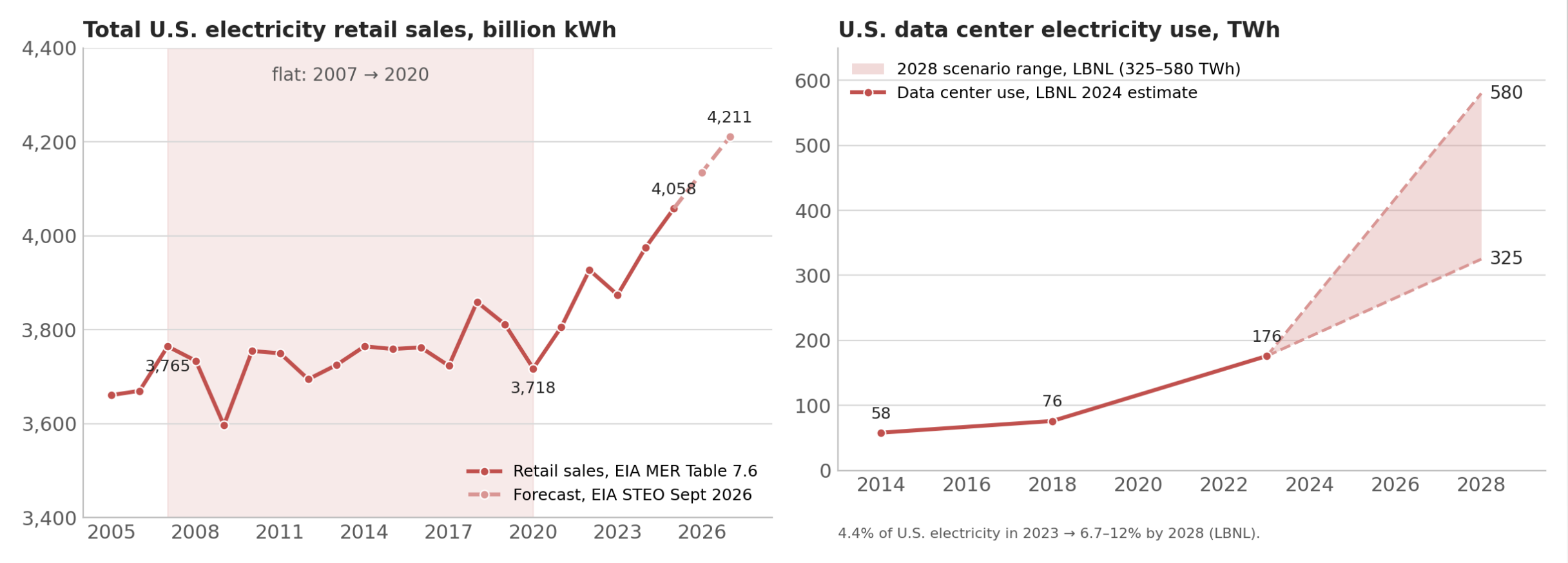


Advanced Reactor PRA under Evolving Conditions: Practitioner Insights, New Paradigms, and Case Study Applications

Constantinos Frantzis
Kaveh Faraji Najarkolaie
Yunfei Zhao
Jennifer Irish
Mohammad Modarres
Michelle (Shelby) Bensi

U.S. electricity demand: flat for 15 years, now rising



Sources: U.S. EIA, Monthly Energy Review Table 7.6 (total retail sales, 2005–2025); Short-Term Energy Outlook, Sept. 2026 (2026–2027 forecast).
Shehabi et al. (2024), 2024 United States Data Center Energy Usage Report, LBNL, doi:10.71468/P1WC7Q.

The nuclear industry is evolving rapidly

Advanced nuclear technologies

SMRs · microreactors · MSRs · LMRs · HTGRs

1

Enhanced safety

inherent features and passive systems

2

Shorter construction timelines

modular, factory-fabricated

3

Lower cost

smaller up-front capital, lower operating cost

4

Lower emissions

firm low-carbon capacity

5

Flexibility

multiple scales, siting and load-following options

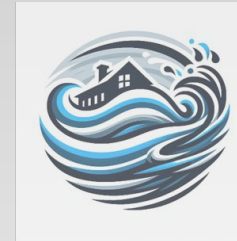
Safer by design — but not immune

Passive systems, weak driving forces, limited operating experience

Hazards whose frequency, severity and duration evolve



Drought



Flooding



Sea Level Rise



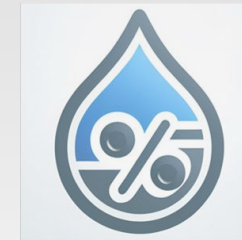
Extreme Cold



Wildfire



Tropical Cyclone

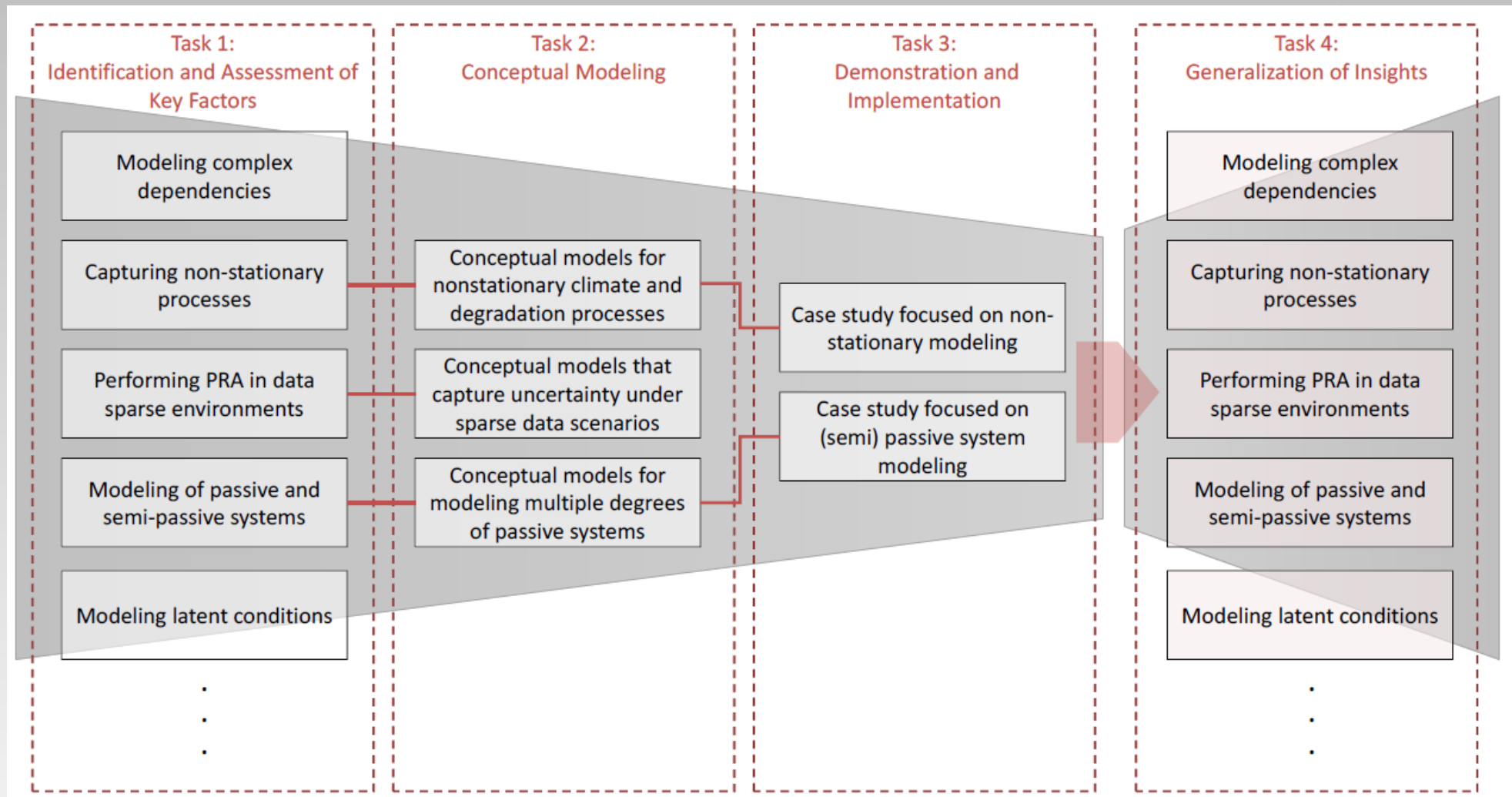


Humidity

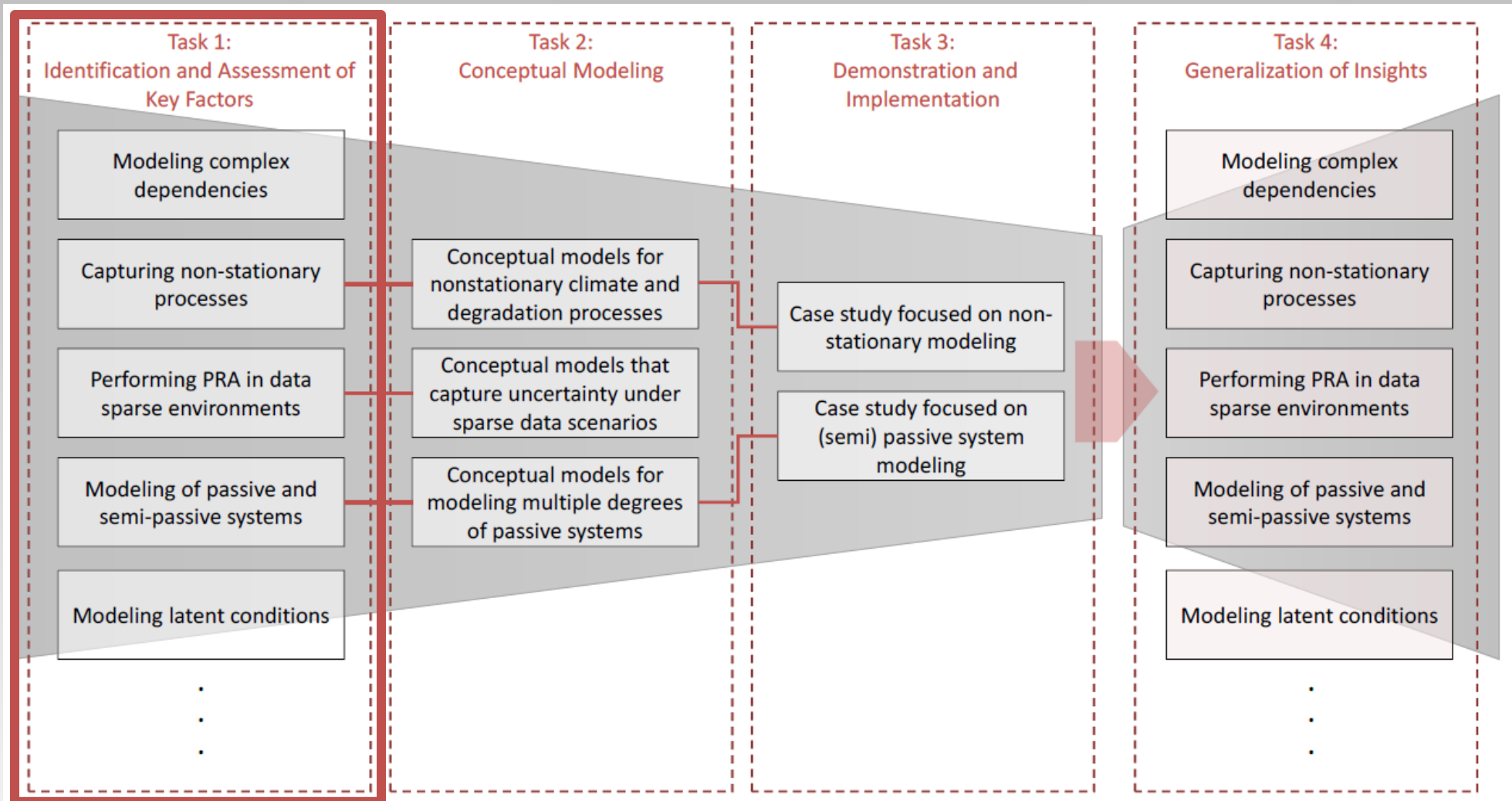


Extreme Heat

Both strain external hazard PRA with present-day tools



Project focus: PRA challenges for advanced reactors exposed to evolving meteorological and hydrological hazards



Project focus: PRA challenges for advanced reactors exposed to evolving meteorological and hydrological hazards

Practitioner questionnaire

Oct 2024 – Feb 2025

500+ recipients · 70 responses

Asked about

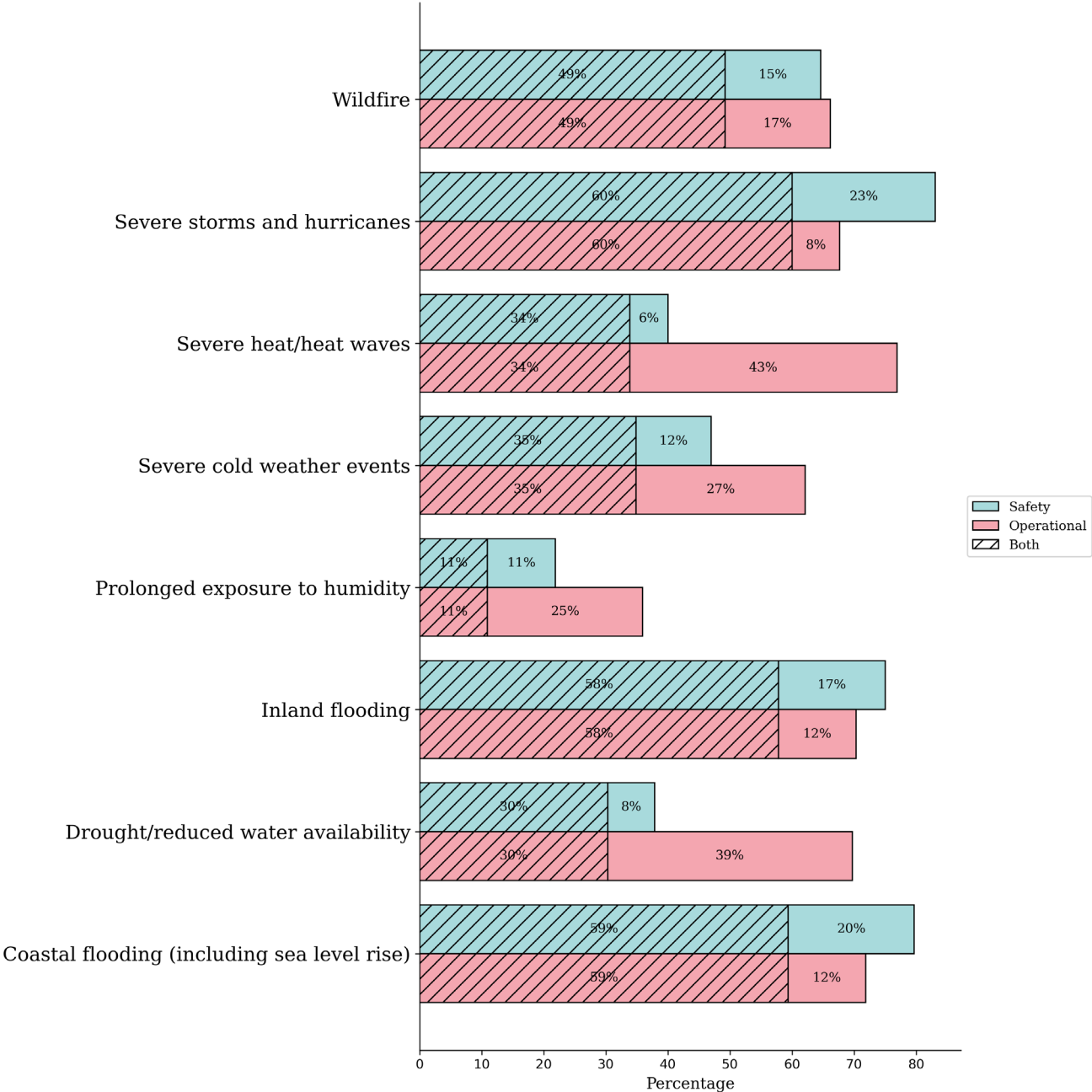
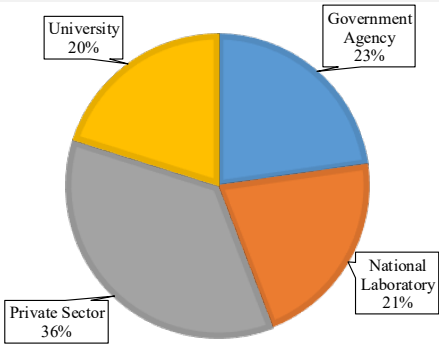
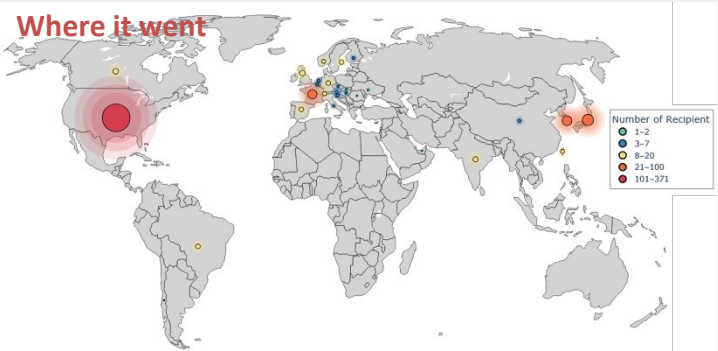
PRA challenges for advanced reactors

Their effect on PRA quality

Tools and strategies in use

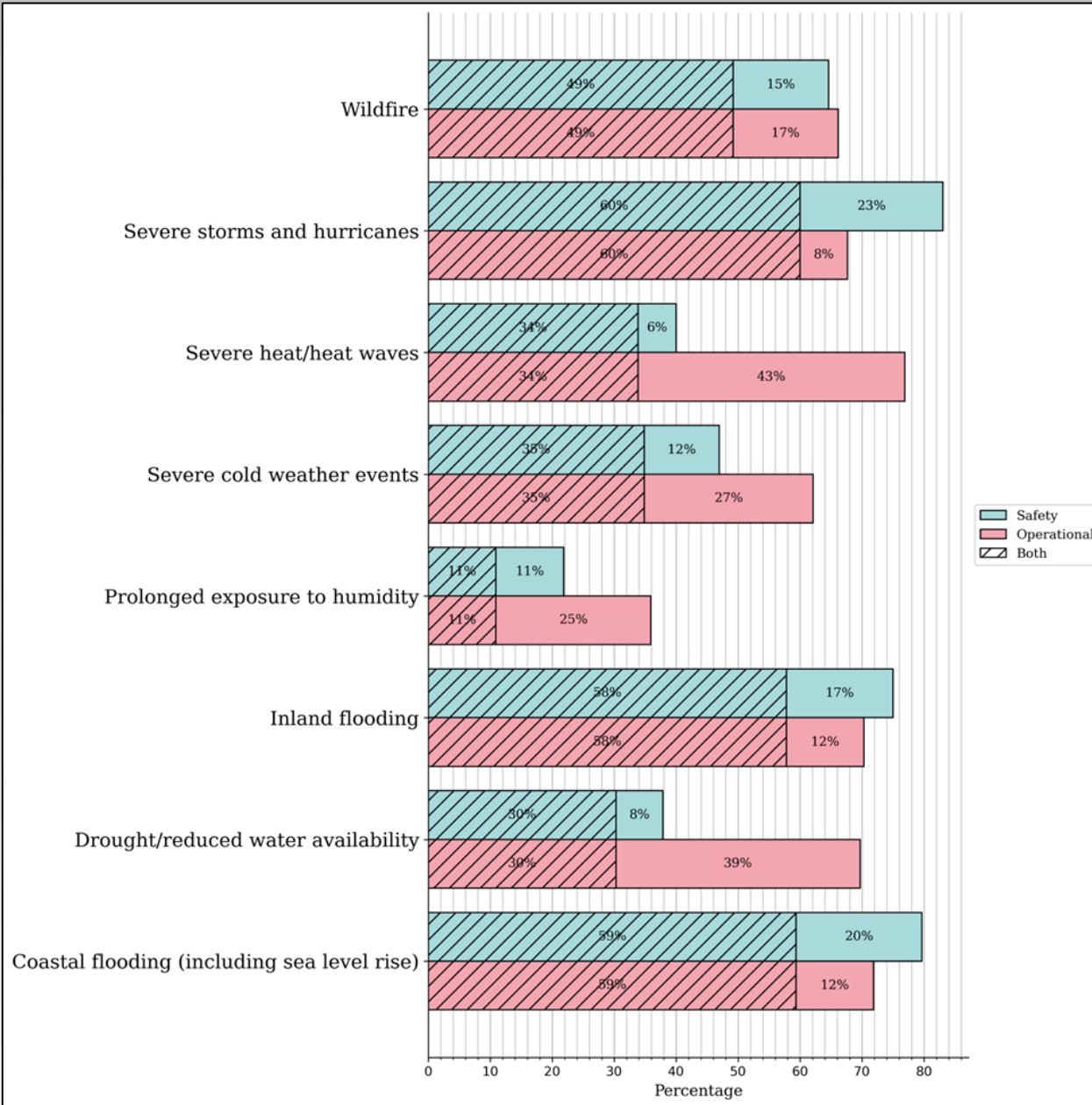
Which weather and water hazards matter

Where it went



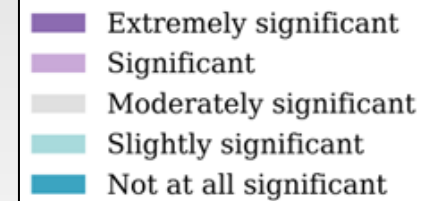
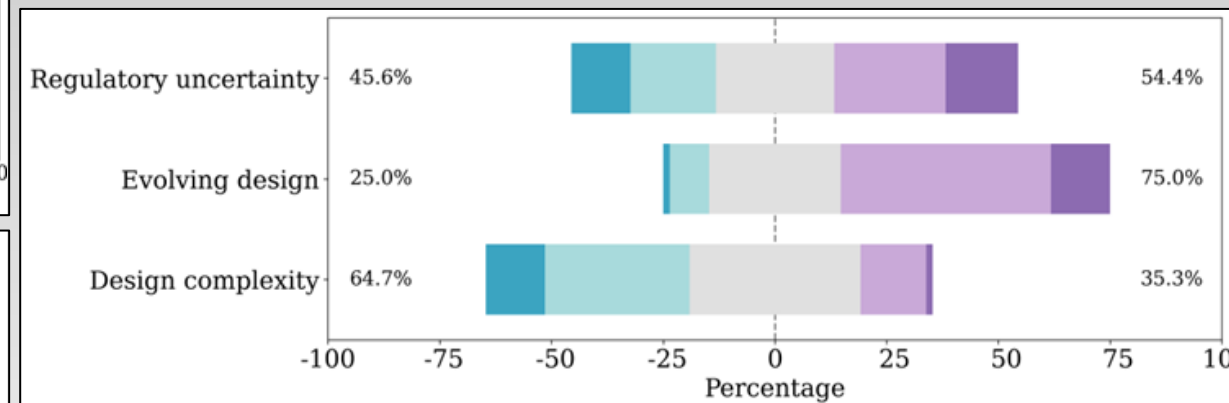
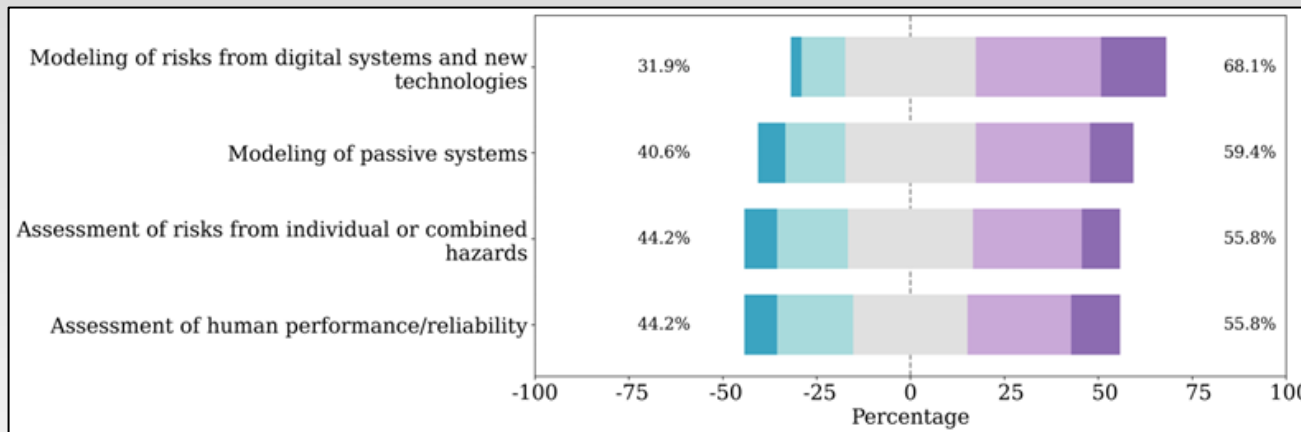
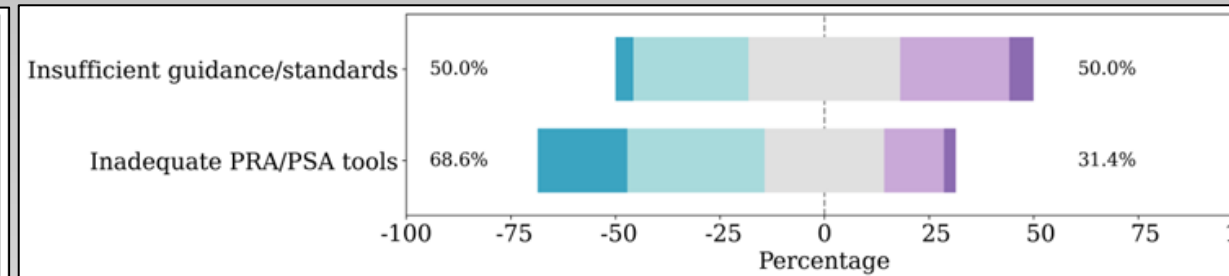
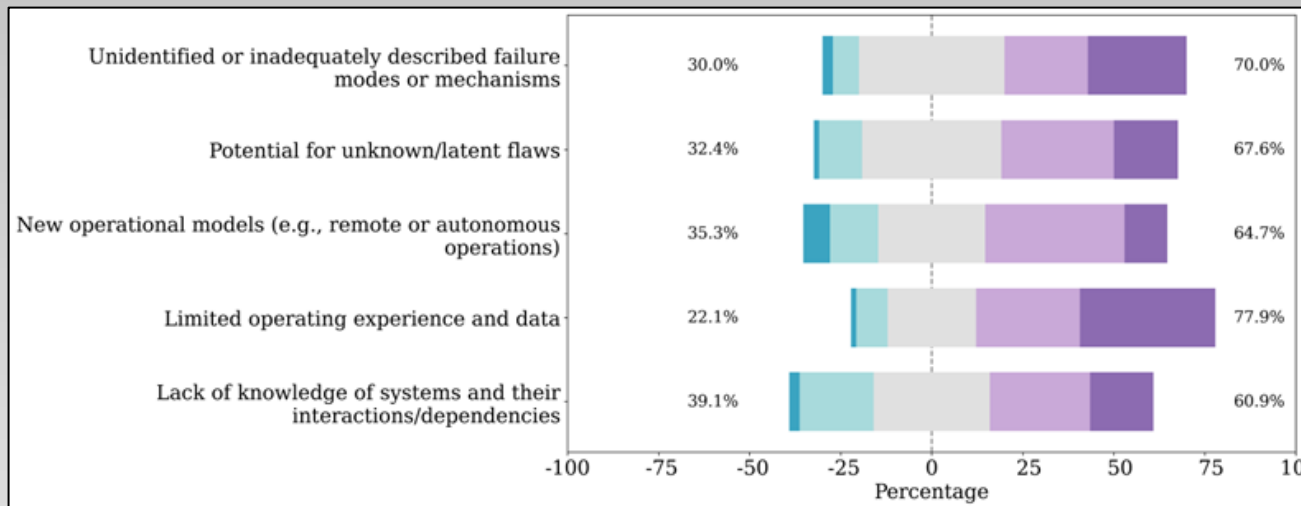
Source: Faraji Najarkolaie, Zhao, Irish, Modarres & Bensi (2026), Nuclear Science and Engineering, doi:10.1080/00295639.2026.2690569

Which hazards matter?



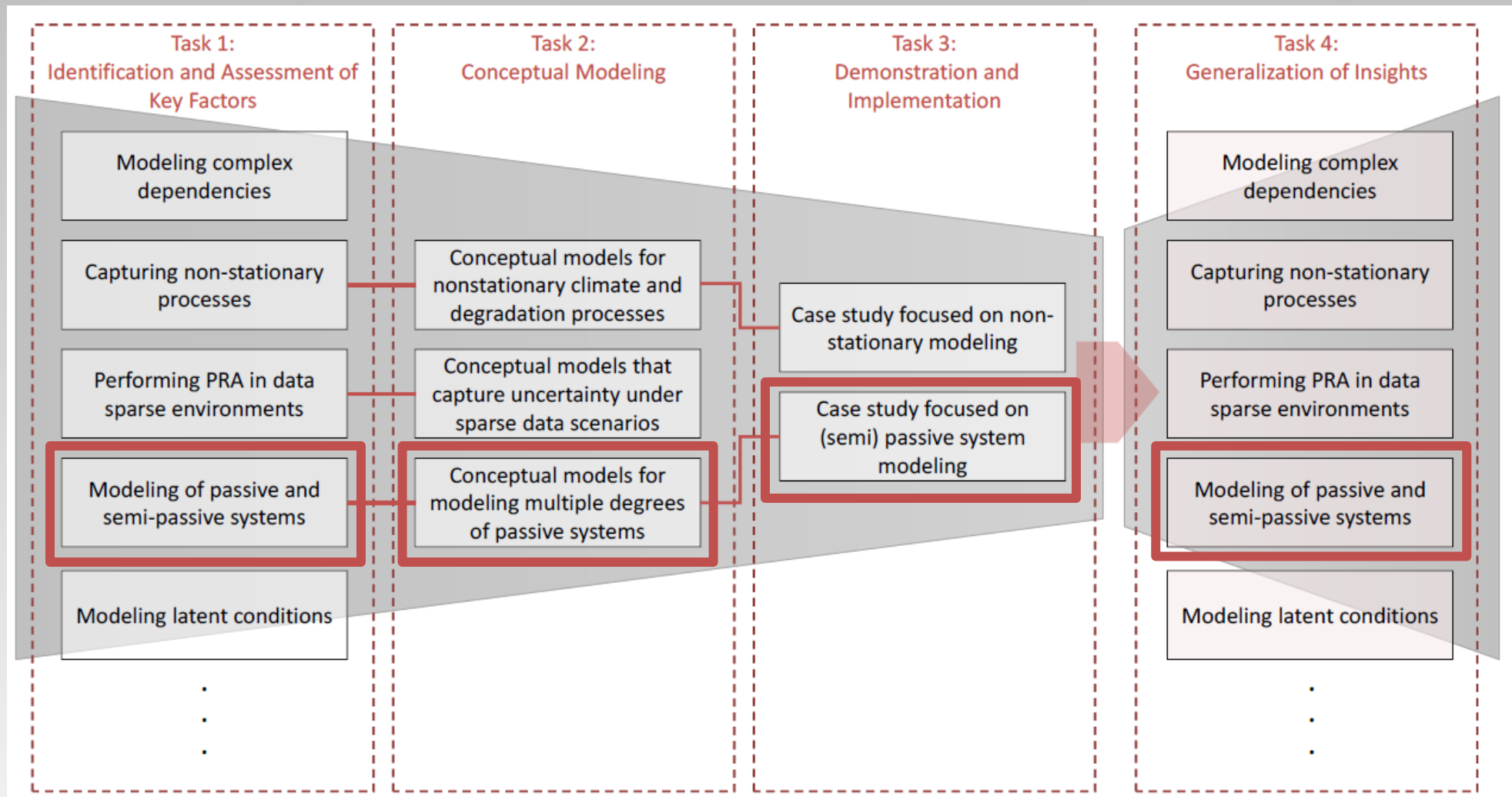
Safety: storms, coastal and inland flooding
Operations: heat, cold, drought, humidity
Both: wildfire

Where the PRA challenges are

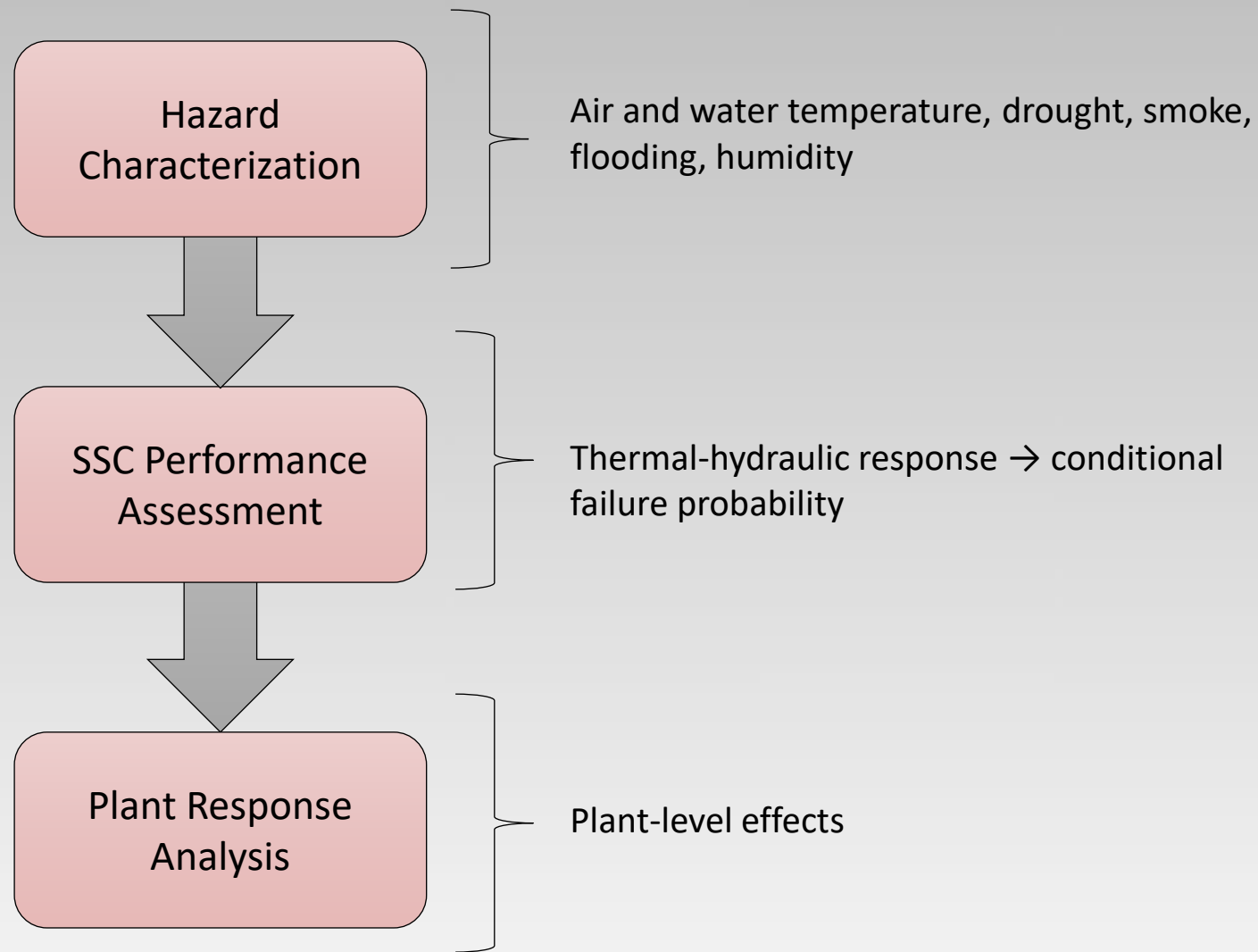


Top three: limited operating experience, evolving design, unidentified failure modes

Also flagged: modeling passive systems and new technologies



Next: passive safety systems under evolving conditions



Open issues

- Uncertainty
- Sparse data
- Validation
- Correlations

Current phase: literature review and exploratory analyses to inform passive-system modeling under non-stationary hazards

Why passive systems are sensitive to these hazards

Common-cause effects	Persistence	Regional reach
Hazard demands and air/water temperature and availability move together	Heat, drought and flood conditions can last days to weeks	Multiple sites or clusters, offsite resources, integrated grids

Non-stationary hydro-meteorological hazards perturb the boundary conditions that weak driving forces depend on

Coupled physics + uncertainty quantification → failure probabilities under varying boundary conditions

Reactor type	Passive system	Heat transfer mechanism	Ultimate heat sink	Key boundary conditions	Refs
Water-cooled SMR	Reactor pool, DHRS	Natural circulation boil-off air convection	Atmosphere (via pool)	Pool inventory, pool temperature, ambient air temperature	[30], [31]
MSR	RVACS ¹ , DRACS ² , Freeze valve, drain tank, coolant at atmospheric pressure	Gravitational drain natural circulation heat pipes	Atmosphere	Ambient air temperature, freeze valve thermal margin	[32], [33], [34], [35]
LMR	RVACS, DRACS, coolant at atmospheric pressure	Natural circulation thermal radiation convection	Atmosphere	Ambient air temperature	[24], [36], [37]
HTGR	Reactor Cavity Cooling System (RCCS)	Thermal radiation Natural convection	Atmosphere	Ambient air temperature	[38], [39], [40], [41], [42]
¹ Reactor Vessel Auxiliary Cooling System, ² Direct Reactor Auxiliary Cooling System					

Boundary conditions are what hydro-meteorological hazards perturb.

Safety: functions retained across moderate ambient variation



Production: environmental / heat-sink temperature among the most influential parameters



Safety margins hold; production margins shrink

Operating experience: generation lost, safety intact

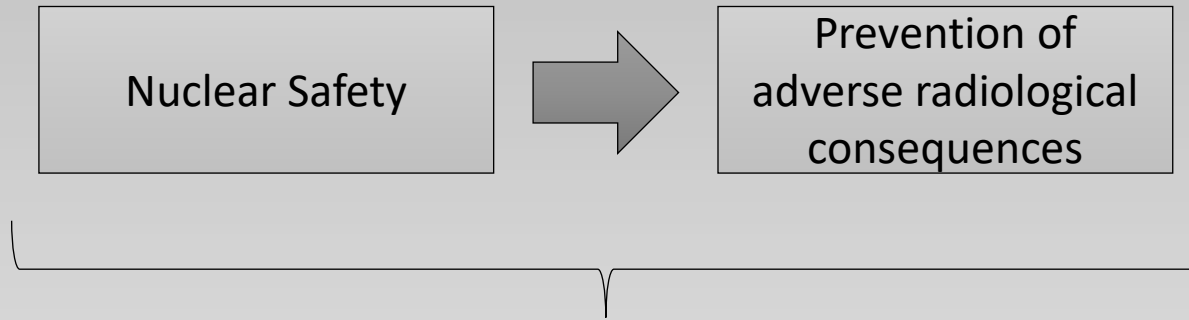
When	Event	What happened	Radiological consequence	Generation consequence
2003 → 2026	Heat waves, France (Rhône, Garonne, Gironde, Seine)	Repeated curtailments and unit shutdowns to respect river discharge limits; ~7 GW offline in July 2025, ~4 GW (~7% of demand) in June 2026	None	Recurring; fleet-wide mean loss projected to rise from ~0.3% to ~1.5% by mid-century
2017	Hurricane Irma, Florida	Unscheduled outages at Turkey Point and St. Lucie	None	Multi-unit, multi-day
2018	Hurricane Florence, North Carolina	Brunswick offline for nine days	None	Nine days, two units
2020	Derecho, Iowa	Duane Arnold cooling towers damaged	None	Plant never returned to service
2025	Heat wave, Switzerland	Beznau: one unit shut, the other derated when the Aare exceeded 25 °C	None	Unit-level shutdown and derate

None of these was a radiological event. Every one was a generation event.
The heat-wave cases were regional, hitting several plants in the same grid at once.

Sources: Collet et al. (2025) Energy 320:135207; U.S. EIA Today in Energy (2017, 2018, 2020); Ember / RTE / ENSI reporting on the 2025 and 2026 European heat waves.

	Deterministic Safety Assessment	Probabilistic Risk (Safety) Assessment	Generation Risk Assessment
Objective	Confirm safety under assumed conditions	Likelihood of adverse consequences	Risk of losing generation
Approach	Plant response to conservative scenarios	Logic models (event / fault trees)	Same logic models, plus balance-of-plant
Metrics	Margins to safety limits	CDF, LERF	Trip and derate frequency, outage duration
Outcomes	Compliance confirmed	Risk insights and contributors	Expected MWh lost and its drivers

The conventional framing



PRA quantifies CDF and LERF

A safe shutdown in a heat dome is not a radiological event but it has a societal cost

Should generation availability be a decision objective?

Essential functions served

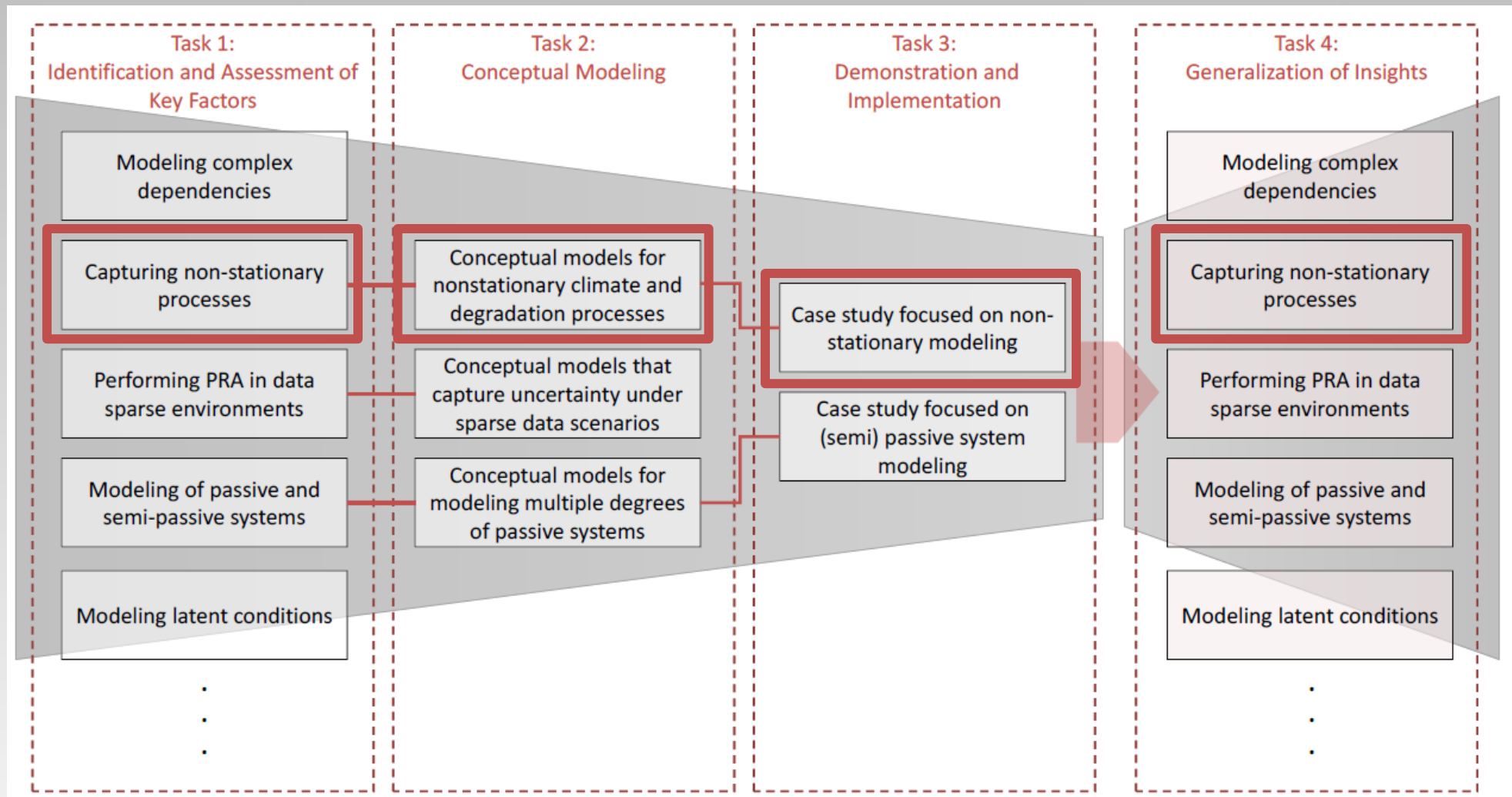
- Energy
- Water
- Transportation
- Health
- Food
- Datacenters/AI



What disruption costs

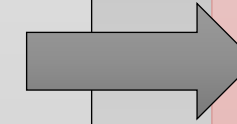
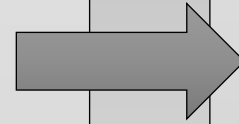
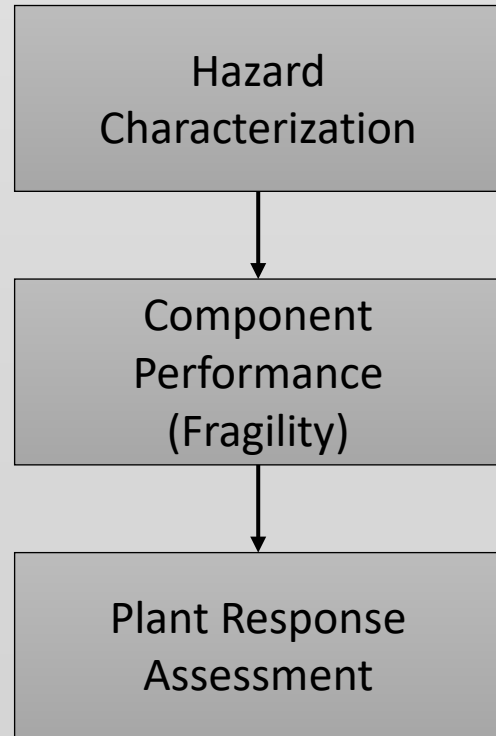
- Well-being
- Economy
- Safety
- Security

Nuclear plants are critical infrastructure



Now: decisions — should generation count? → risk-informed decision-making

External Hazard PRA

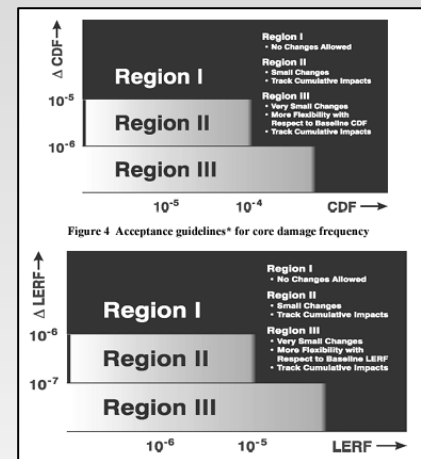


Risk-Informed Decision-Making

Current RIDM guidance assumes stationary risk



Trade-off: treating non-stationarity explicitly costs more up front; the benefit is uncertain



Estimated Reduction in CDF	Staff Action
>10 ⁻⁴ /reactor year	Proceed with the regulatory analysis on a high-priority basis.
10 ⁻⁴ -10 ⁻⁵ /reactor year	The decision whether to proceed with the regulatory analysis is to be made by the responsible division director.
<10 ⁻⁵ /reactor year	Terminate further analysis unless the office director decides otherwise, based upon strong engineering or qualitative justification.

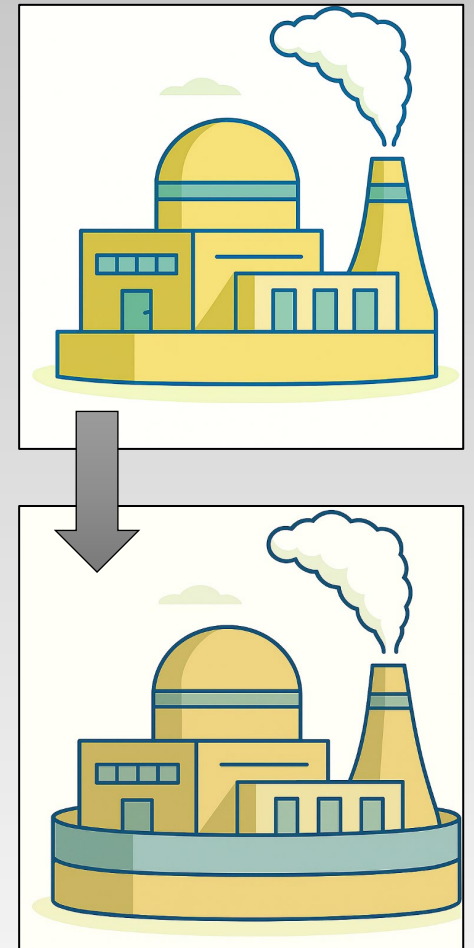
Change in Core Damage Frequency (ΔCDF)/RT	15	1x10 ⁻³	1x10 ⁻⁴	1x10 ⁻⁵	1x10 ⁻⁶
1x10 ⁻³	Proceed To Cost-Benefit Portion of Regulatory Analysis	Proceed To Cost-Benefit Portion of Regulatory Analysis* (Priority)			
1x10 ⁻⁴	Management Decision Whether to Proceed with Cost-Benefit Portion of Regulatory Analysis	Proceed To Cost-Benefit Portion of Regulatory Analysis			
1x10 ⁻⁵	Management Decision Whether to Proceed with Cost-Benefit Portion of Regulatory Analysis	Management Decision Whether to Proceed with Cost-Benefit Portion of Regulatory Analysis			
1x10 ⁻⁶	No Action Taken**	Management Decision Whether to Proceed with Cost-Benefit Portion of Regulatory Analysis			

$\Delta CDF < 1E-6$ $\Delta LERF < 1E-7$
$1E-6 < \Delta CDF < 1E-5$ $1E-7 < \Delta LERF < 1E-6$
$1E-5 < \Delta CDF < 1E-4$ $1E-6 < \Delta LERF < 1E-5$
$\Delta CDF > 1E-4$ $\Delta LERF > 1E-5$

CDF = Core damage frequency
LERF = Large early release frequency

Case study: flood protection for a sample plant

- **Hazard:** external flooding — top safety concern, longest outages
- **Decision variable:** flood-wall height when the design flood may shift
- **Protection strategies**
 - Permanent wall to a bounding height
 - Temporary barriers deployed on forecast
 - Staged foundation, raised as conditions become clearer
- **Decision rules compared**
 - Deterministic scenario · time-dependent PRA · robust decision-making · adaptive pathways



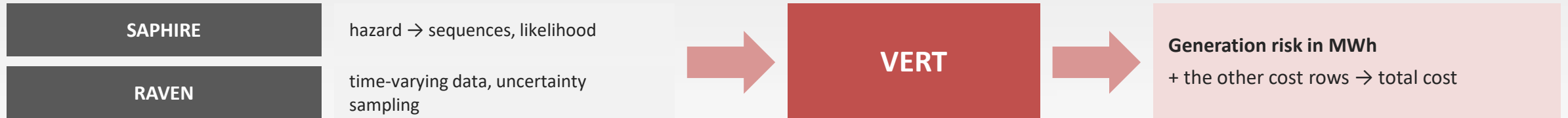
Approach	Treatment of non-stationarity	Treatment of uncertainty	Key strengths	Key limitations
Deterministic scenario-based	Bounding scenarios chosen conservatively		• Transparent • Simple to apply • Familiar to reviewers	• Uncertainty largely implicit • Results hinge on the chosen scenario
Time-dependent PRA	Hazard frequencies and risk metrics are allowed to evolve	Quantitative; parameters carry time-varying distributions	• Systematic uncertainty treatment • Fits existing RIDM frameworks	• Heavy data and model demands • Deep uncertainty is hard to interpret
Robust decision-making	Stress-tests candidate strategies across many plausible futures	Ranks by regret or robustness instead of assigning probabilities	• Works when expected values are not meaningful	• Not directly compatible with current RIDM frameworks • Can blur safety and operational goals
Adaptive pathways / adaptive engineering	Staged actions, monitoring, and triggers let the plant or site change as conditions evolve	Actions keyed to observed developments and trigger points, not fixed probabilities	• Flexible • Defers cost until it is needed	• Needs credible monitoring, defined triggers, and real adaptation options • Up-front analysis must value keeping options open

Where we landed: the deterministic bounding scenario is the baseline; time-dependent PRA and adaptive pathways are the primary candidates; robust decision-making is the cross-check when probabilities are not credible. All four are run on the same case study.

NOTE: Approaches are not direct substitutes → they address different aspects of the non-stationary RIDM problem.

Method: one cost function, in MWh-equivalent

Category	Cost element	How it enters the MWh-equivalent cost
Safety	Radiological consequence of a flood-induced accident	Very rare, very severe; governing term
Generation	Derates, trips, forced outages	MWh from derate × capacity × duration (GRA / VERT)
Generation	Post-flood inspection and recovery	Days offline for inspection after a flood or a deployment
Capital	Wall, staged foundation, or barrier inventory	Up-front \$; staged and temporary options defer it
Operations	Deployment, storage, testing, maintenance	Recurring \$ and labor; scales with deployments
Public perception	Any shutdown read as evidence of risk	Penalty per shutdown event (sensitivity parameter)
Regulatory / licensing	Re-analysis when the design basis is revisited	\$ per design-basis revision
Grid / societal	Replacement power during a regional event	Multiplier when the outage is regional



VERT: Versatile Economic Risk Tool (ISU/INL) · SAPHIRE: Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (INL) · RAVEN: Risk Analysis Virtual Environment (INL)

Upper rows in implementation; lower three carried as sensitivity parameters. Safety remains the governing objective.

Path forward and where we want your input

- **Next**

- Finish the VERT + SAPHIRE + RAVEN cost function
- Run the three flood strategies through the four decision rules
- Generalize across hazards and technologies
- Keep engaging practitioners and hazard experts

Questions for this group

- Should generation availability be an explicit RIDM objective?
- Which cost rows are credible to quantify?
- What data or operating experience are we missing?

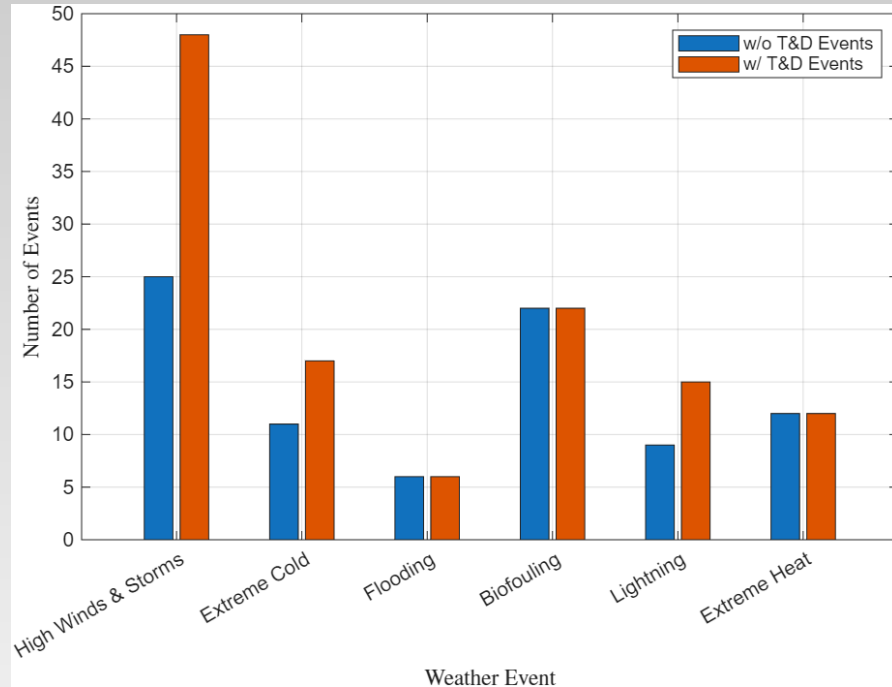
Thank you
Questions and feedback welcome

Acknowledgement

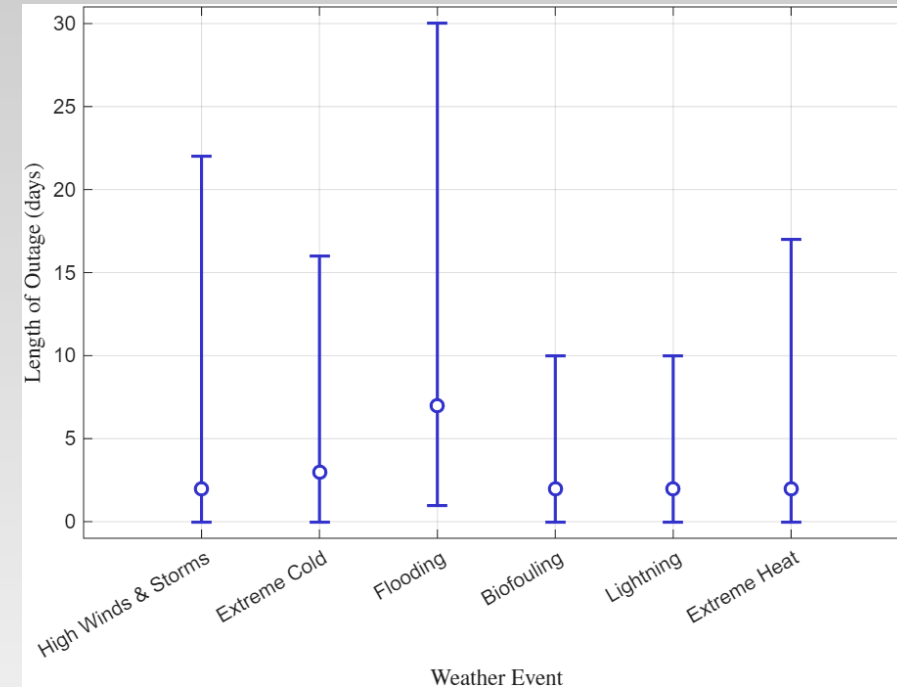
This work is supported by the U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, under grant 31310024M007.

The views expressed are the authors' own and do not necessarily reflect those of the NRC or any other organization.

The same pattern across the U.S. fleet, 2011–2020



Frequency: high winds and storms lead the count, followed by biofouling and extreme cold — all of them boundary-condition hazards, none of them design-basis accidents.



Duration: flooding produces the longest outages (median about a week, up to a month) — which is why the case study targets flood protection.

Why GRA fits the non-stationary problem

It already tracks the outcomes that evolving boundary conditions push on:

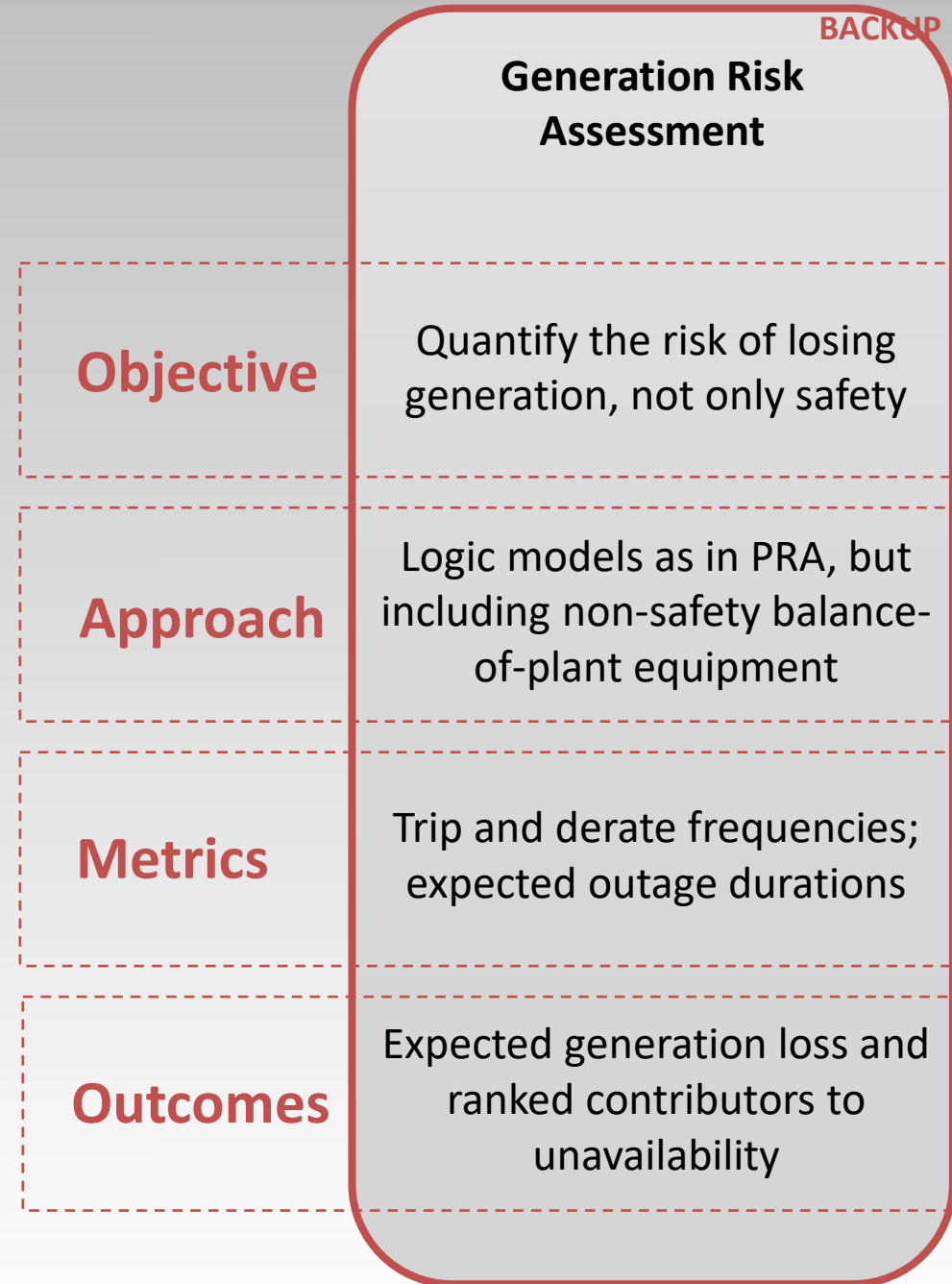
- **Efficiency loss** — net output drops as heat-sink temperature climbs
- **Administrative derates** — operators cut power to hold margin as passive heat rejection weakens
- **Protective trips** — loss of offsite power, drought-limited cooling water, intake fouling, smoke loading
- **Maintenance unavailability** — more inspection, cleaning, and repair for equipment running near its limits

The gap: GRA is in use at only a handful of plants and has not been extended to non-stationary hazard inputs.

A safety by-product

GRA measures production and availability, but its outputs also point at safety-relevant mechanisms:

- More frequent maintenance → more opportunities for error
- Time-critical interventions → operator stress
- More derates and trips → thermal and mechanical cycling



Reactor type	Passive system	Heat transfer mechanism	Ultimate heat sink	Key boundary conditions	Refs
Water-cooled SMR	Reactor pool, DHRS	Natural circulation boil-off air convection	Atmosphere (via pool)	Pool inventory, pool temperature, ambient air temperature	[30], [31]
MSR	RVACS ¹ , DRACS ² , Freeze valve, drain tank, coolant at atmospheric pressure	Gravitational drain natural circulation heat pipes	Atmosphere	Ambient air temperature, freeze valve thermal margin	[32], [33], [34], [35]
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¹ Reactor Vessel Auxiliary Cooling System, ² Direct Reactor Auxiliary Cooling System					

Passive decay heat removal across reactor classes

- Working fluid, geometry, and driving mechanism all differ between water-cooled SMRs, MSRs, LMRs, and HTGRs
- What they share: heat rejection ultimately ends in the atmosphere or hydrosphere, through forces that are weak by design

Those end-of-chain boundary conditions are exactly what hydro-meteorological hazards perturb — alone and in combination.

The cost function, built on VERT's formulation

Starting point — VERT (Miller, Ercanbrack & Pope, ICONE28, 2021): SAPHIRE gives the likelihood of each sequence; consequences are in MWh; RAVEN varies the data over time

Risk = Likelihood $\times$ Consequences

Consequences = Derate(%) $\times$ Rated Capacity (MW) $\times$ (MTTR + TTRP) (hr)

$$\mathbb{E}[C_S] = K_S^{(0)} + \sum_{t=1}^T d_t \left[K_S(t) + O_S(t) + L_S^{\text{dep}}(t) + R_S(t) \right]$$

$$= \sum_k \int_0^\infty \lambda(h, t) \Pr(k | h, s, t) \left[D_k P_{\text{rated}} (MTTR_k + TTRP_k + T_{\text{insp},k}) g(t) + \pi_{\text{pub}} \mathbf{1}\{D_k > 0\} + \rho_{\text{reg}} q_k + C_{\text{rad}} \mathbf{1}\{k \in \text{CD}\} \right] dh$$

$$L_S^{\text{dep}}(t) = v_s(t) [c_{\text{dep}} + P_{\text{rated}} T_{\text{insp},\text{dep}} + \pi_{\text{pub}}] \quad K_S(t) = \mathbb{E}[K_S^{\text{exp}} \mathbf{1}\{\text{trigger}_s(t)\}] \quad X_{\$} \rightarrow X_{\$} / p_e \text{ [MWh]}$$

What each symbol is

k, Pr(k | h, s, t): SAPHIRE end state of a flood-initiated sequence (derate, trip, core damage) and its probability from the fault trees, given flood height h and the protection strategy s in place at time t

$\lambda(h, t)$: annual rate density of flood height h, non-stationary in t; RAVEN samples it together with VERT's failure-rate, MTTR and TTRP data (next slide)

D_k, P_{rated}: derate fraction (1 for a trip) and rated capacity, exactly as in VERT

MTTR_k, TTRP_k, T_{insp}: mean time to repair, time to restore power, and post-flood inspection time before restart

Strategy-specific terms

K_s⁽⁰⁾, K_s(t): up-front capital and staged expansion K_s^{exp}, paid only when a monitoring trigger fires; O_s(t): recurring O&M; d_t: discount factor

v_s(t), c_{dep}: barrier deployments per year, including false alarms, and cost per deployment

g(t), π_{pub} , ρ_{reg} q_k, C_{rad}: grid multiplier, perception penalty, regulatory cost $\times$ revision probability, radiological consequence in MWh-equivalent

p_e: \$/MWh price that converts every dollar term onto the MWh scale

Where each row of the cost table enters the function

Table row	Term in the cost function	What it captures
Safety	$C_{\text{rad}} \mathbf{1}\{k \in \text{CD}\}$	Radiological consequence of a flood-induced core-damage sequence, in MWh-equivalent. Very low probability, very high consequence; the governing term even when its expected value is small.
Generation	$D_k P_{\text{rated}} (MTTR_k + TTRP_k)$	VERT's consequence term: derate fraction $\times$ rated capacity $\times$ repair-and-restore time, summed over the flood-initiated sequences SAPHIRE identifies.
Generation (downtime)	$P_{\text{rated}} T_{\text{insp},k}, \quad P_{\text{rated}} T_{\text{insp},\text{dep}}$	Inspection time before restart after a flood, and after each temporary-barrier deployment.
Capital	$K_s^{(0)}, \quad K_s(t) = \mathbb{E}[K_s^{\text{exp}} \mathbf{1}\{\text{trigger}_s(t)\}]$	Permanent wall or foundation up front; expansion cost only when a trigger fires. Temporary and staged strategies defer part of this.
Operations	$O_s(t), \quad v_s(t) c_{\text{dep}}$	Recurring maintenance, storage and testing; deployment cost per event, including false alarms driven by forecast skill.
Public perception	$\pi_{\text{pub}} \mathbf{1}\{D_k > 0\}$	Penalty per derate or shutdown event, safe or not. Treated as a sensitivity parameter rather than estimated.
Regulatory / licensing	$\rho_{\text{reg}} q_k$	Cost of a design-basis revision $\times$ probability the sequence triggers one.
Grid / societal	$g(t) \geq 1$	Multiplier applied when the outage coincides with a regional event affecting several plants on the same grid.

Upper rows are being implemented in the VERT + SAPHIRE + RAVEN pipeline; Public perception, Regulatory and Grid are carried as sensitivity parameters pending your feedback.

How each decision approach uses the cost function

RAVEN samples the futures ω : the non-stationary hazard $\lambda(h, t; \omega)$ together with VERT's failure-rate, MTTR and TTRP data. Each approach on the earlier table is a different rule for turning the sampled costs $C_s(\omega)$ into a choice of strategy.

Deterministic scenario-based

$$s^*_{\text{det}} = \arg \min_s C_s(\omega_{\text{bound}})$$

Pick one bounding future ω_{bound} (a maximum flood height) and minimize cost there. No distribution over ω is needed — and none is used.

Time-dependent PRA

$$s^*_{\text{TD}} = \arg \min_s \mathbb{E}_{\omega}[C_s(\omega)]$$

Weight the RAVEN samples by their probabilities and minimize expected cost. The most complete use of the information, and the most sensitive to how deep uncertainty is encoded.

Robust decision-making

$$s^*_{\text{RDM}} = \arg \min_s \max_{\omega} \left[C_s(\omega) - \min_{s'} C_{s'}(\omega) \right]$$

Minimize the worst-case regret: how much worse a strategy does than the best strategy for that future. Needs the set of futures, not their probabilities.

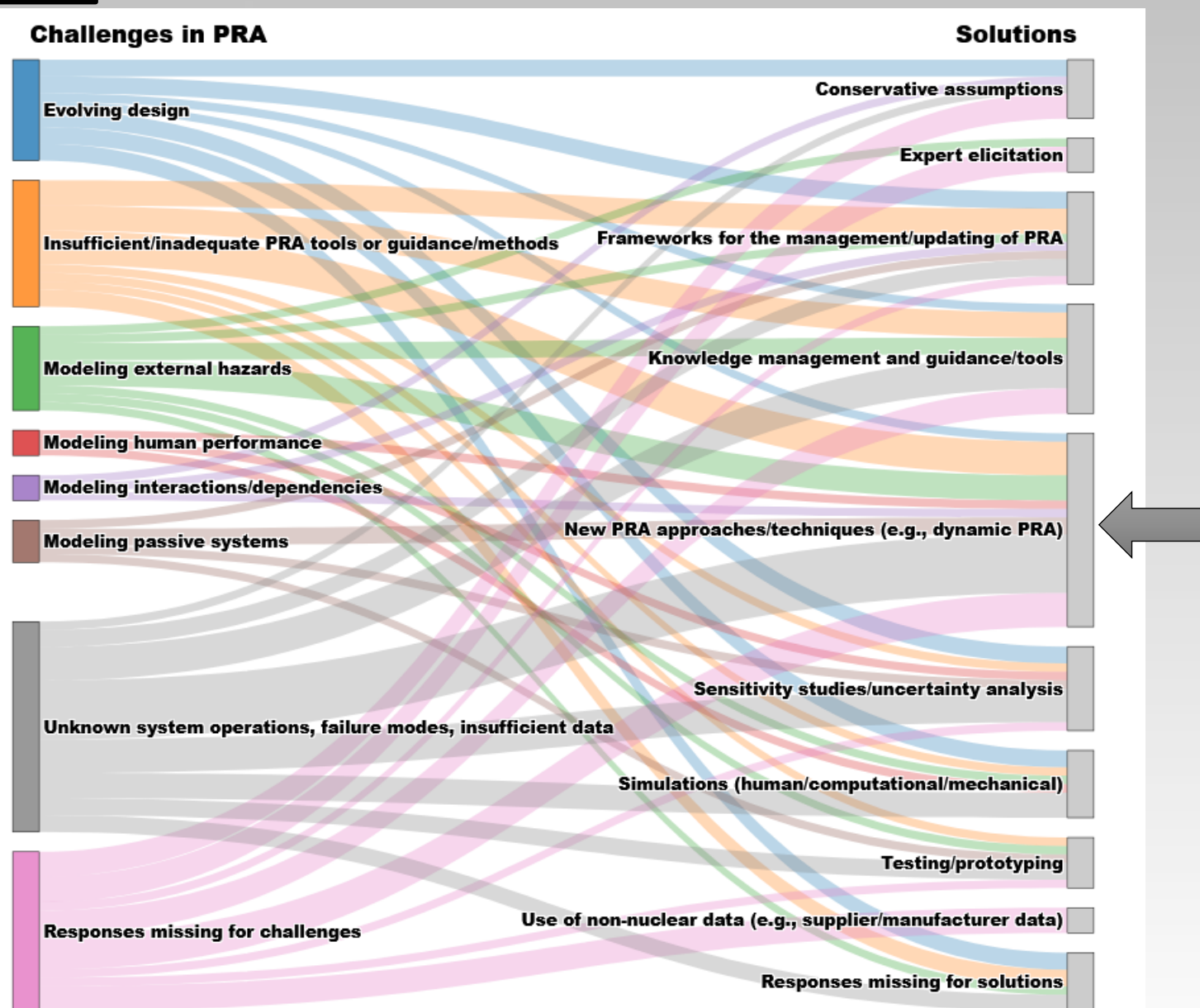
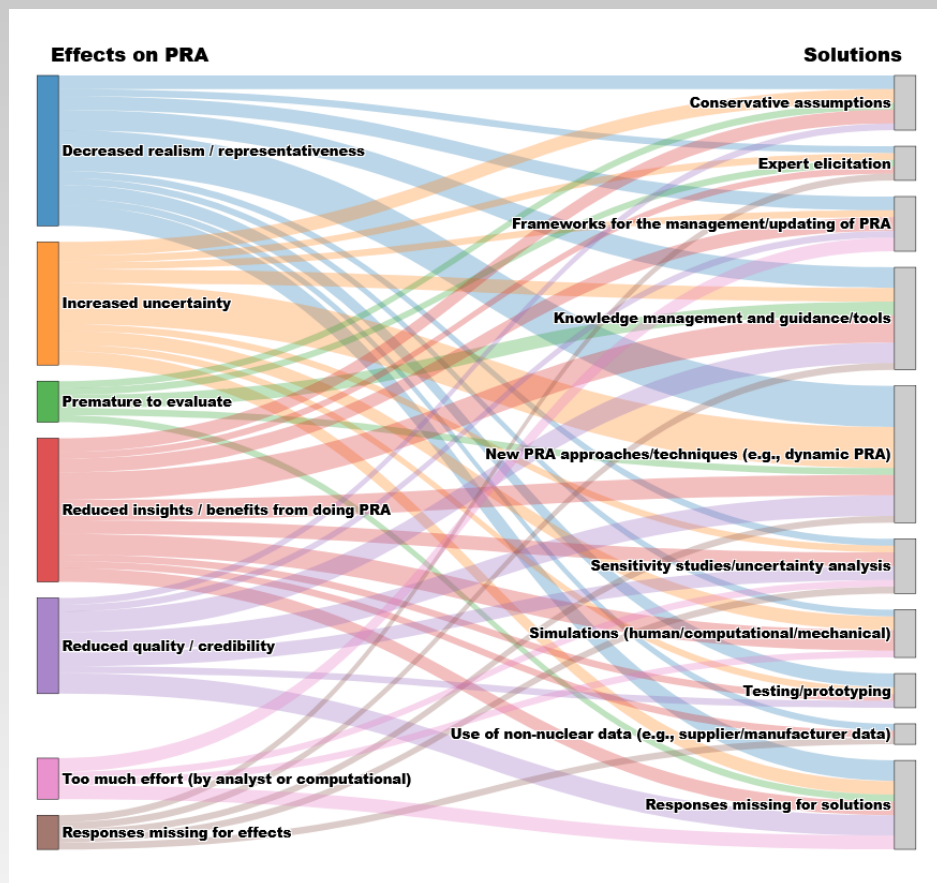
Adaptive pathways

$$s^*_{\text{adapt}} = \arg \min_s \mathbb{E}_{\omega} \left[C_s(\omega \mid \text{trigger}_s(t) \leftarrow h_{1:t}(\omega)) \right]$$

Capital $K_s(t)$ is spent only when the observed flood history $h_{1:t}$ crosses a trigger, so the expectation includes the value of waiting for information.

3. What tools, techniques, or strategies are used to address the above challenges?

BACKUP



Source: Faraji Najarkolaie, Zhao, Irish, Modarres & Bensi (2026), Nuclear Science and Engineering, doi:10.1080/00295639.2026.2690569

