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

WESEP 594

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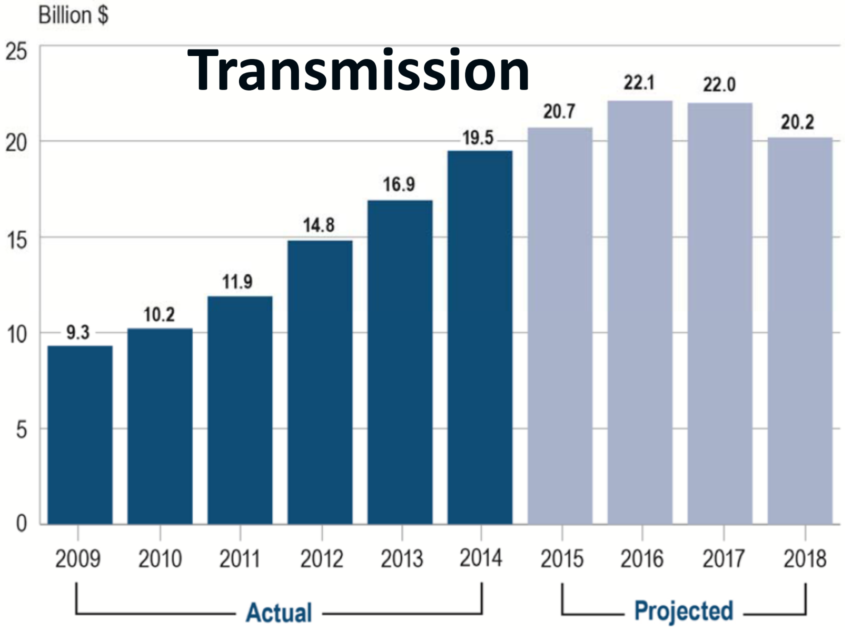
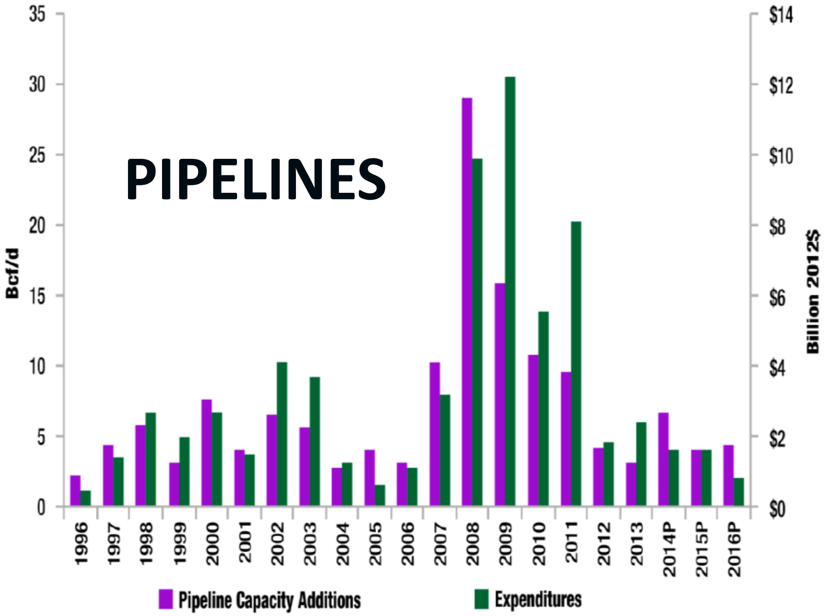
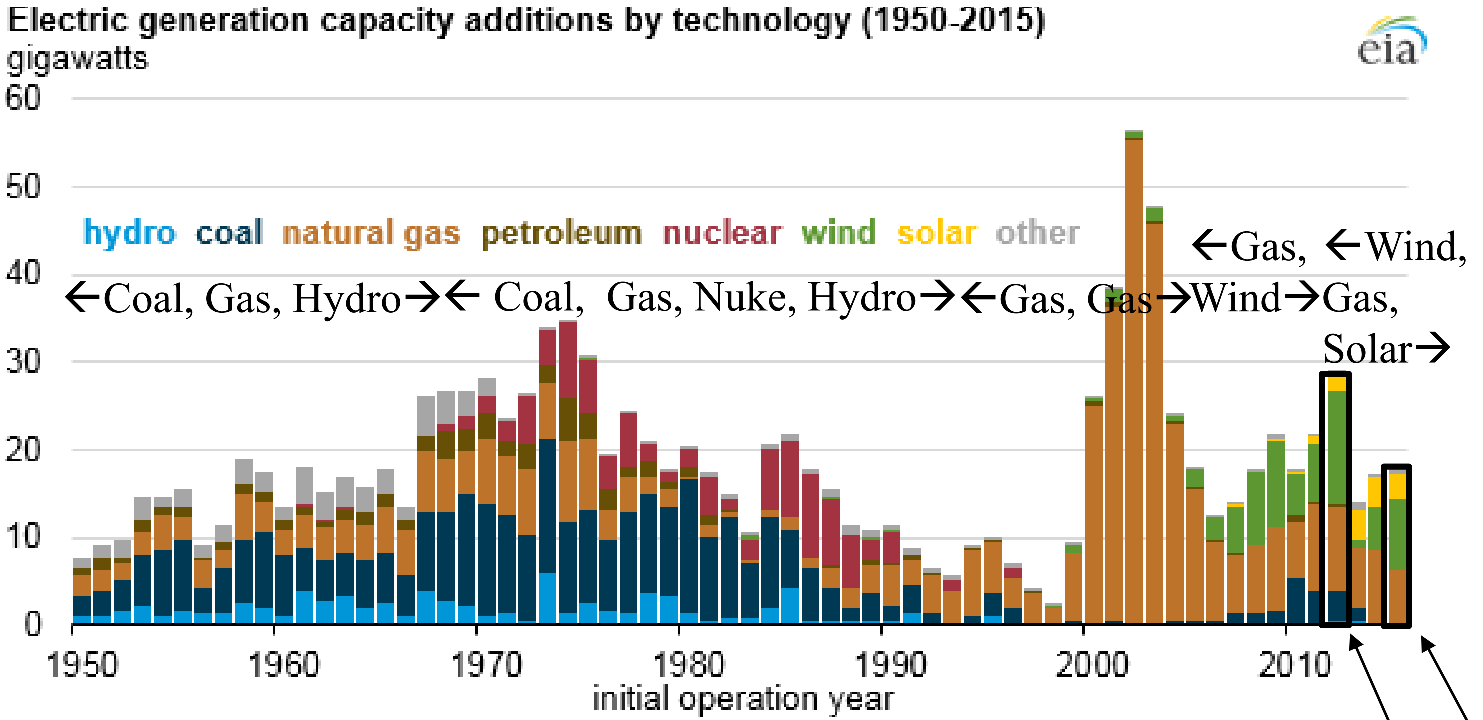
Overview

1. Introduction (G&T)
    - Motivating concepts
    - Approach
    - Mental picture
    - Modeling
2. Applications (G&T)
    - Iowa
    - BPA
    - EI/WI Seam
3. Other infrastructure:
    - natural gas pipelines
    - distributed resources
    - hybrid energy systems
4. Handling uncertainty
5. Conclusions

Motivating concepts







←Coal, Gas, Hydro→← Coal, Gas, Nuke, Hydro→←Gas, Gas→Wind→Gas, Solar→

←Gas, ←Wind,

2012, 2015, wind investment is #1!

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

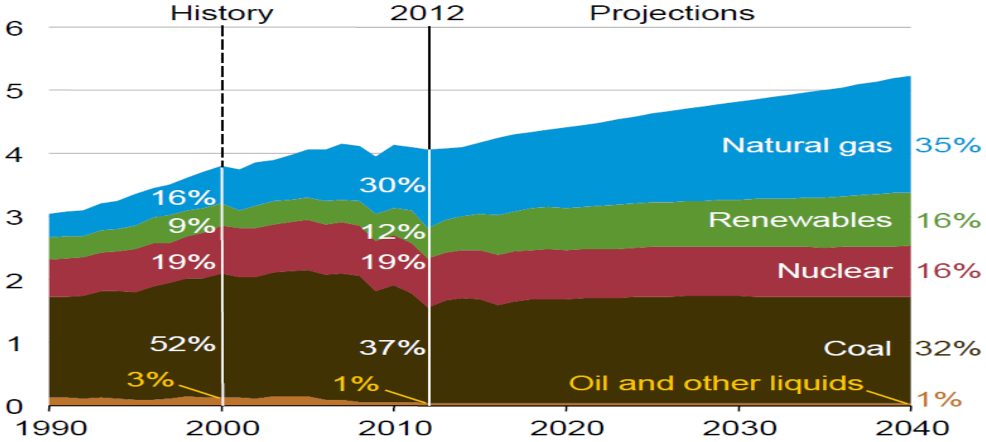
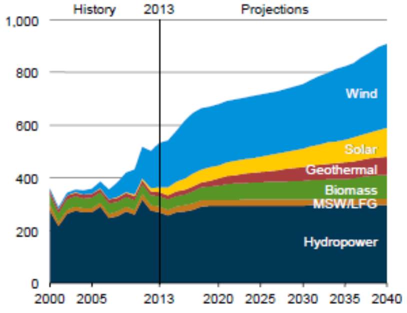
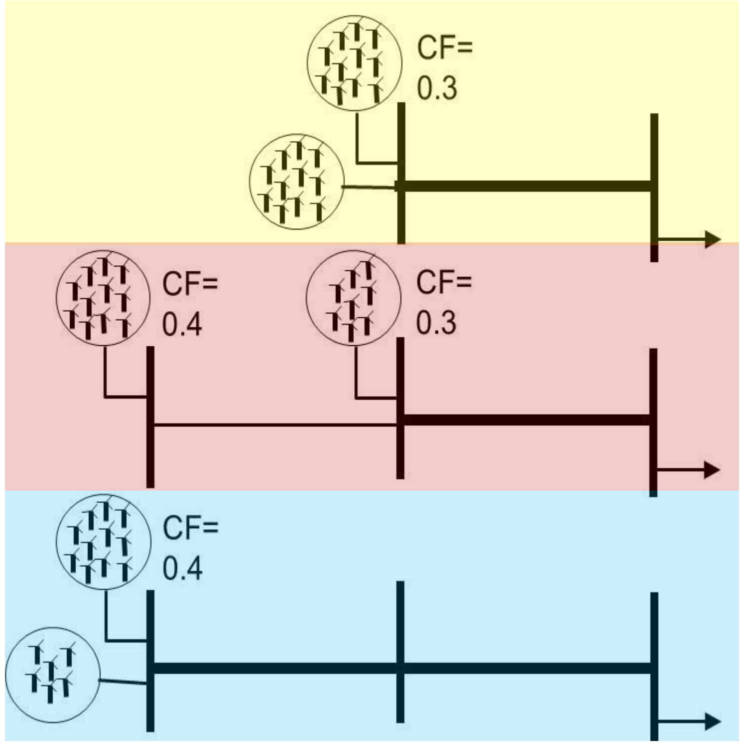


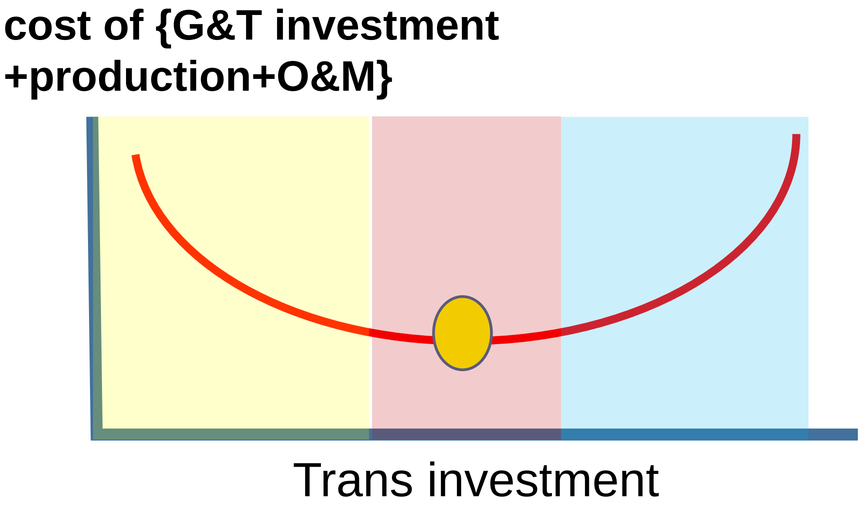
Figure 34. Renewable electricity generation by fuel type in the Reference case, 2000-2040 (billion kilowatthours)



Motivating concepts

Wind & transmission





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

Approach

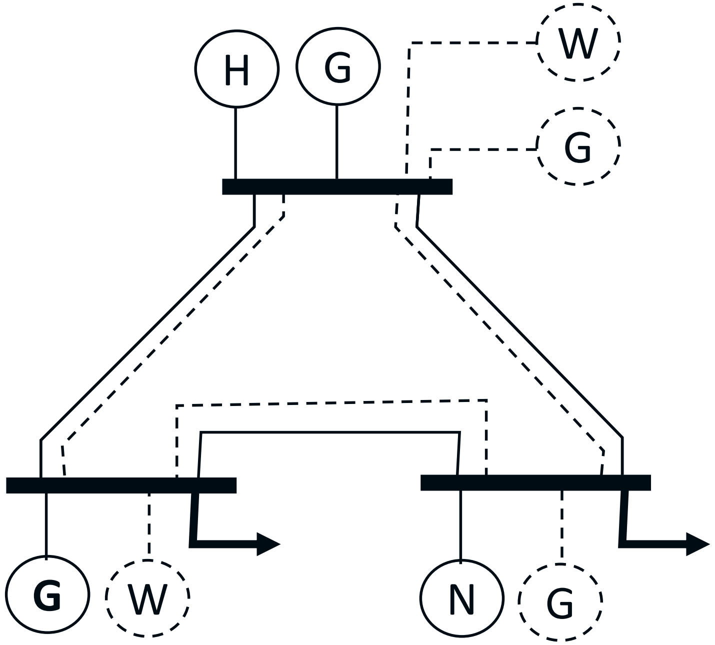
Co-optimization: the simultaneous identification of 2 or more classes of related infrastructure decisions within 1 optimization problem.

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 }

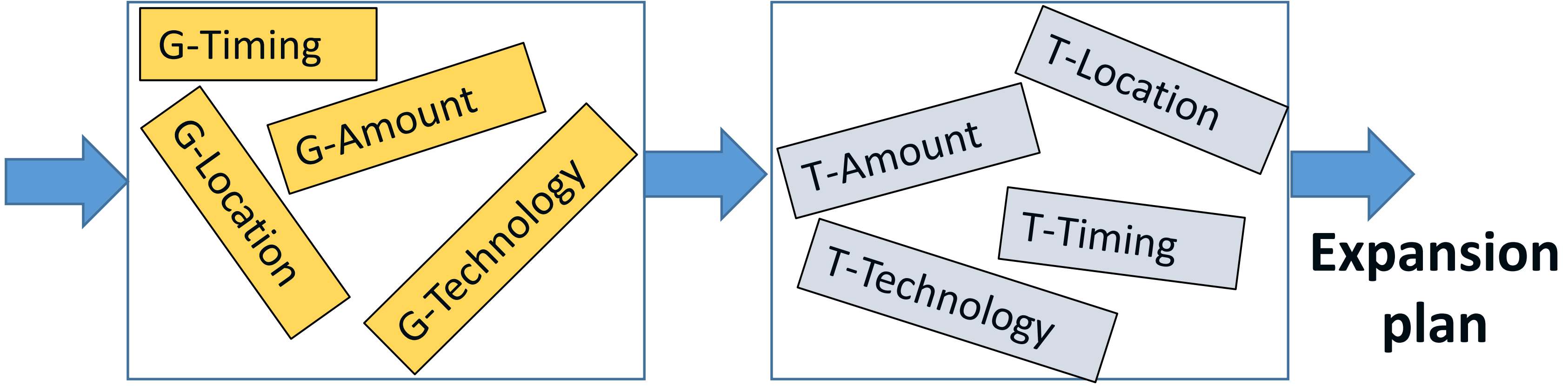
SUBJECT TO:
Investment constraints
Operational, planning, environmental constraints
Uncertainty characterization

Year 1 **Year 2** … **Year N**



Approach

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



Generation Expansion Plan (GEP)

G-Timing

G-Amount

G-Location

G-Technology

Transmission expansion plan (TEP)

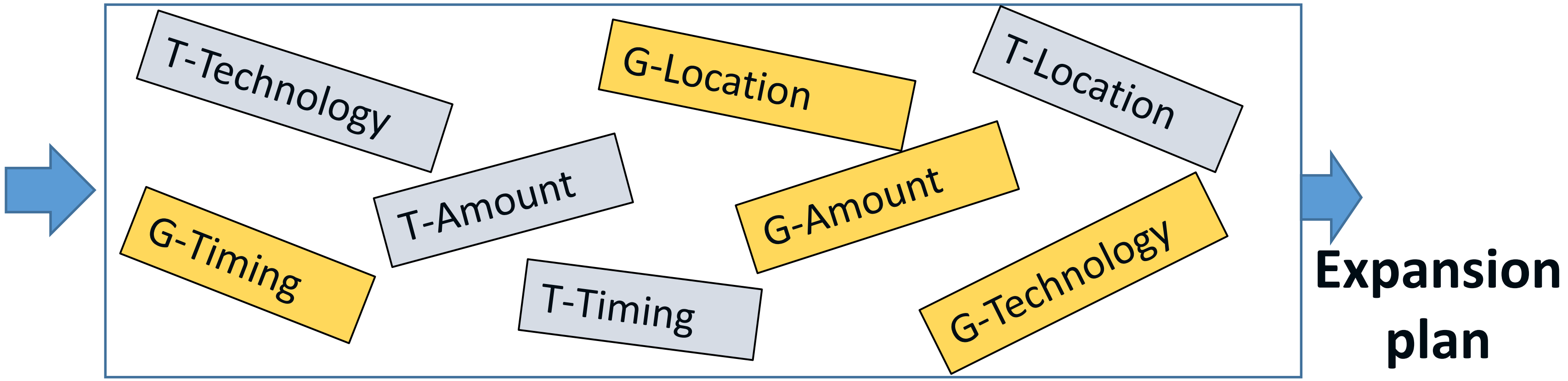
T-Location

T-Amount

T-Timing

T-Technology

Expansion plan



Co-optimized expansion planning decisions (CEP)

T-Technology

G-Location

T-Location

T-Amount

G-Amount

G-Timing

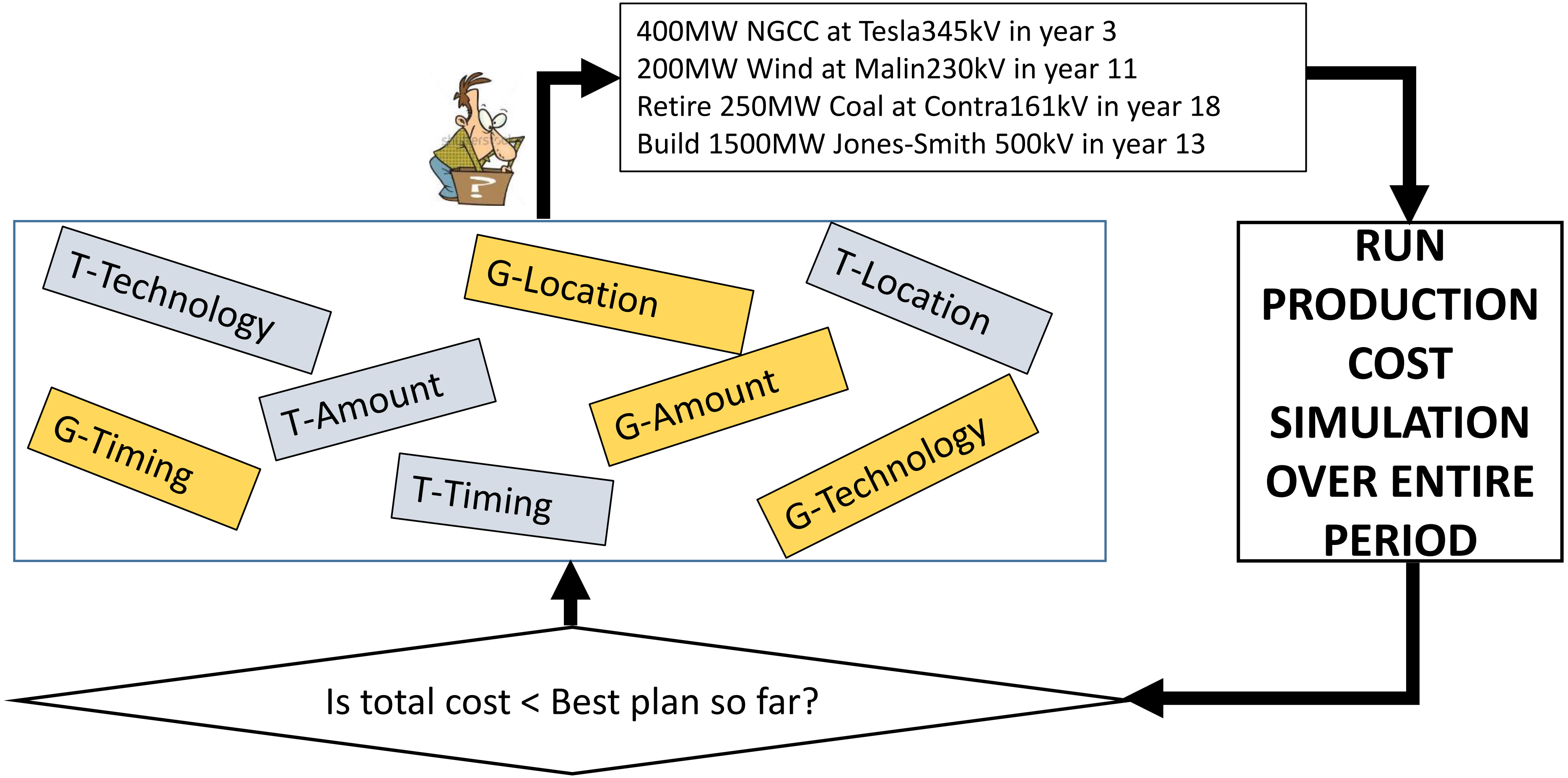
T-Timing

G-Technology

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

RUN PRODUCTION COST SIMULATION OVER ENTIRE PERIOD

T-Technology
G-Location
T-Location
T-Amount
G-Amount
G-Timing
T-Timing
G-Technology

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.

Modeling…

NETWORK

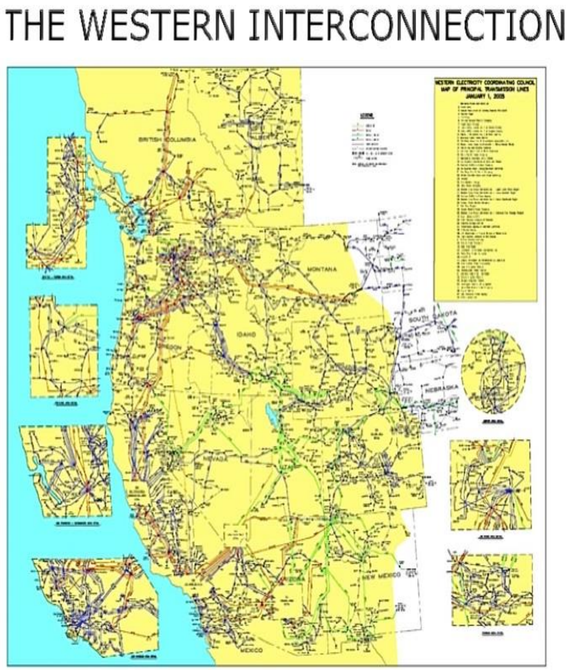
OPERATING (LOAD) BLOCKS

RESOURCES

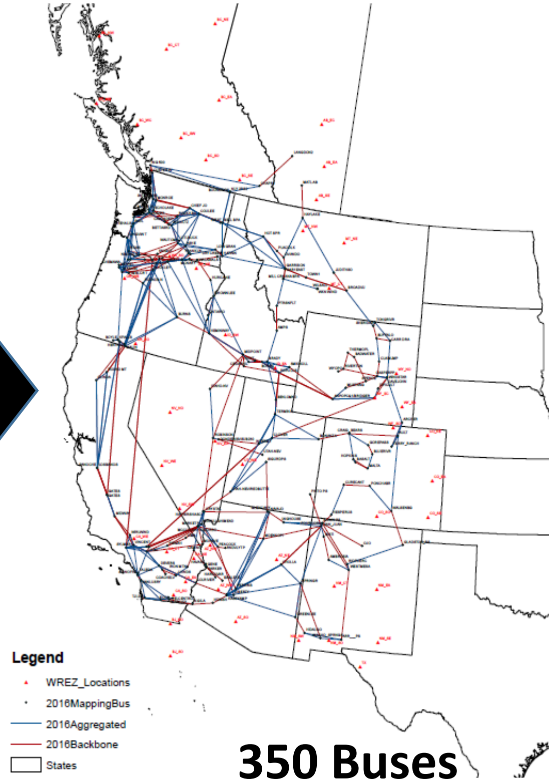
TRANSMISSION

Modeling - Network

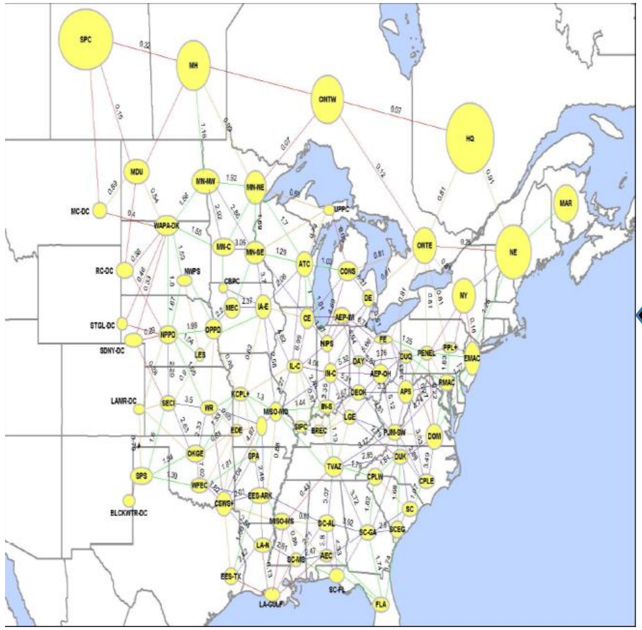
1. **Reduced network is represented using DC power flow, with "normal condition" flow limits. N-1 analysis not done (yet).**



20,000 Buses



350 Buses



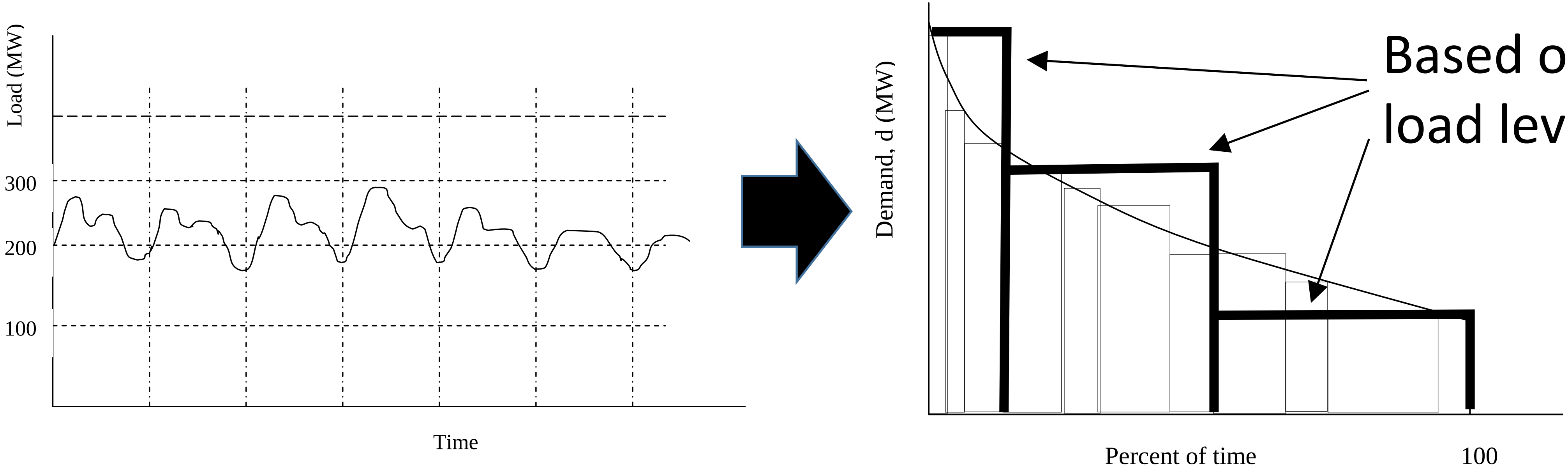
110 Buses

50,000 Buses

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.

Modeling – resources

12. 1 min, 10min, 30min reserve modeled as function of variability; variability a function of load & wind/solar penetration.

REGULATING RESERVES (1 MIN)

CpbltyRegUpRsrvs > k_1[1min netload standard deviation]

CpbltyRegDownRsrvs > k_2[1min netload standard deviation]

LOAD FOLLOWING (10-MIN)

CpbltyLF,UpRsrvs > k_3[10min netload standard deviation]

CpbltyLF,DownRsrvs > k_4[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

$$P_{ij} - z_{ij}B_{ij}\left(\theta_i - \theta_j\right) = 0$$

$$-z_{ij}P_{ij\max} \le P_{ij} \le z_{ij}P_{ij\max}$$

Line is in

z_{ij}=1

$$P_{ij} - B_{ij}\left(\theta_i - \theta_j\right) = 0$$

$$-P_{ij\max} \le P_{ij} \le P_{ij\max}$$

Line is out

z_{ij}=0

$$P_{ij} = 0$$

$$0 \le P_{ij} \le 0$$

Disjunctive: equivalent linear model

$$-1000(1 - z_{ij}) \le P_{ij} - B_{ij}\left(\theta_i - \theta_j\right) \le 1000(1 - z_{ij})$$

$$-z_{ij}P_{ij\max} \le P_{ij} \le z_{ij}P_{ij\max}$$

Line is in

z_{ij}=1

$$0 \le P_{ij} - B_{ij}\left(\theta_i - \theta_j\right) \le 0$$

$$-P_{ij\max} \le P_{ij} \le P_{ij\max}$$

Line is out

z_{ij}=0

$$-1000 \le P_{ij} - B_{ij}\left(\theta_i - \theta_j\right) \le 1000$$

$$-0 \le P_{ij} \le 0$$

Application - Iowa

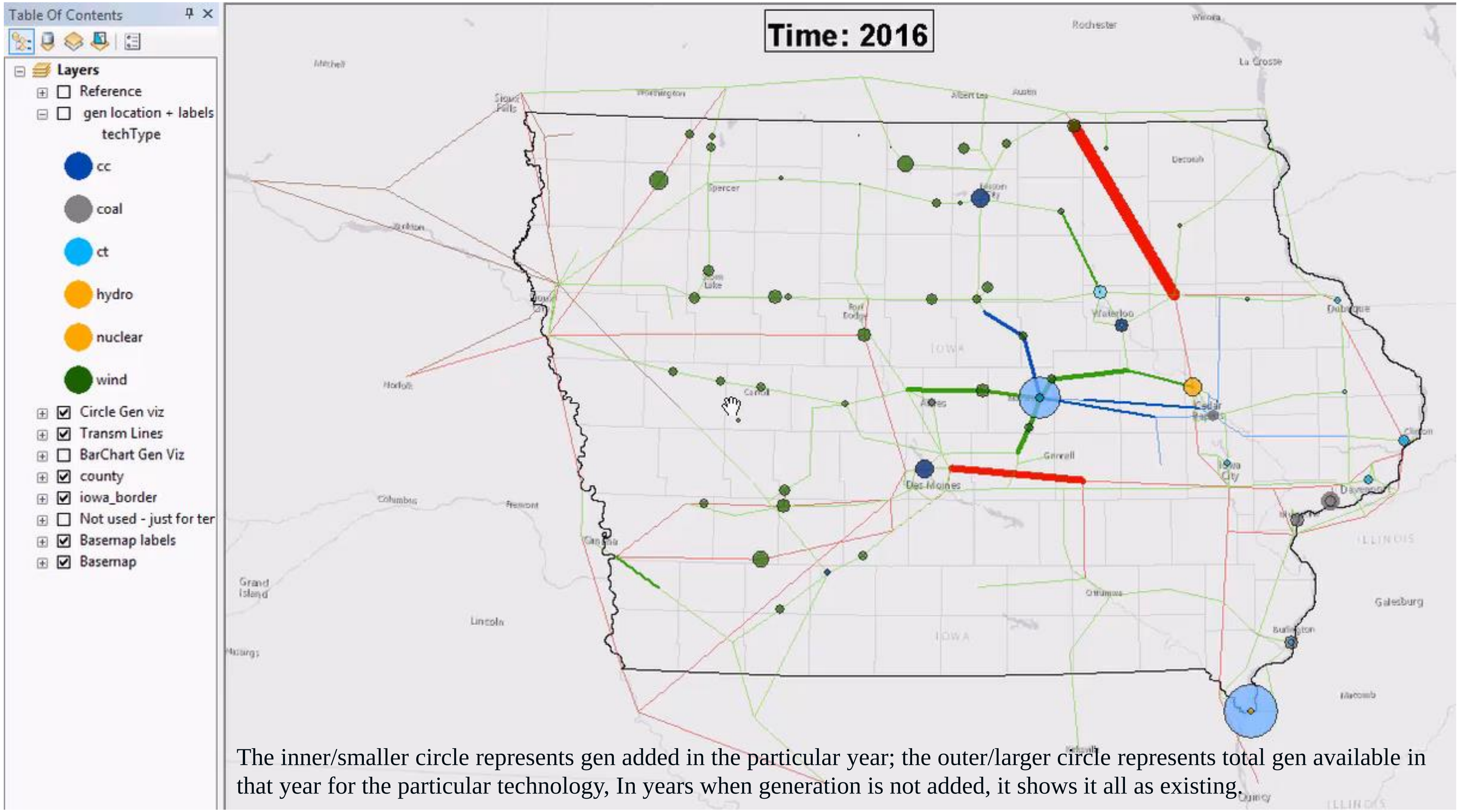
J. McCalley, C. Harding, “Leveraging a Geographic Information System in Co-optimized Generation and Transmission Expansion Planning for High Wind Penetration in Iowa,” funded by the Iowa State University Electric Power Research Center, 8/14-8/16.

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

Abhinav Venkatraman, Year 2 MS Student

Ali Jahanbahni, Post-doctoral researcher

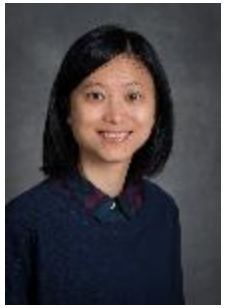
Chris Harding, Associate Professor Geological & Atmospheric Sciences



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.

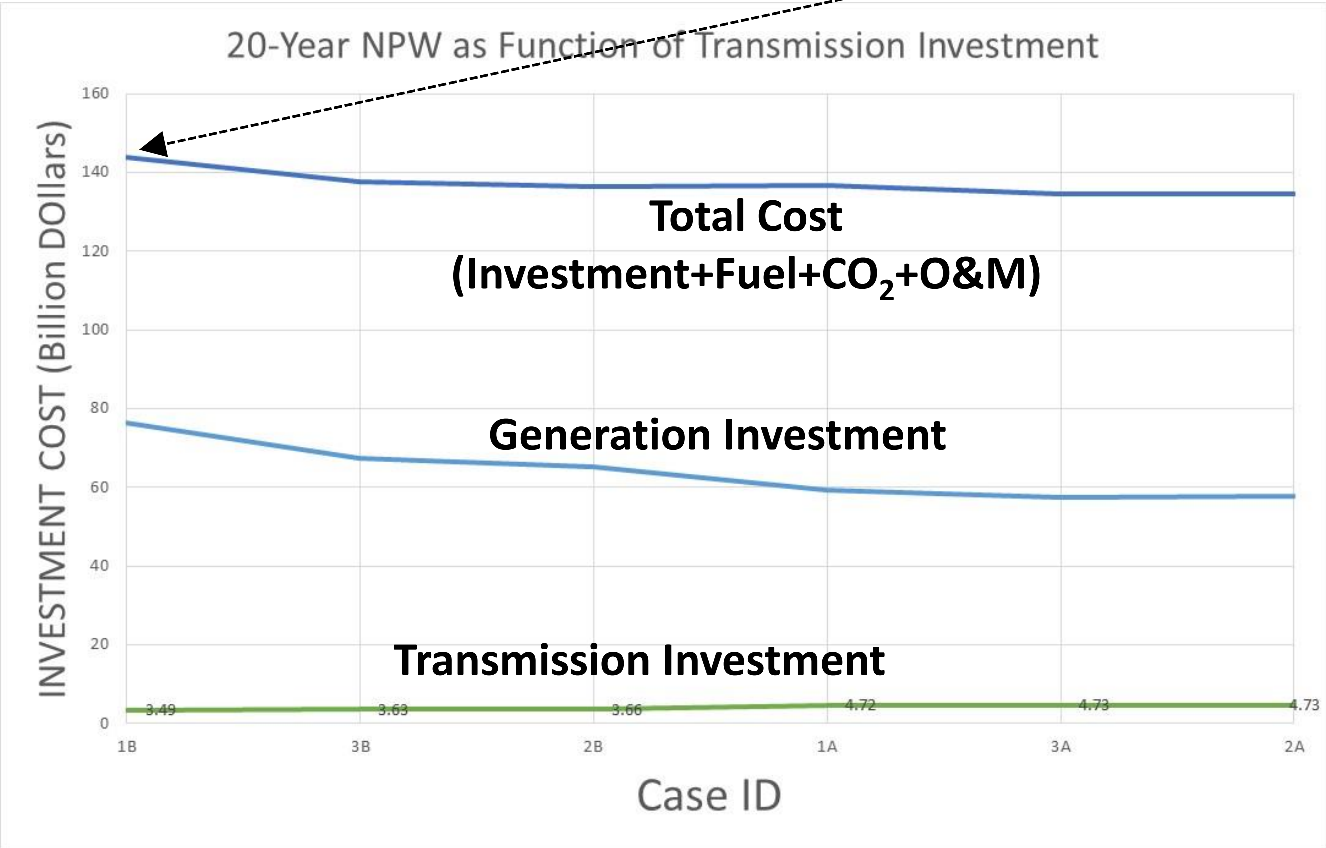
Application - BPA

Patrick Maloney,
Year 2 Ph.D. Student



Ping Liu,
Post-doctoral researcher

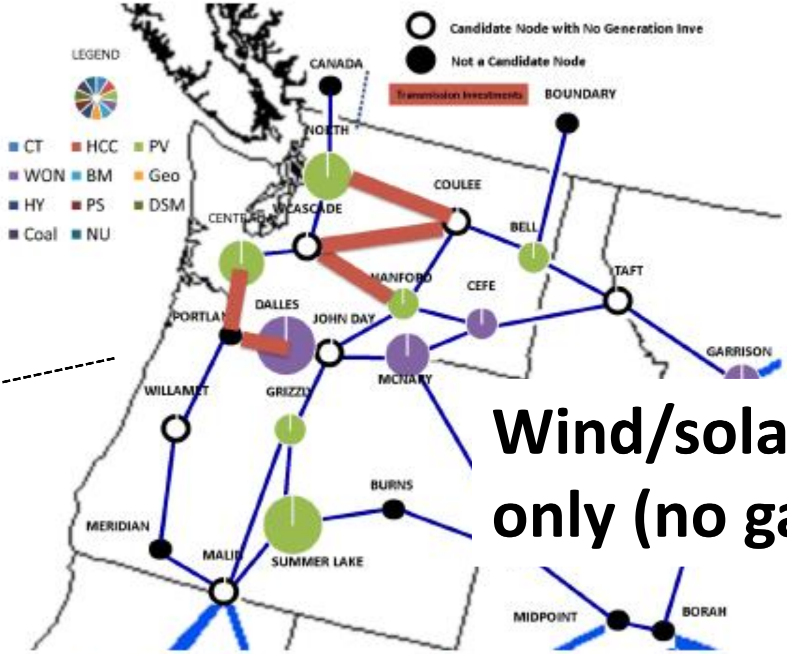
Work done in collaboration with Ben Hobbs, Schad Professor in Env Mngmnt, Director of Env, Energy, Sustanability & Health Institute, Johns Hopkins University



Total Cost
(Investment+Fuel+CO_2+O&M)

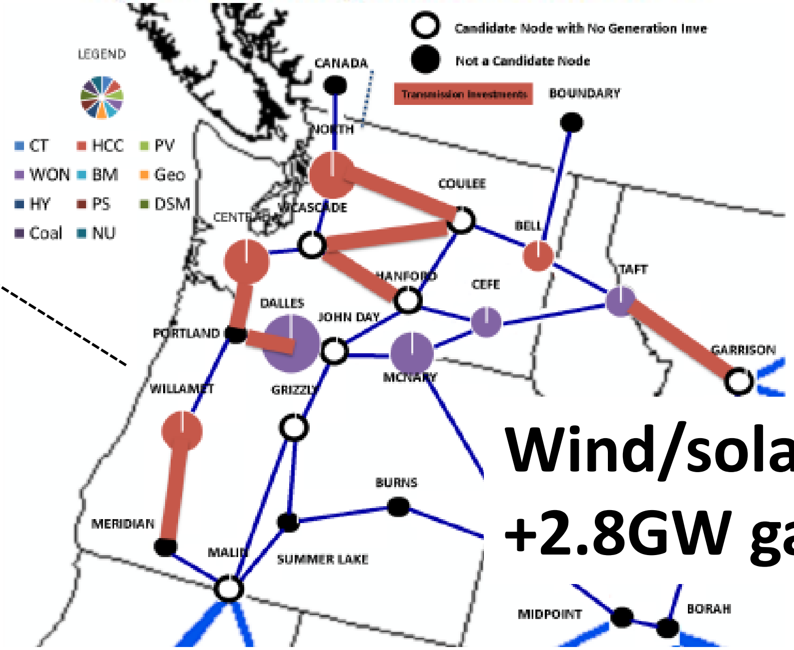
Generation Investment

Transmission Investment



Wind/solar only (no gas)

Figure 12: The line and generation investments in case 1B



Wind/solar +2.8GW gas.

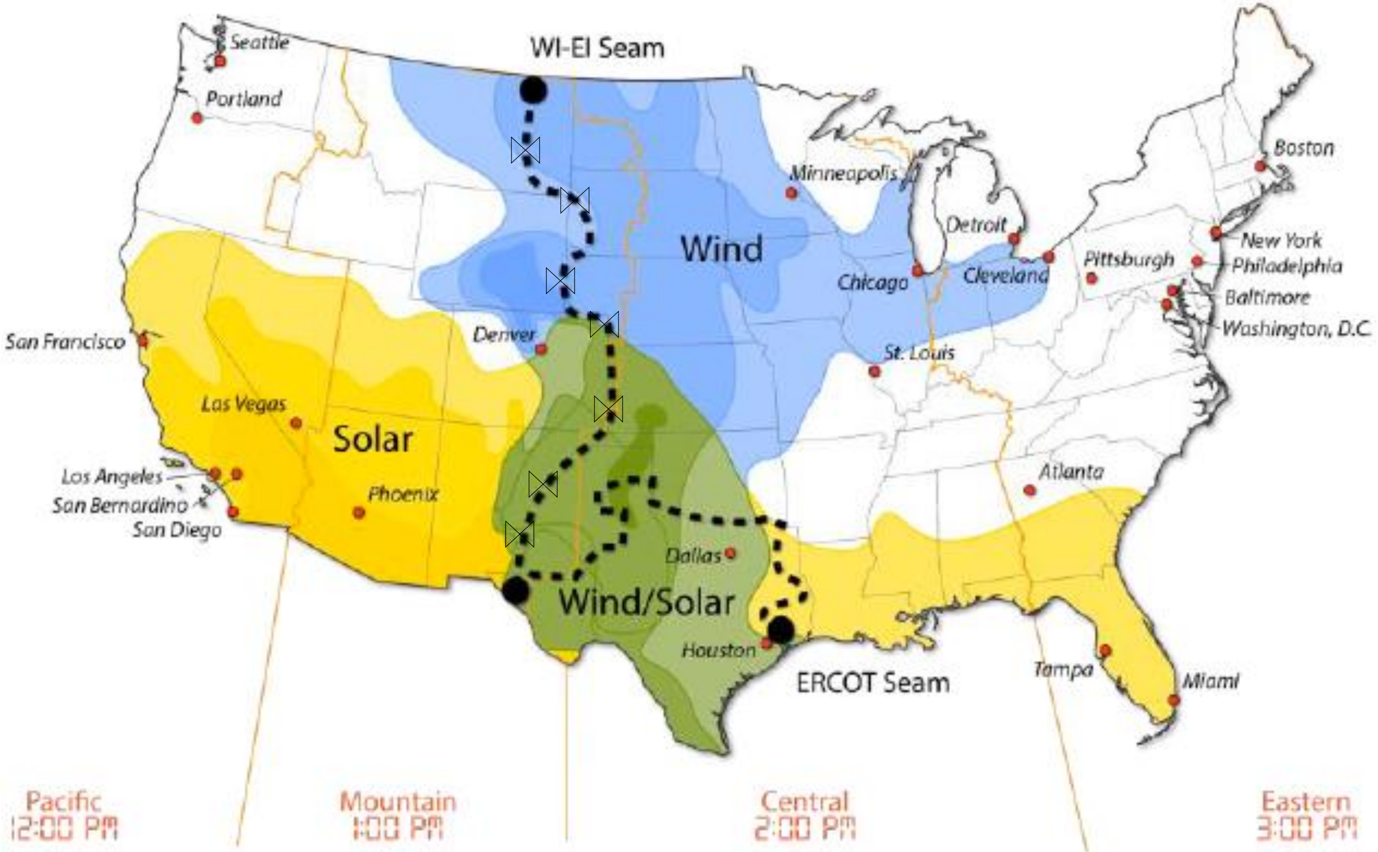
Figure 13: The line and generation investments in case 2A

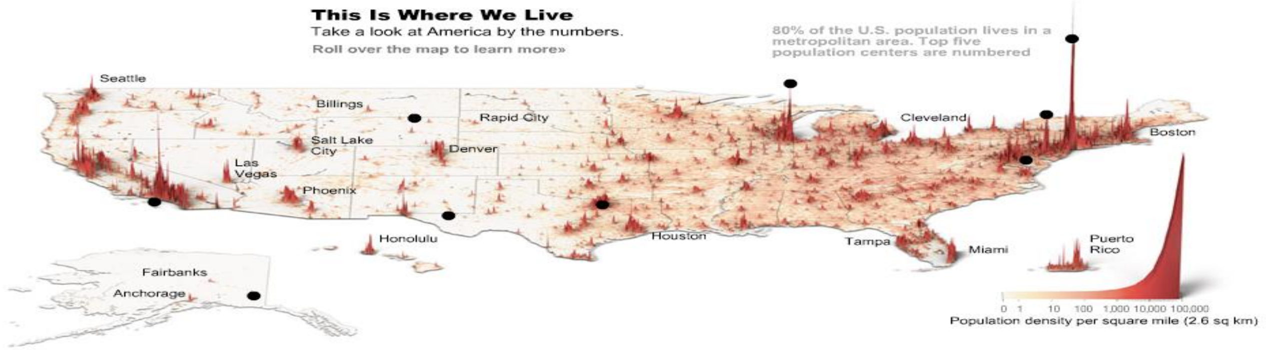
Application – Interconnection Seams Study

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





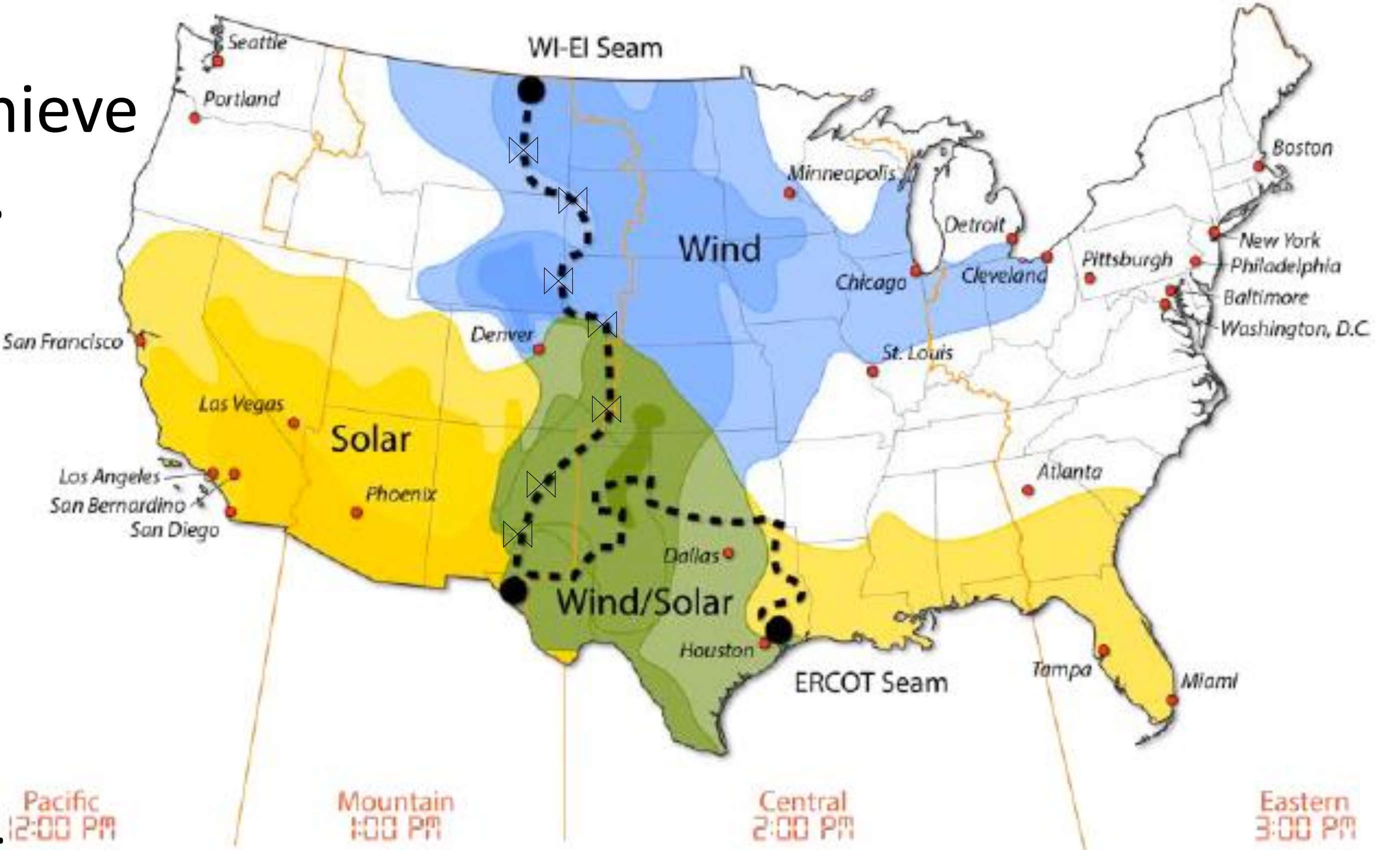
Abhinav Venkatraman, Year 2 MS Student

Ali Jahanbahni, Post-doctoral researcher

Armando Figueroa, Year 3 Ph.D. Student

Hussam Nosair, Post-doctoral researcher

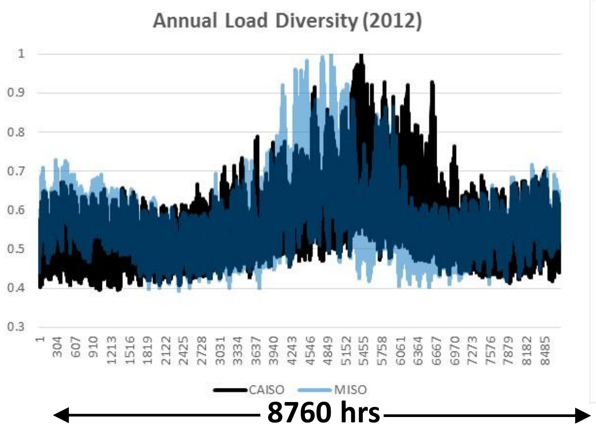
Application – Interconnection Seams Study

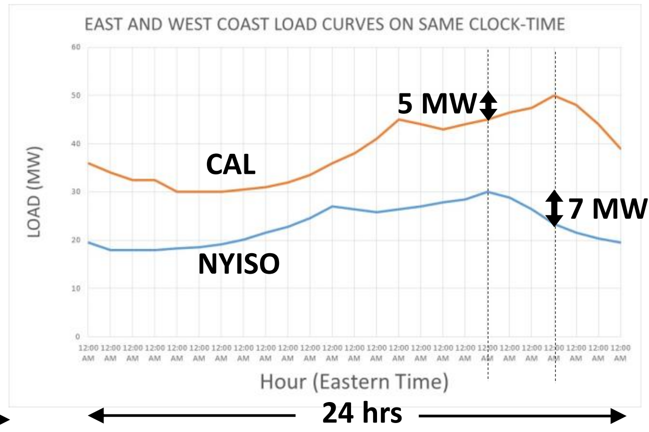


<u>Objective</u>: identify least-cost way to achieve 40% CO_2 reduction rel to 2005 by 2038.

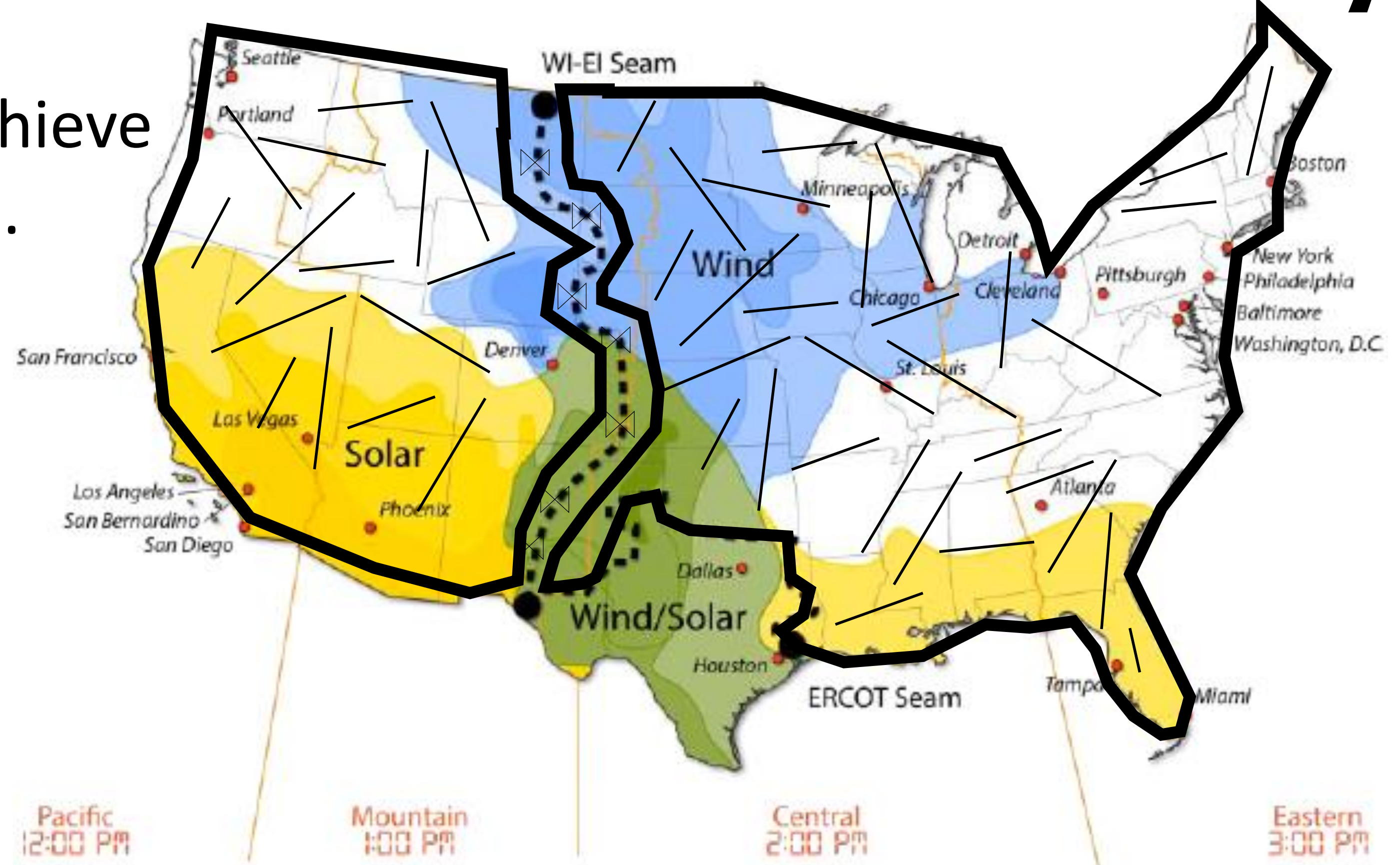
<u>Observations</u>:

- 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

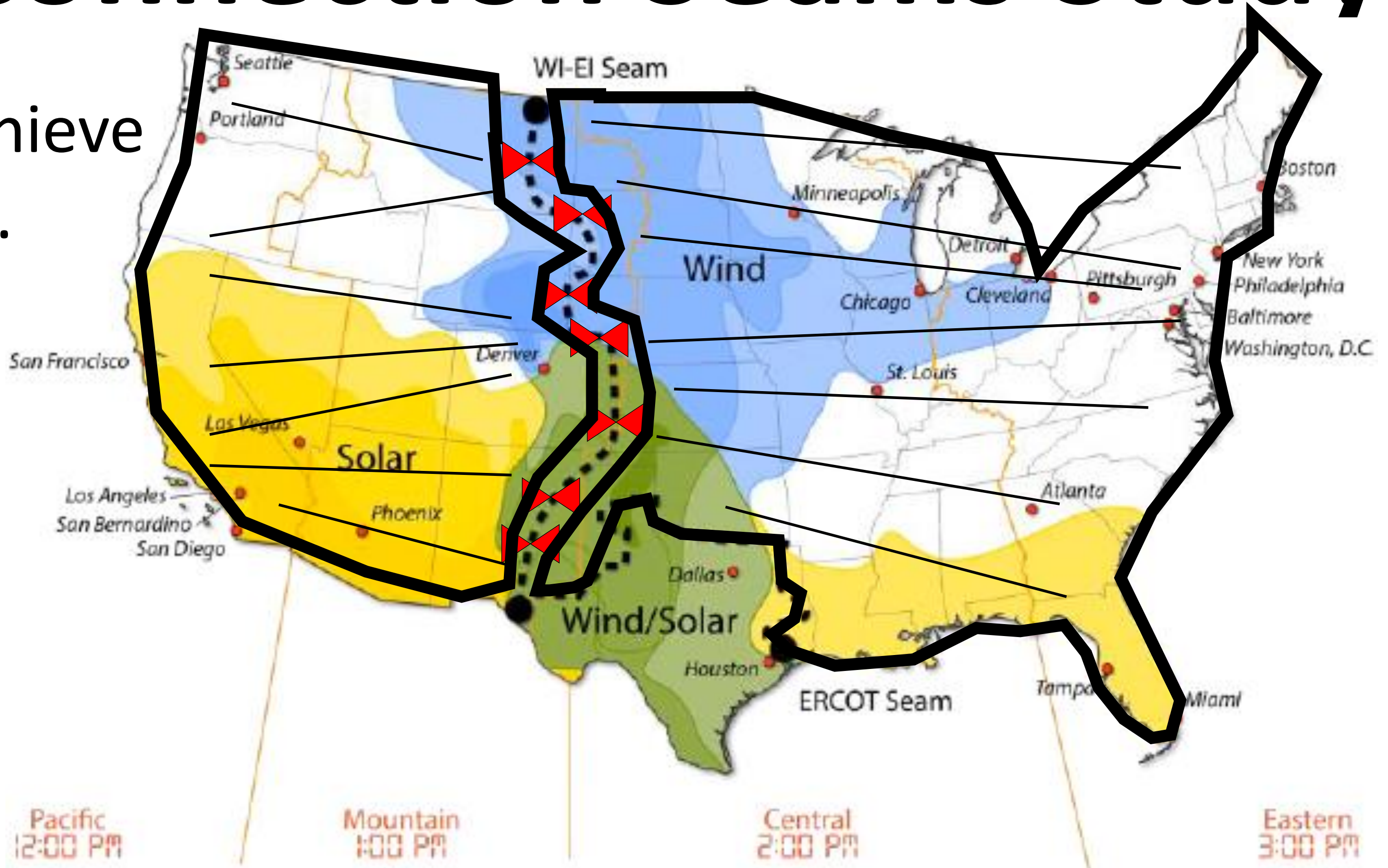


Objective: identify least-cost way to achieve 40% CO_2 reduction rel to 2005 by 2038.

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% CO_2 reduction rel to 2005 by 2038.

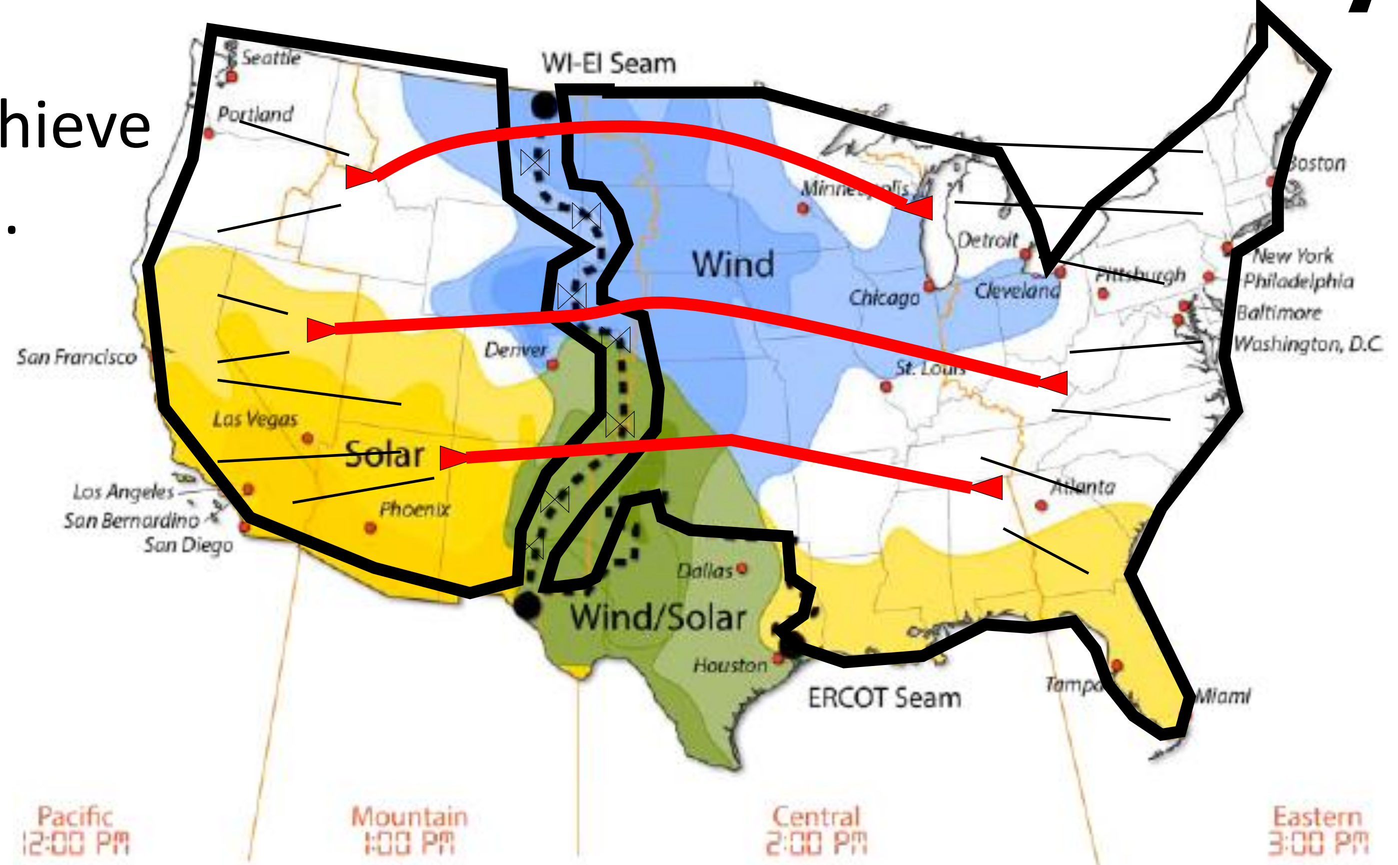
Heavy AC network reinforcement to move power to coasts.

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

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

Reach National RPS of 25% Renewable Energy by 2035 ($B)						
	Case 1 (Baseline)			Case 2A (Upgrade existing B2B)	Difference	Comments
Objective Function Term	Case 1 (EI)	Case 1 (WI)	Total	Total	(ΔNPV/NPVCase1) (%)	
Total NPV	**2,334**	**365**	**2,699**	**2,612**	**3.23%**	**<-- Savings**
Generation Investment NPV	311	61	372	347	0.92%	<-- Lower generation investment
Production Cost NPV	1,523	221	1,744	1,693	1.91%	<-- Lower production cost
Transmission Investment NPV	12	2	15	20	(0.18%)	<-- Additional transmission
FixedO&M NPV	373	73	447	439	0.30%	<-- Lower FixedO&M cost

Application – Interconnection Seams Study



<u>Objective</u>: identify least-cost way to achieve 40% CO_2 reduction rel to 2005 by 2038.

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

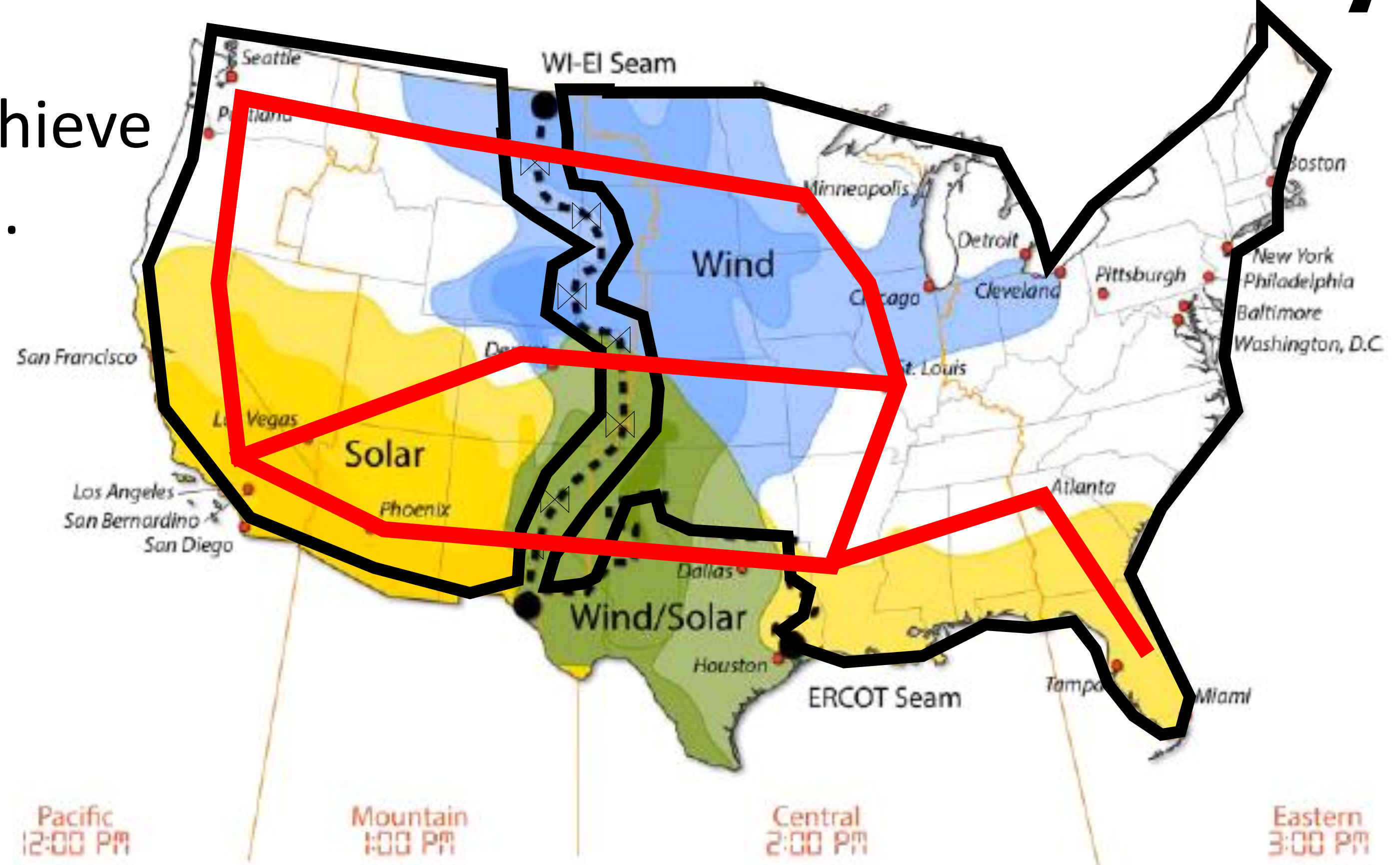
Design 1: No upgrades, i.e., no additional cross-seam capacity.

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

R. Johnson, E. Spyrou, S. Lemos-Cano, J. Ho, A. Figueroa, B. Hobbs, J. McCalley, “EISPC – Co-optimization of transmission and other resources,” NARUC Project 3316T4, 9/14-4/15, funded by the Eastern Interconnection States Planning Council (EISPC).

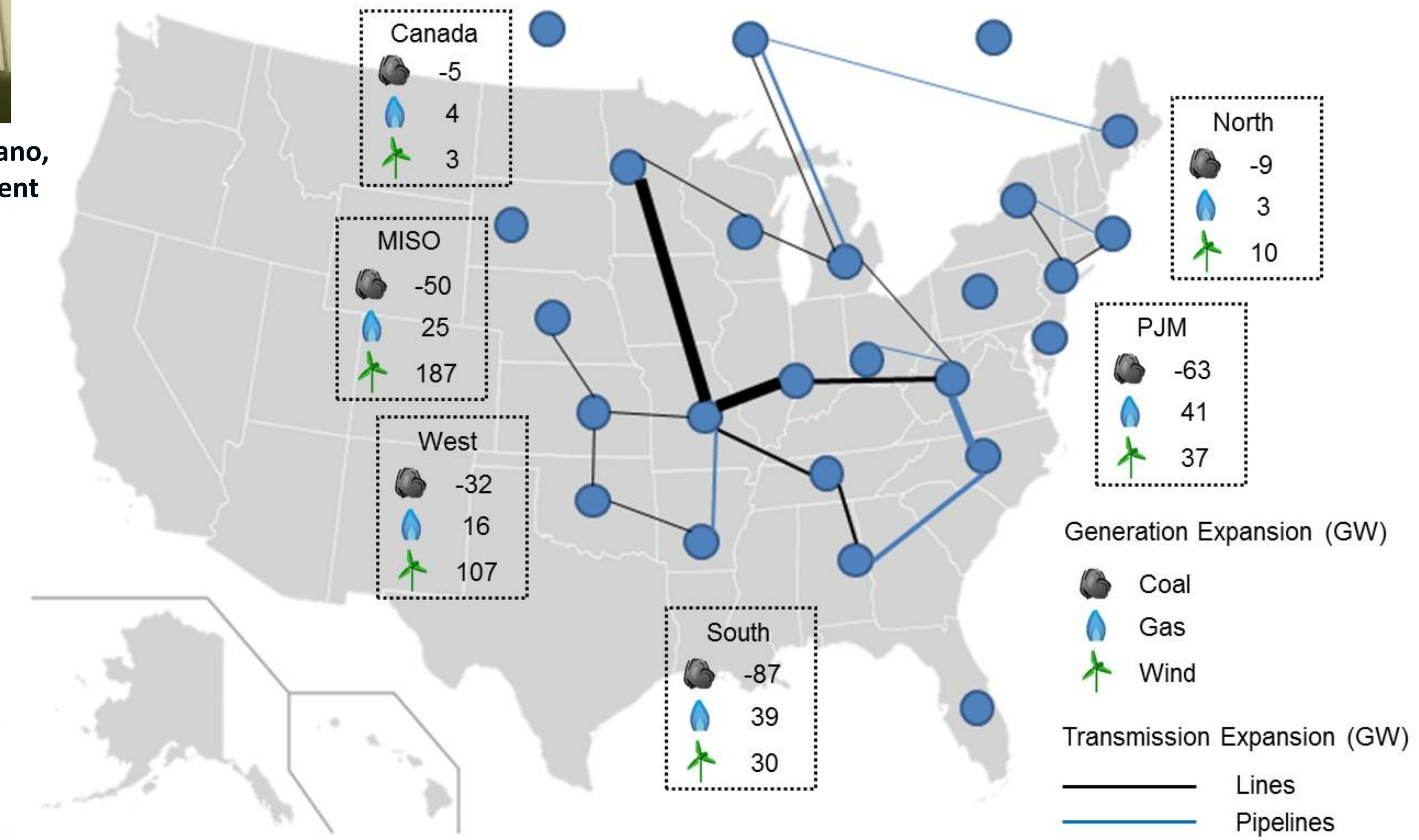
Santiago Lemos-Cano,
Year 4 Ph.D. Student

$$\theta_i - \theta_j = X_{i,j} P_{i,j}$$

$$c_i \ \rho_i \ - c_j \ \rho_j \ = K'_{i,j} G_{i,j}$$

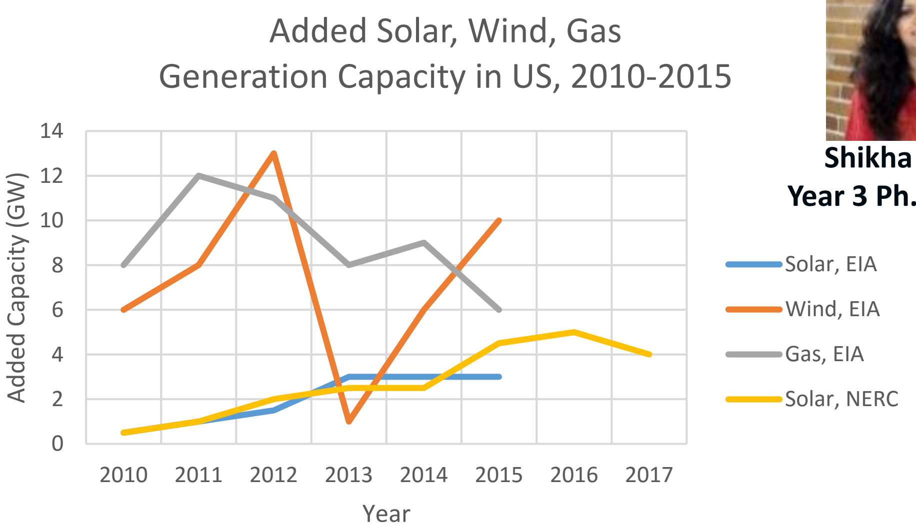
Important difference: Linearized power flow equations are good for MW flows. However, in linearized gas flow equations, constants c_i and c_j are sensitive to pressures, so a piecewise linear gas pipeline model is necessary.

High Carbon Price; w/RPS, 20 years

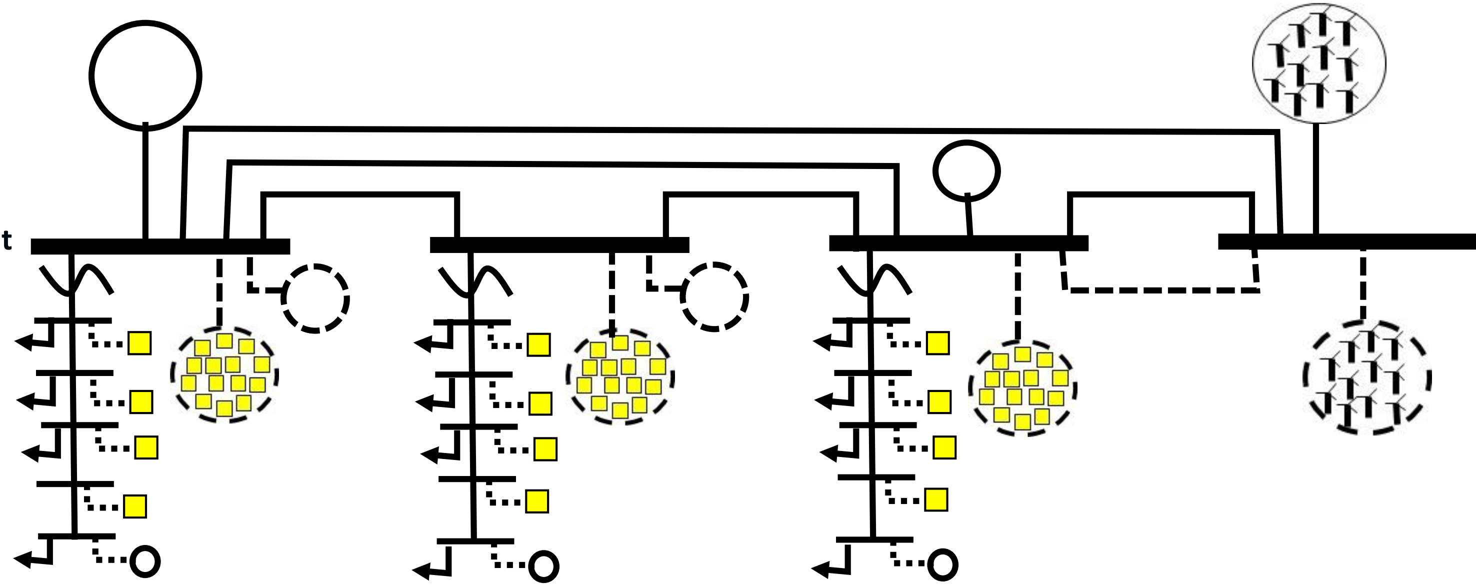


Type, location, timing, & capacity of gen additions change when gas pipelines are considered.

Other infrastructure – distributed resources



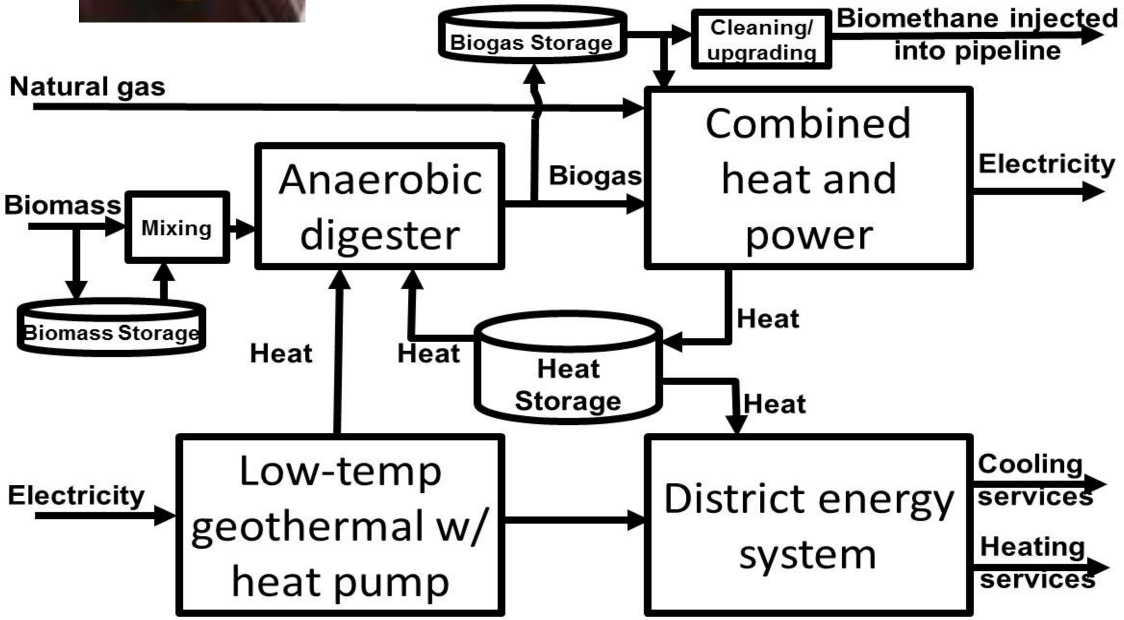
Shikha Sharma
Year 3 Ph.D. Student



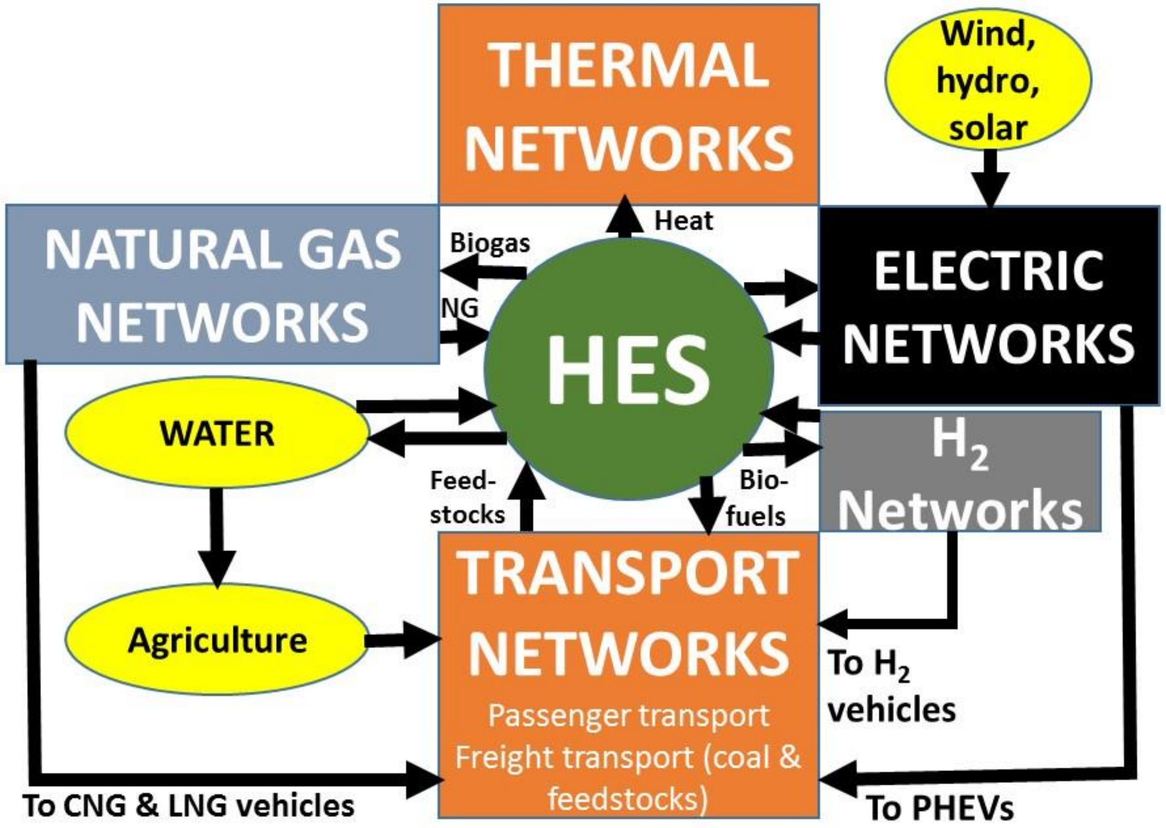
- <u>DG benefits</u>: less transmission, loss reduction.
- <u>Investment cost</u>: LCOE - $242 PV-rooftop; $64 PV-utility, $55 wind; $65 NGCC.
- <u>Reliability</u>: It is unclear whether reliability improves (w/, w/o microgrid), and if it does, whether improvement justifies the cost. Check SAIDI & SAIFI.
- <u>O&M</u>: Low for solar, hi for wind. Low for utility scale, high for DG.
- <u>Green people</u>: Can be satisfied with community solar.
- <u>Analysis</u>: Need co-optimization to answer these questions.

Other infrastructure – hybrid energy systems

Rajaz Amitava
Year 1 Ph.D. Student



Biogas Storage
Cleaning/ upgrading
Biomethane injected into pipeline
Natural gas
Combined heat and power
Anaerobic digester
Biogas
Electricity
Biomass
Mixing
Biomass Storage
Heat
Heat
Heat Storage
Heat
Heat
Electricity
Low-temp geothermal w/ heat pump
District energy system
Cooling services
Heating services



THERMAL NETWORKS
Wind, hydro, solar
NATURAL GAS NETWORKS
Biogas
NG
Heat
HES
ELECTRIC NETWORKS
WATER
Feed-stocks
Bio-fuels
H_2 Networks
Agriculture
TRANSPORT NETWORKS
Passenger transport
Freight transport (coal & feedstocks)
To H_2 vehicles
To CNG & LNG vehicles
To PHEVs

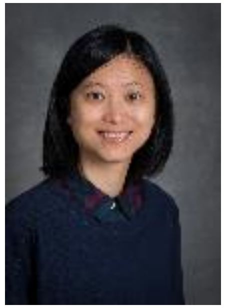
- Integrates heat/cooling, and electricity; renewable because it utilizes biomass.
- Provides partial hedge for high risks of shale gas.
- A new concept of DG, mid-size (1-100MW), located at T/D substation.
- MIMO+cheap storage enables provision of flexibility, resilience, adaptability.
- Requires a new way of thinking: Energy Systems Integration (www.iiesi.org)

Handling Uncertainty

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

Ali Jahanbahni,
Post-doctoral researcher

Patrick Maloney,
Year 2 Ph.D. Student



Ping Liu,
Post-doctoral researcher

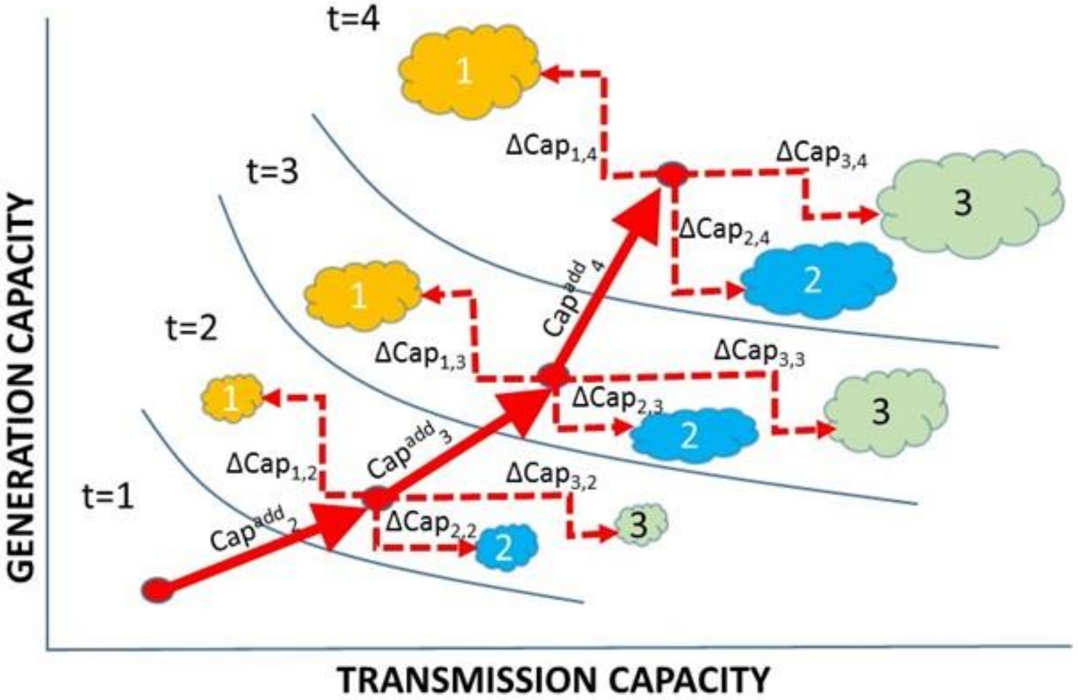
Work done in collaboration with Ben Hobbs, Schad Professor in Env Mngmnt, Director of Env, Energy, Sustanability & Health Institute,
Johns Hopkins University

Minimize:

$$\mathrm{NPW}\{\mathrm{CoreCosts}(\underline{x}) + \Sigma_k \, \Pr_k \times \{\mathrm{OpCost}(\Delta\underline{x}_k)\} + \mathrm{AdaptationCost}(\Delta\underline{x}_k)\}$$

Subject to:

$$\left.\begin{array}{l}\textbf{Operational constraints}\\ \textbf{Flexibility constraints}\\ \textbf{Reliability constraints}\\ \textbf{Resiliency constraints}\end{array}\right\} \textbf{for futures } k=1,\ldots N$$



$\underline{x}$: Core investments, to be used by all futures k

$\Delta\underline{x}_k$: Additional investments needed to adapt to future k

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.