NREL
Transforming ENERGY

Sienna

SOLVING THE MARKET-TO-MARKET PROBLEM IN LARGE SCALE POWER SYSTEMS

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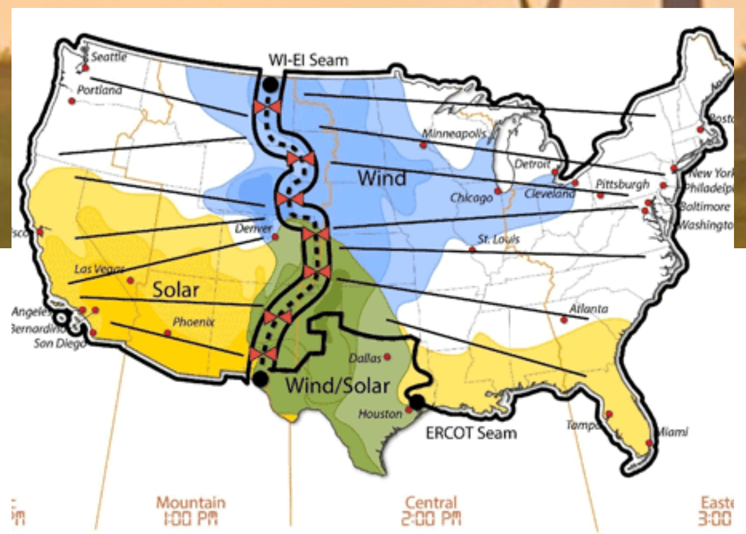
NREL’s Grid Planning and Analysis Center

bridges engineering, economics, and equity

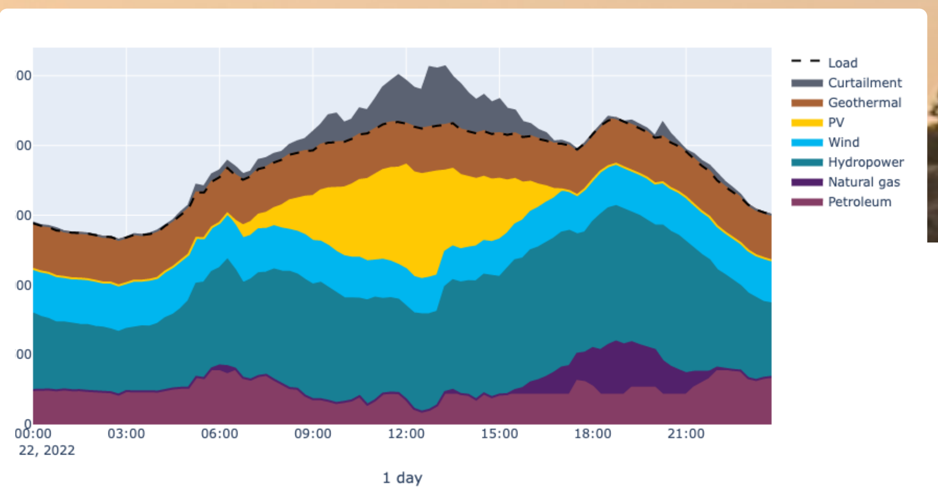
to advance the grid of the future

Bulk Power Systems Modeling for Decision Making



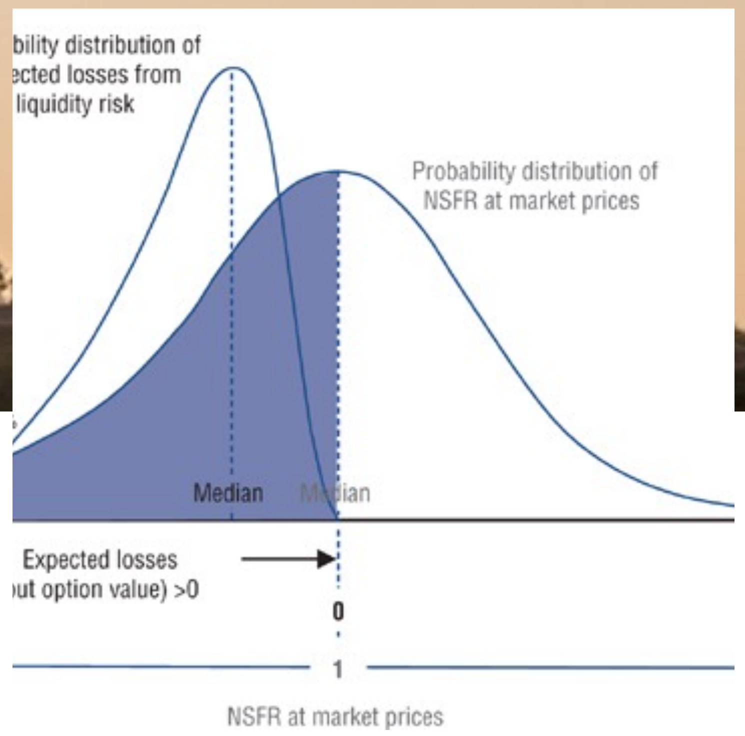
Build

What to build?
Where and When



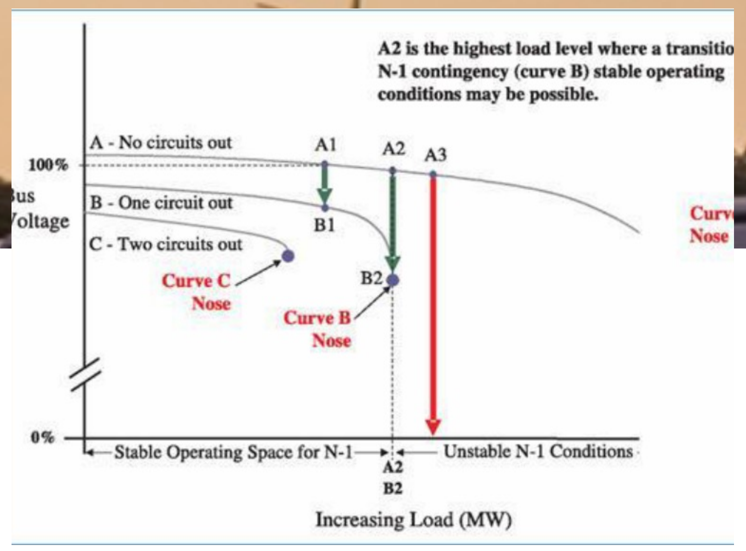
Operate

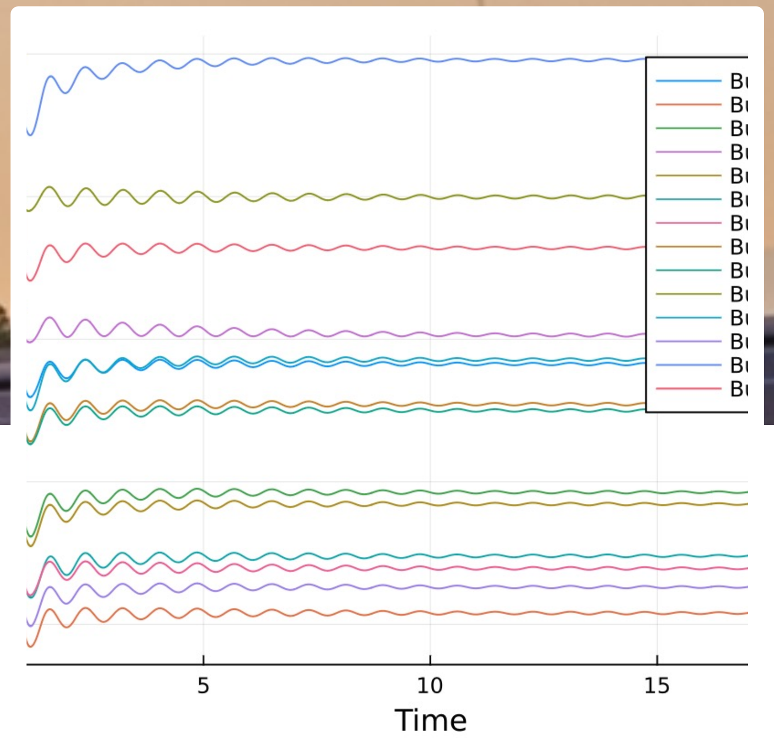
Can the planned system operate?



Adequate

Is supply sufficient under all conditions?





Statically Stable

Dynamically Stable

Can the system be stable under contingencies?

Can the transmission system operate correctly following the physical representation of the assets?

Open-source ecosystem for power system modeling, simulation and optimization

Sienna's three core applications use combinations of packages in the [Julia Programming Language]()

Sienna\Data

Efficient intake and use of energy systems input data

Developed to support modeling with large shares of renewable energy technologies

Sienna\Ops

Simulation of system scheduling, including sequential problems for production cost modeling

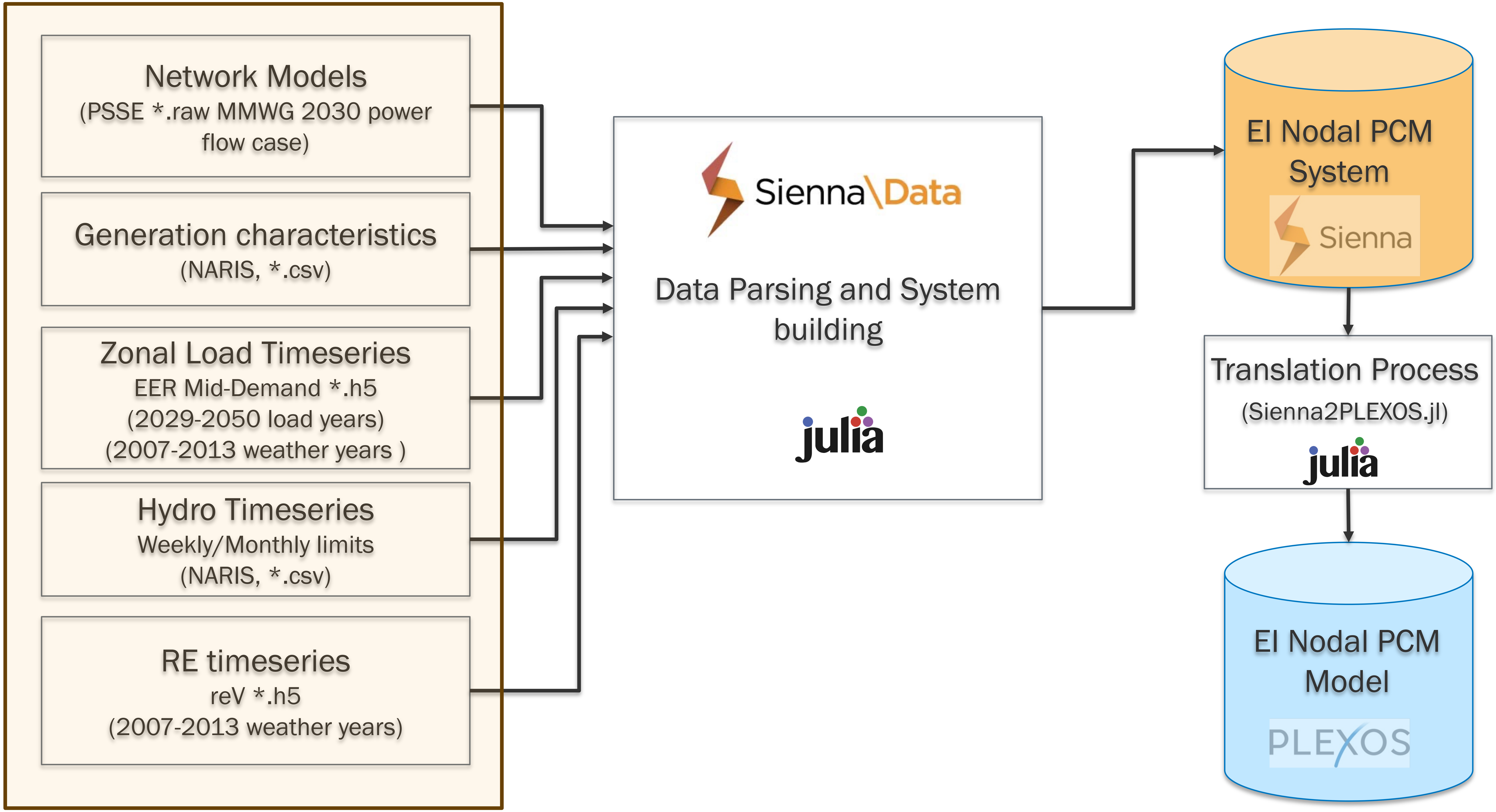
Sienna\Dyn

Simulation of power system dynamic response to disturbances and contingencies

Formerly known as SIIP

https://github.com/NREL-Sienna

Dataset Building Process



Network Models
(PSSE *.raw MMWG 2030 power flow case)

Generation characteristics
(NARIS, *.csv)

Zonal Load Timeseries
EER Mid-Demand *.h5
(2029-2050 load years)
(2007-2013 weather years)

Hydro Timeseries
Weekly/Monthly limits
(NARIS, *.csv)

RE timeseries
reV *.h5
(2007-2013 weather years)

Sienna\Data

Data Parsing and System building

julia

EI Nodal PCM System

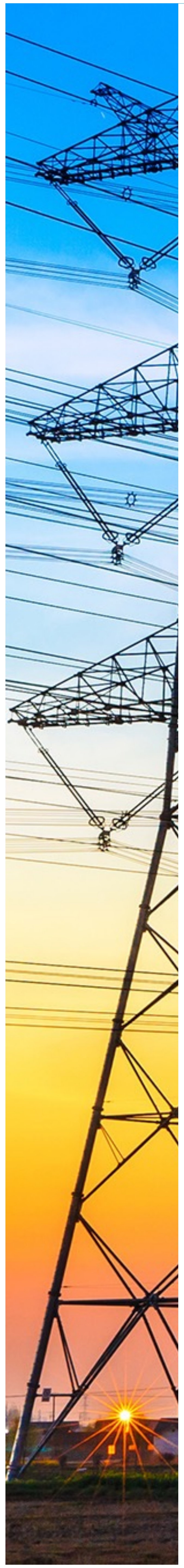
Sienna

Translation Process
(Sienna2PLEXOS.jl)

julia

EI Nodal PCM Model

PLEXOS

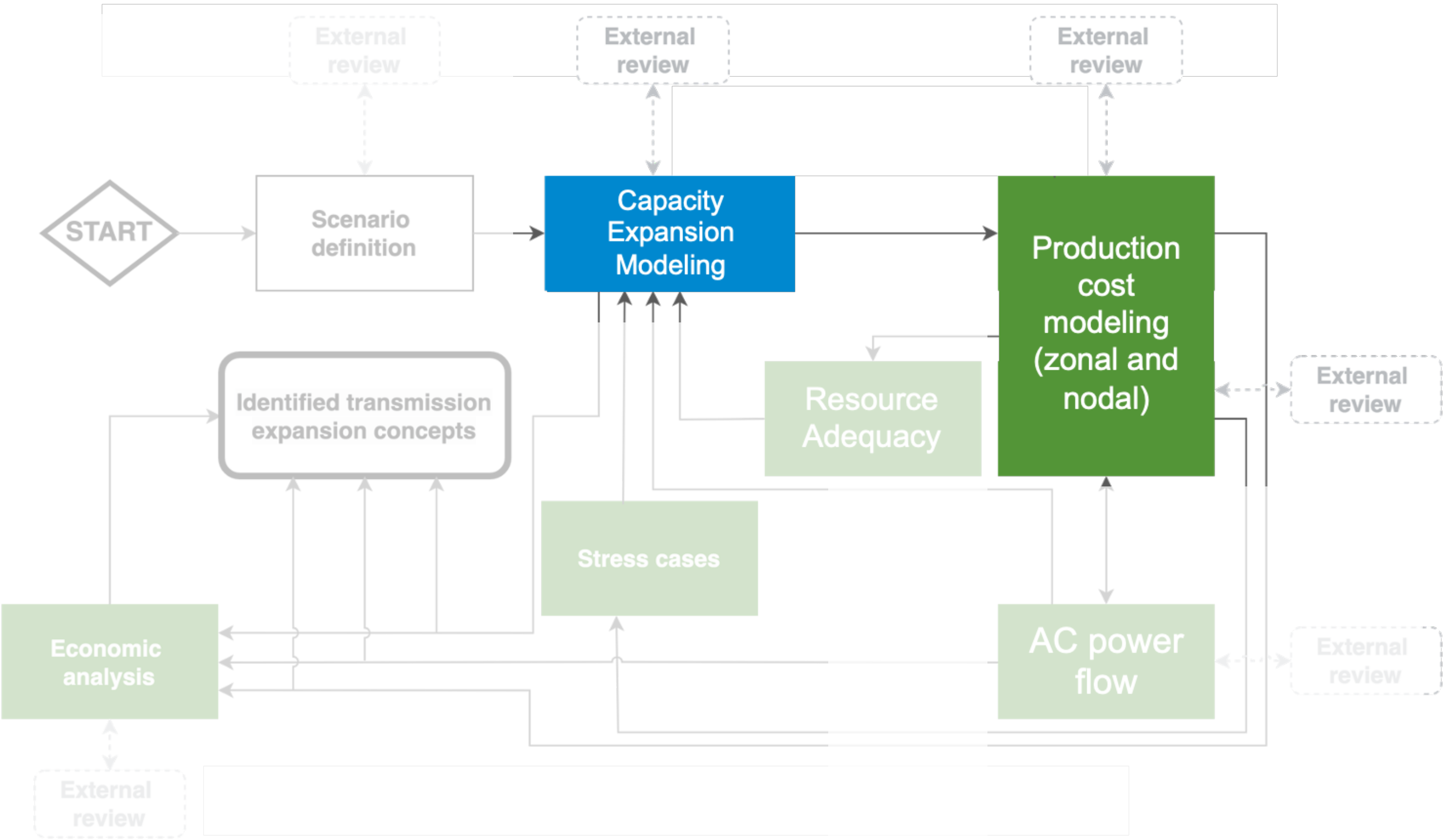


Use Case:
National Transmission Planning Study

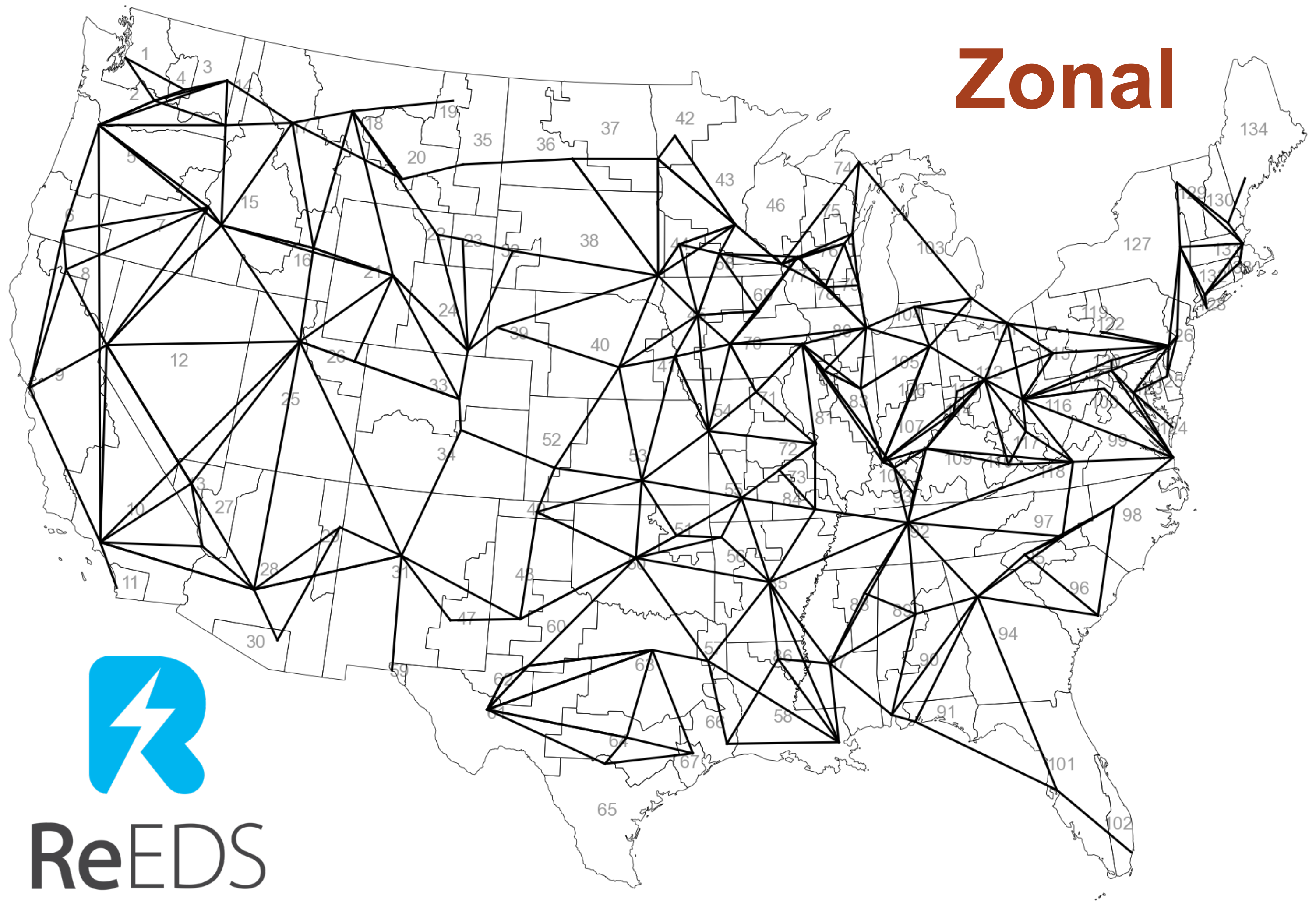
(https://www.energy.gov/gdo/national-transmission-planning-study)

Objectives

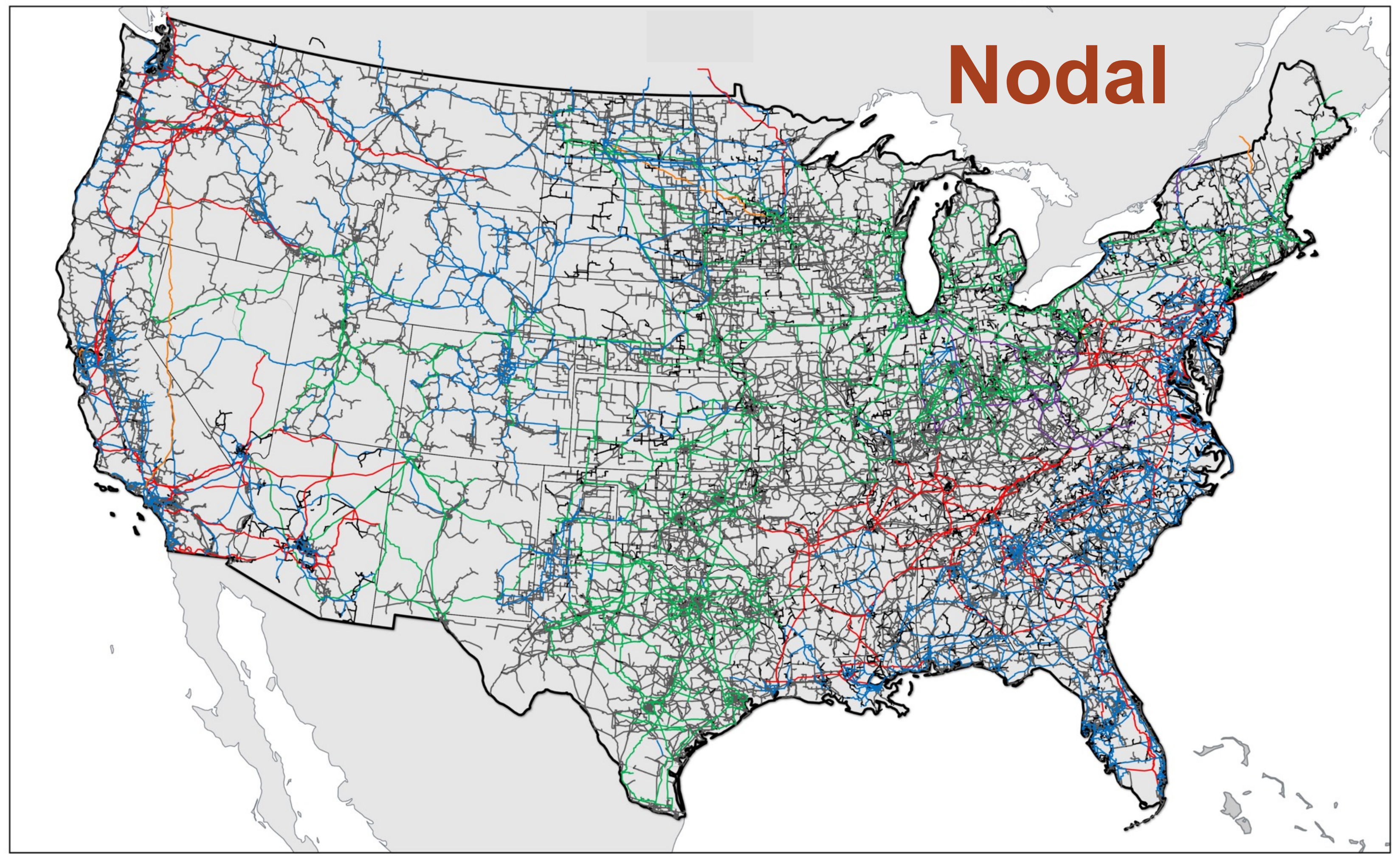
- Identify interregional and national strategies to accelerate cost-effective decarbonization while maintaining system reliability
- Inform regional and interregional transmission planning processes, particularly by engaging stakeholders in dialogue
- Results help inform future DOE funding for transmission infrastructure support



External review
External review
External review
START
Scenario definition
Capacity Expansion Modeling
Production cost modeling (zonal and nodal)
Identified transmission expansion concepts
Resource Adequacy
External review
Stress cases
Economic analysis
AC power flow
External review
External review



ReEDS



Sienna\Data

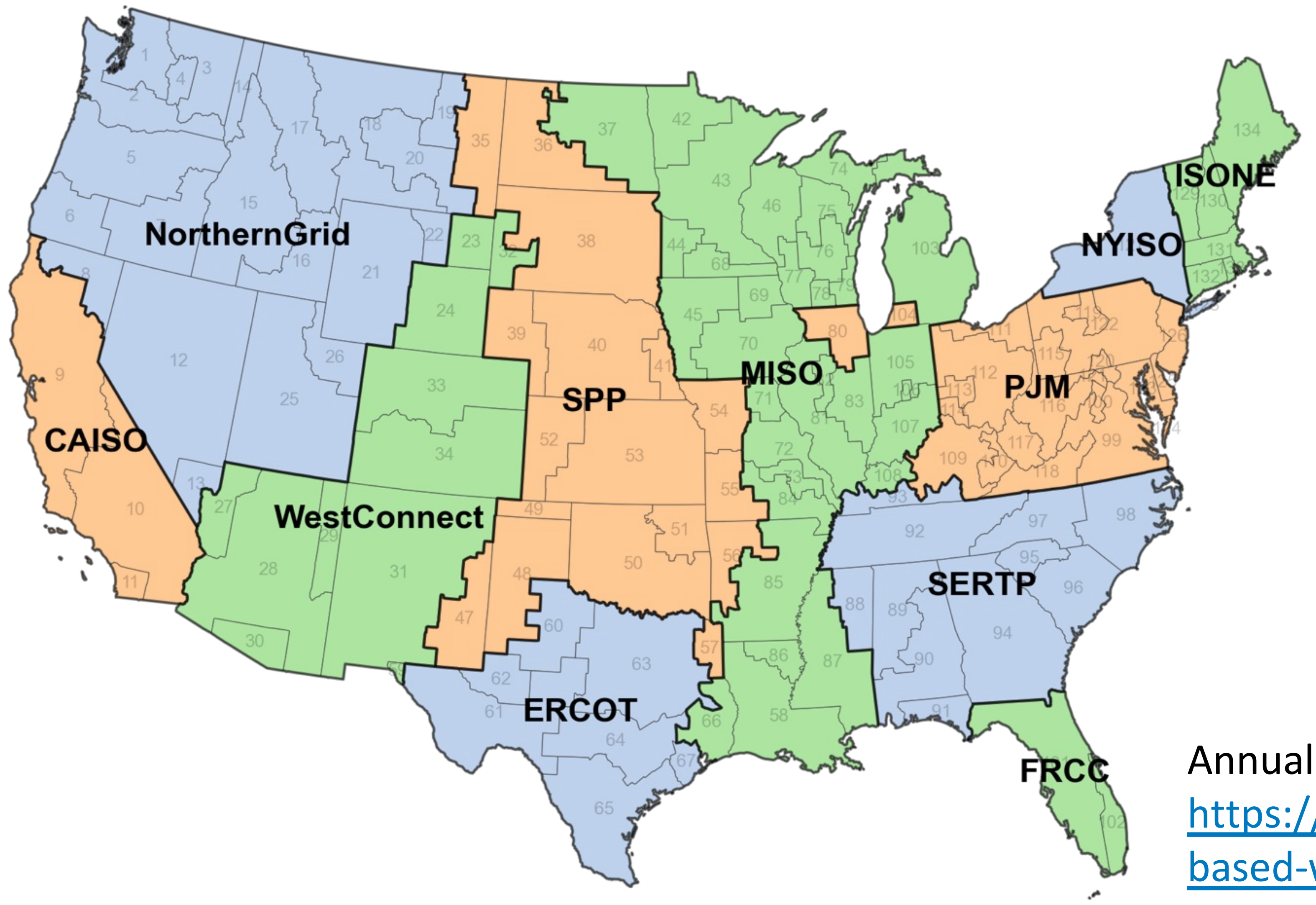
Efficient intake and use of energy systems input data

Sienna\Ops

Simulation of system scheduling, including sequential problems for production cost modeling

Four interregional transmission frameworks

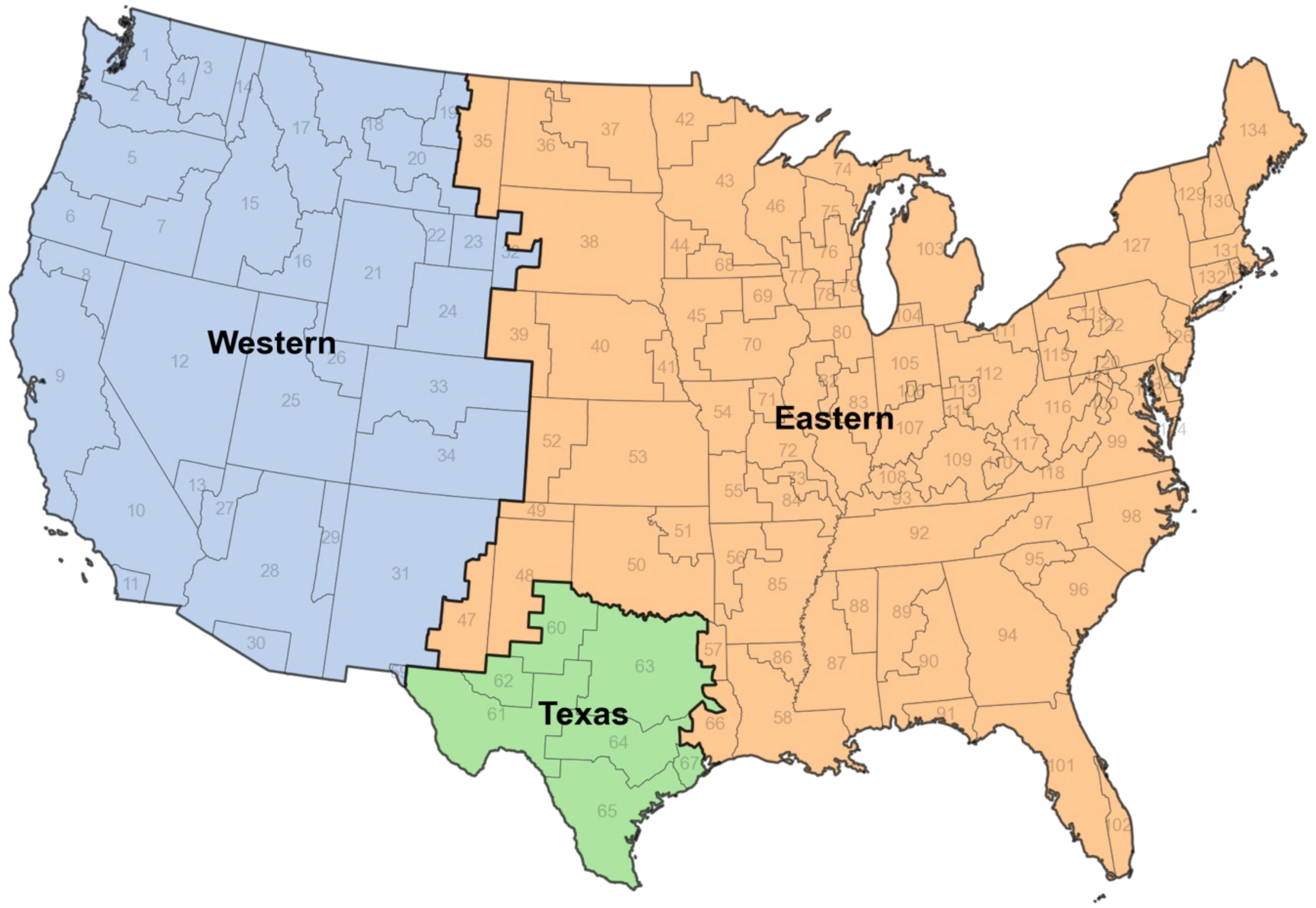
Limited



- AC and existing HVDC expansion allowed within “transmission regions” (FERC order 1000 + ERCOT)
- Annual transmission additions (all types) ≤ 1.83 TW-miles/year

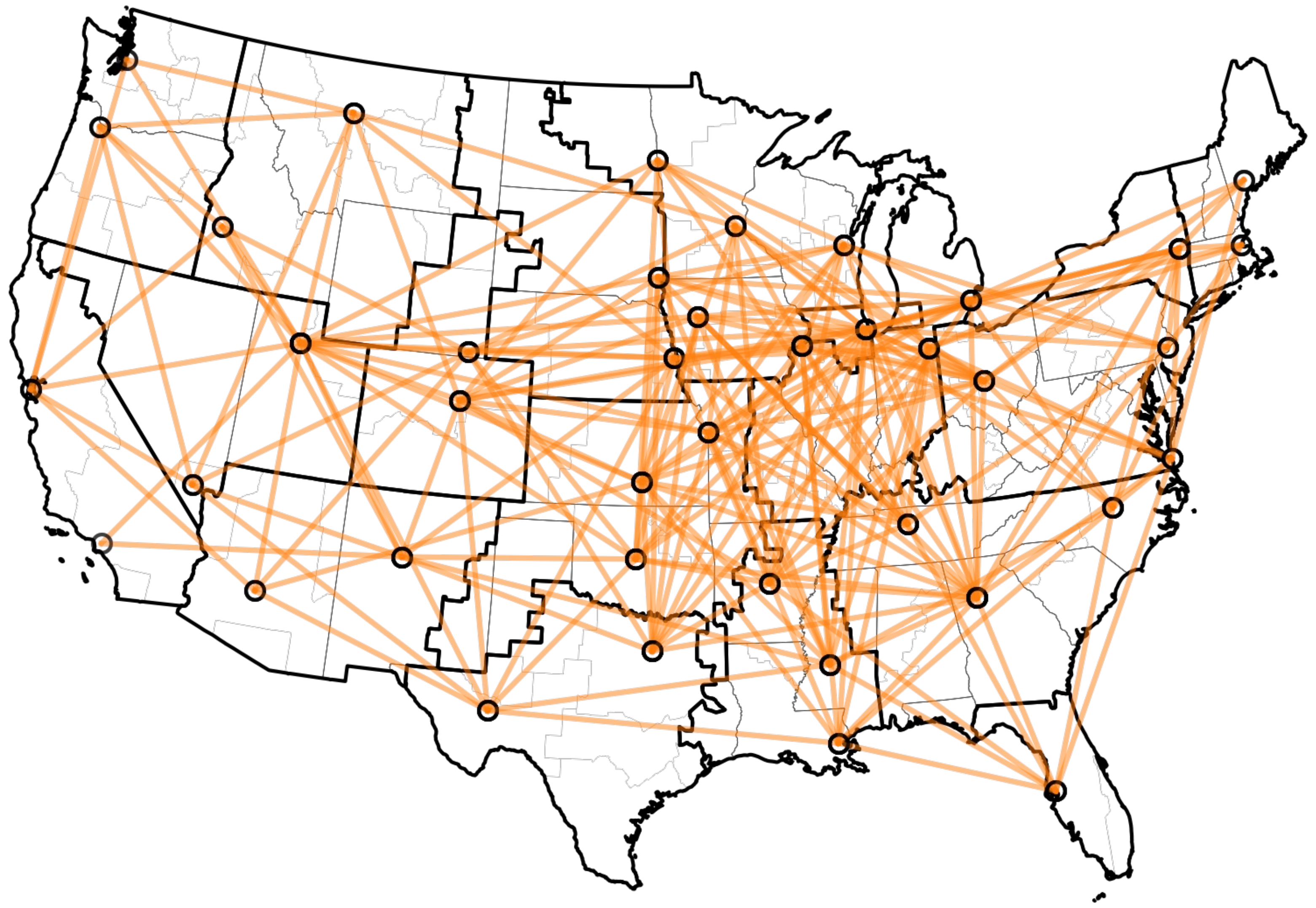
Annual US high-voltage transmission additions: https://www.energy.gov/eere/wind/articles/land-based-wind-market-report-2023-edition

AC



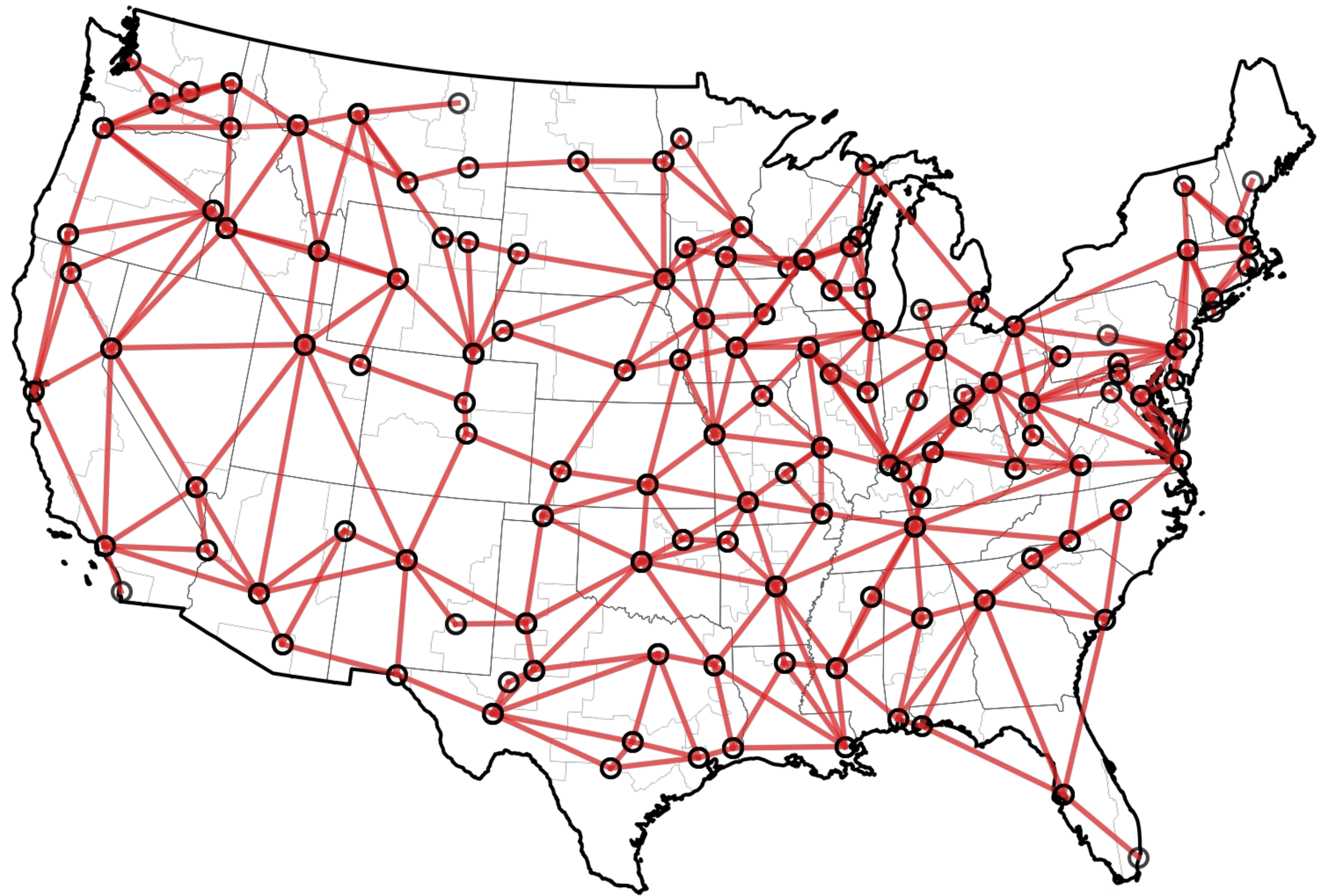
- AC and existing HVDC expansion allowed within interconnections
- No limit on total annual transmission additions

P2P (“point-to-point”)



- AC and existing HVDC expansion allowed within interconnections
- Expansion of B2B interties allowed
- HVDC expansion along 195 new corridors allowed

MT (“multi-terminal”)



- AC and existing HVDC expansion allowed within interconnections
- Multi-terminal HVDC expansion allowed between adjacent regions

MODEL LIMITED CHOICE

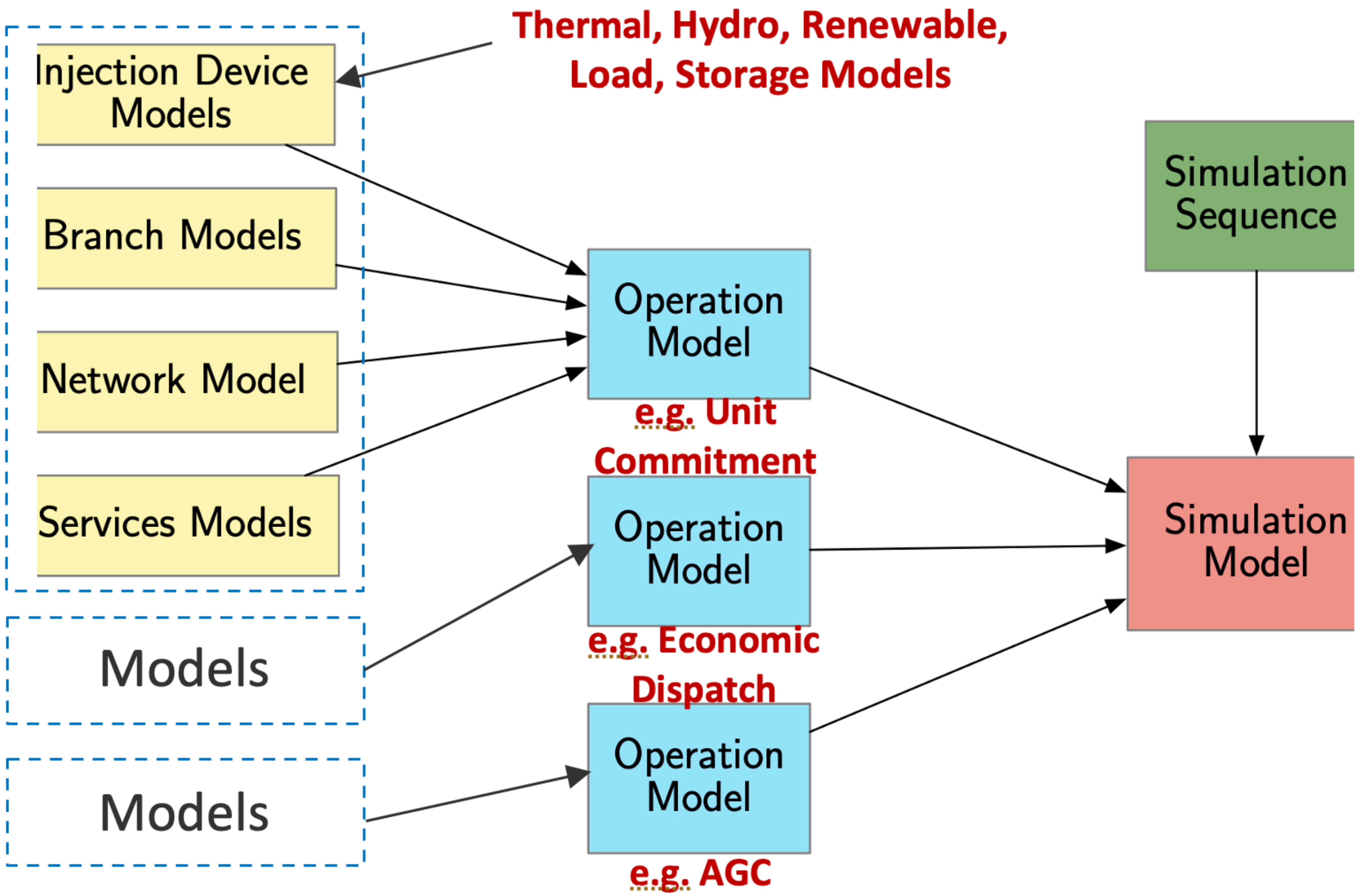
Structural exclusion of certain forms of simulation and analysis

&

Formulation limitations due to restrictions in underlying models or data availability

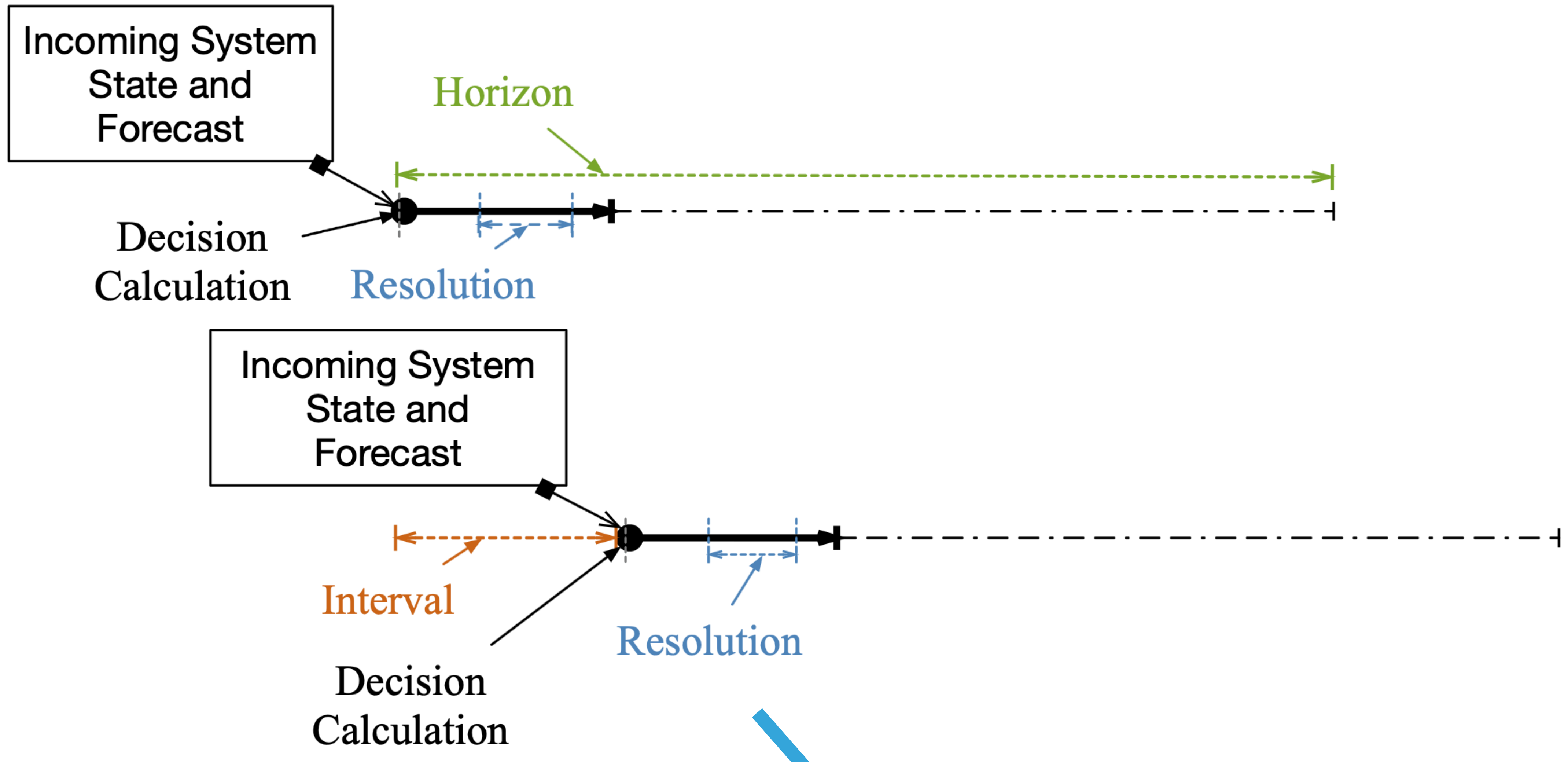
CUSTOMIZATION OF THE UNDERLYING SIMULATION

- Employ a tree-type structure to store the optimization models and related information.
- Define the sequence of solution separately from the problem definitions.
- Support problem level customization of the solution technique and details.

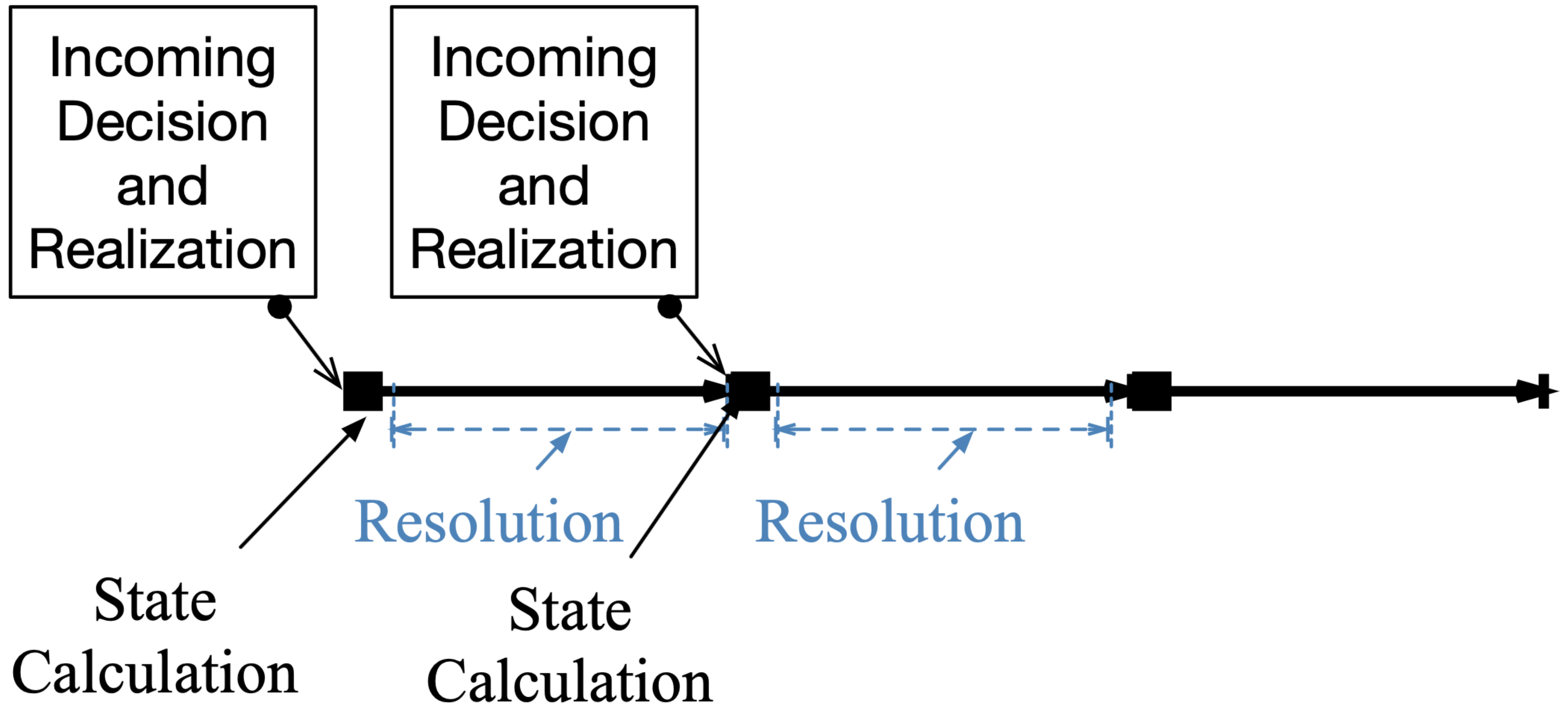


FORMALIZING SIMULATING OPERATIONS

DECISION MODEL



EMULATION MODEL

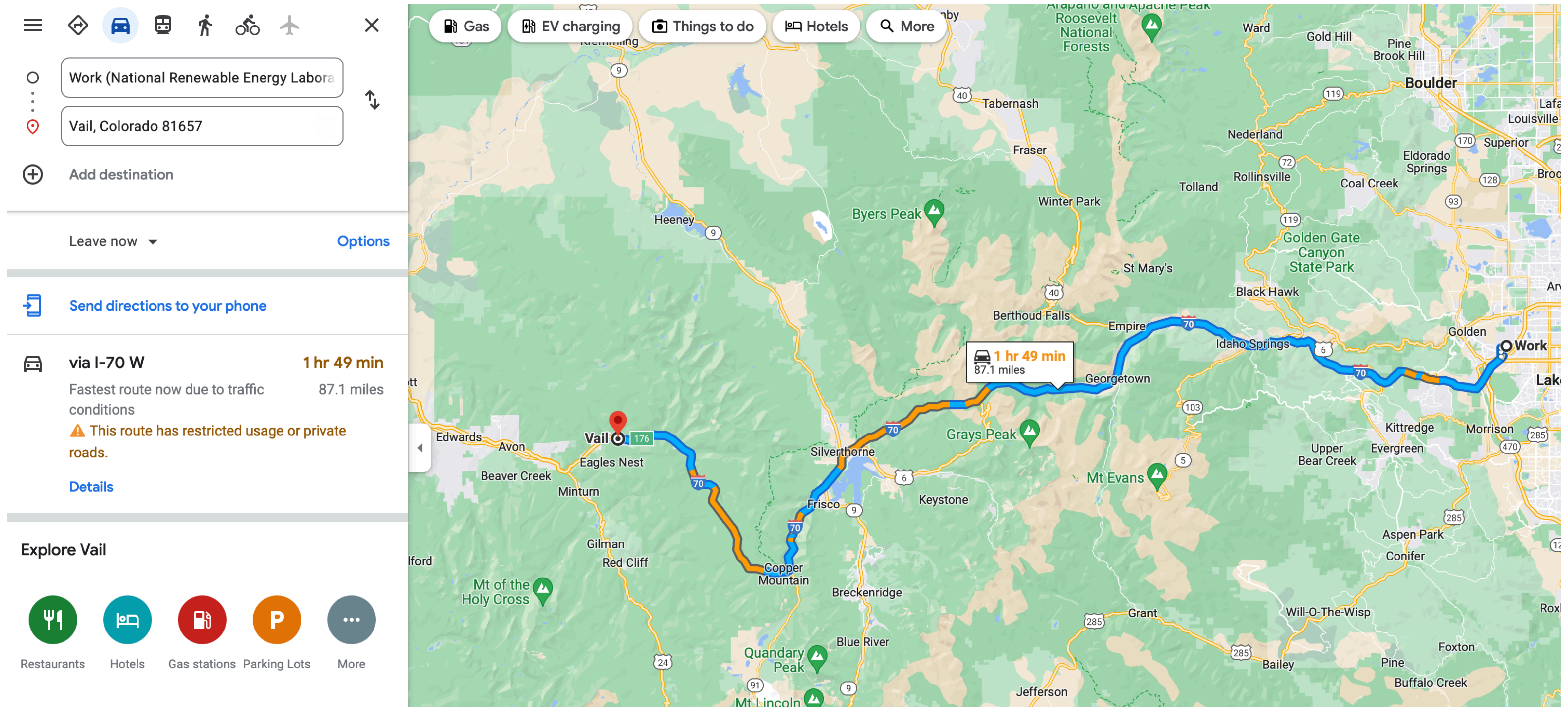


$$\vec{u}_t = F_t(\vec{x}_{t-1}, \vec{u}_{t-1}, \vec{\rho}_t, \Phi | t), \quad \vec{u}_{t_0} = \vec{u}_0$$

$$G_t(\vec{x}_t, \vec{x}_{t-1}, \vec{u}_t, \vec{\psi}_t) = 0, \quad \vec{x}_{t_0} = \vec{x}_0$$

EVERYDAY ANALOGOUS PROCESS

DECISION MODEL



Work (National Renewable Energy Labora

Vail, Colorado 81657

Add destination

Leave now

Options

Send directions to your phone

via I-70 W 1 hr 49 min

Fastest route now due to traffic conditions 87.1 miles

⚠ This route has restricted usage or private roads.

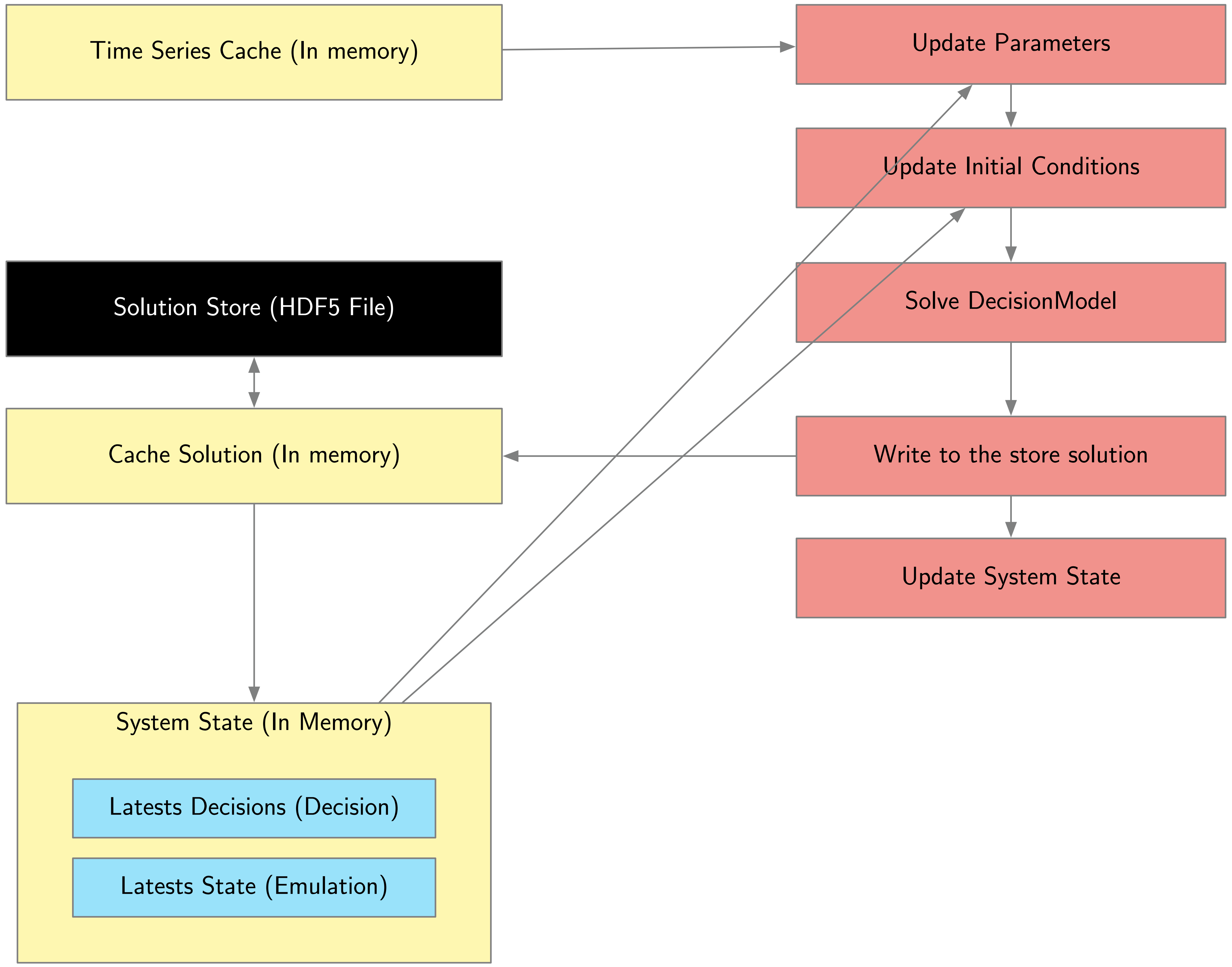
Details

Explore Vail

EMULATION MODEL

SOLVE MODEL FOR MULTI-STAGE SIMULATIONS

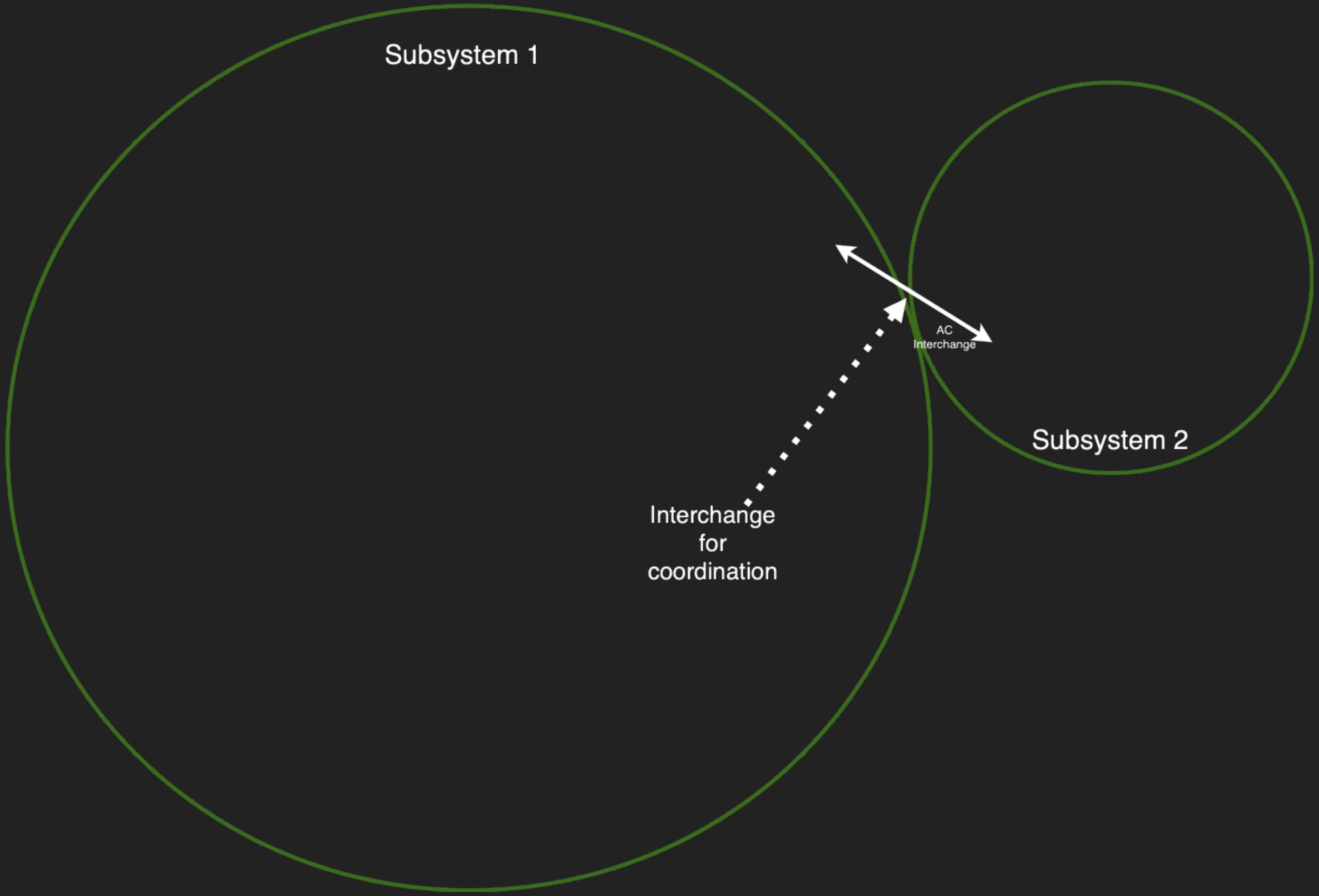
- The simulation has a store for the solution of each stage of the decision making problem.
- The simulator keeps track of the latest value of the decision variables and the system variables in a given state.
- An incumbent solution also speeds up finding the solution for the next step.
- Information written to disk is not retrieved back for the purpose of modeling. I.e., no write-read of LP files for every run.



DEVELOPMENTS FOR M2M SIMULATION ON LARGE SCALE NETWORKS

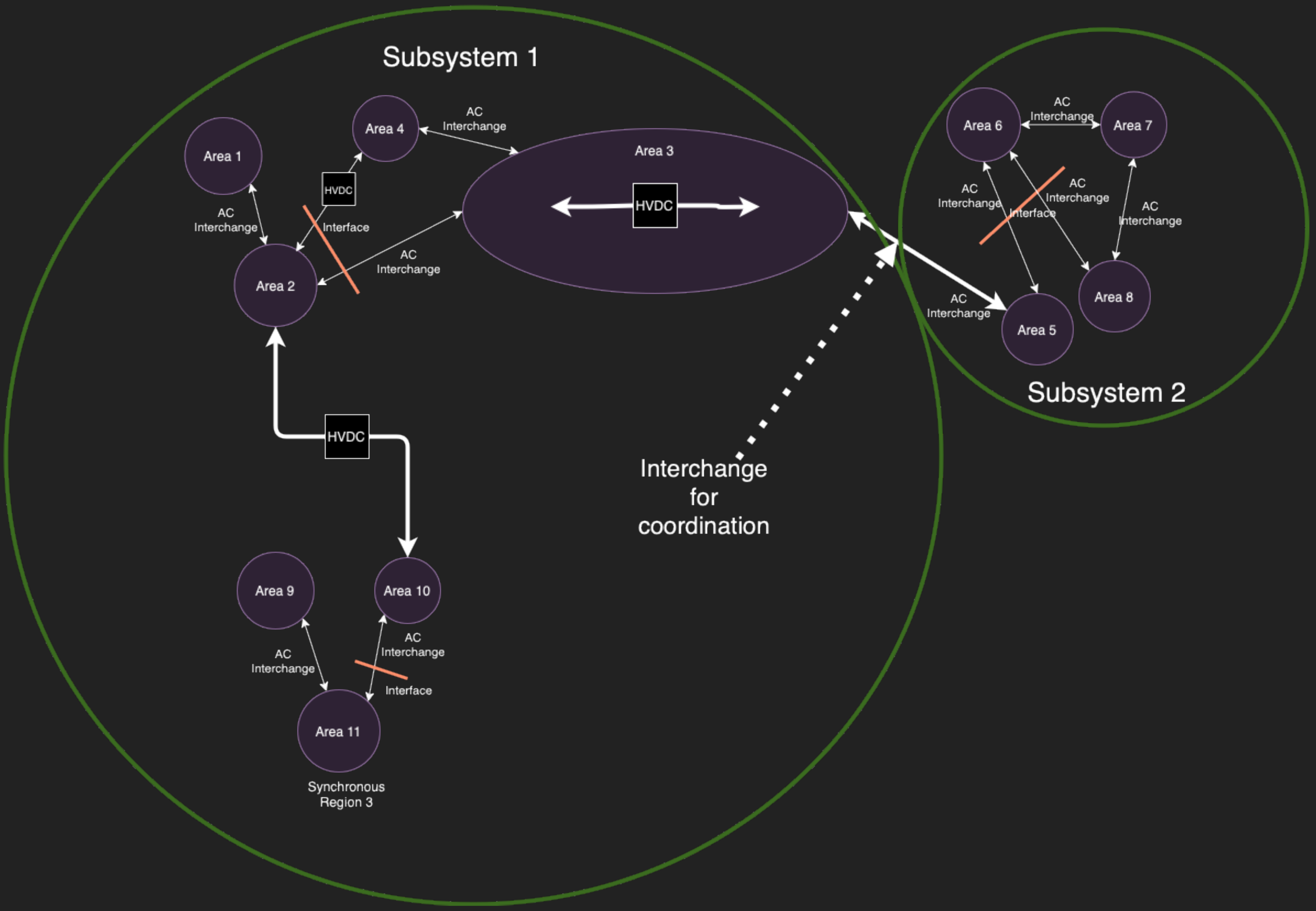
2-SUBSYSTEMS

- We define two Subsystems in an interconnected area that share an interchange.
- The objective is to develop a modeling/simulation platform to assess different techniques to coordinate over this interconnection efficiently.
- Several works have looked at this problem; however, these have not considered other topological challenges



2-SUBSYSTEMS, MULTIPLE AREAS

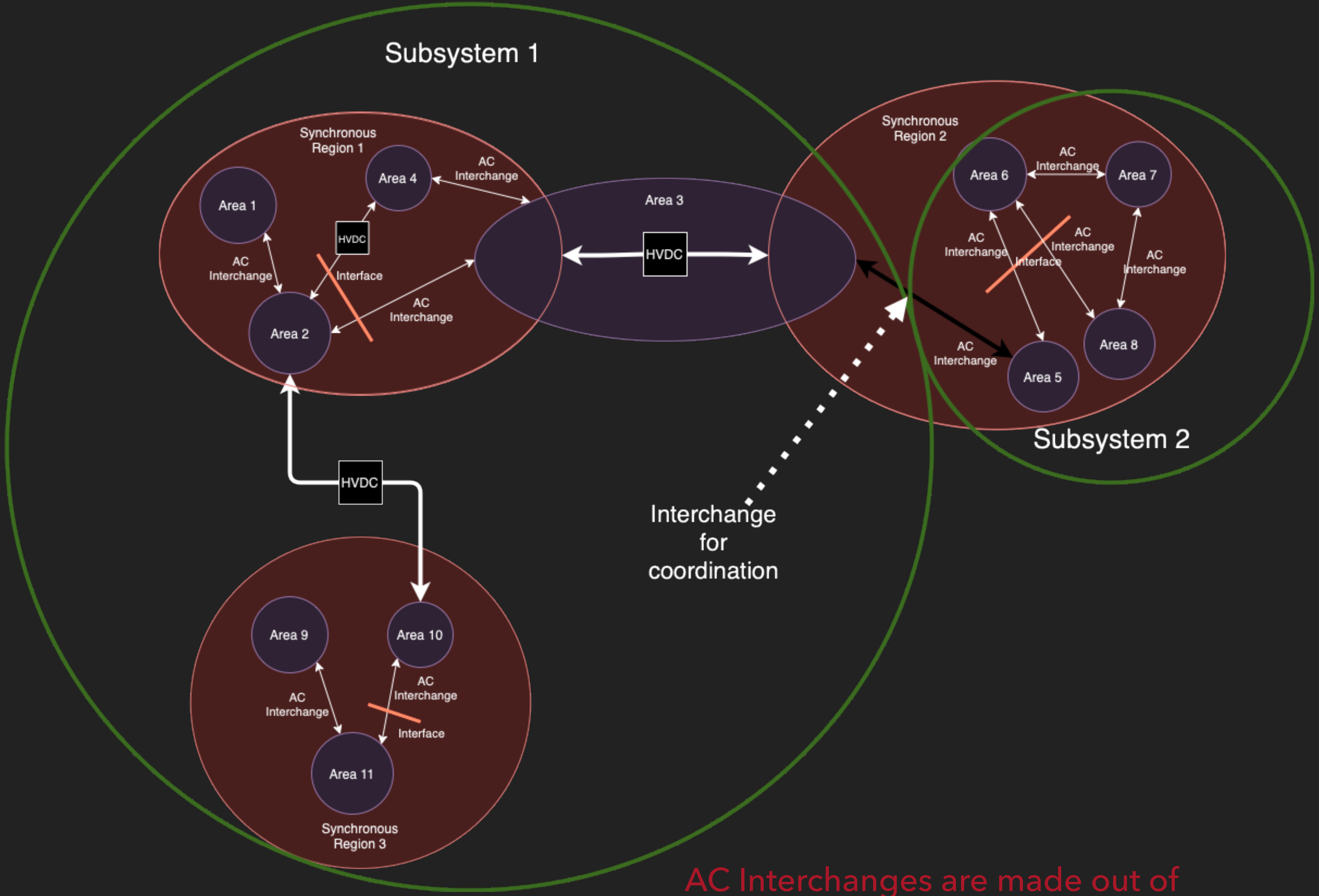
- Each subsystem is composed of several areas for balancing power.
- These areas might be connected by other interchanges internal to the subsystems. The interchanges can be in AC or via HVDC.
- Each subsystem also defines interfaces which might coincide with the interchanges or contain several



AC Interchanges are made out of multiple AC lines

2-SUBSYSTEMS, MULTIPLE AREAS, MULTIPLE SYNCHRONOUS REGIONS

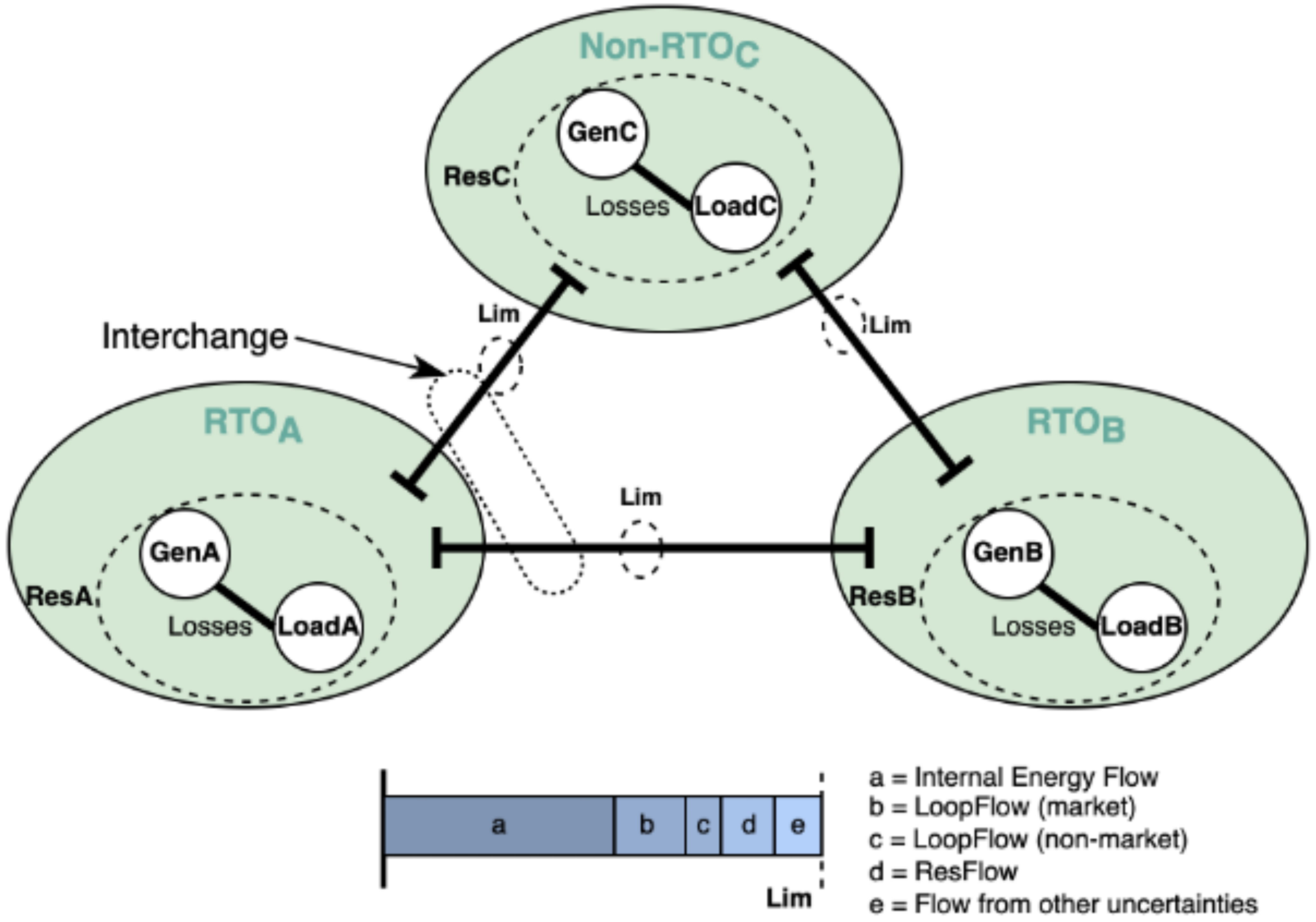
- The areas are split across synchronous regions connected via HVDC.
- Modeling the synchronous regions adequately matters such that the PTDF assumptions are correct and the line flows are estimated correctly.
- The combination of balancing areas, regions and systems makes the problem complex to build and simulate



AC Interchanges are made out of multiple AC lines

COORDINATION PROBLEMS

- Coordinated Transaction / Interchange Optimization
  - Congestion management
  - Settlement cost reductions
- Market to market coordination (M2M) under Joint operating agreements (JOAs)
  - NERC Transmission Line Loading Relief (TLR)
- Reserve sharing group
- Coordination mostly happens in real time, and with significant opportunities for improvement
- Limited coordination in operational forward processes
  - Values and needs for coordination in operational forward processes
  - Intra- and inter-regional HVDC optimization
  - Intra- and inter-regional reserve deliverability



a = Internal Energy Flow
b = LoopFlow (market)
c = LoopFlow (non-market)
d = ResFlow
e = Flow from other uncertainties

SYSTEM COORDINATION

More coordination

Less coordination

System wide constraints	**Co-optimized**	**Individual clearing with coordination**	**Individual clearing without coordination**
Power balance	GenA+GenB=LoadA+LoadB	GenA+NSIA=LoadA GenB+NSIB=LoadB **Interchange optimization**	GenA+NSIA=LoadA GenB+NSIB=LoadB
Transmission constraint (energy flow)	EnergyFlowA+EnergyFlowB ≤Limit	EnergyFlowA+loopflowA≤Limit EnergyFlowB+loopflowB≤Limit **M2M congestion management energy flow**	EnergyFlowA+loopflow≤Limit **On monitoring RTO**
Reserve requirement	ResA + ResB ≥ ResRequirement	ResA ≥ ResRequirementA ResB ≥ ResRequirementB **Reserve sharing group for contingency reserve**	ResA ≥ ResRequirementA ResB ≥ ResRequirementB
Transmission constraint (energy+ reserve flow)	EnergyFlowA + EnergyFlowB + ResFlowA + ResFlowB ≤Limit	EnergyFlowA+ResFlowA+loopflowA≤Limit EnergyFlowB+ResFlowB+loopflowB≤Limit **M2M congestion management with reserve deliverability**	EnergyFlowA+ResFlowA+loopflow ≤Limit **On monitoring RTO**

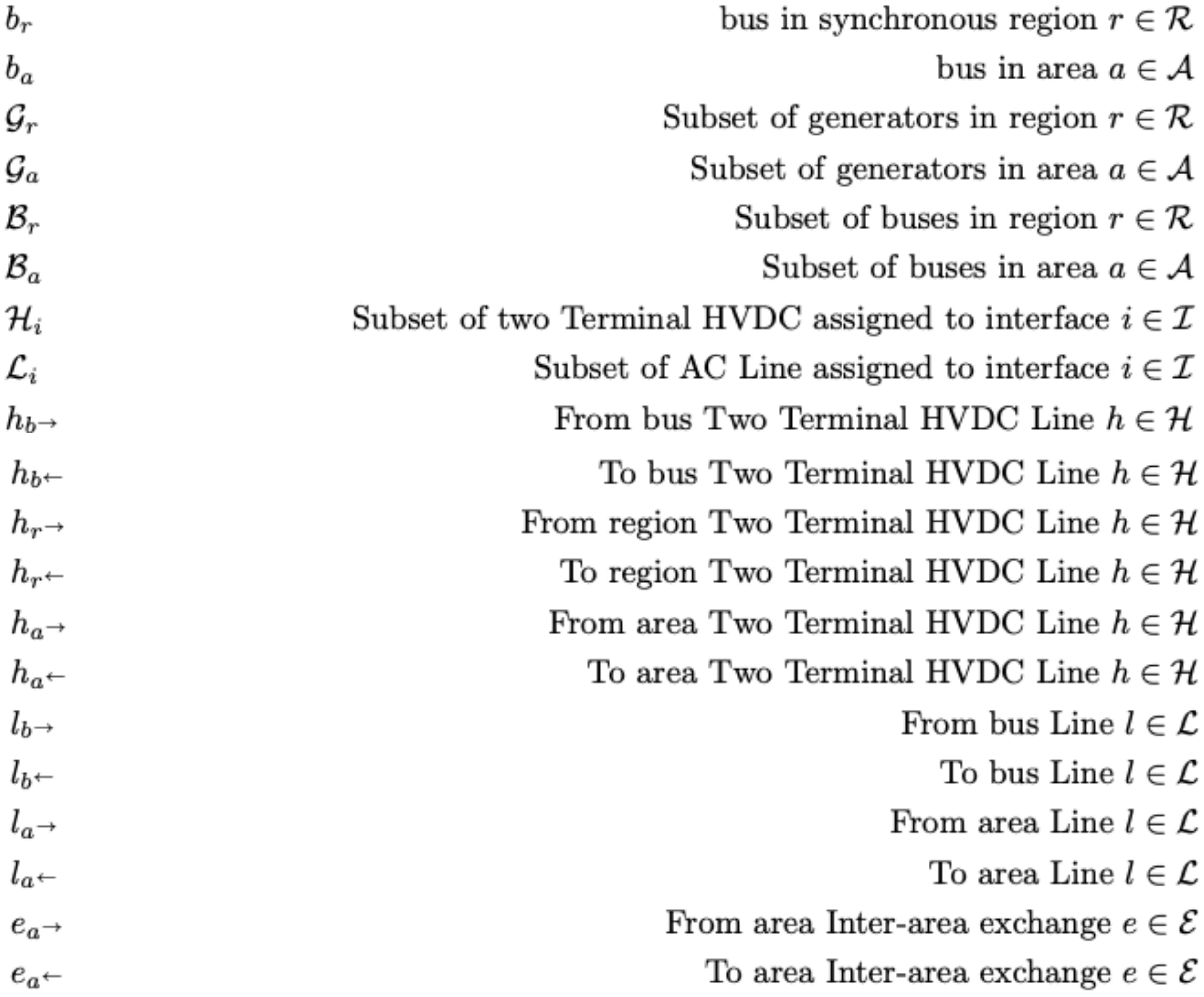
Two RTOs A and B assuming lossless

Red: variables *Black: parameters* *Blue: components with coordination mechanism*

MODEL FORMULATION – SETS

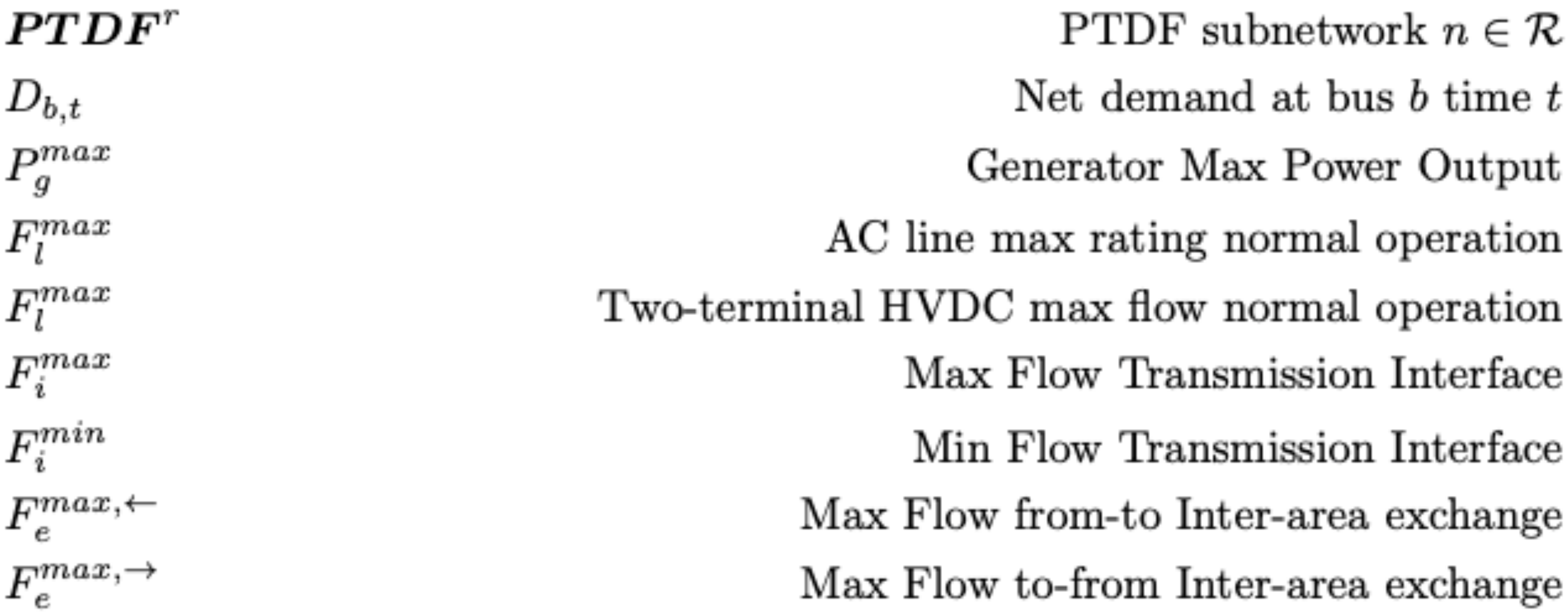
$\mathcal{B}$	System Buses
$\mathcal{R}$	Synchronous Regions
$\mathcal{A}$	Balancing Areas
$\mathcal{L}$	AC Lines
$\mathcal{H}$	Two Terminal HVDC Lines
$\mathcal{E} := \{e \in \mathrm{C}(\mathcal{A}, 2)\}$	Inter-area exchanges
$\mathcal{I}$	Transmission interfaces
$\mathcal{G}$	Generators
$\mathcal{X}$	Feasibility Set
$\mathcal{T} := \{1, \ldots, T\}$	Time steps

MODEL FORMULATION – INDEXING



b_r	bus in synchronous region $r \in \mathcal{R}$
b_a	bus in area $a \in \mathcal{A}$
$\mathcal{G}_r$	Subset of generators in region $r \in \mathcal{R}$
$\mathcal{G}_a$	Subset of generators in area $a \in \mathcal{A}$
$\mathcal{B}_r$	Subset of buses in region $r \in \mathcal{R}$
$\mathcal{B}_a$	Subset of buses in area $a \in \mathcal{A}$
$\mathcal{H}_i$	Subset of two Terminal HVDC assigned to interface $i \in \mathcal{I}$
$\mathcal{L}_i$	Subset of AC Line assigned to interface $i \in \mathcal{I}$
$h_{b\rightarrow}$	From bus Two Terminal HVDC Line $h \in \mathcal{H}$
$h_{b\leftarrow}$	To bus Two Terminal HVDC Line $h \in \mathcal{H}$
$h_{r\rightarrow}$	From region Two Terminal HVDC Line $h \in \mathcal{H}$
$h_{r\leftarrow}$	To region Two Terminal HVDC Line $h \in \mathcal{H}$
$h_{a\rightarrow}$	From area Two Terminal HVDC Line $h \in \mathcal{H}$
$h_{a\leftarrow}$	To area Two Terminal HVDC Line $h \in \mathcal{H}$
$l_{b\rightarrow}$	From bus Line $l \in \mathcal{L}$
$l_{b\leftarrow}$	To bus Line $l \in \mathcal{L}$
$l_{a\rightarrow}$	From area Line $l \in \mathcal{L}$
$l_{a\leftarrow}$	To area Line $l \in \mathcal{L}$
$e_{a\rightarrow}$	From area Inter-area exchange $e \in \mathcal{E}$
$e_{a\leftarrow}$	To area Inter-area exchange $e \in \mathcal{E}$

MODEL FORMULATION – PARAMETERS



$\boldsymbol{PTDF}^r$	PTDF subnetwork $n \in \mathcal{R}$
$D_{b,t}$	Net demand at bus b time t
P_g^{max}	Generator Max Power Output
F_l^{max}	AC line max rating normal operation
F_l^{max}	Two-terminal HVDC max flow normal operation
F_i^{max}	Max Flow Transmission Interface
F_i^{min}	Min Flow Transmission Interface
$F_e^{max,\leftarrow}$	Max Flow from-to Inter-area exchange
$F_e^{max,\rightarrow}$	Max Flow to-from Inter-area exchange

MODEL FORMULATION – VARIABLES & EXPRESSIONS

$$\begin{aligned}
p_{g,t} &\in [0, P_g^{max}] && \text{Generator Power Output} \\
f_{h,t} &\in [-F_h^{max}, F_h^{max}] && \text{HVDC Line flow} \\
f_{e,t} &\in [-F_e^{max,\rightarrow}, F_e^{max,\leftarrow}] && \text{Inter-area exchange flow}
\end{aligned}$$

$$\begin{aligned}
i_{b,t} &:= D_{b,t} - \sum_{g \in \mathcal{G}_b} p_{g,t} + \sum_{\{h \in \mathcal{H} | h_{b\leftarrow} = b\}} f_{h,t} - \sum_{\{h \in \mathcal{H} | h_{b\rightarrow} = b\}} f_{h,t} && \text{Net Injection at bus } b \text{ at time } t \\
f_{l,t} &:= \sum_{l \in \mathcal{L}_r, b \in \mathcal{B}_r} \boldsymbol{PTDF}^r_{l,b} i_{b,t} && \text{Power flow over branch } l \text{ in region } r \text{ at time } t
\end{aligned}$$

MODEL FORMULATION –CONSTRAINTS

$$\min_{\boldsymbol{p},\boldsymbol{f}_h,\boldsymbol{f}_e} \quad \sum_{t\in\mathcal{T},g\in\mathcal{G}} \mathrm{O}_g(p_{g,t})$$

s.t.

$$\begin{aligned}
p_{g,t} &\in \mathcal{X}_g && \forall g\in\mathcal{G},\ \forall t\in\mathcal{T}\\
f_{l,t} &\in \mathcal{X}_l && \forall l\in\mathcal{L},\ \forall t\in\mathcal{T}\\
f_{h,t} &\in \mathcal{X}_h && \forall h\in\mathcal{H},\ \forall t\in\mathcal{T}\\
f_{e,t} &\in \mathcal{X}_e && \forall e\in\mathcal{E},\ \forall t\in\mathcal{T}
\end{aligned}$$

Feasibility sets for the different model components

$$\sum_{g\in\mathcal{G}_r} p_{g,t} + \sum_{\{h\in\mathcal{H}|h_{b\leftarrow}\in r\}} f_{h,t} - \sum_{\{h\in\mathcal{H}|h_{b\rightarrow}\in\mathcal{B}_r\}} f_{h,t} = \sum_{b\in\mathcal{B}_r} D_b \ \forall r\in\mathcal{R},\ \forall t\in\mathcal{T}$$

Synchronous Region Power Balance

$$\sum_{g\in\mathcal{G}_a} p_{g,t} + \sum_{\{E\in\mathcal{E}|e_{a\leftarrow}=a\}} f_{e,t} - \sum_{\{e\in\mathcal{E}|e_{a\rightarrow}=a\}} f_{e,t} = \sum_{b\in\mathcal{B}_a} D_b \ \forall a\in\mathcal{A},\ \forall t\in\mathcal{T}$$

Area Power Balance

$$\sum_{\{l\in\mathcal{L}|l_{a\rightarrow}=e_{a\rightarrow}\wedge l_{a\leftarrow}=e_{a\leftarrow}\}} f_{l,t} - \sum_{\{l\in\mathcal{L}|l_{a\rightarrow}=e_{a\leftarrow}\wedge l_{a\rightarrow}=e_{a\leftarrow}\}} f_{l,t} + \sum_{\{h\in\mathcal{H}|h_{a\rightarrow}=e_{a\rightarrow}\wedge h_{a\leftarrow}=e_{a\leftarrow}\}} f_{h,t} - \sum_{\{h\in\mathcal{H}|h_{a\rightarrow}=e_{a\leftarrow}\wedge h_{a\rightarrow}=e_{a\leftarrow}\}} f_{h,t} \leq f_{e,t} \quad \forall e\in\mathcal{E},\ t\in\mathcal{T}$$

Area Exchange Upper Bound

$$\sum_{\{l\in\mathcal{L}|l_{a\rightarrow}=e_{a\rightarrow}\wedge l_{a\leftarrow}=e_{a\leftarrow}\}} f_{l,t} - \sum_{\{l\in\mathcal{L}|l_{a\rightarrow}=e_{a\leftarrow}\wedge l_{a\rightarrow}=e_{a\leftarrow}\}} f_{l,t} + \sum_{\{h\in\mathcal{H}|h_{a\rightarrow}=e_{a\rightarrow}\wedge h_{a\leftarrow}=e_{a\leftarrow}\}} f_{h,t} - \sum_{\{h\in\mathcal{H}|h_{a\rightarrow}=e_{a\leftarrow}\wedge h_{a\rightarrow}=e_{a\leftarrow}\}} f_{h,t} \geq f_{e,t} \quad \forall e\in\mathcal{E},\ t\in\mathcal{T}$$

Area Exchange Lower Bound

$$\sum_{l\in\mathcal{L}_i} f_{l,t} + \sum_{h\in\mathcal{H}_i} f_{h,t} \leq F_i^{max} \quad \forall i\in\mathcal{I},\ t\in\mathcal{T}$$

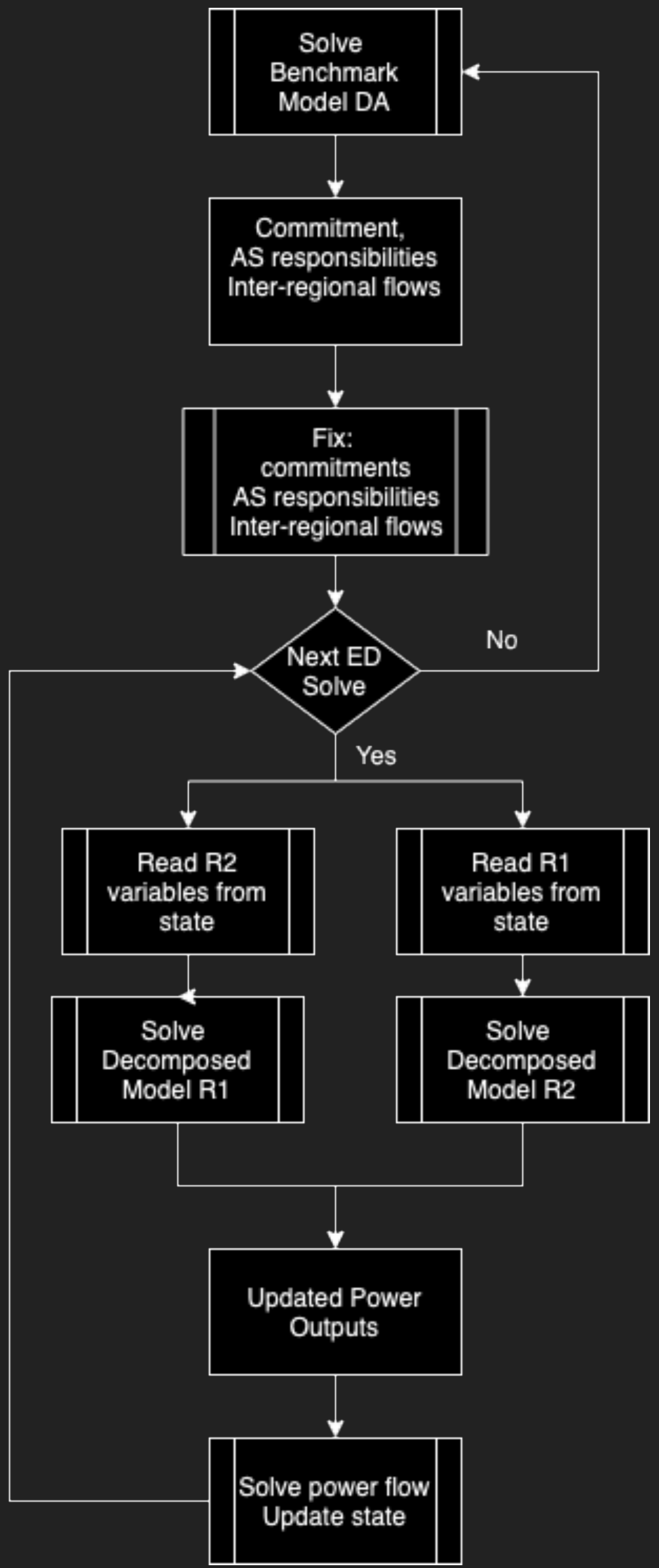
Interface Upper Bound

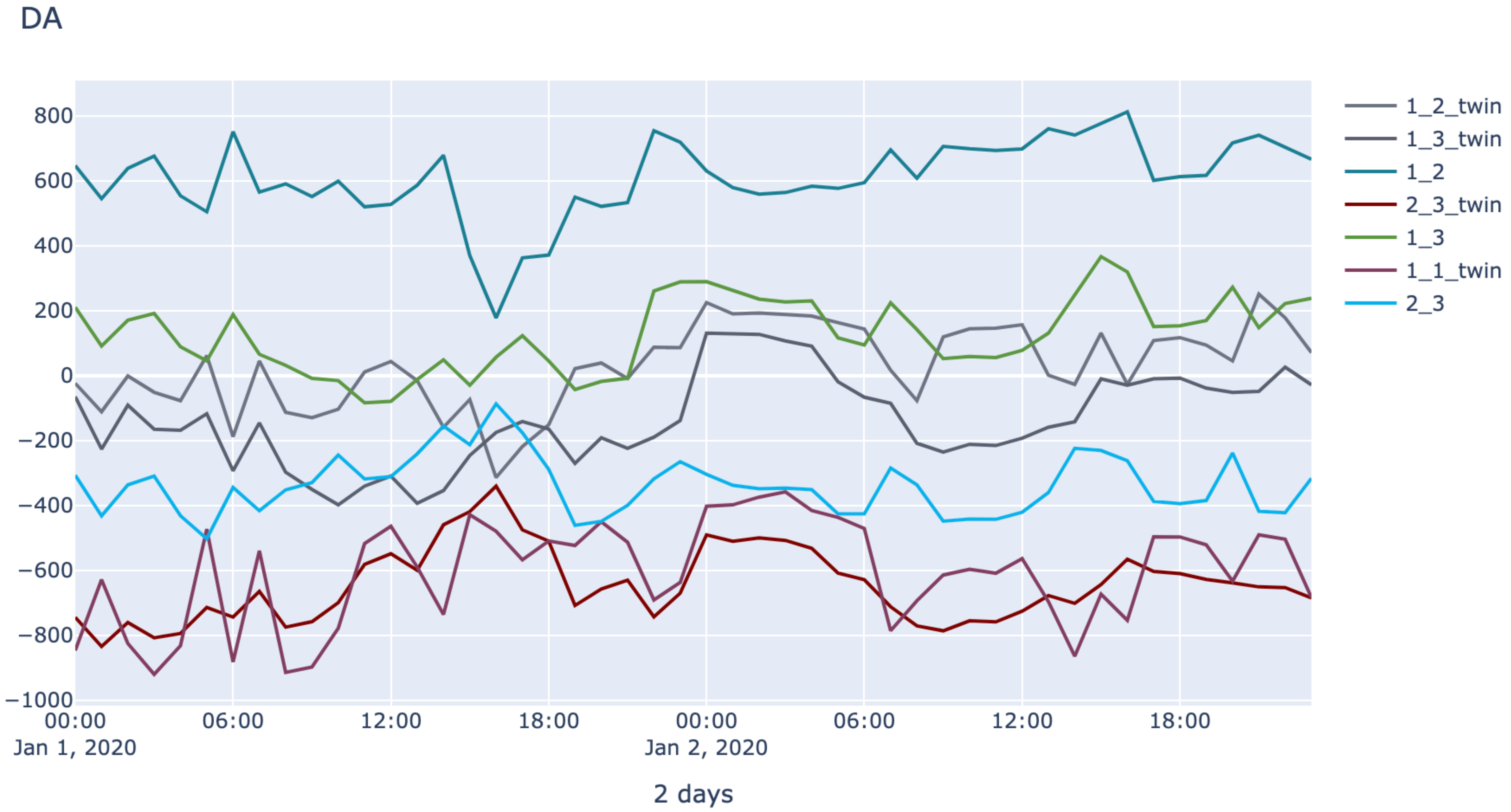
$$\sum_{l\in\mathcal{L}_i} f_{l,t} + \sum_{h\in\mathcal{H}_i} f_{h,t} \geq F_i^{min} \quad \forall i\in\mathcal{I},\ t\in\mathcal{T}$$

Interface Lower Bound

POWERSIMULATIONSDECOMPOSITION.JL

- The simulation workflow takes advantage of the emulator concept to implement the equivalent of the state estimator.
- At each time step in the ED all the variables from the emulator are available to the decomposed model by subsystem. It includes potentially duals from the other subsystem's problem.
- Solving these problems at scale requires several stability tricks:
    - Reduce radial branches in the PTDF and sparsity the matrices
    - Use Ward equivalents to reduce the number of branches from the neighboring region each subproblem needs to solve values for

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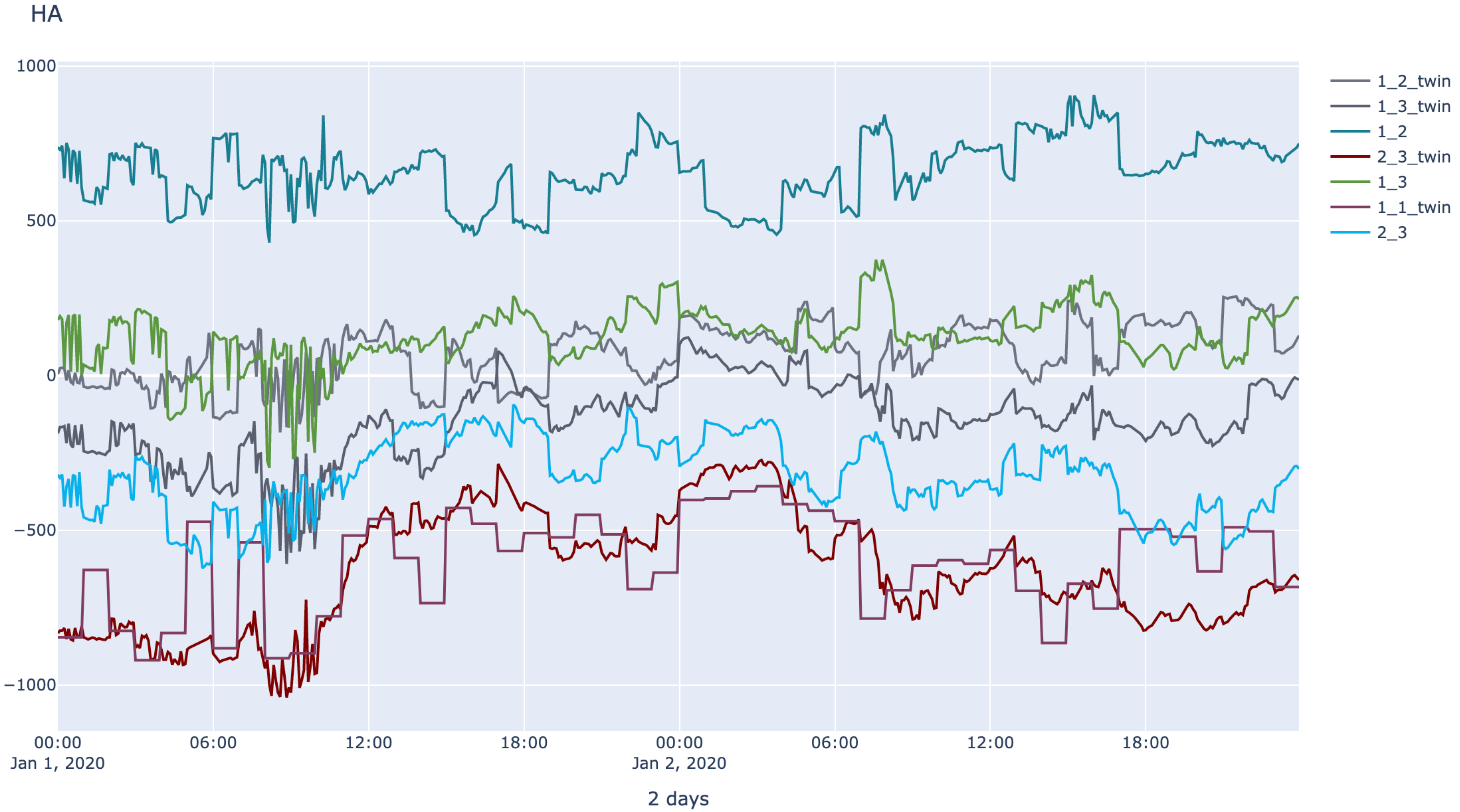
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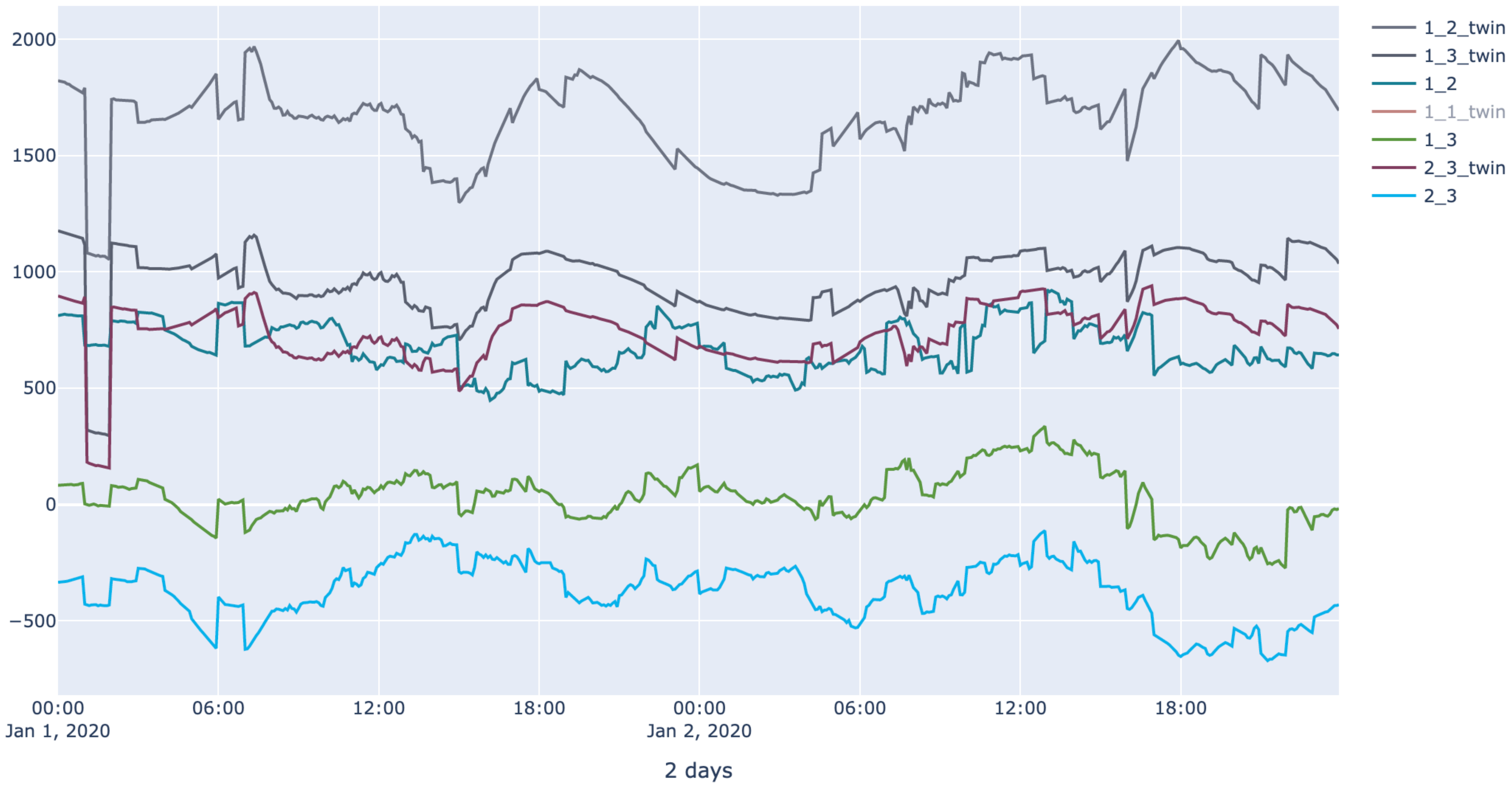
ED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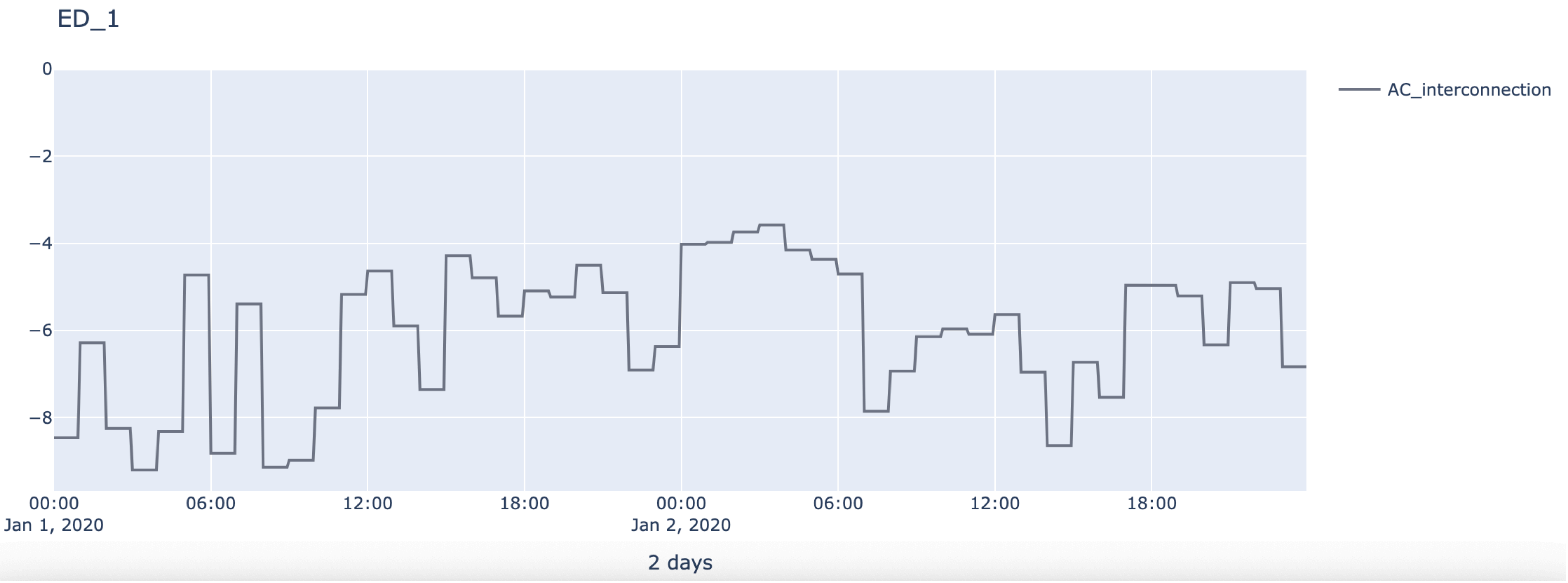
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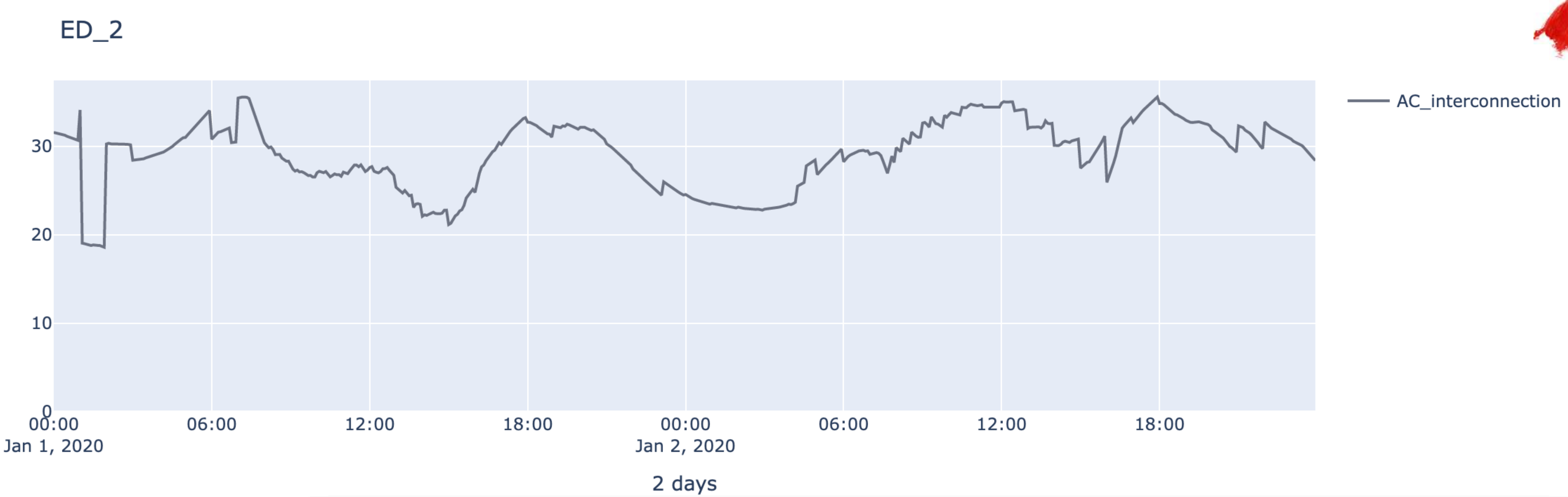
AC_interconnection
2 days

✗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AC_interconnection
2 days

NEXT STEPS

- Testing information sharing approaches (using JuMP parameters) to improve the coordination of the inter-ties and interfaces.
  - Copperplate dual sharing
  - Constraint violation supply function implementation.
- Implement ADMM based iterative approach for geographic decomposition
- Implement MPI parallel version of the algorithms to run in HPC

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6,000+	Downloads
25	Packages
12,968,279	Lines of code
22,000	Commits
694	Github stars
203	Forks
16	Publications
25	Contributors
200	Datasets
20	Project usages
1,000,000+	HPC simulation hours

Thank You!

Sienna