National Laboratory of the Rockies

Integrated Reliability and Economic Modeling for Transmission Across Large Regions: **A Space Odyssey**

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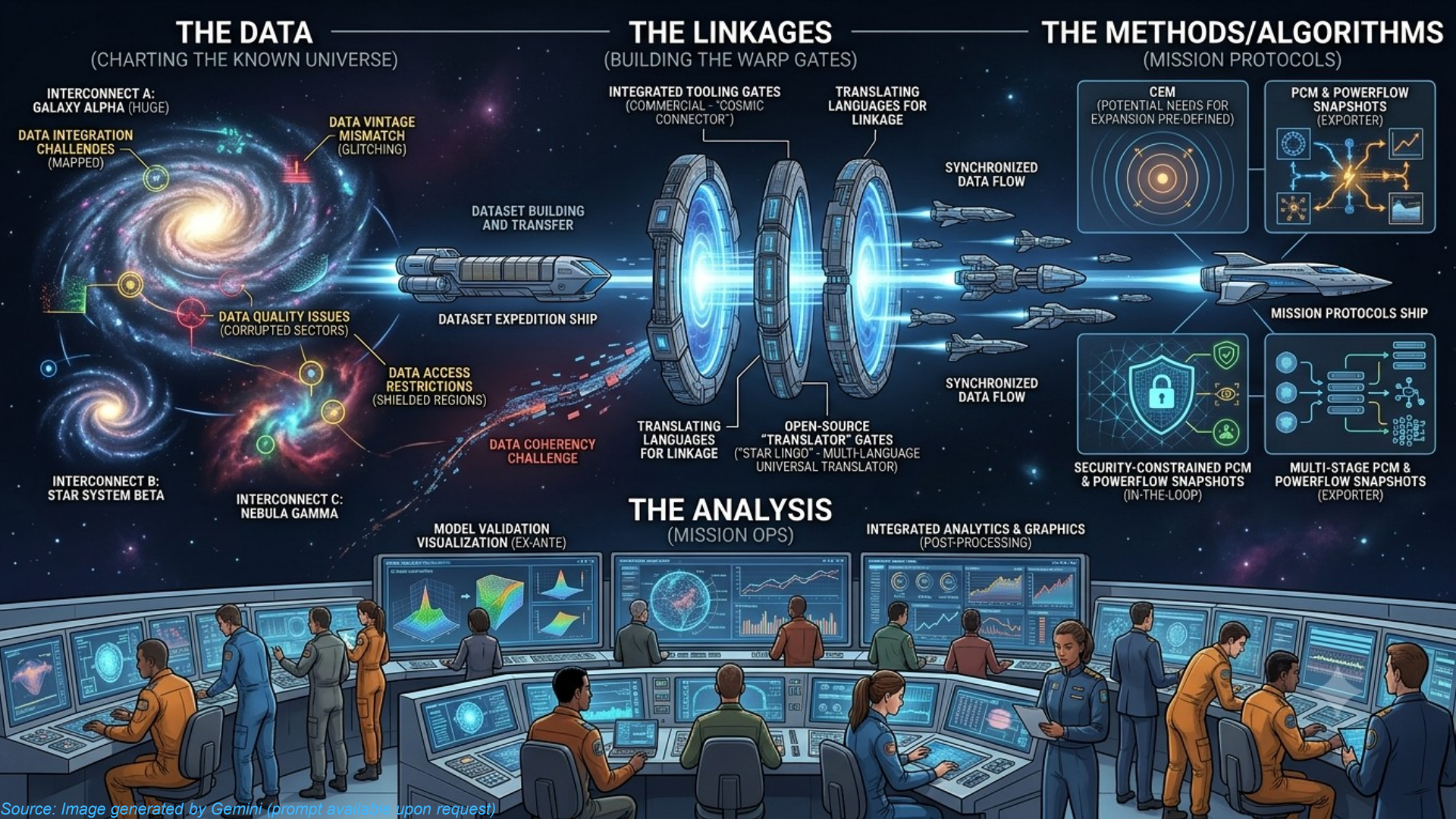
Acknowledgements: David Palchak, Jose-Daniel Lara, Pedro Andres Sanchez Perez

Photo from Adobe Stock 256750697

An odyssey

“a long wandering or voyage usually marked by many changes of fortune”

- Merriam Webster



Source: Image generated by Gemini (prompt available upon request)

Mind the gap

ECONOMIC UNIVERSE

- Long-run Gx/Tx changes
- Typically zonal resolution[1]
- Approximated temporal resolution
- Approximated transfer needs.

- Domains:
  - Capacity expansion models (CEM)
  - Resource adequacy (RA)
  - Production cost models (PCM)

Gap
?

RELIABILITY UNIVERSE

- Operate available Gx/Tx
- Nodal resolution
- Hourly/sub-hourly
- Physical constraint enforcement.

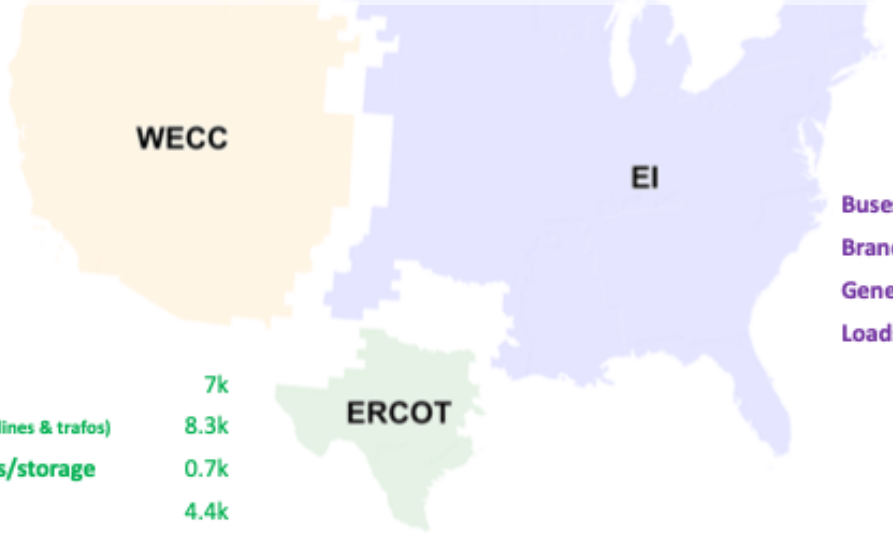
- Domains:
  - Production cost models (PCM)
  - Powerflow (DC/AC)
  - Contingency analysis (security-constrained operations)
  - Phasor dynamics (voltage, angle, frequency)
  - EMT and resonance dynamics (SSR, fast voltage recovery).

[1] Sometimes nodal CEM (less typical); Gx = generation; Tx = transmission

The data

Charting the known (and unknown) universe

Goal: *Unified, validated, transmission-level datasets ready for (industry) use to feed economic/reliability models at national scale*



Buses	28.8k
Branches (lines & trafos)	33.4k
Generators/storage	4.8k
Loads	13.1k

Buses	95.9k
Branches (lines & trafos)	115.7k
Generators/storage	10.5k
Loads	41.2k

Buses	7k
Branches (lines & trafos)	8.3k
Generators/storage	0.7k
Loads	4.4k

Large-scale model building requires partnering, coordination and discipline

- Data access
- Data formatting
- Data vintage
- Data integration

Source: NLR

Source: tenor.com

What data hazards need to be navigated?

Spatial Resolution Mismatch

- Admin boundaries ≠ power system areas or AC subnetworks (coherency across modelling domains)
- Mapping errors propagate to dispatch patterns (plant- vs unit-specific)
- Careful disaggregation and validation needed

Temporal Resolution Gaps

- CEM ≠ PCM hourly dispatch
- More inter-temporal data needed (ramp limits, minimum up/down times)

Data Vintage and Quality

- Old data is not bad data
- Validate, Validate, Validate
- Vintage updates trigger model rebuilds

Topology & Ownership Changes

- Large-scale models are living sets of data (not datasets): network topology changes, demand evolution, retirements, new builds, rerating/repowering.
- Synchronization across domains and tools is operationally intensive (institutionally difficult).

Data Controls

- Parts of data are sensitive e.g. CEII
- Others are public and not sensitive
- Workflow automation must enforce access controls across the full chain (economic and reliability models).

Scale & Compute

- Interconnect-wide cases (and their combinations) can become extremely large optimization problems - data problems are not modelling problems.

CEII – Critical Energy Infrastructure Information

The linkages

Building the warp gates

Linkages reduce silos and resulting fragmentation (two main paths towards integration)

Integrated Platforms

Single-tool (open-source and/or commercial) CEM/RA + PCM + powerflow/dynamics in one framework

Characteristics

- Consistent data model across domains
- No translation step between modules
- Commercial support & validated workflows
- Lower integration overhead for end-user

Limitations

- License cost & proprietary data/linkage lock-in
- Often requires full plugin suite (CEM/RA, PCM, powerflow/dynamics)
- Less flexibility for bespoke methods

Linkage Tooling

Modular chain: best-in-class tools connected via translation & interoperability layers

Characteristics

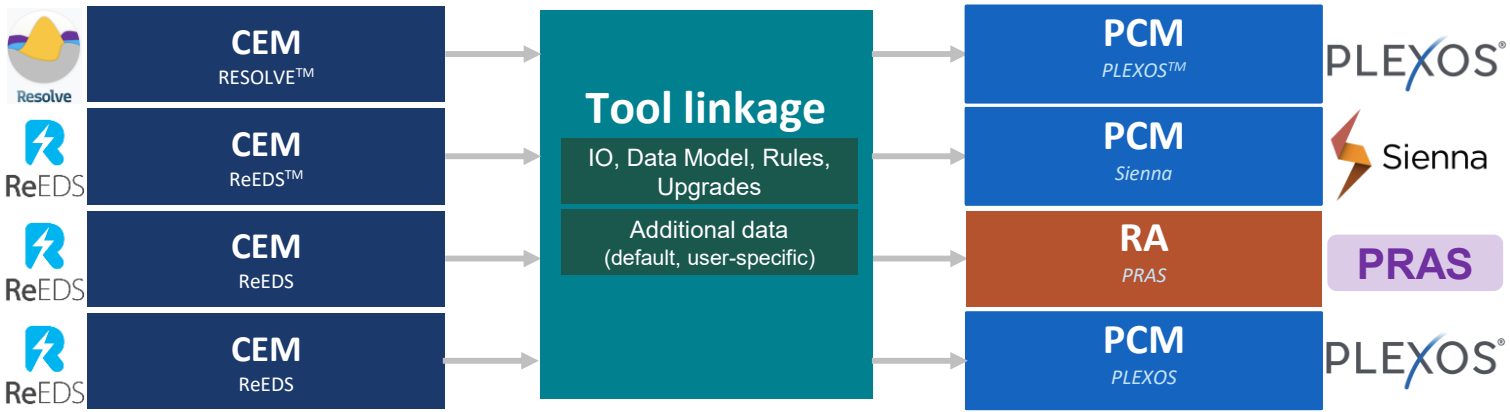
- Domain-specific best-of-breed tools
- Transparency & reproducibility
- Flexible: swap any tool in the chain

Limitations

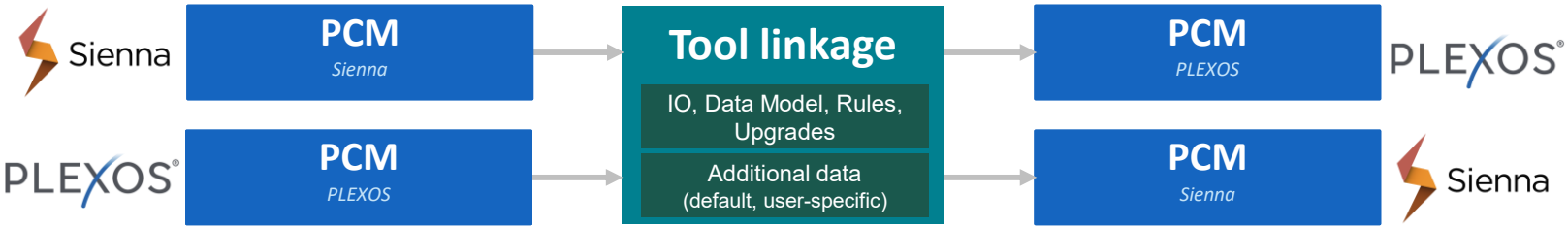
- Requires robust data translation layer
- Version compatibility management across tools
- Zonal→nodal mapping introduces uncertainty

Example of linkage tooling (pipelines)

Domain linkages



Cross-platform linkages



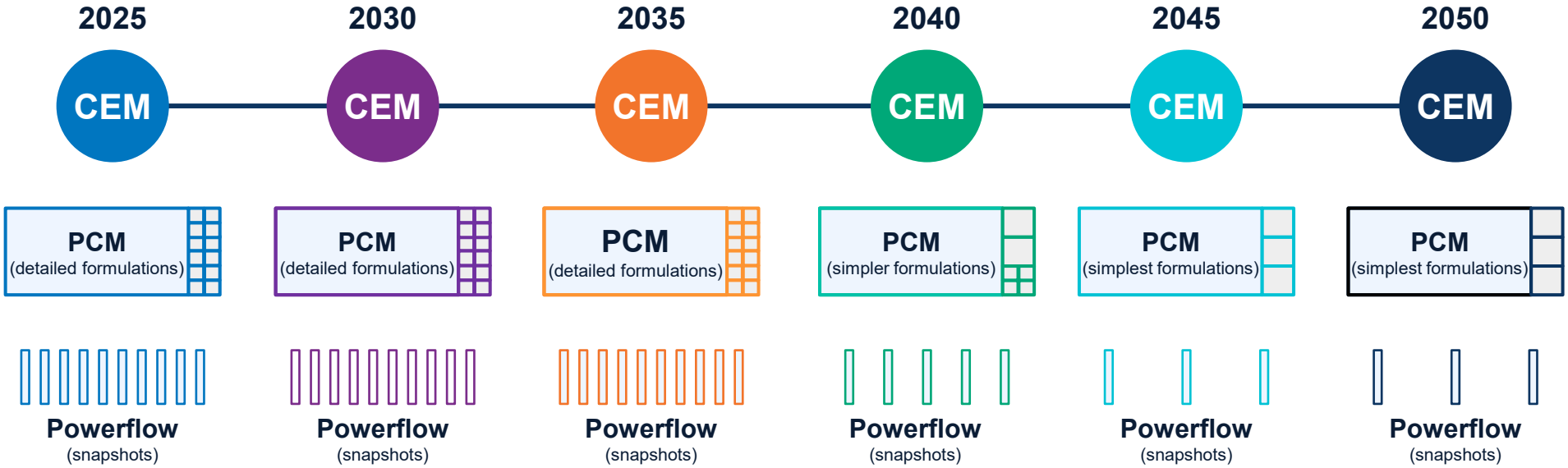
NOTE: Tools logos are shown to represent existing capabilities only
NLR has implemented this with R2X (all code is available at https://github.com/NatLabRockies/R2X and PyPi)

The methods/algorithms

Mission protocols

Example methods/algorithms (“Mission Protocols”)

Time horizon integration across independent tools



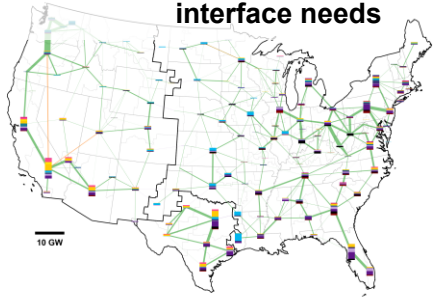
Grid evolution captured: Each stage reflects a changed portfolio from CEM
Selective depth: Not all stages (years) need all the details (e.g. multi-stage security-constrained PCM, security-constrained PCM, single-stage PCM) - triage by horizon, scenario criticality and timelines
Rolling horizon: Forward (reverse) time horizon to support nodally specific investments of least-regret

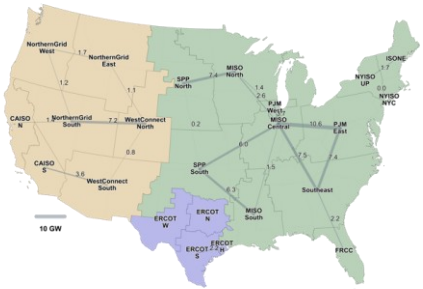
Example methods/algorithms (“Mission Protocols”)

Sample results applied at an inter-regional scale

CEM
(2035)

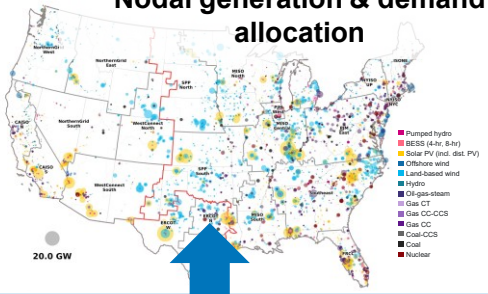
Generation, demand and interface needs



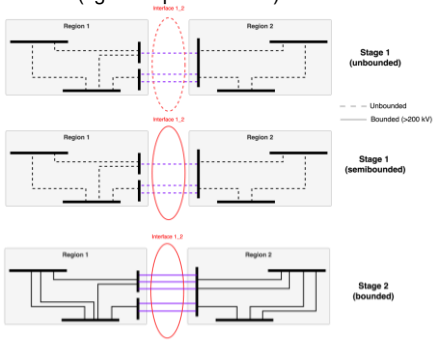


PCM
(2035)

Nodal generation & demand allocation

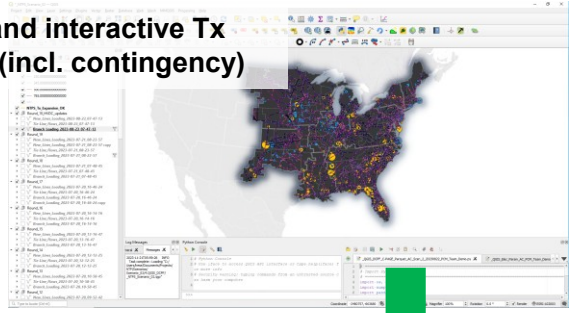


Additional transmission (+ constraints)
(tighter representation)



Powerflow
(2035)

Iterative and interactive Tx expansion (incl. contingency)



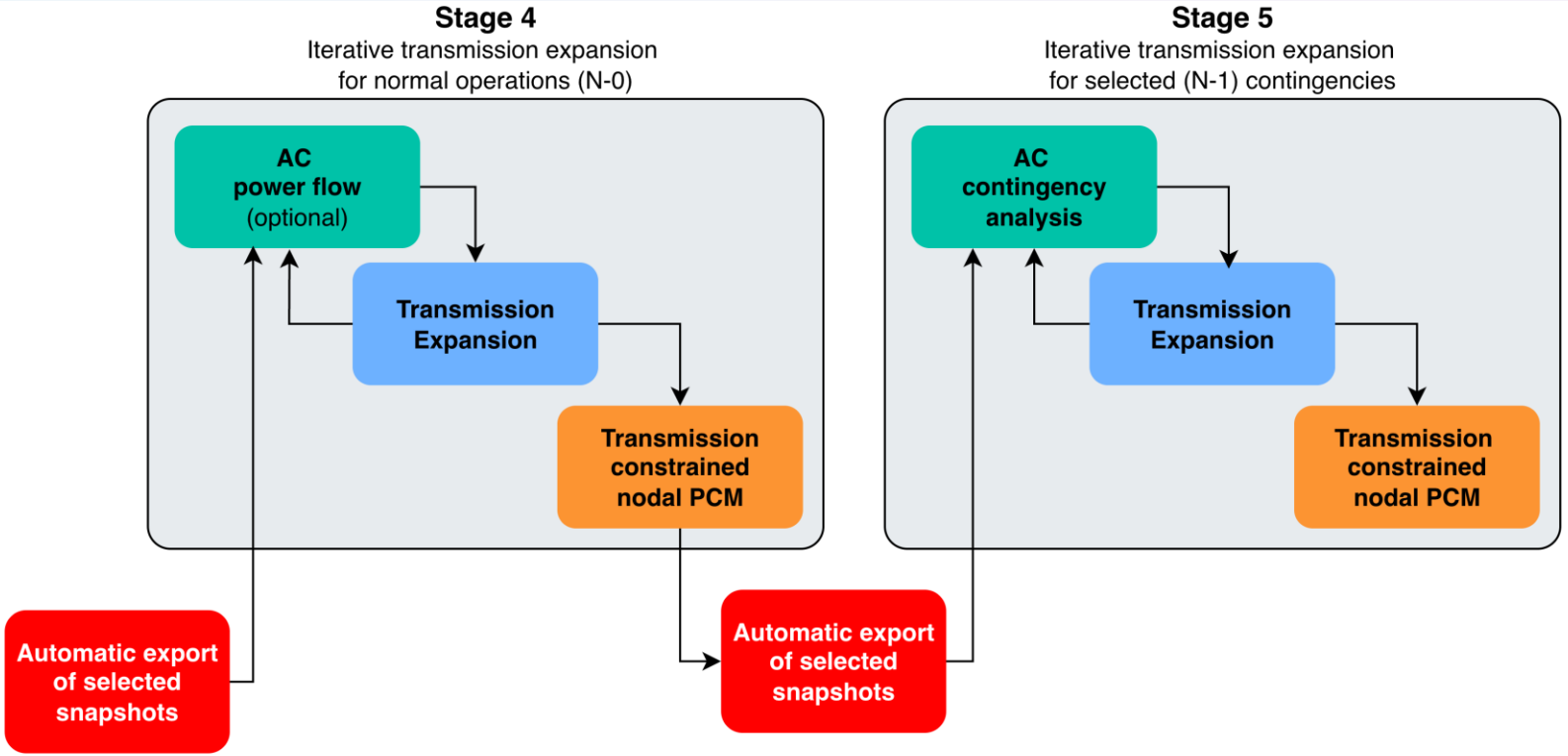
Inter-regional transmission solutions
(2035)

NOTE: All graphics are examples

Example methods/algorithms (“Mission Protocols”)

Automation of tool linkages and increasingly representing reliability concerns

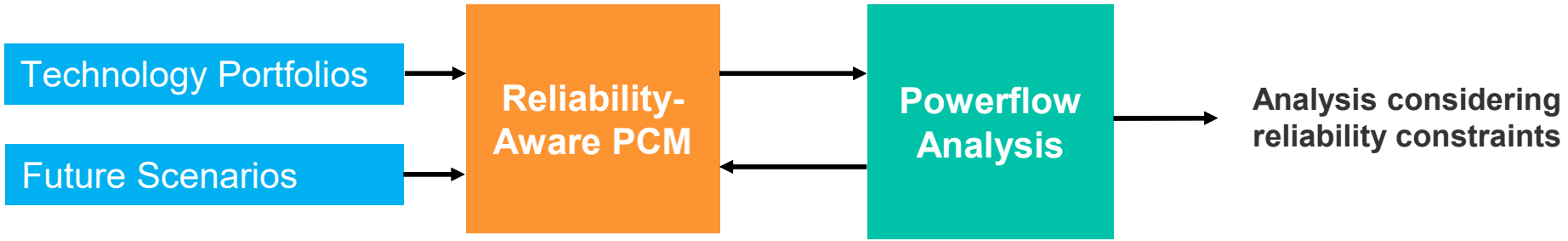
More refined treatment of transmission networks



[As next steps for large-scale AC powerflow feasibility]

Example methods/algorithms (“Mission Protocols”)

Reliability-aware PCM + powerflow



Benefits:

- **Reliability-aware PCM (i.e., security-constrained)** captures value of transmission investments in relieving congestion under contingency.
- **Powerflow “in-the-loop”** captures reliability impact across a wider range of operational conditions. *Represents a shift in the planning standard away from pre-determined snapshots.*

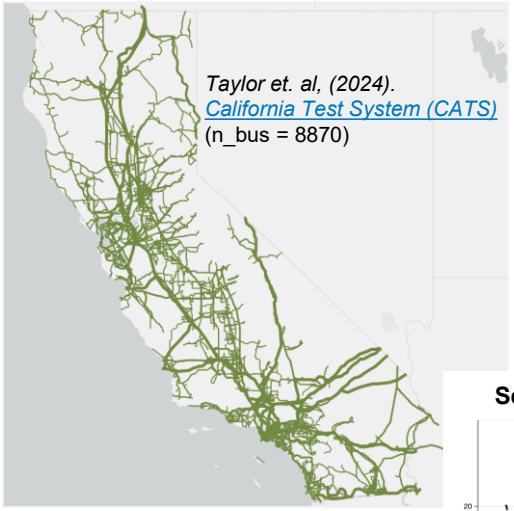
Challenges:

- Ensuring AC powerflow convergence across many operating points (bad topology, initial conditions, reactive power gaps)
- Increased computational burden of security-constrained PCM (especially large-scale systems)
- Translation between multiple tools (see “linkage tooling”)

Source: NLR (J. Lara, 2026)

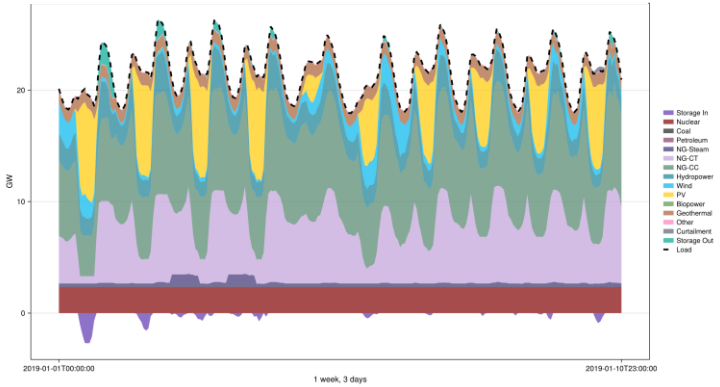
Example methods/algorithms (“Mission Protocols”)

Reliability-aware PCM + powerflow

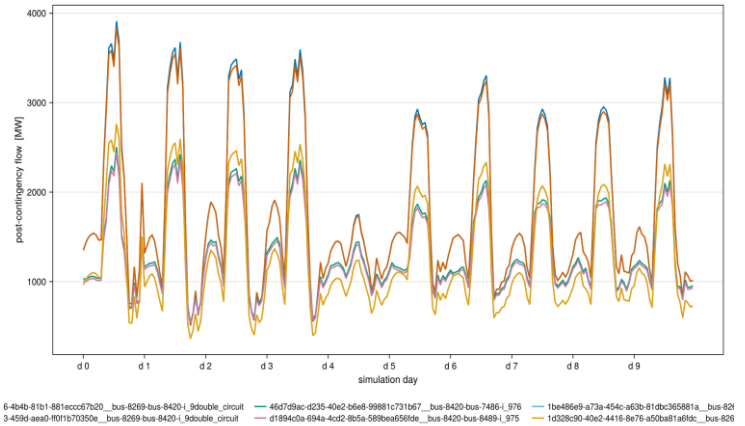


- Security-constrained PCM (10 largest branches)
- Evaluated powerflow in-the-loop (DC in this case)
- BONUS: Export powerflow case file (PSS/E) for any/all time-steps and for any size system
- Scaling to large-scale industry cases (EI) in progress

Security-constrained unit commitment (10 days)



Post-contingency flow (monitored branch) – top 6 contingencies



Source: NLR (J. Lara, 2026)

NOTE: Implemented in Sienna (https://sienna-platform.github.io/Sienna/)

The analysis

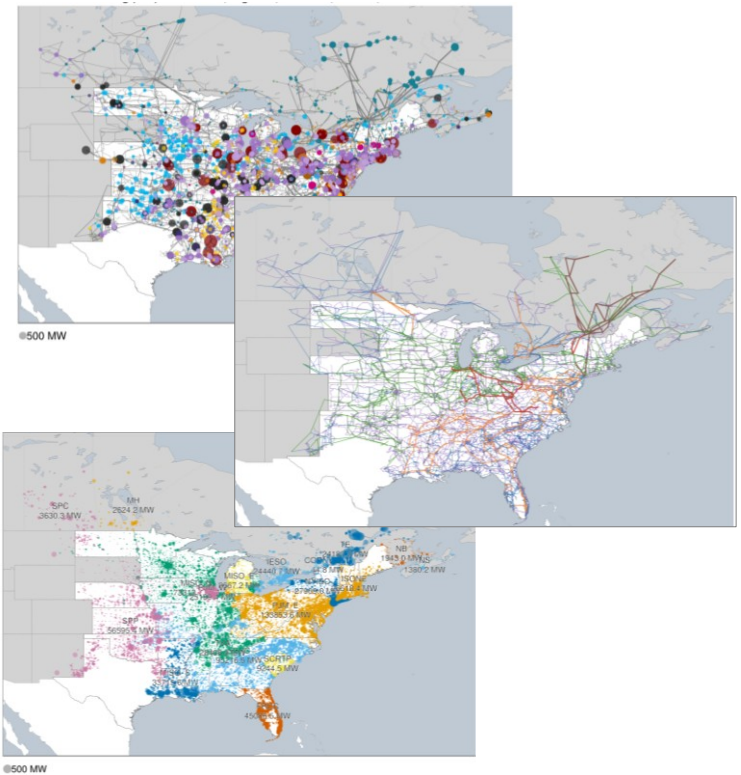
Mission ops

“Mission Ops”

Data and model validation + visualization

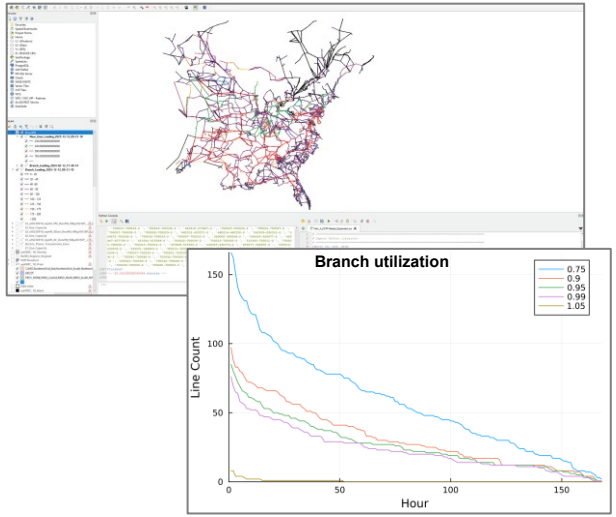
Static/interactive mapping

(large-scale datasets debugging, sharing)

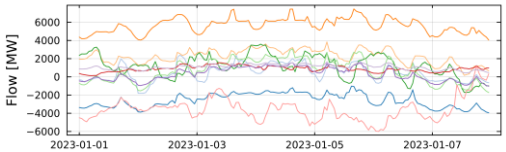


Integrated GIS platforms

(iterative and interactive transmission expansion)

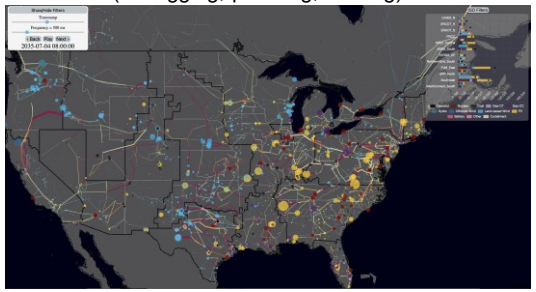


Branch/Interface flows + utilization

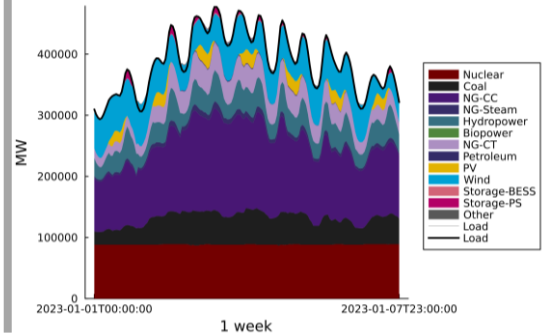


Spatial results visualization (Dashboards)

(debugging, planning, sharing)



Supply-demand balances



NOTE: All graphics are examples

Conclusions

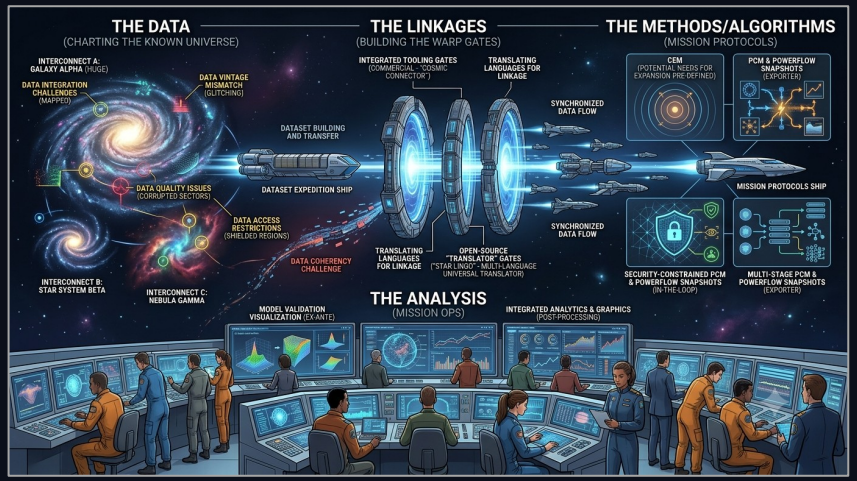
Mission status

Conclusions

(“Mission Status”)

The data:

Large-scale, continuously updated datasets can underpin every analysis - get them right first



Source: Image generated by Gemini (prompt available upon request)

The linkages:

Tool linkages or integrated tooling bridge economic portfolios to reliability models - these warp gates are the unlock

The methods:

Numerous “protocols”: Match the method to the mission

The analysis:

Ex-ante validation + integrated analytics + visualization close the loop - Calibrated models with visualized results create actionable reliability insights

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Thank you

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