MILP FORMULATION AND NESTED DECOMPOSITION FOR PLANNING OF ELECTRIC POWER INFRASTRUCTURES

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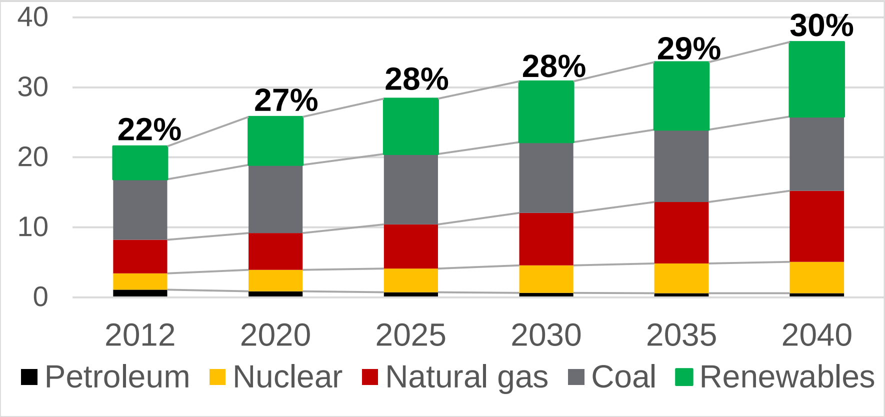
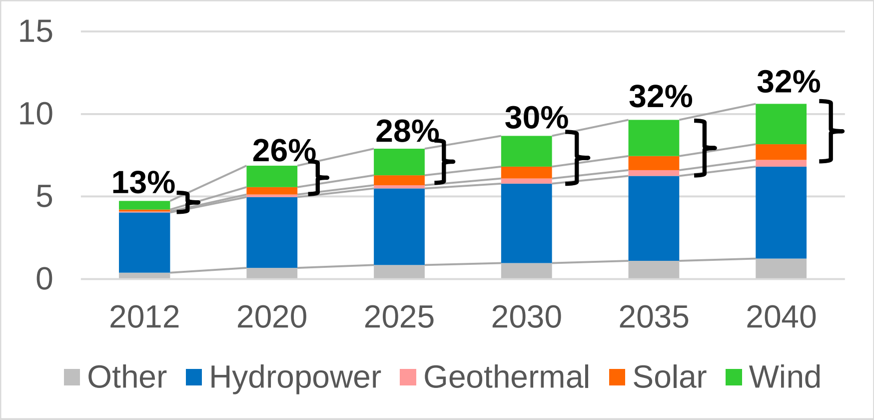
Motivation

Electricity mix gradually shifts to lower-carbon options

World net electricity generation by fuel, 2012-40 (trillion kWh)*

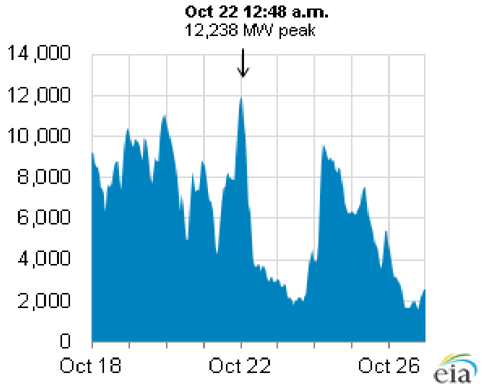


World net electricity generation from renewable power by fuel, 2012-40 (trillion kWh)*



*EIA, *Annual Energy Outlook 2016*

High variability in the renewables capacity factor



- Increasing contribution of intermittent renewable power generation in the grid makes it important to include **operational details** at the **hourly** (or sub-hourly) **level** in long term planning models to capture their variability.

Problem Statement

Given a region with:

A set of **existing** and **potential generators** with the respective

- generation technology*

if existing:

nuclear: steam turbine

coal: steam turbine

natural gas:

- steam turbine,
- gas-fired combustion turbine,
- and combined cycle

solar: photo-voltaic

wind turbines

if potential:

nuclear: steam turbine

coal: IGCC w/ or w/o carbon capture

natural gas:

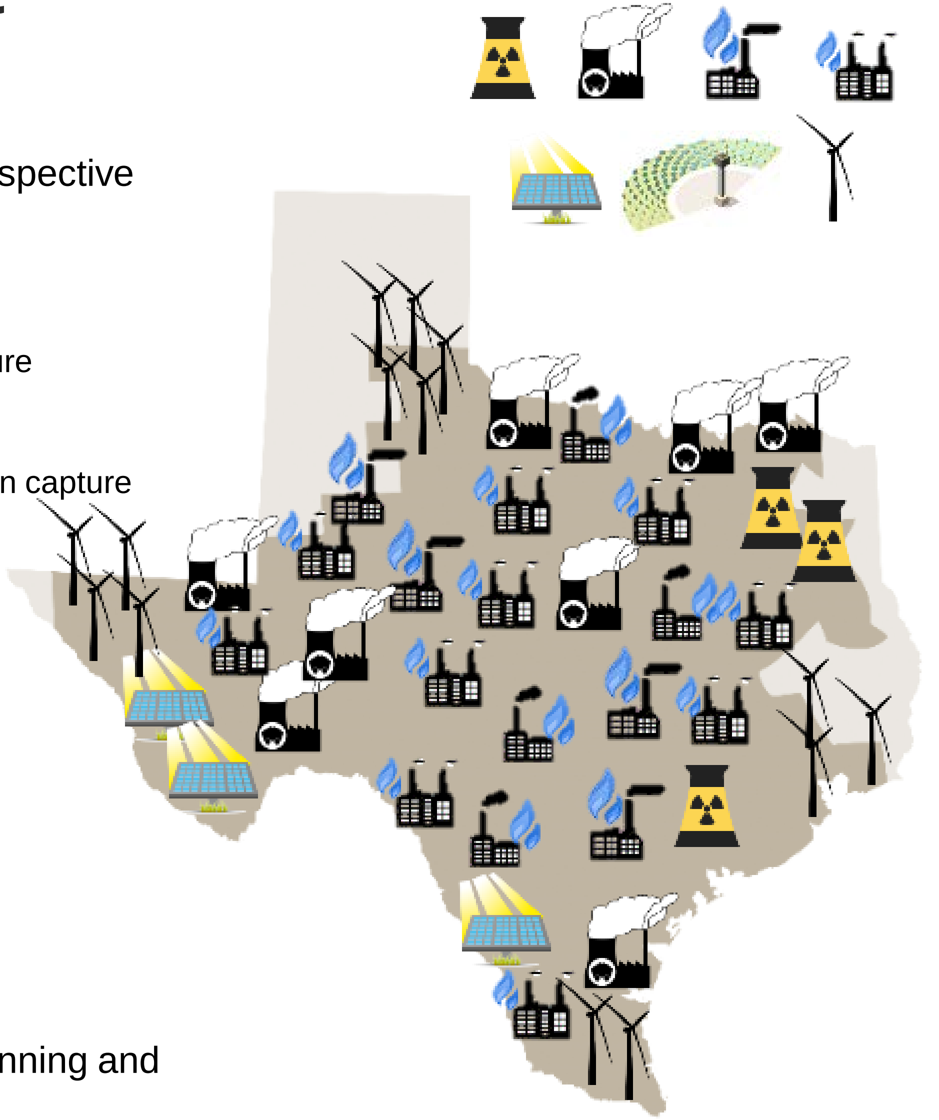
- gas-fired combustion turbine,
- combined cycle w/ or w/o carbon capture

solar:

- photo-voltaic
- concentrated solar panel

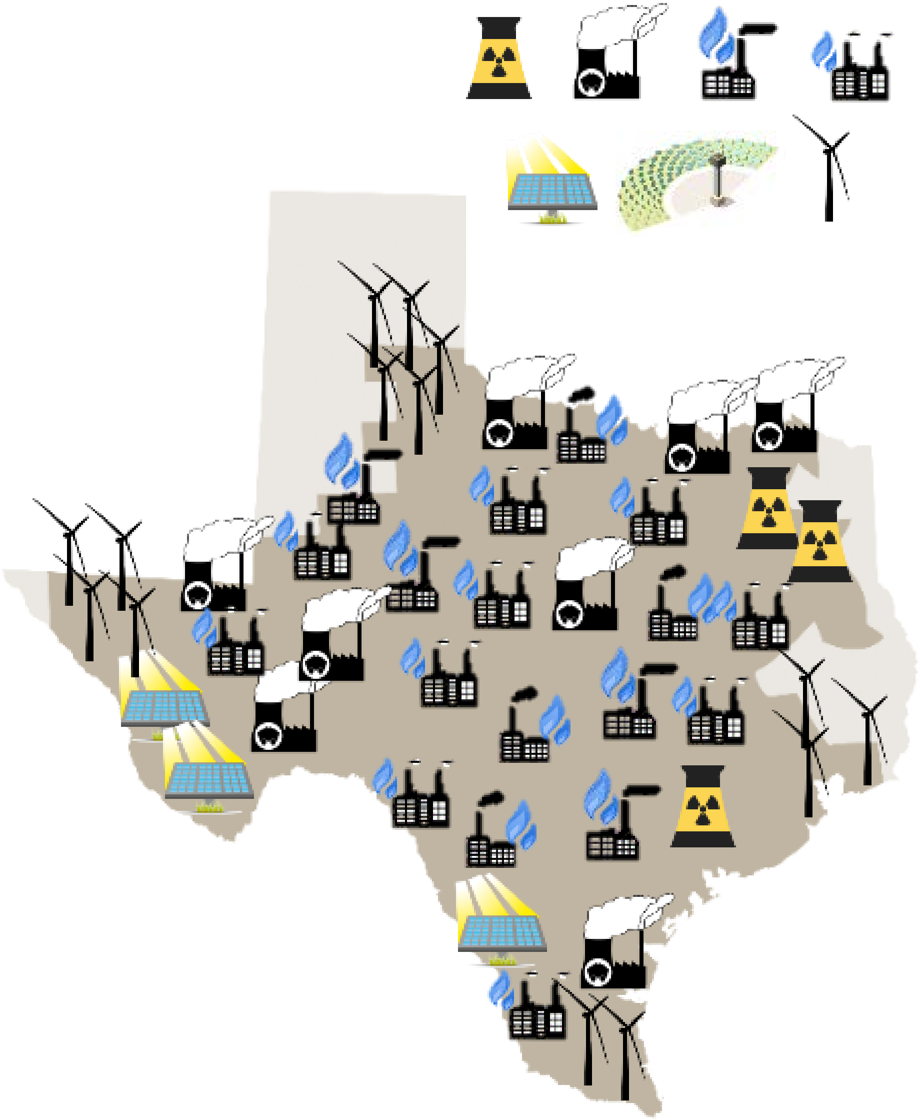
wind turbines

- location, if applicable
- nameplate capacity
- age and expected lifetime
- CO_2 emission
- operating costs
- investment cost, if applicable
- operating data
  - if thermal: ramping rates, operating limits, spinning and quick-start maximum reserve
  - If renewable: capacity factor



* Assume no hydropower

Problem Statement



Given:

- Projected load demand over the time-horizon at each location
- Distance between locations
- Transmission loss per mile

Find:

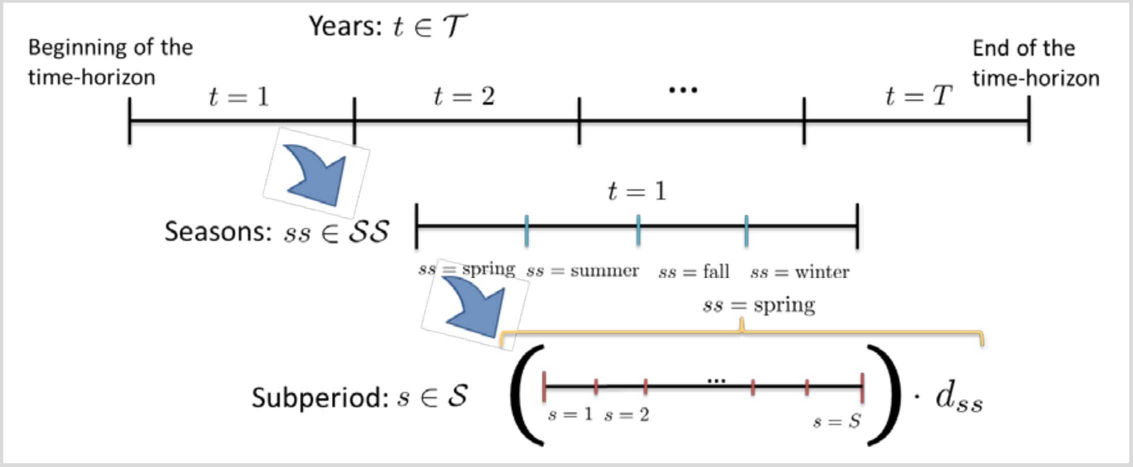
- **When**, **where**, **which type** and in **how many** generators to **invest**
- When to **retire** the generators
- Whether or not to **extend their lifetime**
- **Power flow** between locations
- Detailed **operating schedule**

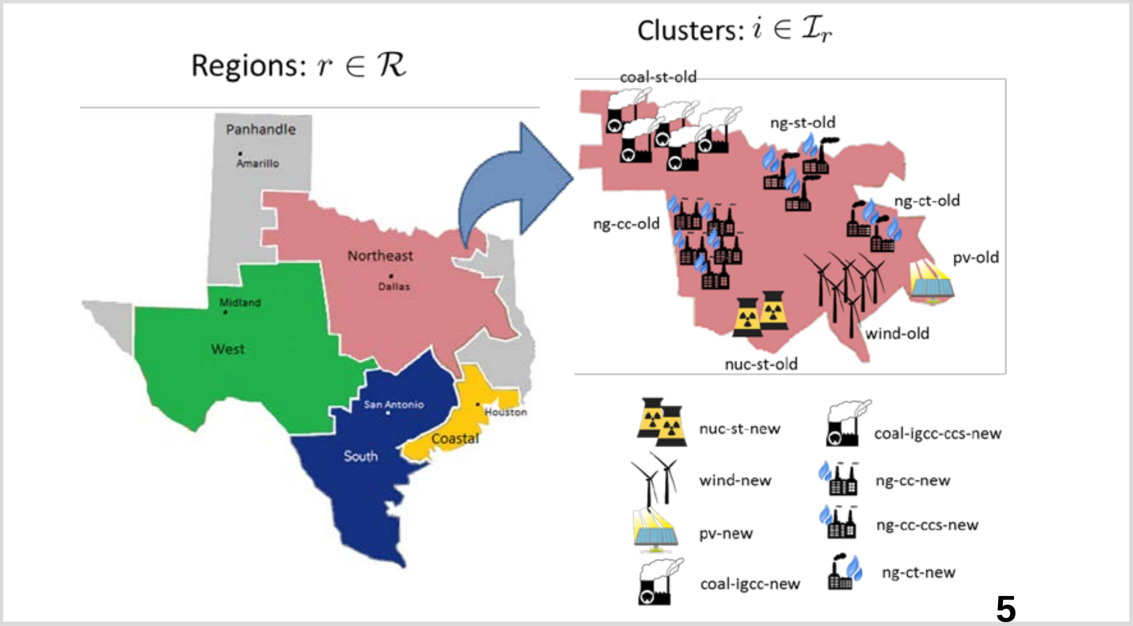
in order to minimize the overall operating, investment, and environmental costs

Modeling Strategies

To tackle the multi-scale aspect and reduce the size of the model

- Time scale approach:
  - 1 representative cycle per season (e.g., a day or a week) 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*
- Transmission representation
  - Flow in each line is determined by the energy balance between each region *r*.
  - This approximation ignores *Kirchhoff's Circuit Law*





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

MILP Model

Continuous variables:
- Power output at sub-period *s*
- Curtailment generation slack at *s*
- Power flow between regions at *s*
- Deficit from renewable quota at *t*
- Spinning reserve at *s*
- Quick-start reserve at *s*

Integer variables:
- no. of generators installed at period *t*
- no. of generators built at *t*
- no. of generators retired at *t*
- no. of generators with life extended at *t*
- no. of generators ON at sub-period *s*
- no. of generators starting up at *s*
- no. of generators shutting down at *s*

Summary of constraints:

- **Energy balance:** ensures that the sum of instantaneous power generated at region *r* plus the net power flow being sent to this region equal the load demand plus a slack for curtailment.
- **Capacity factor:** limits the generation of renewable generators to be equal to a given fraction of the capacity in each hour.
- **Unit commitment constraints:** compute the startup and shutdown, operating limits and ramping rates for thermal generators.
- **Operating reserve constraints :** determine the maximum contribution per thermal generator for spinning and quick-start reserves, and the minimum total operating reserves.
- **Investment constraints :** ensure that the planning reserve and renewable energy contribution requirements are satisfied, and limit the yearly installation per generation type.
- **Constraints of number of generators:** define the number of generators that are operational, built, retired, and have their life extended at each time period *t*.

MILP Model

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Objective function:

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

- Variable operating cost
- Fixed operating cost
- Startup costs
- Cost of investments in new generators
- Cost to extend the life of generators that achieved their expected lifetime
- Fuel consumption
- Carbon tax for CO_2 emission
- Penalty for not meeting the minimum renewable annual energy production requirement

Even with the approximations adopted, this is still a very large MILP model.
In order to allow longer representative cycles per season, we propose a decomposition algorithm based on **Nested Benders Decomposition*.**

*Birge, J.R., *Decomposition and Partitioning Methods for Multistage Stochastic Linear Programs*, 1985
Pereira, M.V.F., Pinto, L.M.V.G, *Multi-stage stochastic optimization applied to energy planning*, 1991
Sun & Ahmed, *Nested Decomposition of Multistage Stochastic Integer Programs with Binary State Variables,* 2016

Nested Decomposition for Mixed-Integer Multi-period Problems

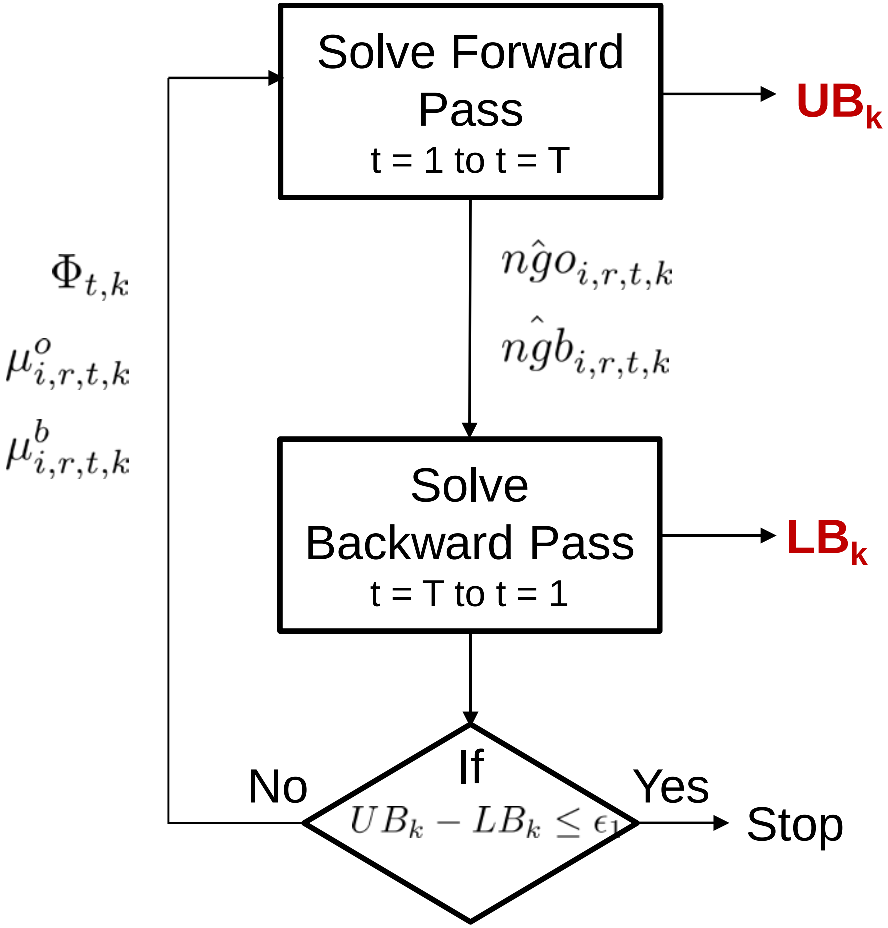
Basic idea:

- 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.

Birge, J.R., *Decomposition and Partitioning Methods for Multistage Stochastic Linear Programs*, 1985
Pereira, M.V.F., Pinto, L.M.V.G, *Multi-stage stochastic optimization applied to energy planning*, 1991
Zou, J., Ahmed, S., Sun, X.A., *Nested Decomposition of Multistage Stochastic Integer Programs with Binary State Variables,* 2016

Nested Decomposition Algorithm

1. Set iteration k = 1, and tolerance ϵ_1.
2. Solve the Forward Pass for time periods $t = 1, \ldots, T$, and store the fixed values for $n\hat{g}b_{i,r,t,k}$ and $n\hat{g}o_{i,r,t,k}$.
3. Compute **upper bound**.
4. Solve the Backward Pass for time periods $t = T, \ldots, 1$, and generate the cuts (expected future cost).
5. Compute **lower bound**.
6. If $UB_k - LB_k \leq \epsilon_1$, STOP.
7. If not, set k = k+1, go back to step 2.



Solve Forward Pass

t = 1 to t = T

UB_k

$n\hat{g}o_{i,r,t,k}$

$n\hat{g}b_{i,r,t,k}$

$\Phi_{t,k}$

$\mu^o_{i,r,t,k}$

$\mu^b_{i,r,t,k}$

Solve Backward Pass

t = T to t = 1

LB_k

If $UB_k - LB_k \leq \epsilon_1$

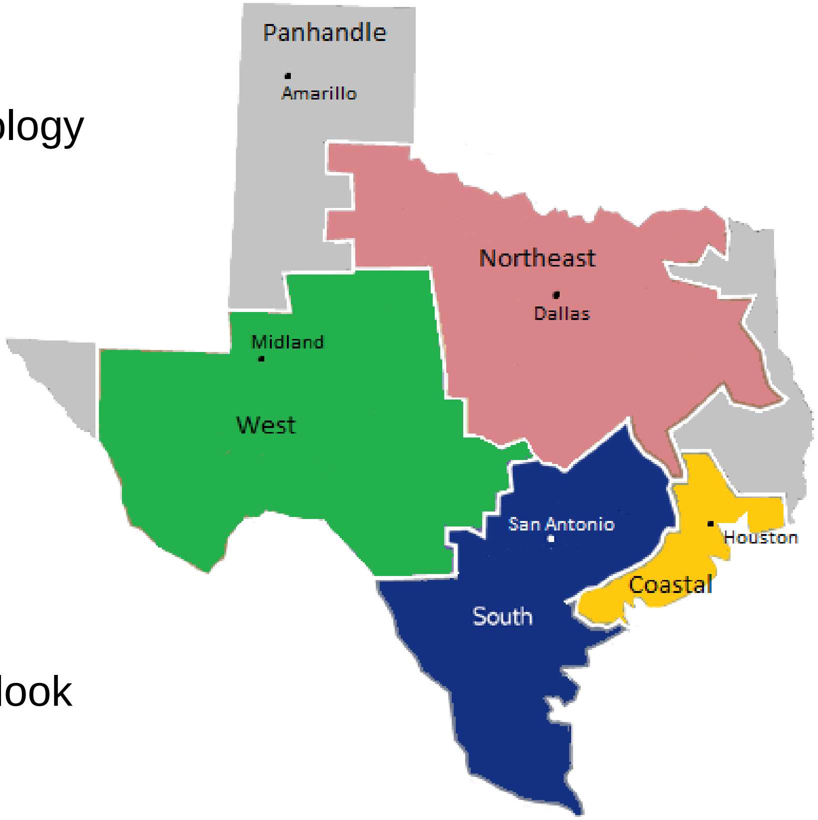
No

Yes

Stop

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
- No imposed carbon tax
- No renewable generation quota requirement
- Maximum transmission line capacity



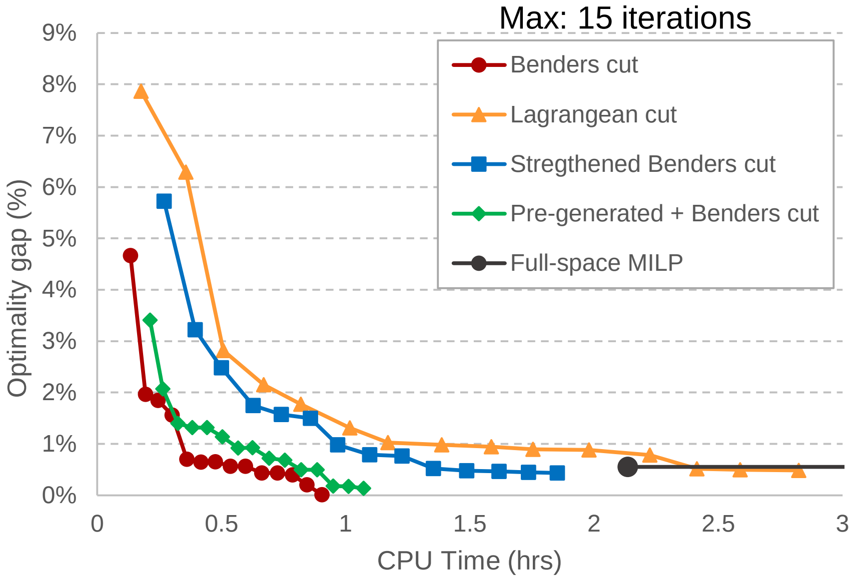
Algorithm Performance

1 representative day per season

Full-space MILP Model
Integer variables: 413,644
Continuous variables: 594,147
Equations: 1,201,761

Solver: CPLEX 12.6.3
optcr: 1%
CPU Time: 2.1 hours
Optimality gap: 0.55%

Optimality gap over solution time

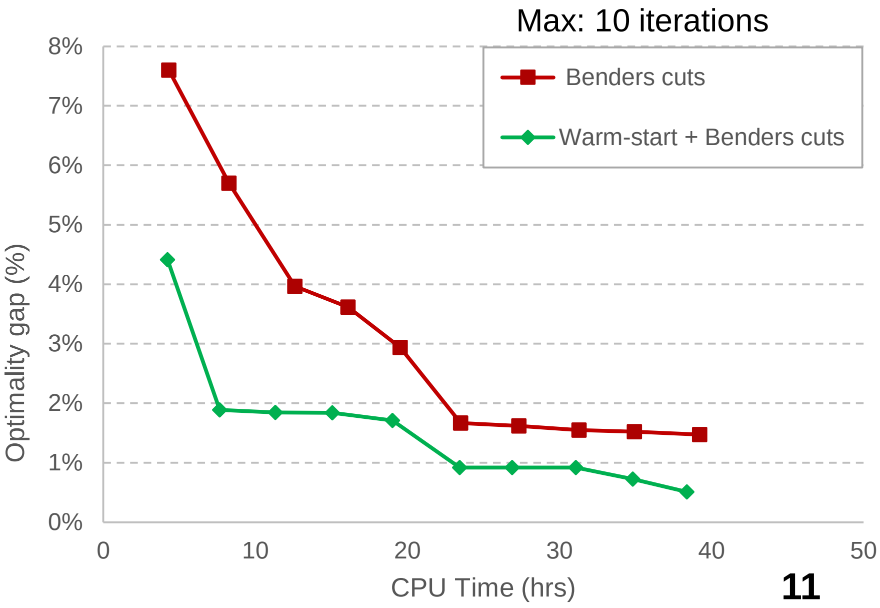


1 representative week per season

Full-space MILP Model
Integer variables: 2,901,96
Continuous variables: 4,136,547
Equations: 8,476,641

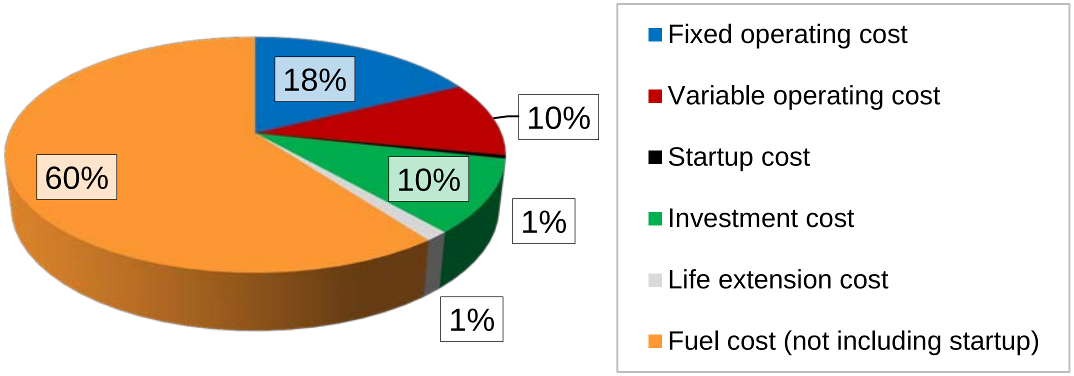
Solver: CPLEX 12.6.3
optcr: 1%
CPU Time: **Out of memory! (Does not solve)**

Optimality gap over solution time

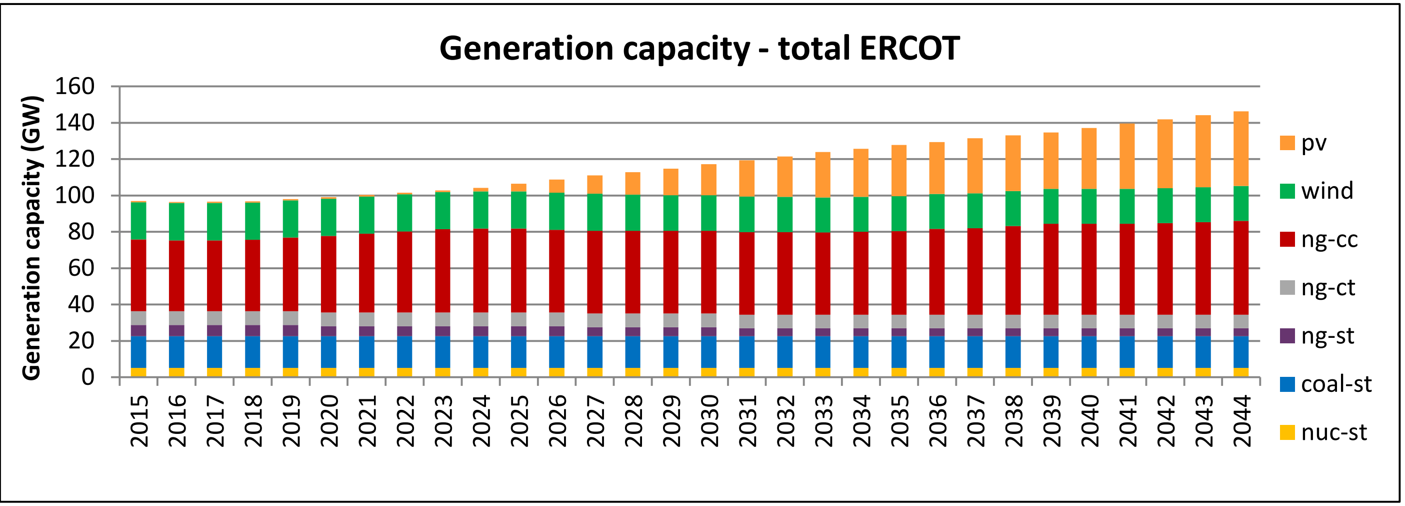


Results

- 1 representative week per season



Total cost:
$198.0 billions



61-fold increase in **PV-solar** capacity
31% increase in **natural gas combined-cycle** capacity
6% decrease in **wind** capacity
30% decrease in **natural gas steam turbine**

Conclusions

- Time scale, region and clustering approaches reduce considerably the size of the MILP planning model.
- Decomposition algorithm greatly speeds up the solution, and allows longer representative cycles per season.
- For ERCOT region, future growth in generation capacity will be met by a portfolio of different generation technologies.

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CAPD CENTER

Thank you!