Renewable-Motivated Co-optimized Expansion Planning of Generation, Transmission, Distribution and Natural Gas Systems

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3. Other infrastructure:
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   • hybrid energy systems
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Motivating concepts

Electric generation capacity additions by technology (1950-2015) gigawatts

- Hydro
- Coal
- Natural gas
- Petroleum
- Nuclear
- Wind
- Solar
- Other

- Gas, Wind
- Coal, Gas, Hydro
- Coal, Gas, Nuke, Hydro
- Gas, Wind
- Solar

Figure 13. Electricity generation by fuel, 1990-2040 (trillion kilowatthours)

- Natural gas (35%)
- Renewables (16%)
- Nuclear (16%)
- Oil and other liquids (2%)
- Coal (32%)

Figure 14. Renewable electricity generation by fuel type in the Reference case, 2006-2040 (billion kilowatthours)

2012, 2015, wind investment is #1!
Motivating concepts

Wind & transmission

...it gets more interesting when considering natural gas generation, rooftop and utility solar PV, and pipelines.
Approach

Co-optimization: the simultaneous identification of 2 or more classes of related infrastructure decisions within 1 optimization problem.

Make investment & retirement decisions to MINIMIZE:

PRESENT WORTH

G&T Investment costs
+ Fixed O&M Costs
+ Var O&M Costs
+ Fuel Costs
+ Reserve costs
+ Environmental Costs

SUBJECT TO:
Investment constraints
Operational, planning, environmental constraints
Uncertainty characterization

Year 1 Year 2 ... Year N
Approach

It is useful when decisions for two infrastructure classes are interdependent.

Generation Expansion Plan (GEP)  Transmission expansion plan (TEP)

Co-optimized expansion planning decisions (CEP)

Expansion plan

Expansion plan
Mental picture

For each combination of investment choices, it computes O&M (including production costs) over entire period. The plan that minimizes total investment+O&M is selected.

400MW NGCC at Tesla345kV in year 3
200MW Wind at Malin230kV in year 11
Retire 250MW Coal at Contra161kV in year 18
Build 1500MW Jones-Smith 500kV in year 13

Is total cost < Best plan so far?
Mental picture

• Not predictive
• Rather, exploratory!

• Enables identification of most economic designs subject to imposed constraints & how designs perform over specified conditions.
• Comparative interpretation is useful, e.g., compare cost of meeting a clean-energy goal with or without transmission investment.
1. Reduced network is represented using DC power flow, with "normal condition" flow limits. N-1 analysis not done (yet).

2. The optimization is multi-period over the planning horizon, generally with 1 period per year.

3. The objective function is the net present worth of all operation and investment costs over the planning horizon.

4. End effects addressed via use of 40 additional years of final year operation cost.

5. Load is modeled for each of 4 seasons using 3 load blocks per season.

6. Similar operating conditions, in terms of load levels and wind/solar levels, are assumed to be identical.

7. Load growth modeled via peak and energy growth.

8. Wind/solar/hydro resource data is synchronized with load blocks.

9. Generation operation cost modeled with VOM, FOM, energy cost, reg/LF/cont reserve costs, ramp rates, & emissions.

10. A single dispatch of entire EI/WECC is used, augmented by hurdle rates between pricing regions (identifies best economics).

11. Reserve constraints modeled regionally, interconnection-wide, or nationally.

12. Reserve sharing requires deliverability constraints.

13. 1 min, 10 min, 30 min reserve modeled as function of variability; variability a function of load & wind/solar penetration.

14. Contingency reserve modeled as largest contingency within the region in which reserve requirement is enforced.

15. For each load block & region, planning reserve imposed for region's hourly {peak + other regions' deliverable capacity}.

16. Retirements can occur in three ways: forced, end-of-life, or based on cost (unit FOM+VOM exceeds savings from using it).

17. Generation investments modeled as technology and location-specific investment cost per MW, with continuous variables.

18. Existing/candidate transm modeled w/ impedances. Candidate transm modeled disjunctively (integer variables).

19. Multiple DC & AC transm technologies with cost a function of technology, length, subs, terminals; only DC crosses seams.

20. AC transm capacity a function of length between substations per St Clair curve; substations separated by < 200 miles.

21. Line losses approximated as linear function of flows.
1. Reduced network is represented using DC power flow, with “normal condition” flow limits. N-1 analysis not done (yet).

The problem is mixed integer linear program, modeled over 20 yrs; computational tractability prohibits large networks.
Modeling – operating blocks

5. Load is modeled for each of 4 seasons using 3-4 load blocks per season.

6. Similar operating conditions, in terms of load levels and wind/solar levels, are assumed to be identical.

Based only on load levels.

Based on load levels & wind, solar levels.

➔ Identifies similar network flow patterns.

Each operating block is treated without temporal interdependence of other blocks.
12. 1 min, 10min, 30min reserve modeled as function of variability; variability a function of load & wind/solar penetration.

REGULATING RESERVES (1 MIN)
- \( \text{CpbltyRegUpRsrvs} > k_1 \text{[1min netload standard deviation]} \)
- \( \text{CpbltyRegDownRsrvs} > k_2 \text{[1min netload standard deviation]} \)

LOAD FOLLOWING (10-MIN)
- \( \text{CpbltyLF,UpRsrvs} > k_3 \text{[10min netload standard deviation]} \)
- \( \text{CpbltyLF,DownRsrvs} > k_4 \text{[10min netload standard deviation]} \)

These are provided by gen and/or demand that can be controlled. They are procured in the market (they cost money!).

These reflect netload variability. They change with amount & geo-diversity of wind/solar. They prevent under-investment in flexible resources.
Modeling – transmission

18. Existing/candidate transm modeled w/ impedances. Candidate transm modeled disjunctively (integer variables).

Nonlinear model

\[ P_{ij} - z_{ij} B_{ij} (\theta_i - \theta_j) = 0 \]

\[ -z_{ij} P_{ij}^{\text{max}} \leq P_{ij} \leq z_{ij} P_{ij}^{\text{max}} \]

Line is in

\[ z_{ij} = 1 \]

\[ P_{ij} - B_{ij} (\theta_i - \theta_j) = 0 \]

\[ -P_{ij}^{\text{max}} \leq P_{ij} \leq P_{ij}^{\text{max}} \]

Line is out

\[ z_{ij} = 0 \]

\[ P_{ij} = 0 \]

\[ 0 \leq P_{ij} \leq 0 \]

Disjunctive: equivalent linear model

\[ -1000(1 - z_{ij}) \leq P_{ij} - B_{ij} (\theta_i - \theta_j) \leq 1000(1 - z_{ij}) \]

\[ -z_{ij} P_{ij}^{\text{max}} \leq P_{ij} \leq z_{ij} P_{ij}^{\text{max}} \]

Line is in

\[ z_{ij} = 1 \]

\[ 0 \leq P_{ij} - B_{ij} (\theta_i - \theta_j) \leq 0 \]

\[ -P_{ij}^{\text{max}} \leq P_{ij} \leq P_{ij}^{\text{max}} \]

Line is out

\[ z_{ij} = 0 \]

\[ -1000 \leq P_{ij} - B_{ij} (\theta_i - \theta_j) \leq 1000 \]

\[ -0 \leq P_{ij} \leq 0 \]
Application - Iowa


Grow wind from 6.2GW to 20 GW in 20 yrs.

Abhinav Venkatraman, Year 2 MS Student
Ali Jahanbahni, Post-doctoral researcher
Chris Harding, Associate Professor
Geological & Atmospheric Sciences

The inner/smaller circle represents gen added in the particular year; the outer/larger circle represents total gen available in that year for the particular technology. In years when generation is not added, it shows it all as existing.
Application - BPA

Work done in collaboration with Ben Hobbs, Schad Professor in Env Mngmnt, Director of Env, Energy, Sustainability & Health Institute, Johns Hopkins University

Patrick Maloney, Year 2 Ph.D. Student
Ping Liu, Post-doctoral researcher

20-Year NPW as Function of Transmission Investment

Total Cost (Investment+Fuel+CO₂+O&M)

Generation Investment

Transmission Investment

Wind/solar only (no gas)

Wind/solar +2.8GW gas.
Application – Interconnection Seams Study

PROJECT TEAM

- National Renewable Energy Laboratory, Aaron Bloom (LEAD)
- Pacific Northwest National Laboratory, Yuri Makarov
- Oak Ridge National Laboratory, Fran Li
- Argonne National Laboratory, Jianhui Wang
- Iowa State University, Jim McCalley
- Southwest Power Pool, Jay Caspary
- Midcontinent Independent System Operator, Dale Osborn
- Western Area Power Administration, Rebecca Johnson

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Hussam Nosair, Post-doctoral researcher
**Application – Interconnection Seams Study**

**Objective:** identify least-cost way to achieve 40% CO₂ reduction rel to 2005 by 2038.

**Observations:**

- **Existing B2B very low capacity**
- **Best wind resource mainly in EI; best solar resource mainly in WI;**
  - transmission enables use of both everywhere.
- **Diurnal load diversity (time zones)**
  - CAL can compete 5MW in NY during NY peak;
  - NY can compete 7MW in CAL during CAL peak.
  - Reduces cost during each regions hi-cost hour for energy and/or for contingency reserves.
  - Reduces cost during other hrs if markets allow.
- **Annual load diversity (geo-differences)**
  - CAL’s 5MW (or more) can reduce NY capacity;
  - NY’s 7MW (or more) can reduce CAL capacity.
Application – Interconnection Seams Study

Objective: identify least-cost way to achieve 40% CO₂ reduction rel to 2005 by 2038.

Heavy AC network
reinforcement to move power
from each interconnection’s
resources its load centers

Design 1: No HVDC upgrades, i.e., no additional cross-seam capacity.
Application – Interconnection Seams Study

Objective: identify least-cost way to achieve 40% CO₂ reduction rel to 2005 by 2038.

Heavy AC network reinforcement to move power to coasts.

Design 1: No upgrades, i.e., no additional cross-seam capacity.
Design 2-A: Reconfigured seam - additional B2B capacity only.
<table>
<thead>
<tr>
<th>Objective Function Term</th>
<th>Case 1 (Baseline)</th>
<th>Case 2A (Upgrade existing B2B)</th>
<th>Difference (ΔNPV/NPVCa se1) (%)</th>
<th>Comments</th>
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</thead>
<tbody>
<tr>
<td>Total NPV</td>
<td>2,334</td>
<td>365</td>
<td>2,699</td>
<td>2,612</td>
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<tr>
<td>Generation Investment NPV</td>
<td>311</td>
<td>61</td>
<td>372</td>
<td>347</td>
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<td>Production Cost NPV</td>
<td>1,523</td>
<td>221</td>
<td>1,744</td>
<td>1,693</td>
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<td>Transmission Investment NPV</td>
<td>12</td>
<td>2</td>
<td>15</td>
<td>20</td>
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<tr>
<td>FixedO&amp;M NPV</td>
<td>373</td>
<td>73</td>
<td>447</td>
<td>439</td>
</tr>
</tbody>
</table>
Application – Interconnection Seams Study

Objective: identify least-cost way to achieve 40% CO₂ reduction rel to 2005 by 2038.

Pay more for HVDC line but reduce AC transmission reinforcement in each interconnection.

Design 1: No upgrades, i.e., no additional cross-seam capacity.

Design 2-A: Reconfigured seam - additional B2B capacity only.

Design 2-B: Reconfigured seam - additional capacity via B2B/HVDC lines.
Application – Interconnection Seams Study

Objective: identify least-cost way to achieve 40% CO$_2$ reduction rel to 2005 by 2038.

Save money by avoiding most AC reinforcement but pay high cost for macrogrid overlay.

Design 1: No upgrades, i.e., no additional cross-seam capacity.
Design 2-A: Reconfigured seam - additional B2B capacity only.
Design 2-B: Reconfigured seam - additional capacity via B2B/HVDC lines
Design 3: Macrogrid overlay.
Other infrastructure – natural gas pipelines


θᵢ - θⱼ = Xᵢ,ⱼPᵢ,ⱼ

cᵢρᵢ - cⱼρⱼ = K′ᵢ,ⱼGᵢ,ⱼ

Important difference: Linearized power flow equations are good for MW flows. However, in linearized gas flow equations, constants cᵢ and cⱼ are sensitive to pressures, so a piecewise linear gas pipeline model is necessary.

High Carbon Price; w/RPS, 20 years

Type, location, timing, & capacity of gen additions change when gas pipelines are considered.
**Other infrastructure – distributed resources**

![Graph showing added solar, wind, and gas generation capacity in the US from 2010 to 2015.]

- **DG benefits**: less transmission, loss reduction.
- **Investment cost**: LCOE - $242 PV-rooftop; $64 PV-utility, $55 wind; $65 NGCC.
- **Reliability**: It is unclear whether reliability improves (w/, w/o microgrid), and if it does, whether improvement justifies the cost. Check SAIDI & SAIFI.
- **O&M**: Low for solar, hi for wind. Low for utility scale, high for DG.
- **Green people**: Can be satisfied with community solar.
- **Analysis**: Need co-optimization to answer these questions.
Integrates heat/cooling, and electricity; renewable because it utilizes biomass.
Provides partial hedge for high risks of shale gas.
A new concept of DG, mid-size (1-100MW), located at T/D substation.
MIMO+cheap storage enables provision of flexibility, resilience, adaptability.
Requires a new way of thinking: Energy Systems Integration (www.iiesi.org)
Handling Uncertainty

Global (not parametric) uncertainties expressed as: Yes, No; or H, M, L

Minimize:
\[ \text{NPW}\{\text{CoreCosts}(x) + \sum_k \text{Pr}_k \times \{\text{OpCost}(\Delta x_k)\} + \text{AdaptationCost}(\Delta x_k)\} \]

Subject to:
- Operational constraints
- Flexibility constraints
- Reliability constraints
- Resiliency constraints

for futures \(k=1,\ldots,N\)

\(x\): Core investments, to be used by all futures \(k\)
\(\Delta x_k\): Additional investments needed to adapt to future \(k\)

Work done in collaboration with Ben Hobbs, Schad Professor in Env Mngmnt, Director of Env, Energy, Sustainability & Health Institute, Johns Hopkins University
Take-aways

1. Wind energy has been/will continue to be a go-to energy resource.
2. New transmission is essential for reaching clean-energy goals at lowest cost.
3. DG is good but community solar is better.
4. Hybrid energy systems provide clean flexibility.
5. We cannot predict the future but computational tools should be used to explore it.