



Sienna

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

José Daniel Lara
Yonghong Cheng

A group of people in a control room are looking at large digital displays. The displays show various data visualizations, including maps, charts, and a 3D model of a power plant. The room has large windows on the left side, and the overall atmosphere is professional and technical. The text "NREL's Grid Planning and Analysis Center" is overlaid on the image in a large, white, sans-serif font. Below it, the text "bridges engineering, economics, and equity" is overlaid in a smaller, green, sans-serif font. At the bottom, the text "to advance the grid of the future" is overlaid in a large, white, sans-serif font. The background image shows a control room with several people standing and looking at large digital displays. The displays show various data visualizations, including maps, charts, and a 3D model of a power plant. The room has large windows on the left side, and the overall atmosphere is professional and technical. The text "NREL's Grid Planning and Analysis Center" is overlaid on the image in a large, white, sans-serif font. Below it, the text "bridges engineering, economics, and equity" is overlaid in a smaller, green, sans-serif font. At the bottom, the text "to advance the grid of the future" is overlaid in a large, white, sans-serif font.

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to advance the grid of the future

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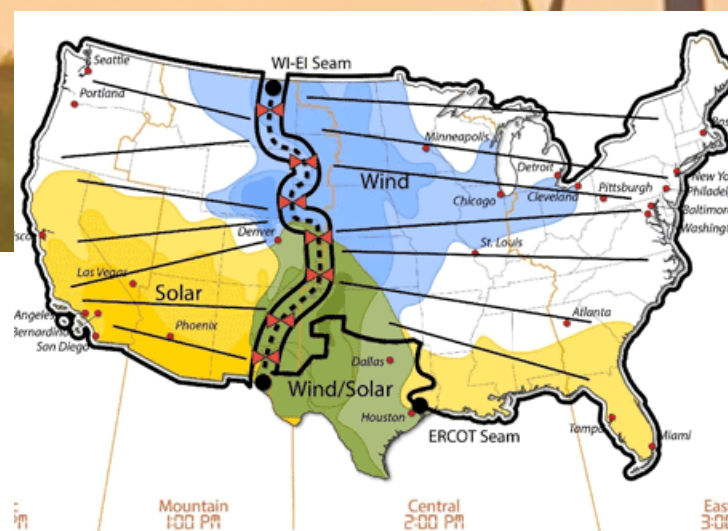
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NREL's Grid Planning and Analysis Center

bridges engineering, economics, and equity

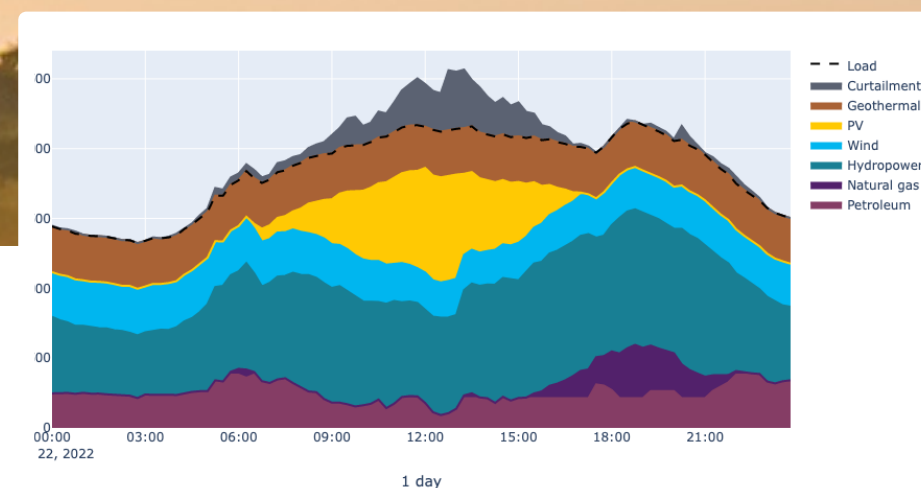
to advance the grid of the future

Bulk Power Systems Modeling for Decision Making



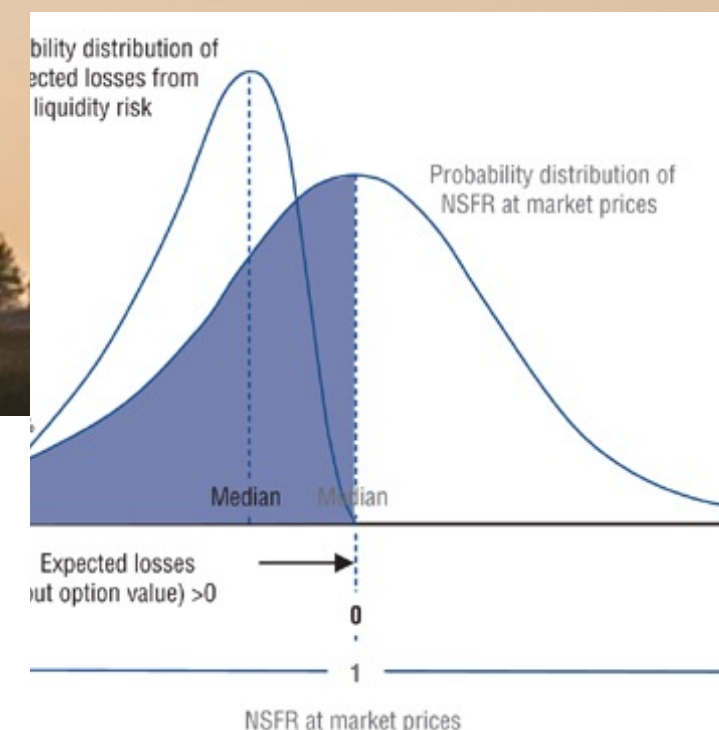
Build

What to build?
Where and When



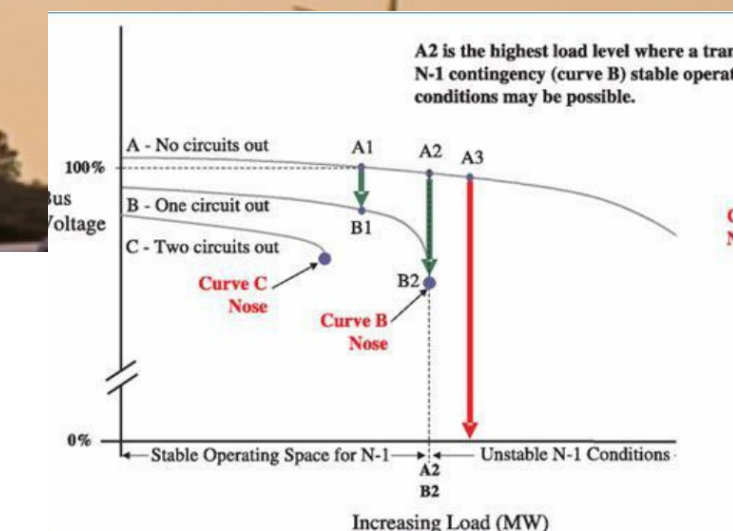
Operate

Can the planned
system operate?



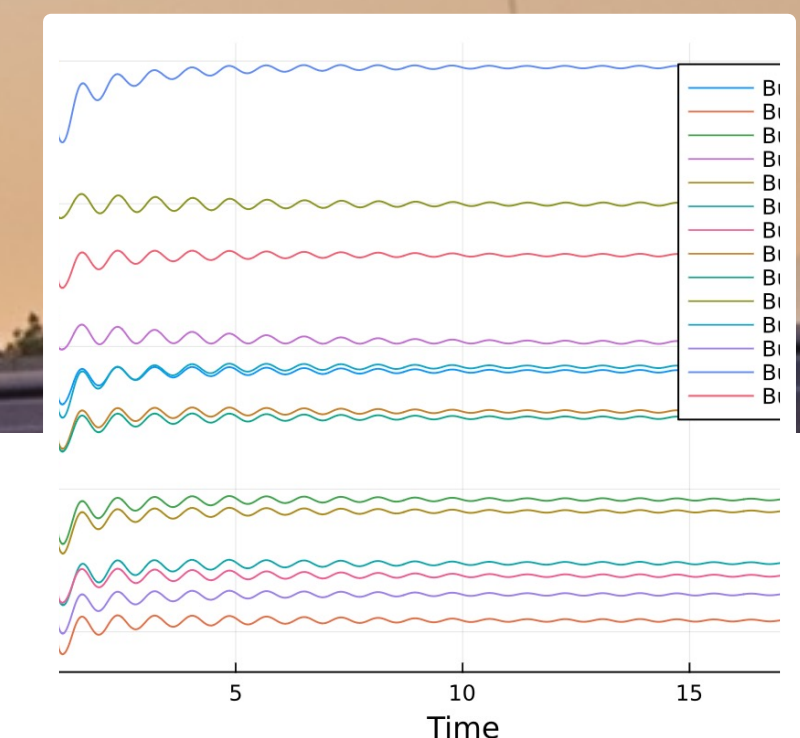
Adequate

Is supply sufficient
under all conditions?



Statically
Stable

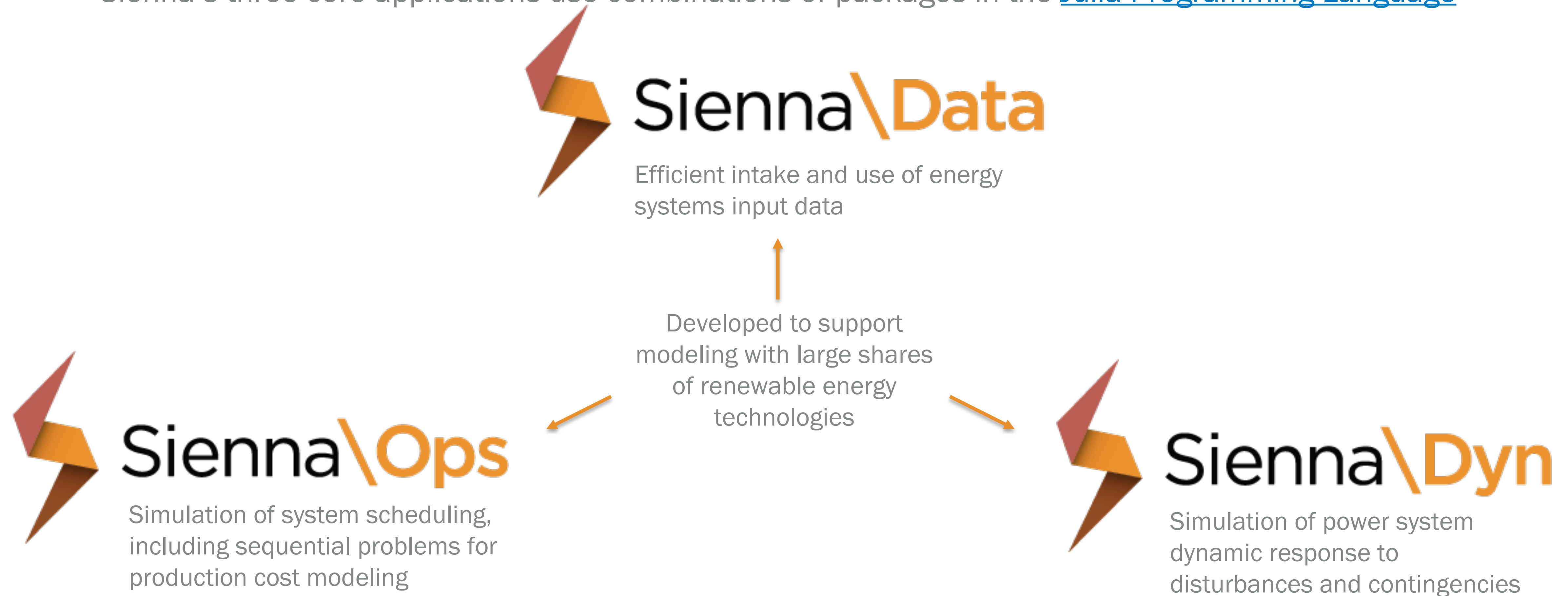
Can the system be stable under contingencies?
Can the transmission system operate correctly
following the physical representation of the assets?



Dynamically
Stable

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

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

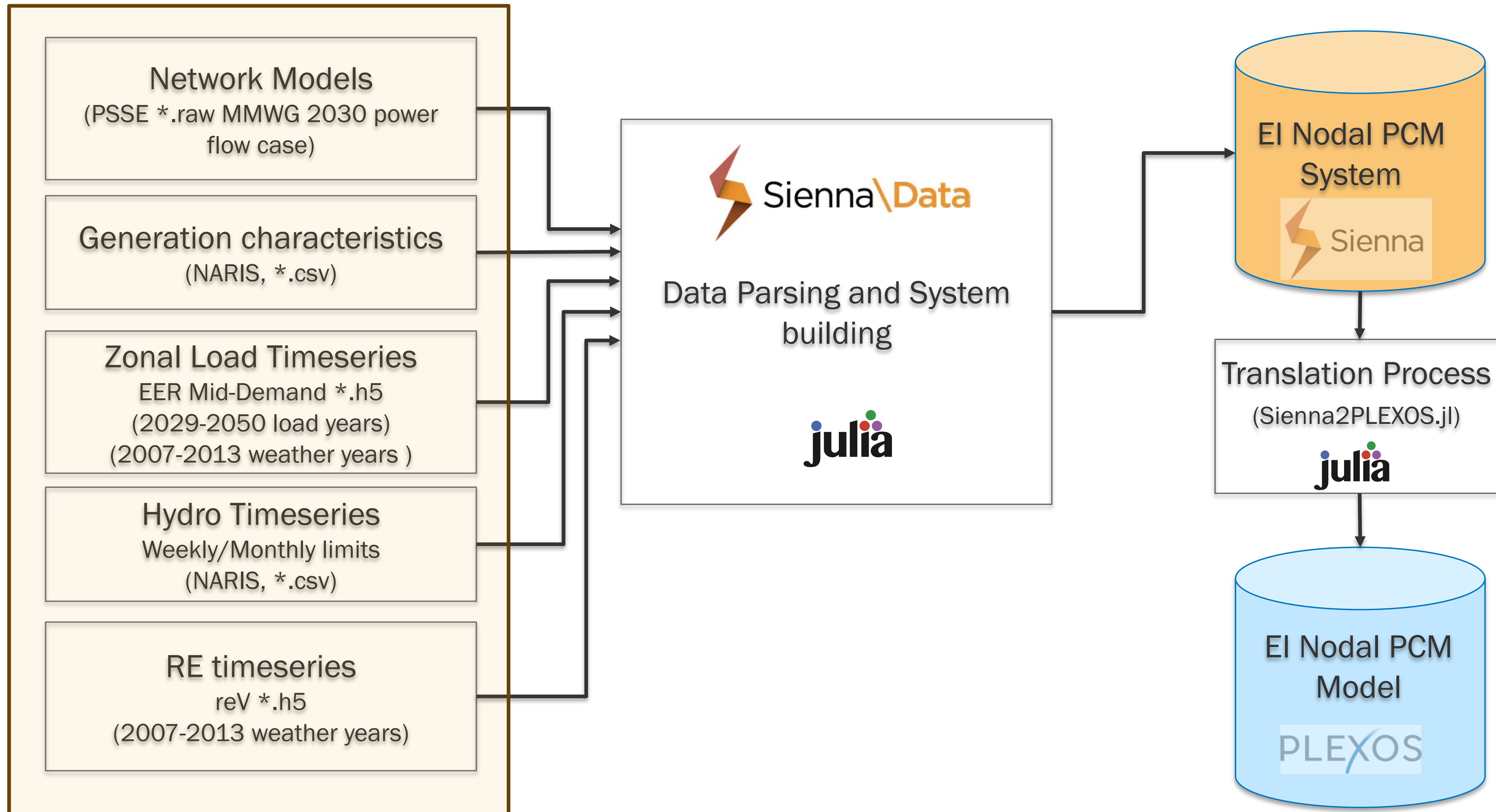


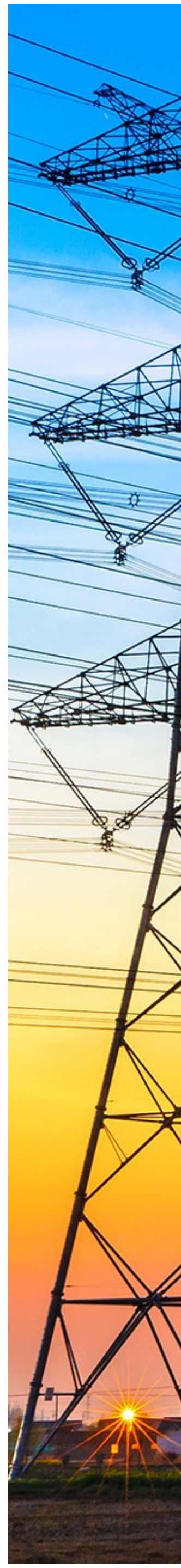
Formerly known as SIIP



<https://github.com/NREL-Sienna>

Dataset Building Process





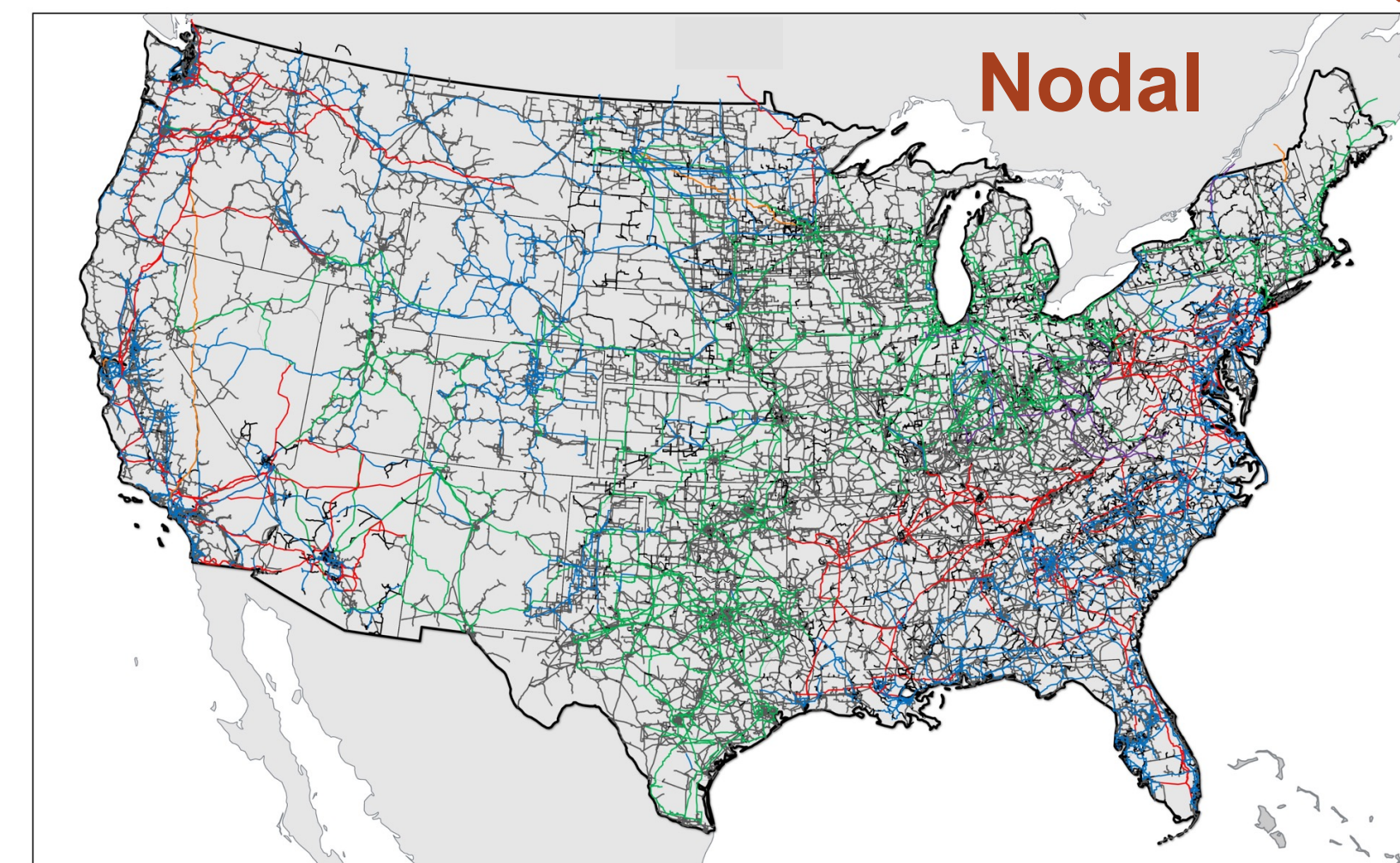
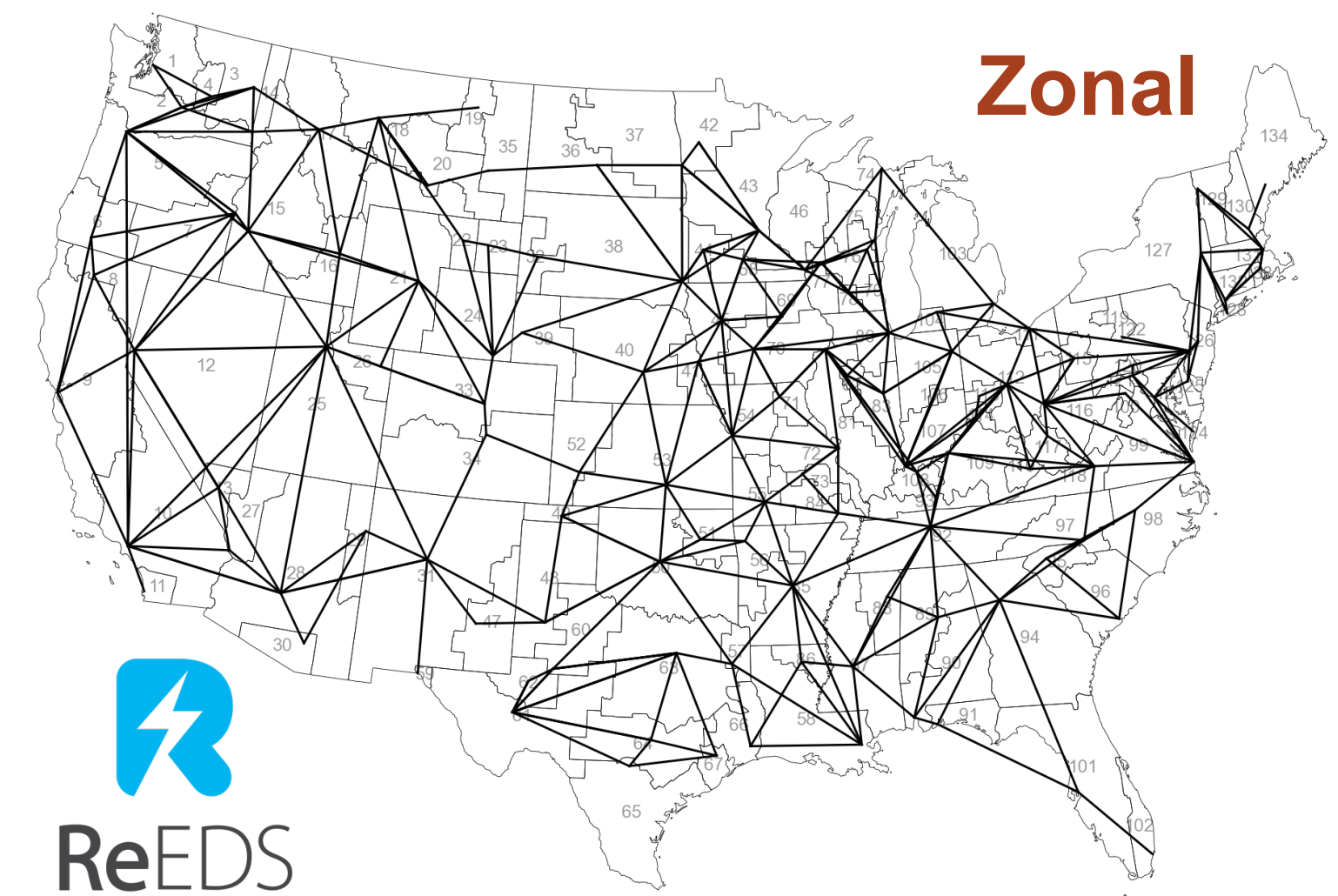
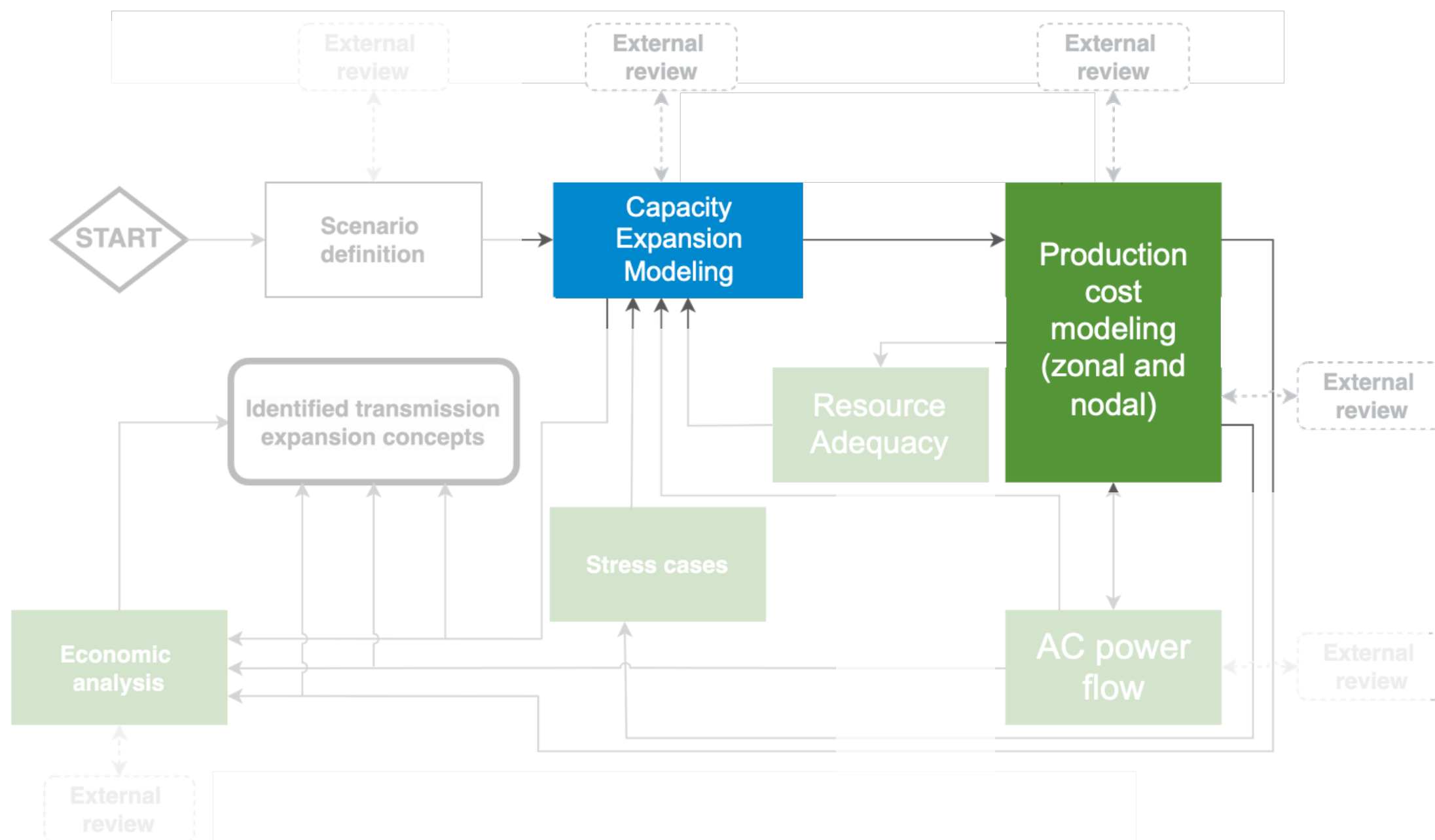
Use Case:

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



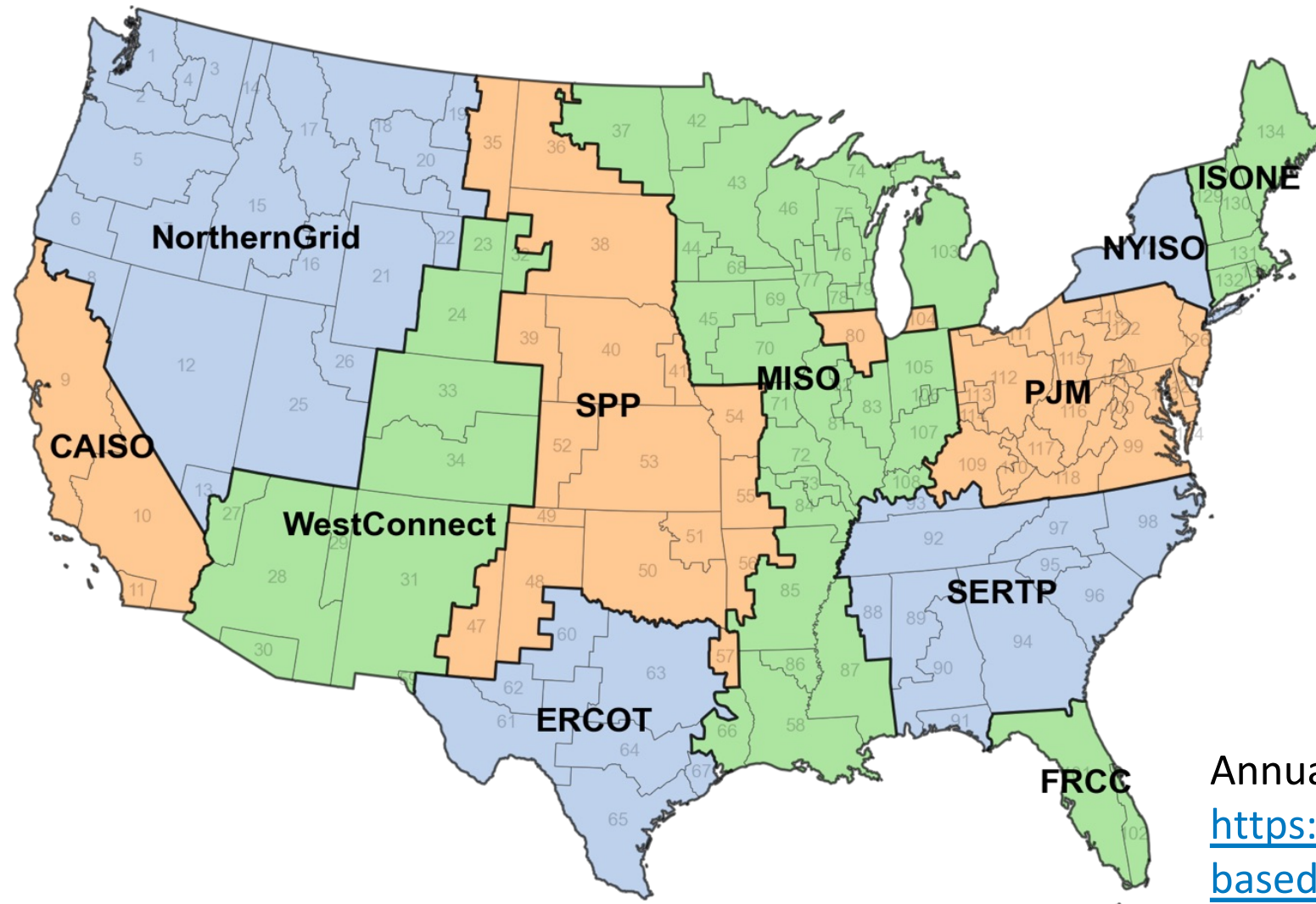
Sienna\Data
Efficient intake and use of energy systems input data

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

Four interregional transmission frameworks

23

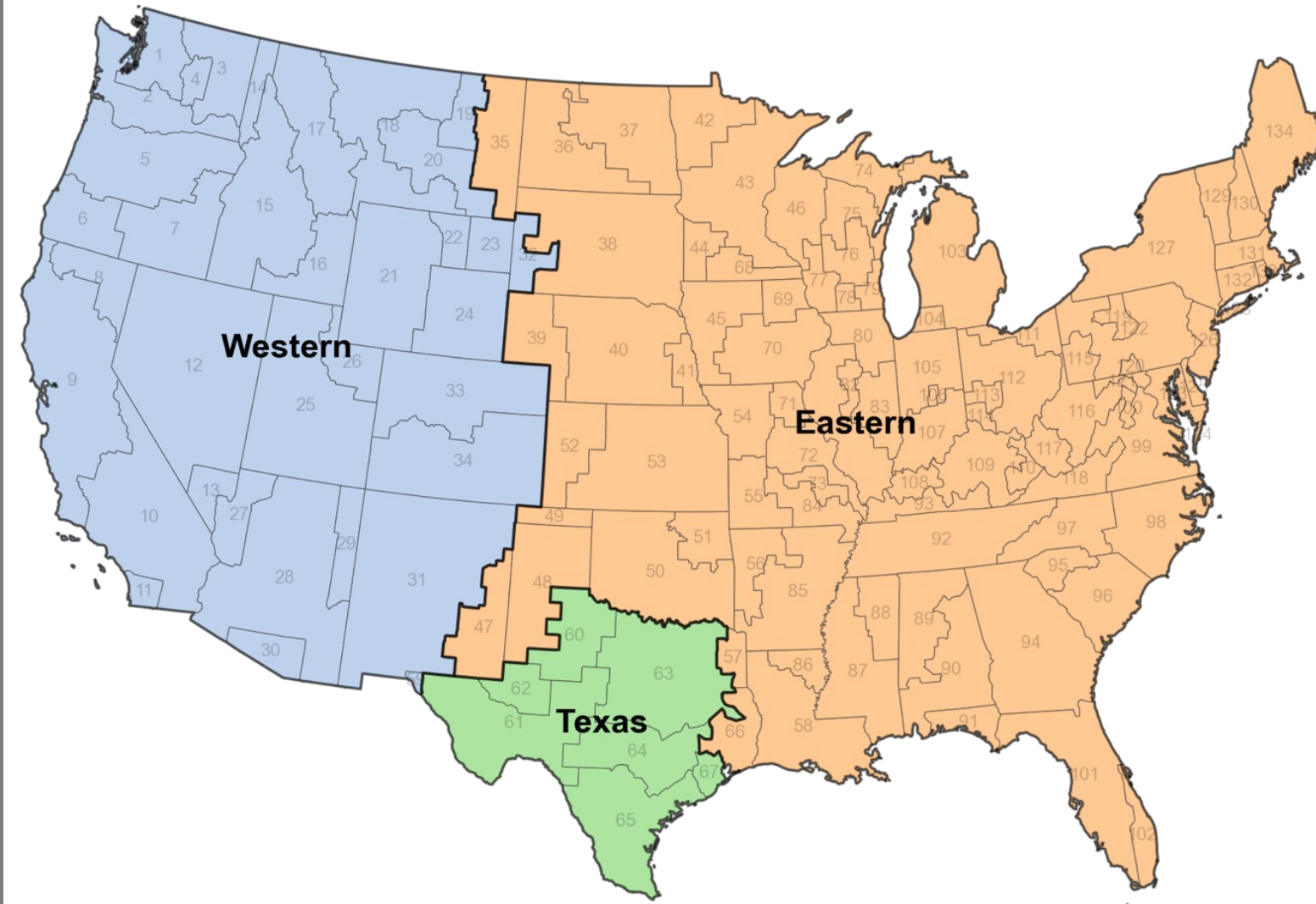
Limited



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

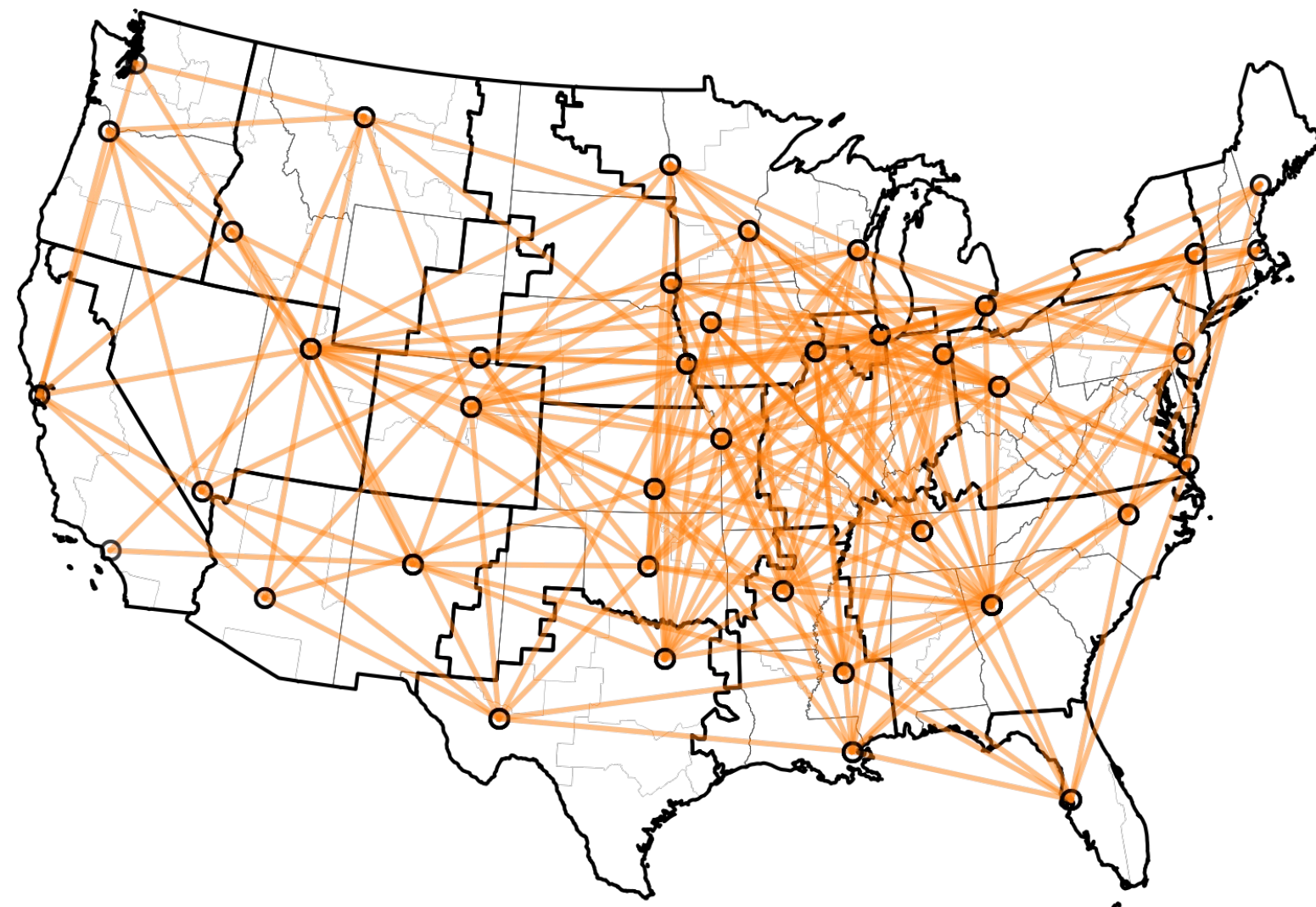
Annual US high-voltage transmission additions:
<https://www.energy.gov/eere/wind/articles/land-based-wind-market-report-2023-edition>

AC



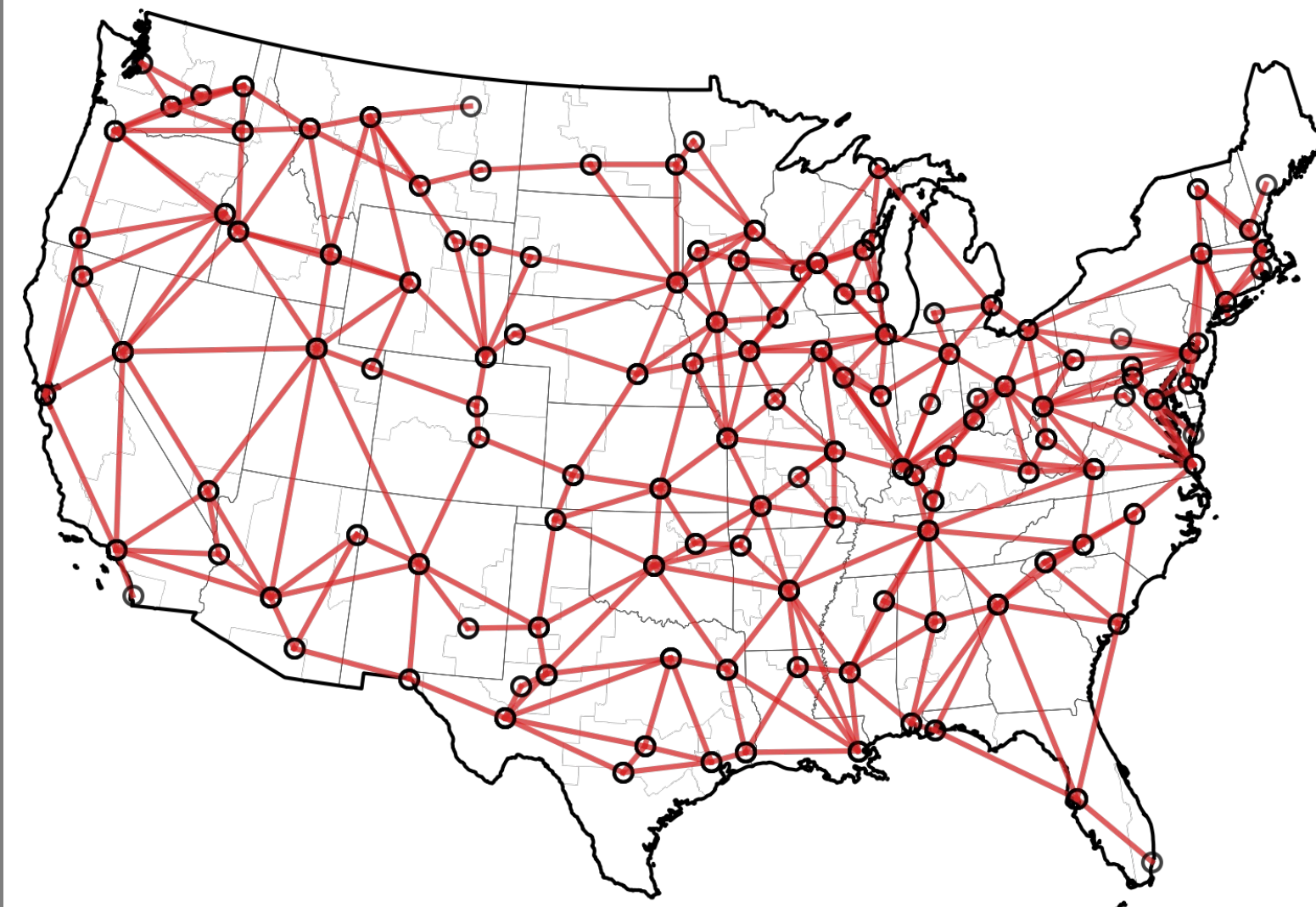
- AC and existing HVDC expansion allowed within interconnections
- No limit on total annual transmission additions

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

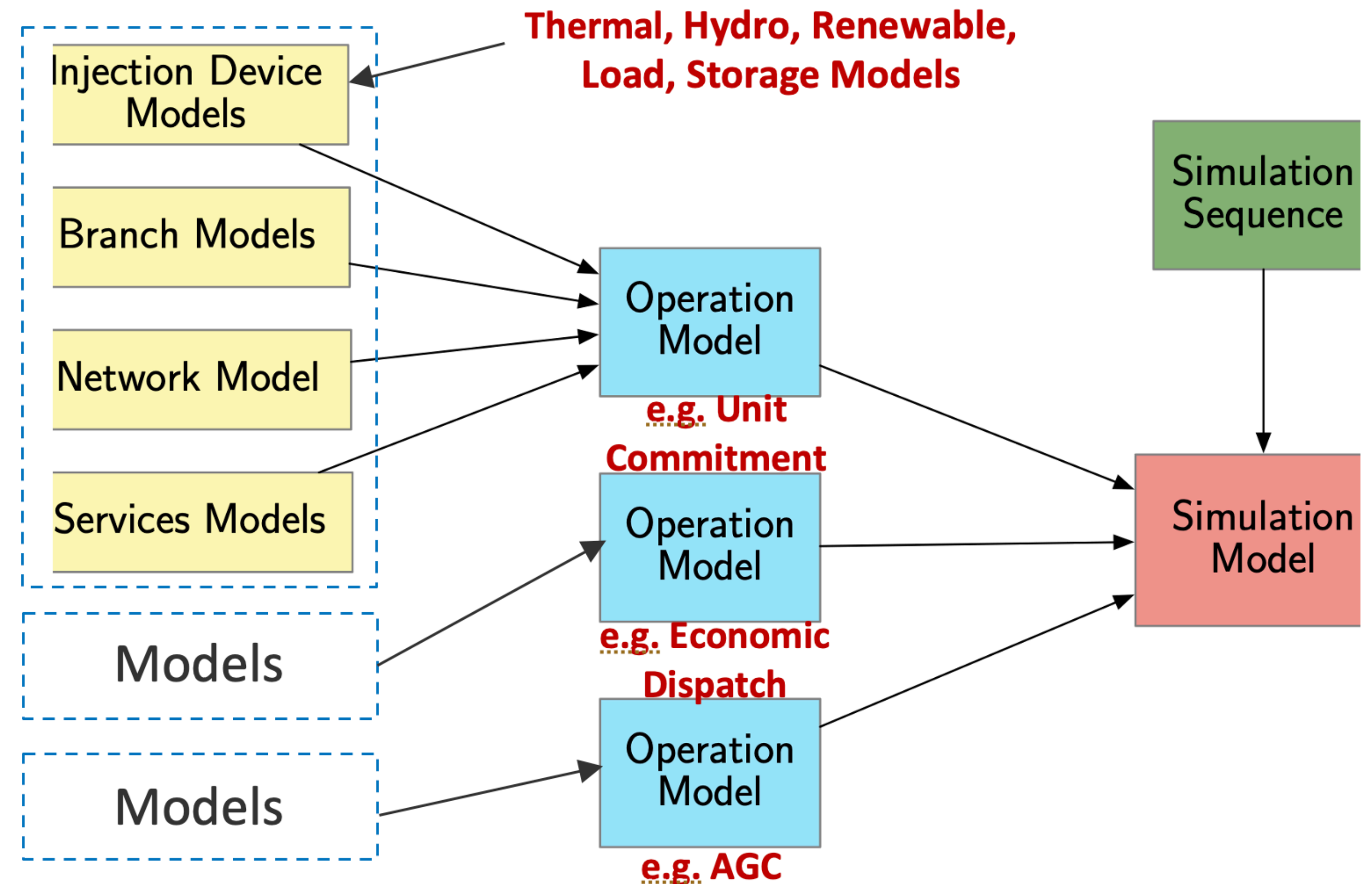


MODEL LIMITED CHOICE⁸

**Structural exclusion of certain
forms of simulation and analysis
&
Formulation limitations due to
restrictions in underlying models or
data availability**

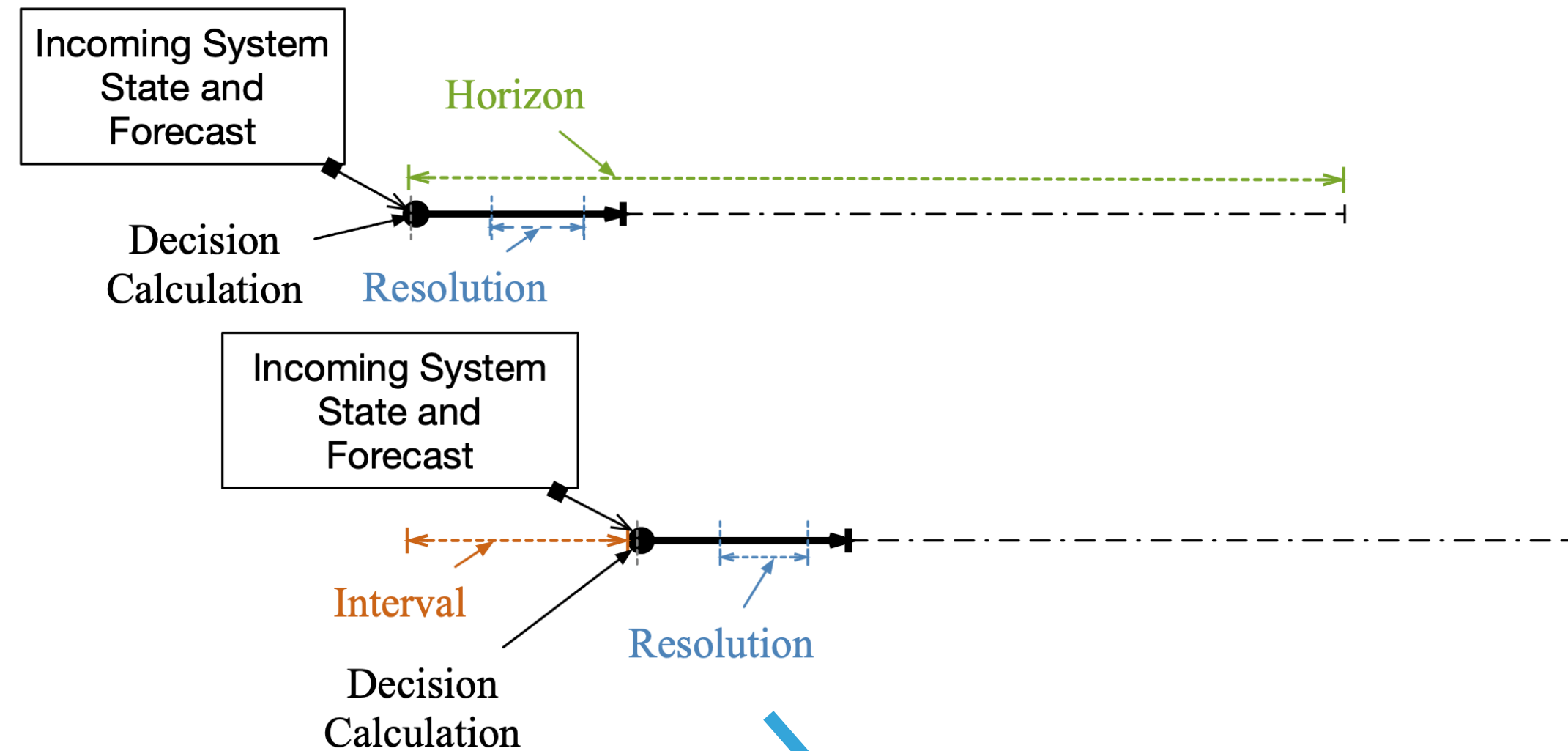
CUSTOMIZATION OF THE UNDERLYING SIMULATION

- ▶ 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

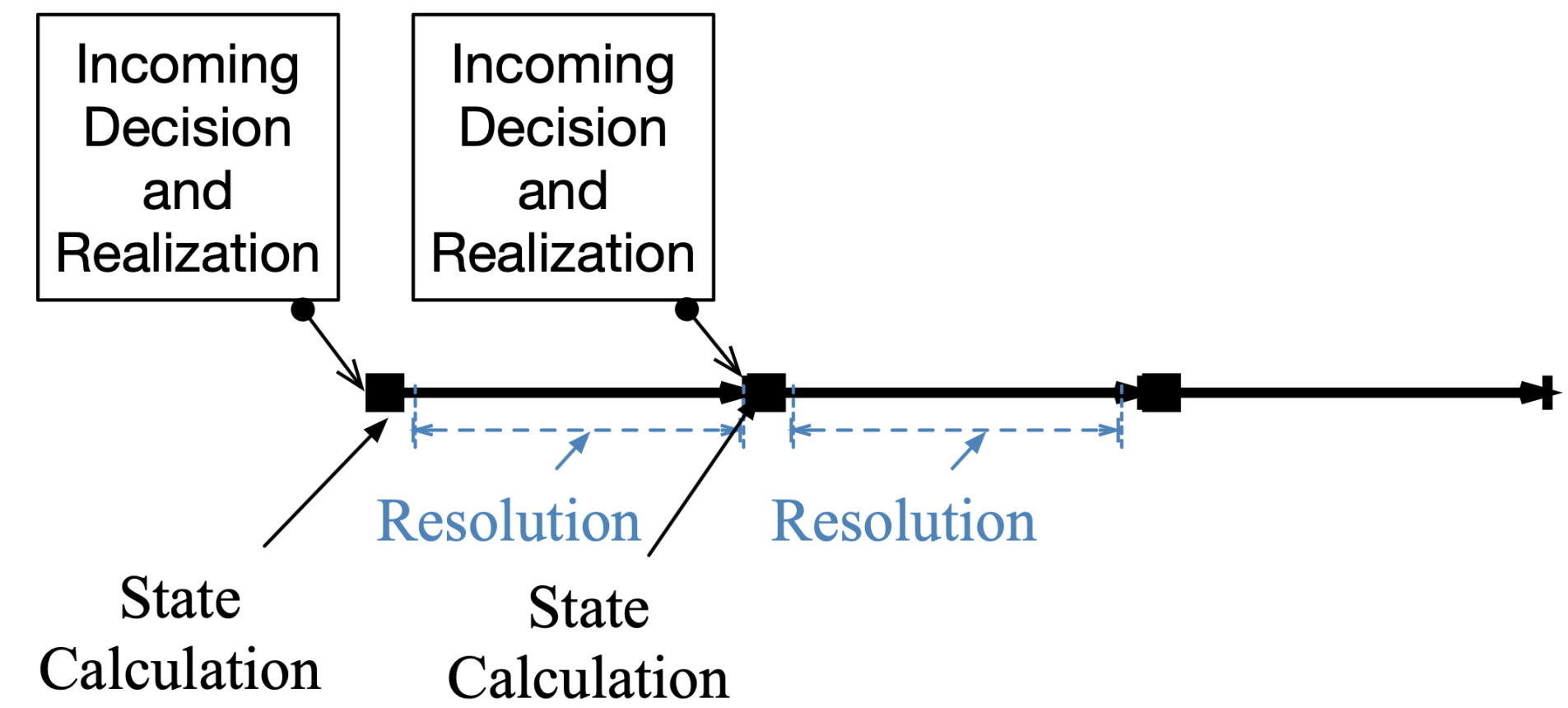
DECISION MODEL



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

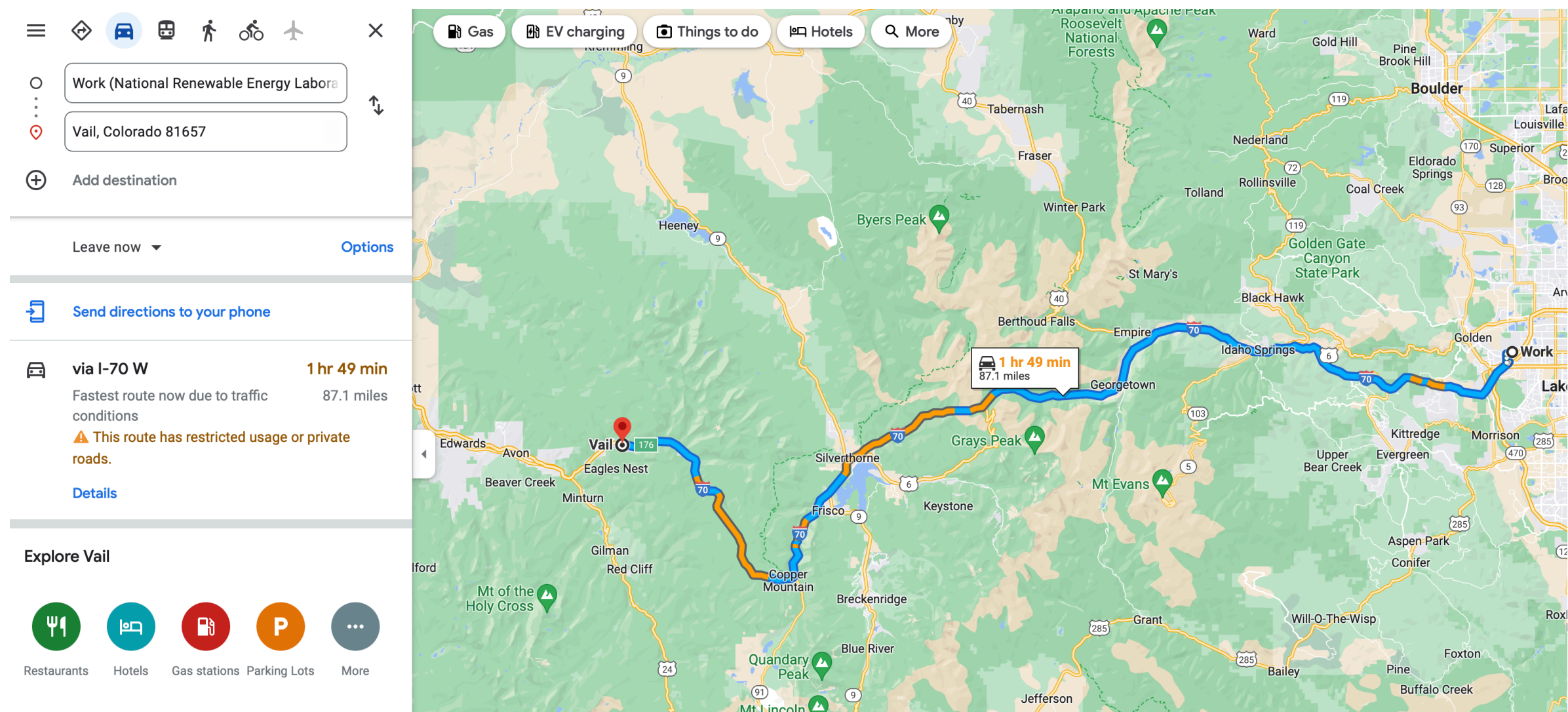
$$G_t(\vec{x}_t, \vec{x}_{t-1}, \vec{u}_t, \vec{\psi}_t) = 0, \quad \vec{x}_{t_0} = \vec{x}_0$$

EMULATION MODEL



EVERYDAY ANALOGOUS PROCESS

DECISION MODEL

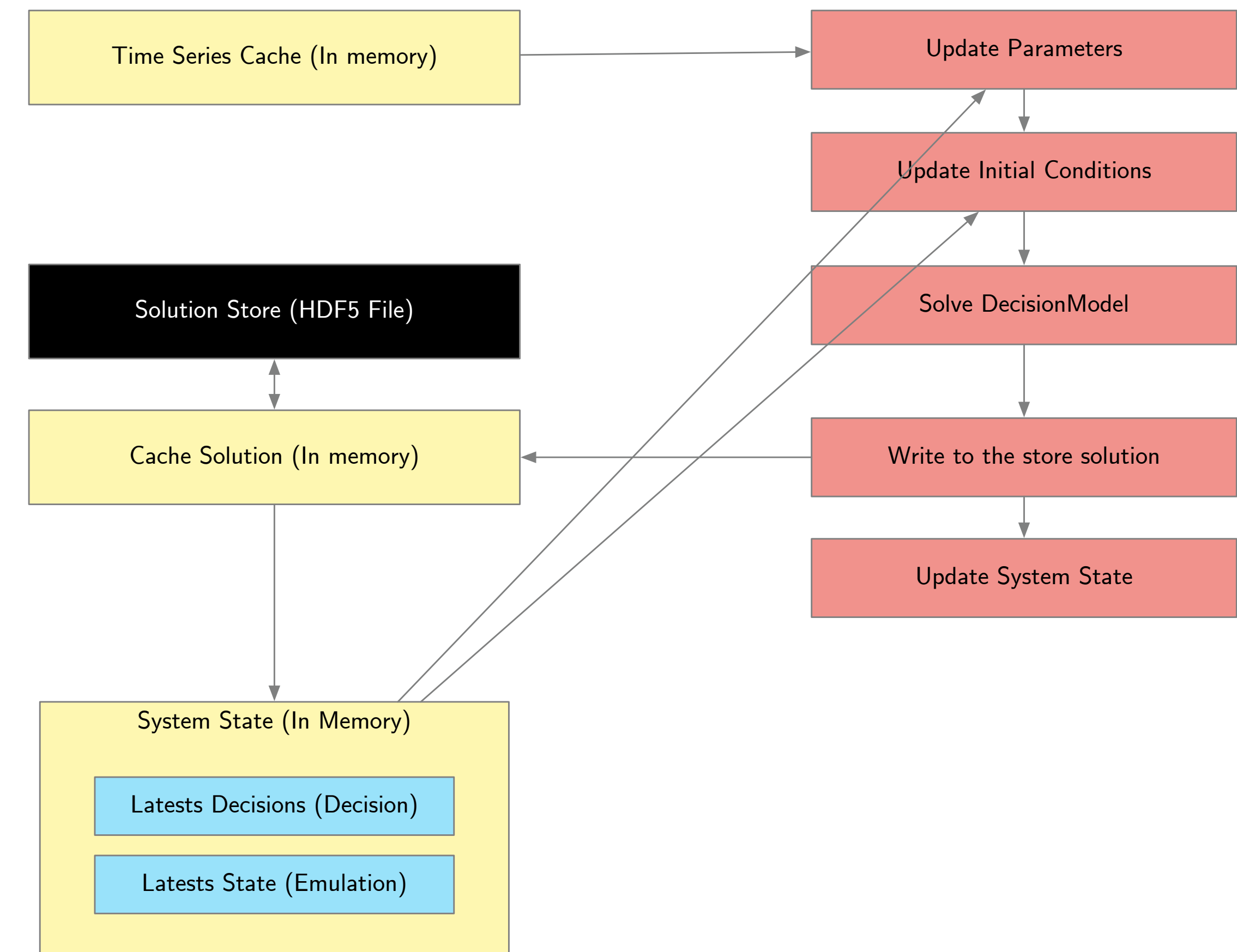


EMULATION MODEL



SOLVE MODEL FOR MULTI-STAGE SIMULATIONS

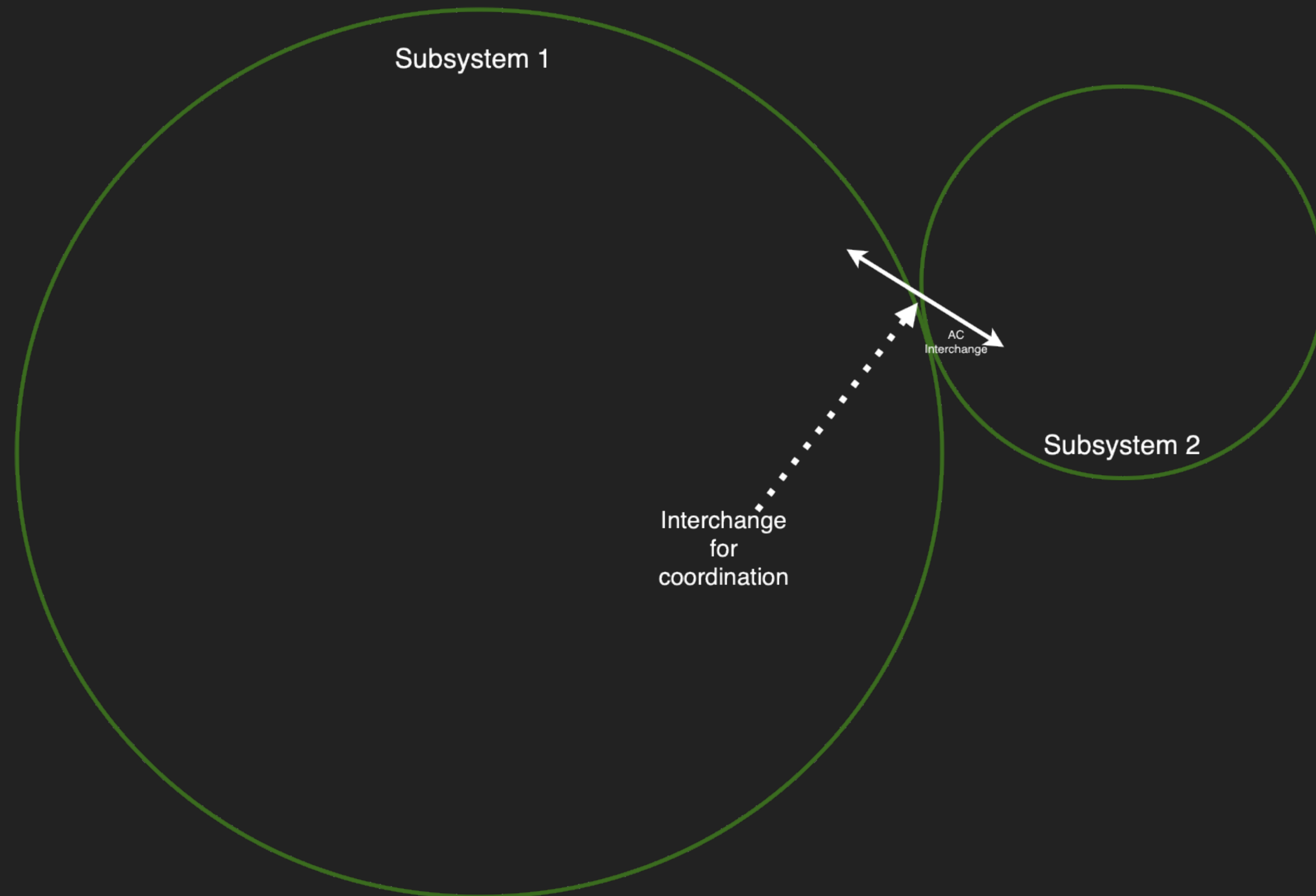
- ▶ The simulation has a store for the solution of each stage of the decision making problem.
- ▶ The simulator keeps track of the latest value of the decision variables and the system variables in a given state.
- ▶ An incumbent solution also speeds up finding the solution for the next step.
- ▶ Information 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

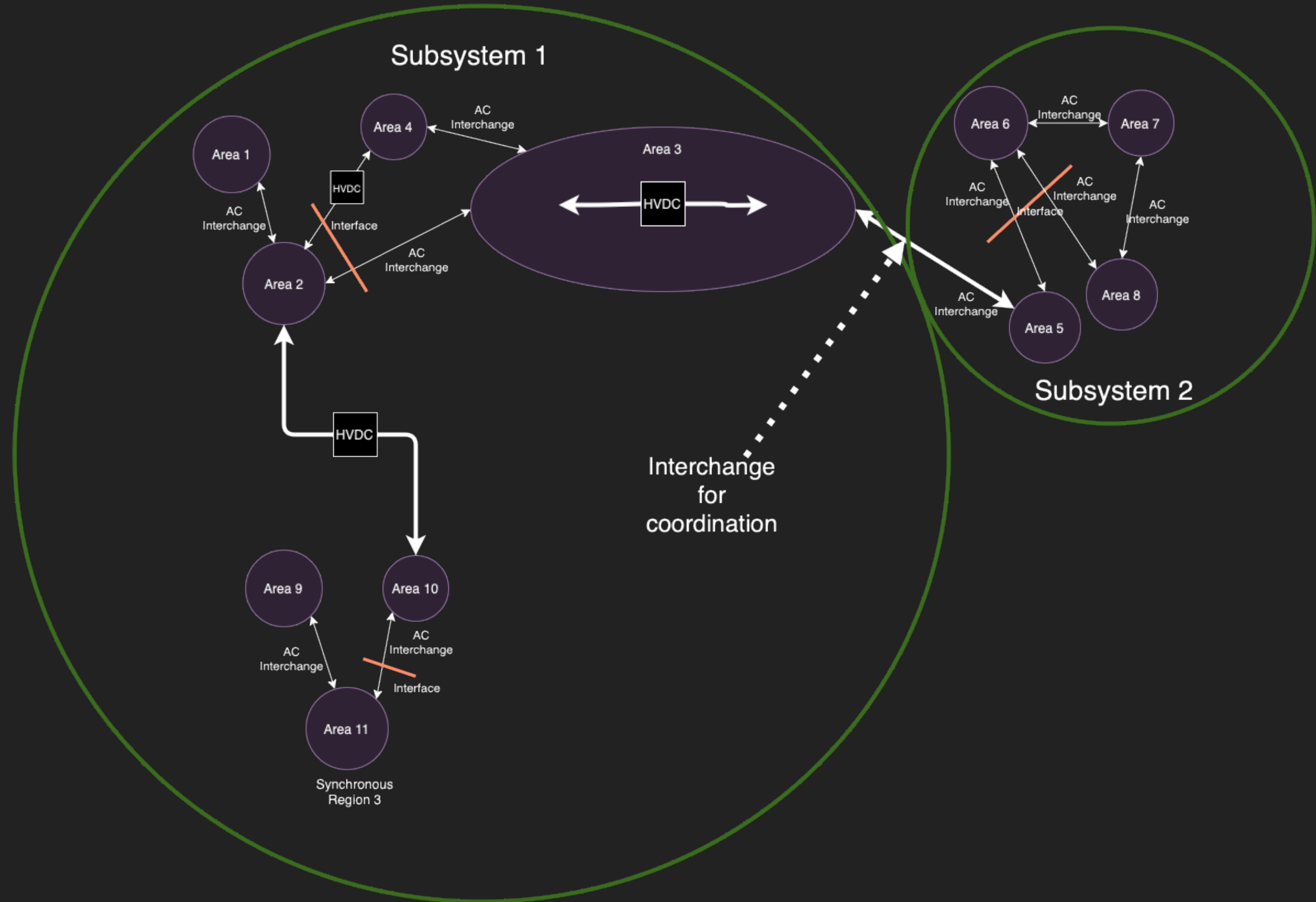
2-SUBSYSTEMS

- ▶ 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

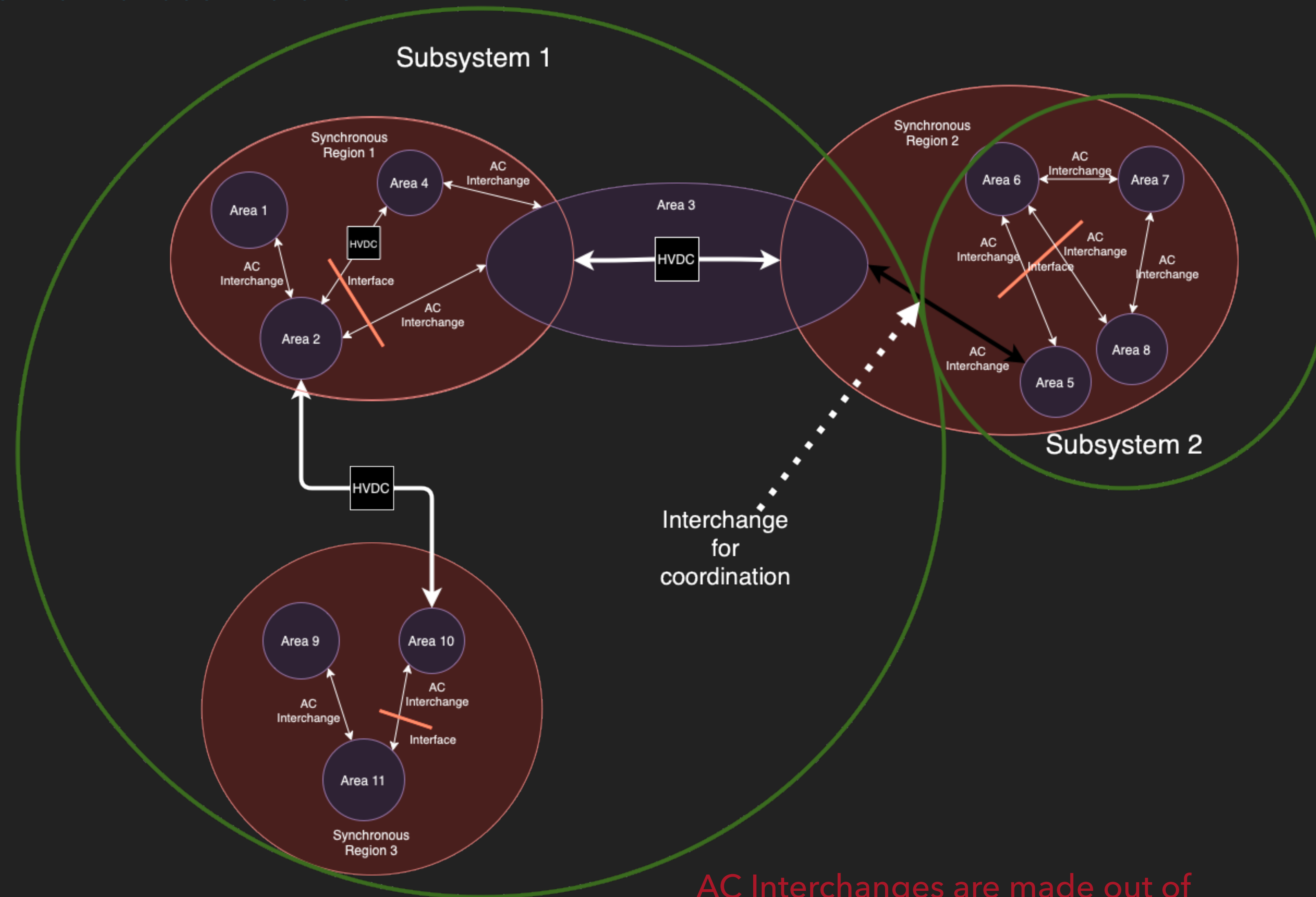
- ▶ Each subsystem is composed of several areas for balancing power.
- ▶ These areas might be connected by other interchanges internal to the subsystems. The interchanges can be in AC or via HVDC.
- ▶ Each subsystem also defines interfaces which might coincide with the interchanges or contain several



AC Interchanges are made out of multiple AC lines

2-SUBSYSTEMS, MULTIPLE AREAS, MULTIPLE SYNCHRONOUS REGIONS

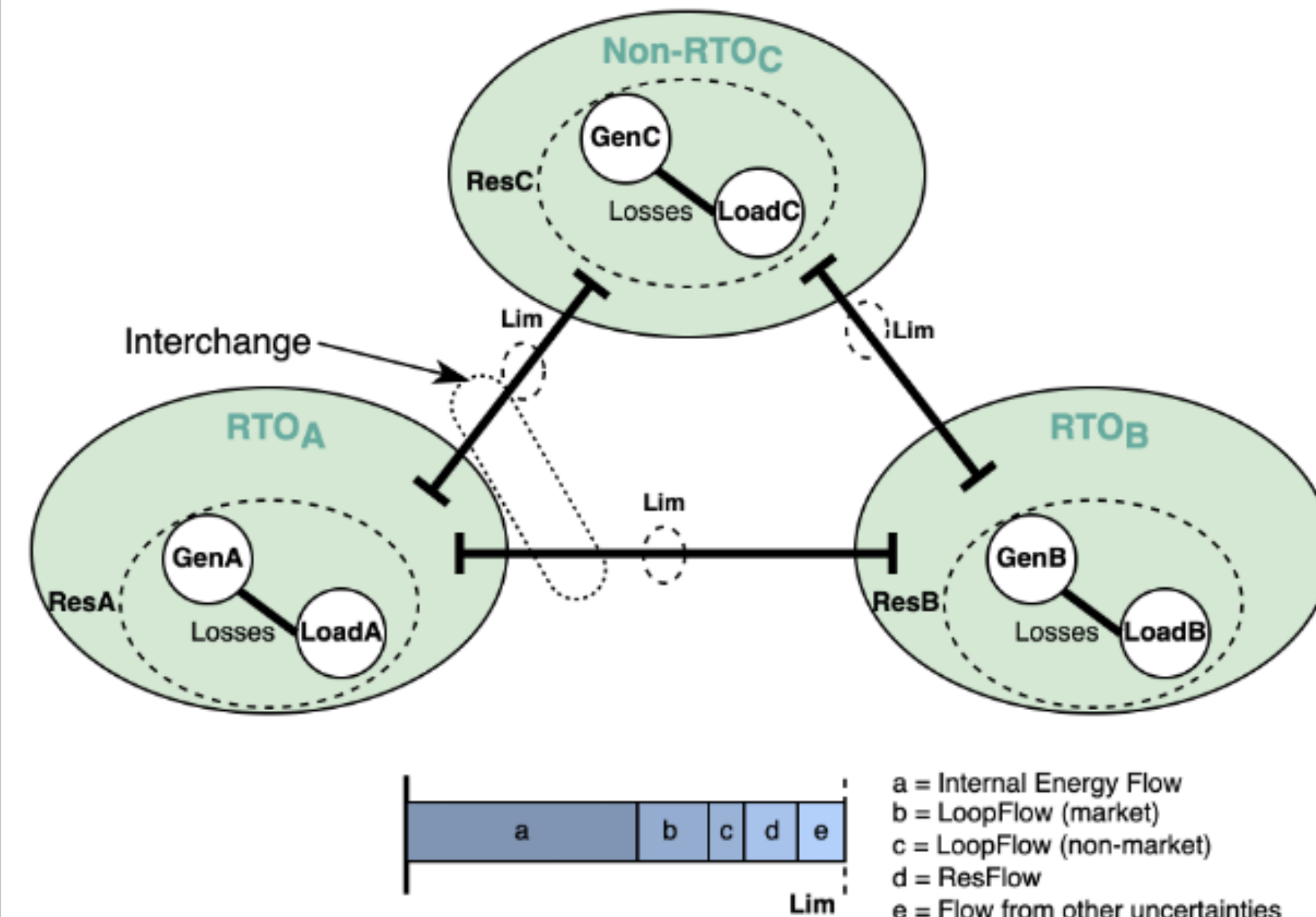
- ▶ The areas are split across synchronous regions connected via HVDC.
- ▶ Modeling the synchronous regions adequately matters such that the PTDF assumptions are correct and the line flows are estimated correctly.
- ▶ The combination of balancing areas, regions and systems makes the problem complex to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





System wide constraints	Co-optimized	Individual clearing with coordination	Individual clearing without coordination
Power balance	<u>GenA+GenB=LoadA+LoadB</u>	<u>GenA+NSIA=LoadA</u> <u>GenB+NSIB=LoadB</u> Interchange optimization	<u>GenA+NSIA=LoadA</u> <u>GenB+NSIB=LoadB</u>
Transmission constraint (energy flow)	<u>EnergyFlowA+EnergyFlowB</u> ≤Limit	<u>EnergyFlowA+loopflowA</u> ≤Limit <u>EnergyFlowB+loopflowB</u> ≤Limit M2M congestion management energy flow	<u>EnergyFlowA+loopflow</u> ≤Limit On monitoring RTO
Reserve requirement	ResA + ResB ≥ ResRequirement	ResA ≥ <u>ResRequirementA</u> ResB ≥ <u>ResRequirementB</u> Reserve sharing group for contingency reserve	ResA ≥ <u>ResRequirementA</u> ResB ≥ <u>ResRequirementB</u>
Transmission constraint (energy+ reserve flow)	<u>EnergyFlowA + EnergyFlowB</u> + <u>ResFlowA + ResFlowB</u> ≤Limit	<u>EnergyFlowA+ResFlowA+loopflowA</u> ≤Limit <u>EnergyFlowB+ResFlowB+loopflowB</u> ≤Limit M2M congestion management with reserve deliverability	<u>EnergyFlowA+ResFlowA+loopflow</u> ≤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
$\mathcal{E} := \{e \in \mathcal{C}(\mathcal{A}, 2)\}$	Inter-area exchanges
$\mathcal{I}$	Transmission interfaces
$\mathcal{G}$	Generators
$\mathcal{X}$	Feasibility Set
$\mathcal{T} := \{1, \dots, T\}$	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

$PTDF^r$	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

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

$$i_{b,t} := D_{b,t} - \sum_{g \in \mathcal{G}_b} p_{g,t} + \sum_{\{h \in \mathcal{H} | h_b \leftarrow = b\}} f_{h,t} - \sum_{\{h \in \mathcal{H} | h_b \rightarrow = b\}} f_{h,t} \quad \text{Net Injection at bus } b \text{ at time } t$$

$$f_{l,t} := \sum_{l \in \mathcal{L}_r, b \in \mathcal{B}_r} \mathbf{PTDF}_{l,b}^r i_{b,t} \quad \text{Power flow over branch } l \text{ in region } r \text{ at time } t$$

MODEL FORMULATION – CONSTRAINTS

$$\min_{\mathbf{p}, \mathbf{f}_h, \mathbf{f}_e} \sum_{t \in \mathcal{T}, g \in \mathcal{G}} O_g(p_{g,t})$$

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

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

Synchronous Region Power Balance

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

Area Power Balance

$$\sum_{\{l \in \mathcal{L} | l_a \rightarrow = e_a \rightarrow \wedge l_a \leftarrow = e_a \leftarrow\}} f_{l,t} - \sum_{\{l \in \mathcal{L} | l_a \rightarrow = e_a \leftarrow \wedge l_a \rightarrow = e_a \rightarrow\}} f_{l,t} + \sum_{\{h \in \mathcal{H} | h_a \rightarrow = e_a \rightarrow \wedge h_a \leftarrow = e_a \leftarrow\}} f_{h,t} - \sum_{\{h \in \mathcal{H} | h_a \rightarrow = e_a \leftarrow \wedge h_a \rightarrow = e_a \rightarrow\}} f_{h,t} \leq f_{e,t} \quad \forall e \in \mathcal{E}, t \in \mathcal{T}$$

Area Exchange Upper Bound

$$\sum_{\{l \in \mathcal{L} | l_a \rightarrow = e_a \rightarrow \wedge l_a \leftarrow = e_a \leftarrow\}} f_{l,t} - \sum_{\{l \in \mathcal{L} | l_a \rightarrow = e_a \leftarrow \wedge l_a \rightarrow = e_a \rightarrow\}} f_{l,t} + \sum_{\{h \in \mathcal{H} | h_a \rightarrow = e_a \rightarrow \wedge h_a \leftarrow = e_a \leftarrow\}} f_{h,t} - \sum_{\{h \in \mathcal{H} | h_a \rightarrow = e_a \leftarrow \wedge h_a \rightarrow = e_a \rightarrow\}} f_{h,t} \geq f_{e,t} \quad \forall e \in \mathcal{E}, t \in \mathcal{T}$$

Area Exchange Lower Bound

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

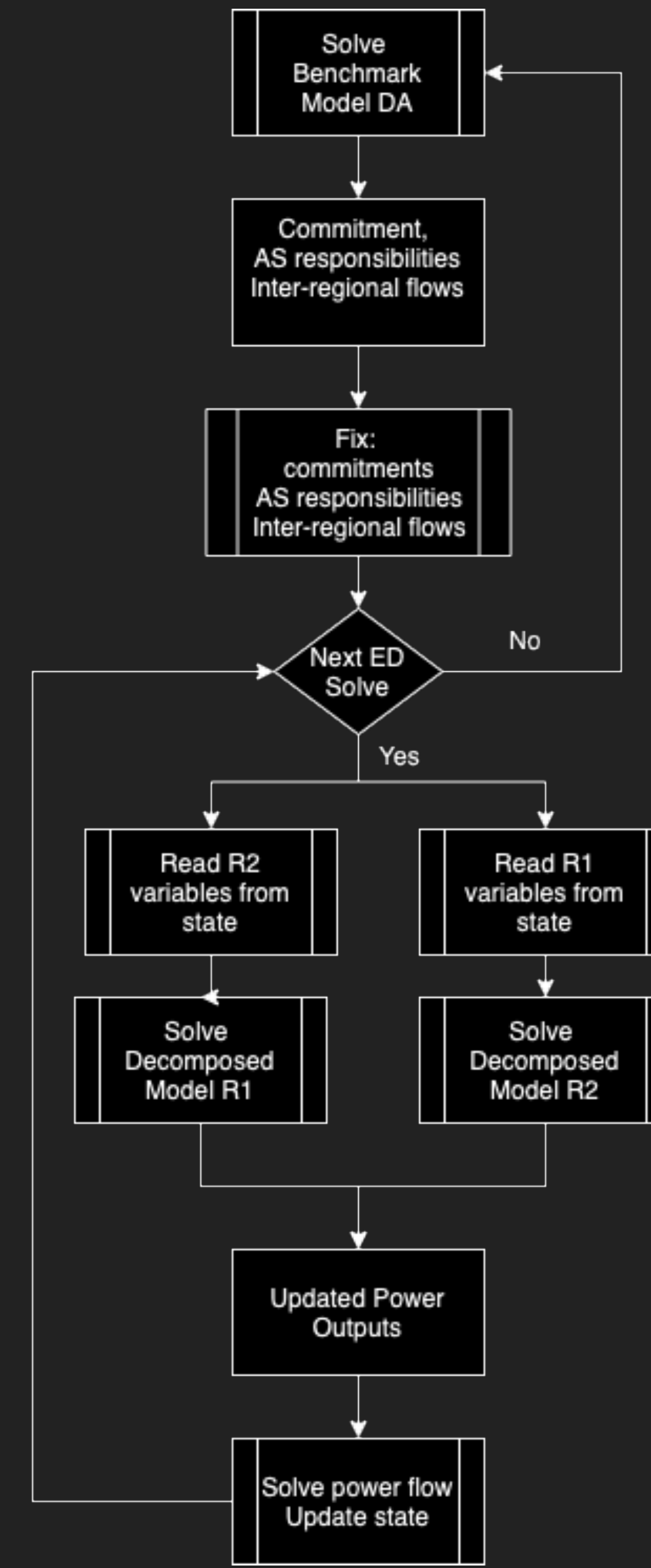
Interface Upper Bound

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

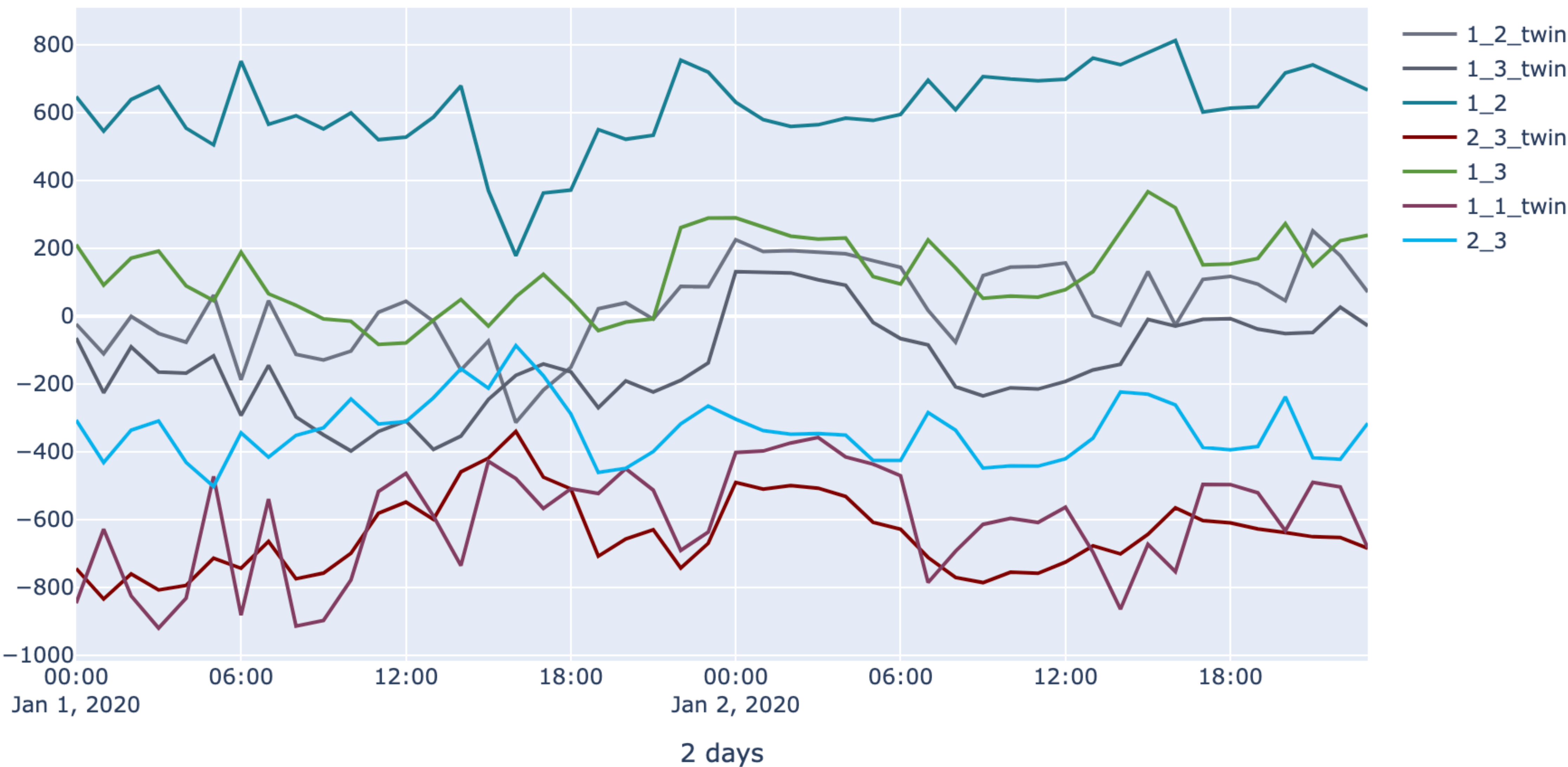
Interface Lower Bound

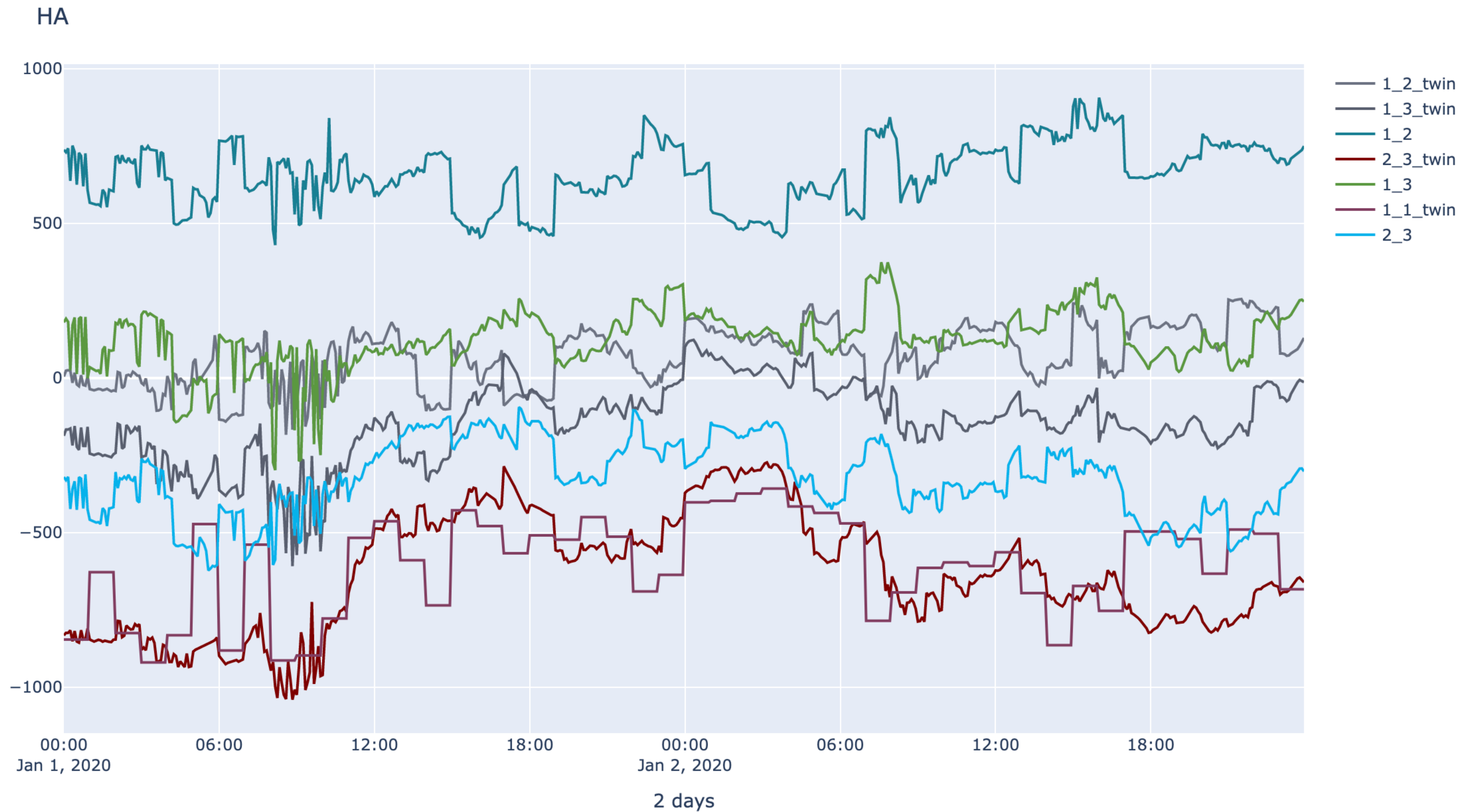
POWERSIMULATIONSDECOMPOSITION.JL

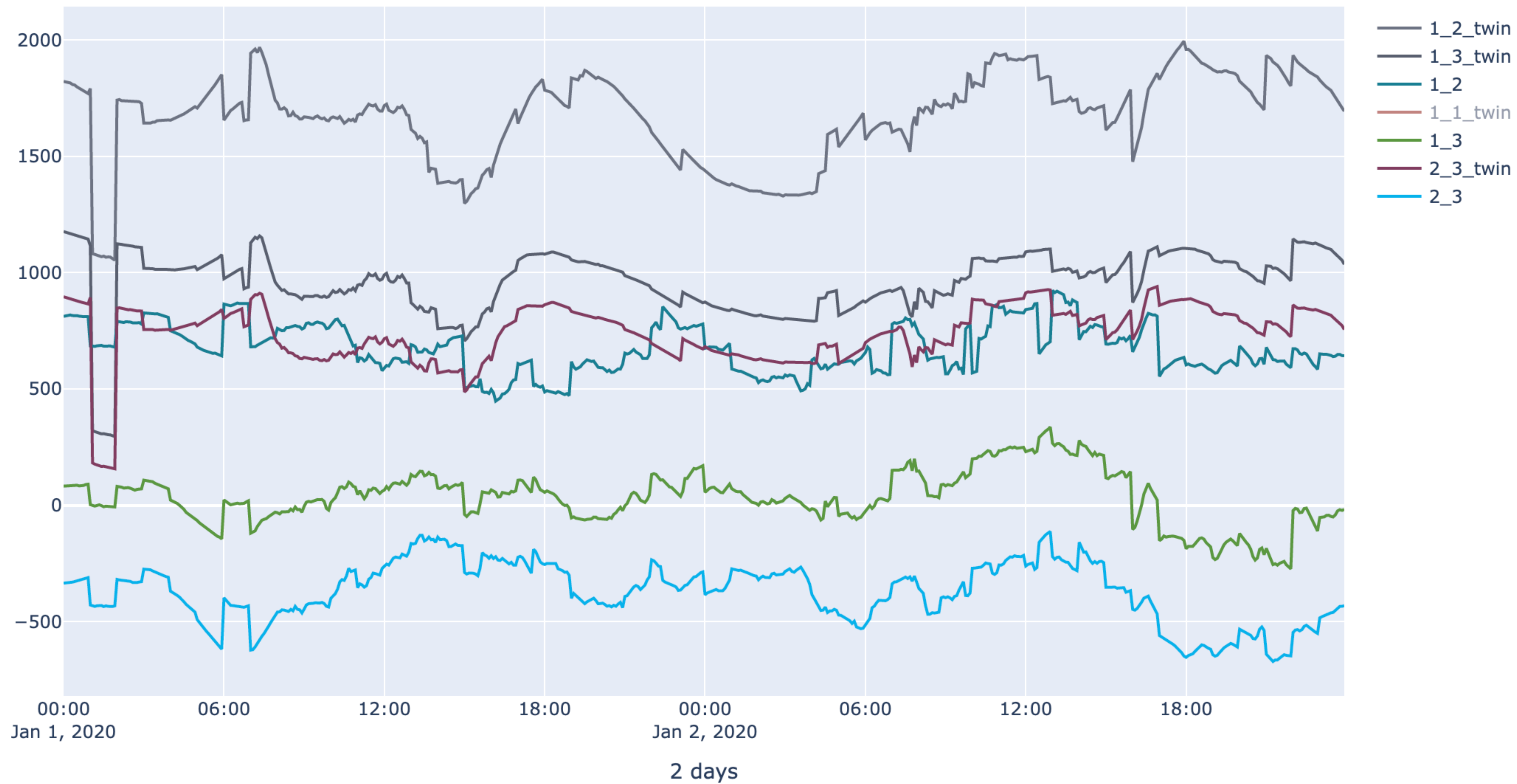
- ▶ The simulation workflow takes advantage of the emulator concept to implement the equivalent of the state estimator.
- ▶ At each time step in the ED all the variables from the emulator are available to the decomposed model by subsystem. It includes potentially duals from the other subsystem's problem.
- ▶ 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



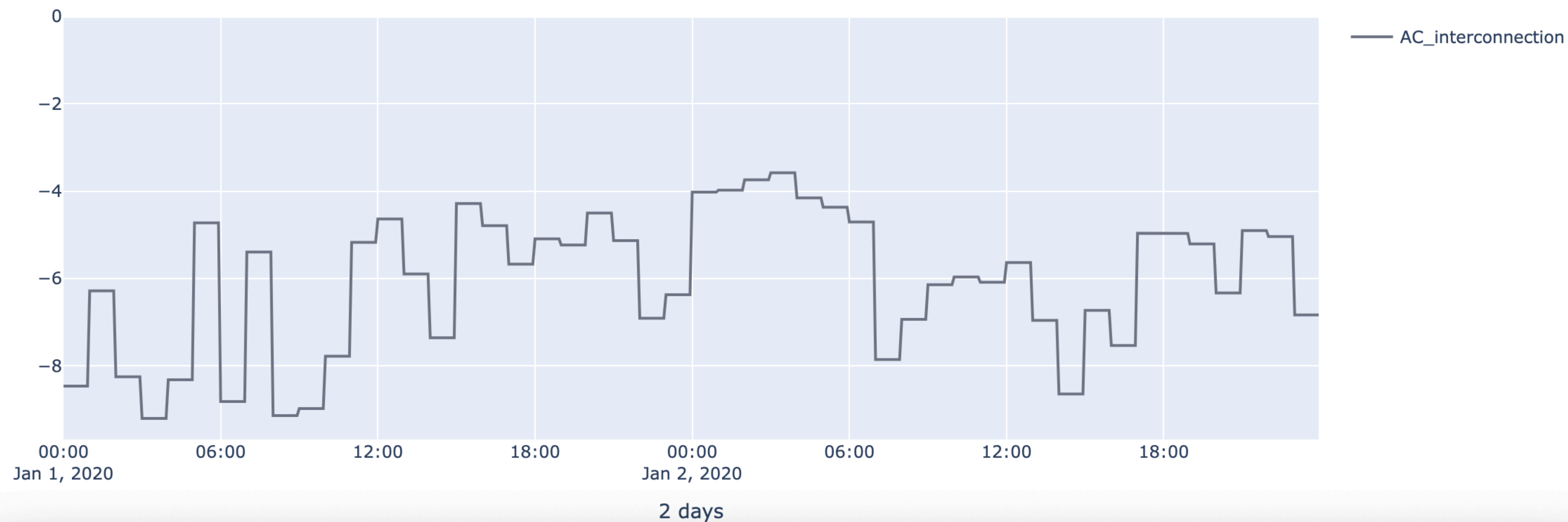
DA



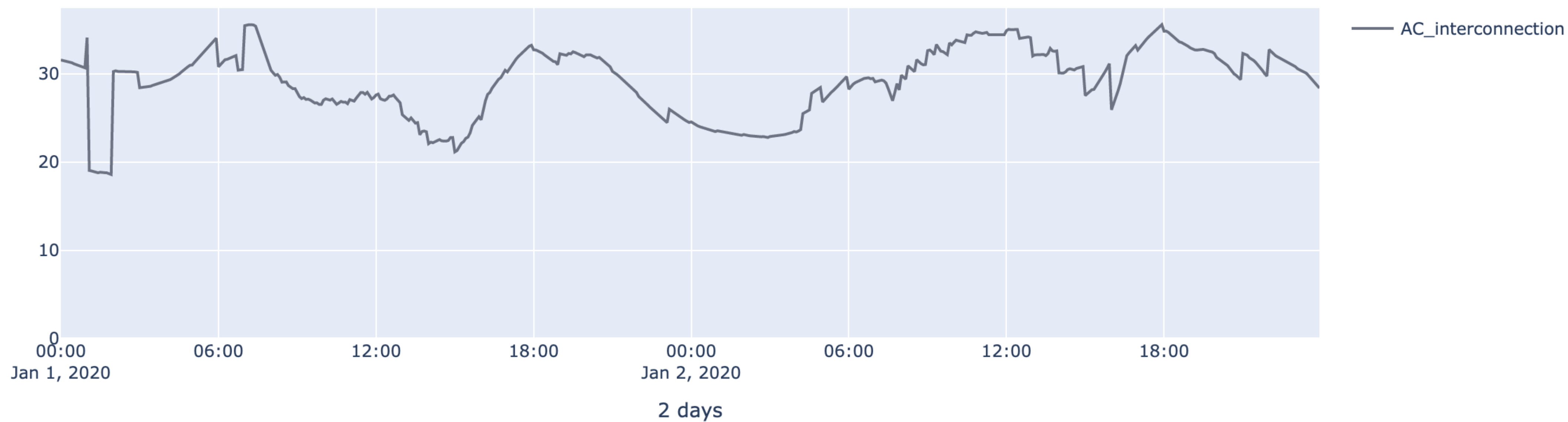




ED_1



ED_2



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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22,000 Commits

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203 Forks

16 Publications

25 Contributors

200 Datasets

20 Project usages

1,000,000+ HPC simulation
hours

Thank You!

