement and expansion capacity across transmission interfaces. Lower values represent permitting and siting bottlenecks, while higher values enable greater transmission buildout flexibility.	-50	100
`Demand_MW_z*`	Zonal electricity demand scaling parameter representing uncertainty in electrification growth from electric vehicles, heat pumps, and industrial demand. Higher values correspond to increased demand growth and peak system stress.	-20	20
`Demand_Flexibility_Multiplier`	Scaling factor controlling the availability of flexible demand resources such as demand response and smart charging. Higher values represent greater load flexibility and system-responsive electrification.	0.9	1.1
`Siting_MaxCap_Multiplier`	Scaling factor applied to maximum renewable deployment limits to represent land-use and permitting constraints. Lower values correspond to stronger siting restrictions and reduced expansion feasibility.	0.8	1.2
`Can_retrofit`	Controls whether existing generating units are eligible for retrofit or repowering pathways. This parameter evaluates the importance of retrofit-enabled assets in achieving cost-effective system decarbonization.	0	1

3.3.2 Parameter Bound Selection

Uncertainty bounds were selected to represent potential variation in technology costs, policy strength, infrastructure expansion, demand growth, and resource availability in long-term power system planning. Bounds were based on energy systems literature, policy assumptions, engineering judgment, and operational feasibility within the GenX framework.

Continuous parameters, such as technology costs, siting limits, and demand flexibility, were represented using bounded scaling ranges around baseline values. Policy-related parameters, including CO_2 caps, energy share requirements, and reserve constraints, were represented using bounded perturbation ranges, while binary planning decisions such as retirement, retrofit, and nuclear expansion eligibility were represented using discrete $\{0, 1\}$values. All parameters were implemented at zonal resolution across the 11-zone system, allowing independent or grouped regional perturbations during Morris trajectory generation. Morris sampling levels, trajectory counts, and grouped perturbation structures were selected to balance uncertainty coverage with computational tractability.

3.4 GenX Capacity Expansion and Optimization

For each Morris trajectory point, the GenX framework solved a constrained least-cost capacity expansion problem that minimized total system cost over the planning horizon while satisfying operational, transmission, reliability, and policy constraints. The optimization simultaneously determined generation expansion, storage deployment, transmission expansion, generator dispatch, and reserve allocation decisions under varying uncertain parameter realizations.

For each trajectory evaluation, the workflow consisted of:

1. Updating uncertain parameter values,
2. Constructing the scenario-specific GenX instance,
3. Activating the corresponding policy constraints,
4. Executing the optimization model, and
5. Extracting outputs for post-processing.

The Morris framework operated as a post-optimization sensitivity analysis layer coupled to GenX outputs. Each trajectory therefore required repeated independent optimization evaluations across the sampled uncertainty space. Outputs included both system-wide and zonally resolved planning metrics, including system cost, CO_2 emissions, prices, curtailment, firm capacity, transmission expansion, transmission flows, and transmission losses. For the NY State 2040 Current Policy model configuration used in this study, the framework generated 86 output metrics per Morris evaluation, enabling both aggregate and spatially resolved sensitivity analysis across the 11-zone system.

3.5 Morris Elementary Effect

The Morris method evaluates uncertainty by generating trajectories in the parameter space, where one parameter is perturbed at a time while all others remain fixed. Grouped design matrices were used to preserve coordinated zonal and policy-linked perturbations during trajectory generation. The resulting trajectories were mapped to bounded parameter values and evaluated through repeated GenX optimization runs.

Elementary effects were computed independently for each system-wide and zonal output metric. The elementary effect of parameter $i$for output metric $y$is defined as (Morris 1991):

$$EE_i = \frac{y(x_{t+1}) - y(x_t)}{\Delta_i}$$

where:

- $y(\cdot)$denotes the selected optimized GenX output metric, and
- $\Delta_i$represents the perturbation step size in the parameter space.

For each trajectory evaluation, optimized GenX outputs were collected and aggregated within a post-processing framework. Elementary effects were evaluated across outputs including system cost, emissions, transmission, curtailment, reliability, and zonal planning metrics. Multiple trajectories were generated to improve uncertainty space coverage. Elementary effects were computed from paired trajectory evaluations and aggregated across all trajectories for each uncertain parameter and output metric. Only finite-valued simulations were retained, and no normalization was applied to preserve the physical scale of outputs.

The global importance of each uncertain parameter was quantified using the mean absolute elementary effect (Morris 1991):

$$\mu_i^* = \text{mean}(\mid EE_i \mid)$$

This metric measures the average influence of a parameter on a selected system-wide or zonal output metric. Higher values of μ_i^*indicate greater overall parameter importance.

The variability of parameter influence was quantified using the variance of elementary effect (Campolongo et al. 2007):

$$\sigma_i^2 = \frac{1}{n-1}\sum_{r=1}^{n}(E\,E_{i,r} - \bar{EE_i})^2$$

This metric captures nonlinear behavior and parameter interactions for each evaluated output metric. Larger values indicate stronger interactions or greater sensitivity variation across the uncertainty space. Together, $\mu_i^*$and σ_i^2identify parameters that are both influential and structurally nonlinear across system-wide and zonal optimization outputs.

3.6 Visualization of Sensitivity Structure

Sensitivity results were visualized in a two-dimensional log-log effect structure space defined by (Campolongo et al. 2007):

$$x_i = \mid \mu_i^* \mid, y_i = \mid \sigma_i^2 \mid$$

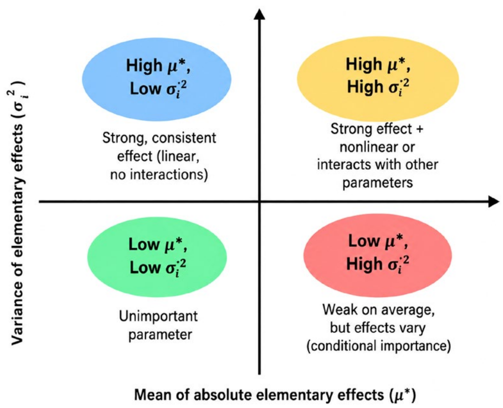


Figure 2: Morris qualitative interpretation framework to identify parameter importance as well as nonlinear parameter interaction on model outputs using mean absolute elementary effect (μ^*)and the variance of elementary effects (σ^2)

As illustrated in Figure 2, parameters with high (μ^*) values are considered globally influential on model outputs, while larger (σ^2) values indicate nonlinear behavior or interactions with other uncertain parameters.
To assess the importance of uncertain input parameters on system-wide and zonal outputs and how they rank against alternative policy constraints, a dashboard was created to assist with policy decision planning. Dashboard visualizations were developed for post-processing and sensitivity interpretation. Public release of the dashboard framework is reserved for future work.

3.7 Justification for Morris Screening Method

The Morris method was selected because the study evaluates a relatively large number of uncertain planning parameters within a computationally intensive capacity expansion modeling framework. Variance-based global sensitivity methods, such as Sobol analysis, typically require thousands of model evaluations to accurately estimate first-order and higher-order sensitivity effects, making their application computationally expensive for large-scale optimization models. In contrast, the Morris method provides an efficient screening approach that identifies influential parameters using substantially fewer model runs while still capturing nonlinear and interaction effects through the analysis of elementary effects. This balance between computational efficiency and sensitivity information makes the Morris method well-suited for policy-constrained capacity expansion planning studies involving multiple uncertainty dimensions.

3.8 Morris Experimental Design

The Morris sensitivity analysis was performed using 10 trajectories across 40 uncertain input parameters, resulting in a design matrix containing 155 parameter perturbation experiments. Binary policy variables were evaluated using two sampling levels, while continuous GenX planning parameters were evaluated using four sampling levels. The analysis was conducted across multiple policy scenarios, requiring repeated GenX optimization model evaluations to estimate elementary effects and parameter sensitivities. All simulations were executed on the Binghamton University Spiedie high-performance computing cluster using the Gurobi optimization solver. The selected experimental design provided sufficient coverage of the uncertainty space while maintaining computational tractability for large-scale capacity expansion analysis. Parameter rankings, elementary effects, and sensitivity trends were evaluated across policy scenarios to assess the consistency and stability of the resulting Morris sensitivity measures.

4. Data Collection

This paper presents a Morris-based global sensitivity analysis framework integrated with the GenX capacity expansion model for the New York 2040 planning system (MIT Energy Initiative and Princeton University ZERO Lab 2026). The framework evaluates uncertainty interactions across policy, technology, transmission, and demand assumptions while preserving zonal structure within a multi-region planning environment. The study focuses on the Current Policy 2040 scenario and examines both system-wide and zonally resolved planning sensitivities under multiple policy activation configurations.

The baseline NY State 2040 planning model was developed using a Power Genome-to-GenX workflow by Dr. Neha Patankar and provided the underlying system representation and policy assumptions used in this uncertainty analysis study (Patankar et al. 2026). The Morris-based uncertainty analysis framework grouped zonal perturbation methodology, policy activation structure, and sensitivity post-processing workflow were developed as part of the present work.

5. Results and Discussion

5.1 Numerical Results

This section presents Morris sensitivity analysis results across multiple policy activation configurations within the Current Policy *P*3 planning case. System-wide and zonal outputs are examined to evaluate how alternative policy constraints influence the importance and interaction structure of uncertain planning parameters.

Table 3: Top five uncertain input parameters with the highest Morris sensitivity importance for System Cost and NYC Zone J (Z8) zonal cost under multiple policy configurations.

Output	Policy	InputParameter	Mean	Variance	Rank
System Cost	CapResMar	Demand_MW_z8	2.5524547698993535e9	3.877880401673345e16	1
System Cost	CapResMar	Demand_MW_z9	7.819522374330933e8	2.711631361561178e15	2
System Cost	CapResMar	Demand_MW_z7	6.284463708635492e8	1.8283037233983628e15	3
System Cost	CapResMar	Demand_MW_z4	5.03445248331574e8	1.2968992562218272e15	4
System Cost	CapResMar	Demand_MW_z2	3.3700703893287665e8	4.949935147710868e14	5
System Cost	CO2Cap	Demand_MW_z8	7.276089629320994e9	6.065479099336608e17	1
System Cost	CO2Cap	Demand_MW_z9	1.558990675414409e9	1.3934566726273832e17	2
System Cost	CO2Cap	Demand_MW_z7	1.1718787610072567e9	1.9801030323140648e15	3
System Cost	CO2Cap	Demand_MW_z4	8.343067417042224e8	2.7663299918620466e14	4
System Cost	CO2Cap	Demand_MW_z6	5.285325273998611e8	1.2303079161733983e14	5
System Cost	Combined_Policy	Demand_MW_z8	7.19412372232877e9	6.523144115985559e16	1
System Cost	Combined_Policy	Demand_MW_z9	1.8684723487248218e9	4.038288009895124e16	2
System Cost	Combined_Policy	Demand_MW_z7	1.2798849157512922e9	6.378978131407497e15	3
System Cost	Combined_Policy	Demand_MW_z4	8.511300227509762e8	1.6518410627480638e15	4
System Cost	Combined_Policy	Demand_MW_z6	5.3403825090546376e8	4.7555084316491175e14	5
System Cost	Current_Policy	Demand_MW_z8	2480058161	2.47757E+16	1
System Cost	Current_Policy	Demand_MW_z9	757016712.5	1.03786E+15	2
System Cost	Current_Policy	Demand_MW_z7	608241989.6	6.99772E+14	3
System Cost	Current_Policy	Demand_MW_z4	468149566.8	4.38202E+13	4
System Cost	Current_Policy	Demand_MW_z6	304372556.8	3.30135E+13	5
System Cost	ESR	Demand_MW_z8	6.20452048959587e9	5.166719658396762e16	1
System Cost	ESR	Demand_MW_z9	1.9570020707921221e9	3.51060061414435e16	2
System Cost	ESR	Demand_MW_z7	1.3357685653944764e9	5.671447822571906e16	3
System Cost	ESR	Demand_MW_z4	8.779047736898478e8	3.7000648135646544e14	4
System Cost	ESR	Demand_MW_z2	5.72494088515467e8	1.620444934382046e14	5

Output	Policy	InputParameter	Mean	Variance	Rank
ZonalCost_NYC_Z8	CapResMar	Gas_Ret_2	1.44E+07	8.737337908646522e13	1
ZonalCost_NYC_Z8	CapResMar	Demand_MW_2	1.2041303966961034e7	6.568266498114265e14	2
ZonalCost_NYC_Z8	CapResMar	Gas_Ret_8	4.530700645682904e6	5.934171420886346e13	3
ZonalCost_NYC_Z8	CapResMar	Demand_MW_3	3.890274279426459e6	4.471528183047882e13	4
ZonalCost_NYC_Z8	CapResMar	Demand_MW_8	2.3699493743088846e6	2.440291396441004e14	5
ZonalCost_NYC_Z8	CO2Cap	Gas_Ret_2	1.25E+07	37740.324701711426	1
ZonalCost_NYC_Z8	CO2Cap	Demand_MW_5	3178.210505582393	3.118780349130517e7	2
ZonalCost_NYC_Z8	CO2Cap	Demand_MW_6	2134.37295	4.050880754731875e7	3
ZonalCost_NYC_Z8	CO2Cap	Demand_MW_7	2114.844378	1.1766344558294669e8	4
ZonalCost_NYC_Z8	CO2Cap	Demand_MW_3	2019.894126	7.155342554374295e7	5
ZonalCost_NYC_Z8	Combined_Policy	Demand_MW_2	1.0126483992239486e8	8.24656858571921e15	1
ZonalCost_NYC_Z8	Combined_Policy	Demand_MW_3	5.0576247388599604e7	2.007844045569586e15	2
ZonalCost_NYC_Z8	Combined_Policy	Demand_MW_4	2.065976850542015e7	1.2348591659364295e15	3
ZonalCost_NYC_Z8	Combined_Policy	Demand_MW_8	1.4774591815511206e7	7.240105841526515e14	4
ZonalCost_NYC_Z8	Combined_Policy	Demand_MW_6	1.3349760359732473e7	7.351779927110385e14	5
ZonalCost_NYC_Z8	Current_Policy	Gas_Ret_2	2.47E+07	3.717302897980022e13	1
ZonalCost_NYC_Z8	Current_Policy	Demand_MW_2	3.9441124940746855e6	5.520514184328903e13	2
ZonalCost_NYC_Z8	Current_Policy	Demand_MW_9	2.2338166665745904e6	3.4904294170359504e13	3
ZonalCost_NYC_Z8	Current_Policy	Demand_MW_8	2.1029664346738686e6	5.928012368466577e12	4
ZonalCost_NYC_Z8	Current_Policy	Gas_Ret_8	1.6974248927640498e6	2.0998511846787105e13	5
ZonalCost_NYC_Z8	ESR	Demand_MW_2	5.6449140899388604e7	8.480699530854145e15	1
ZonalCost_NYC_Z8	ESR	Demand_MW_3	4.046963853456834e7	4.317236480882359e15	2
ZonalCost_NYC_Z8	ESR	Demand_MW_8	1.7923131021570306e7	9.50966835361462e14	3
ZonalCost_NYC_Z8	ESR	Gas_Ret_2	1.38E+07	3.198621949995953e11	4
ZonalCost_NYC_Z8	ESR	Demand_MW_9	4.91E+06	3.441337027647305e14	5

Based on the baseline analysis as shown in Table 3, System-wide cost sensitivity is demand-dominated, while zonal downstate costs exhibit coupled sensitivity to both demand growth and thermal retirement uncertainty. Demand parameter for zone 8 (Demand_MW_8) exhibited the highest μ* value across all policy scenarios, confirming that demand uncertainty is the dominant driver of statewide planning costs. For NYC Zone 8, Gas_Ret_2 and Gas_Ret_8 exhibited strong zonal sensitivity, suggesting that specific natural gas resources play an important role in supporting downstate reliability, transmission flows, and local cost stability within the NYC-region planning environment. The strong influence of external zones suggests the importance of interregional coordination and transmission coupling, which will be explored in future work.

For comparison of all Policy case scenarios, system cost shows electrification-driven demand uncertainty remains the dominant driver regardless of policy structure. Policy activation altered the spatial distribution of dominant demand sensitivities while preserving demand growth as the primary statewide uncertainty driver. We see this where Demand_MW_6 is replaced by Demand_MW_2 for ESR and CapResMar policy case scenario for System Cost.

For NYC Zone 8 cost analysis, Gas_Ret_2 exhibited the highest Morris sensitivity under the Baseline scenario (μ*=1.44e7=8.73e13), indicating that gas retirement assumptions strongly influence local planning costs. Under the ESR scenario, demand-related parameters became more influential, with Demand_MW_2 exhibiting the highest sensitivity (μ*=5.64e7, σ=8.48e15). Under the Combined Policy scenario, demand parameters occupied all Top-5 sensitivity rankings, indicating that electrification-driven demand uncertainty becomes the dominant driver of zonal planning outcomes.

Due to space limitations, complete multi-output sensitivity result tables and supplementary zonal analyses are not included in the present conference paper. Additional results and supporting datasets are available upon request. Dashboard visualizations, release reserved for future work, was developed for post-processing and sensitivity interpretation.

5.2 Graphical Results

Although several external transmission-connected zones (NENG_Rest (Z1), PJM_EMAC (Z10) and PJM_Rest (Z11)), exhibited strong sensitivity influence within preliminary analyses, the discussion presented here focuses on New York State is comprised of eleven geographic zones from western New York (Zone A(Z2)) through Long Island (Zone K (Z9)). A map of the NYISO load zones is shown in Figure 3a to emphasize in-state planning behavior under the evaluated policy configurations (New York Independent System Operator 2023). Figures 3b and 3c present dashboard-based visualizations of Morris sensitivity results highlighting the most influential input parameters for system-wide and zonal cost metrics. The dashboard framework supports filtering by policy scenario, system output, and zonal parameter configuration. Figure 3d shows System cost sensitivity results demonstrated strong stability across all policy scenarios. Demand growth parameters consistently ranked among the most influential variables, indicating that future electricity demand uncertainty remains the primary driver of system cost outcomes. The introduction of carbon reduction, renewable energy, and reliability policies produced only minor changes in parameter rankings, suggesting that demand growth assumptions have a greater impact on long-term planning costs than individual policy constraints. Figure 3e shows unlike system-level results, parameter importance at the zonal level varied across policy configurations. Under the Baseline scenario, NYC Zone 8 costs were primarily influenced by gas retirement and demand growth assumptions. The CO_2Cap and ESR scenarios increased sensitivity to electrification-driven load growth and renewable integration, while the Capacity Reserve Margin policy increased the importance of firm capacity and reliability-related planning decisions. Under the Combined Policy scenario, demand-related uncertainties emerged as the dominant drivers of zonal planning outcomes, highlighting the growing importance of accurate demand forecasting under simultaneous decarbonization and reliability requirements.

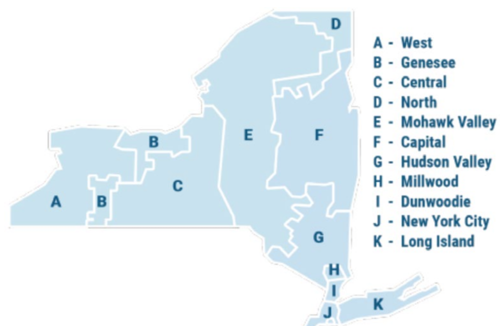


Figure 3: (a) NYISO load zone map.

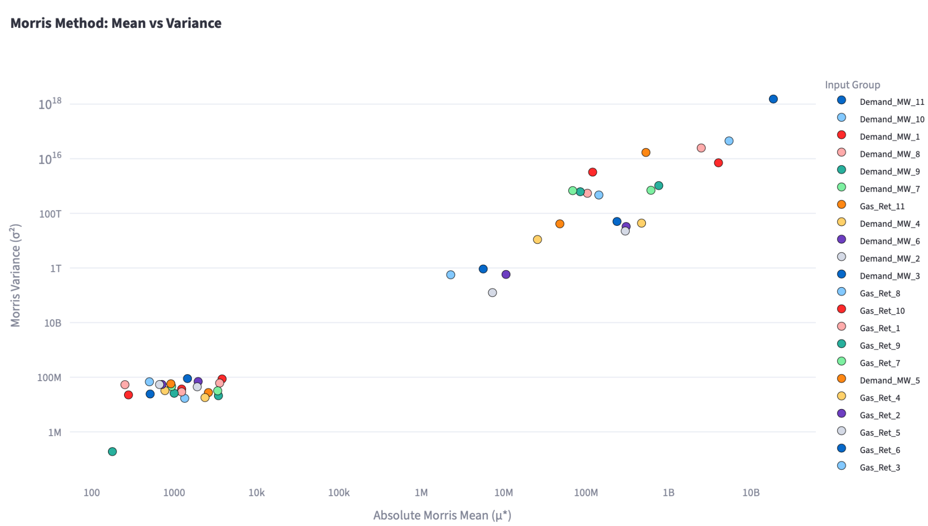


Figure 3(b): Dashboard visualization of Morris global sensitivity analysis results showing input parameter importance for System Cost under the baseline Current Policy 2040 scenario.

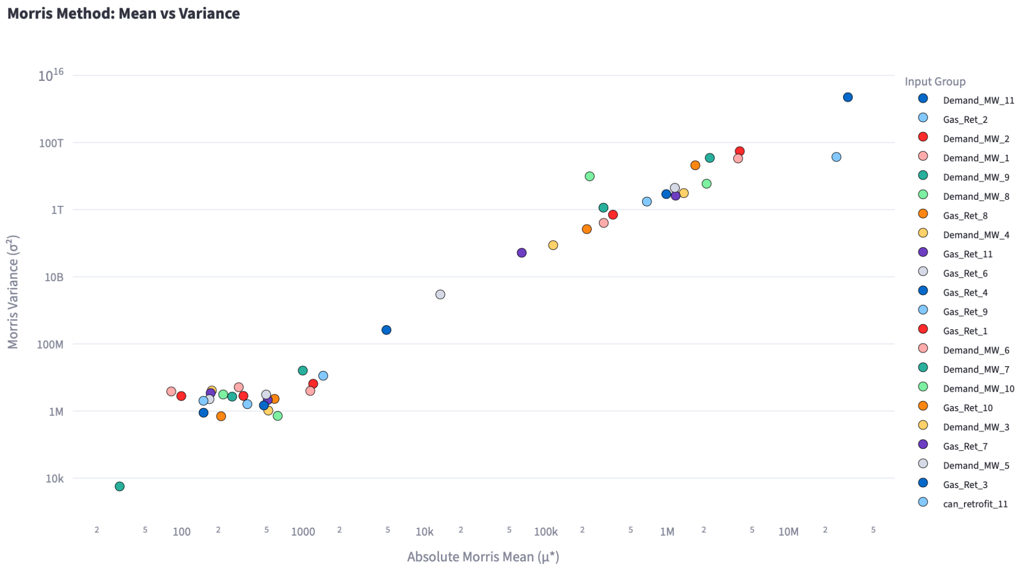


Figure 3(c): Dashboard visualization of Morris global sensitivity analysis results showing input parameter importance for NYC Zone J (Z8) zonal cost under the baseline Current Policy 2040 scenario.

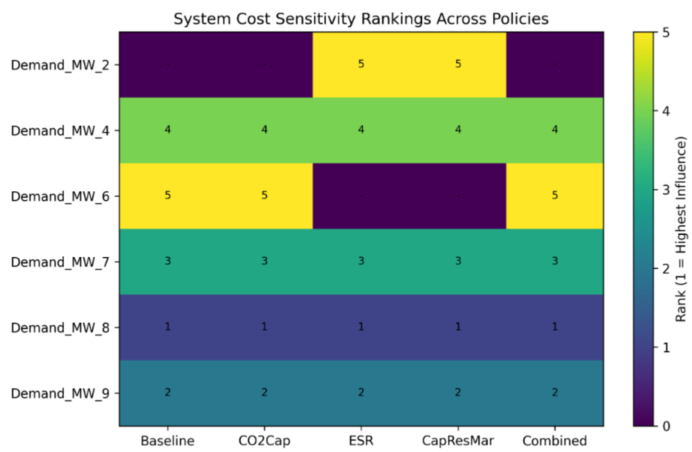


Figure 3d: Heatmap visualization of Morris GSA showing input parameter importance for system cost across different policy scenarios

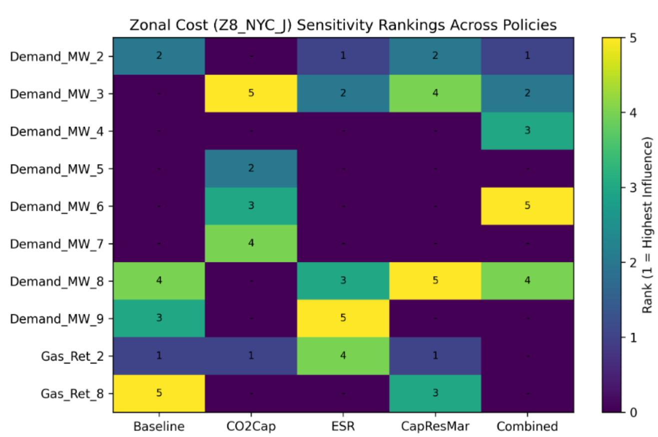


Figure 3e: Heatmap visualization of Morris GSA showing input parameter importance

For NYC (Z8) zonal cost across different policy scenarios

5.3 Proposed Improvements

Future work will extend the framework to reliability- and resilience-focused uncertainty analysis, including extreme weather conditions, probabilistic reliability assessment, and interregional transmission interactions within broader multi-system planning environments. Additionally, zonal analysis can be conducted across different infrastructure investment and tax relief policy scenarios. Incorporating machine learning techniques for uncertainty classification and surrogate modeling could improve computational efficiency for large-scale sensitivity studies involving higher-dimensional parameter spaces.

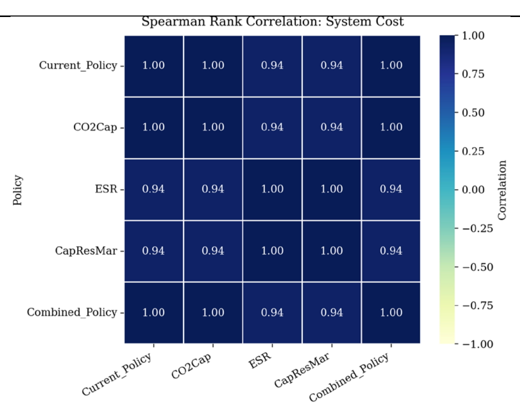
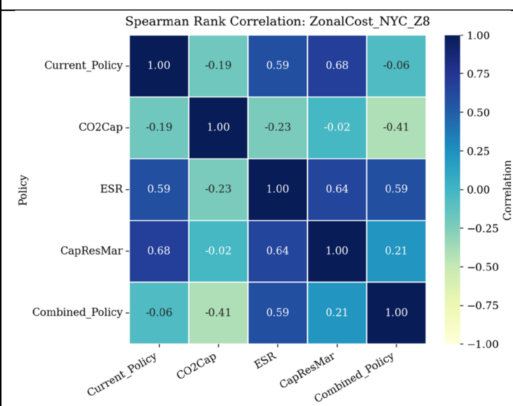
5.4 Validation

The Morris-based uncertainty analysis framework was validated through consistency checks of the GenX optimization outputs and comparison of model behavior under multiple policy activation and parameter perturbation scenarios. Baseline optimization results were first evaluated to confirm that the New York State 2040 planning model produced feasible generation, storage, and transmission expansion solutions consistent with the underlying Current Policy scenario assumptions developed by Patankar et al. (2026).

Validation of the uncertainty framework was further performed by examining the stability and reproducibility of Morris elementary effect calculations across multiple screening trajectories. Sensitivity rankings and zonal response behaviors were evaluated to ensure that parameter perturbations produced physically meaningful planning responses consistent with expected system behavior under varying demand growth, transmission expansion, renewable deployment, and policy conditions.

To provide quantitative validation of the Morris sensitivity framework, rank correlation analysis was performed across all policy scenarios. In Figure 3f, Spearman rank correlation and Kendall tau coefficients were calculated to evaluate the stability of parameter importance rankings for both System Cost and Zonal Cost (NYC Zone 8). For System Cost, the average Spearman correlation was 0.966 and the average Kendall tau coefficient was 0.920, indicating very strong agreement in parameter rankings across policy scenarios. These results demonstrate that dominant demand-related parameters remained consistently influential regardless of policy configuration, supporting the reproducibility and robustness of the Morris screening framework.

In contrast, Zonal Cost (NYC Zone 8) exhibited greater sensitivity to policy-specific assumptions, with average Spearman and Kendall tau values of 0.181 and 0.154, respectively. The lower rank correlations indicate that local planning costs are influenced by interactions between policy constraints, demand growth, and resource retirement assumptions, resulting in greater variability in parameter importance rankings. This behavior is consistent with the spatially resolved nature of the analysis and highlights the value of zonal sensitivity assessment. Overall, the validation results confirm the stability of system-level sensitivity rankings while demonstrating the framework's ability to capture policy-dependent uncertainty at the regional level.

Correlation Type	System Cost Validation	Zonal Cost – NYC Z8
Spearman Rank Correlation		

Kendall Tau Coefficient

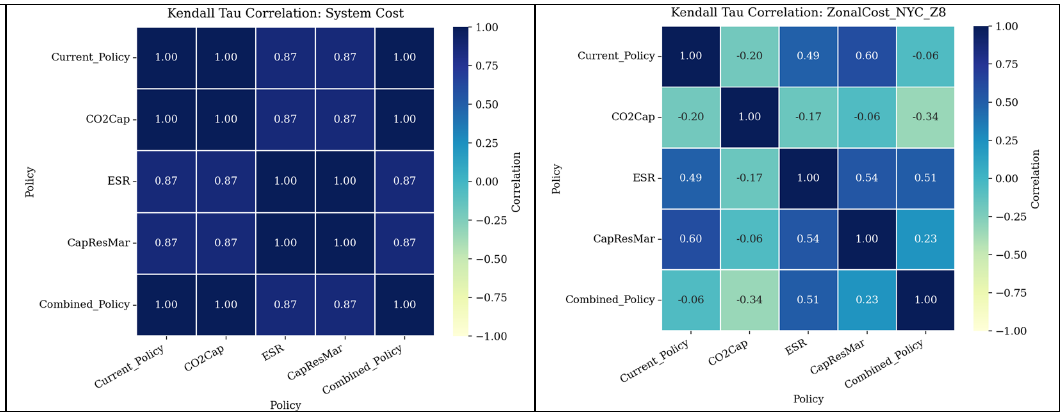


Figure 3f: Spearman rank correlation and Kendall tau correlation matrices used to evaluate ranking stability across policy scenarios.

In Table 4, Coefficient of variation (CV) analysis was also performed to evaluate the consistency of Morris sensitivity magnitudes across policy scenarios. For System Cost, the dominant demand-related parameters exhibited relatively low to moderate CV values ranging from 28.7% to 47.3%, indicating stable parameter influence despite changes in policy assumptions. In contrast, several NYC Zone 8 parameters exhibited substantially higher CV values, exceeding 100% in some cases, reflecting stronger policy-dependent variability in local planning sensitivities. These results further support the observed differences between system-level stability and zonal sensitivity behavior.

Table 4: Coefficient of variation (CV) of dominant Morris sensitivity parameters across policy scenarios for System Cost and Zonal Cost – NYC Zone8.

Output	Parameter	CV (%)
System Cost	Demand_MW_4	28.7
System Cost	Demand_MW_6	28.8
System Cost	Demand_MW_7	35.6
System Cost	Demand_MW_2	36.6
System Cost	Demand_MW_8	41.9
System Cost	Demand_MW_9	47.3
ZonalCost_NYC_Z8	Gas_Ret_2	34.4
ZonalCost_NYC_Z8	Demand_MW_8	88.8
ZonalCost_NYC_Z8	Demand_MW_2	103.5
ZonalCost_NYC_Z8	Demand_MW_3	107.6
ZonalCost_NYC_Z8	Demand_MW_6	141.4

6. Conclusion

This paper presented a Morris-based global sensitivity analysis framework integrated with the GenX capacity expansion model to evaluate uncertainty propagation across multi-zone, policy-constrained long-term power system planning scenarios. The framework combined grouped zonal uncertainty perturbations, dynamic policy activation, and repeated GenX optimization evaluations to examine both system-wide and spatially resolved planning sensitivities within the New York 2040 planning environment.

Results showed that electricity demand growth was the dominant driver of statewide planning costs across all policy configurations. Demand_MW_8 and Demand_MW_9 consistently ranked among the most influential parameters across all policy scenarios, exhibiting the highest μ^* values and demonstrating that demand uncertainty is the dominant driver of system cost outcomes. Policy constraints changed spatial sensitivity behavior, particularly in downstate regions where zonal costs were strongly influenced by natural gas retirement assumptions. Under combined policies, sensitivity behavior became more demand-driven and system-wide, while some regions exhibited weak or negligible responses under isolated policy conditions.

The results further demonstrated the value of spatially resolved sensitivity analysis for identifying regional planning risks, policy interactions, and operational dependencies that may not be visible through system-wide metrics alone. The proposed framework enables scalable evaluation of uncertainty across technology, policy, transmission, and demand assumptions while preserving zonal structure within the optimization process. This study is subject to several limitations. The analysis was performed using a screening-based Morris method and a predefined set of uncertainty ranges within a single planning horizon and scenario framework. Higher-order parameter interactions, probabilistic uncertainty distributions, and operational reliability constraints were not explicitly evaluated.

Future work will extend the framework through variance-based sensitivity methods, probabilistic reliability and resilience metrics, higher-resolution zonal representations, and the incorporation of extreme weather and climate-related uncertainties to support more robust long-term power system planning.

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Biographies

Shane Menezes is a PhD candidate in Systems Science at Binghamton University (SUNY). His research focuses on the reliability, resilience, and optimization of the New York State energy grid. His work combines modeling, simulation, sensitivity analysis, operations research, and network science. His research interests extend to net-zero carbon emission policy targets and future uncertainties, including the impacts of extreme weather events.

Dr Neha Patankar is an Assistant Professor at the School of Systems Science and Industrial Engineering at Binghamton University (SUNY). Her expertise is in multi-attribute computational modeling and decision-making for energy transition, focusing on the rapidly evolving electricity sector. Her research supports energy policy decisions under deep techno-economic uncertainty, reveals system-wide technology and resource tradeoffs, and evaluates pathways for economy-wide decarbonization. Before joining Binghamton University, she earned a PhD in Operations Research from North Carolina State University and served as an associate research scholar at Princeton University. During this time, she worked on the REPEAT(opens in a new window) and Open Energy Outlook(opens in a new window) projects highlighted by several U.S. news outlets. These projects provide a regular, timely, and independent environmental and economic evaluation of federal energy and climate policies.