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INTEGRATED MATHEMATICAL MODELING AND OPTIMIZATION OF POWER GRID RELIABILITY AND RESILIENCE UNDER EXTREME WEATHER AND RAPID LOAD GROWTH TO STRENGTHEN ENERGY SECURITY AND NATIONAL INFRASTRUCTURE RESILIENCE.

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ABSTRACT
Reliable electricity underpins economic activity, essential services, and national infrastructure. Extreme weather can damage network assets while increasing electricity demand, and rapid load growth can erode the capacity margins available to manage these disruptions. This study proposes an integrated mathematical framework for evaluating grid reliability and resilience under concurrent weather hazards and rising demand. The framework combines weather-dependent component failure and repair models, spatial load growth scenarios, and constrained power flow to estimate service interruptions and recovery trajectories. A stochastic optimization model evaluates investments in network reinforcement, energy storage, and flexible demand alongside operational decisions on reserve deployment and restoration sequencing. Candidate strategies are compared using expected unserved energy, interruption duration, critical load restoration time, and total system cost. Sensitivity analyses examine how correlated outages, uncertain demand growth, and prolonged repairs affect investment priorities and operational performance. By linking routine supply adequacy with service continuity and recovery during severe events, the framework supports coordinated planning and emergency response. Its intended contribution is to identify cost-effective measures that maintain electricity supply to critical facilities and strengthen national energy security under uncertainty.

Keywords:
Power grid reliability, infrastructure resilience, extreme weather, load growth, stochastic optimization, energy security.

1. INTRODUCTION

1.1 Electricity continuity and national infrastructure

Electricity supports healthcare, water supply, communications, transport and emergency response. A single substation outage can interrupt hospital equipment, pumping stations and telecommunications facilities that depend on the same local electricity supply [1]. These dependencies can also delay recovery when communications fail or damaged roads prevent repair crews from reaching affected equipment during severe weather [2].

Annual supply adequacy describes the ability of available resources to meet demand across plausible operating conditions over a year. Event resilience concerns how much service the system maintains during a severe disruption and how quickly it restores interrupted supply [3]. Within this study, energy security is assessed through expected shortage hours, expected unserved energy and the time required to restore critical load. A regional case informs national infrastructure planning through the essential services it supplies and the documented dependencies connecting those services to the wider network.

1.2 Why extreme weather and rapid load growth require joint analysis

Consider a transfer-constrained zone where new industrial connections raise baseline demand before a prolonged heatwave. Additional air conditioning increases peak demand while high temperatures can reduce generator output and transmission ratings [4]. Widespread heat can also place neighboring zones under stress simultaneously, reducing the support they can provide. Other hazards, such as flooding or high winds, can disable multiple assets within the same exposed area [5]. Concentrated load growth can shift the binding constraint to a particular local substation or supply corridor even when aggregate capacity appears sufficient.

Average demand forecasts and isolated contingency assessments provide useful planning reference points for evaluating proposed network investments [6]. A joint analysis examines whether coincident stresses cause longer interruptions when storage is depleted or repair access is restricted. The resulting investment choice depends on the cause of interrupted service. Additional supply addresses resource shortages, reinforcement improves transfer

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capability, and hardening or additional restoration resources can limit damage or shorten recovery at exposed locations.

1.3 Research aim, questions and contribution

This study integrates weather-conditioned demand, failure and repair models with chronological grid simulation and stochastic investment optimization. Chronological simulation links changing demand and equipment availability to network constraints and service restoration [7]. Three questions guide the analysis. First, how do severe weather and spatially concentrated load growth jointly affect annual shortage risk and disruption during individual events? Second, which combinations of reinforcement, hardening, storage, flexible demand and restoration resources reduce those risks within a common planning budget? Third, how do integrated plans compare with conventional expansion or targeted hardening when tested on independent historical events and plausible future scenarios?

The framework traces each investment through changes in asset availability and network deliverability to the electricity supplied to critical loads. It evaluates annual adequacy [8] alongside the depth and duration of critical service interruptions [9]. These questions determine the grid boundary, infrastructure dependencies and service outcomes represented in the model.

2. SYSTEM SCOPE, HAZARD SCENARIOS AND EVALUATION CRITERIA

2.1 Grid boundary and critical-service representation

Define the study region by its electrical boundary, including modeled internal buses or zones and the interfaces through which it exchanges power with neighboring systems [6]. Specify the base year, target years and investment stages. Inventory generation by technology and location, storage by power and energy capacity, and transfer interfaces by direction and rating. Classify demand as critical or other load and record the location, hourly demand profile and minimum service requirement of each critical load class [7].

Represent hospitals, water facilities and communications sites individually where feeder topology, backup supply, fuel endurance and switching arrangements are documented. Energizing a bus establishes upstream supply availability. Facility continuity also depends on the delivery path and the site's ability to transfer between grid and backup supply [8]. Where those details are unavailable, report the fraction of modeled critical demand served at the bus or zone. Use hourly dispatch for annual adequacy assessment and specify a separate restoration timestep suited to the resolution of switching and repair records. Apply consistent boundaries across portfolios.

2.2 Compound hazard and rapid load growth scenarios

Select hazards using the region's exposure history and the assets within the study boundary. Describe each weather event by intensity, onset, duration and spatial footprint, including overlap with other hazards. A heatwave may increase cooling demand and lower equipment ratings, while flooding can interrupt supply and restrict repair access [9]. Preserve shared weather exposure across neighboring zones and assets so simultaneous stresses remain visible [10].

Specify load growth by zone and customer class. Vary commissioning dates for large connections and state assumptions about their contribution to coincident peak demand and the flexibility available during shortages [11]. Cross two weather conditions with two growth paths to form four matched scenario families. Pair reference weather with reference growth and rapid growth, then repeat both growth paths under severe weather. Hold the starting fleet, network and operating rules constant when isolating the effects of weather and growth. Compare the combined case with each individual stress and the reference case. Use probability-weighted annual trajectories to estimate expected risk. Report selected high-consequence events separately and interpret their outcomes as conditional on the specified compound stress.

2.3 Reliability, resilience and standards comparison

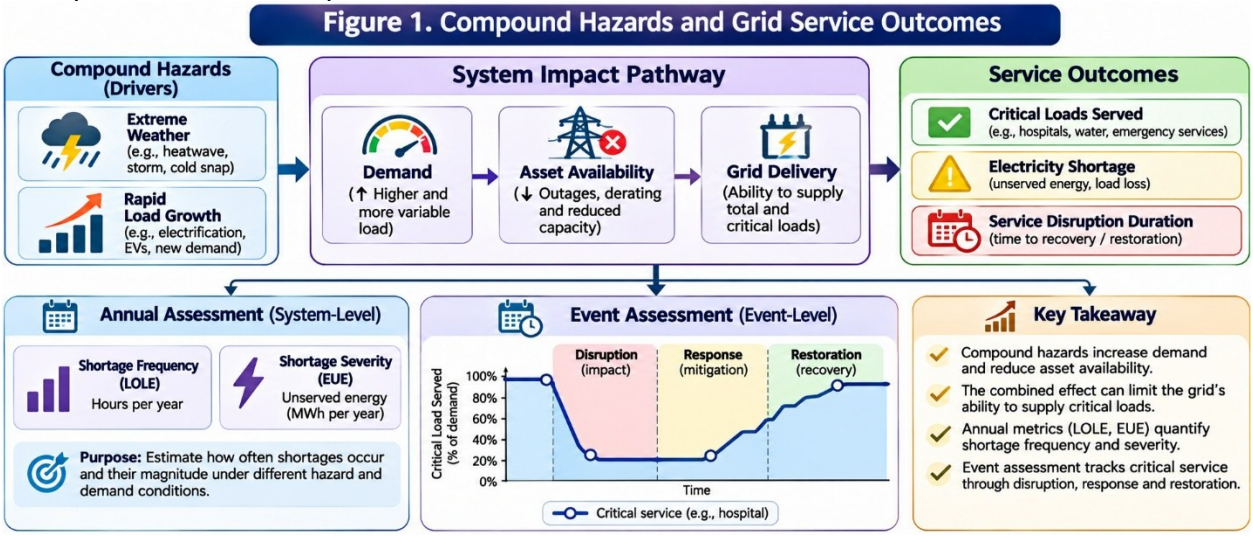
Prespecify annual loss of load expectation (LOLE) in hours and expected unserved energy (EUE) in megawatt-hours [12]. Before assigning thresholds, identify the applicable jurisdiction, planning authority and counting convention. For individual events, report the minimum fraction of critical load served, interruption duration and time to sustained restoration. Define sustained restoration using a specified service fraction and minimum holding period.

Use ENTSO-E's European Resource Adequacy Assessment as a methodological comparator for hourly LOLE and expected energy not served [13]. For an applicable North American case, compare modeled blackstart arrangements with NERC EOP-005 provisions on cranking paths and initial switching [14]. Confirm the governing edition and entity scope before assessing alignment. Set study-specific critical service and tail-risk criteria according to essential service requirements and tolerance for severe losses. These scenarios and criteria

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determine the weather observations, demand records, asset information and restoration evidence required to develop the model and test its performance.



3. DATA ACQUISITION, QUALITY CONTROL AND FEATURE ENGINEERING

3.1 Weather, demand and growth inputs

Acquire timestamped electricity demand and weather observations at the spatial resolution of the modeled grid. Map weather stations or grid cells to demand zones and exposed assets, retaining the original coordinates, time resolution and coverage. Record event dates, locations and footprints, including wind direction, persistent temperatures and flood depths where relevant and available [12]. Align weather and demand histories on a common chronology so regional peaks and concurrent exposures remain identifiable.

Define gross and net demand according to the reporting boundary, including how distributed generation is treated. Flag intervals when outages or curtailment suppressed recorded demand. Where unrestricted demand can be reconstructed, retain the estimate and its uncertainty separately from metered demand. Compile historical large-load additions and forward assumptions for industrial connections, electrification and other major developments [13]. Record the source, publication date, commissioning window and scenario basis for each projected increment. Distinguish committed connections from speculative additions and record their assumed coincidence with existing peak demand in each modeled zone.

3.2 Network, damage and restoration records

Compile network topology, equipment identifiers, normal and emergency ratings, generator availability and maintenance histories. Record storage power and energy limits, efficiency and operating restrictions. For each outage, document affected assets, onset, end, cause and observed damage [14]. Separate confirmed physical damage from protective trips and temporary deratings because recovery requirements differ. Link records to the topology and equipment configuration in service at the time of the event.

Use repair logs and switching records to distinguish outage onset, repair completion, asset energization and restoration of customer service [15]. Record crew assignments, spare availability, travel restrictions and backup supply where documented. Identify whether restoration occurred through repair, feeder transfer or temporary generation. Flag uncertain causes, incomplete work orders and unknown restoration times, retaining the original evidence and its level of certainty. Compile investment costs, operating costs and construction lead times for candidate interventions. State the currency, price year and cost boundary, and convert monetary inputs to a common real price basis before comparing investment options across planning years and portfolios.

3.3 Synchronization, quality control and mean deviation

Align timestamps, geographic identifiers and operating states before joining records. Check extreme values against weather observations and event logs before classifying them as errors [16]. Apply common aggregation windows and report valid coverage, sample size, mean, standard deviation and mean absolute deviation by zone, season and event class. Distinguish missing timestamps from right-censored durations, where observation ends before restoration. Retain censoring indicators for recovery models and identify the durations included in descriptive summaries.

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Equation 1. Mean absolute deviation about the mean

$$\mathrm{MAD}_{\bar{x}} = \frac{1}{n}\sum_{i=1}^{n}|x_i - \bar{x}|, \qquad \bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i.$$

Here, x_i is a comparable observation, such as daily peak demand in MW, n counts eligible observations and $\bar{x}$ is their arithmetic mean. Signed deviations sum to zero. Taking absolute values before averaging prevents cancellation and expresses dispersion in the original units [17]. Calculate each statistic for one variable and a consistently defined population.

3.4 Engineering predictors and planning inputs — 190 words

Construct weather predictors for intensity above defined thresholds, accumulated exposure, event duration and simultaneous exposure across neighboring assets. Select thresholds and lookback windows using engineering evidence and development data. Build demand predictors from calendar effects, heating and cooling requirements, recent peaks and changes in connected load known at forecast issuance [18]. Define the forecast horizon before calculating lagged variables. Use weather observations for historical reconstruction and weather forecasts for operational predictions when those forecasts are available.

Add asset class, location, rating and protection characteristics to failure models. For recovery models, use damage classification, accessibility, elapsed outage time and crew or spare availability as recorded at the prediction stage [19]. Update these predictors when new information becomes available. Keep future load growth and candidate hardening or crew expansion measures in the planning scenarios. Document how each intervention modifies equipment ratings, fragility or repair capacity, and identify effects based on engineering assumptions. Fit imputation, scaling and feature selection within each training fold. Record feature definitions, source timestamps and transformation rules so model inputs can be reconstructed for unseen periods and events before the resulting trajectories enter the chronological grid simulation and optimization.

Table 1. Data sources, engineered variables and provenance

Variable	Source and version to record	Spatial and temporal resolution	Units	Transformation	Availability at prediction time	Quality check	Main limitation
Electricity demand	Meter or system operator extract and revision date	Bus or zone, native interval	MW	Calendar effects, recent peaks and demand adjusted for documented interruptions where feasible	Metered history through the forecast issue time	Reconcile gross and net definitions and check outage flags	Unrestricted demand may require estimation
Weather and hazard exposure	Station archive, gridded dataset or forecast issue version	Site or grid cell, native interval	°C, m/s, degrees, m	Threshold exceedance, cumulative exposure and spatial overlap	Observations available by issue time, plus forecasts issued by then	Verify timestamps, location mapping and event footprints	Regional weather data may miss local extremes
Large-load growth	Connection register and planning scenario vintage	Zone and load class, commissioning stage	MW, date	Dated additions and assumed coincident demand	Based on the planning information available at each stage	Reconcile project status and check for duplicate additions	Commissioning dates and load profiles may change
Network and asset state	Asset register, topology snapshot and outage extract	Asset or interface, operating interval	MW, h, state	Exposure mapping, availability and derating indicators	Asset attributes and operating states known at issue time	Match each record to the topology in service	Damage causes and temporary ratings may be incomplete

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Variable	Source and version to record	Spatial and temporal resolution	Units	Transformation	Availability at prediction time	Quality check	Main limitation
Repair and service restoration	Work orders, dispatch logs and switching records	Asset or service area, event timestamp	h, crew count, state	Elapsed duration, accessibility, resource availability and censoring indicators	Information recorded by the recovery forecast time	Reconcile repair, energization and service restoration timestamps	Logging delays can obscure the sequence of actions
Intervention and cost inputs	Engineering estimates and investment scenario version	Asset or zone, planning stage	Currency, MW, MWh, months	Common real price basis and commissioning schedules	Scenario or decision inputs available at the planning stage	Check cost boundaries, capacity limits and lead times	Intervention effects may depend on engineering assumptions

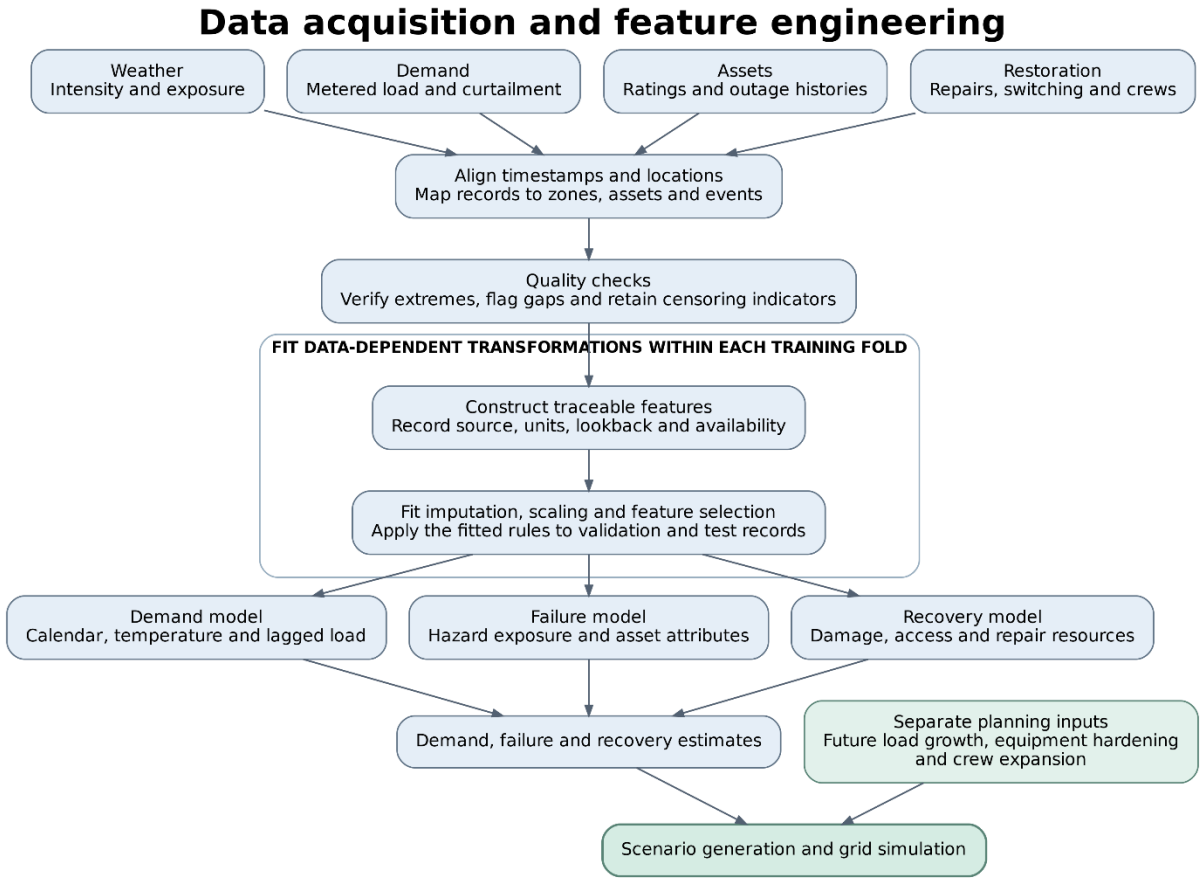


Figure 2. Data acquisition and feature engineering.

4. MODEL TRAINING, HYPERPARAMETER TUNING AND INDEPENDENT TESTING

4.1 Prediction targets and benchmark models

I estimate hourly demand quantiles, interval failure probabilities for assets available at the start of each interval, and repair durations for failed assets. For demand, I compare candidate forecasts with seasonal persistence and weather-sensitive regression [17]. For failures, I use historical rates by asset class and regularized logistic regression as benchmarks [18]. For repair, I compare a survival model with historical survival curves stratified by

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damage class. Both approaches retain right-censored cases [19]. I estimate statistical relationships from historical observations and take equipment ratings and operating limits from engineering records. Over the planning horizon, I condition forecasts on specified weather trajectories and dated load additions. I update projected demand as new connections enter service and retain scenario identifiers so each forecast can be traced to its assumptions by planning year.

4.2 Chronological splits and event holdouts

I allocate approximately 70% of eligible records to training, 15% to validation and 15% to locked testing using chronological blocks. I keep event onset, clustered failures and recovery together. Where repeated observations from the same assets could bias a transfer assessment, I group their histories and hold out the relevant assets. Within development data, I use rolling-origin validation and insert gaps where predictor or target windows would cross partition boundaries [20]. I fit preprocessing inside each training fold.

Where coverage permits, I withhold a complete severe event or geographic area to test transfer. I document actual dates, eligible observations, event counts by partition and departures from the planned allocation. I also reserve independent simulation trajectories for portfolio evaluation and open them after locking investment plans [21]. I label unprecedented climate conditions or demand growth as stress tests. Their outcomes describe performance under specified assumptions, while historical holdouts test agreement with observations. I report these assessments separately for each prediction task.

4.3 Hyperparameter tuning and probability calibration

I set comparable search budgets and record parameter ranges, random seeds and stopping rules. Depending on the model, I tune regularization, tree depth, minimum leaf size, learning rate, feature subsampling and lookback length. I assess demand quantiles with pinball loss and interval coverage, and repair duration with censoring-aware scores [22]. I use validation data for recalibration and preserve the original event distribution when testing models trained with weights or resampling.

Equation 2. Brier score for asset failure predictions

$$\mathrm{BS} = \frac{1}{n}\sum_{i=1}^{n}(\hat{p}_i - y_i)^2.$$

Here, n counts eligible asset intervals, $\hat{p}_i$ is the predicted failure probability and y_i equals one for failure and zero otherwise. Squaring and averaging produces a dimensionless score whose expected value is minimized at the true conditional probability [23]. The expected score equals outcome variance plus squared probability bias. I interpret it alongside calibration plots and precision–recall measures. Where event counts permit, I report scores by hazard severity and asset class. I select settings using validation performance on each task.

4.4 Locked testing and scenario generation

I lock predictors, fitted parameters and calibration before opening the historical test sets. I report demand errors, failure calibration and repair duration performance with uncertainty and event counts. I then check whether generated trajectories reproduce coincident demand peaks, clustered failures and prolonged recovery [24]. I use shared weather fields with correlated residuals or explicit common-cause states to represent dependence. I document scenario weights and check whether scenario reduction removes important joint extremes. I retain dataset identifiers for development, historical testing and scenario fidelity checks. The locked models then supply demand, damage and recovery trajectories for chronological grid simulation and independent evaluation of the selected long-term investment plans under matched conditions.

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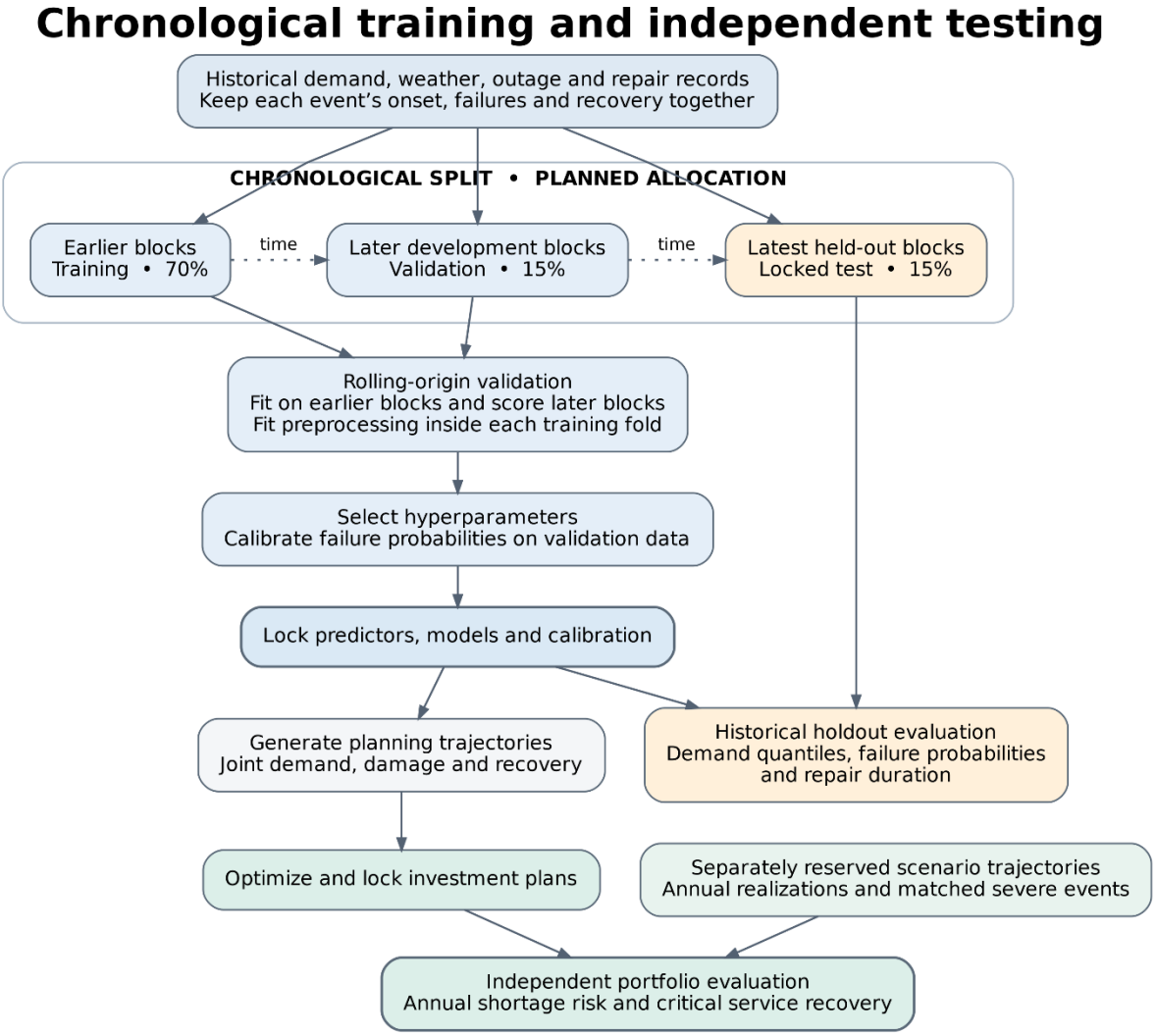


Figure 3. Chronological training and independent testing.

5. GRID SIMULATION, SERVICE RESTORATION AND INVESTMENT OPTIMIZATION

5.1 Weather-conditioned demand and asset availability

I generate hourly zonal demand from a weather-responsive baseline and dated additions by load class. I account for each addition's commissioning date, contribution to coincident peaks and available flexibility. I sample failures only for assets available at the start of an interval. Common storm tracks, flood footprints and temperature fields preserve shared exposure across assets [22]. After conditioning on exposure, I examine residual failure clustering and test whether a common-cause state improves its representation [23].

Equation 3. Failure probability over one interval

$$p^{F}_{i,t,s} = 1 - \exp\left[-\lambda_{i,t,s}\left(H_{i,t,s}, a_i, x_i\right)\Delta t\right].$$

In Equation 3, the hazard $\lambda_{i,t,s}$ is the conditional failure rate in inverse hours for asset i, interval t and scenario s. It depends on local exposure $H_{i,t,s}$, asset attributes a_i and hardening choice x_i. For constant hazard across the interval Δt, exponential survival gives the probability of remaining failure free. Subtracting survival from one gives the probability of failure within the interval. I document whether hardening adjustments come from engineering evidence or scenario assumptions. I combine repair durations with access delays and resource availability to determine when equipment becomes eligible for energization under the modeled operating conditions. Repair completion and energization receive separate timestamps.

5.2 Constrained dispatch and feasible restoration

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I dispatch generation within its available capacity and enforce directional transfer limits. For storage, I carry the state of charge between intervals, account for charging and discharging efficiencies, and enforce power and energy bounds. I limit demand response by activation duration, eligible load and rebound where applicable [24]. Dispatch uses the system information available at the decision time.

I schedule repair tasks subject to crew capacity, access conditions, spare availability and task precedence. I allow energization once equipment is available and a feasible supply path exists. Where the model represents blackstart, I enforce startup readiness and staged load pickup [25]. Candidate switching and energization sequences from a zonal model require separate checks of voltage, frequency and protection coordination.

Equation 4. Zonal power balance

$$G_{z,t,s} + P^{\mathrm{dis}}_{z,t,s} - P^{\mathrm{ch}}_{z,t,s} + I_{z,t,s} + R_{z,t,s} + U_{z,t,s} = D_{z,t,s}.$$

In Equation 4, all terms are in MW. G denotes dispatched generation, P^{dis} storage discharge, P^{ch} charging, I net imports, R voluntary demand reduction, U involuntary unserved load, and D demand before reductions. The equality follows from power conservation. Moving R and U to the demand side leaves the served load, which equals net physical supply. I constrain both reductions by eligible demand without double counting and track critical and other shortages separately. I enforce network feasibility at every step and scenario.

5.3 Annual adequacy and critical load recovery

I estimate annual shortage risk using complete chronological trajectories for each planning year.

Equation 5. Annual shortage duration and energy

$$(\mathrm{LOLE}_h, \mathrm{EUE}) = \sum_s p_s \sum_{t \in \mathcal{Y}_s} \Delta t_t \left(\mathbf{1}\left\{ \sum_z U_{z,t,s} > \varepsilon \right\}, \sum_z U_{z,t,s} \right).$$

In Equation 5, $\mathcal{Y}_s$ denotes the intervals of one simulated year, p_s its probability weight, and ε the numerical shortage threshold in MW. The weights sum to one. The indicator counts each interval once when total system shortage exceeds \(\varepsilon\). Multiplying by interval duration and weighting across trajectories gives expected shortage hours per year. The second component multiplies unserved MW by hours and averages across trajectories, yielding expected unserved energy in MWh per year [26]. I document how solver residuals are treated and check sensitivity to the shortage threshold.

For selected events, I plot critical service from onset through recovery.

Equation 6. Event-level critical service and critical energy not served

$$\phi_{t,s} = 1 - \frac{U^{\mathrm{crit}}_{t,s}}{D^{\mathrm{crit}}_{t,s}}, \qquad Q^{\mathrm{crit}}_s = \sum_{t \in \mathcal{E}_s} U^{\mathrm{crit}}_{t,s}\, \Delta t_t.$$

In Equation 6, D^{crit} is scheduled critical demand and U^{crit} is its unserved portion, both in MW. For intervals with positive critical demand, subtracting the unserved share from one gives the served fraction. Summing unserved power times interval duration over event window \(\mathcal E_s\) gives critical energy not served in MWh [27].

I report minimum service, disruption duration and elapsed time from event onset to sustained restoration. I prespecify the service threshold and the consecutive duration required to meet it. I treat incomplete recoveries as right-censored at the simulation cutoff. I record the last observed service fraction. Comparisons with planning criteria use the same time resolution and counting convention.

5.4 Risk-aware investment and emergency operations

I optimize investment timing, hardening, transfer upgrades, storage, flexible demand, spares and restoration resources. I enforce budgets, lead times and technical limits. Scenarios with the same revealed history share decisions until their information diverges [28]. I test whether richer dispatch assumptions or greater operational foresight change the preferred plan.

Equation 7. Conditional value at risk of annual critical energy not served

$$\mathrm{CvaR}_\alpha(L) = \min_\eta \left[\eta + \frac{1}{1-\alpha} \sum_s p_s \max(L_s - \eta, 0) \right].$$

In Equation 7, L_s is annual critical energy not served in MWh for a designated target year. The confidence level α defines the upper tail mass $1-\alpha$. The optimized threshold η and the probability-weighted excess above it yield the mean loss in that tail, with excess divided by the tail mass [29]. I use annual scenario probabilities for this calculation and report selected stress events separately.

Equation 8. Risk-aware planning objective

$$\min_{x,u} \sum_s p_s \sum_{y \in \mathcal{P}} \frac{C^{\mathrm{inv}}_{y,s}(x) + C^{\mathrm{op}}_{y,s}(u)}{(1+r)^{y-y_0}} + \gamma\, \mathrm{CvaR}_\alpha(L).$$

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In Equation 8, x denotes investment decisions, u operating decisions, and $\mathcal{P}$ the planning years. I discount investment and operating costs to base year y_0 at rate r and average their present values using scenario probabilities. The weight γ converts tail risk from MWh to present-value currency. I enforce annual adequacy limits and critical recovery requirements alongside the objective. I report the solver optimality gap and reevaluate the locked plan on independent chronological trajectories to assess annual adequacy and recovery under severe compound weather stresses.

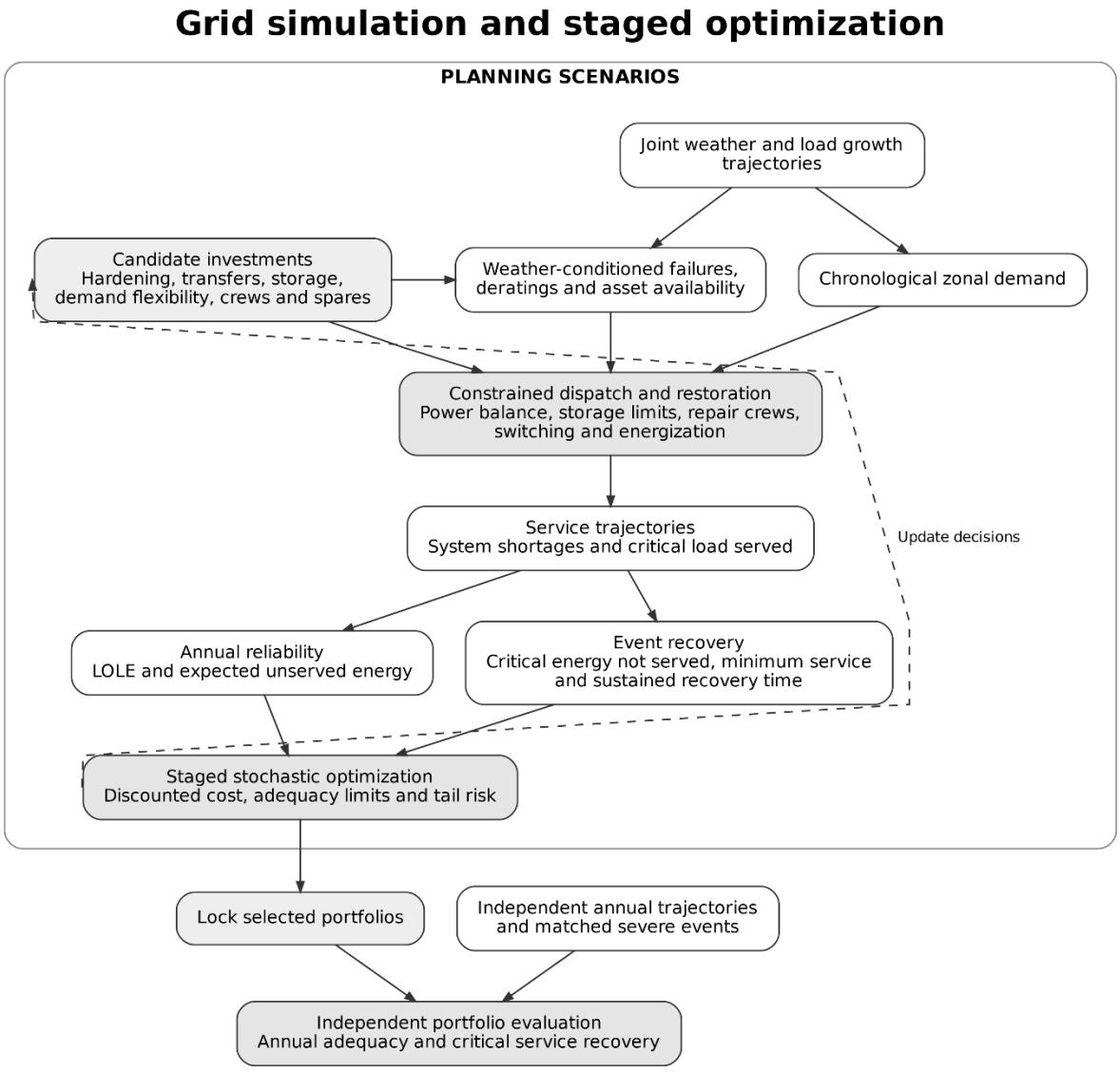


Figure 4. Grid simulation and staged optimization.

6. BENCHMARKING, RESULTS AND SENSITIVITY ANALYSIS

6.1 Prediction quality and historical event replay

Report the observation dates, geographic coverage, eligible asset intervals and counts of failures and repairs. Give the realized training, validation and test allocations, including any complete event reserved for transfer testing. Compare demand quantile loss and interval coverage against seasonal persistence and weather-sensitive regression. Compare failure probabilities against historical asset-class rates and regularized logistic regression using Brier scores and calibration plots [28]. Assess repair duration against damage-class benchmarks using measures that accommodate censoring [29].

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For each replayed event, align observed and reconstructed outage onset, affected zones, peak interrupted demand and restoration milestones. Check whether the reconstruction reproduces concurrent failures and prolonged repairs. Report gaps in asset records, unresolved repair durations and sparse coverage of severe hazards. Identify which quantities come from observations and which are simulated. Relate the largest discrepancies to the reliability and recovery estimates used in portfolio comparisons.

6.2 Portfolio benchmarking and compound-event effects

Evaluate four portfolios on matched independent trajectories: the committed-project reference, conventional capacity expansion, targeted hardening with the reference restoration policy, and integrated investment and restoration optimization. State the planning year, budget, available technologies, crew limits and commissioning constraints. Compare portfolios at equal budgets where feasible. Use equal-risk comparisons only when portfolios attain comparable outcomes under the same risk definition [30].

For each portfolio, report discounted investment and total system costs, annual loss of load expectation (LOLE) and expected unserved energy (EUE). For individual events, report critical energy not served, minimum critical service and time to sustained restoration. Compare the joint weather and growth case with the reference and each stress alone. Estimate their interaction by subtracting both single-stress outcomes from the combined outcome and adding back the reference. A positive interaction for EUE indicates that the combined increase exceeds the sum of the separate increases under matched assumptions [31].

Estimate uncertainty for paired portfolio differences using independent trajectory batches or resampling by weather year or event, as appropriate. Report unrecovered events as censored and identify the evaluation horizon.

Table 2. Independent reliability and resilience benchmarking

Portfolio	Planning year	Evaluation basis	Discounted investment / total cost ($m)	LOLE (h/year)	EUE (MWh/year)	Critical energy not served (MWh/event)	Minimum critical service (%)	Sustained recovery time (h)	Uncertainty or censoring
Committed projects	2035	Weighted annual trajectories	520 / 1,860	12.4	3,240	N/A	N/A	N/A	LOLE range 10.8–14.0 h/year
Conventional expansion	2035	Weighted annual trajectories	670 / 1,980	5.6	1,460	N/A	N/A	N/A	LOLE range 4.6–6.6 h/year
Targeted hardening	2035	Weighted annual trajectories	620 / 1,920	8.1	1,980	N/A	N/A	N/A	LOLE range 6.9–9.3 h/year
Integrated plan	2035	Weighted annual trajectories	670 / 1,950	3.2	780	N/A	N/A	N/A	LOLE range 2.5–3.9 h/year
Committed projects	2035	Heatwave with rapid industrial load growth	N/A	N/A	N/A	620	54	>48	Right-censored at 48 h
Conventional expansion	2035	Same heatwave and load growth case	N/A	N/A	N/A	430	63	39	Recovery confirmed within 48 h
Targeted hardening	2035	Same heatwave and load	N/A	N/A	N/A	270	74	29	Recovery confirmed within 48 h

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Portfolio	Planning year	Evaluation basis	Discounted investment / total cost ($m)	LOLE (h/year)	EUE (MWh/year)	Critical energy not served (MWh/event)	Minimum critical service (%)	Sustained recovery time (h)	Uncertainty or censoring
		growth case							
Integrated plan	2035	Same heatwave and load growth case	N/A	N/A	N/A	150	84	18	Recovery confirmed within 48 h

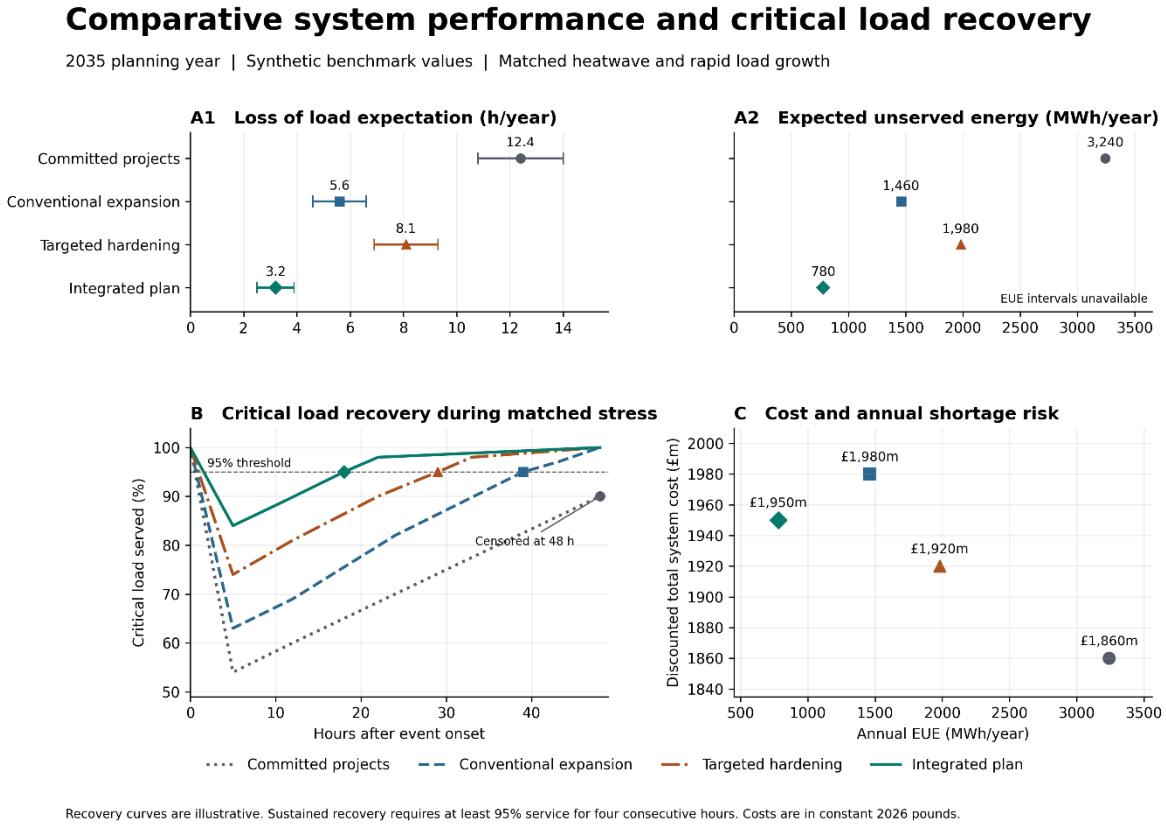


Figure 5. Comparative system performance and critical load recovery.

6.3 Standards, benchmarks and interpretation

Compare annual adequacy outcomes with the criterion adopted by the applicable planning authority. Record the jurisdiction, governing edition, system boundary, assessment period and counting convention before assessing attainment. Where uncertainty spans the criterion, report the result as inconclusive under the prespecified decision rule. Use the European Resource Adequacy Assessment methodology to compare chronological sampling and shortage metrics where relevant [32].

For network contingency performance, examine the applicable event set and identify which thermal, voltage and stability checks the model covers. For restoration, compare modeled energization paths, switching sequences, blackstart availability and operating limits with the applicable plan requirements [33]. Specify the additional engineering studies, operating records or approved procedures needed for a formal determination.

Assess critical service recovery against the study's stated threshold and holding period. Where a test grid is used, report methodological comparability and attainment of study criteria. Explain how aggregated loads and

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simplified network representation limit conclusions about individual facilities. Table 3 records the evidence and the decision basis for each assessment, including any outstanding checks.

Table 3. Standards and engineering acceptance matrix

Assessment domain	Authority or reference	Edition and applicability	Metric convention	Acceptance criterion	Evidence evaluated	Outcome	Interpretation limit
Resource adequacy	Applicable regional planning authority	Record governing edition and study area	Match shortage hours or days, assessment period and geography	Applicable adequacy threshold and uncertainty rule	Independent LOLE and EUE estimates	Pending	Applies to the modeled boundary and counting convention
Adequacy methodology	ENTSO-E European Resource Adequacy Assessment	Record comparator edition and relevant provisions	Chronological hourly assessment and weighted annual outcomes	Document methodological alignment and departures	Weather years, outage sampling, imports and shortage calculations	Pending	Establishes comparability with the selected methodology
Network contingency performance	Applicable transmission planning requirements	Record edition, entity scope and contingency categories	Event-specific thermal, voltage and stability checks	Applicable operating limits for each event class	Contingency cases, power flows and supporting studies	Pending	Findings cover checks completed at the modeled resolution
Restoration planning	Applicable restoration requirements, including NERC EOP-005 where relevant	Verify edition, jurisdiction and entity scope	Energization paths, switching sequence and operating limits	Applicable restoration plan provisions	Blackstart assumptions, simulated sequences and operating records	Pending	Formal assessment depends on the required engineering and procedural evidence
Critical service recovery	Study-specific objective	Prespecified for defined critical loads and events	Service fraction, holding period and elapsed time	Study threshold for sustained restoration	Event trajectories, recovery times and censoring flags	Pending	Applies to the modeled loads and evaluated events

6.4 Sensitivity, uncertainty and robustness

Vary hazard intensity, spatial failure dependence, load growth concentration, repair capacity, storage duration, import availability, investment costs and the tail-risk weight. Test individual changes first, followed by combinations that could reverse portfolio rankings [34]. Shift the timing and location of major connections to examine whether scarcity changes from system-wide capacity shortage to local transfer congestion.

Compare common-cause outages and delayed repairs against matched cases with each mechanism disabled in turn. Report their effects on critical energy not served and examine whether those effects interact. Recalculate annual and tail-risk estimates under alternative scenario weights. Check convergence across independent batches and disclose the number of trajectories contributing to the upper tail [32].

Identify assumptions that change the preferred resource, investment year or project location. Distinguish probability-weighted sensitivity results from outcomes conditional on selected stress events. Report whether changes in portfolio ranking persist after accounting for sampling uncertainty and differences in cost assumptions across scenarios [29].

6.5 Reproducibility and operational limits

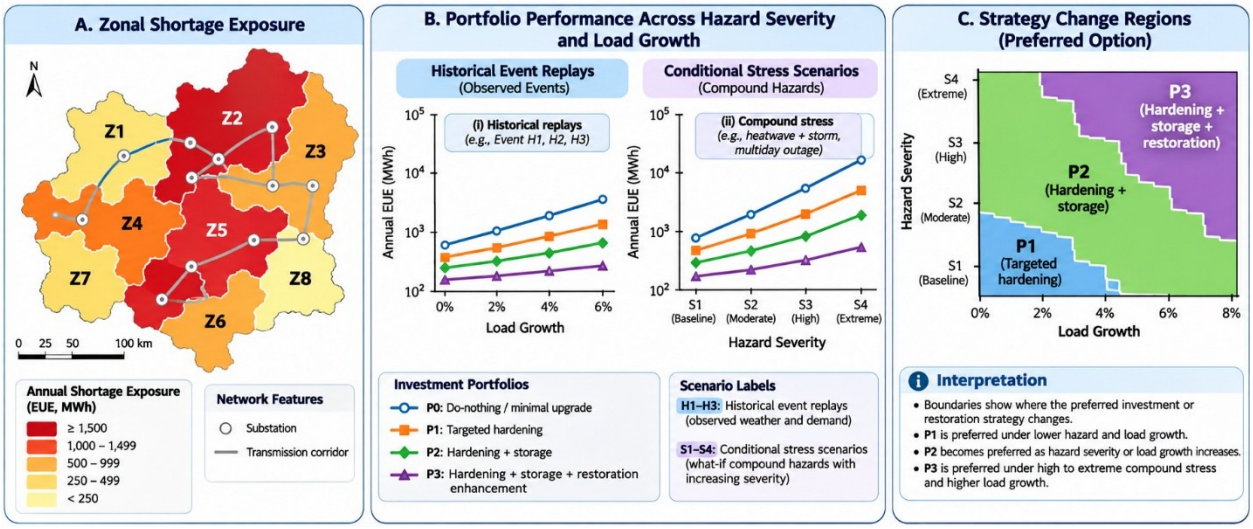
Record data versions, software releases, scenario counts, random seeds, runtime, solver tolerances and optimality gaps. Document scenario reduction, dispatch information and rules for restoration eligibility so the comparisons can be reproduced. Discuss how simplified networks, incomplete facility records and uncertainty in future hazards

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affect estimated shortages and recovery times [35]. Identify operational restrictions left outside the model, including switching, protection or crew constraints where applicable. Explain which results depend on the modeled grid, historical weather coverage or assumed intervention effects. Populate tables and figures from completed analyses and retain links between each result and its run identifier. These limits determine which investment choices can be supported and which require further validation.

Figure 6. Compound Stress and Investment Sensitivity



7. CONCLUSIONS AND INFRASTRUCTURE PLANNING IMPLICATIONS

7.1 Main findings and contribution

Held-out demand, failure and repair model scores remain unavailable for comparison with their benchmarks. In the synthetic 2035 comparison, the integrated plan reduced LOLE from 5.6 to 3.2 hours per year and EUE from 1,460 to 780 MWh per year relative to conventional expansion. Both portfolios required $670 million in discounted investment. Integrated total cost was $30 million lower, with an illustrative LOLE range of 2.5–3.9 hours per year. Under the combined heatwave and rapid growth scenario, the integrated plan maintained at least 84% critical service and reached sustained recovery in 18 hours. Targeted hardening recovered ten hours sooner than conventional expansion despite higher annual EUE. Matched single-stress cases are needed to establish whether the compound stress changes investment priorities.

7.2 Implications for energy security and critical infrastructure

Additional firm capacity addresses shortages when available supply falls below demand. Reinforcement improves deliverability where local transfer limits constrain service despite sufficient generation elsewhere. Hardening reduces exposure at vulnerable assets, while crews, spares and switching capability can shorten critical service interruptions. Planners should link investment timing to confirmed connections, projected corridor loading and documented changes in hazard exposure. Operators should verify restoration sequences, crew availability and achievable recovery times. Critical infrastructure owners should confirm minimum service requirements, feeder dependencies and backup endurance. Joint review of these inputs can identify which actions protect the critical loads represented in the study and when escalating exposure or load growth warrants revising the plan.

7.3 Validation priorities and transferability

The dependence between weather-related failures and repair delays could change the preferred portfolio. Validation should prioritize severe-event records that link outage timing, crew access and switching to actual service restoration. Facility-level checks should confirm feeder dependencies and backup endurance wherever continuity is assessed. Transfer to another grid requires rebuilding local demand, hazard and asset models, applying the relevant planning criteria and reevaluating candidate portfolios on independent trajectories before investment decisions.

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