National Laboratory of the Rockies

Integrated reliability and economic modeling for transmission across large regions: **A Space Odyssey**

Jarrad WRIGHT

ESIG Spring Technical Workshop
June 2026

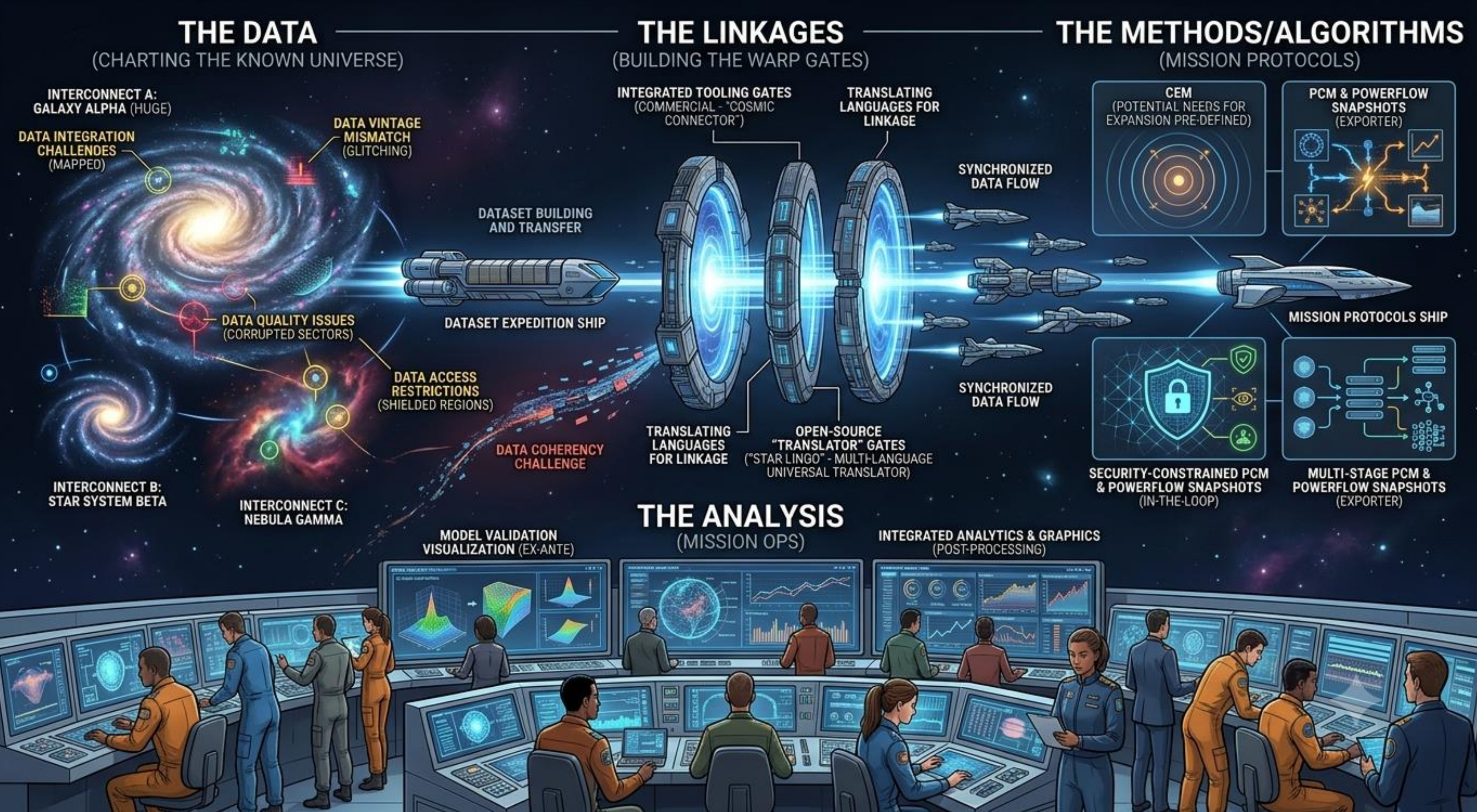
Acknowledgements: David Palchak, Jose-Daniel Lara, Pedro Andres Sanchez Perez

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.

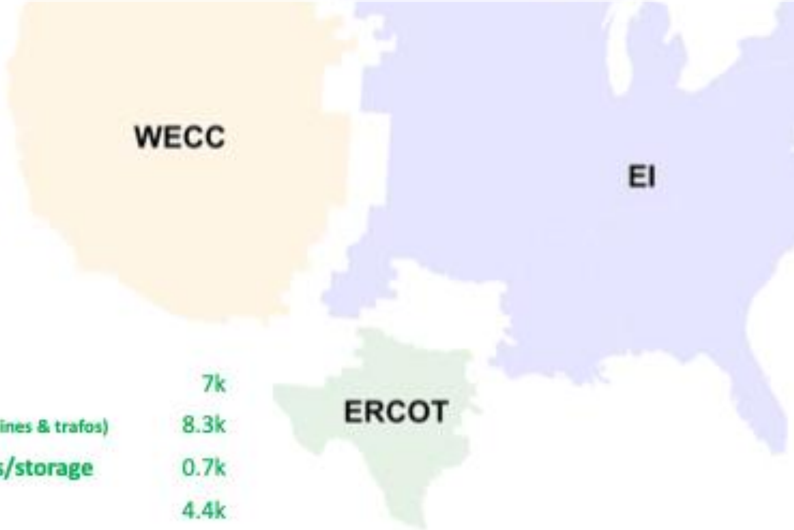
- Domains:
  - Production cost models (PCM)
  - Powerflow (DC/AC)
  - Contingency analysis (security-constrained operations)
  - Phasor dynamics (voltage, angle, frequency)
  - EMT and resonance dynamics (SSR, fast voltage recovery).

[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*



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

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

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

Large-scale model building requires partnering, coordination and discipline

Source: NLR

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

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 can propagate to dispatch patterns (plant- vs unit-specific)
- Careful disaggregation and validation needed at zonal seams.

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 change, demand evolution, retirements, new builds, rerating/repowering.
- Synchronization across domains and tools is operationally intensive (institutionally difficult).

Data Controls

- Chunks 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 with varying characteristics across economic and reliability domains.

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

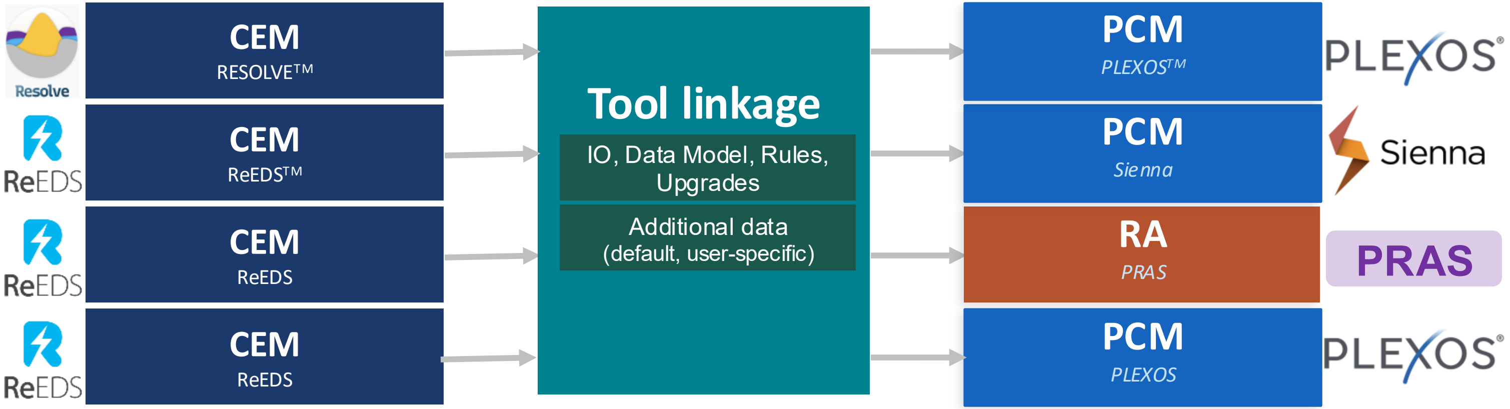
- Domain-specific best-of-breed tools
- Transparency & reproducibility
- Flexible: swap any tool in the chain

Limitations

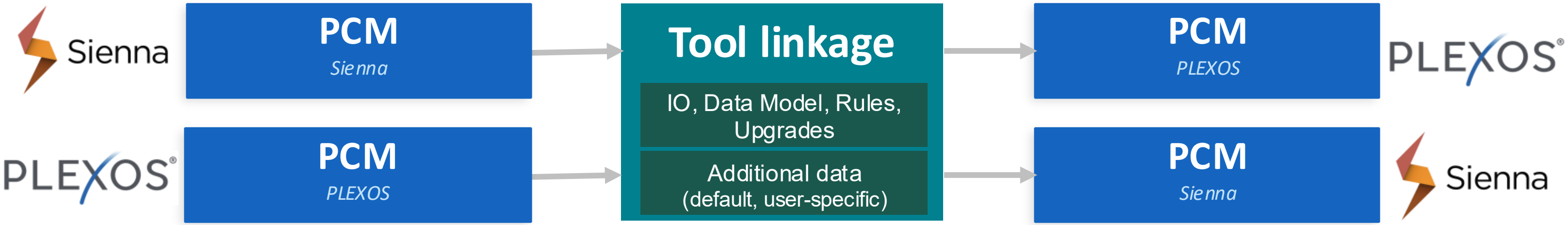
- Requires robust data translation layer
- Version compatibility management across tools
- Zonal→nodal mapping introduces uncertainty

Example of linkage tooling (pipelines)

Domain linkages



Cross-platform linkages



NOTE: Tools logos are shown to represent existing capabilities only

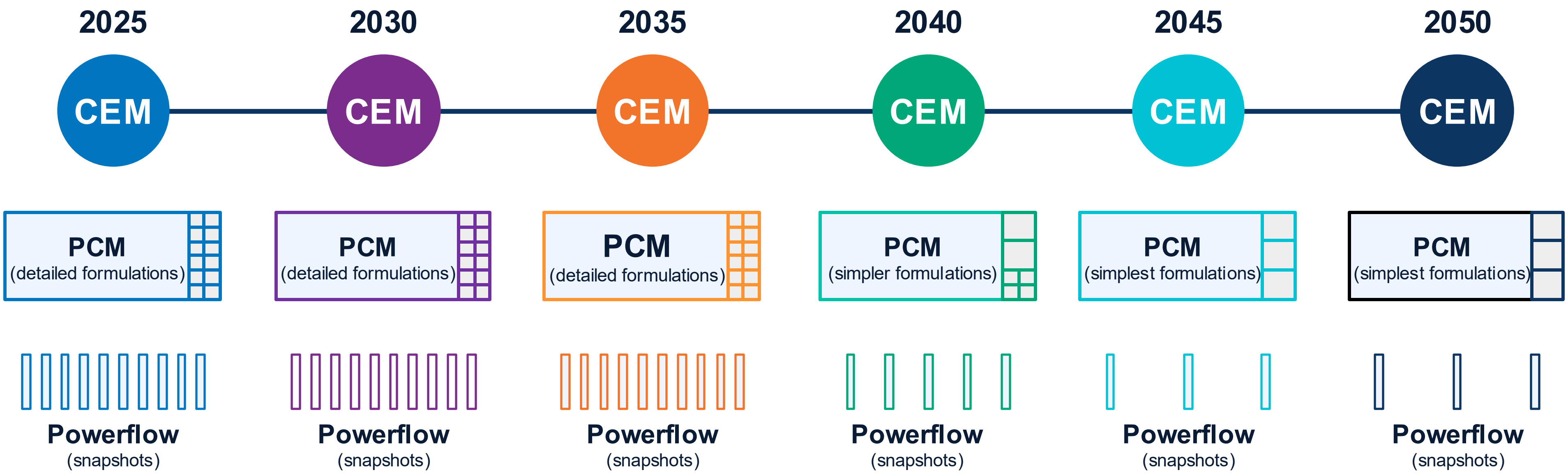
NLR has implemented this with R2X (all code is available at https://github.com/NatLabRockies/R2X and PyPi)

The methods/algorithms

Mission protocols

Example methods/algorithms (“Mission Protocols”)

Time horizon integration across independent tools



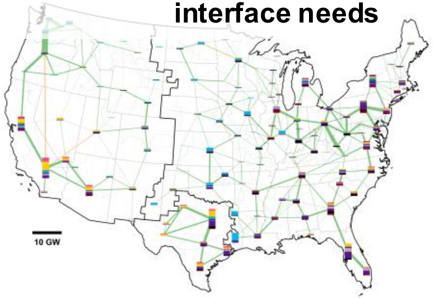
Grid evolution captured: Each stage reflects a changed portfolio from CEM
Selective depth: Not all stages (years) need all the details (e.g. multi-stage security-constrained PCM, security-constrained PCM, single-stage PCM) - triage by horizon, scenario criticality and timelines
Rolling horizon: Forward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

Example methods/algorithms ("Mission Protocols")

Sample results applied at an inter-regional scale

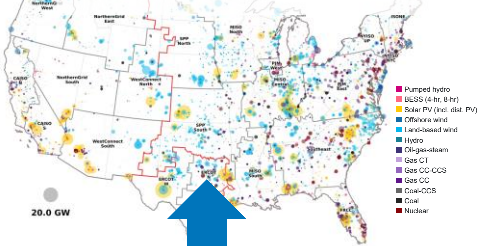
CEM
(2035)

Generation, demand and interface needs

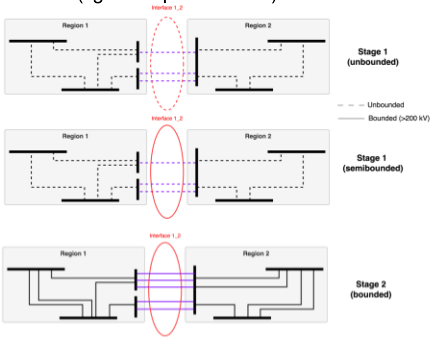


PCM
(2035)

Nodal generation & demand allocation

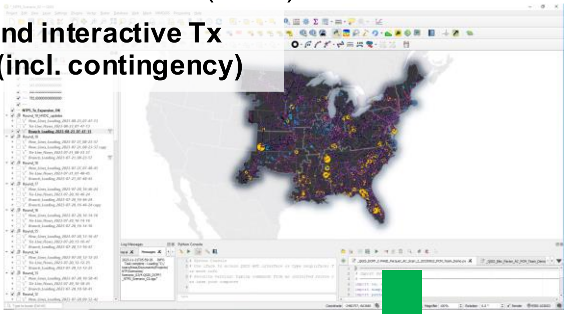


Additional transmission (+ constraints)
(tighter representation)



Powerflow
(2035)

Iterative and interactive Tx expansion (incl. contingency)

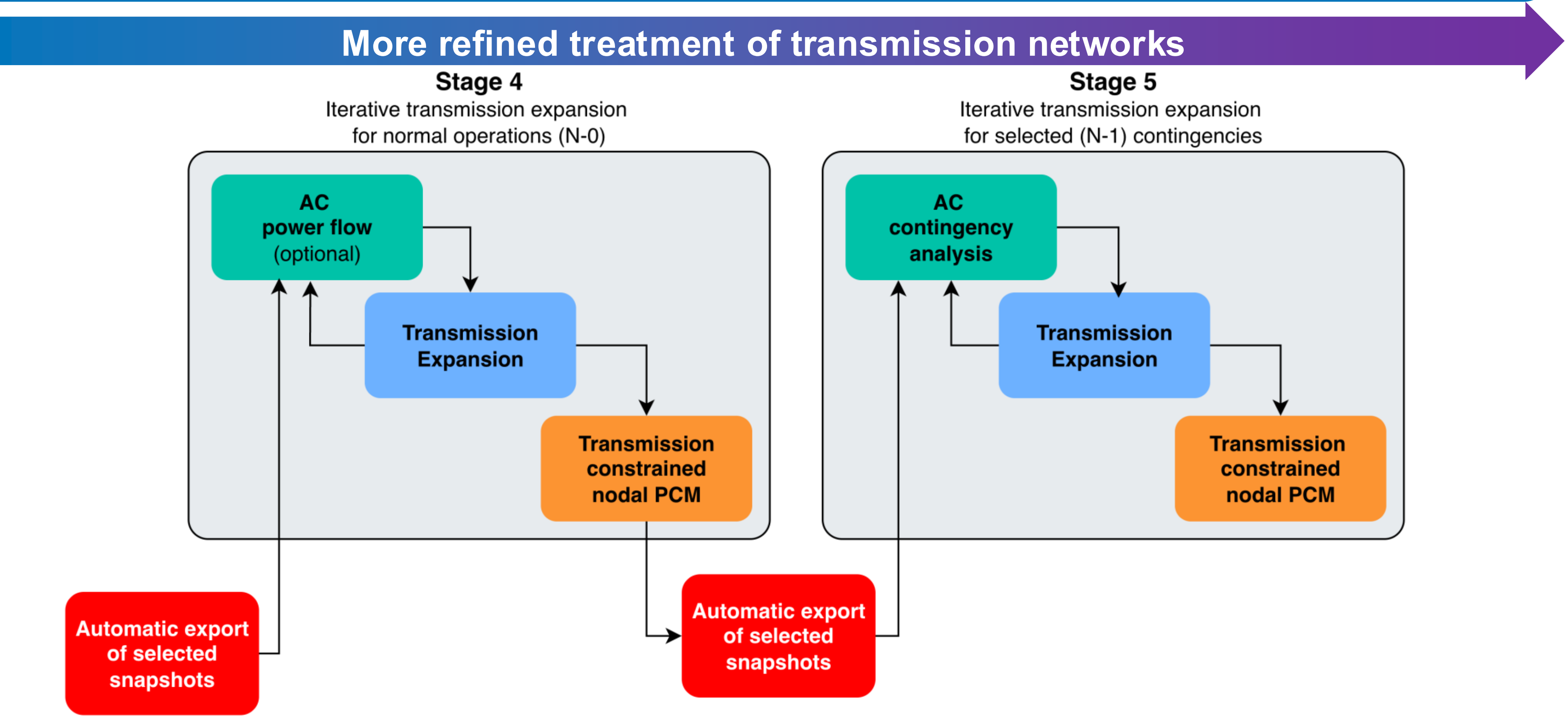


Inter-regional transmission solutions
(2035)

NOTE: All graphics are examples

Example methods/algorithms ("Mission Protocols")

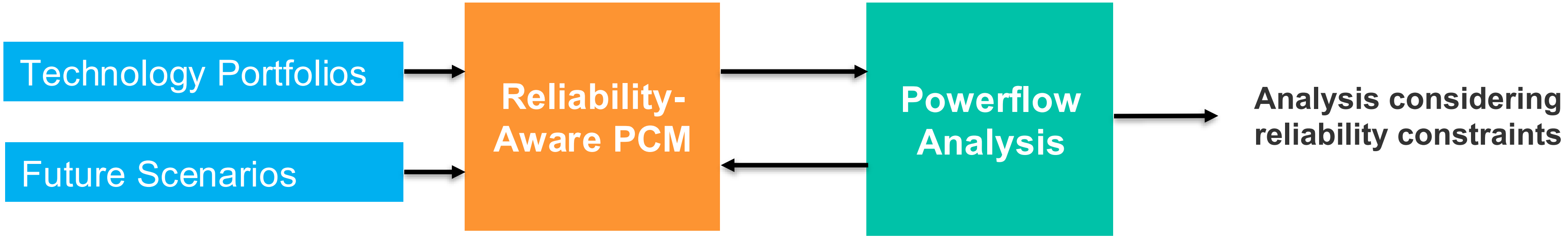
Automation of tool linkages and increasingly representing reliability concerns



[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.*

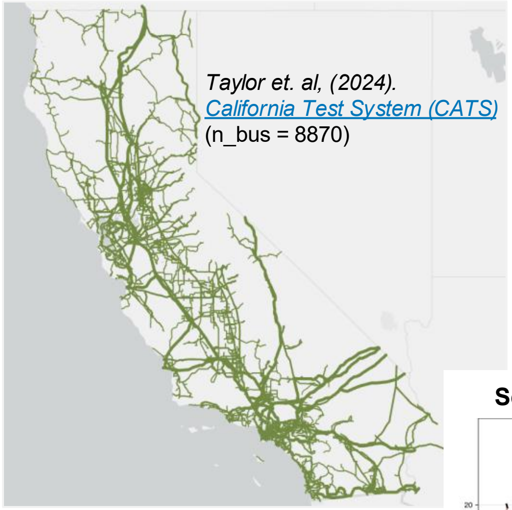
Challenges:

- 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”)

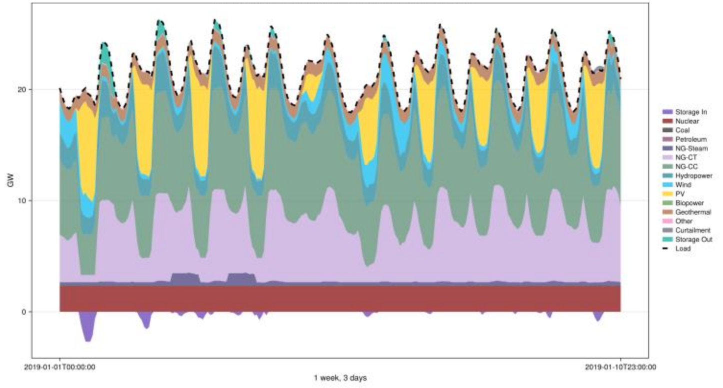
Reliability-aware PCM + powerflow



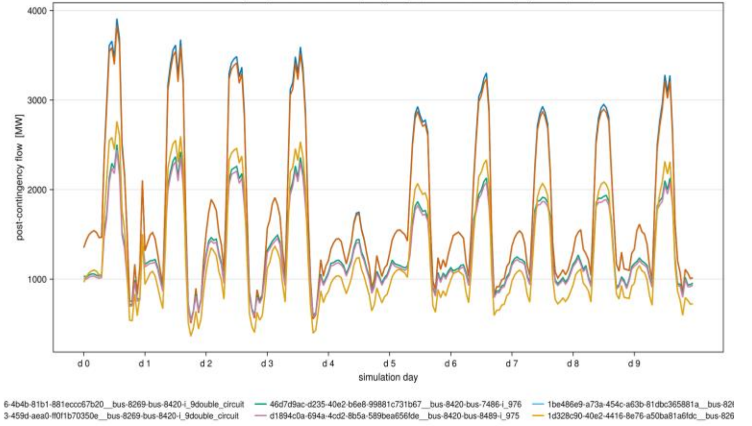
Taylor et. al, (2024).
California Test System (CATS)
(n_bus = 8870)

- 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

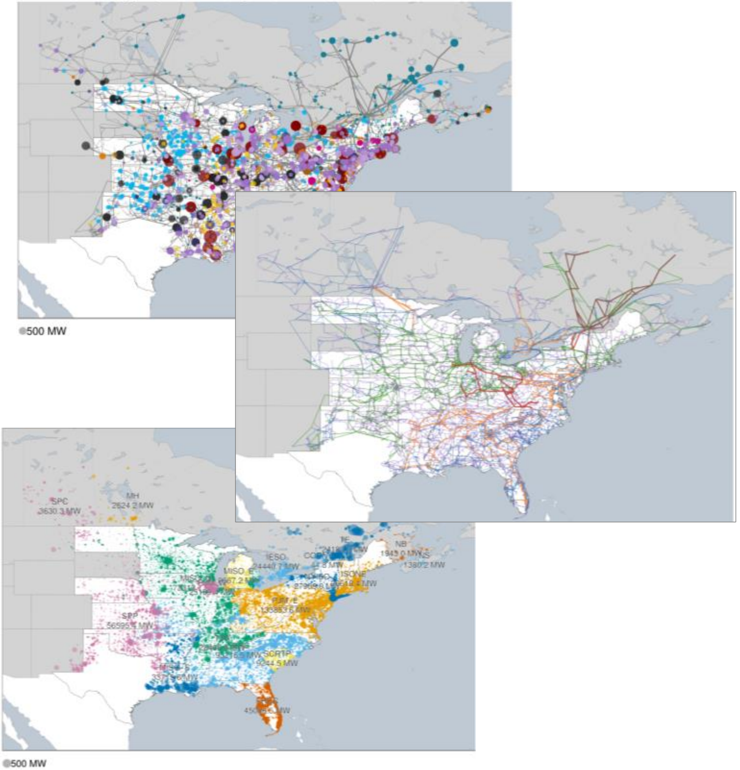
Mission ops

“Mission Ops”

Data and model validation + visualization

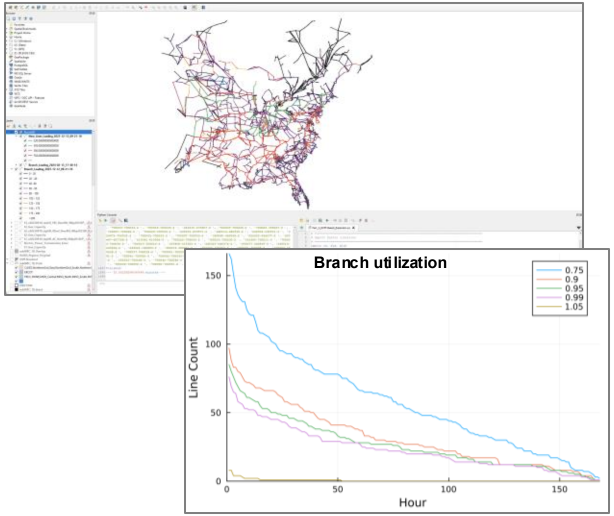
Static/interactive mapping

(large-scale datasets debugging, sharing)

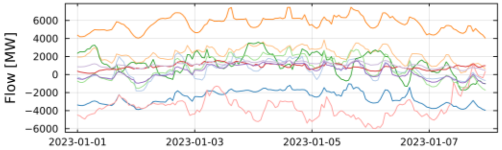


Integrated GIS platforms

(iterative and interactive transmission expansion)

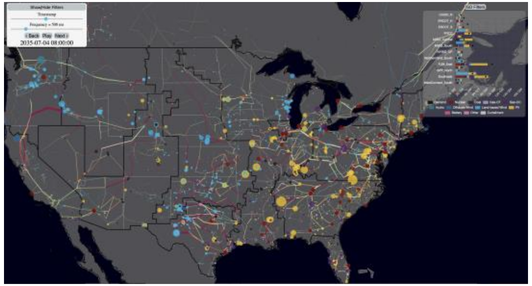


Branch/Interface flows + utilization

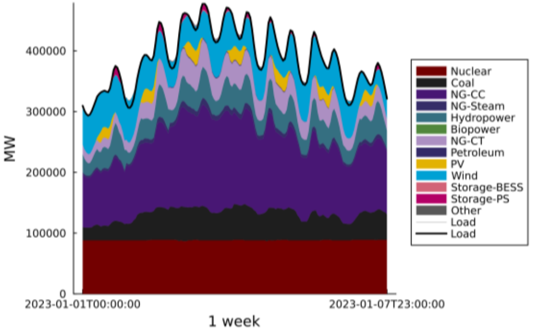


Spatial results visualization (Dashboards)

(debugging, planning, sharing)



Supply-demand balances



NOTE: All graphics are examples

Conclusions

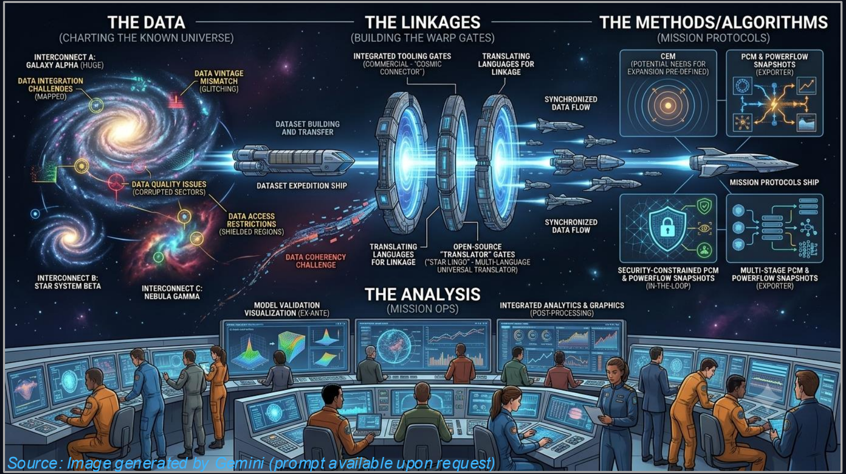
Mission status

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

This work was authored by the National Laboratory of the Rockies for the U.S. Department of Energy (DOE), operated under Contract No. DE-AC36-08GO28308. Funding provided by the Office of Electricity (formerly “Grid Deployment Office”). The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

Thank you

Jarrad WRIGHT

jarrad.wright@nlr.gov

NLR/PR-6A40-100850

National Laboratory of the Rockies

Photo from Getty Images 181828180