PLEXOS®
Integrated Energy Model


# CO-OPTIMIZATIONS OF NATURAL GAS AND POWER SECTORS WITH PUBLIC POLICY AND INSTITUTIONAL REFORM

Carnegie Mellon University
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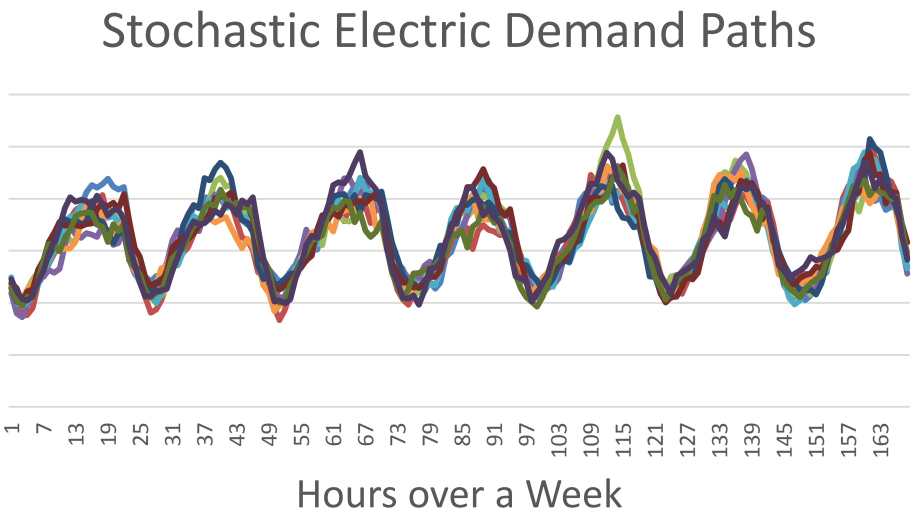
# Topics

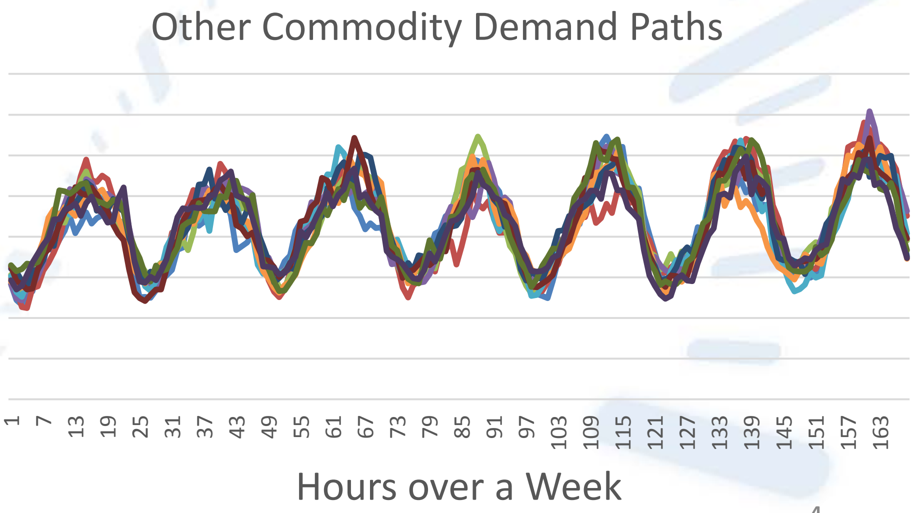
- Multi Commodity Co-Optimizations
- Multi Sector Energy Efficiency and Demand Response
- GHG and Pollution
- Co-Optimization of Electric and Natural Gas Production Cost
- Gas Electric Planning Process
- Energy Storage
- Gas and Coal Gen Efficiency
- Capacity Markets
  - Consideration of Adequacy of Supply for System Expansion Planning
- Co-Optimization of Transmission and Other Resources
- EISPC Co-Optimization Features Demonstrations
- Stochastic Optimizations for Integration of Renewables

# Multi-Commodity Co-Optimizations

# ➤ Expansion with Stochastic Commodity Demands



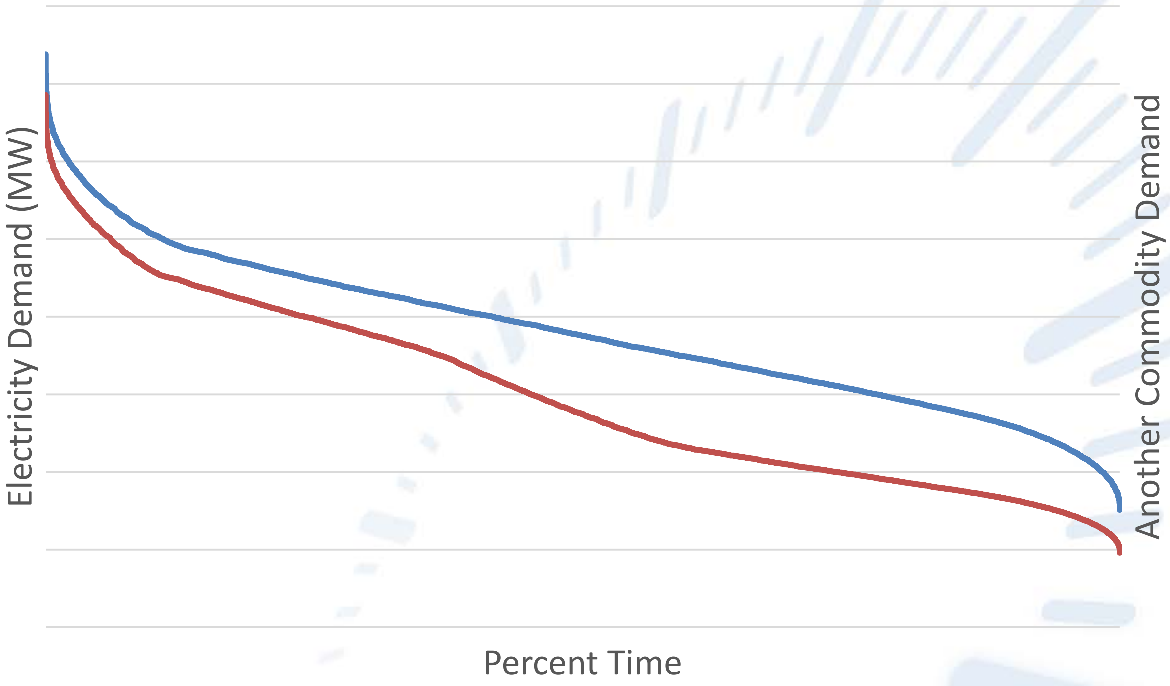

Stochastic Decomposition



# ➢ Multi Commodity Demand Duration Curves

- Multi Sector CapEx and OpEx Least Cost Optimization

- Primary and Secondary demand curve optimizations

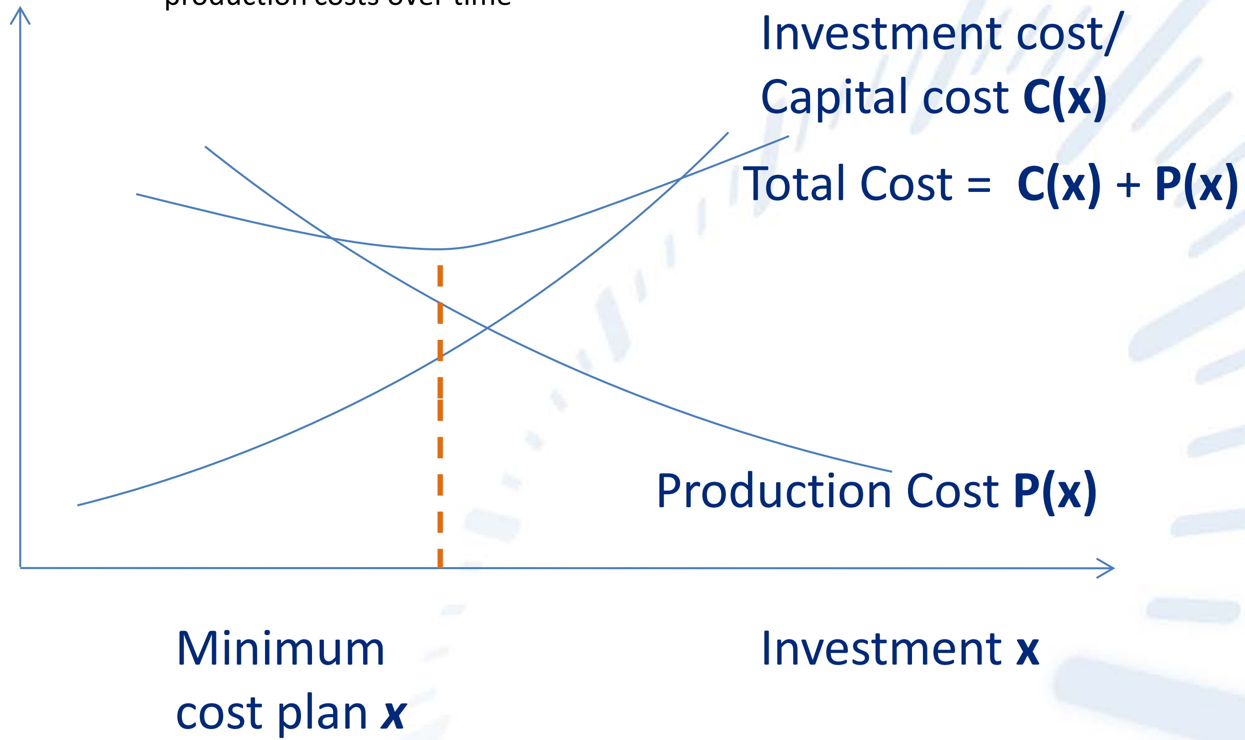


# ➢ Least Cost Optimization

Objective: Minimize net present value of the sum of investment and production costs over time

- Chart shows the minimization of total cost of investments and of production cost
- As more investments made production cost trends down however investment cost trends up

Cost $



# ➢ Illustrative Least Cost Optimization

$$\text{Minimize} \overbrace{\sum_{y=1}^{Y}\sum_{i=1}^{I}(\underset{\substack{\uparrow\\ \textit{Individual Unit}\\ \textit{Build Cost}}}{BuildCost_i} \times \underset{\substack{\uparrow\\ \textit{Amount Built}}}{Build_{i,y}})}^{\textit{Investment Cost}} + \overbrace{\sum_{t=1}^{T}\left(\sum_{i=1}^{I} \underset{\substack{\uparrow\\ \textit{Individual Unit}\\ \textit{Production Cost}}}{ProdCost_i} \times \underset{\substack{\uparrow\\ \textit{Individual Unit}\\ \textit{Production}}}{Prod_{i,t}}\right)}^{\textit{Production Cost}} + \underset{\substack{\uparrow\\ \textit{VOLL}}}{ShortCost} \times \underset{\substack{\uparrow\\ \textit{Unserved}\\ \textit{Energy}}}{Shortage_t}$$

subject to

Supply and Demand Balance: $\sum_{i=1}^{I} Prod_{i,t} + Shortage_t = Demand_t \quad \forall t$

Production Feasible: $Prod_{i,t} \le ProdMax_i \quad \forall i,t$

Expansion Feasible: $Build_{i,y} \le BuildMax_{i,y} \quad \forall i,y$

Integrality: $Build_{i,y}$ $integer$

Reliability: $LOLE(Build_{i,y}) \le LOLETarget \quad \forall y$

*∀ = for all*
*y = year*
*t = interval*
*i = unit*
*Y = Horizon*

This simplified illustration shows the essential elements of the mixed integer programming formulation. Build decisions cover generation, generation cooling types, water use costs, transmission, gas pipeline, coal transport, water pipe, as does supply and demand balance and shortage terms. The entire problem is solved simultaneously, yielding a true co-optimized solution.

# Constraints Driving Decisions

- Investment Constraints
  - Renewable Energy Laws
  - 10 – 30 year horizon
  - Minimum zonal reserve margins (% or MW)
  - Reliability criteria (LOLP Target)
  - Inter-zonal transmission expansion (bulk network)
  - Resource addition and retirement candidates (*i.e.* maximum units built / retired )
  - Water Pipe
  - Gas Pipeline
  - Coal Transport
  - Build / retirement costs
  - Age and lifetime of units
  - Technology / fuel mix rules
- Operational Constraints
  - Energy balance
  - Ancillary Service requirements
  - Optimal power flow and limits
  - Resource limits:
    - energy limits, fuel limits, emission limits, water use, etc.
  - Emission constraints
- User-defined Constraints:
  - Practically any linear constraint can be added to the optimization problem

## Algorithms

- Chronological or load duration curves
- Large-scale mixed integer programming solution
- Deterministic, Monte Carlo; or
- State-of-the-art Stochastic Optimization (optimal decisions under uncertainty)

## Stochastic Variables

- Set of uncertain inputs $\omega$ can contain any property that can be made variable:
  - Load
  - Fuel prices
  - Electric prices
  - Ancillary services prices
  - Hydro inflows
  - Wind energy, *etc*
  - Discount rates
  - Others
- Number of samples $S$ limited only by computing memory
- First-stage variables depend on the simulation phase
- Remainder of the formulation is repeated $S$ times

# Multi Sector Energy Efficiency and Demand Response

# ➢ Energy Efficiency and Demand Response Data and Parameters

- Information about sources and data gathering strategy:
  - Fixed values of loads (or at very high prices) can be derived from regional natural resources forecasting. The final tuning can be based on current and (recent) historical values using a back cast validation.
  - Unserved energy prices are publicly available at regional level in most countries.
  - Residential and commercial load functions are created with at least and not limited to: shaping based on regression, time of day, and weather input models and sizing based on econometric models.
  - The link between natural resource potential and price-dependent industrial load can be created based on various publications by governmental and private organizations on resource price forecasting trends.
  - Large-scaled mining industrial replacement costs are available from various local resources and from organizations in most regions.
  - Aggregated energy efficiency investment cost with geographical information will be determined according to energy efficiency (for short-run) functions with disaggregation level based on social distribution parameters complemented by research of various publications on modern energy efficiency models (eg. intelligent buildings, building masks)

- Among others, the main parameters that define a responsive load in PLEXOS are:
  - Expected Load, $/kW, Fixed Load/ Generation, regional factor, Unserved Energy Price.
  - Purchase price/quantity, Max/Min Load, Benefit functions, Min/Max Daily/Weekly/Monthly
  - Energy Loads, Fixed DSP Price/quantity, time of day use patterns

# ➢ Energy Efficiency and Demand Response Modeling

- Fixed-energy load ($L_{fixed}$) are usually representative of the portion of the system load that is "curtailable" at some cost (unserved energy) usually higher than the operational costs. This is a common approach for representing the unresponsive portion of the load, mostly linked to the residential and commercial components.

- Price-dependent: ($L_{price}$) This is a generic representation. A common approach for modeling is defining either: piecewise linear price/quantity curves, stepwise curtailable quantities, fixed prices/quantities purchasers and DSP programs at regional, zonal or nodal level.

- Resource-planning dependent loads ($L_{rp}$) are purchasers modelled as expansion "anti-generator" candidates: This means they preserve all the expansion qualities of generators such as building/retirement costs, FO&M costs, debt/equity costs, economic/technical lifetime, but their net injection to the system is negative. These are optimally decided since it is defined (in the objective function) as a trade-off between investing (increased investment cost) and decommitting other higher magnitude loads. This is a powerful approach for modelling lumpy investment impact at industrial level, including replacement costs, determining both an optimal timing and staging.

# GHG and Pollution

# ➢ GHG and Pollution

- Many studies require cost and benefits analysis of pollutants and GHG's where this white paper we discuss emission modeling and analysis of systems.
- Generation of electricity by fossil-fired plant produces a range of combustion by-products such as NOx (NO and NO2), SOx (SO and SO2) and CO2 or solid particles:
  - A database may include production details, constraints, and taxes on any number of emissions.
  - Emissions can be produced, absorbed (scrubbed), constrained, and penalized across all or any subset of generators and/or fuels.
  - Constraints can be placed on the total of any emission and/or on a subset of producers across any time period including multi-annual constraints.
  - There is no limit the number of emission limits modelled.
  - Emission grandfather rights can be modelled.

# ➢ GHG and Pollution Modeling

- Emission Class: (eg COx, NOx, SOx, Solid Particle, etc). Emissions can be associated with Generation and Fuel Offtake by defining the following properties:
  - Emission Generators [Production Rate] property defines the functional relationship between megawatt generation and emissions.
  - Emission Fuels [Production Rate] property defines the functional relationship between fuel usage and emissions.
- Abatement
  - The abatement of emissions is modelled either:
    - As a simple proportion of emissions via the Emission Generators Removal Rate property combined with Removal Cost; or
    - Using Abatement objects
    - Abatement objects provide detailed modelling of the physical and cost aspects of abatement technologies as well allowing the simulator to optimize the choice of technologies employed from a set of defined alternatives.

# ➢ Emission Constraints, Caps, Taxes, Protocols

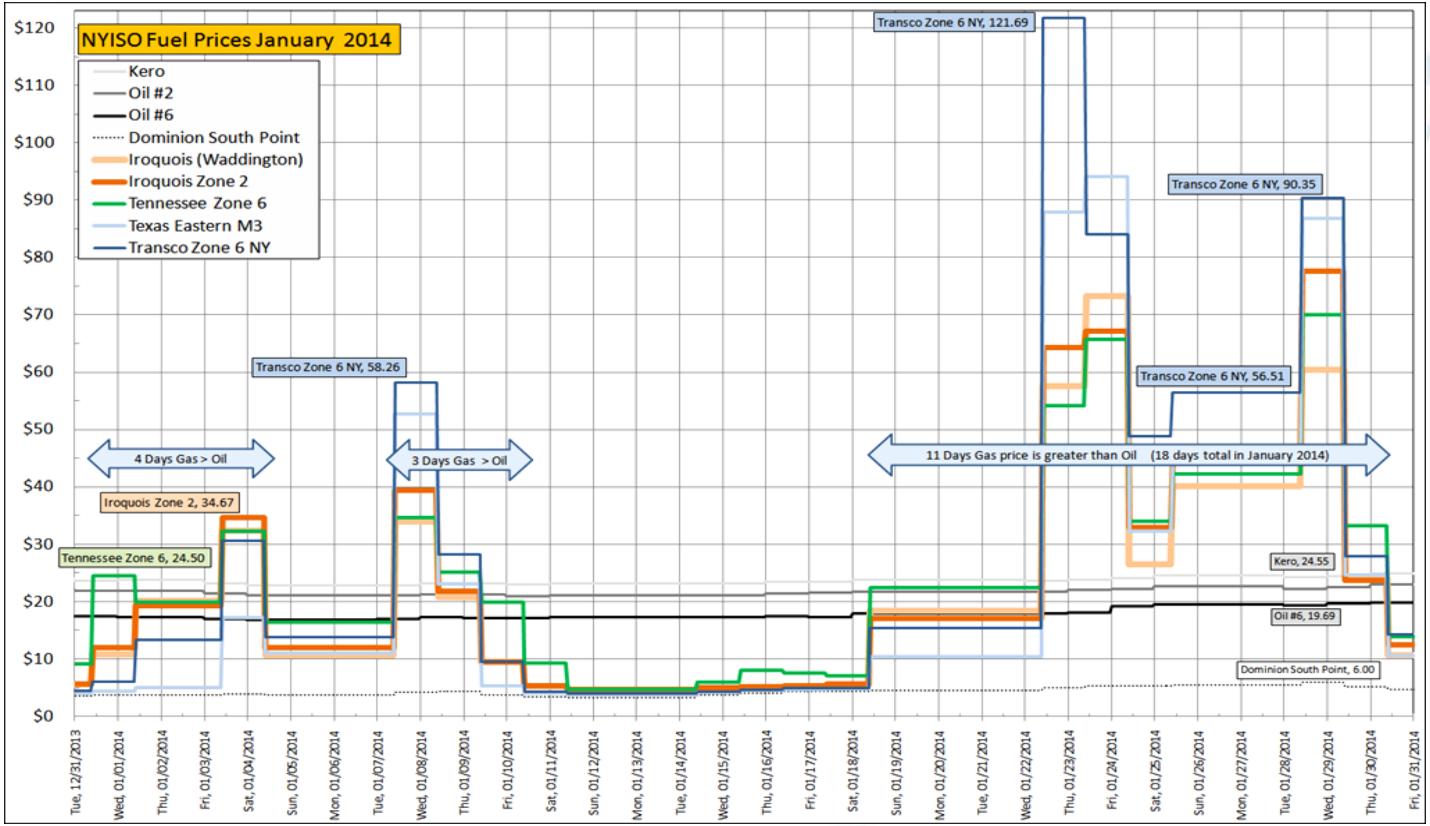
- More complex emission constraints are created using Constraint objects.
- The emission constraints are fully integrated into the mathematical programming problem, the dispatch and pricing outcome will reflect the economic impact of the constraints.
- This means that, when an emission constraint is binding, lower emitting plant will be favored over high emission plant, thus the merit-order of generators will change.
- However generators in many schemes that implement the environmental protocol have incumbent generating companies with given grandfather rights to emit or compliance timeframes.
- This allocation of rights can be modelled using the Company Emissions property.
- These allocations pass back to the company and affect Net Profit. When running models this will result in generator bidding behavior reflective of the net position with respect to emissions e.g. a high emitter may retain its place in the merit order if its allocation of emission right is high enough.
- In addition to or instead of modelling physical emission limits, emission taxes/prices can be modelled either by:
  - Setting the emission Shadow Price directly; or
  - Defining a soft constraint i.e. one with one or more bands of penalty price.

# Costs and Benefits

- It is possible with detailed modeling of emissions and emission constraints and pricing to then determine costs and benefits.
- Costs could be short run costs of emission production at a penalty price or capital costs of removing emissions or different capacity expansion decisions to minimize emissions.
- Benefits can be emissions reductions as well as cleaner environment and avoidance of short run costs of emissions productions and or credits for not producing emissions.
- There are many useful metrics such as emission intensity for a power sector both before and after expansion cases as well as financial, economic, and production metrics for emissions.
- The optimization can minimize NPV of a system capacity expansion scenario with emission reduction targets. A base line emission target scenario is easily created.
- As well the optimization can minimize emissions during short run production cost simulations as well.

# Co-Optimization of Electric and Natural Gas Production Cost

# ➢ Fuel Prices Reported by NYISO Winter 2013-14




- Natural Gas Prices Spiked above oil for 18 out of 31 days in January 2014

Source: NYISO Report to MIWG March 13, 2014

## ➢ Illustrative Formulation of Co-Optimization of Natural gas and Electricity Markets

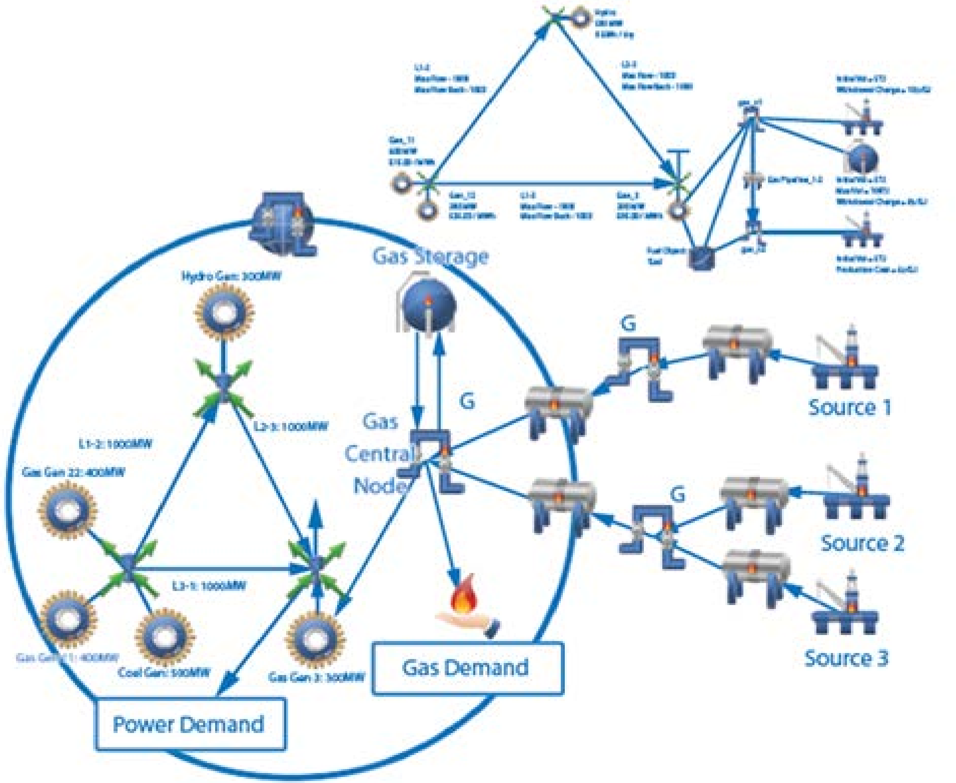
- Objective:
  - Co-Optimization of Natural Gas Electricity Markets

- Minimize:
  - Electric Production Cost + Gas Production Cost + Electric Demand Shortage Cost + Natural Gas Demand Shortage Cost
- Subject to:
  - [Electric Production] + [Electric Shortage] = [Electric Demand] + [Electric Losses]
  - [Transmission Constraints]
  - [Electric Production] and [Ancillary Services Provision] feasible
  - [Gas Production] + [Gas Demand Shortage] = [Gas Demand] + [Gas Generator Demand]
  - [Gas Production] feasible
  - [Pipeline Constraints]
  - others

# ➢ Electric and Gas Infrastructure Strategic Planning Models

Co-optimization of Electric and Natural Gas Infrastructure Production and Investment Planning

- Gas / Electric Price Forecasting
- Gas / Electric Supply and Demand Balances
- Gas / Electric Asset Valuations
- Combined Gas / Electric Planning
- Gas / Electric System Adequacy
- Individual Sector Analysis (Gas or Electric)
- Fuel Diversity
- Congestion and Basis Risk Analysis

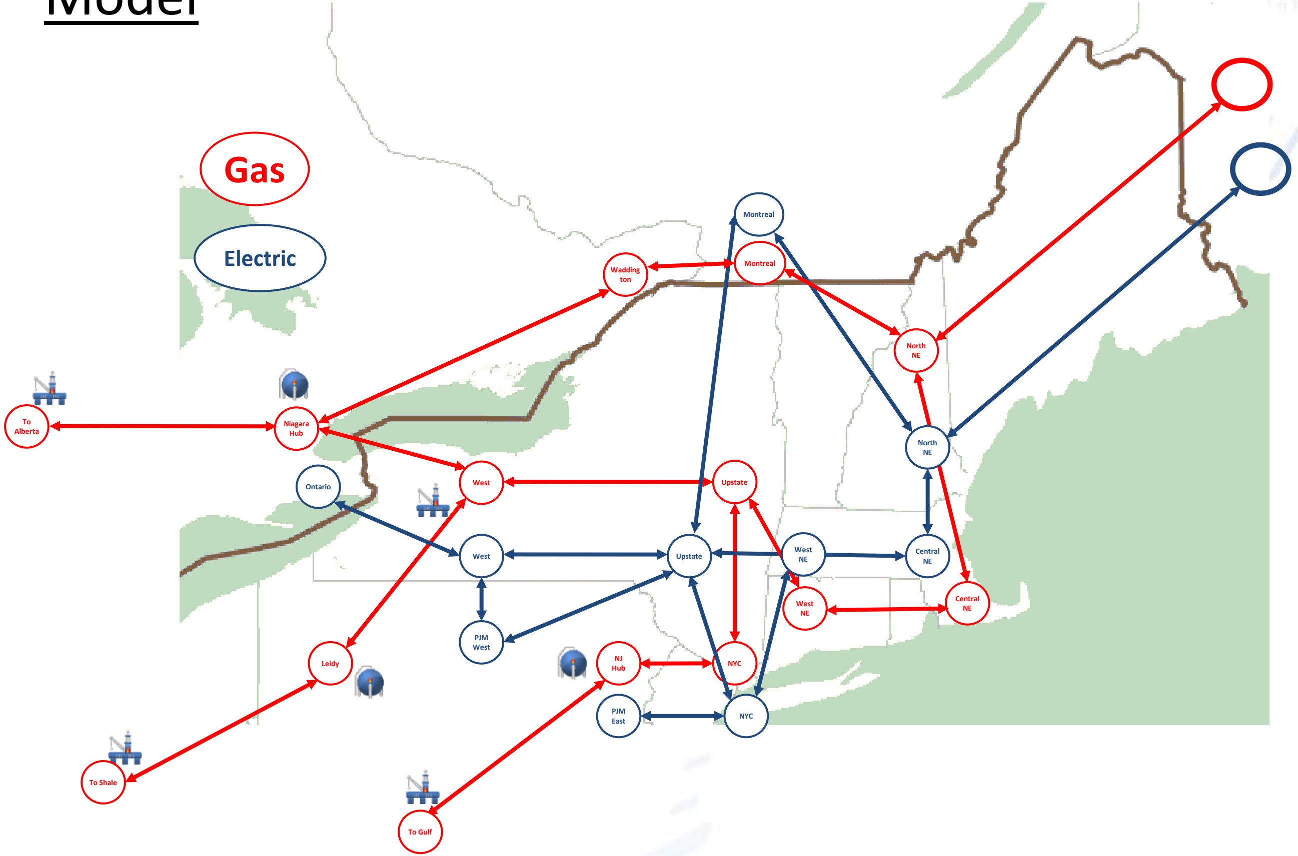


- **PLEXOS Example:**

  **Co-Optimization of Natural Gas and Electricity Markets**

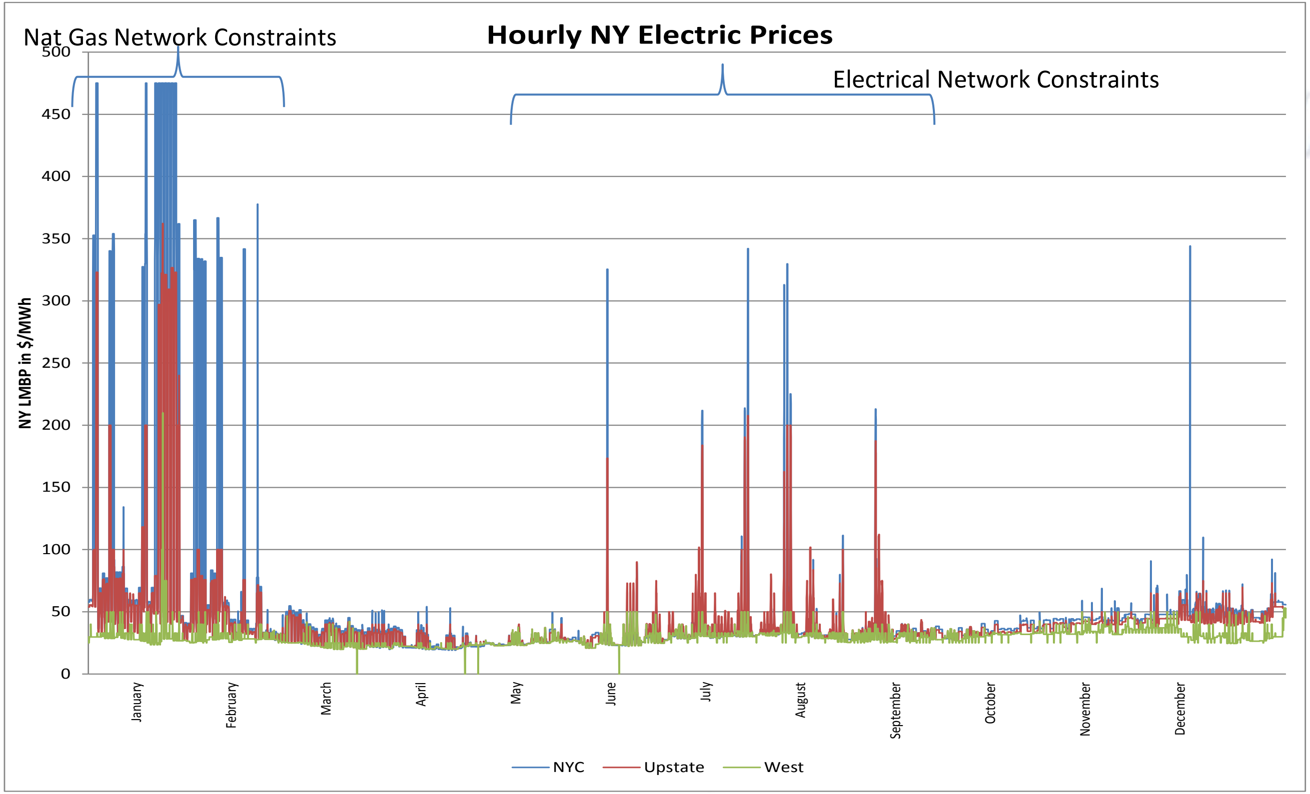
  for simplified northeast model

# ➢ Simplified Combined Electric & Natural Gas Model



# ➢ Simplified Model Results

## NY Electric LBMP



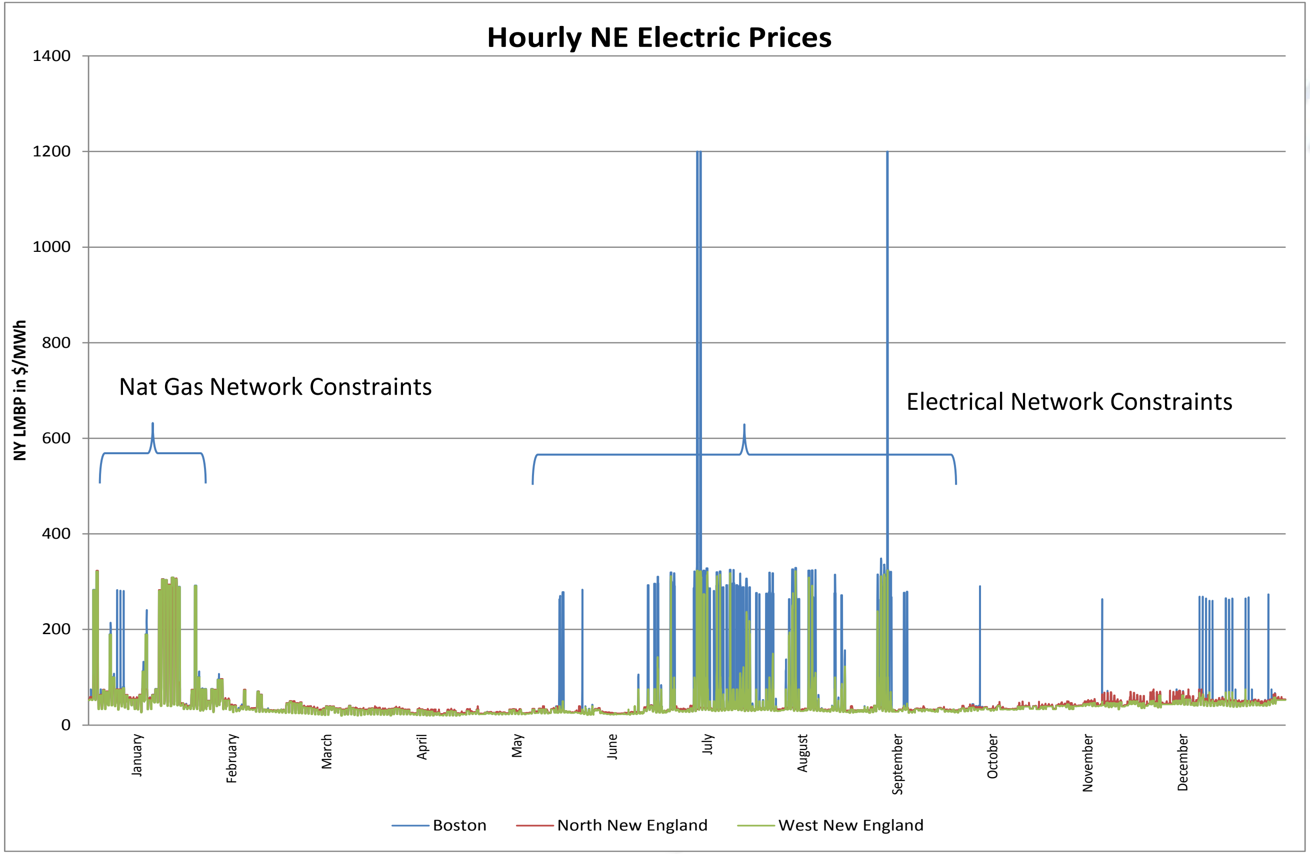

Electric Prices for

- NYC (Zones J-K);
- Upstate (Zones F-I);
- West (Zones A-E).

Prices in Winter influenced by natural gas shortages. Summer prices reflect electric constraints calculated by PLEXOS.

# ➢ Simplified Model Results

## ISONE LMP




Electric Prices for ISONE.

Prices in Winter influenced by natural gas shortages. Summer prices reflect shortages calculated by PLEXOS.

# Gas Electric Planning Process

# Planning Process

## Power Sector

- 10 Year Plans
- Stakeholder Process
- Planning Coordinators
- Integrated Resource Plans
- Modeling Workgroups
- Regional Reliability Standards
- Planning Process Cost Recovery
- Regional Operations Planning

## Natural Gas Sector

- No 10 year plans
- Stakeholder Process Pipeline to LDC
- No Planning Coordinators
- No Integrated Resource Plans
- No modeling workgroups
- No Regional Reliability Standards
- No shared cost allocation for planning pipelines
- Proposed project with open season

# Strategic Planning Gas Electric

- Cost Recovery Mechanism
- Gas Electric Planning Coordinator Function
- Stakeholder Process
- 10 year plans
- Reliability Standards
- Least Cost Multi Sector Co-Optimized Planning
- National vs. Regional
- Operational Planning

# Energy Storage

# Co-Optimization of Ancillary Services Requirements for Renewables

- Integration of the intermittency of renewables requires study of Co-Optimization of Ancillary Services and true co-optimization of Ancillary services is done on a sub-hourly basis

- More and more the last decade, it has been recognised that AS and Energy are closely coupled as the same resource and same capacity have to be used to provide multiple products when justified by economics.

- The capacity coupling for the provision of Energy and AS, calls for joint optimisation of Energy and AS.

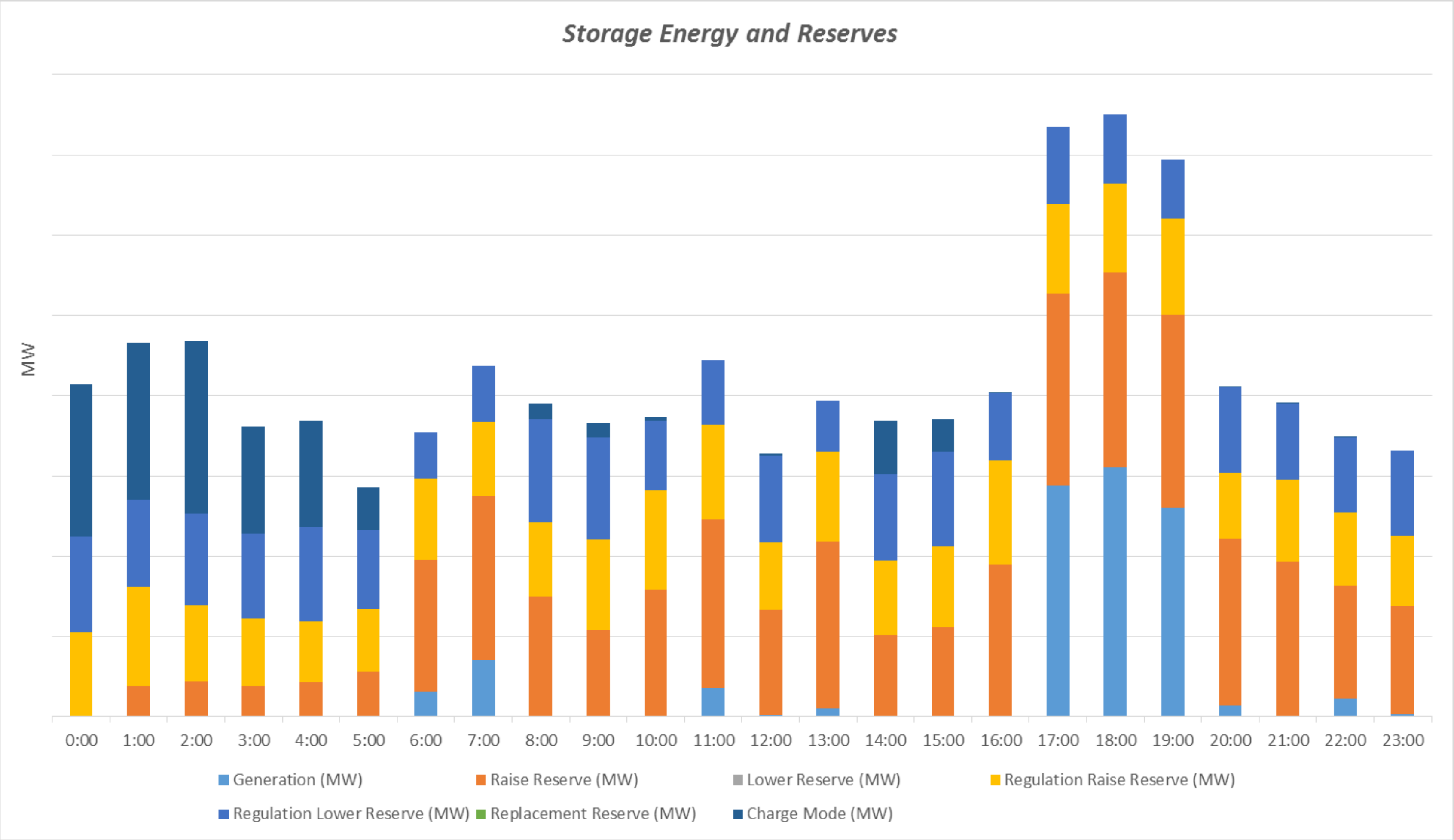
# Ancillary Services

Reliable and Secure System Operation requires the following product and Services (not exhaustive):

1. **Energy**
2. Regulation & Load Following Services – AGC/Real time maintenance of system's phase angle and balancing of supply/demand variations.
3. Synchronised Reserve – 10 min Spinning up and down
4. Non-Synchronised Reserve – 10 min up and down
5. Operating Reserve – 30 min response time
6. Voltage Support – Location Specific
7. Black Start – (Service Contracts)

- **Example:**

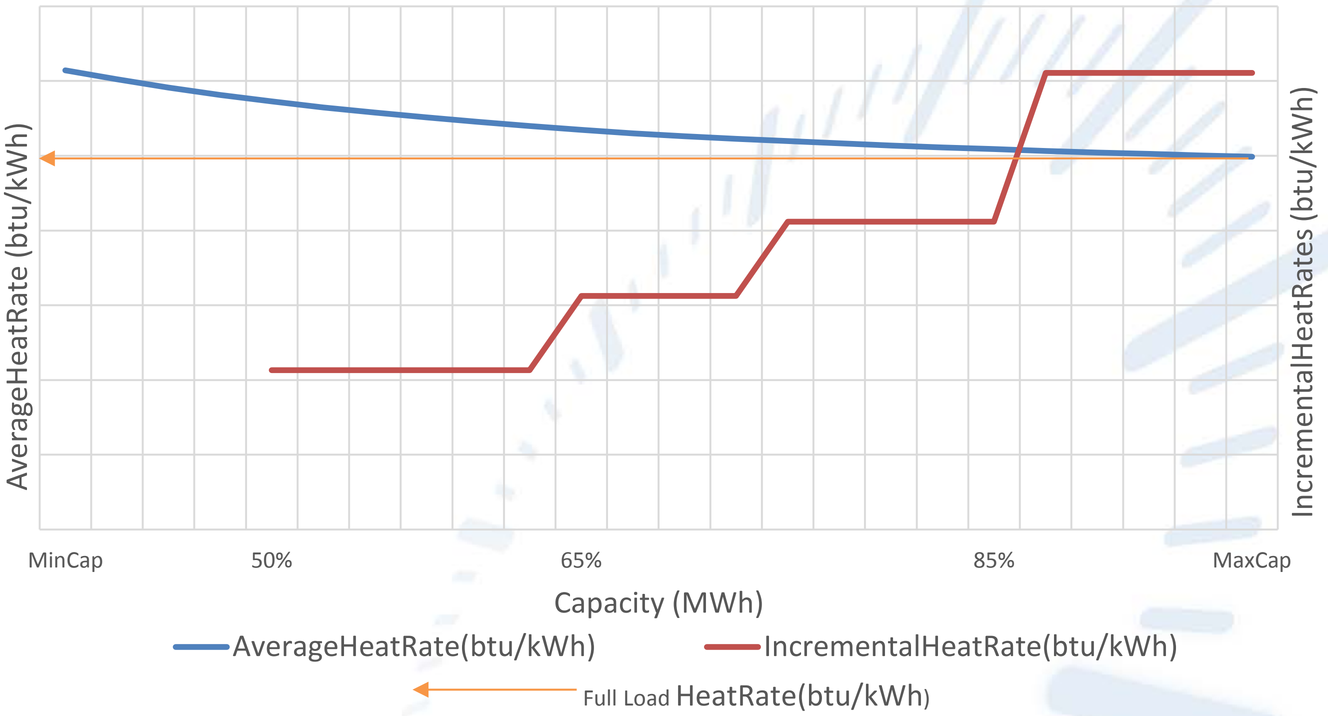
  **Co-Optimization of Ancillary Services for Energy Storage to Balance Renewables**


Storage Energy and Reserves
MW
0:00 1:00 2:00 3:00 4:00 5:00 6:00 7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00 21:00 22:00 23:00
Generation (MW)
Raise Reserve (MW)
Lower Reserve (MW)
Regulation Raise Reserve (MW)
Regulation Lower Reserve (MW)
Replacement Reserve (MW)
Charge Mode (MW)

# Gas and Coal Gen Efficiency

# Gas and Coal Gen Efficiency

System expansion for obtaining higher capacity factors leads to better over all efficiency and lower carbon intensity



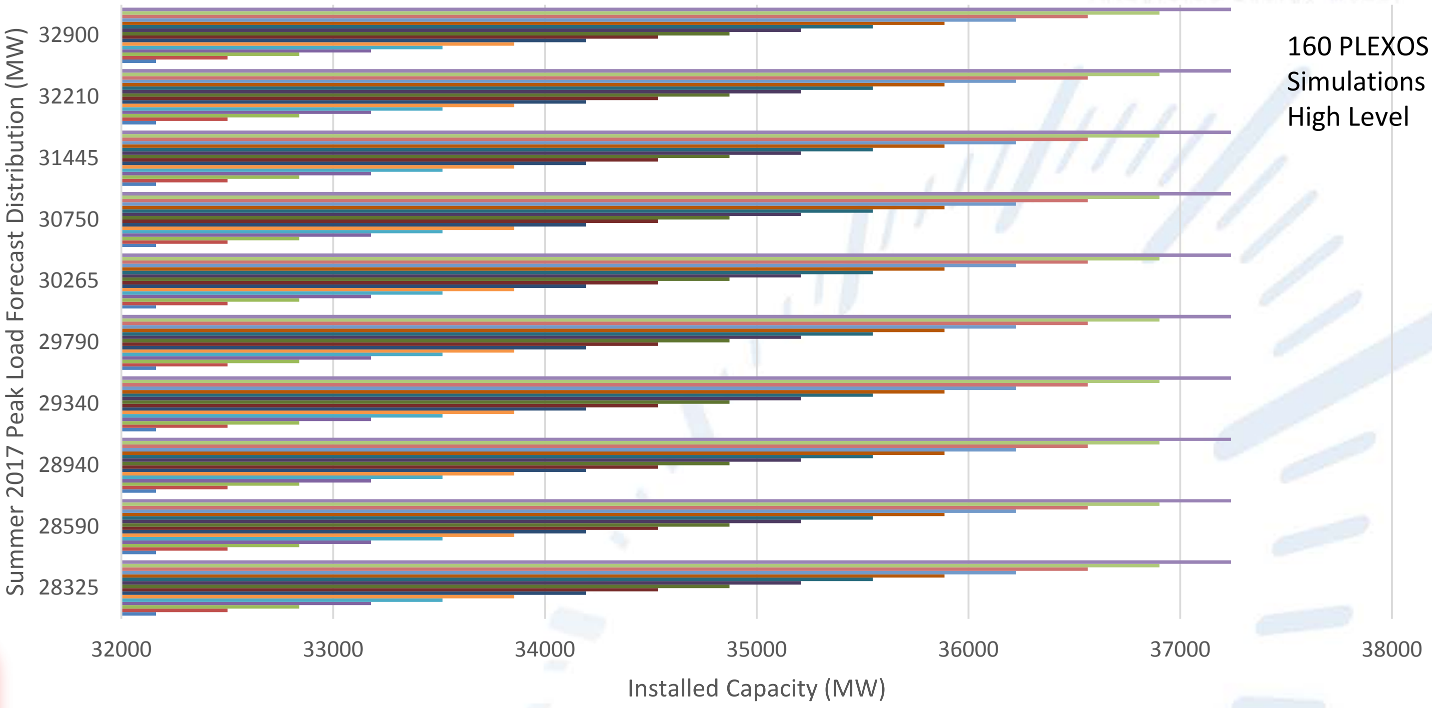
# Capacity Markets

- **Example:**

  **Consideration of Adequacy of Supply for System Expansion Planning**

# ➢ Calculated 1-in-10 LOLE

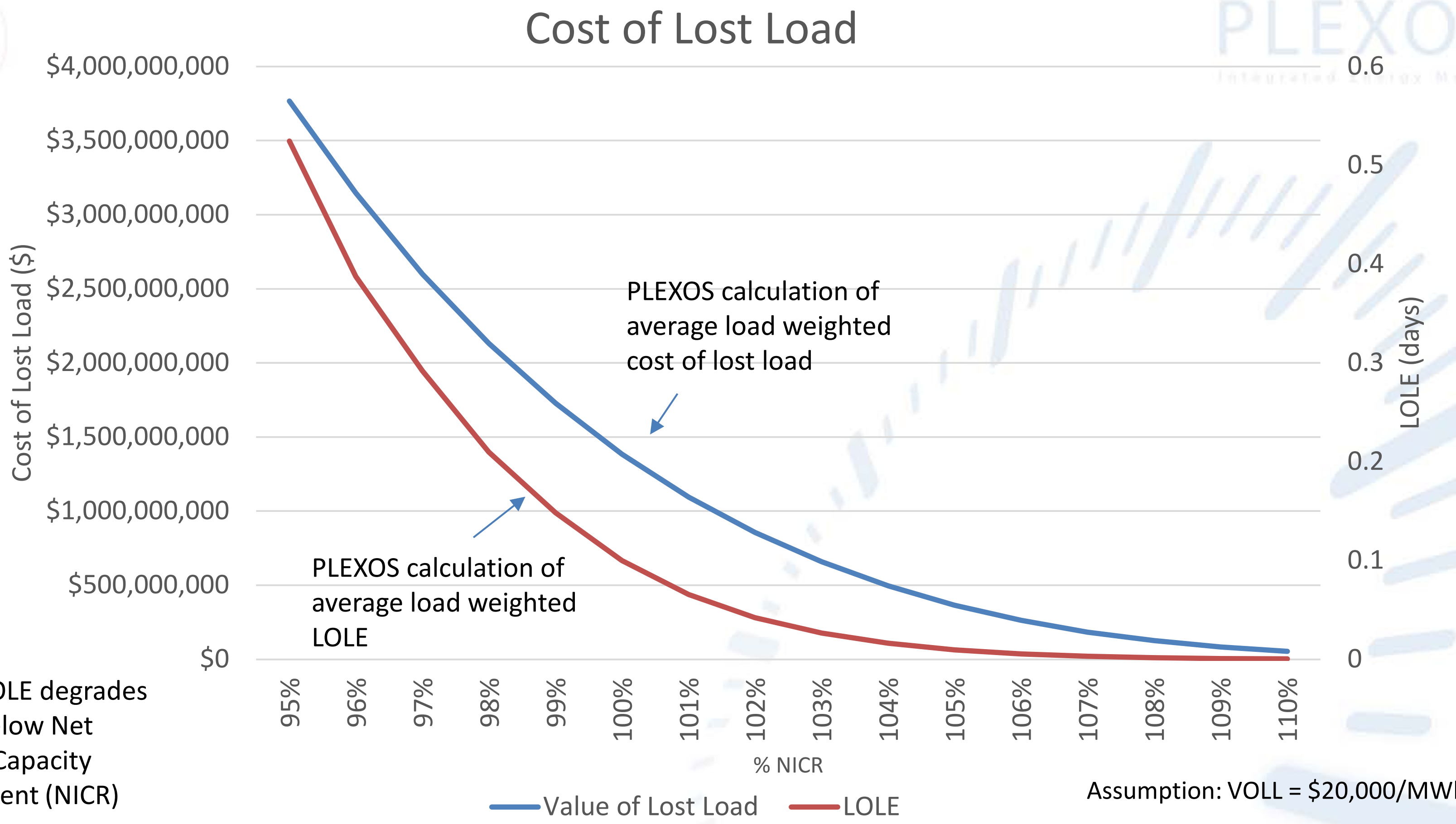
| Forecast Probability | 2017 Peak Load Forecast |
|---|---|
| 10/90 | 28,325 |
| 20/90 | 28,590 |
| 30/70 | 28,940 |
| 40/60 | 29,340 |
| 50/50 | 29,790 |
| 60/40 | 30,265 |
| 70/30 | 30,750 |
| 80/20 | 31,445 |
| 90/10 | 32,210 |
| 95/5 | 32,900 |




160 PLEXOS Simulations of High Level

Results:
NICR = 33,855 MW
LOLE ~ 0.1

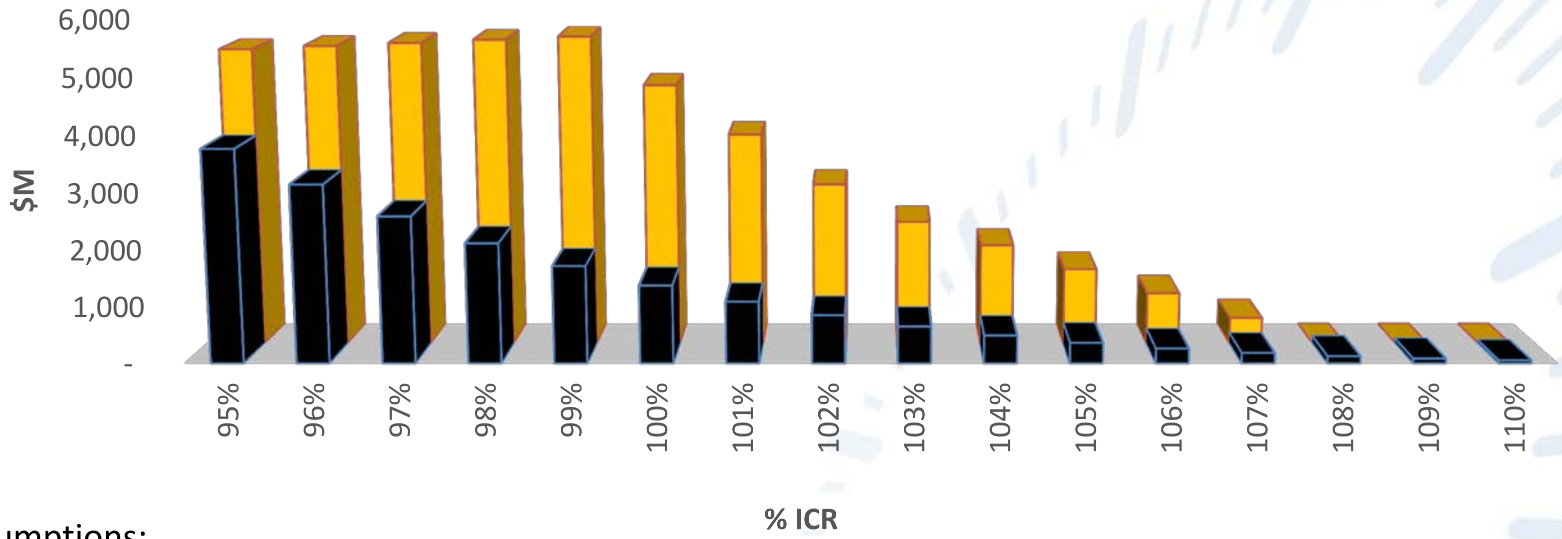
- Simulated load risk in calculating Loss of Load Expectation (LOLE)
- Simulated multiple capacity levels




- System LOLE degrades rapidly below Net Installed Capacity Requirement (NICR)

Assumption: VOLL = $20,000/MWh

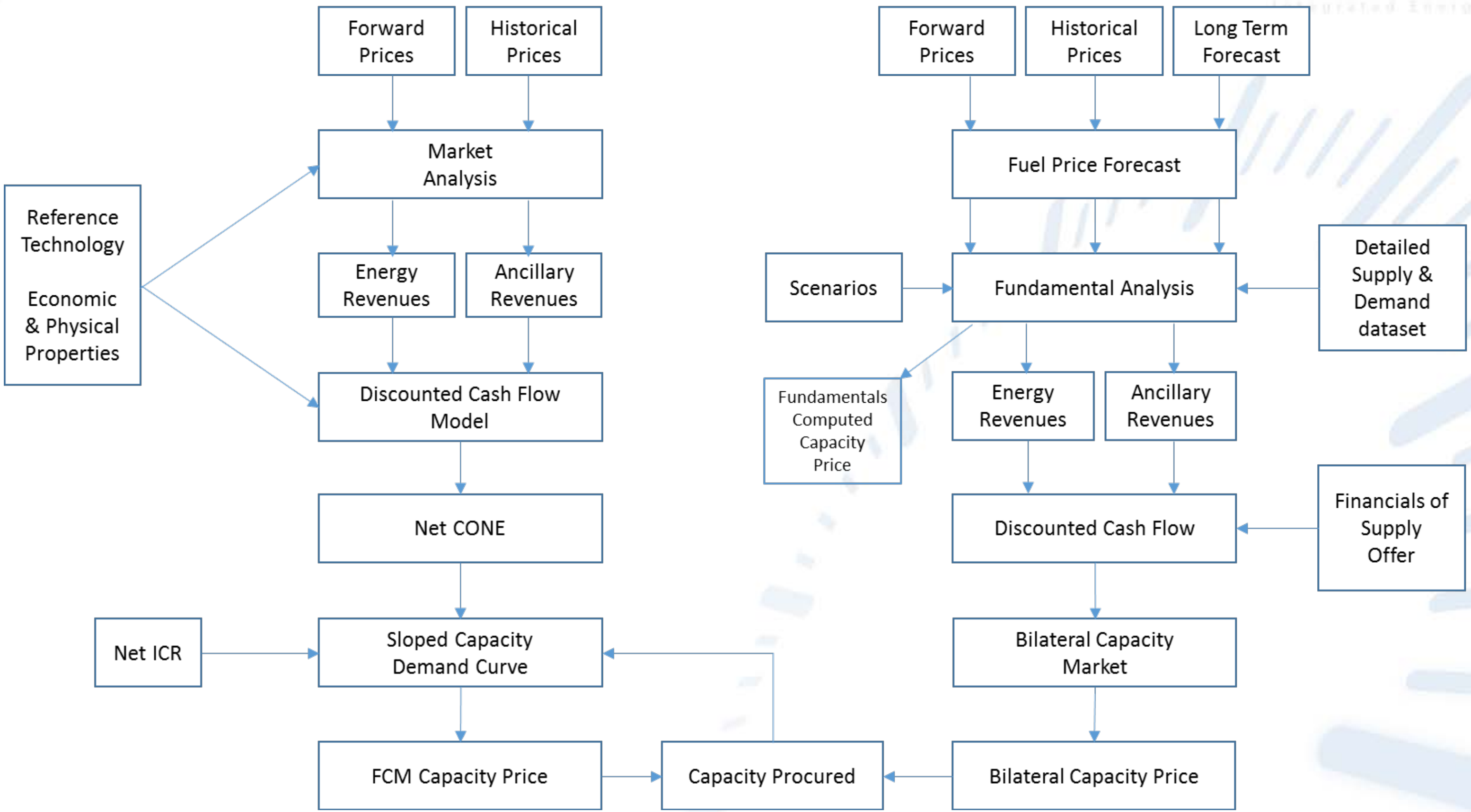
# CAPACITY MARKET COST VS. UNSERVED ENERGY COST




<u>Assumptions:</u>
Net Cone = 11.08 $/kW-m
VOLL = $20,000/MWh

# Forward Capacity Market

# Bilateral Capacity Market



# EISPC Project

# ➢ EISPC Co-Optimization Demonstration Project

- The National Association of Regulatory Utility Commissioners (NARUC) and Eastern Interconnection States' Planning Council (EISPC) have awarded Energy Exemplar a demonstration project with PLEXOS® for the Co-Optimization of Transmission with other Resources. This demonstration study is a proof of concept to test the efficacy of co-optimizing investments and planning of transmission with other resources. EISPC believes co-optimization has the potential for advancing the state-of-the-art in planning processes to enhance the resource planning analysis.

- EISPC is a council of 39 US State Regulatory Jurisdictions and 8 Canadian Provinces

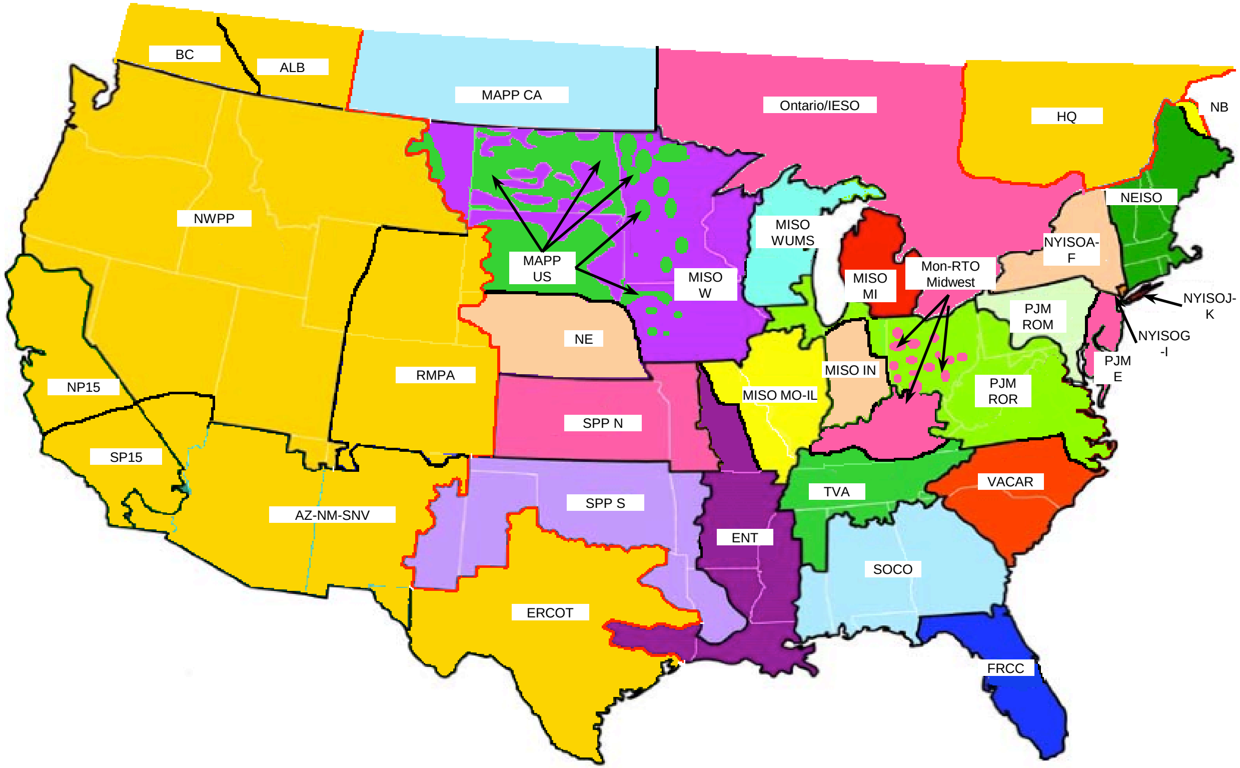
- The demonstration project has three primary tasks:

  Task 1: Evaluation of co-optimization of transmission and other resources.

  Task 2: Evaluation of co-optimization of transmission with generation and at least one of the following: demand response or energy storage.

  Task 3: Evaluation of co-optimization techniques to address electric and natural gas operational and planning issues.

# EIPC Map




Replicated in PLEXOS

# ➢ Team

- Energy Exemplar, the developer of PLEXOS® Integrated Energy Model, has joined with Johns Hopkins and Iowa State Universities to demonstrate the current tools available for the co-optimization of transmission and other resources to NARUC and EISPC.

- In additional to this team of professionals and researchers in co-optimization of energy resources, the following parties have joined the team as collaborators for this EISPC demonstration project:

- Midcontinent Independent System Operator (MISO);
- Independent System Operator of New England (ISO-NE); and
- Oak Ridge National Laboratory.

# Key Feature Demonstrations

**Co-Optimization of Transmission and other Resources**

- Transmission Expansion and Generation Expansion
- Retirement Logic
- RPS Constraints
- DSM
- Energy Storage
- Carbon Price Influencing Build/Retire Decisions
- Max and Min Reserve Margins

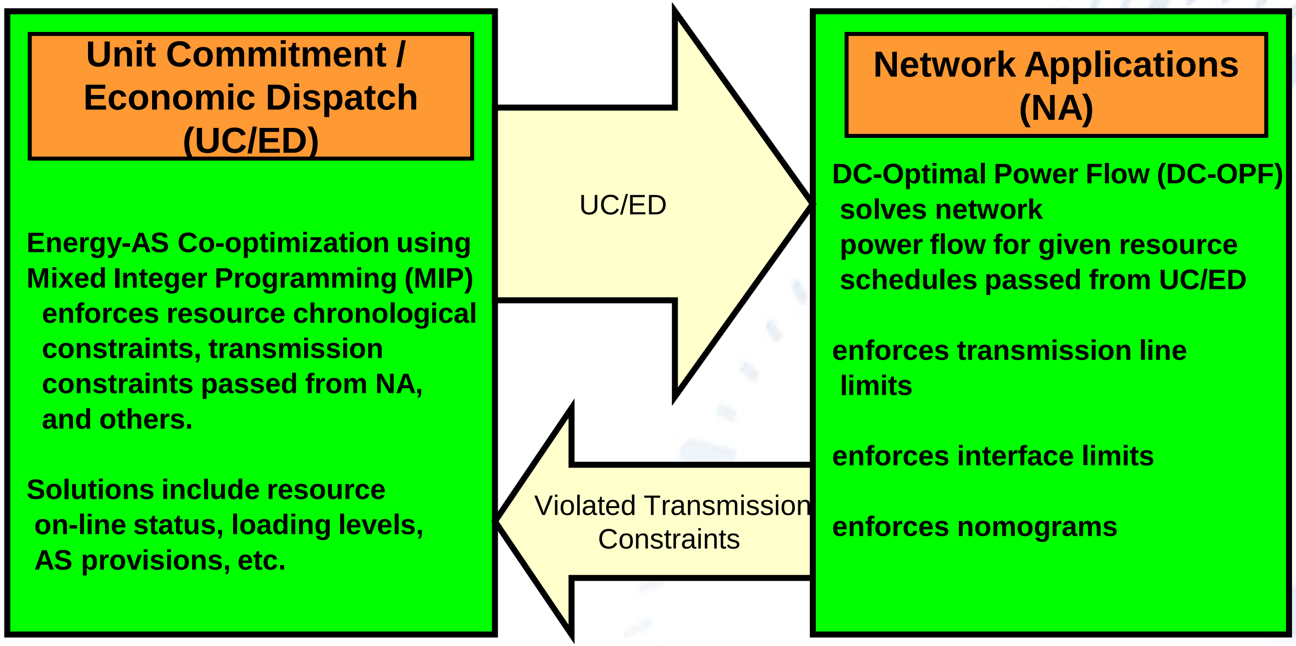
**Co-Optimization of Electric and Gas Sectors**

- Co-Optimization of Production cost of Gas and Electric
- Co-Optimized Expansion of Gas and Electric Networks

# Example
# Co-Optimization of Transmission and Other Resources

# Security Constrained Unit Commit /Economic Dispatch

- SCUC / ED consists of two applications: UC/ED and Network Applications (NA)
- SCUC / ED is used in many power markets in the world include CAISO, MISO, PJM, etc.



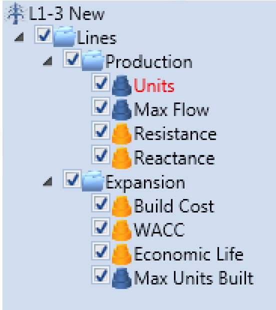
# ➢ Simple Example: G&T Co-Optimization

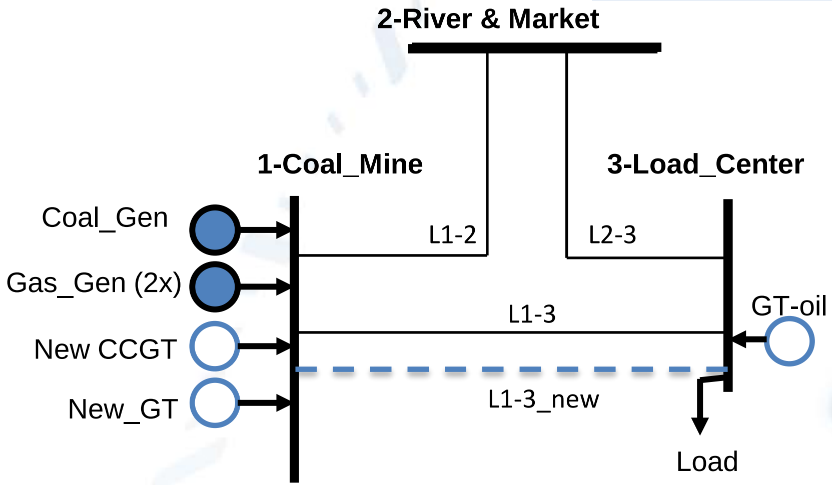
Intermediate/advanced exercises:

1. Create a locational model by defining new GT (operating on Oil) candidate close to the load.
2. Solve the trade-off expansion problem of building Oil-fired GT or reinforcing the transmission system (building a second circuit L1-3 at 10 Million $$). WACC = 12% and Economic Life Year = 30, not earlier than 1/1/2015

Enable following Line expansion properties:

| Line | Max Flow (MW) |
|---|---|
| L1-2 | 500 |
| L2-3 | 500 |
| L1-3 | 500 |



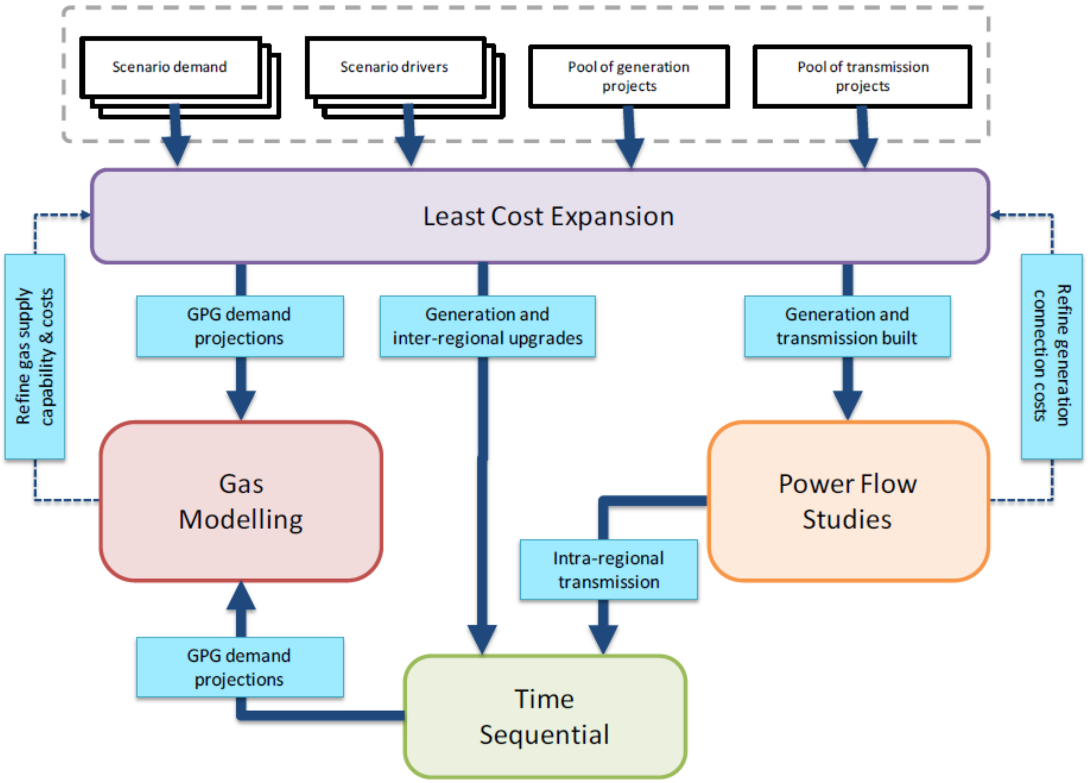



# ➢ Generation and Transmission Expansion Results

Generation Expansion

Transmission Expansion


# ➢ Australian ISO Use of PLEXOS of Co-Optimization of Generation and Transmission in planning



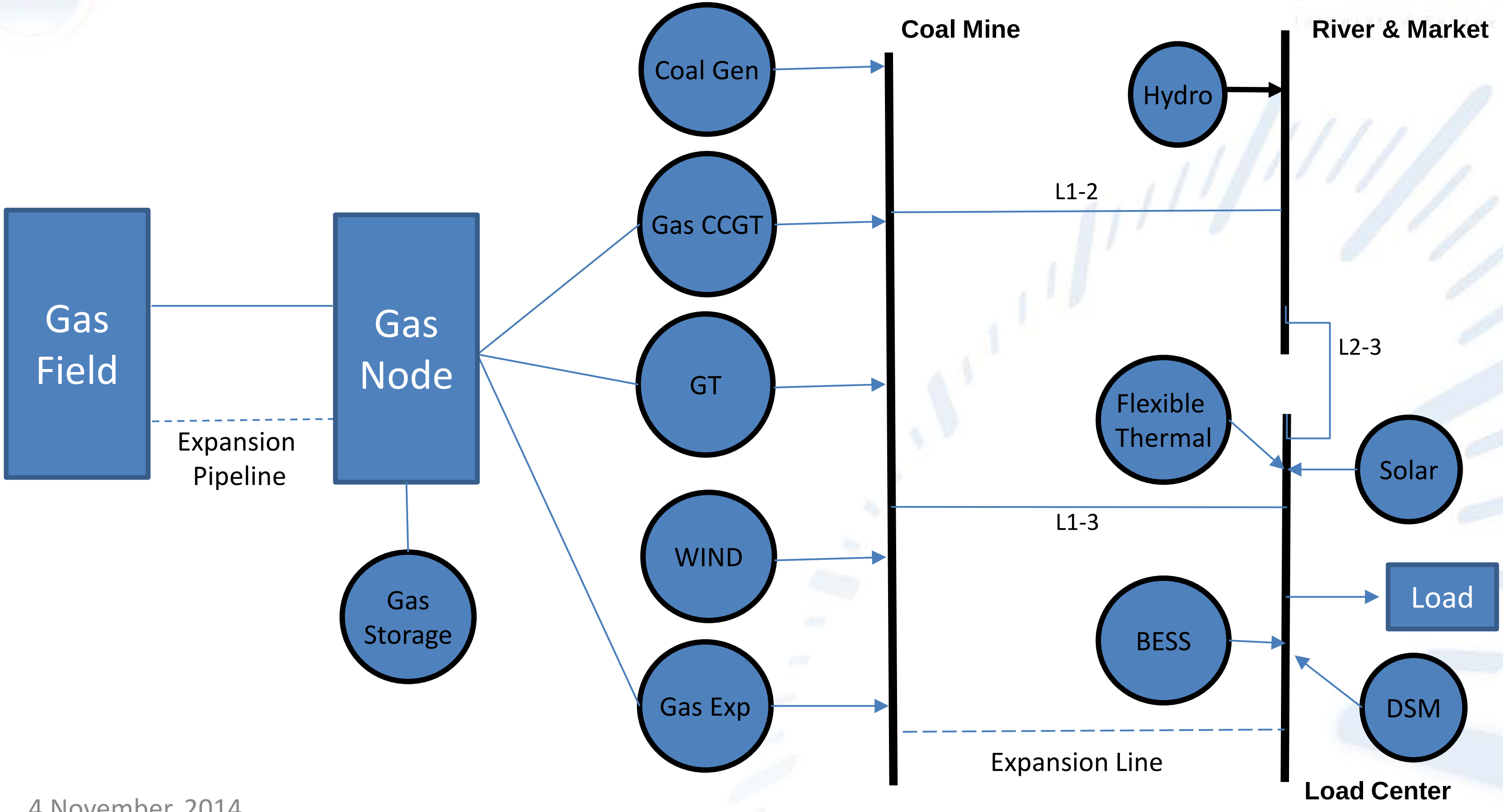

Least-cost expansion modelling delivers a co-optimized set of new generation developments, inter-regional transmission network augmentations, and generation retirements across the NEM over a given period. This provides an indication of the optimal combination of technology, location, timing, and capacity of future generation and inter-regional transmission developments.
The least-cost expansion algorithm invests in and retires generation to minimize combined capital and operating-cost expenses across the NEM system.

This optimization is subject to satisfying:

- The energy balance constraint, ensuring supply matches demand for electricity at any time,
- The capacity constraint, ensuring sufficient generation is built to meet peak demand with the largest generating unit out of service, and
- The Large-Scale Renewable Energy Target (LRET) constraint, which mandates an annual level of generation to be sourced from renewable resources.

# EISPC Co-Optimization Features Demonstrations

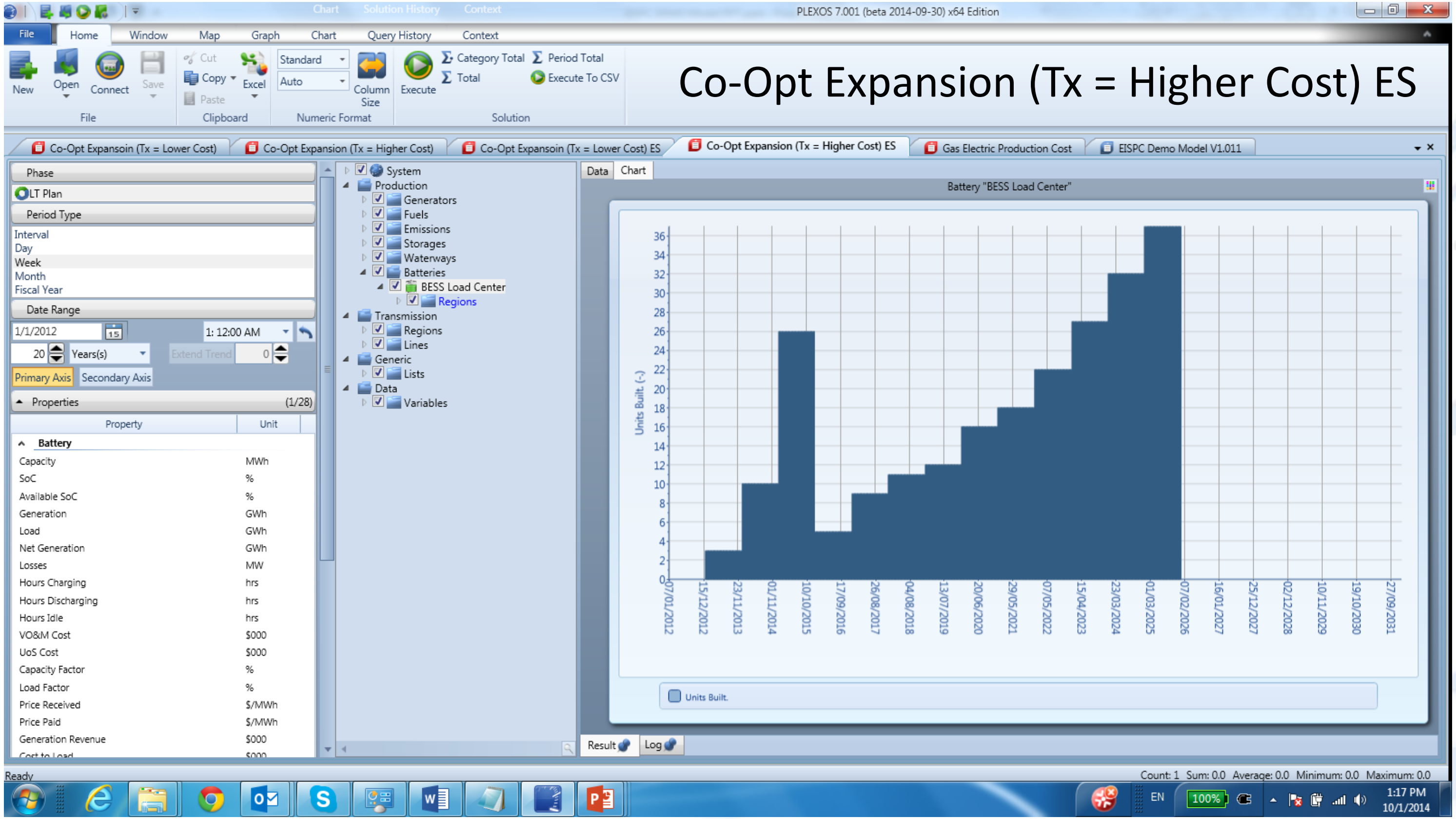
# ➢ Multiple Co-Optimizations Demonstration PLEXOS® Model



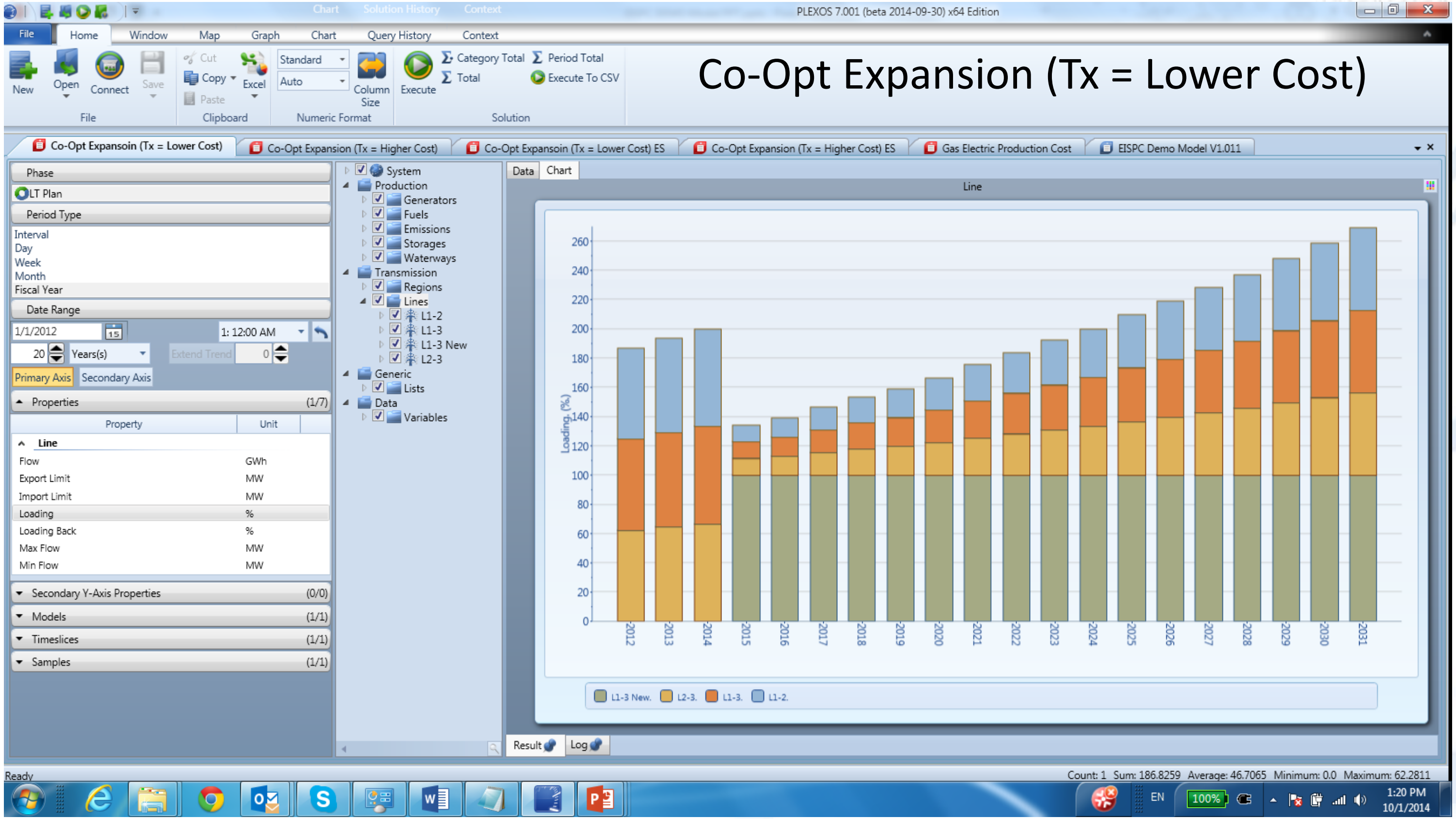
# ➢ Demonstration Models

| Model | Demonstration |
|---|---|
| Task 1: | 20 Year Horizon – First 10 Years Results |
| Co-Opt Expansion (Tx = Higher Cost) | Builds local resources at demand center |
| Co-Opt Expansion (Tx = Lower Cost) | Builds remote resources and expands transmission |
| Task 2: | |
| Co-Opt Expansion (Tx = Higher Cost) ES | Builds local resources and expands batteries at load center |
| Co-Opt Expansion (Tx = Lower Cost) ES | Builds remote resources and expands transmission and ads local batteries |
| Task 3: | |
| Co-Opt Gas Electric Production Cost | Co-Optimizes gas electric production cost |
| Co-Opt Gas Electric Capacity Expansion | TBD |

# BESS Expansion during Co-Optimization of Transmission and other Resources



# ➢ Simultaneous Transmission and Generation Expansion

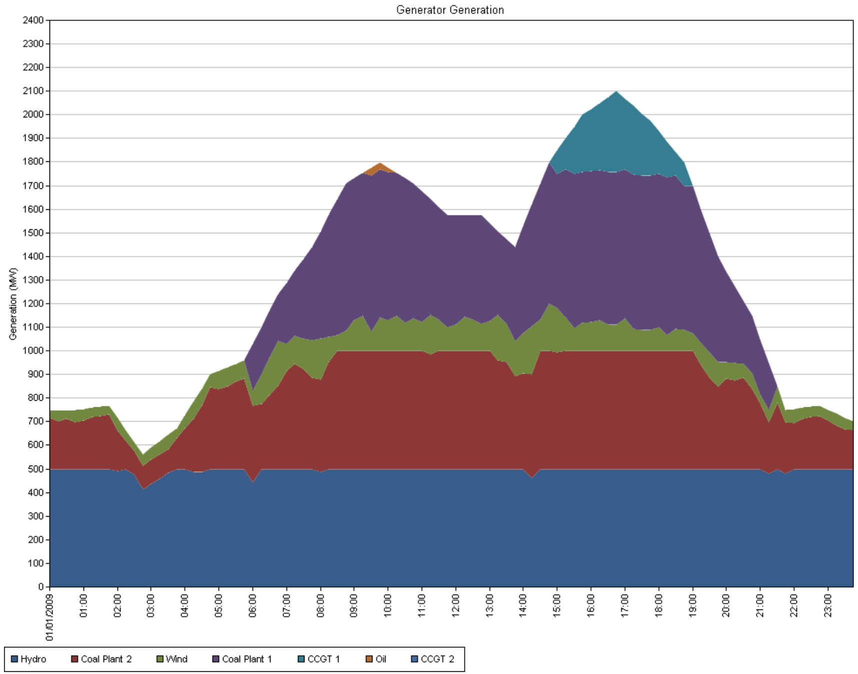


# Stochastic Optimizations

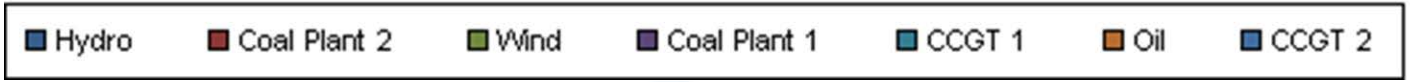
- **PLEXOS Example:**

  **Sub-Hourly Energy and Ancillary Services Co-Optimization**

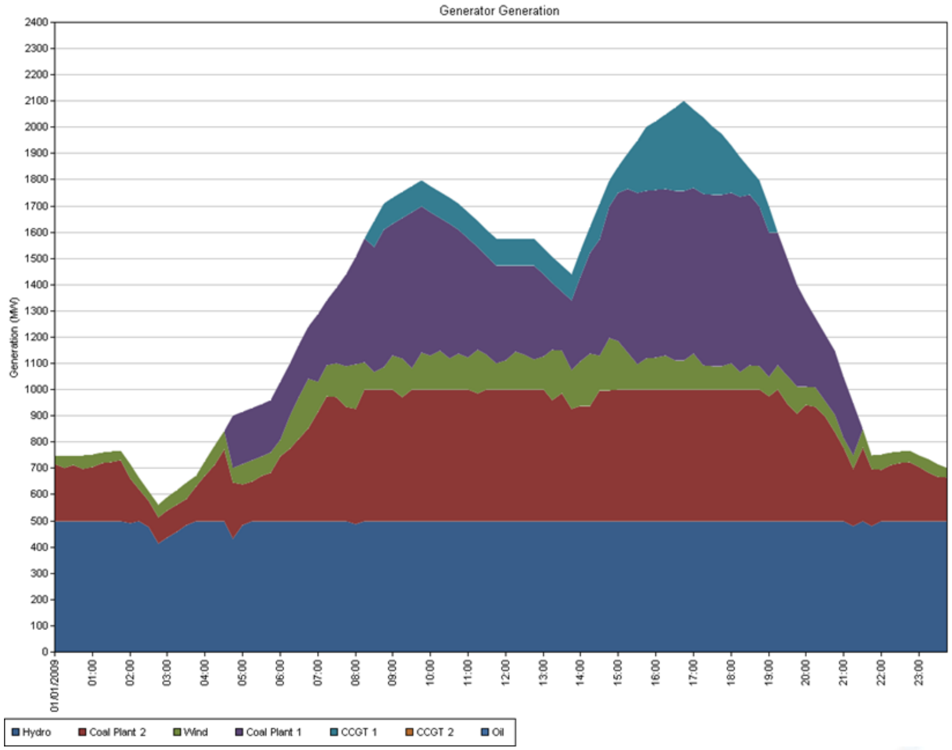
# PLEXOS Base Model Generation Result




- Peaking plant in orange operating at morning peak
- Some displacement of hydro to allow for ramping
- Variable wind in green

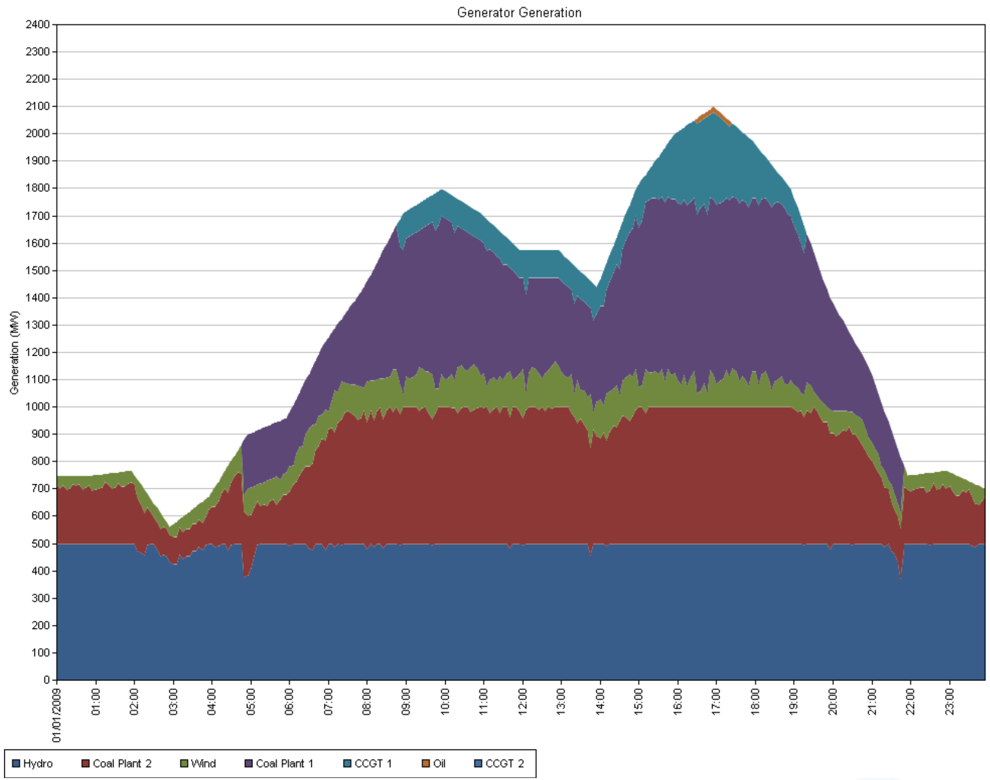


# Spinning Reserve Requirement




- CCGT now runs all day to cover reserves and energy
- Coal plant 2 also online longer
- Oil unit not required
- Less displacement of hydro generation for ramping

# ➢ PLEXOS higher resolution dispatch – 5 Minute Sub-Hourly Simulation




- Oil unit required at peak for increased variability
- Increased displacement of base load to cover for ramping constraints

## ➢ Energy/AS Stochastic Co-optimisation!!!

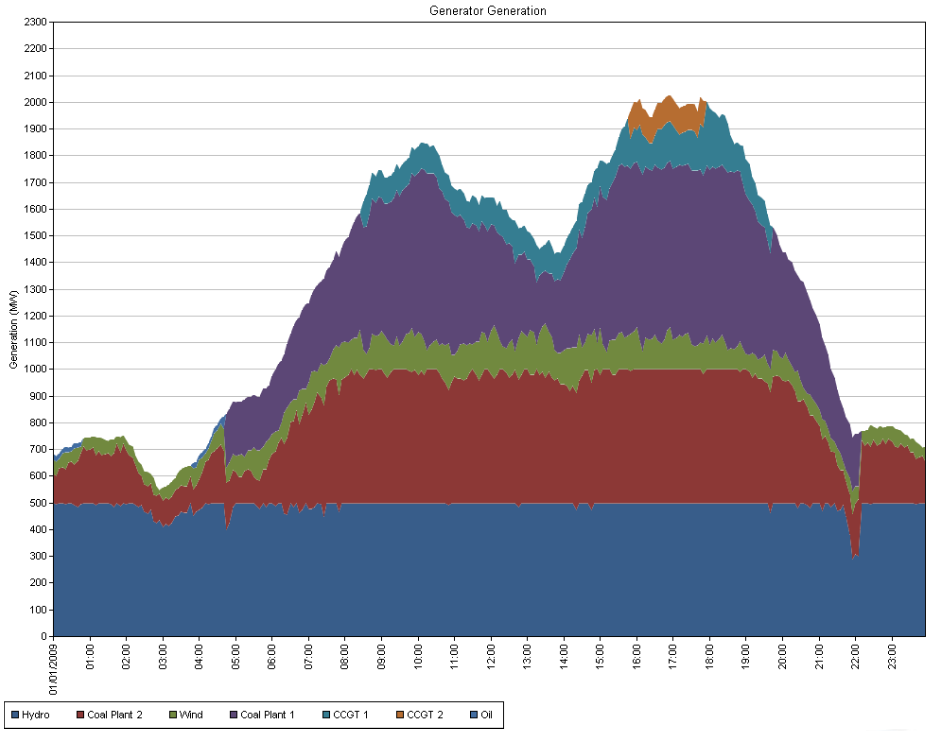
So far the model example has had perfect information on future wind and load requirements.

Uncertainty in our model inputs should affect our decisions – Stochastic optimisation (SO)

- The goal of SO then is to find some policy that is feasible for all (or almost all) the possible data instances and maximise the expectation of some function of the decisions and the random variables

**What decision should I make now given the uncertainty in the inputs?**

# ➢ Energy/AS Stochastic Co-optimisation




- Even though load lower (wind unchanged) more units must be committed to cover the possibility of high load and low wind
- These units must then operate at or above Minimum Stable Level