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Institute for the Design of Advanced Energy Systems

Grid-level modeling:

Opportunities and program plan

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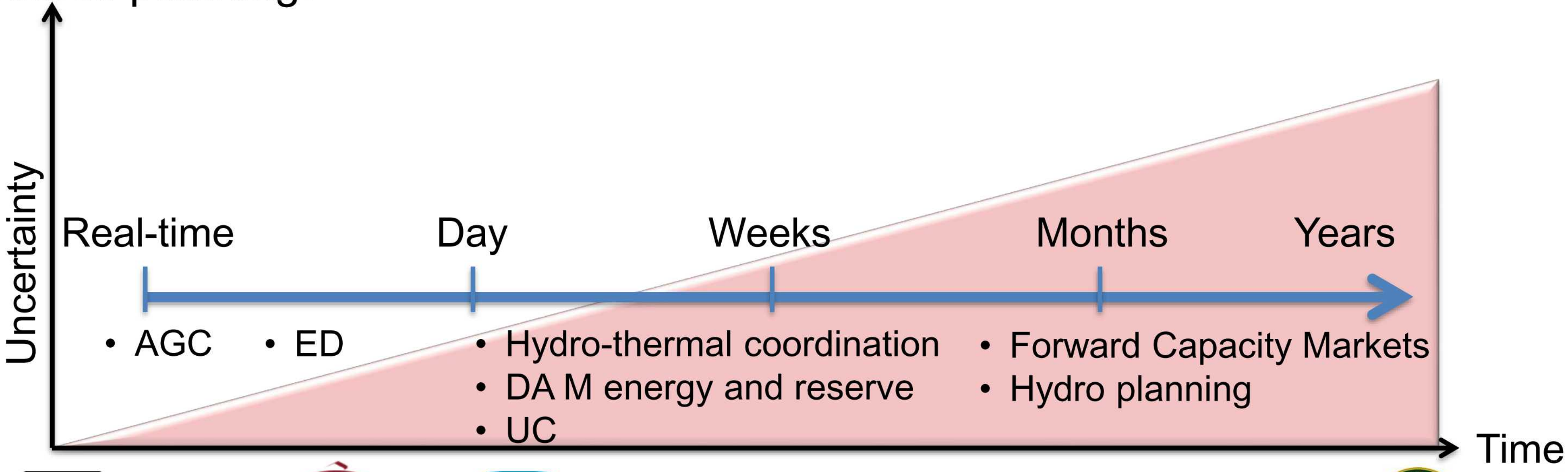
Power System Planning/Operations

- Decision making in power systems looks at processes ranging from very large time horizons to near real-time:
  - **Seconds**: Automatic Generation Control (AGC).
  - **Minutes**: Economic Dispatch (ED).
  - **Hours**: Intra-day look-ahead processes, dynamic economic dispatch.
  - **Days**: Hydro-thermal coordination, day-ahead UC of energy and reserves, intra-day UC.
  - **Years, Seasons, Months, Weeks**: Resource adequacy, transmission and hydro resource planning.



Operating the electric power grid

- Conceptually simple:

$$\sum demand = \sum generation - \sum losses \quad \forall\, t \in T$$

  - This is just a single(*) component process flow network with fixed demands and controllable supplies
  - Managed by Independent System Operators (ISO's) / Regional Transmission Operators (RTO's)

- In practice, this is complicated by
  - No (significant) storage
  - Dynamic constraints (ramp rates)
  - Transmission limitations
  - Security (reliability) requirements
  - Market constraints

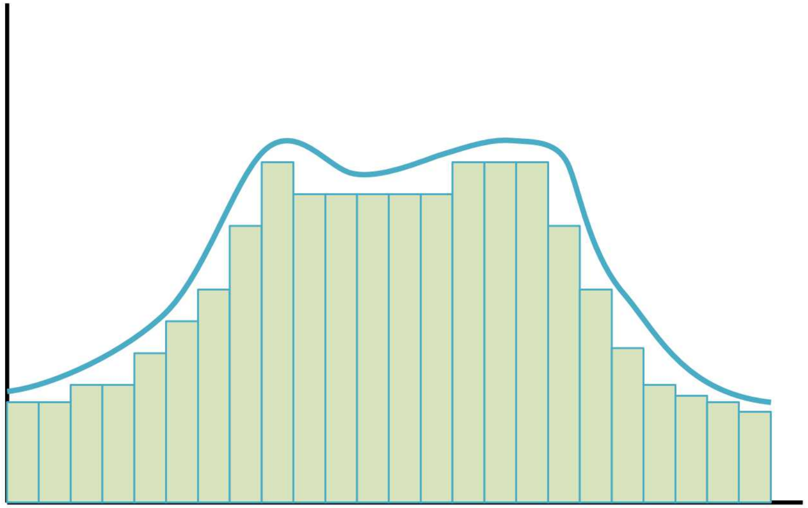
(*) Actually, it is a 2-component system (real and reactive power) with "conversion" at every node, but for the purposes of this talk we will follow industry's lead and allow a small angle assumption to only work with the "DC" optimal power flow model.

An ISO’s view of operating the grid (1)

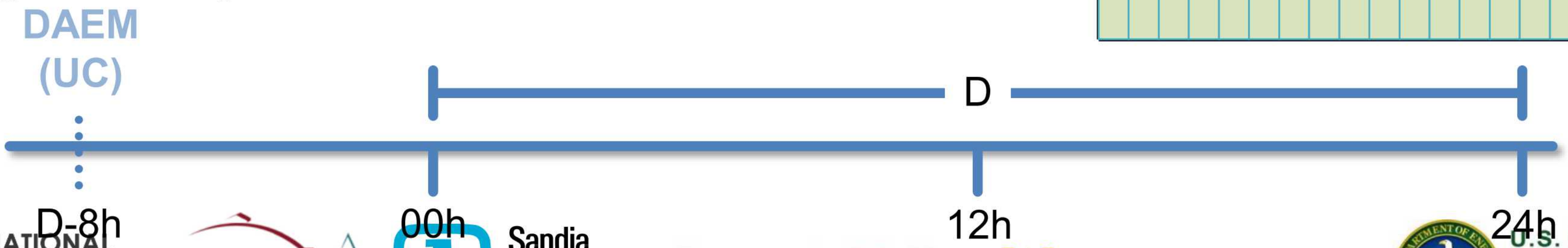
- [Unit Commitment]: Plan a day ahead (1600h)
  - Demand forecast
  - Generator bids
  - Produce:
    - Hourly (on/off) schedules for all participants
    - Hourly interconnect schedules
    - Hourly DAEM Locational Marginal Prices (LMPs)

“Day Ahead Market” (DAM)

“Day Ahead Energy Market” (DAEM)

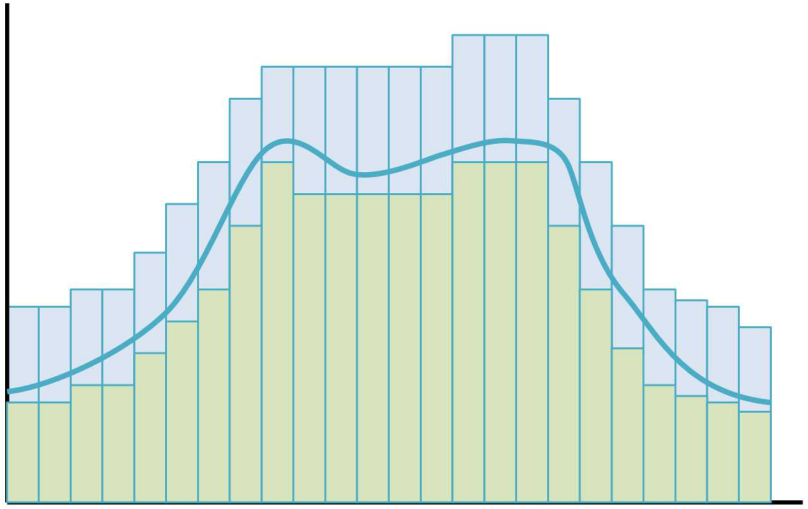


- So what’s the problem?
  - *No one believes the forecast.*
  - *Things go wrong*



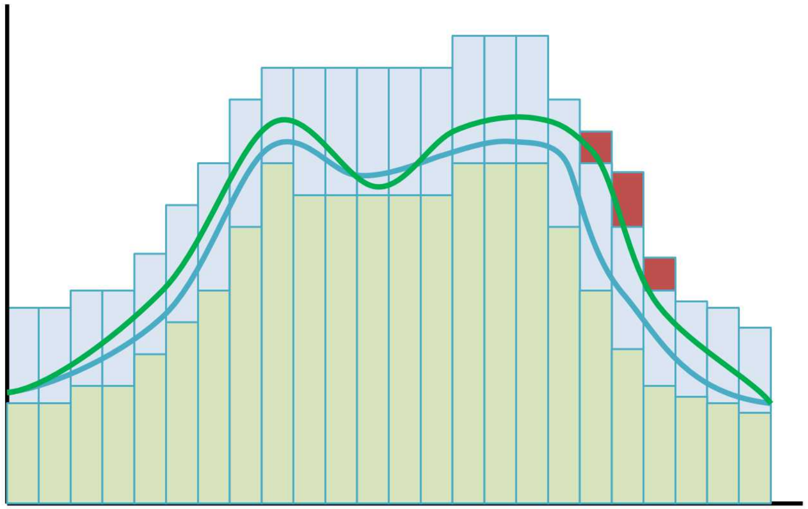
An ISO’s view of operating the grid (2)

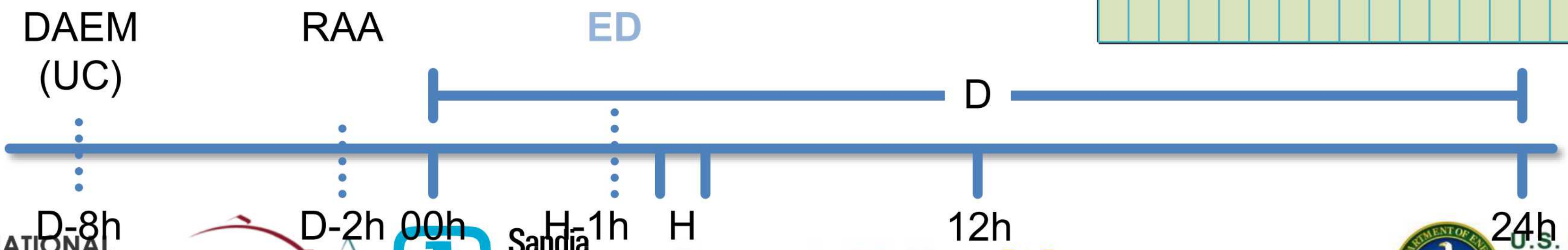
- [Reliability Unit Commitment]: Modify the plan
  - Reserve Adequacy Analysis – allocate reserves to meet load
    - Standard: 10% reserve requirement
  - Contingency analysis
    - *N-1*: survive loss of any (1) generator or (non-radial) line
  - Produces:
    - Additional commitments (DAEM respected)
    - Updated generator dispatch points



An ISO’s view of operating the grid (3)

- [Economic Dispatch]: operate the grid / serve actual load
  - H – 1h: Look-ahead economic dispatch
  - H: Hourly economic dispatch
  - H+5*n*: 5-minute economic dispatch
  - Produces:
    - Updated dispatch points (generator output levels)
    - Additional commitments (fast-start units)

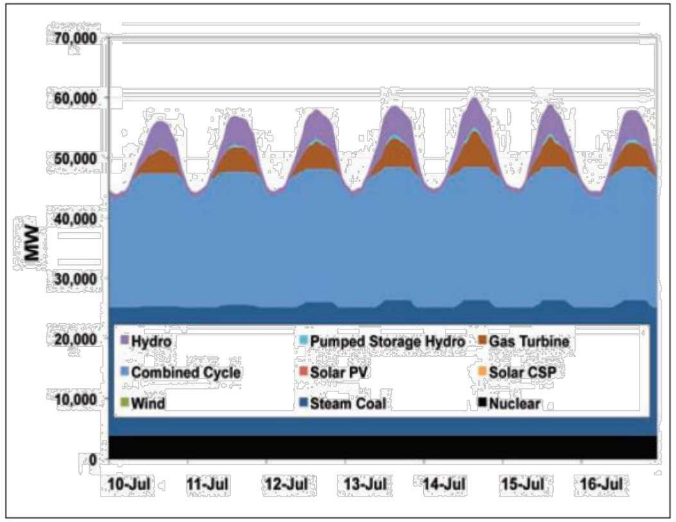


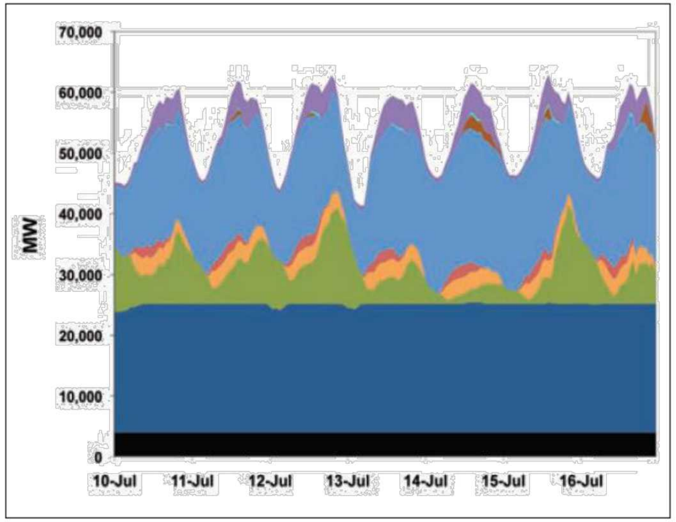


Why is IDAES concerned with Grid Modeling?

- Each market is cleared through an optimization algorithm
  - "Simulating" the markets is tractable and predictive

- Grid operations are the "ground truth" that evaluates the quality / impact of the designs we produce through IDAES
  - Will new plant designs be built?
  - Will new plants participate / be profitable *if* they are built?





0% and 30% renewable penetration reproduced from NREL 2010 *Western Wind and Solar Integration Study*

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  - Will new plant designs be built?
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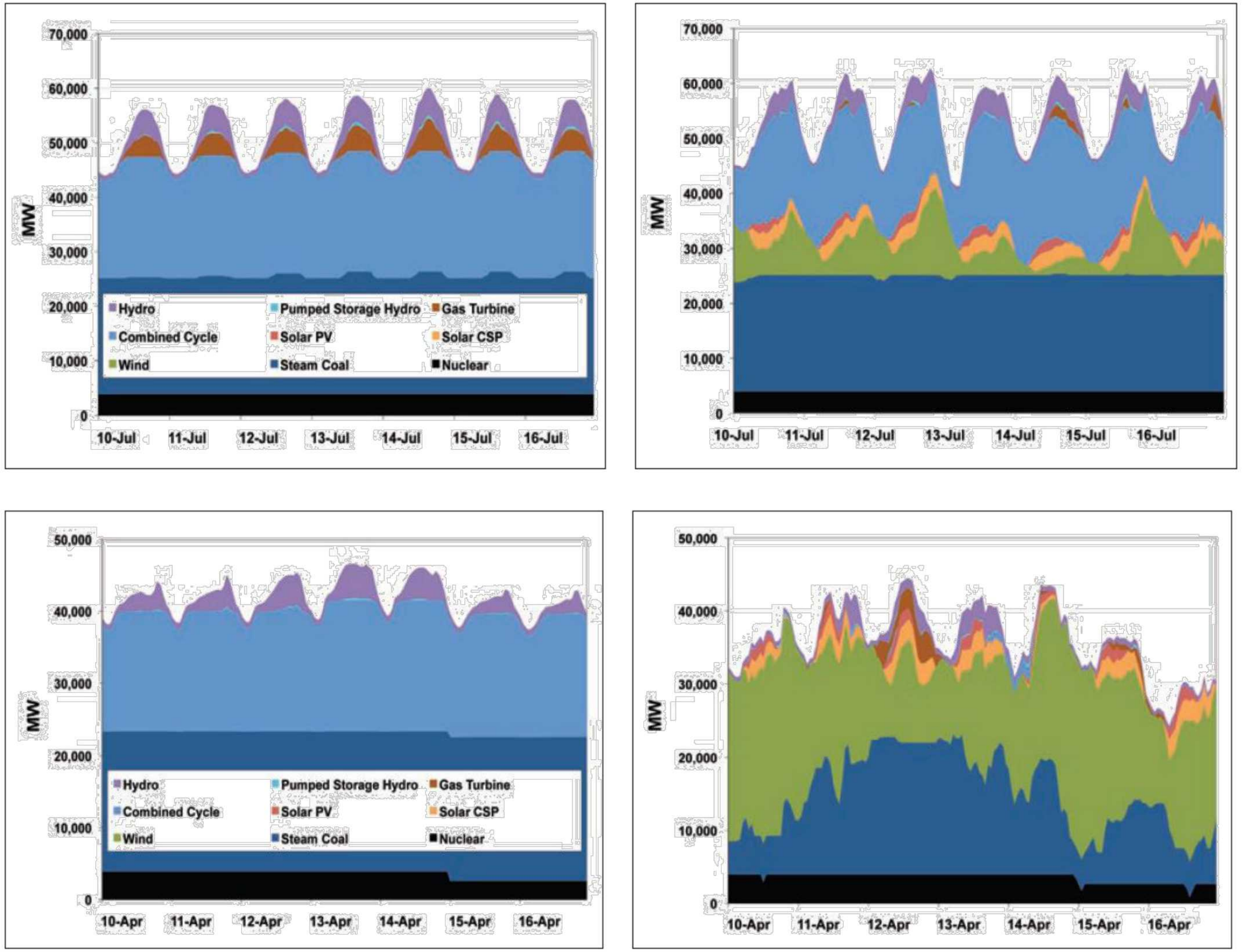
- Changing grid conditions are imposing new operating modes for existing plants



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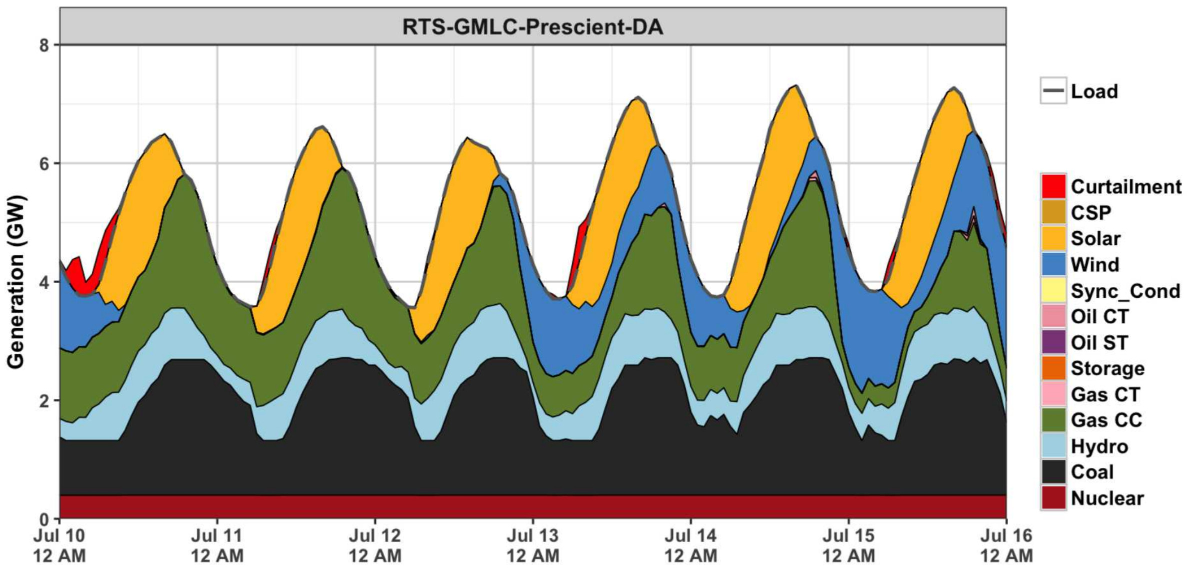
Grid-level modeling: capabilities and goals

- **Challenge: To identify plant performance targets and siting / build-outs that ensure profitability in a power systems operation context**

- **State-of-the-art power systems simulation and optimization analytics**
  - Long-term investment planning
  - Production cost modeling

- **Developing / Extending key capabilities**
  - **Prescient**: An open source production cost modeling (PCM) tool, simulating power systems operations at high levels of fidelity
  - **Expansion planning**: Automatically determine a set of candidate plants to achieve power system expansion goals, which are validated using PCM



Stack graph showing generator fleet dispatch levels over the course of a week, on the RTS-GMLC test system

- **Main goals**
  - Precisely quantify the viability of candidate plant configurations in a market power systems context…
  - … to ensure long-term viability

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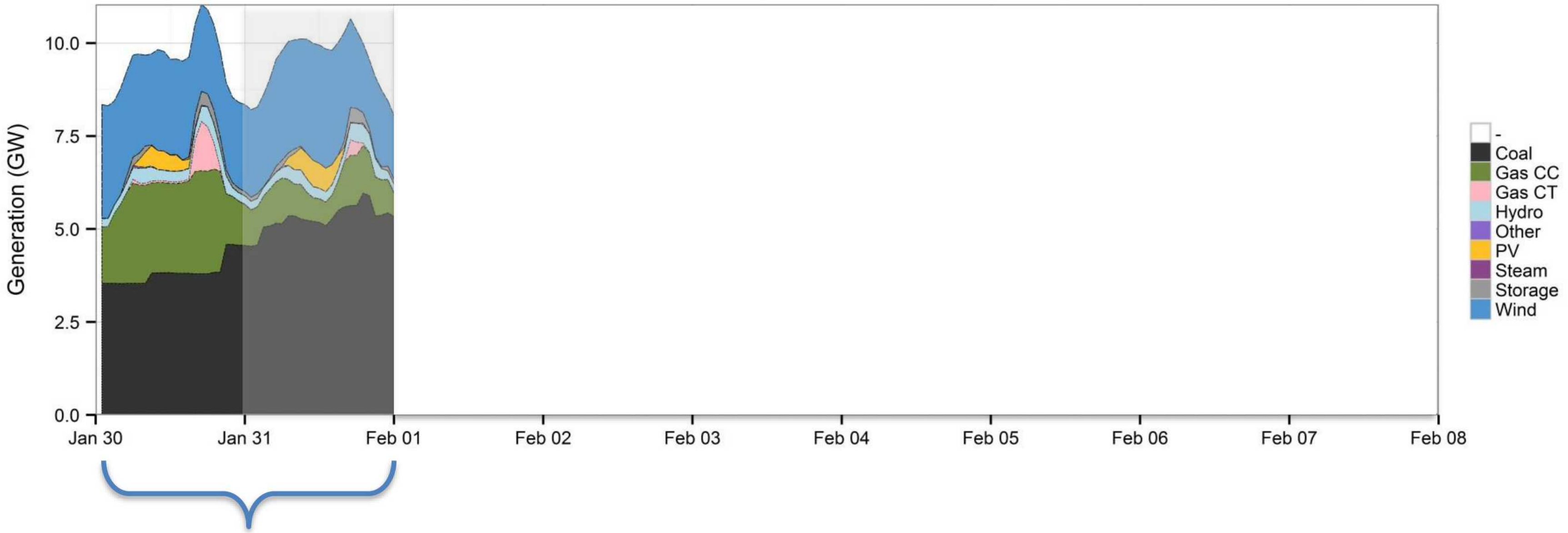
Part 1

Production Cost Modeling for Detailed Plant Behavioral Analysis

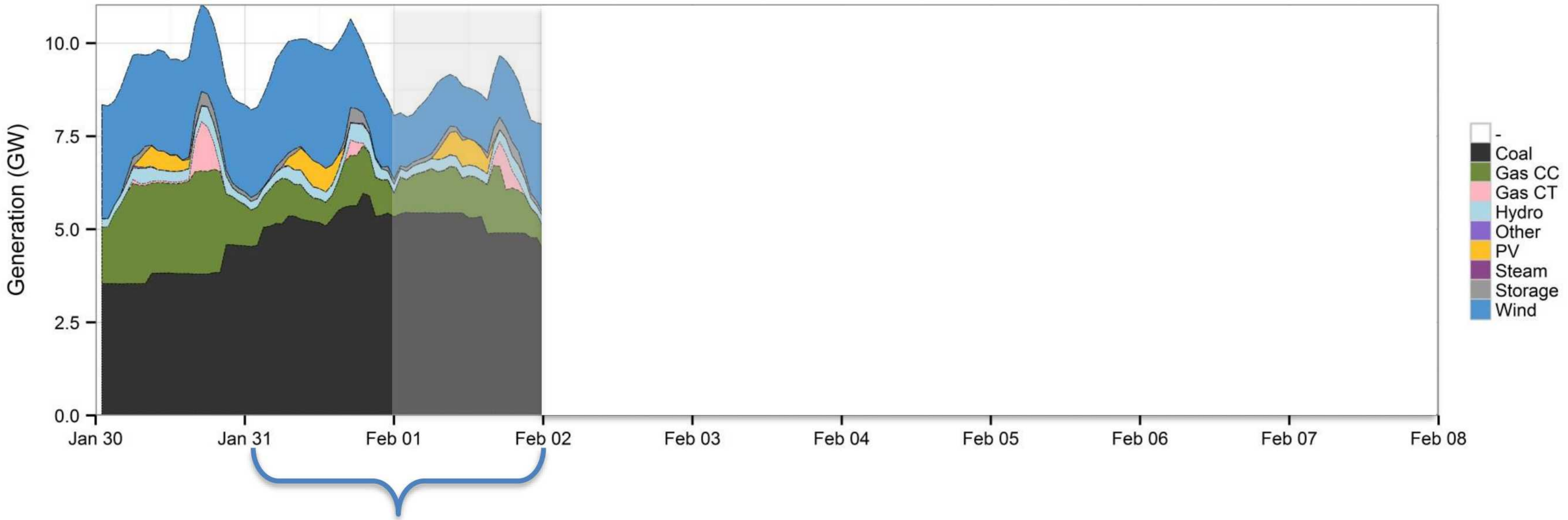
What is a Production Cost Model (PCM)?



optimization horizon:
48 hours

- **Intertemporal Unit-Commitment & Economic Dispatch (UC/ED)** - *Mixed Integer Programming problem (MIP)*

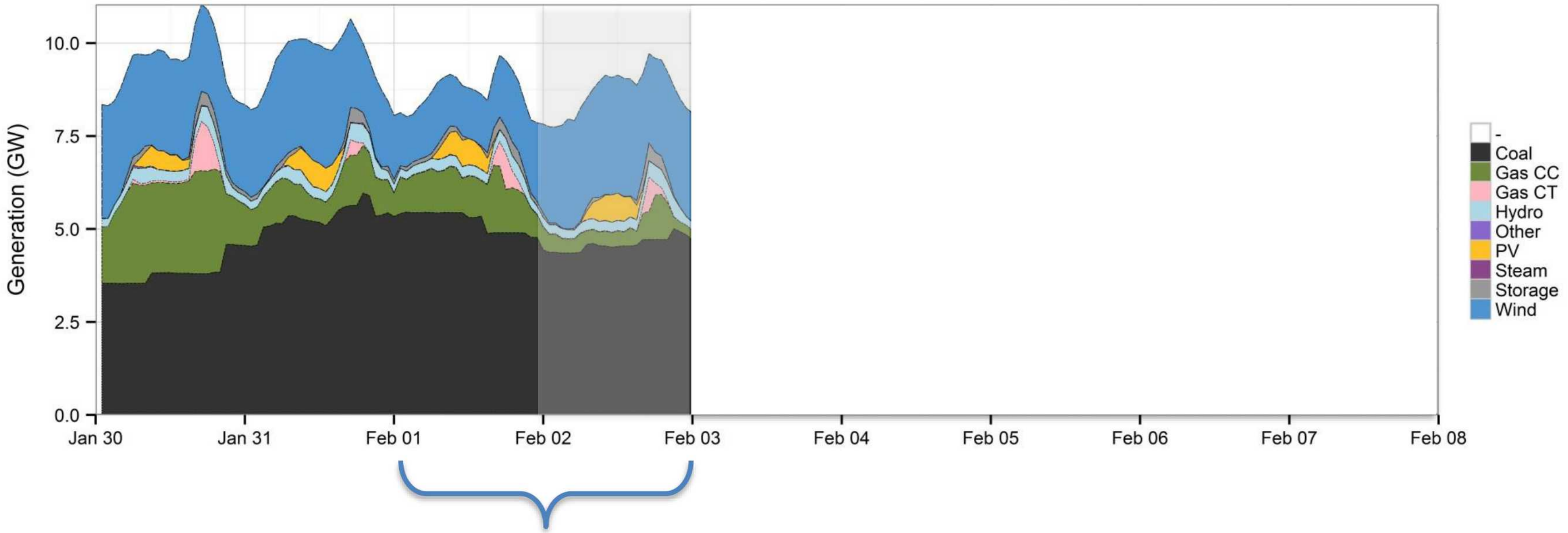
What is a Production Cost Model (PCM)?



rolling forward in
24 hour increments

- **Intertemporal Unit-Commitment & Economic Dispatch (UC/ED)** - *Mixed Integer Programming problem (MIP)*
- **Sequential UC/ED Steps**

What is a Production Cost Model (PCM)?



The state of the system at time t=0 is dependent on:

1. Generator commitment status: on/off
2. If "on": hours of continuous operation; current ramp rate
3. If "off": hours since last operation (minimum shut down duration)

- **Intertemporal Unit-Commitment & Economic Dispatch (UC/ED)** - *Mixed Integer Programming problem (MIP)*
- **Sequential UC/ED Steps**

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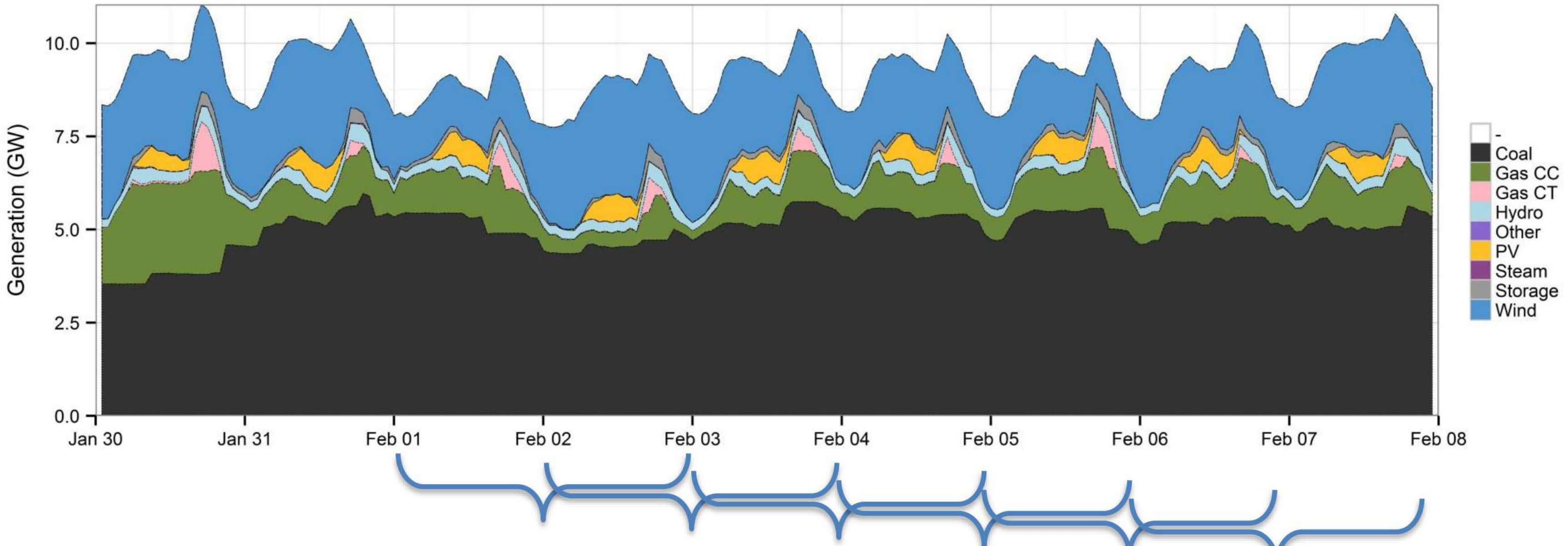
What is a Production Cost Model (PCM)?



Individual MIP computation times can exceed multiple days. Annual solutions can easily become impractically long.

- **Intertemporal Unit-Commitment & Economic Dispatch (UC/ED)** - *Mixed Integer Programming problem (MIP)*
- **Sequential UC/ED Steps**

No explicit opportunity for parallelism

Production Cost Modeling: Key IDAES needs

- To evaluate candidate designs, IDAES needs an accepted, open PCM
  - Two key parts: system model and PCM software

- Open system model
  - "Real" system models exist, but access and distribution is (very) limited
  - IDAES will leverage a realistic, open test case being developed by the DOE Grid Modernization Laboratory Consortium (**RTS-96-GMLC**)

- Open PCM Software
  - Sandia-developed **Prescient PCM**

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

RTS-96-GMLC: a realistic synthetic reference system

- **RTS-96-GMLC: Adding realism to the RTS-96 test case**
  - RTS-96: “The IEEE Reliability Test System-1996. A report prepared by the Reliability Test System Task Force of the Application of Probability Methods Subcommittee”
  - Resolving shortcomings: data errors, adding temporal resolution & congestion, updating generation mix

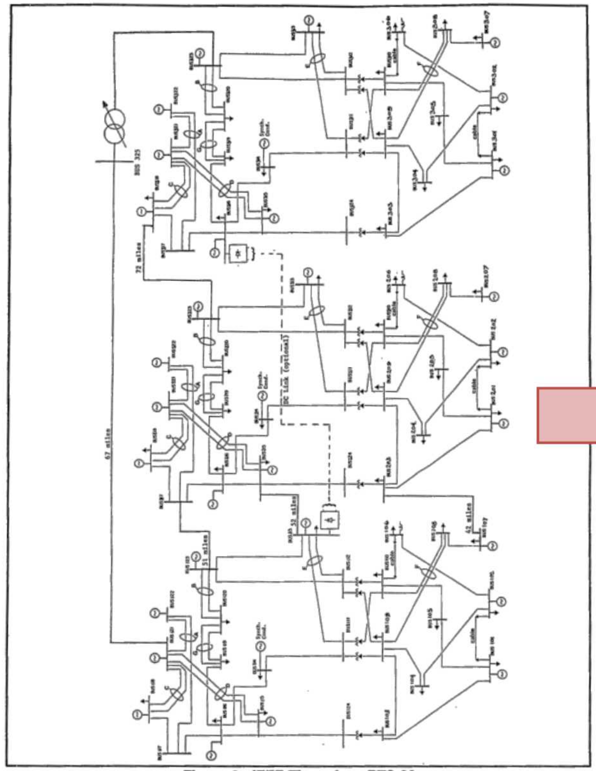
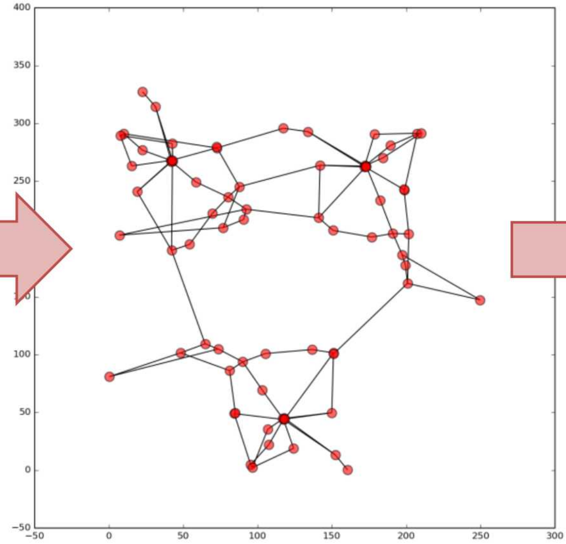
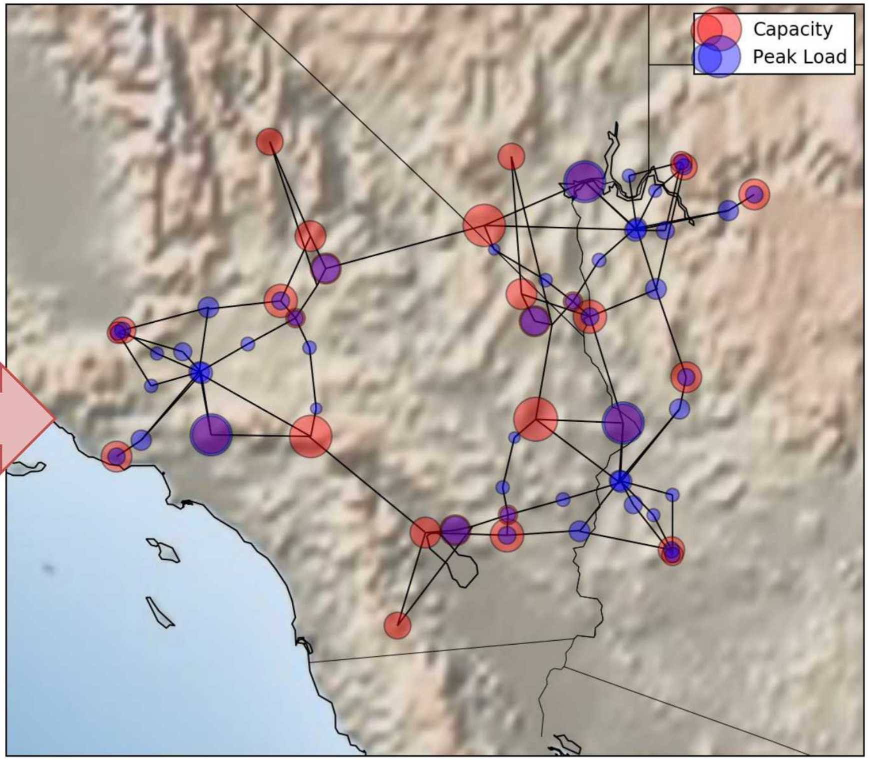


Figure 4 - IEEE Three Area RTS-96

Relative RTS-GMLC node locations based on line lengths

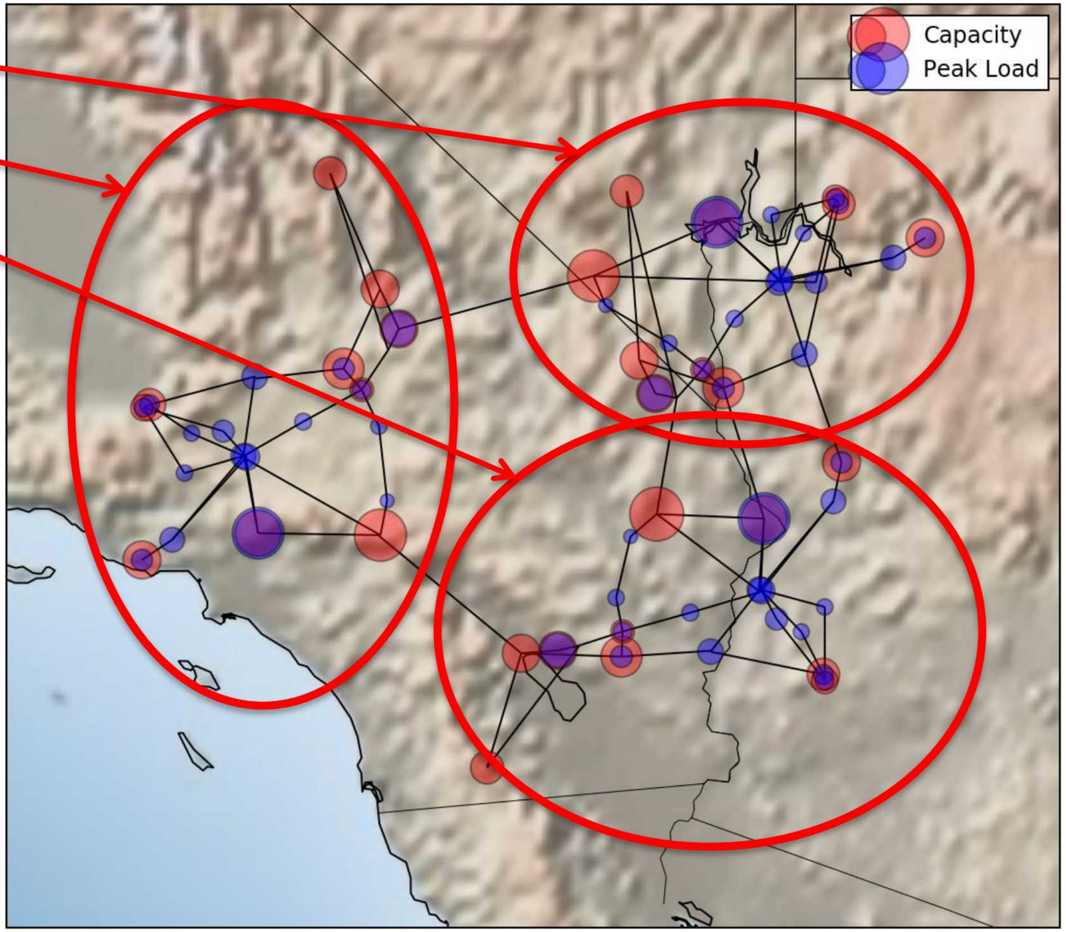




Not intended to represent existing infrastructure

Ensuring geographic and temporal coincidence of weather driven data

- Superimpose regional load profiles
  - Nevada Energy – Region 2
  - LA Division of Water and Power – Region 3
  - Arizona Public Service Company – Region 1

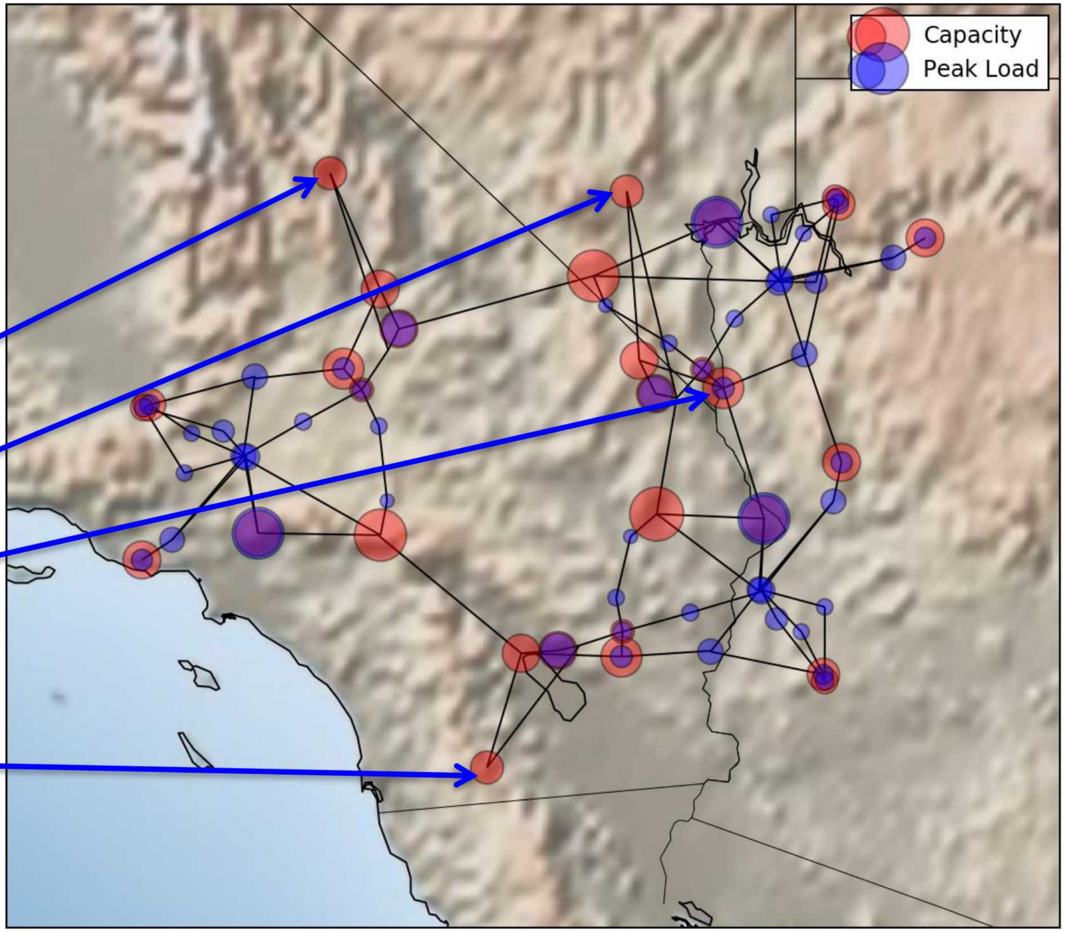


Not intended to represent existing infrastructure

Ensuring geographic and temporal coincidence of weather driven data

- Superimpose regional load profiles
  - Nevada Energy – Region 2
  - LA Division of Water and Power – Region 3
  - Arizona Public Service Company – Region 1

- Add hourly hydroelectric data
  - Devil Canyon Dam
  - Davis Dam
  - Parker Dam



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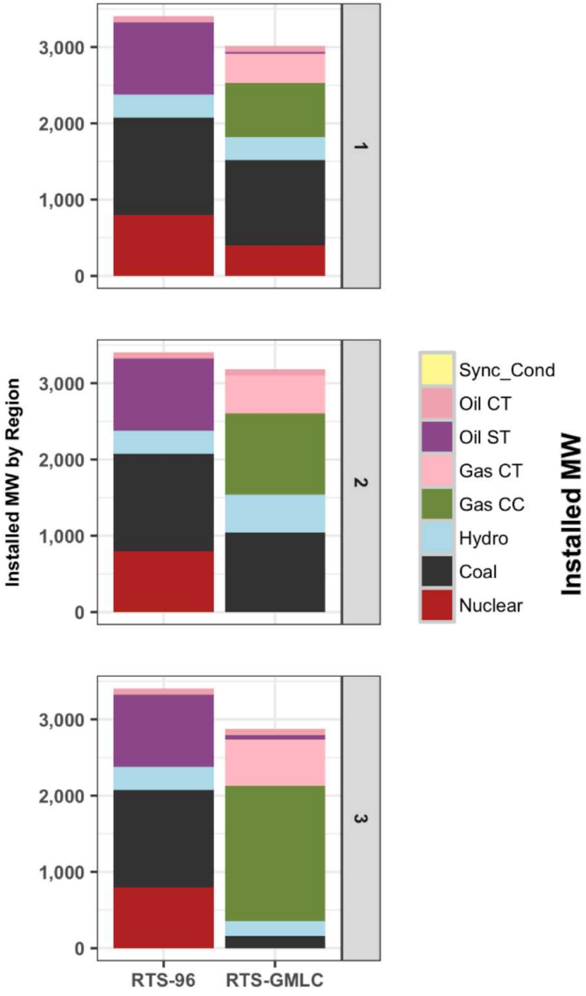
Updated conventional generation fleet

- Added two new generator types to the RTS dataset:
  - 25 MW NG-CT
  - 125 MW NG-CC

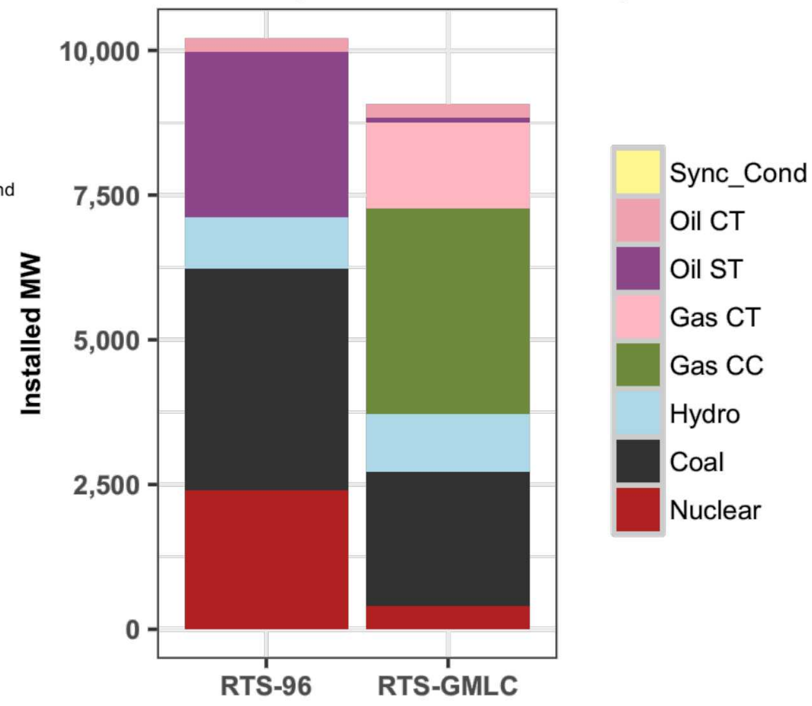
- New generator parameters are based on:
  - Average values from WECC TEPPC 2024 case
  - Wartsilla, Gas Power Journal, Siemens, GE:

- Replaced some existing oil and coal generation with NG-CC and NG-CT generators

Regional Capacity



Total System Capacity



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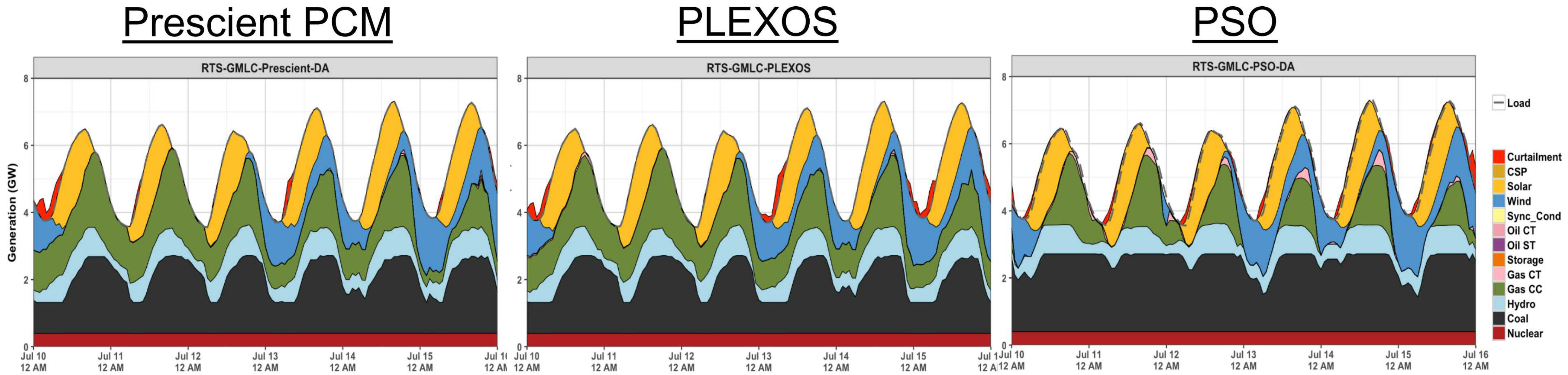
Prescient: an open-source PCM for IDAES

- Prescient PCM
  - Developed at Sandia National Laboratories
  - Open source PCM built on Pyomo
  - Validated against commercial PCM tools
    - PLEXOS – Energy Exemplar
    - PSO – Polaris Systems Optimization



IDAES PCM Plan

- Completed
  - Identification of an open power systems case, for use with Prescient PCM
  - Answer: NREL's RTS-GMLC case

- In progress, soon to be completed
  - Perform basic parameter sweep over key coal unit performance metrics
  - Analyze impact of parameter changes to market participation
  - Primary goal is first-order understanding of relationships

- Moderate-term
  - More comprehensive consideration of ancillary service models
  - Integration of wear-out models in PCM context

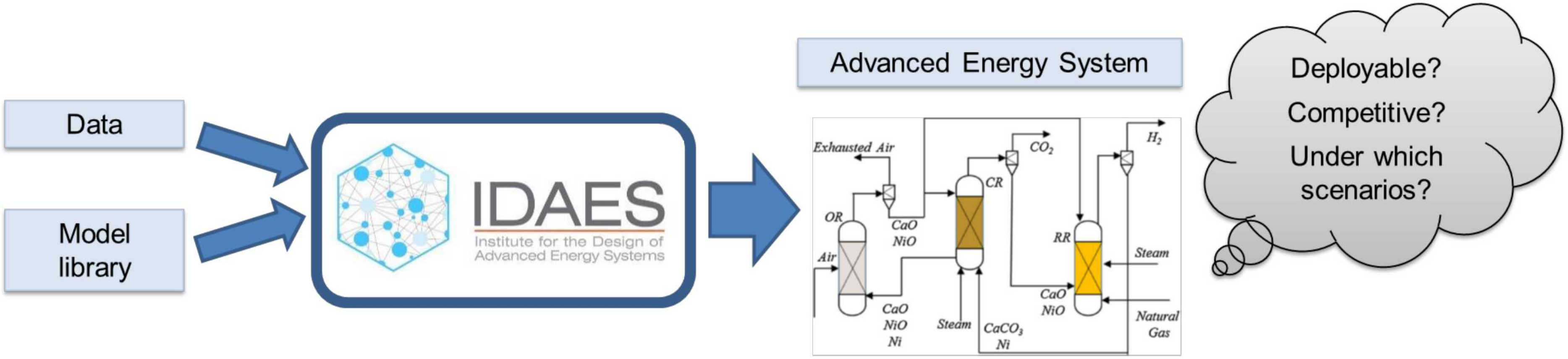
Part 2

Long-Term Expansion Planning for Grid Infrastructure

Energy Infrastructure Planning Model

- Evaluate the changes in generation and transmission infrastructure required to meet the projected demand for electricity over the next few decades.
  - Support decision-making process in the energy sector.
  - Evaluate various scenarios of future energy demand growth.
  - Ensure robustness of the energy system.
  - Study the impact of resource cost trends and policy shifts.

- Test the *deployability* of the new technologies proposed by IDAES under different scenarios.



Improvements over currently available commercial software

(e.g., Markal, TIMES, ReEDS) .

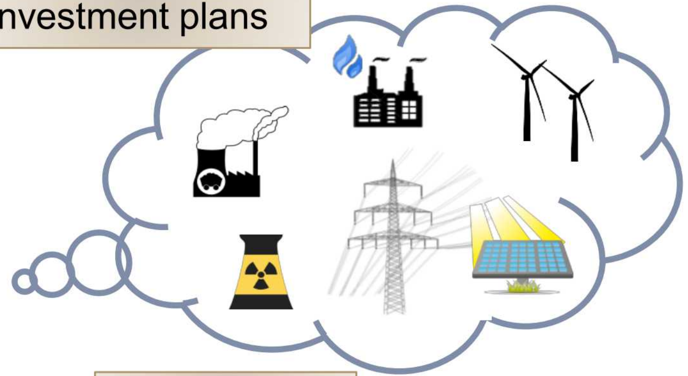
- Mixed-integer Linear Programming model.
  - Helps determine what is built when over long term horizon (20-40 years)
- Allows **hourly** and **sub-hourly** representation of time.
  - Captures the dynamics of the renewable generation and load demand.
  - Includes **unit commitment** of thermal generators.
- Detailed representation of **retirement** and **retrofit** of old generators
  - Important for regions with **aging** generation and transmission **infrastructure** (e.g., United States).

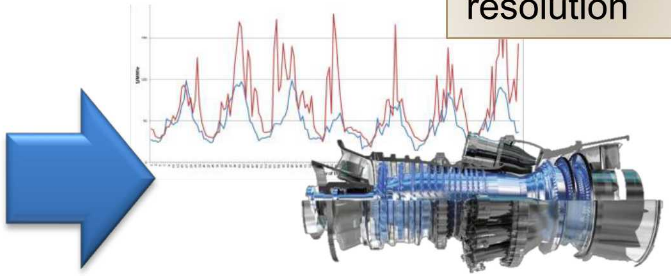
- **Open source**.
  - Researchers will have **access** to all the code and will be able to modify it within the platform.
- Allows the solution of **large instances** without the need of a supercomputer.
  - Due to algorithmic strategies (Nested Decomposition algorithm).
- As a **future step**, it will be extended to **handle uncertainties** in:
  - fuel price;
  - renewable generation;
  - new technology costs and performance.

Modeling Challenges

- **Temporal multi-scale aspect of the problem:**
  - For a 30 year horizon, there are **262,800** hourly sub-periods of time

Long term investment plans

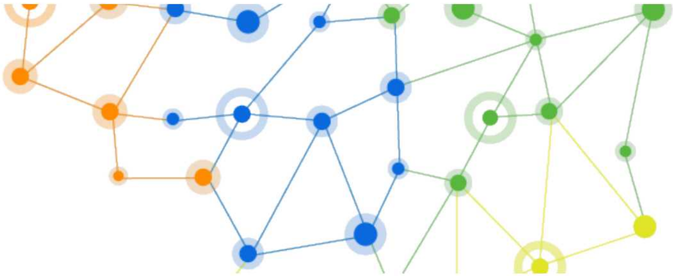




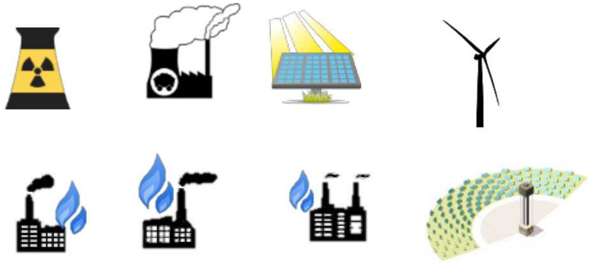
Hourly time resolution

- **Spatial multi-scale aspect of the problem**
  - Large number of potential locations
  - Large number of generators

Large region



Individual generators



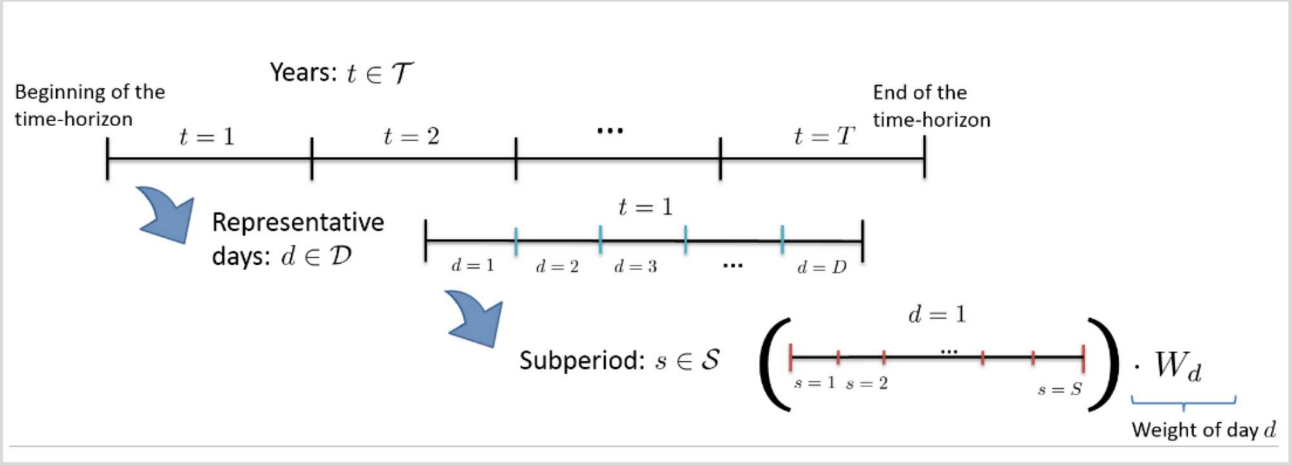
- **Very large-scale models** (million to tens of millions of equations and variables)
- Performance/cost targets are not easy to come up with
  - These models have million **co-depended parameters** regarding different aspect such as investment and operations cost in the generation and transmission level, load demand, renewable source availability, and environmental constraints.

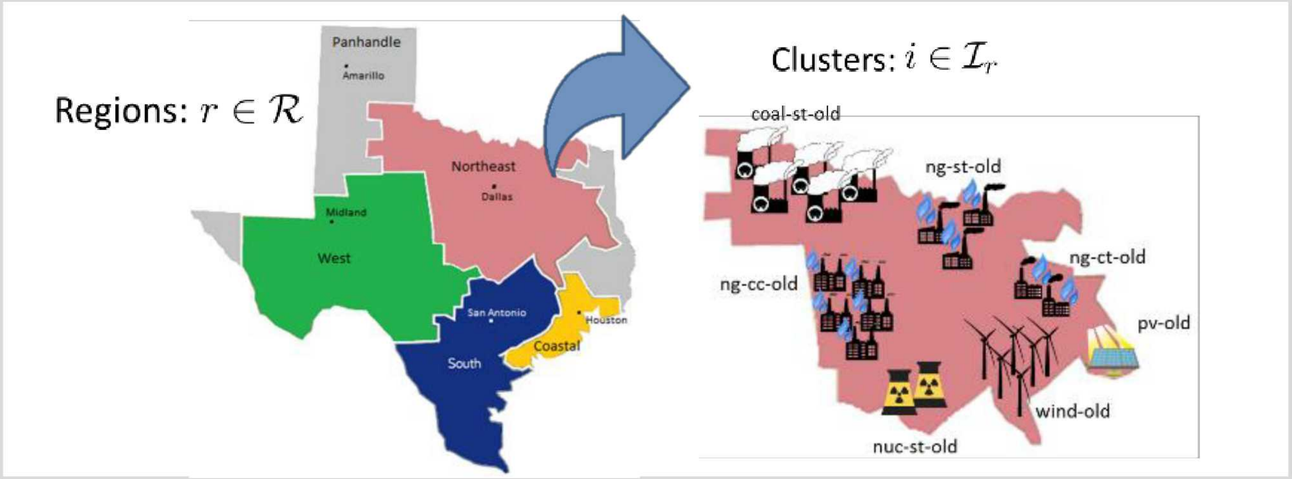
Modeling Strategies

- **Time scale approach:**
  - *d* representative days per year with hourly level information
- **Region and cluster representation**
  - Area represented by a few zones
  - Potential locations are the midpoint in each zone
  - Clustering of generators*

*Palmintier, B.S., Webster M.D., *Heterogeneous unit clustering for efficient operational flexibility modeling,* 2014

- **Transmission representation**
  - Flow in each line is determined by the energy balance between each region r.





Formulation and Solution Strategy

MILP Multi-period Model

- Energy balance
- Capacity factor of the renewable generators
- Unit commitment constraints
- Operating reserve constraints
- Investment constraints.
- Generators balance

Objective function:

Minimization of the net present cost over the planning horizon comprising:

- Operating, startup, investment and retrofit costs
- Fuel consumption
- Environmental costs (if applicable)

Nested Decomposition Algorithm

Basic Idea

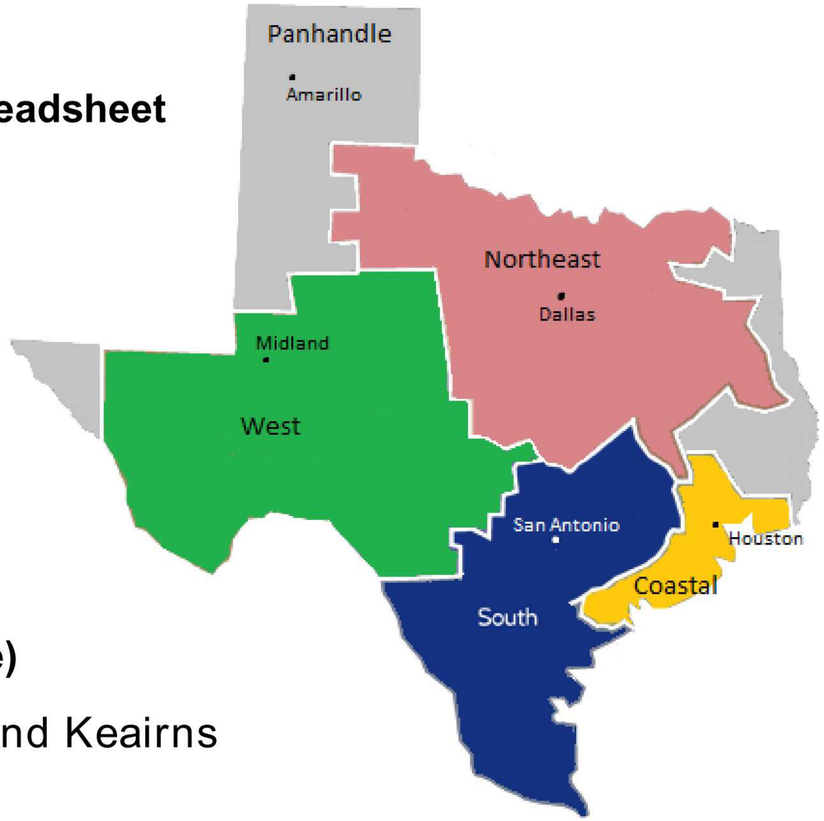
- This algorithm decomposes the problem by time period, which in this case is **by year**.
- It consists of **Forward** and **Backward Passes**.
- The **Forward Pass** solves the problem in myopic fashion (1 year time horizon).
- The **Backward Pass** projects the problem onto the subspace of the linking variables by adding cuts.

Multiple valid cuts to be chosen by the user.

Provides **significant computational savings**.

Case Study: ERCOT (Texas)

- **30 year time horizon (1st year is 2015)**
- **Data from ERCOT database**
- **Cost information from NREL (Annual Technology Baseline (ATB) Spreadsheet 2016**
- **All costs in 2015 USD**
- **Regions:**
  - Northeast (midpoint: Dallas)
  - West (midpoint : Glasscock County)
  - Coastal (midpoint: Houston)
  - South (midpoint : San Antonio)
  - Panhandle (midpoint : Amarillo)
- **Fuel price data from EIA Annual Energy Outlook 2016 (reference case)**
- Advanced fossil fuel data from Iyengar et al. (2014), and Newby and Keairns (2013).
- Storage device data from Schmidt et al. (2017), and Luo et al. (2015).



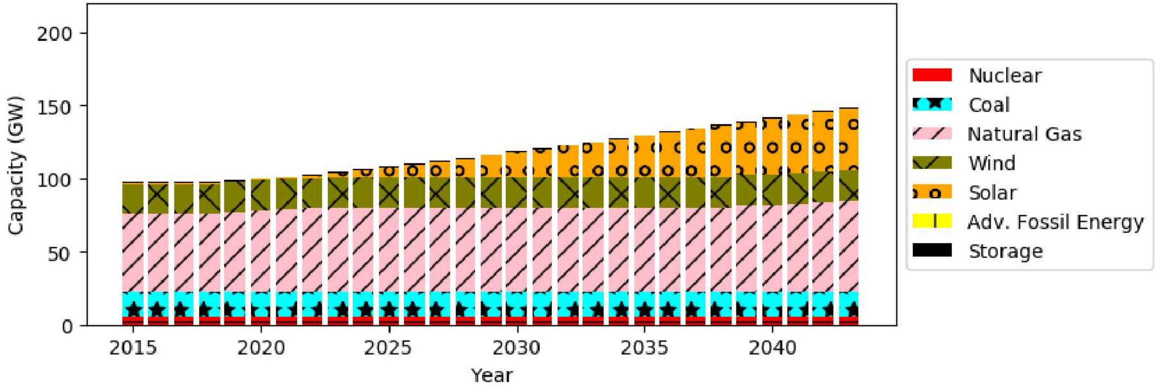
ERCOT, 4 representative days per year

Discrete variables: 500,500
Continuous variables: 810,181
Equations: 1,730,491
Solver: Gurobi

PYOMO

- **Scenario 1: No** carbon tax.

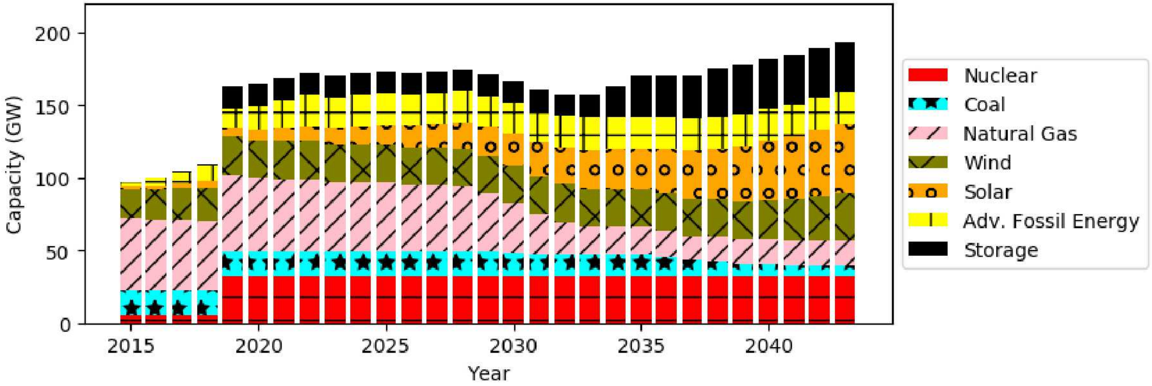
Solution time
Full-space: 10.1 hours
Nested Decomposition: 5.2 hours



Natural gas favored to handle renewable generation and load demand

- **Scenario 2:** Carbon tax **starting at $10/tonne in year 2020, and increasing linearly to $100/tonne in 2029.**

Solution time
Full-space: 4.0 hours
Nested Decomposition: 2.8 hours



Advanced fossil fuels, nuclear and storage favored instead of natural gas

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Conclusions

- Powerful multiscale optimization model for planning electric power infrastructures
- Potential for evaluating new IDAES technologies under a variety of scenarios.
- Massive computational savings through algorithmic improvements.

Future steps

- Improve the representation of the transmission.
- Test the model for other U.S. ISOs.
- Perform a sensitivity analysis with an actual technology developed by IDAES.
- Extend the formulation to multi-stage stochastic programming