A Unit Commitment Assessment of Compressed Air Energy Storage in Texas' Electricity Market

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WHAT STARTS HERE CHANGES THE WORLD

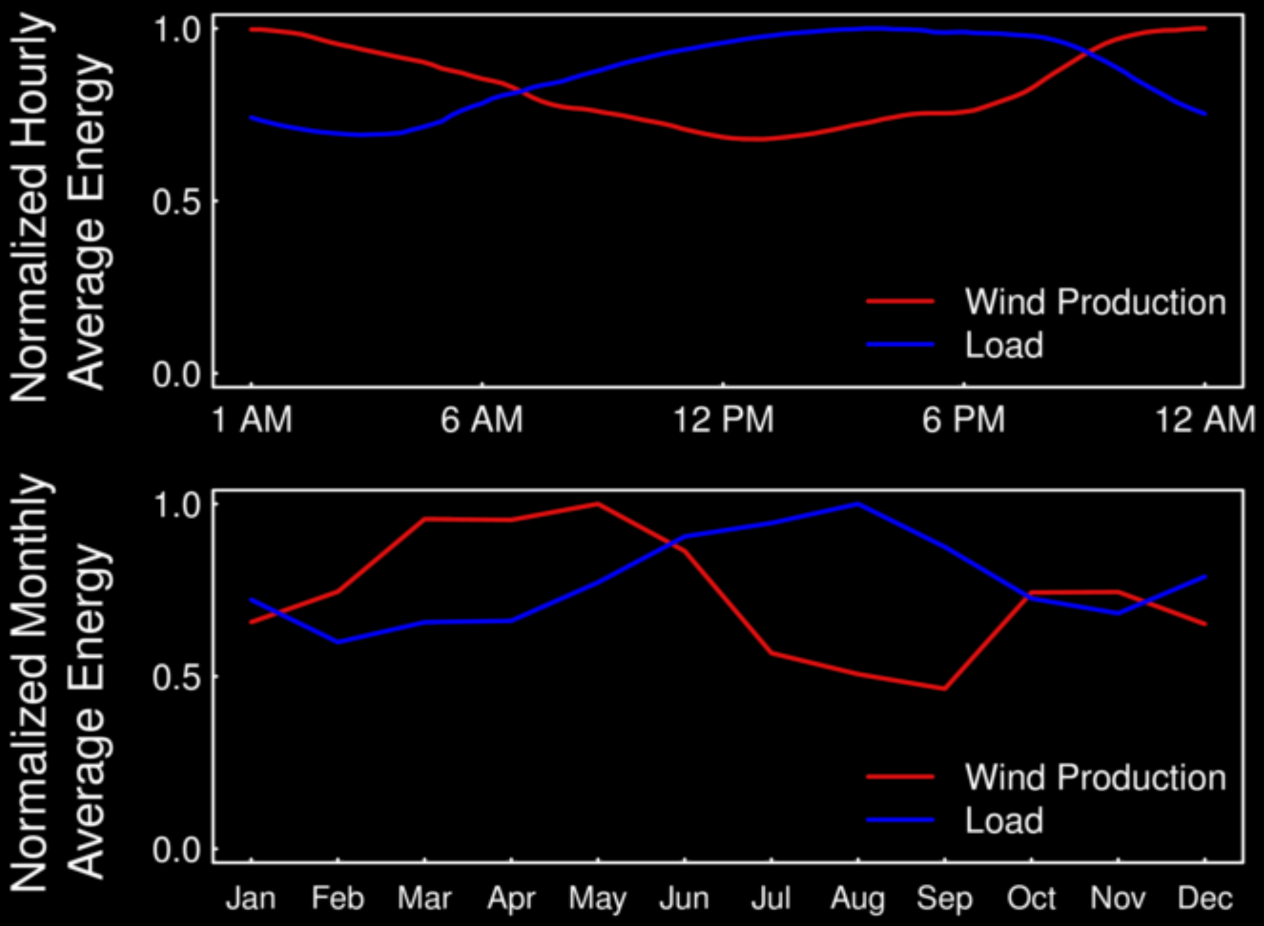
Key research findings

- High wind penetration leads to more dynamic electricity market prices
- Impacts of higher wind volatility are non-linear and become more intense
- CAES was utilized extensively and has a promising economic outlook

This work involves some specialized language and acronyms

- Comment on vocabulary
  - Ancillary services (RegUp, RegDn, RRS, NSRS)
  - Electricity demand/Load
  - Net Load = Load – Wind Generation
  - Wind variability/volatility
- Comment on acronyms
  - ERCOT, CAES, UC&D, NG
- Not all analyses and results are in this presentation

Output from wind turbines does not correlate well with demand



(data from ERCOT 2013)

Energy storage technologies that add flexibility can help compensate for renewables

- Pumped Hydroelectric Storage (PHS)
- Thermal Energy Storage (TES) & Ice/Cold Water Storage
- Compressed Air Energy Storage (CAES)
- Other Storage Options
  - Conventional batteries & flow cell batteries
  - Flywheels
  - Synthesized fuels (hydrogen, etc)
  - Ultracapacitors

Must consider application

To be economical, storage might have to provide a bundle of services

- Arbitrage
- Reserves (primary, secondary, tertiary)
- Voltage support
- Transmission congestion relief
- Transmission investment deferral
- Demand shifting/peak reduction
- Integrating variable resources
- Capacity firming
- Off grid reliability
- Customer side
  - Demand charge reduction
  - Power quality
  - Backup power
  - Bill reduction

Only services with direct revenues

How can we capture more of the values of storage??

State of Energy Storage Literature

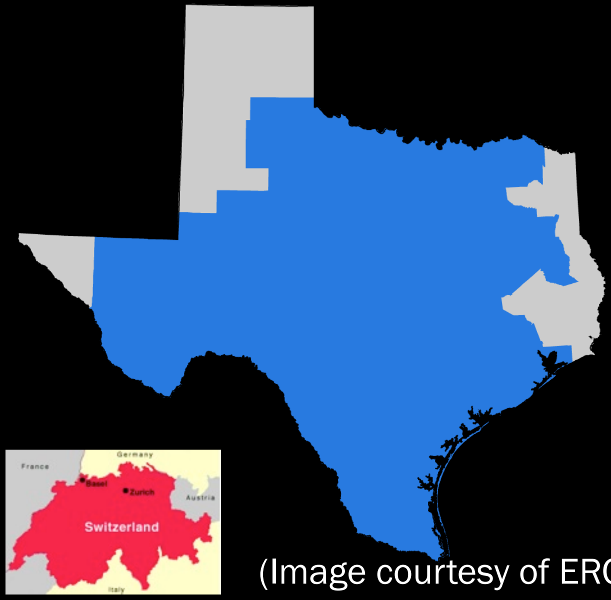
- Existing Studies:
  - Benefits of storage coupled with wind/solar
  - Historical economic feasibility of storage
- Lack of models that include energy storage in dispatch optimization
- Unknown:
  - Impact on the generating fleet, market operation, and environment of
    - Future wind penetration and variability
    - Deployment of energy storage systems
  - Economic feasibility of modern CAES systems

My work aims to fill these gaps

Background

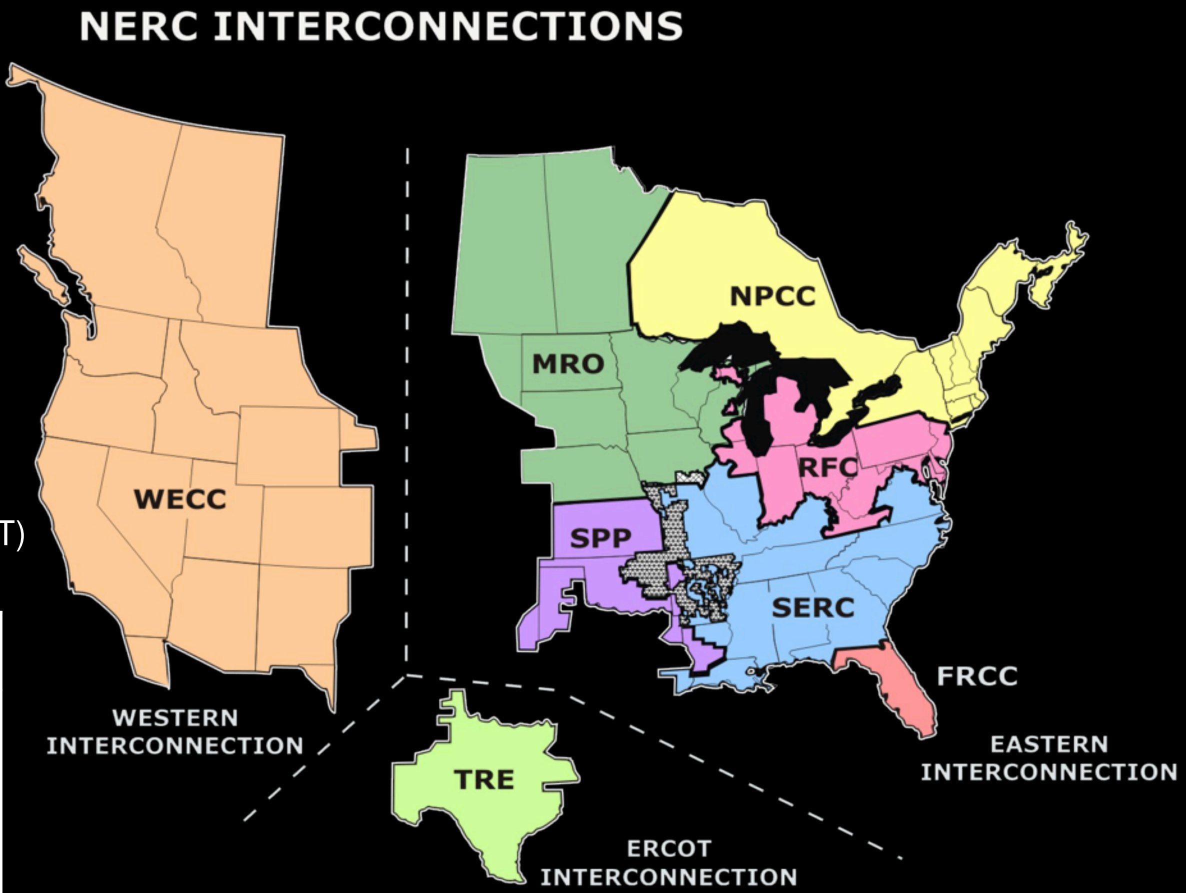
Introduction to Texas' Electric Grid (ERCOT), Wind Power, CAES, UC&D models

ERCOT is one of three independent electric grids in the US



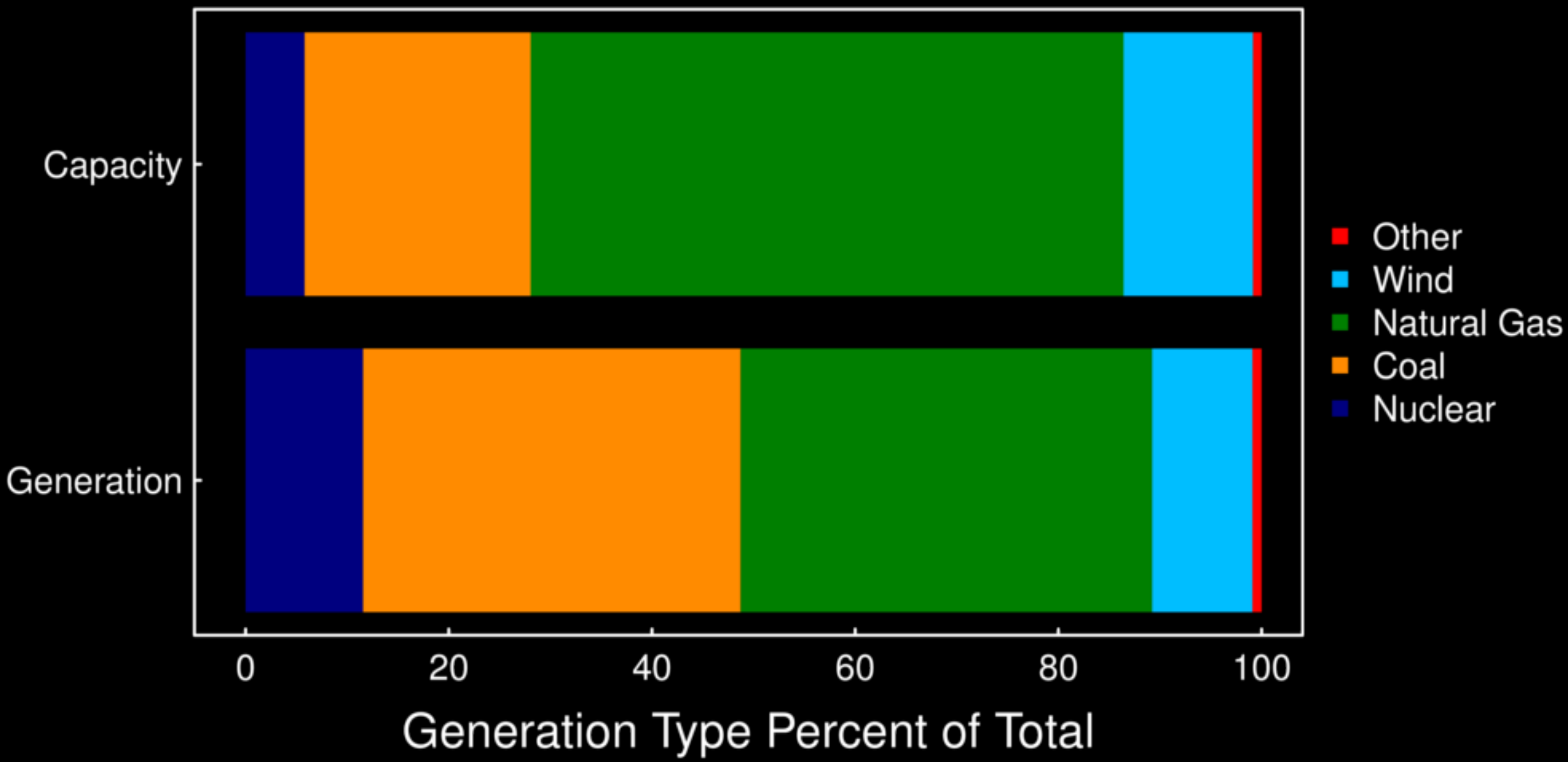
(Image courtesy of ERCOT)

	ERCOT	Switzerland
Size (km^2)	518,000	41,300
Pop (million)	22	8
Peak Load (GW)	68	10



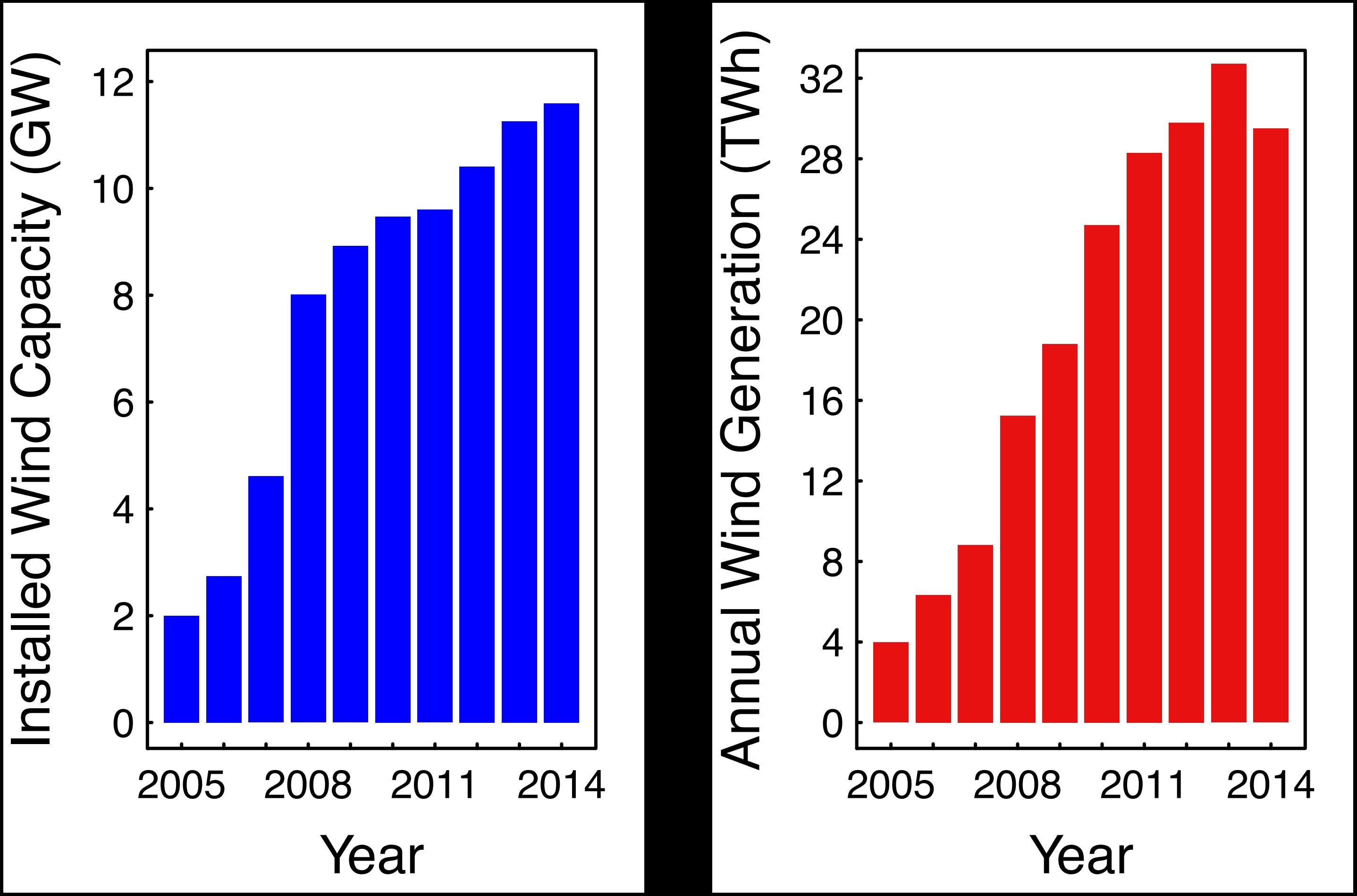
(Image courtesy of NERC)

ERCOT's fuel mix is diverse but heavy on natural gas

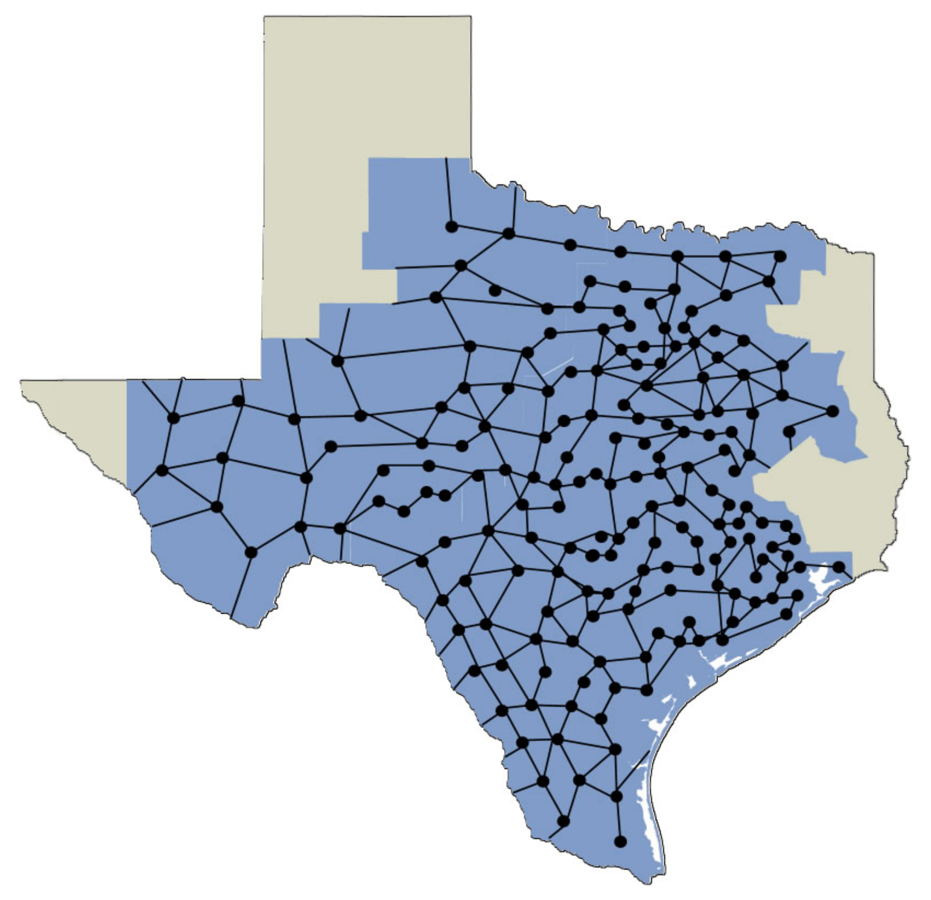


(ERCOT 2013)

Wind energy in ERCOT has grown rapidly over the past decade



ERCOT utilizes and energy only nodal market design



(Image courtesy of ERCOT)

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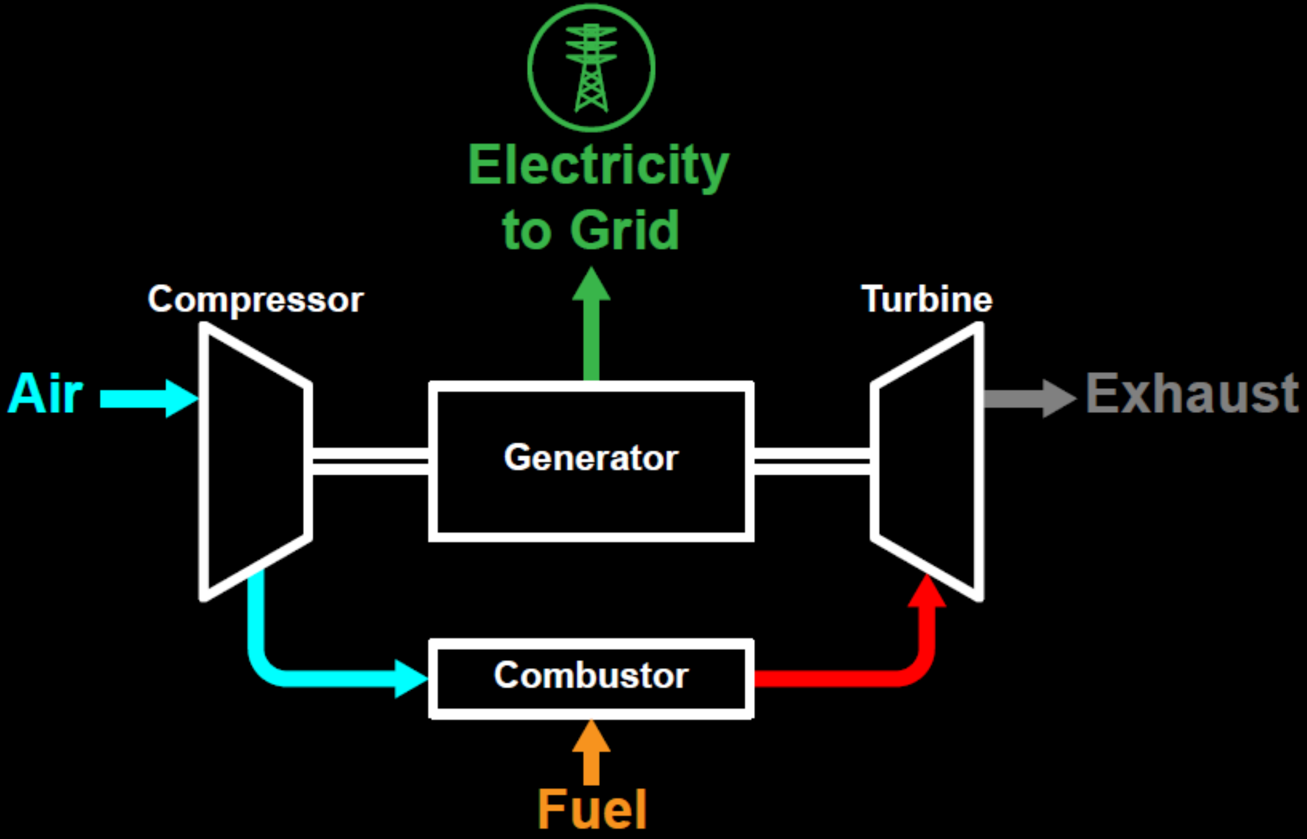
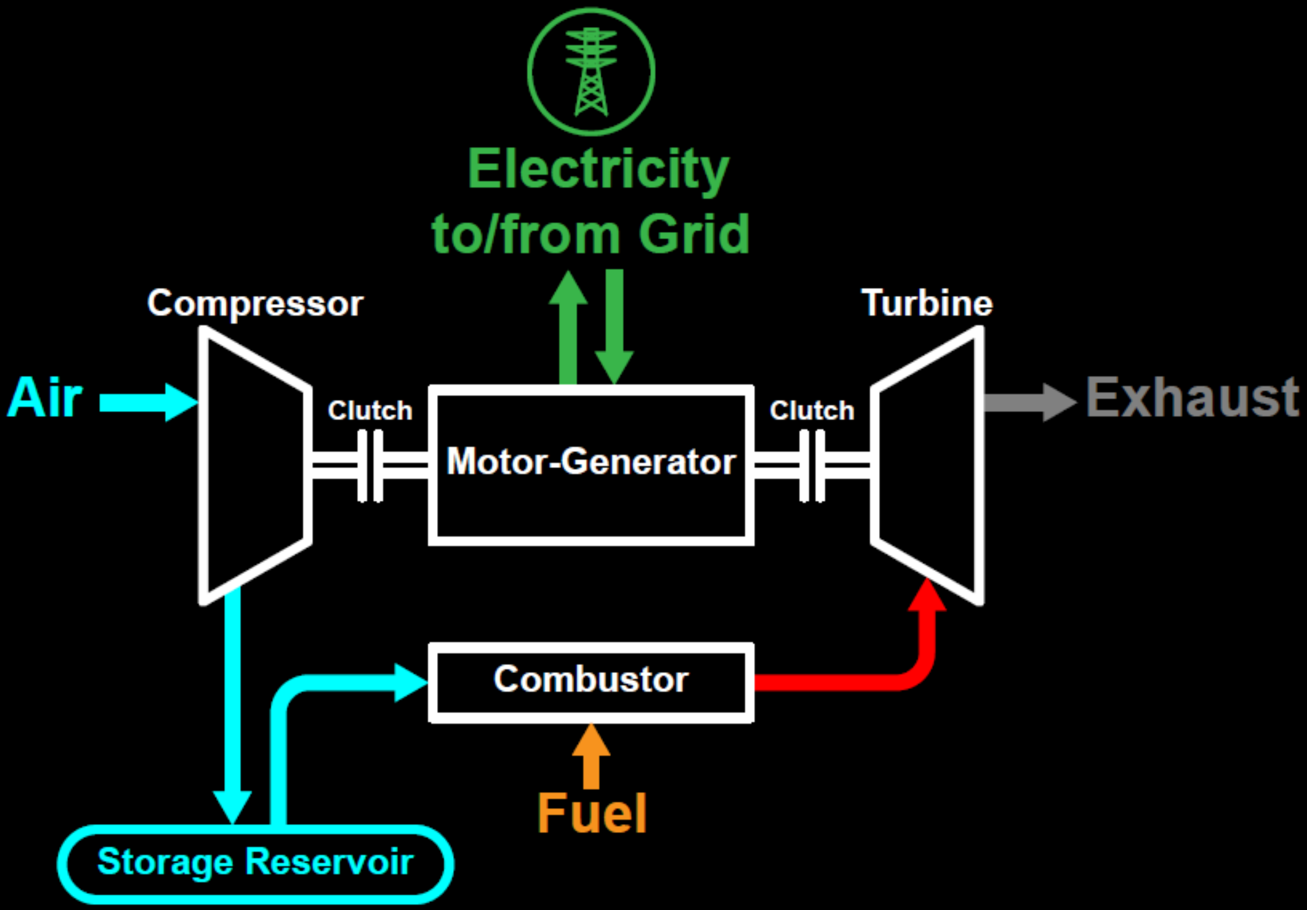
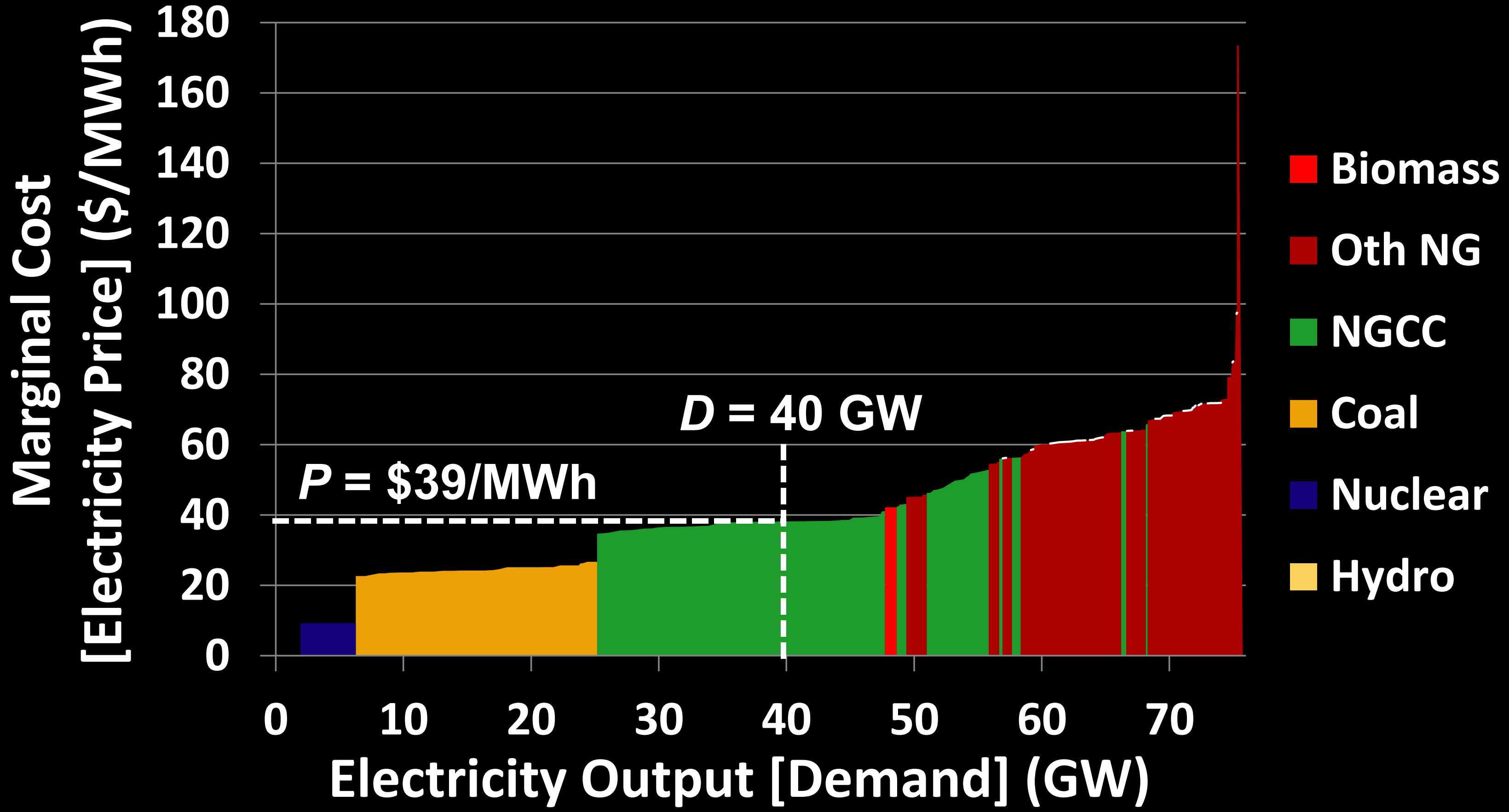
A gas turbine uses a common shaft for the compressor, turbine, and generator



A CAES compressor and turbine operate independently



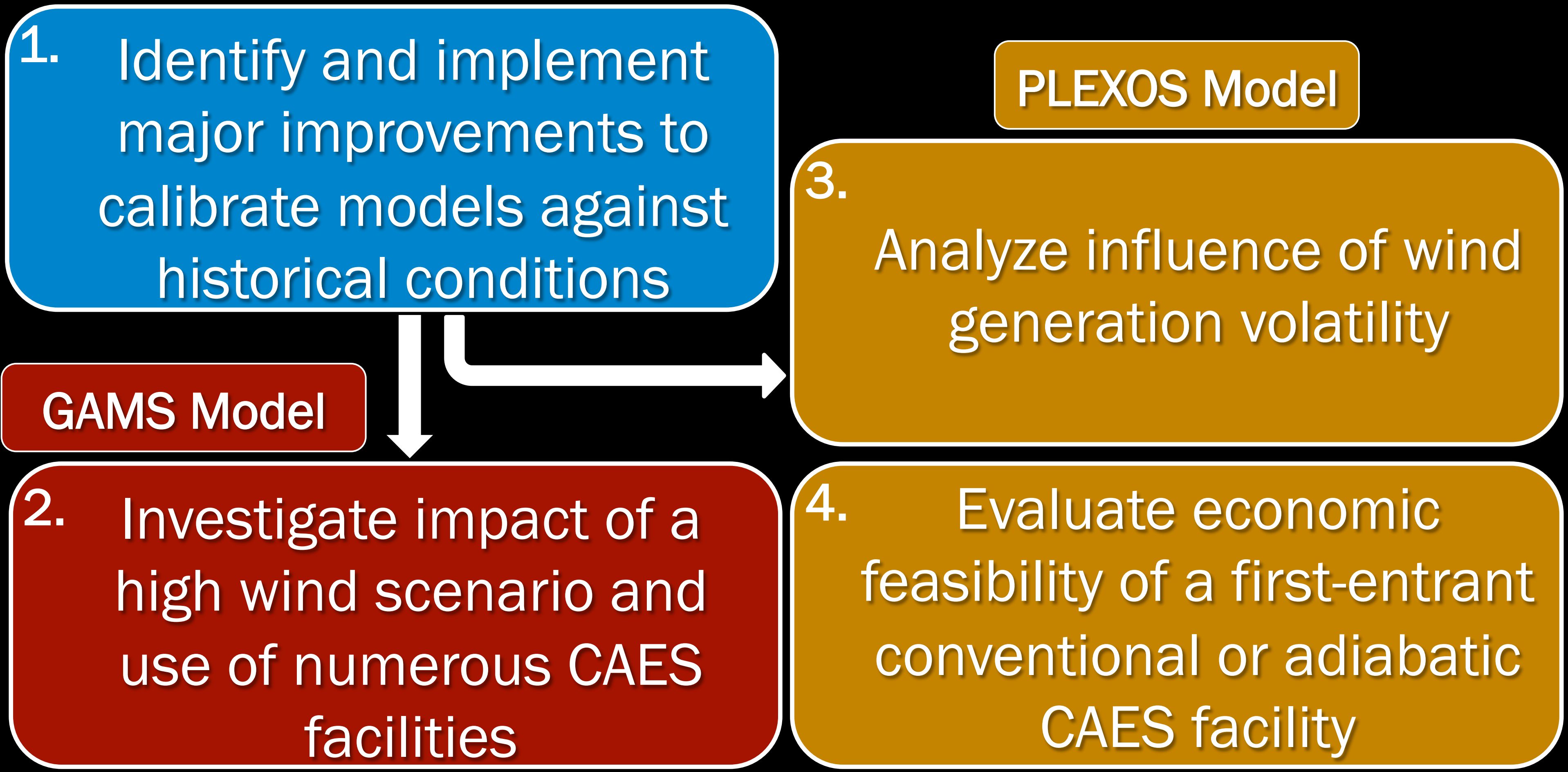
A UC&D model mimics the actual optimization and dispatch of an electricity market



UC&D models are useful for a variety of reasons

- Overcome most limitations of current literature
  - Don’t assume historical prices or price forecasts
  - Account for complex generator parameters (ramp rates, minimum up/down times, etc.)
  - Don’t assume the same historical electricity market
  - Capture the impact on the dispatch and prices of storage
- Useful types of analysis can be done by UC&D models
  - New market designs
  - New entrants into the market (storage)
  - Factors that change the load/net-load pattern
  - Other environmental constraints

My research had four main objectives



1. Identify and implement major improvements to calibrate models against historical conditions

GAMS Model

2. Investigate impact of a high wind scenario and use of numerous CAES facilities

PLEXOS Model

3. Analyze influence of wind generation volatility

4. Evaluate economic feasibility of a first-entrant conventional or adiabatic CAES facility

We developed 2 UC&D models of ERCOT that recreate the dispatch

<table>
<tr><th>GAMS Model</th><th>PLEXOS Model</th></tr>
<tr><td>1 week per simulation
Constant average heat rates</td><td>1 year per simulation
Variable marginal heat rates</td></tr>
<tr><td colspan="2">Energy and Ancillary Services
Generating unit specific ERCOT plant database
User specifies load and wind generation</td></tr>
</table>

- I built on this foundation with major model improvements and an overhauled plant database

Output and price results you'll see include all these limitations

- No transmission
- No strategic generator behavior
- Use of perfect daily forecasts & near perfect future day forecast
- No AS deployments (non-stochastic)
- Use of generator-type parameters

➢ Primary impact: do not replicate scarcity conditions

Objective 1:
Identify and implement major improvements to calibrate UC&D models against historical conditions

1. Identify and implement major improvements to calibrate models against historical conditions

GAMS Model

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PLEXOS Model

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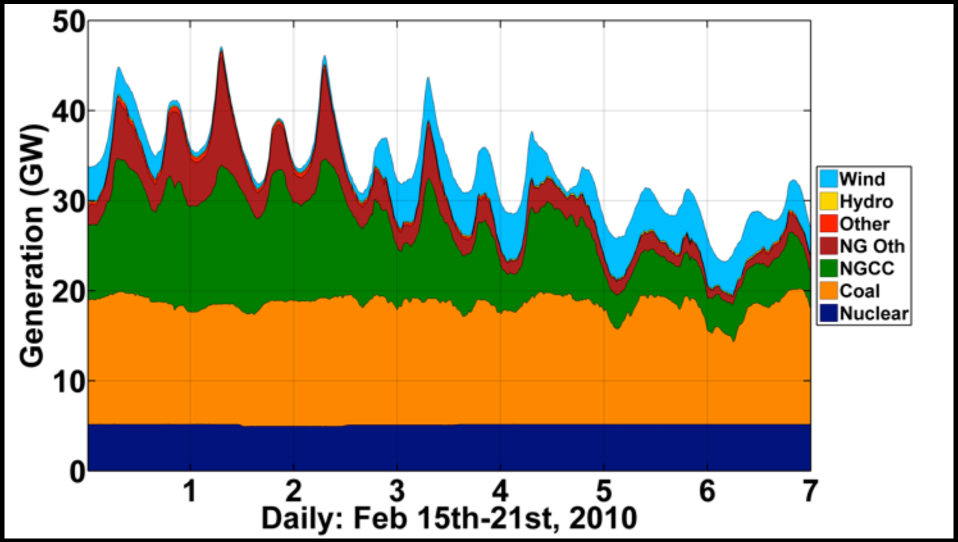
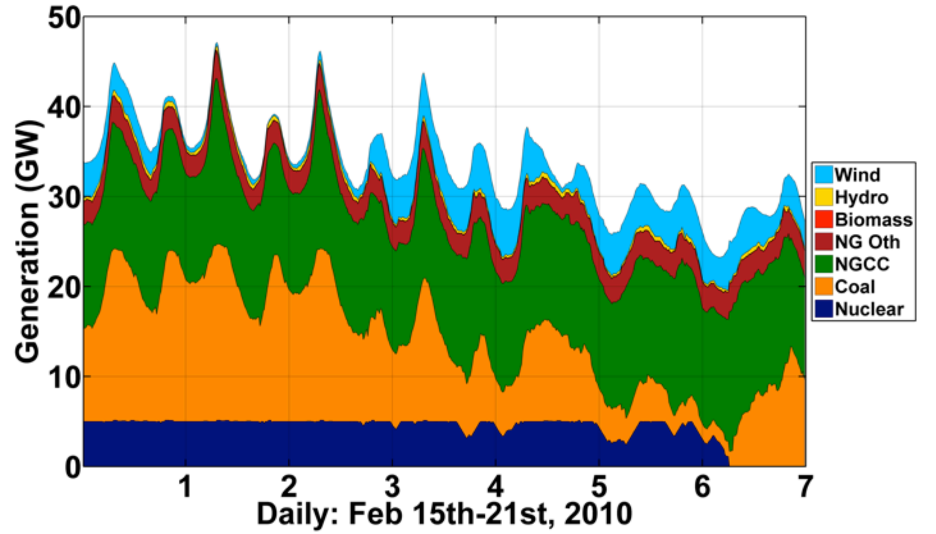
Significant improvements have been made to calibrate the models

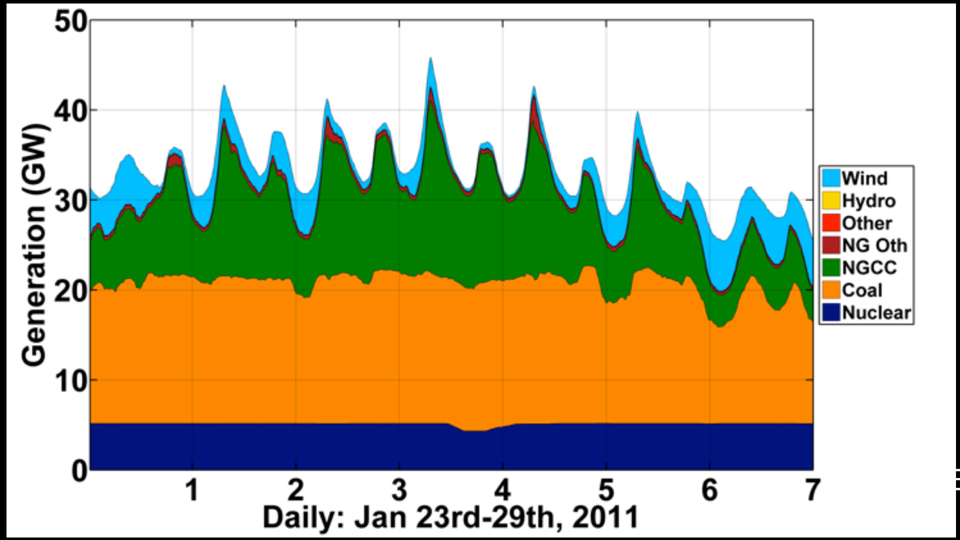
Historical – 2010 Winter week



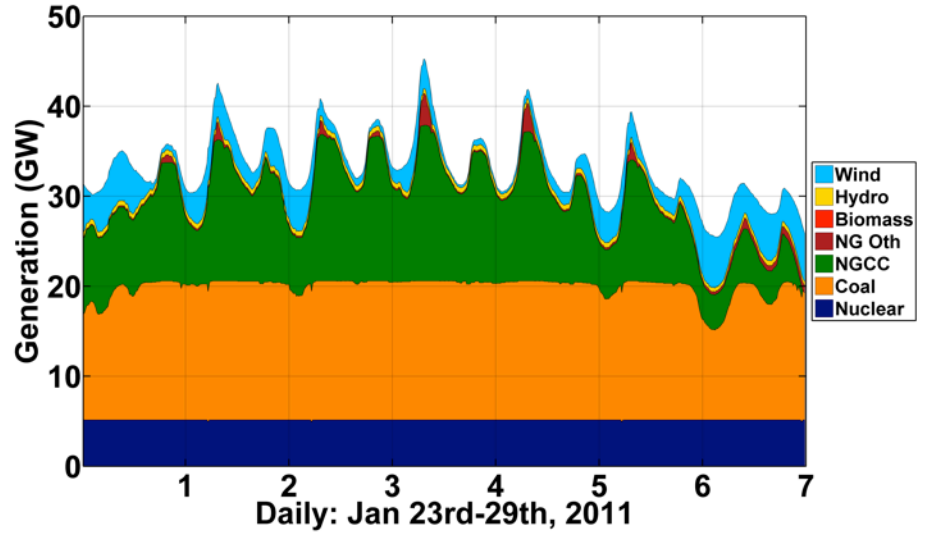
Initial GAMS model – 2010 Winter week



Historical – 2011 Winter week



Final GAMS model – 2011 Winter week



Calibration was a long process with many steps but will never be perfect

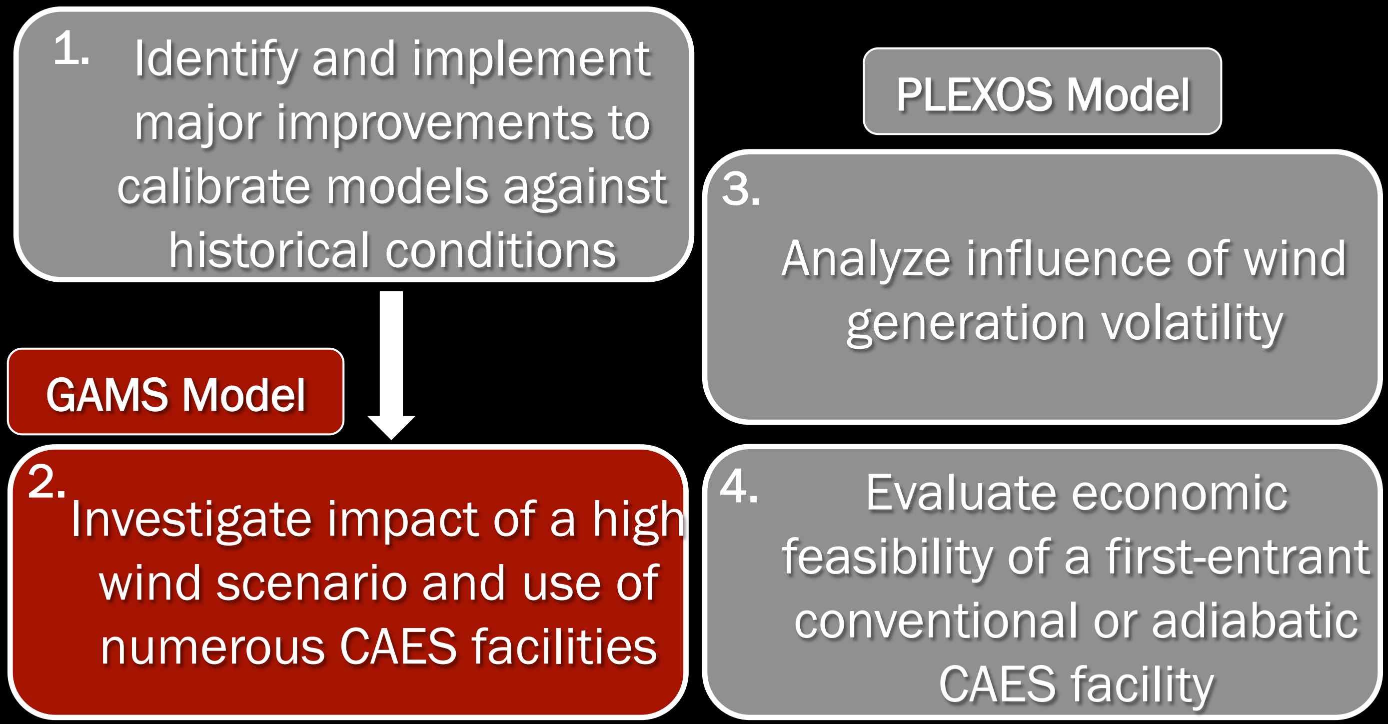
- Significantly enhanced some model aspects
  - Dispatch by generator type
  - Ancillary service prices
- Still don’t replicate highest price spikes
- Scarcity revenue adders = $74/kW-yr
  - Scarcity revenue = $60/kW-yr
  - ORDC revenue = $14/kW-yr

Conclusions: Model Calibration

– Models results should reflect actual behavior in the ERCOT electricity market

Studies on high wind penetration and utilization of CAES

Objective 2:
Investigate the impact on the dispatch of future high wind output and use of numerous CAES facilities



1. Identify and implement major improvements to calibrate models against historical conditions

GAMS Model

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PLEXOS Model

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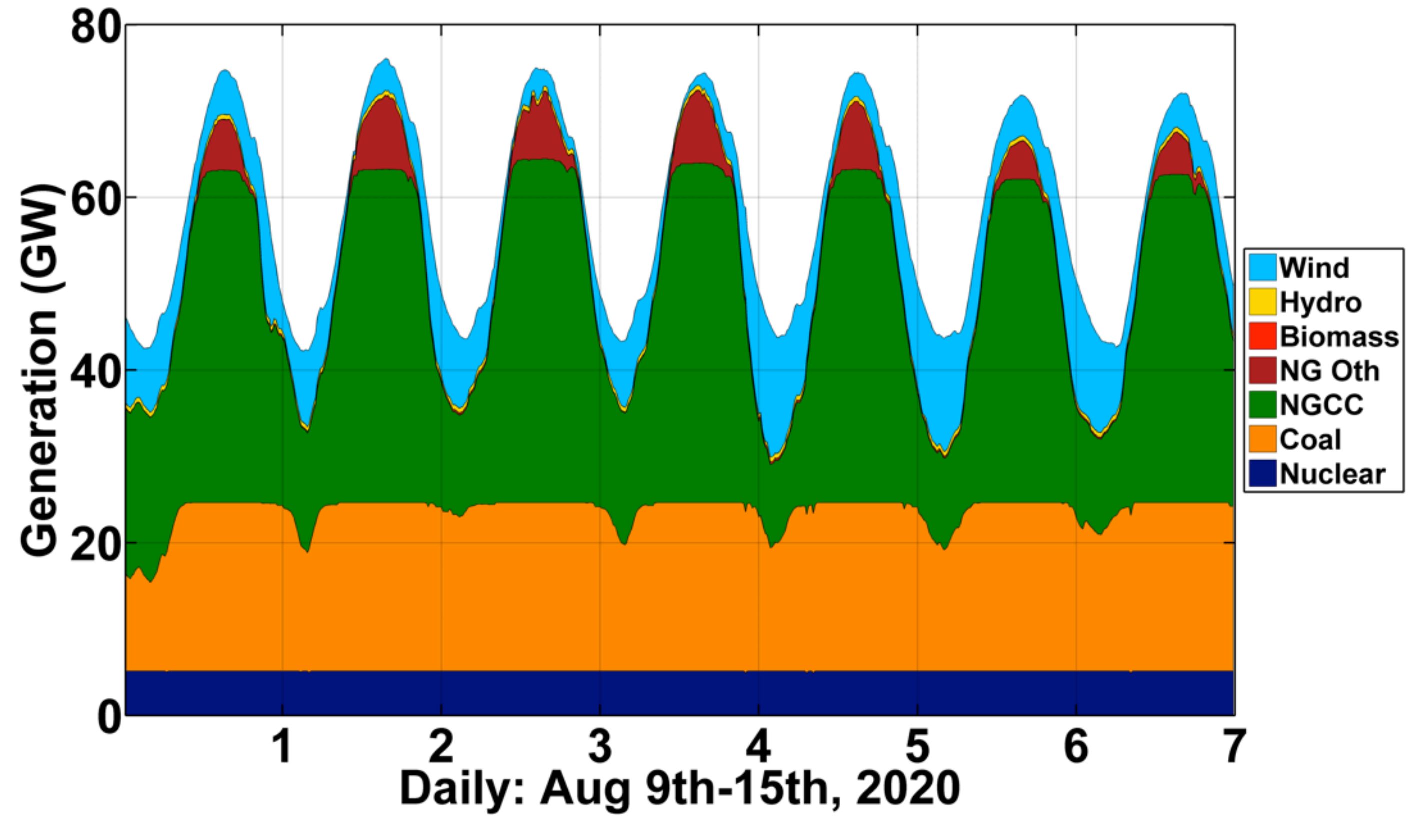
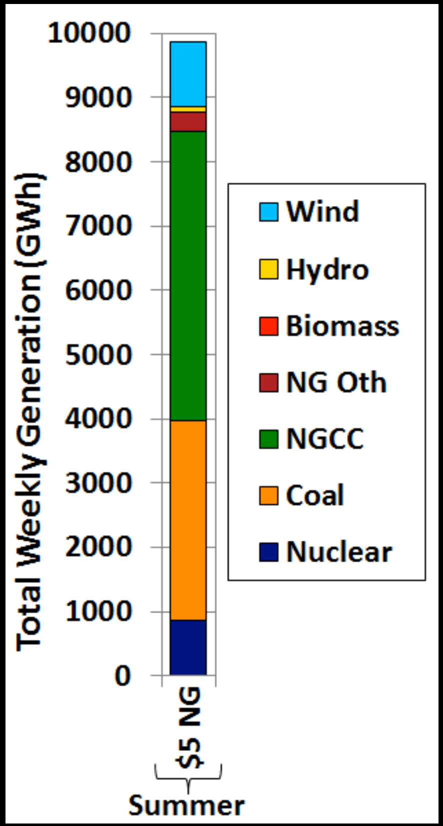
4. Evaluate economic feasibility of a first-entrant conventional or adiabatic CAES facility

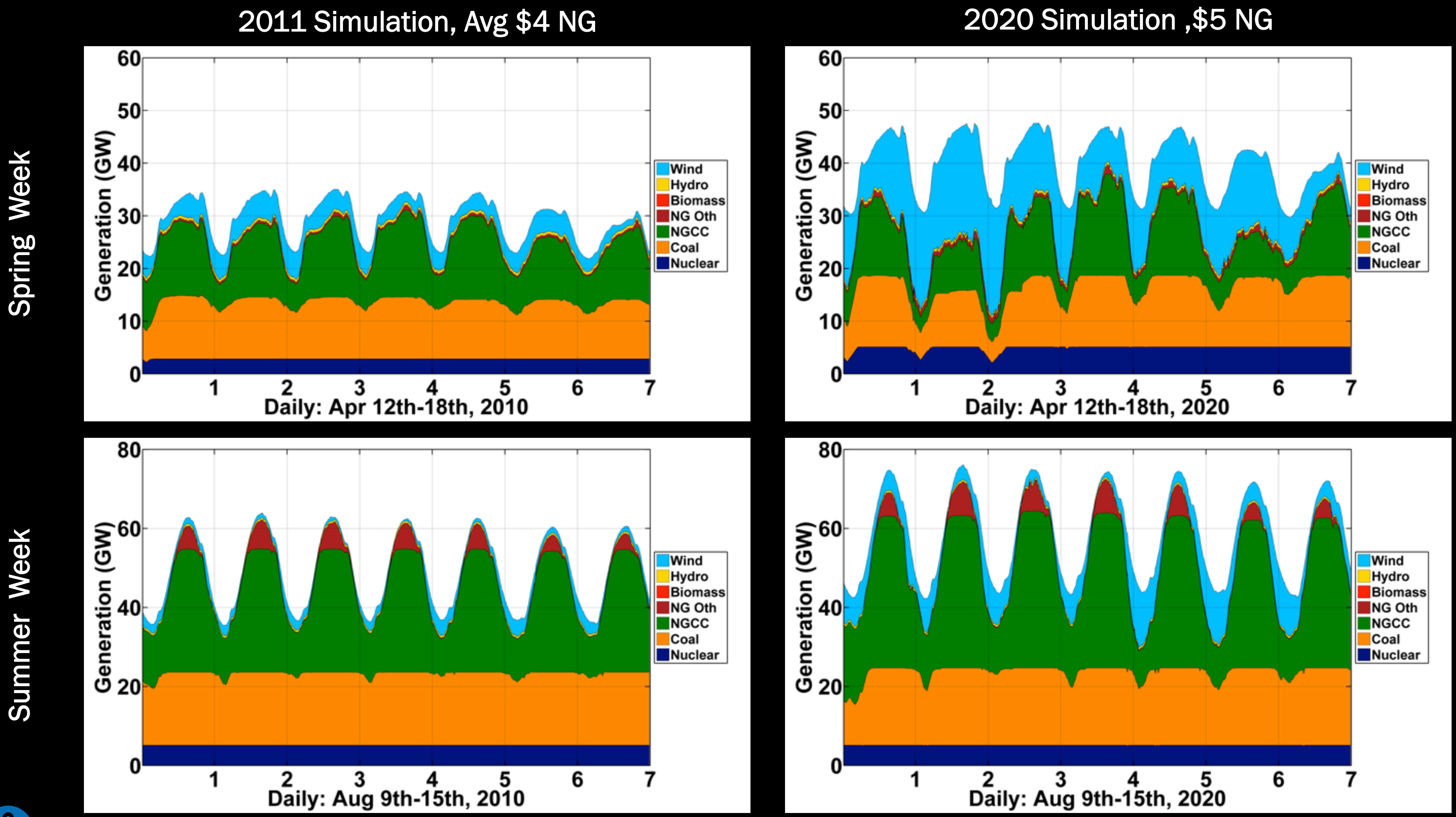
Results will be shown over the week or accumulated

2020 Summer, $5 NG





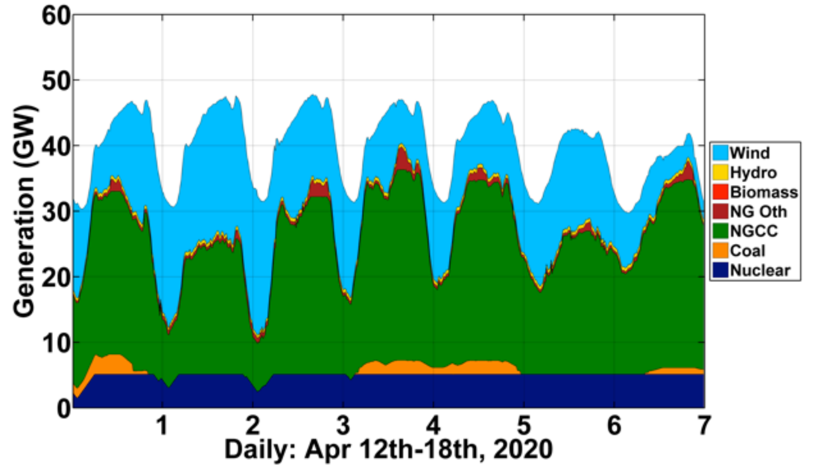
High wind penetration resulted in more dynamic requirements



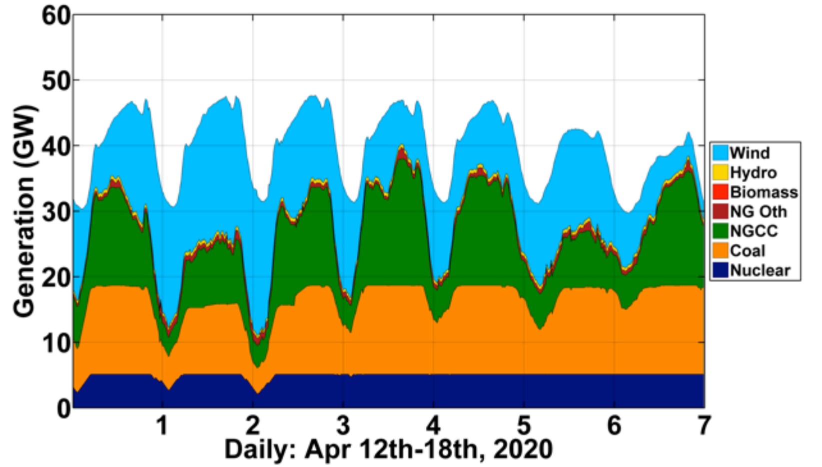
Natural gas price influences fuel switching between coal & NGCC

Spring Week

$3 NG

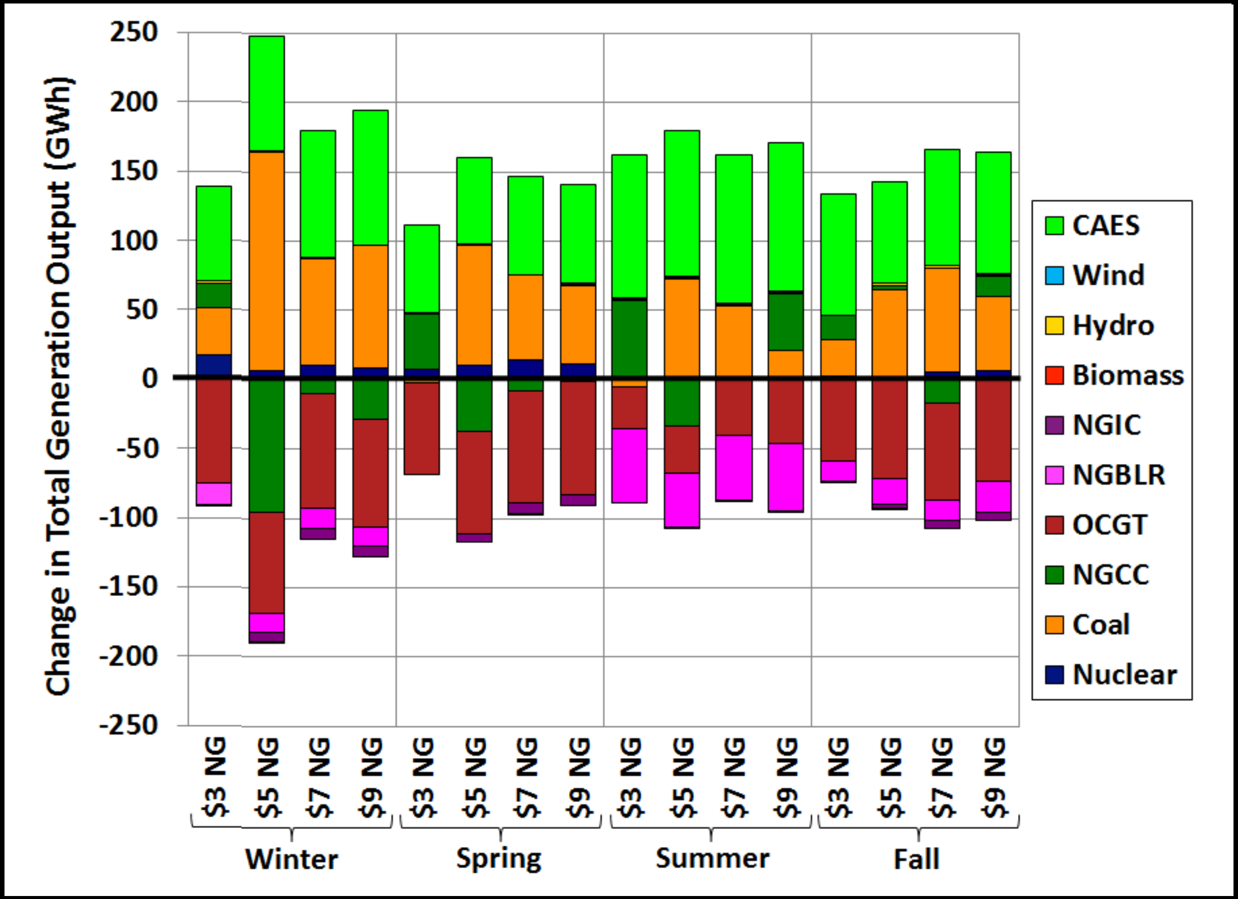


$5 NG



Ability to use CAES for electricity offsets other high cost generators

Each Difference = (with CAES) – (without CAES)



For each generator type

Positive – with CAES, used more

Negative – with CAES, used less

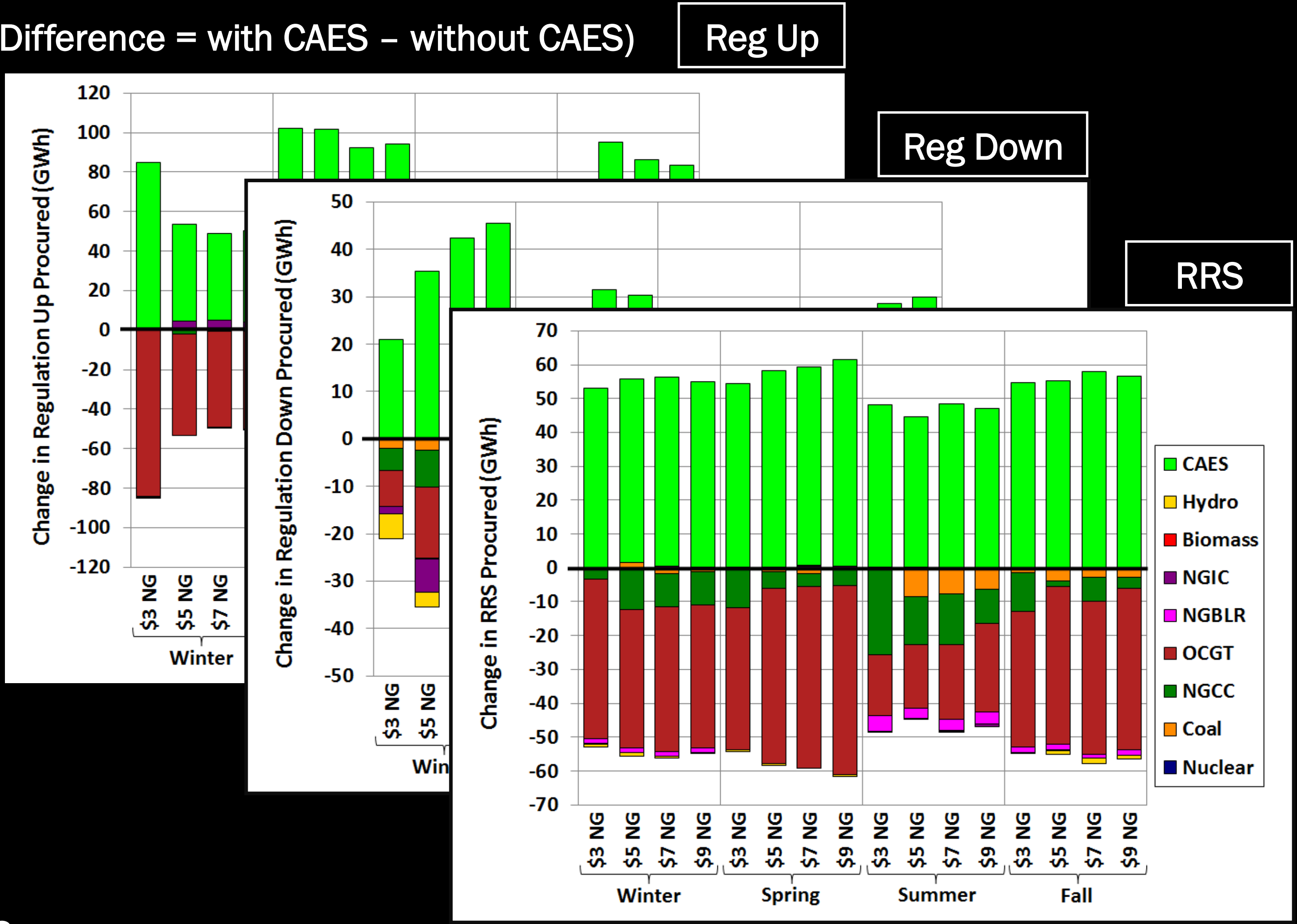
Negatives → higher cost generators

Positives → lower cost generators

- CAES provides electricity at lower cost
- Enhanced use of lower cost infrastructure

CAES is also utilized in ancillary service markets

(Each Difference = with CAES – without CAES)



<u>For each generator type</u>

Positive – with CAES, used more

Negative – with CAES, used less

Negatives → higher cost generators

- CAES provides these services at a lower cost

Use of bulk CAES leads to reduced total operational costs

<u>For each generator type</u>

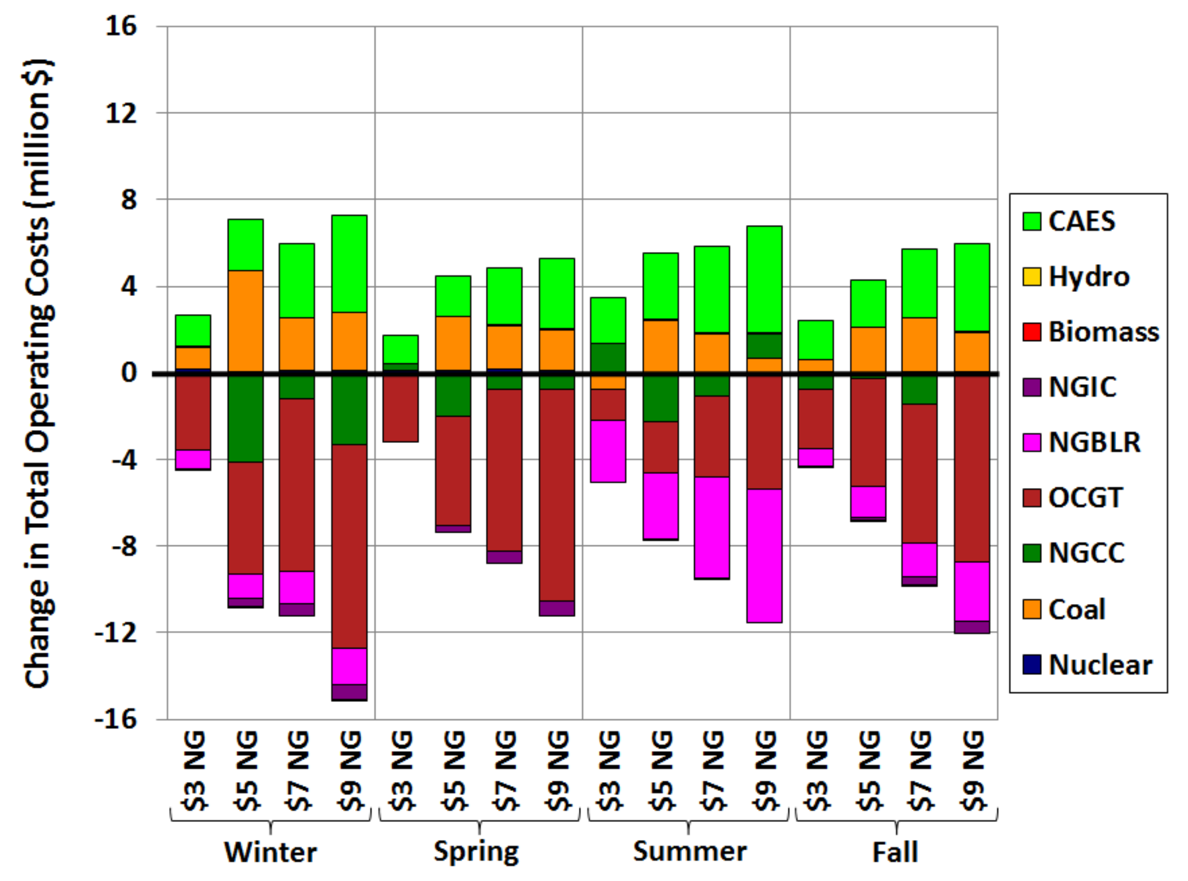
Positive – with CAES, used more, added costs

Negative – with CAES, used less, reduced costs

Negatives > Positives

➢ Net: lower total costs

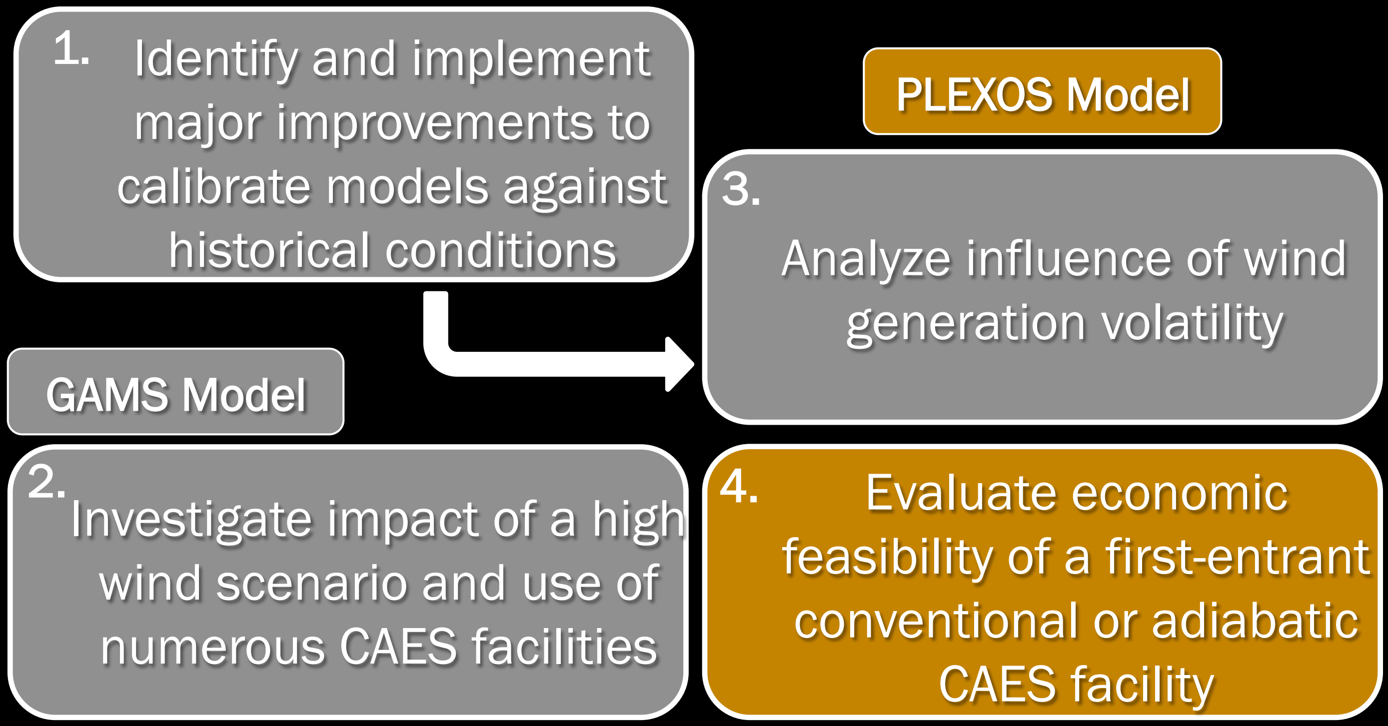
(Each Difference = with CAES – without CAES)



Conclusions: High wind penetration and bulk CAES

- High wind penetration led to more dynamic net load and reduced use of base load generators
- Natural gas price is a key factor in the dispatch
- Available CAES facilities were utilized for electricity & ancillary services
- CAES displaced higher cost generators leading to a reduction in total dispatch costs

Objective 4:
Evaluate the potential economic feasibility of a first entrant conventional or adiabatic CAES facility



1. Identify and implement major improvements to calibrate models against historical conditions

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2. Investigate impact of a high wind scenario and use of numerous CAES facilities

PLEXOS Model

3. Analyze influence of wind generation volatility

4. Evaluate economic feasibility of a first-entrant conventional or adiabatic CAES facility

CAES system operates in a common mode all year

Capacity use

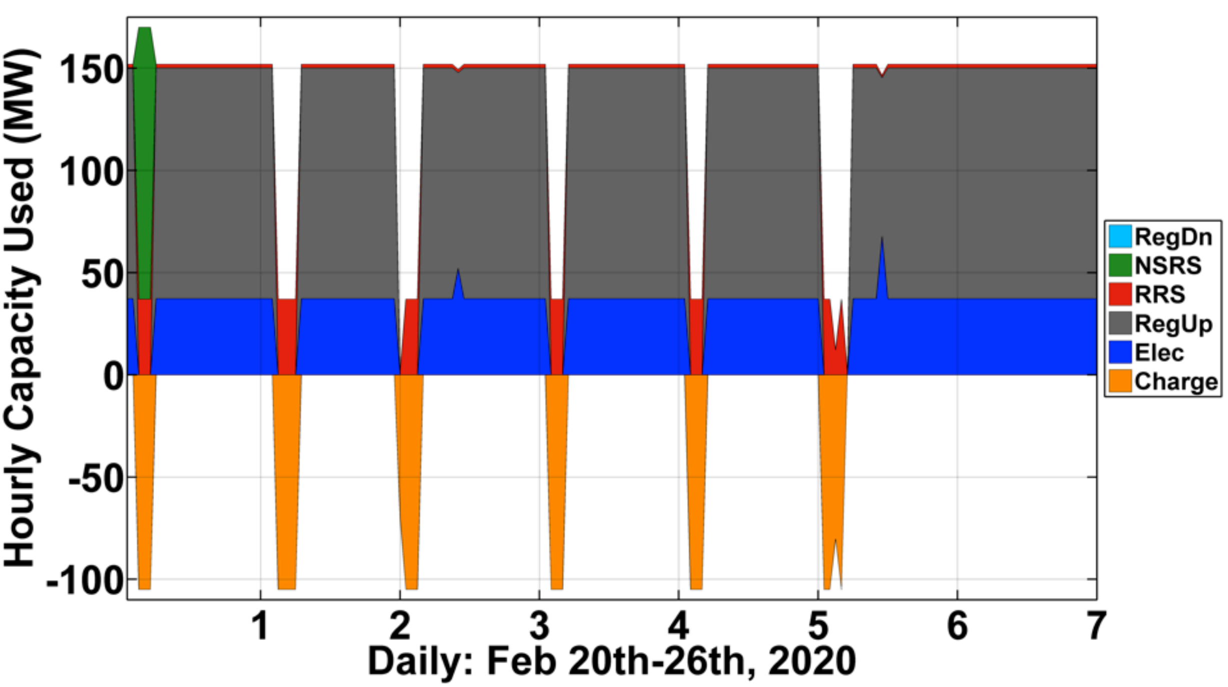
Positive – output capacity

Negative – input capacity
Negative will not be shown in remaining figures

Discharging
- Minimum electricity output
- Remaining capacity sold as RegUp

Charging
- Max input capacity
- Some input capacity also sold as RRS
- Output capacity sold as NSRS during charging

CAES: MedV, $3 NG



AA-CAES system requires more frequent and longer charging periods

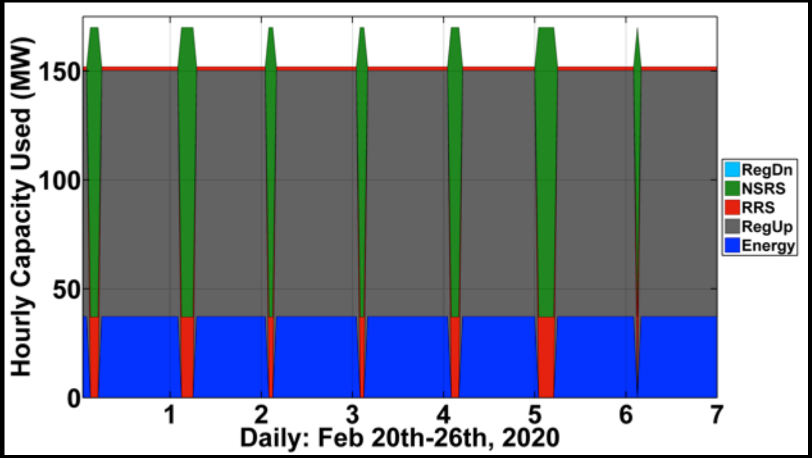
AA-CAES

Higher CER → requires more electricity input

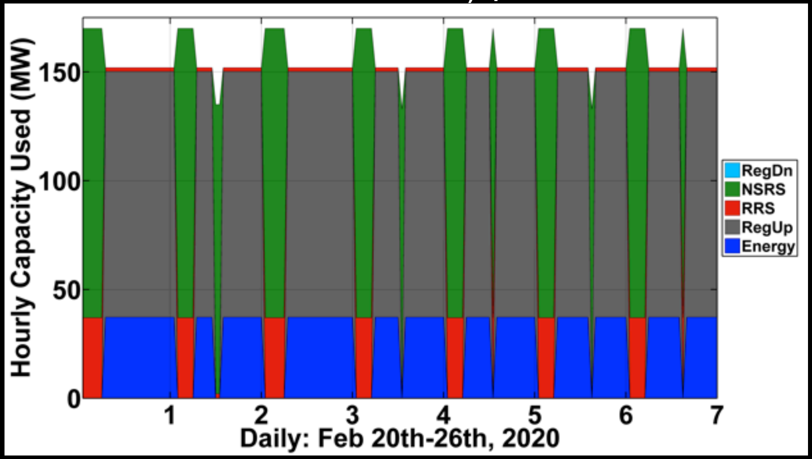
Both systems

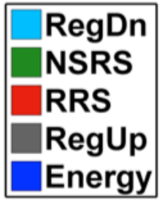
- Always either charging or discharging
- Constantly high capacity utilization

CAES: MedV, $5 NG



AA-CAES: MedV, $5 NG





High utilization rates indicate CAES system has desirable benefits

Capacity Factors

Calculated using the rated output capacity (135 MW)

> 100% → output and input capacity are used

- Always either charging or discharging
- When discharging – using all available capacity
- When charging – using all available capacity

NG Price ($/MMBtu)	CAES Capacity Factor Energy +AS (%)
3	98
5	106
7	109
9	112

Economic feasibility of a first entrant CAES system looks promising

CAES Cost of New Entry (CONE)

135-180 ($/kW-yr)

Profits > CONE

- ➢ Positive investment opportunity (under these future conditions)

Compare CONE to achievable profits

– Add profits from scarcity = 74 ($/kW-yr)

NG Price ($/MMBtu)	Total Operating Profits ($/kW-yr)	
	CAES	AA-CAES
3	141	161
5	188	218
7	239	282
9	286	342

Conclusions: CAES economic feasibility

- Single operational mode/behavior
  - Could be different with multiple CAES units included
- Extremely high level of utilization
  - Minimized operating costs
  - Minimized charging time & charging costs
  - Profits during this operating mode were always positive
- Favorable economic feasibility for both CAES systems
  - Higher NG prices yielded higher profits with identical operating behavior

Summary of Conclusions

CAES can aid wind power and appears economically attractive

- Model achieves accurate recreation of historical conditions
- Natural gas price is a key factor in the dispatch
- Higher wind penetration leads to increased dynamic market behavior
  - Impacts from wind volatility become more intense
  - CAES can mitigate impacts on base load generators
- first-entrant CAES facility shows favorable economic feasibility
  - Extremely high level of utilization
  - Higher NG prices led to higher profitability

Suggestions for future work

- Possible model improvements
  - Transmission
  - Uncertainty in load or wind output (stochastic)
- Possible analyses
  - Coastal vs. Inland wind
  - Bulk CAES deployment
  - Future load variability
  - Possible role of demand response

➢ PLEXOS model is a unique and powerful tool for analysis on the energy and electricity systems

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