# Integrated Energy System: Co-optimization & Design Issues


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Year 1 | Year 2 | . . . | Year N

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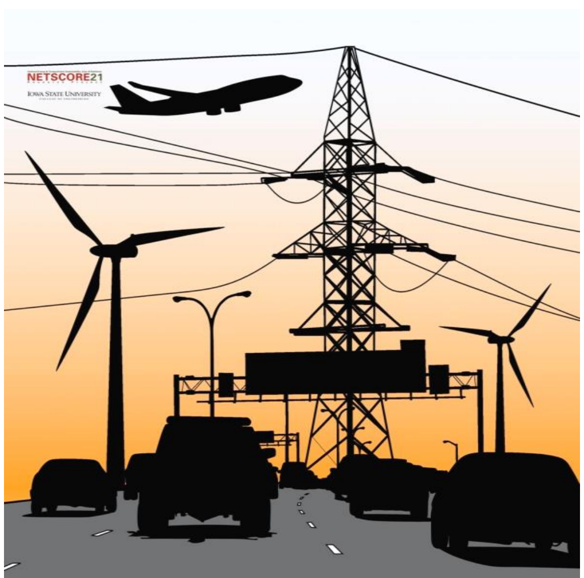
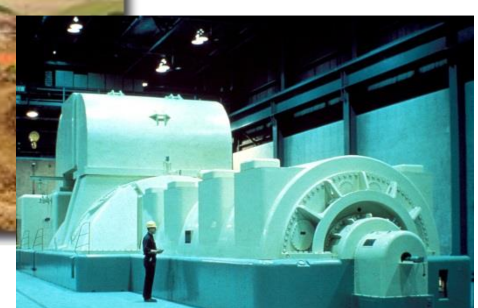


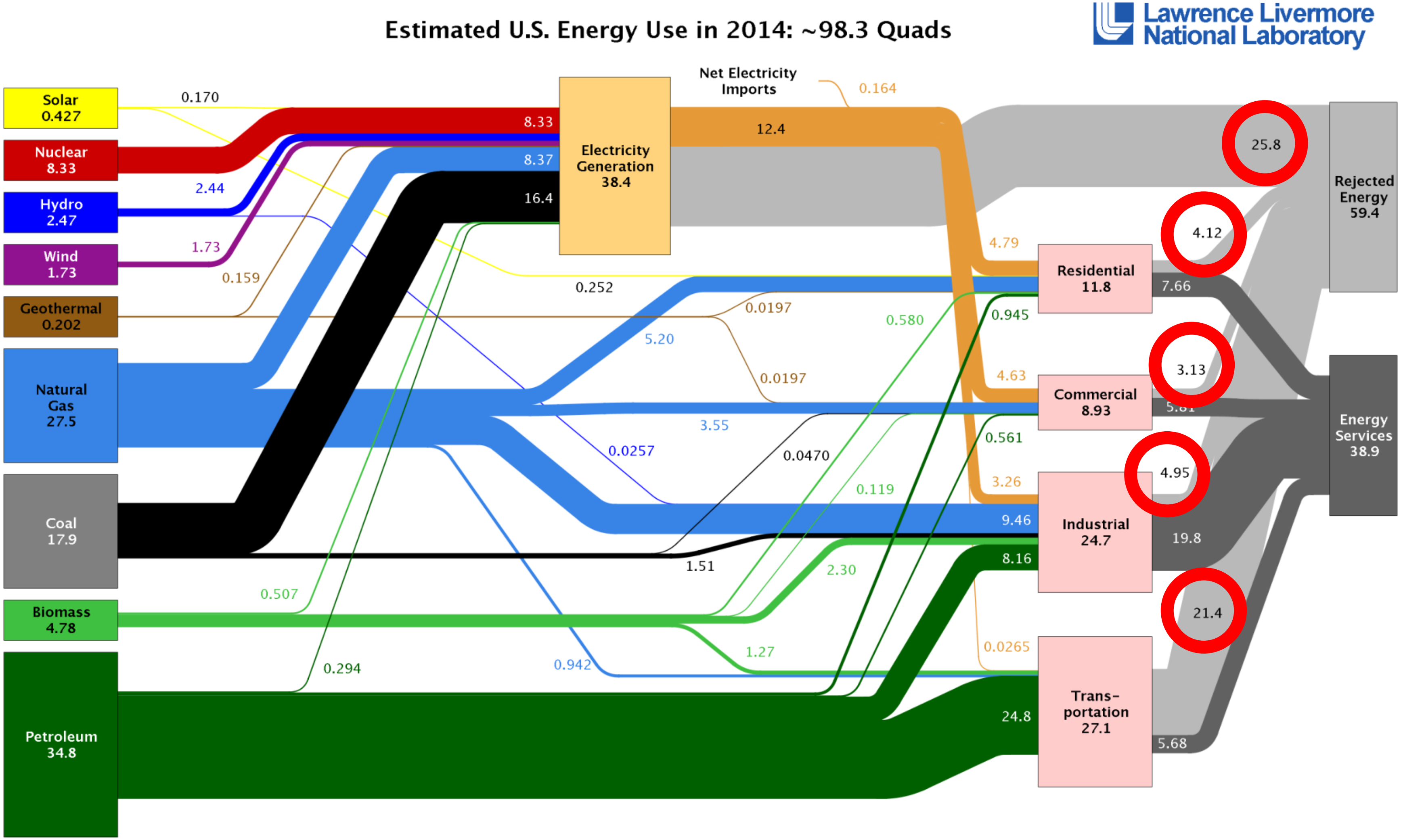



# Overview

1. A high-level view of:
   - US energy, transportation, water, GHG
   - Strategies to address GHG: abatement curves
2. Orientation of this discussion
3. Expansion planning: modeling and issues
4. Impedance vs. pipes&bubbles
5. Co-optimization for
   - G&T
   - G&T&Pipeline
   - G&T&Pipeline&Fuels&Transportation
6. Design objectives
7. Design procedure
8. Conclusions

# US Energy Flow- 2014

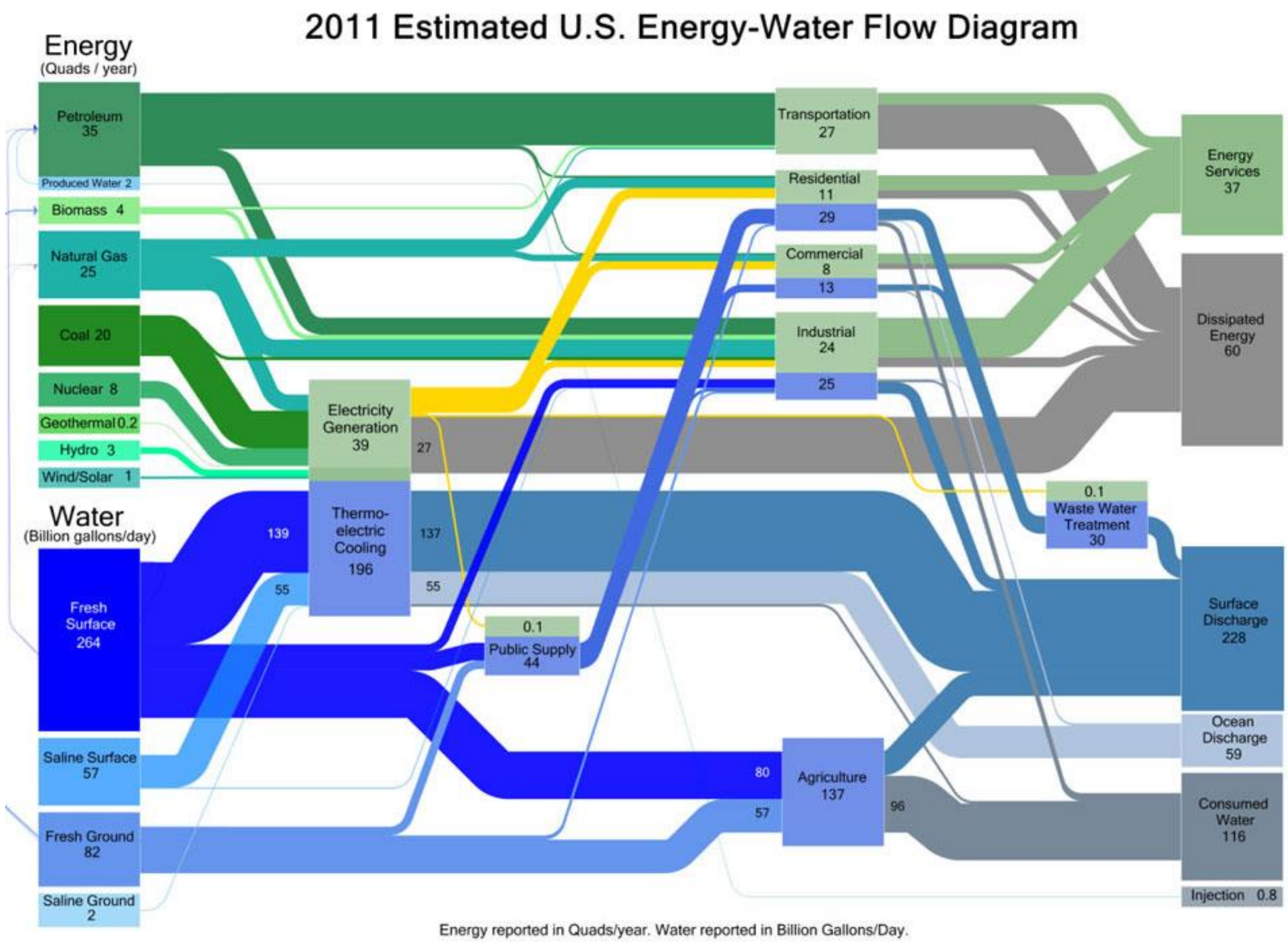
The 59.4 Quads of rejected energy, identified by the 5 red circles, represent opportunities to reduce the total energy consumed in the US.




Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

# US Energy/Water Flow- 2011

A recent report [1] indicates several major U.S. groundwater aquifers are stressed and are being depleted, particularly the Ogallala Aquifer in the Midwest. The diagram indicates most fresh groundwater use is for irrigation➔ Focus on technology choices which reduce groundwater withdrawals?




K. Zerrenner, "New graphic from DOE illustrates the energy-water-land nexus," http://blogs.edf.org/energyexchange/2014/07/24/new-graphics-from-doe-illustrate-the-energy-water-land-nexus/.

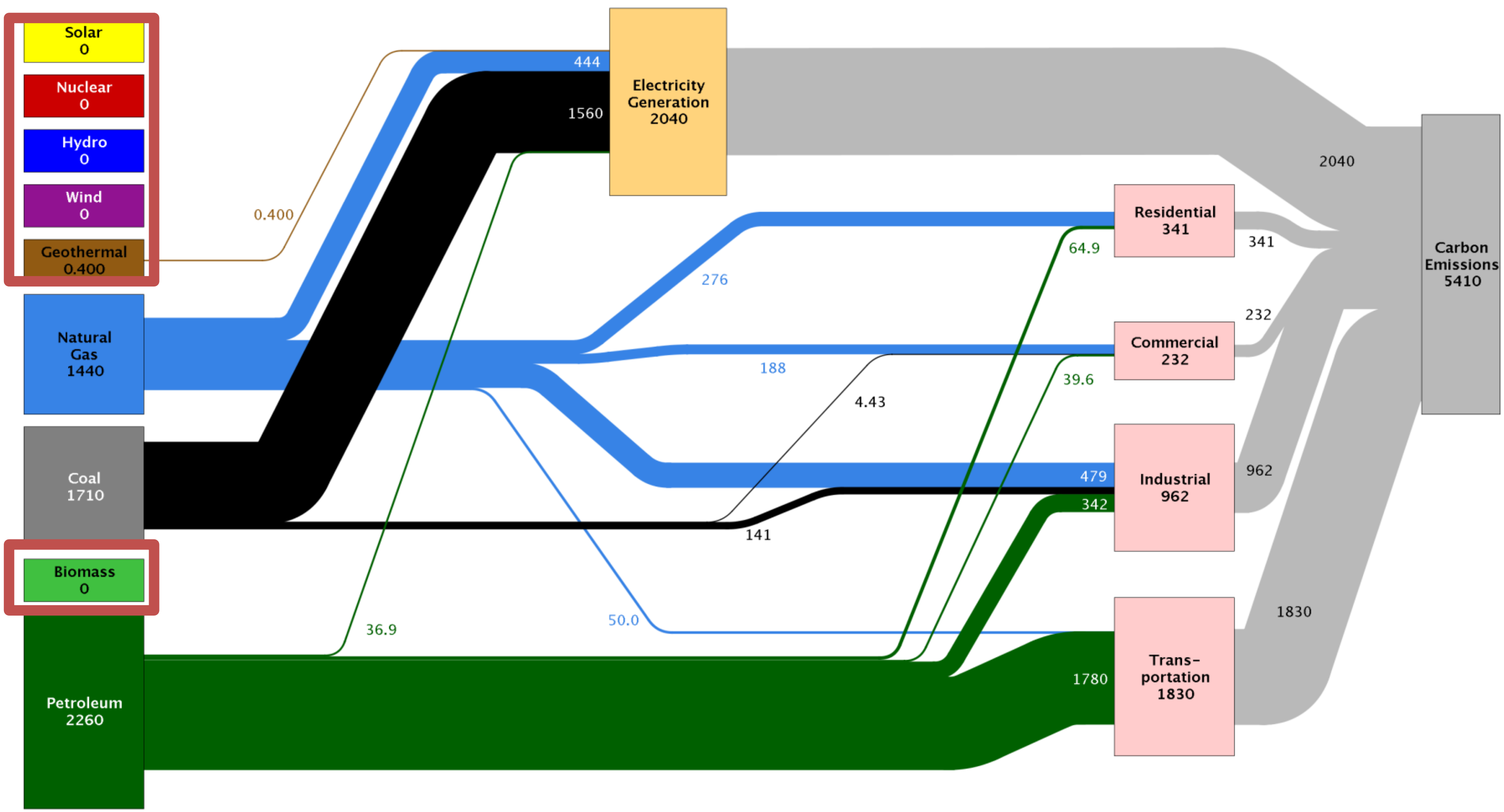
[1] A. Richey, B. Thomas, M. Lo, J. Reager, J. Famiglietti, K. Voss, S. Swenson, and M. Rodell,"Quantifying renewable groundwater stress with GRACE," to appear in Water Resources Research, available at http://onlinelibrary.wiley.com/doi/10.1002/2015WR017349/pdf.

# US Carbon Emissions - 2014

Technologies which do not produce GHG or produce very little (highlighted in red boxes), need to displace the highest GHG emitters (coal and petroleum) and eventually, natural gas as well.

Estimated U.S. Carbon Emissions in 2014: ~5,410 Million Metric Tons

Lawrence Livermore National Laboratory




Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2015. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Carbon emissions are attributed to their physical source, and are not allocated to end use for electricity consumption in the residential, commercial, industrial and transportation sectors. Petroleum consumption in the electric power sector includes the non-renewable portion of municipal solid waste. Combusition of biologically derived fuels is assumed to have zero net carbon emissions – the lifecycle emissions associated with producing biofuels are included in commercial and industrial emissions. Totals may not equal sum of components due to independent rounding errors. LLNL-MI-410527

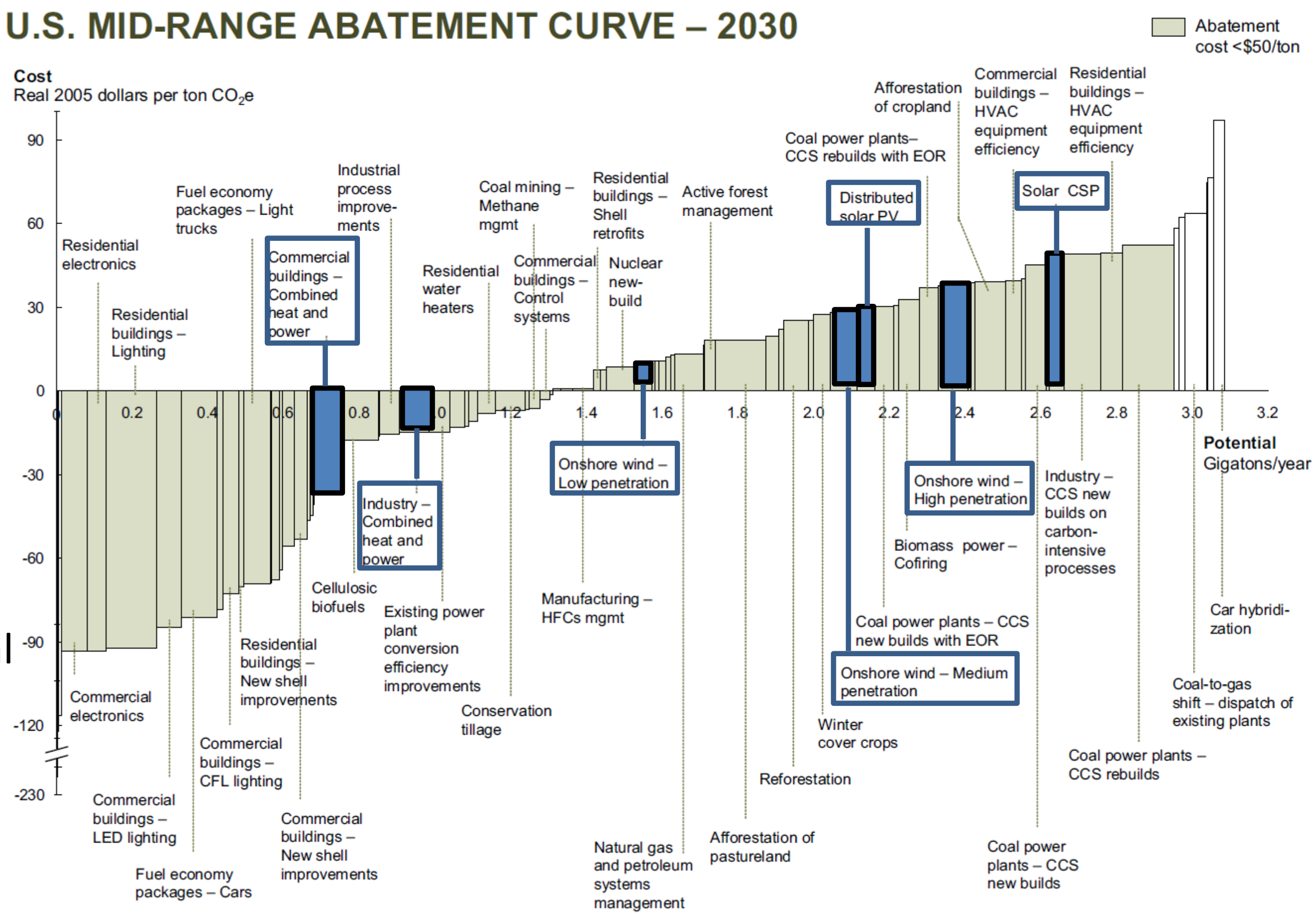
# Abatement Curves

The below abatement curve shows, for each technology option,

- Economics, height on the vertical axis: the average cost, compared to a reference, of avoiding 1 ton $CO_{2e}$ in \$/ton (negative values indicate net benefit to the economy over the lifecycle of the option whereas positive values indicate net cost to the economy);
- Impact, width on horizontal axis: The amount of $CO_{2e}$ that can be reduced annually via this option.

➔A major objective of the ESI work should be, for the technology options, to make the height more negative and to increase the width (increase the impact, i.e., the $CO_{2e}$ that can be reduced annually via this option).

➔The technology options in blue are identified because I think they have high potential for an attractive combination of economics and impact.




McKinsey & Company, "Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost?" U.S. Greenhouse Gas Abatement Mapping Initiative, Executive Report, December, 2007, available at www.mckinsey.com/en/Client_Service/Sustainability/Latest_thinking/Reducing_US_greenhouse_gas_emissions.aspx. There is a 2010 revision at http://www.mckinsey.com/client_service/sustainability/latest_thinking/greenhouse_gas_abatement_cost_curves.

# Orientation of This Discussion

**technology** Solar PV/thermal, biofuels, fuel cells, storage, heat pumps…

**cmmnty/ind** Flex-fuel poly-generation power plants
Or Energy Hub, Hybrid Energy System,
Virtual Power Plant

**city** District heat/cooling systems
Local transportation systems

**state**

**region** Local transmission & pipeline systems

**intrconnctn** Long distance freight & passenger transportation

**nation** Hi capacity interregional transmission

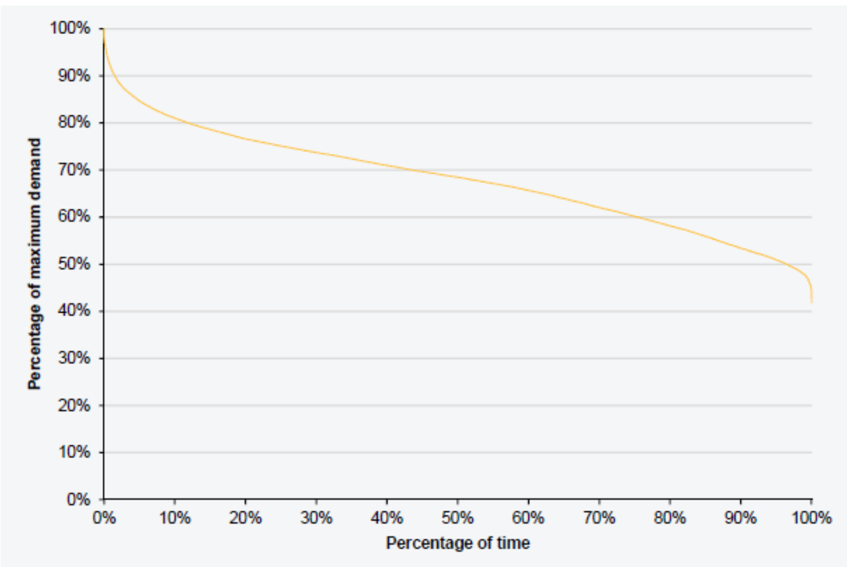
**continent**

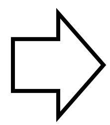
# Expansion Planning

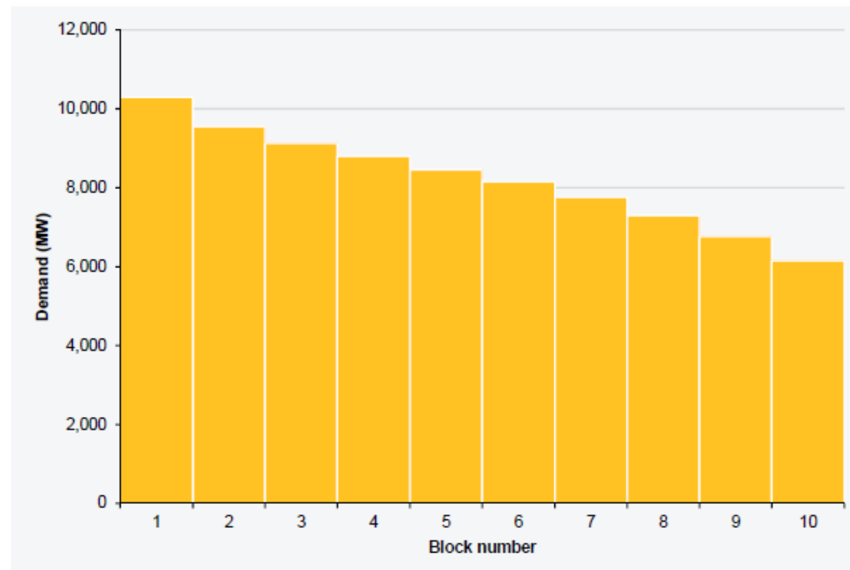
- Generation expansion planning (GEP): identifies least cost generation investments assuming transmission is infinite.
- Transmission expansion planning (TEP): identifies least cost transmission plan assuming a particular generation expansion plan.
- Co-optimized expansion planning (CEP): does both GEP and TEP simultaneously.

# Expansion Planning

- An exploratory/design app; not a predictive app.
- It is multi-period
- Demand modeled via “blocks” of load duration curve:





# Expansion Planning

- Costs include:
  - Investment
  - operation/maintenance
- Objective: minimize present worth of all costs over simulation period
- Discount rate, i
- Time value of money:

$$PW = FW(t) \times \frac{1}{(1+i)^t}$$

A \$100 cost at t=20yrs, with i=5%, has PW=\$37.69.

➔Pushing the same cost further out in time reduces its PW.

# Expansion Planning

- Retirements: forced or decision
- End-effects: artificial end to time means
  - Calculation does not see full operational life of investments which will bias in favor of investments with high O&M
  - So either "salvage" remaining life of investment as a revenue at the end year T:

$$PW(SV) = -SV(T) \times \frac{1}{(1+i)^T}$$

  - or extend to account for operational cost to end of life:

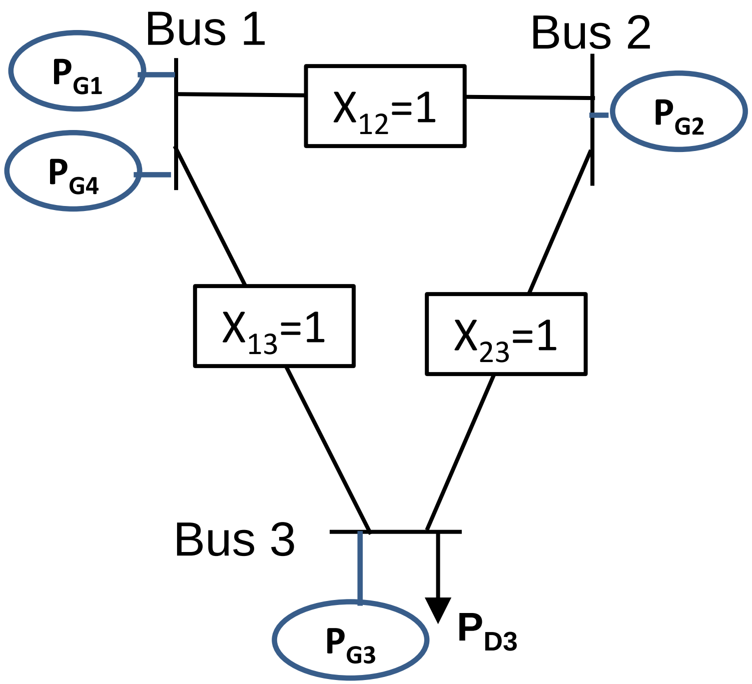
$$PW(OC) = \sum_{t=T}^{T+LIFE} \left(FOM(t) + VOM(t) + FC(t)\right) \times \frac{1}{(1+i)^t} = \sum_{t=T}^{T+LIFE} TOC(t) \times \frac{1}{(1+i)^t}$$

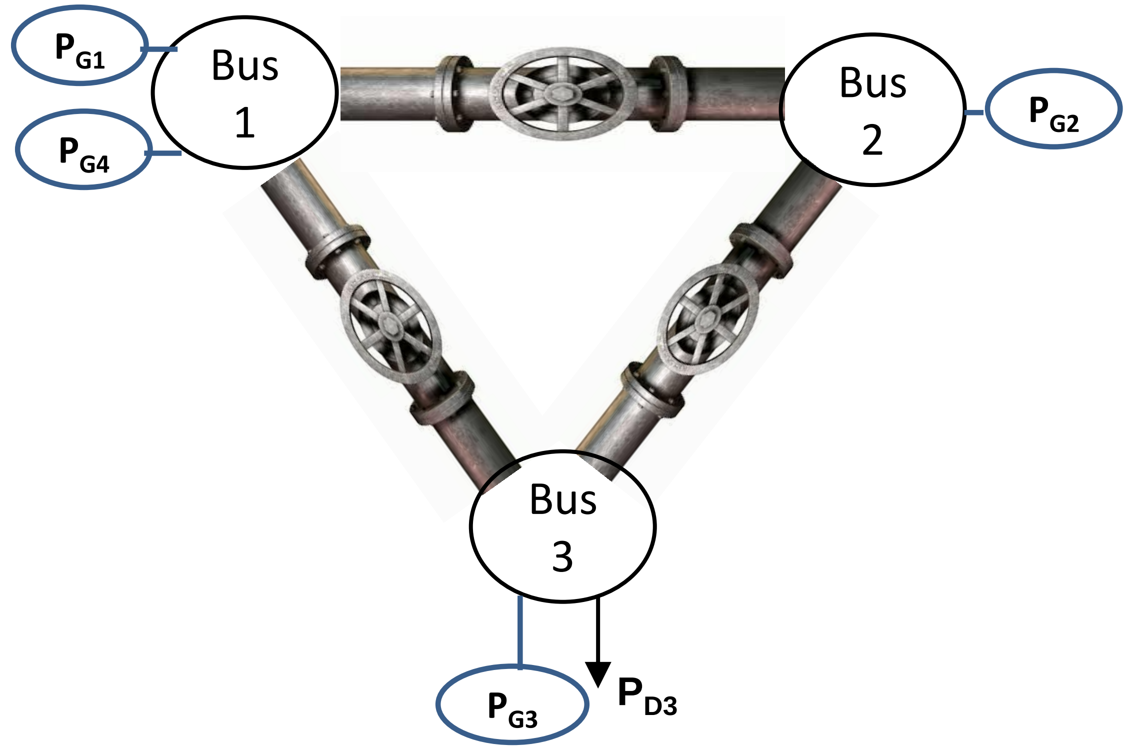
Simple approach: assume TOC(t)=TOC (same for all t). Then:

$$PW(OC) = TOC \sum_{t=T}^{T+LIFE} \frac{1}{(1+i)^t}$$

  - But do not include both PW(SV) and PW(OC).

# Impedance (MIP) vs. Pipes&Bubbles (LP)




Inject 1 MW into bus 1 to supply 1 MW load at bus 3.

For impedance model

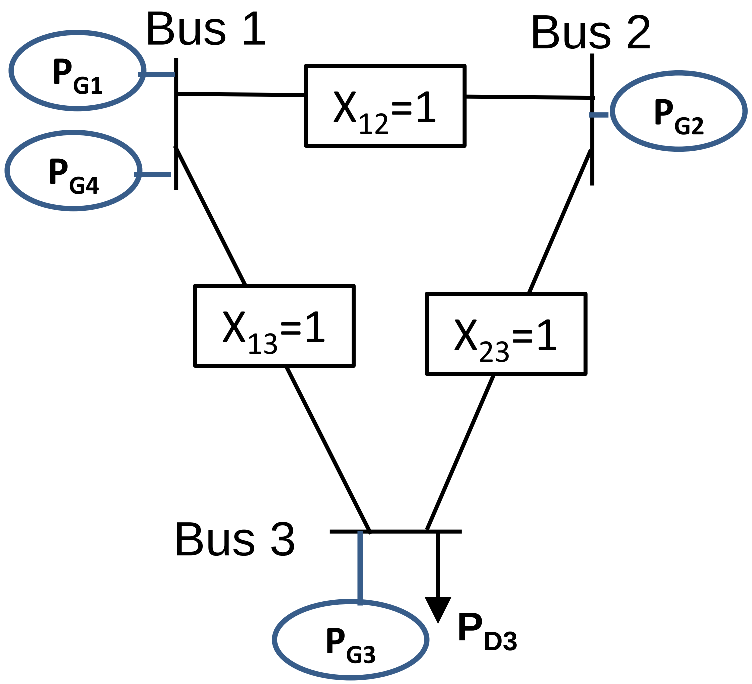
$$P_{13} = 1\frac{2}{1+2} = 0.67$$

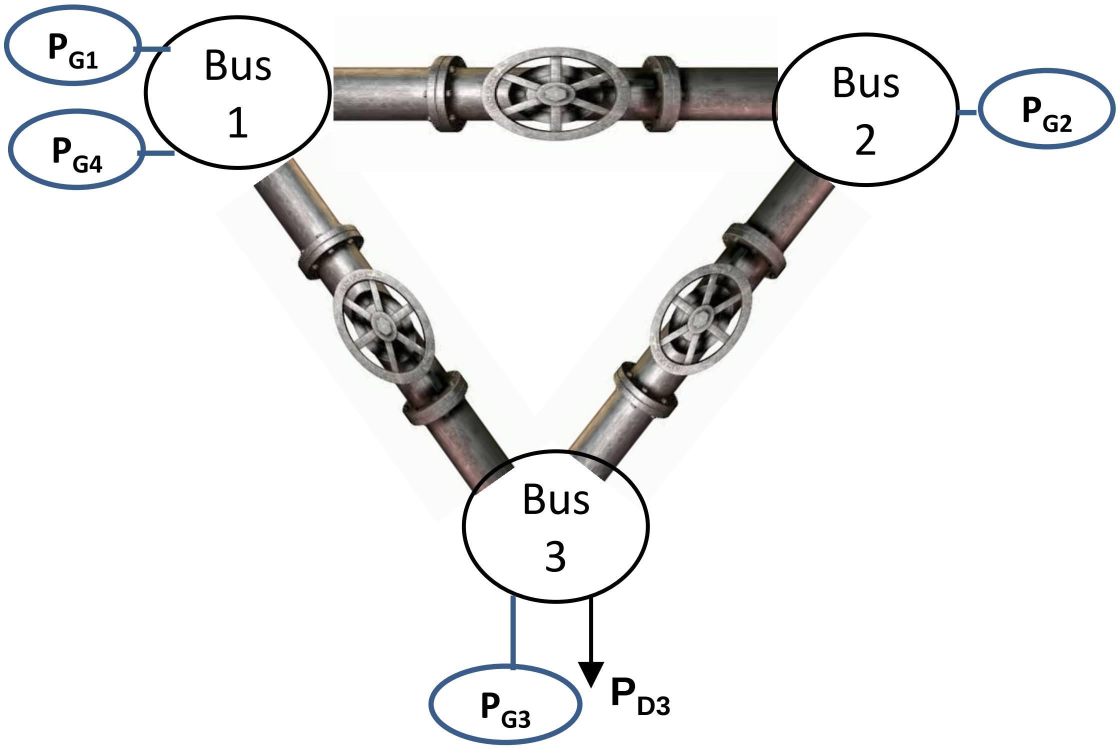
For P&B model

$$0 \le P_{13} \le 1$$

**That is, we can obtain any split we want, depending on how we coordinate the valves.**

# Impedance vs. Pipes&Bubbles

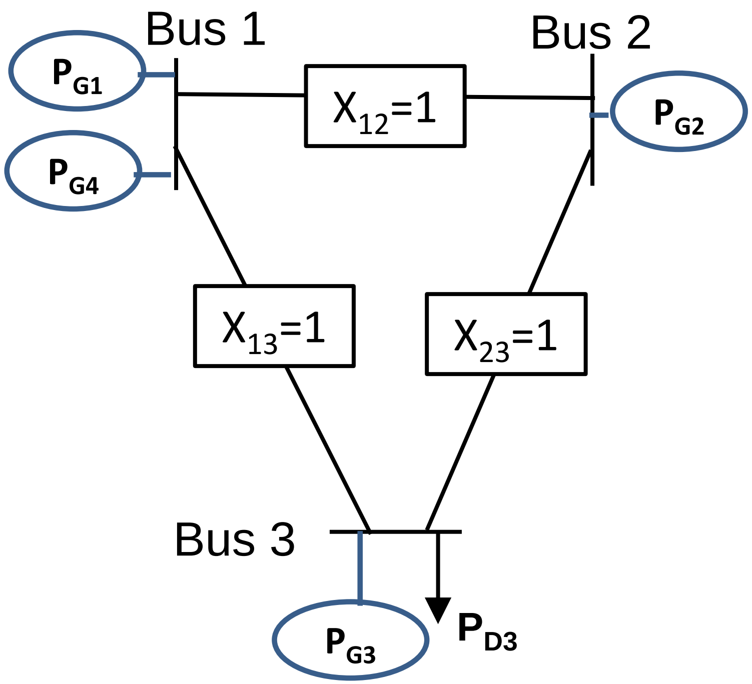


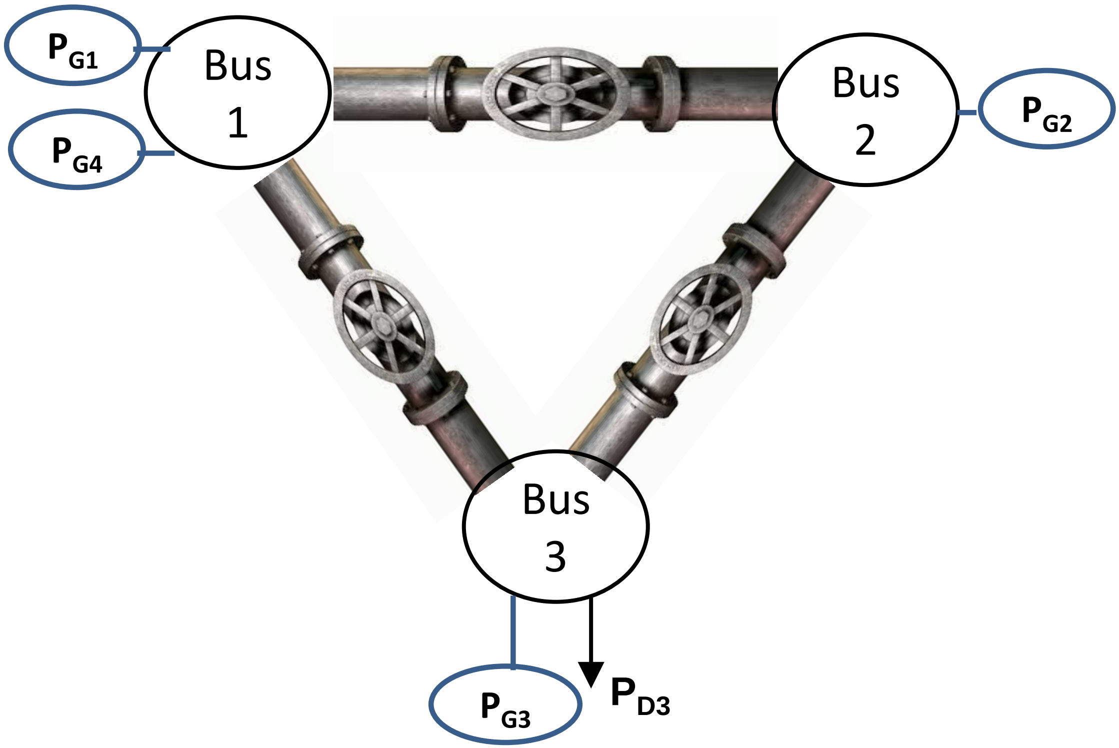




Both enforce nodal balance, i.e.,

$$\underbrace{P_{Di}}_{\substack{Demand\\ at\ Bus i}} + \underbrace{\sum_j P_{ij}}_{\substack{Line\ Flow\ Out\\ of\ \ Bus\ i}} = \underbrace{P_{Gi}}_{\substack{Generation\\ at\ Bus i}}$$

# Impedance vs. Pipes&Bubbles




Both use linear models for existing transmission

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

$$-P_{i,j\max} \le P_{ij} \le P_{i,j\max}$$

$$-P_{i,j\max} \le P_{ij} \le P_{i,j\max}$$

# For Generation Expansion

**Impedance model**

**MIN GenInvestCost+**
**GenOpCost**
**Subject to:**
**Nodal Balance Constraint**
**Line flow calculation for existing ccts**
**Line flow constraint for existing ccts**

**Pipes & Bubbles model**

**MIN GenInvestCost+**
**GenOpCost**
**Subject to:**
**Nodal Balance Constraint**
**Line flow constraint for existing ccts**

- All equations are linear with the variables.
- Therefore both problems are linear programs.

➔ Use the impedance model and obtain the better fidelity with little increase in computation time.

# For Transmission Expansion

## Impedance model

**MIN GenInvestCost+**
**GenOpCost+**
**TransInvestCost**
**Subject to:**
**Nodal Balance Constraint**
**LineFlow calculation - existing ccts**
**LineFlow constraint - existing ccts**
**LineFlow calculation - candidate ccts**
**LineFlow constraint - candidate ccts**

Because transmission lines with impedance are either in or out, this problem is mixed integer.

**But there is even worse news ☹…**

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

**The integer variable is multiplied by the angles ➔A <u>nonlinear</u> mixed integer program!**

## Pipes & Bubbles model

**MIN GenInvestCost+**
**GenOpCost+**
**TransInvestCost**
**Subject to:**
**Nodal Balance Constraint**

**LineFlow constraint - existing ccts**

**LineFlow constraint - candidate ccts**

This problem treats line capacity as a continuous variable and so remains a linear program.

# For Transmission Expansion

## What is the problem?

For the impedance model, the TEP results in an integer, nonlinear circuit flow expression

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

This means the problem is a MINLP.

MINLP are very difficult to solve because they combine the combinatorial difficulties of integer programs with the nonconvexity difficulties of nonlinear programs.

And so… we use the disjunctive representation, which replaces the nonlinear integer expression with two integer inequalities.

**disjunctive: serving to divide or separate.**

# For Transmission Expansion

## 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**

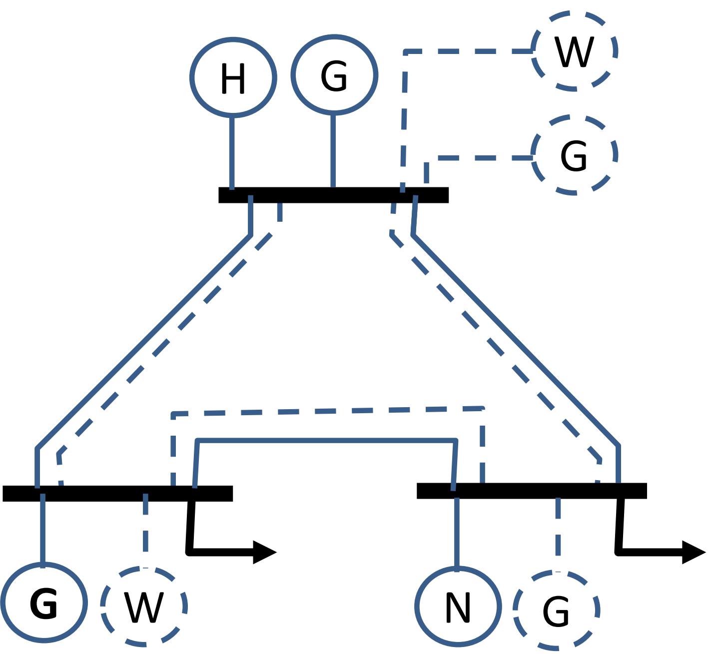
$$-1000 \le P_{ij} - B_{ij}\left(\theta_i - \theta_j\right) \le 1000$$

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

# Co-optimized Infrastructure (CI) Design

**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** {
Investment costs
+ Fixed O&M Costs
+ Var O&M Costs
+ Environmental Costs
}

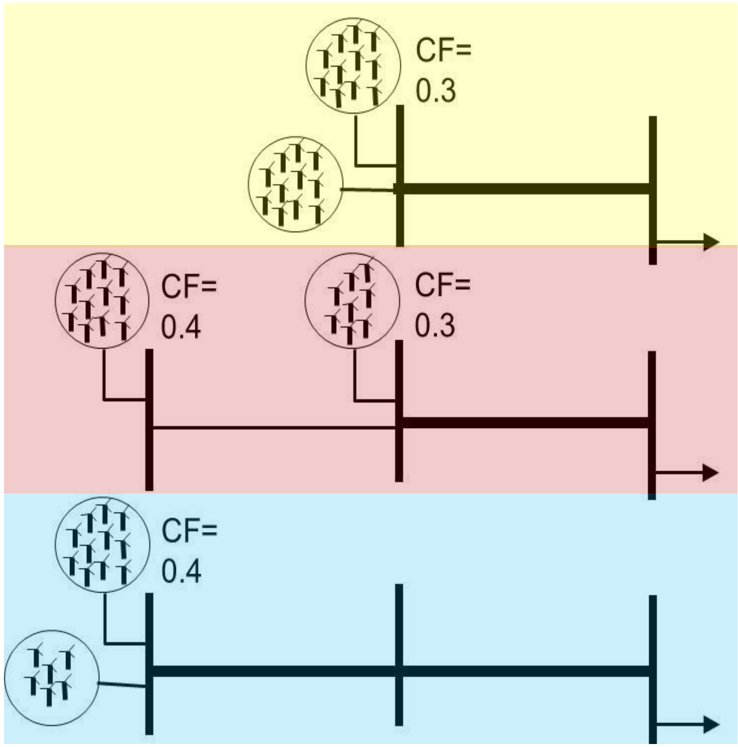
**SUBJECT TO:**
Operational & environmental constraints
on energy, fuels, transportation, water
Uncertainty characterization

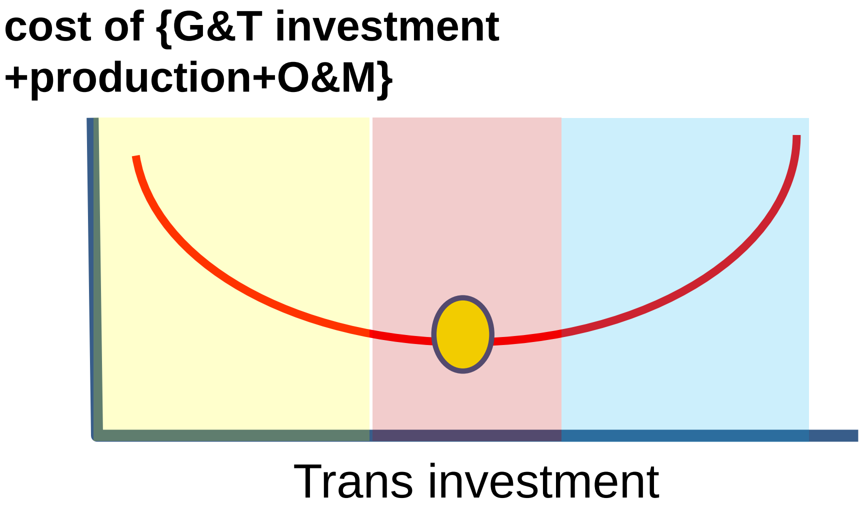
**Year 1** **Year 2** . . . **Year N**

# Co-optimization: what is it?

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

## Wind & transmission



# Co-optimization: why?

**Amount/location of gen & load influence transm needs.**

**Transmission availability influences generation location.**

**Traditional approach**

<u>GEP</u>: Optimize gen invest +fixed & variable O&M given fixed transmission

<u>TEP</u>: Optimize trans invest +fixed & variable O&M given fixed gen plan

**T&G plan**

**Better approach**

<u>GEP</u>: Optimize gen invest +fixed & variable O&M given fixed transmission

<u>TEP</u>: Optimize trans invest +fixed & variable O&M given fixed gen plan

**T&G plan**

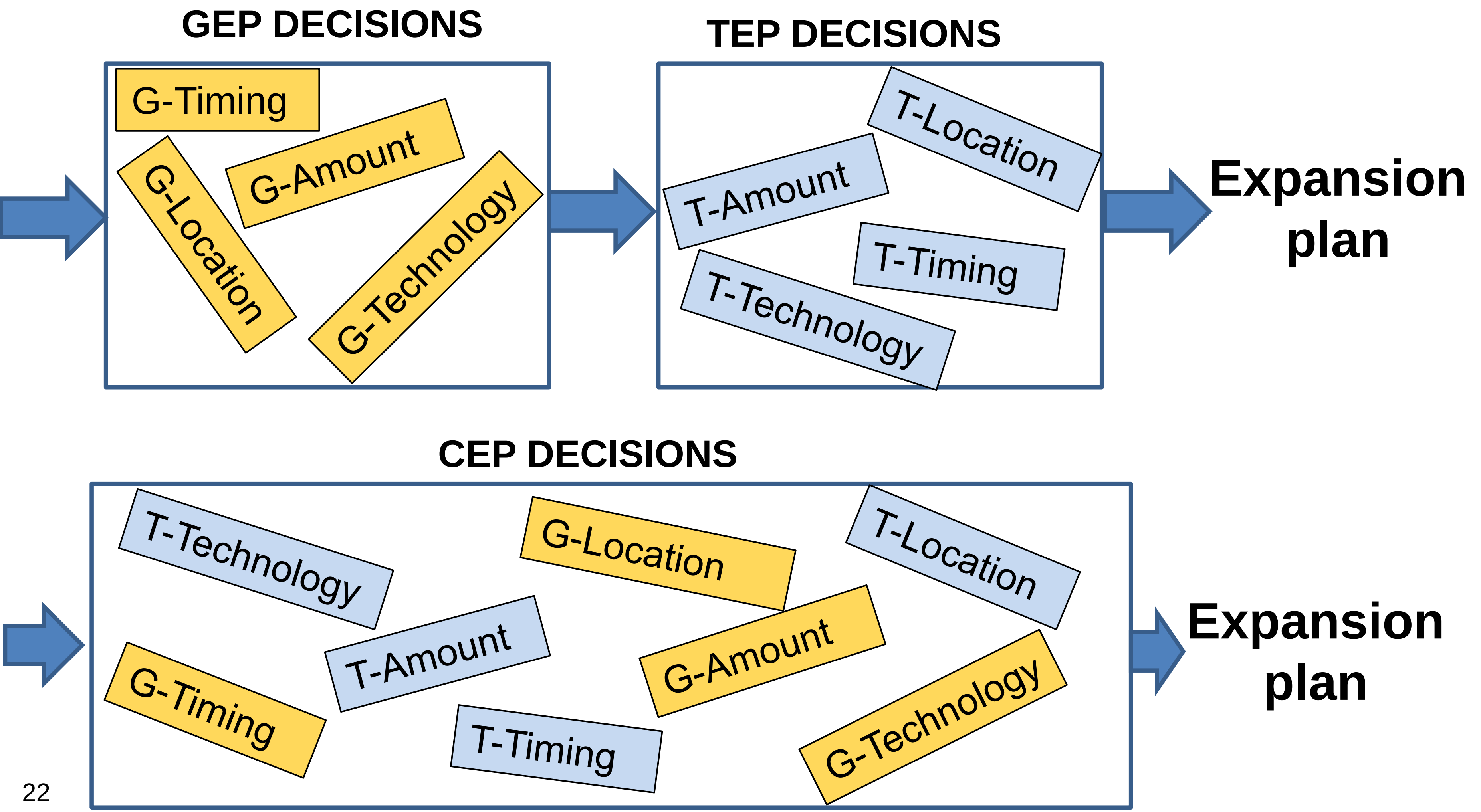
**Best approach**

<u>CEP</u>: Optimize gen invest+trans investment +fixed & variable O&M.

**T&G plan**

# Co-optimization: why?

**It is useful when decisions for one infrastructure class affect decisions for another infrastructure class.**



# Co-optimization: why?

**A co-optimization of two related decisions must be as good as, or better than, a sequence of individual optimizations.**

Better? In what sense?

**FROM CEP** → **NPW Cost{G&Tinvest+prod+O&M}**

$\leq$ **NPW Cost{Ginvest+prod+O&M}** ← **FROM GEP**

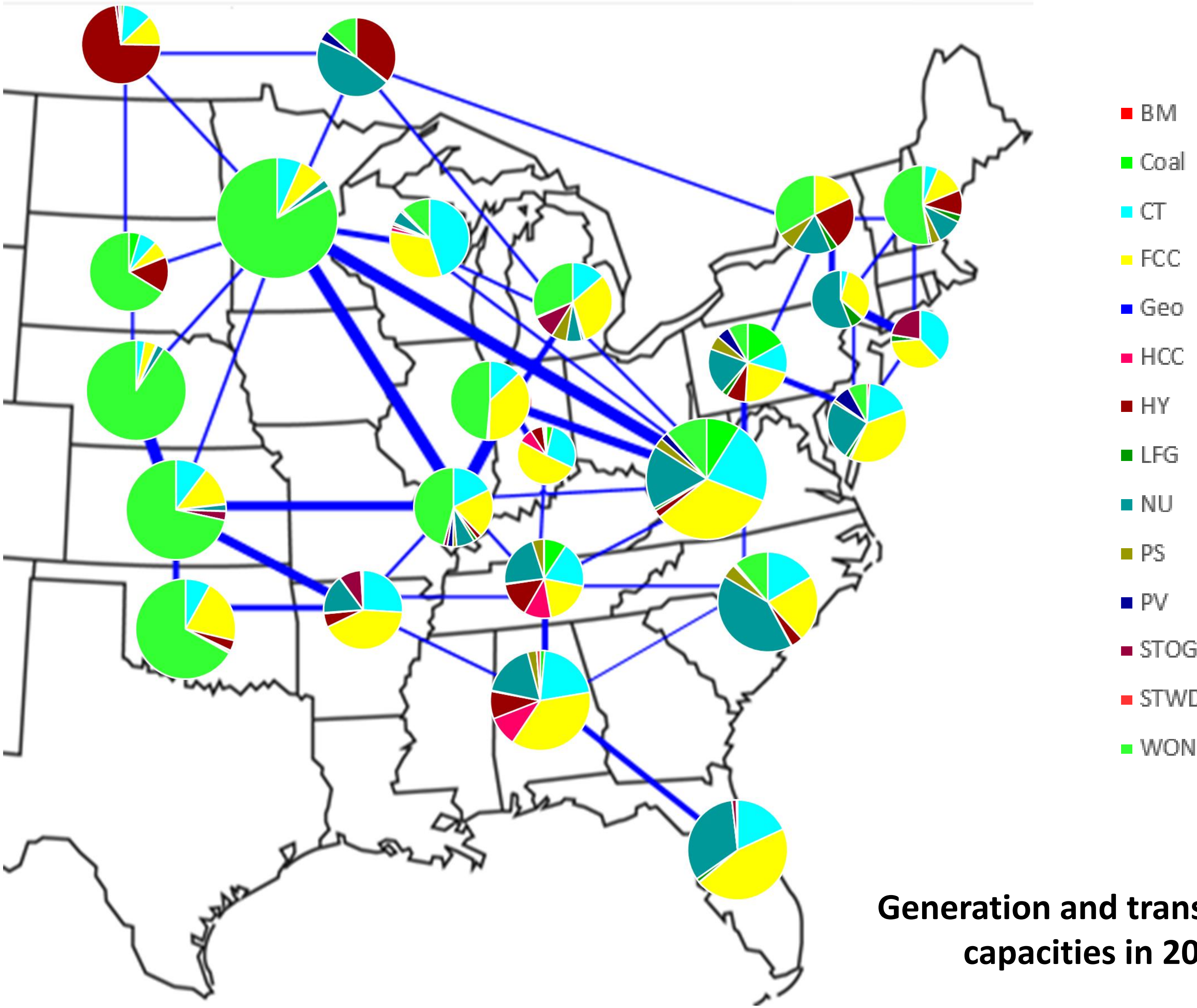
**+NPW Cost{Tinvest}** ← **FROM TEP**

Co-optimization identifies less costly solutions, while satisfying all GEP and TEP constraints.

# Illustration using EI model

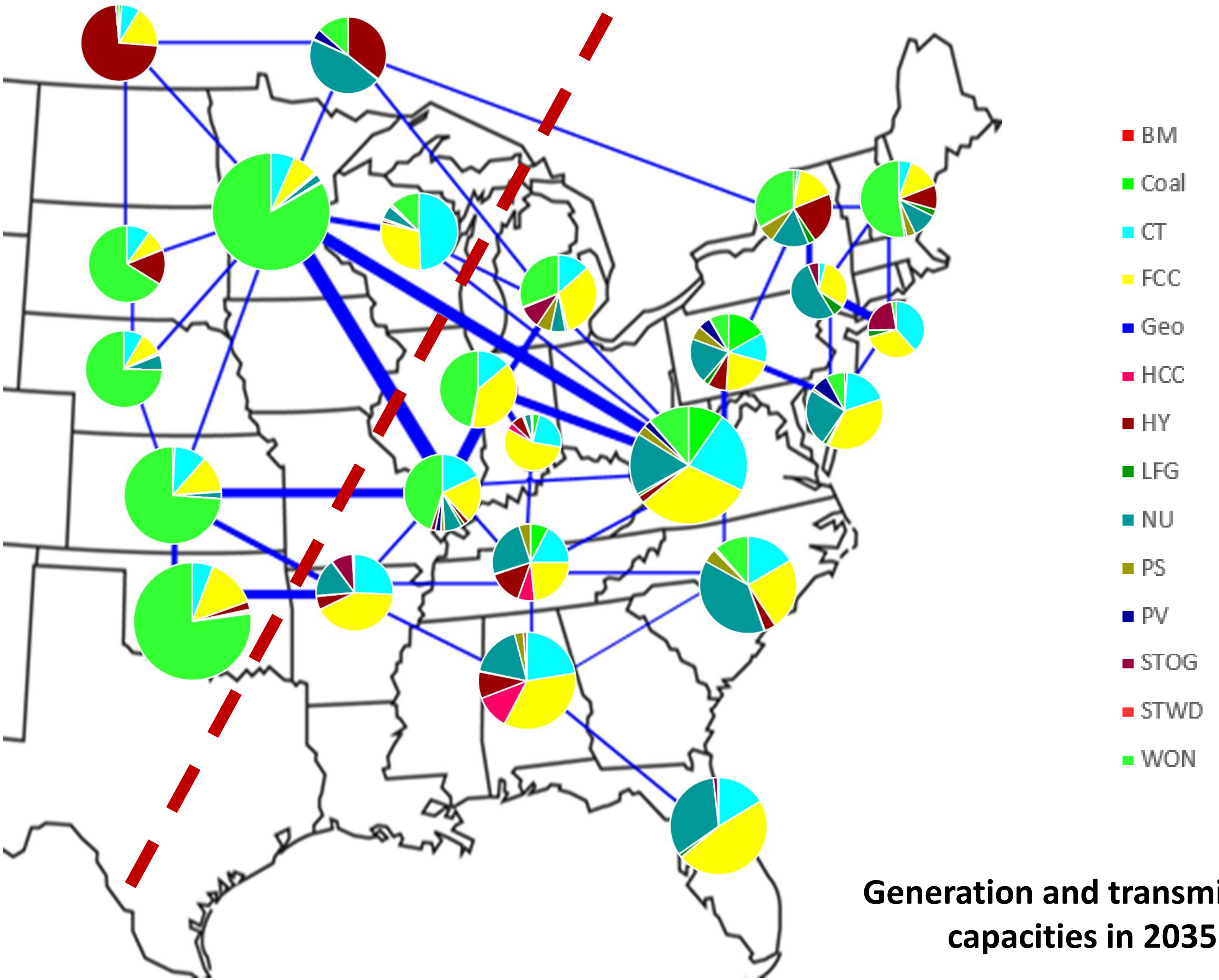
- EI 24-node, using ISU co-optimization model
- 20 years simulation
- Each node is characterized using EI data
  - Demand, capacity factor, capacity credit, reserves requirements
- Each year is modeled through 20 load blocks
- 19 Generation technologies
- 37 Transmission line interfaces
- Salvage model for end effects

# Sequential (P&B)




**Generation and transmission capacities in 2035**

# Co-optimization (P&B)




**Generation and transmission capacities in 2035**

# Illustration 2 (EI Model) - Costs

| Cost Category (NPV) | Sequential Model (Pipes & Bubbles) | Co-optimization (Pipes & Bubbles) |
|---|---:|---:|
| Gen Investment | $736B | $735B |
| Tx Investment | $23.7B | $17.6B |
| Operational | $1544B | $1546B |
| Total Cost | $2304B | $2299B |

# PIPELINES INVESTMENT COST

| NATURAL GAS CHARACTERISTICS | |
|---|---|
| Energy Content (MMBTU/MMcf) | 1,027 |

| PIPELINE CHARACTERISTICS | |
|---|---|
| Diameter (inch) | 42 |
| Transmission Capacity (MMcf/day) | 1,800.0 |
| Transmission Capacity (MMcf/hour) | 75.00 |

| COMPRESSOR STATION CHARACTERISTICS | |
|---|---|
| Distance between stations (miles) | 50 |
| Power (HP per station) | 25,000 |

| PIPELINE INVESTMENT COSTS | |
|---|---|
| Pipeline Investment Cost (*) ($ per inch - mile) | $\boxed{155{,}000}$ |
| Pipeline Investment Cost ($ per mile) | 6,510,000 |

This is high.

| COMPRESSOR STATION COSTS | |
|---|---|
| Compressor Station Inv. Cost (*) ($ per HP) | 2,600 |
| Compressor Station Inv. Cost ($ per mile) | 1,300,000 |

(*) Source: North America Midstream Infrastructure through 2035: Capitalizing on Our Energy Abundance. The INGAA Foundation. March 18, 2014

$$6{,}510{,}000\$/mile + \$1{,}300{,}000\$/mile = \$7{,}810{,}000\$/mile$$

$$\frac{7{,}810{,}000\$/mile}{75mmcf/hr} = 104{,}133\$/(mmcf/hr \times mile)$$

$$\frac{104{,}133\$/mmcf/hr \times mile)}{1027mmbtu/mmcf} = 101.4\$/(mmbtu/hr \times mile)$$

| PIPELINE SYSTEM INVESTMENT COSTS | |
|---|---|
| Pipeline System Investment Cost ($ per mile) | 7,810,000 |
| Pipeline System Investment Cost ($ per (MMcf/hr x mile)) | 104,133 |
| Pipeline System Investment Cost ($ per (MMBTU/hr x mile)) | 101.40 |

**Obtain "post-combustion" values: 101.4*7196=730,000$/GW-mile**

# TRANSMISSION LINE INVESTMENT COST

| CONVENTIONAL COMBINED CYCLE PLANT CHARACTERISTICS | |
|---|---|
| Heat Rate (MMBTU/GWh) | 7,196 |

| TRANSMISSION LINE INVESTMENT COSTS | |
|---|---|
| Transmission Line Investment Cost ($ per GW - mile) | $\boxed{1{,}000{,}000}$ |
| Transmission Line Investment Cost ($ per (MMBTU/h x mile)) | 139.0 |

This is low.

Similar analysis, but of a specific case, done by BPA and AGA, is here:
www.northwestchptap.org/NwChpDocs/Transmission_and_N_Gas_Comparing_Pipes_and_Wires_032304.pdf

# PIPELINE FLOW MODELS

**ASSUMPTIONS**

**One-dimensional, horizontal, compressible, isothermal, steady-state flow**

Isothermal flows are used for modeling slow transients, like normal operational demand changes.

**HIGH-FIDELITY MODEL**

SET OF PARTIAL DIFFERENTIAL EQUATIONS
- Mass conservation law
- Momentum conservation law
- Energy conservation law

**APPROXIMATE MODEL**

SET OF NONLINEAR ALGEBRAIC EQUATIONS

**Turbulent flows in rough pipes**

- Panhandle B Eqts
- AGA Partially Turbulent Eqts
- Weymouth Eqts

$$\rho_i^2 - \rho_j^2 = K_{i,j} G_{i,j}^2$$

Weymouth equations are frequently used in the design of transmission networks, because they usually overestimate the pressure drop calculations and are thus conservative – see Mohitpour et al. (2003)

We may linearize the Weymouth equations about selected pressure conditions to obtain:

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

# ELECTRIC vs. GAS TRANSMISSION MODELING

$$\overbrace{\theta_i - \theta_j}^{\text{voltage phasor angles}} = X_{i,j}\overbrace{P_{i,j}}^{\text{real power flow}}$$

**Linearized Power Flow Equation - Steady state real power flow across circuits is determined by the difference in voltage phasor angles between the terminating buses.**

**The reactance defines the transmission line characteristics**

**This constant defines the pipeline characteristics**

$$\underbrace{c_i\ \rho_i - c_j\ \rho_j}_{\text{Terminal pressures}} = K'_{i,j}\underbrace{G_{i,j}}_{\text{NG flow rate}}$$

**Linearized Weymouth Equations - The natural gas flow rate across a pipeline is determined by the difference of the pressures between the terminating buses.**

<u>Important difference</u>: Linearized power flow equations are pretty 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.

# MODEL 0 (MINLP, dsjnctve electric/nonlinear gas)

**Minimize: Generation Costs & Transmission Lines Costs (operational & investment)** **+** **Production & Storage Operational Costs and Pipelines Operational & Investments Costs**

**subject to**

**ELECTRIC SYSTEM CONSTRAINTS**

Electric Generating Units constraints
- Maximum power output (capacity credit)
- Maximum electricity output (capacity factor)

Transmission network constraints
- Node power balance eqts
- **DC Power flow eqts**
- Transmission lines capacity bounds

Power system security and reliability constraints
- Electric Generating Units reserves

Generation capacity constraints
- Balance (additions and retirements)
- Lower and upper bounds

**Transmission lines investment constraints using a Disjunctive Model**

**INTEGERS**

**GAS SYSTEM CONSTRAINTS**

NG Wells Production constraints
- Bounds on the production levels

Transmission network constraints
- Node gas balance eqts
- **Gas flow – pressure eqts**
- Pipelines capacity bounds

**NONLINEAR**

NG Storage constraints
- Lower and upper storage levels (storage, injection, and withdrawal).
- Energy balance constraints

**Pipelines investment constraints using a Disjunctive Model**

**INTEGERS**

# POSSIBLE GAS/ELECTRIC EXPANSION MODELS

| Model Number | Electric line representation | Gas pipeline representation | Type of problem | Difficulty |
|---|---|---|---|---|
| Model 0 | Linear disjunctive | Nonlinear disjunctive | MINLP | Extreme |
| Model 1 | Linear disjunctive | Linear disjunctive | MILP | Very high |
| Model 2 | Linear disjunctive | P&B | MILP | High |
| Model 3 | P&B | Linear disjunctive | MILP | High |
| Model 4 | P&B | P&B | LP | Low |

# SOLUTION APPROACHES

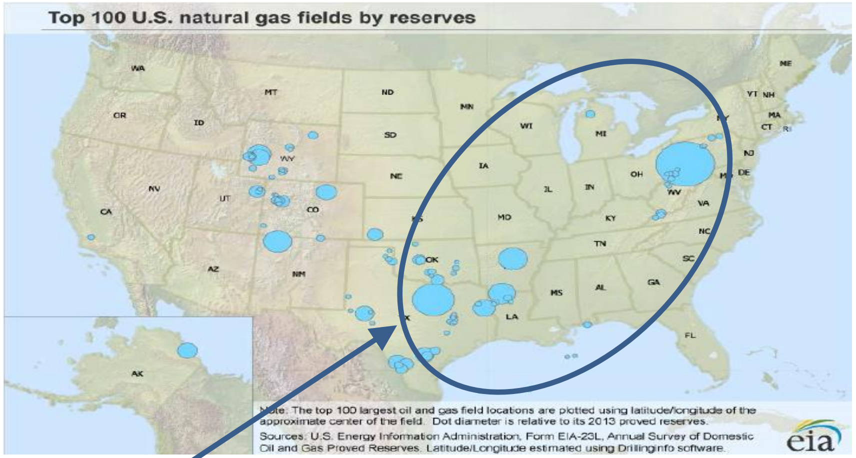
In all strategies, limit candidate expansion lines (electric + gas) as much as possible.

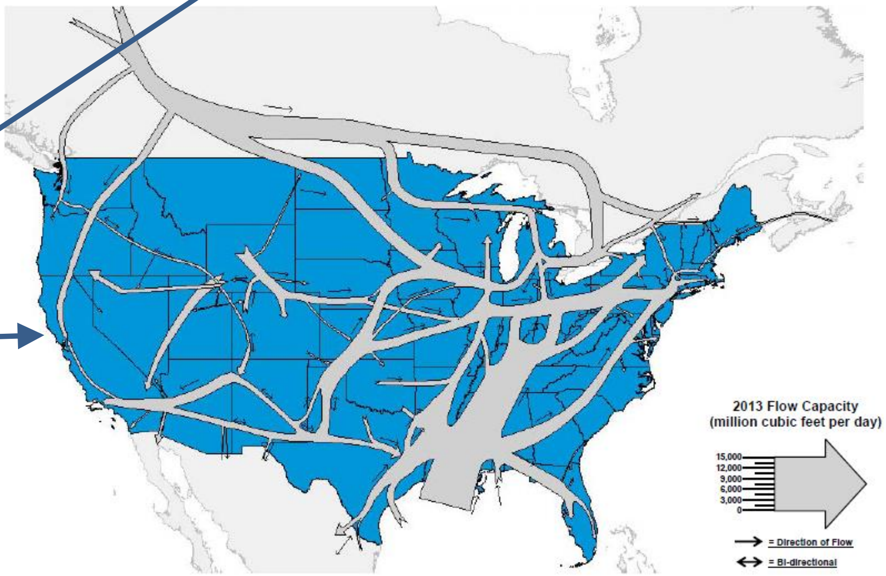
1. Model 1 w/PWL gas lines: Solve model 1 w/1-piece PWL for each gas line.
2. Model 1 with successive linearizations:
   a. Solve model 1 w/1-piece PWL for each gas line.
   b. Resolve model 1 linearizing about solution obtained in (a). Repeat until change in solution is within tolerance.
3. Model 4-Initialization: Use Model 4 (fully P&B) to obtain initial solution to use in linearization. Then use either approach 1 or 2 above.
4. Model 2-Model 3: Iterate between models 2 and 3.

➔We have used approach #1.

# SYSTEM DESCRIPTION

- **EI 24-node**
- **20 years simulation**
- **Each node characterized using EI data**
  - ➔**Demand, capacity factor, capacity credit, reserves requirements**
- **Each year modeled via 20 load blocks**
- **19 Generation technologies**
- **10 Natural Gas production areas, EIA**
- **37 Transmission line interfaces**
- **32 Pipeline interfaces, from EIA**
- **Salvage model for end effects**



# ILLUSTRATION USING EI MODEL – RESULTS (Pipes & Bubbles modeling)

| Cost Category (NPV) | Co-optimization: Generation and Transmission | Co-optimization: Generation, Transmission and Pipelines |
|---|---|---|
| Gen Investment | $735B | $732B |
| Tx Investment | $17.6B | $18.4B |
| Pipeline Investment | - | $11.5B |
| Operational | $1546B | $1516B |
| Total Cost | $2299B | $2278B |

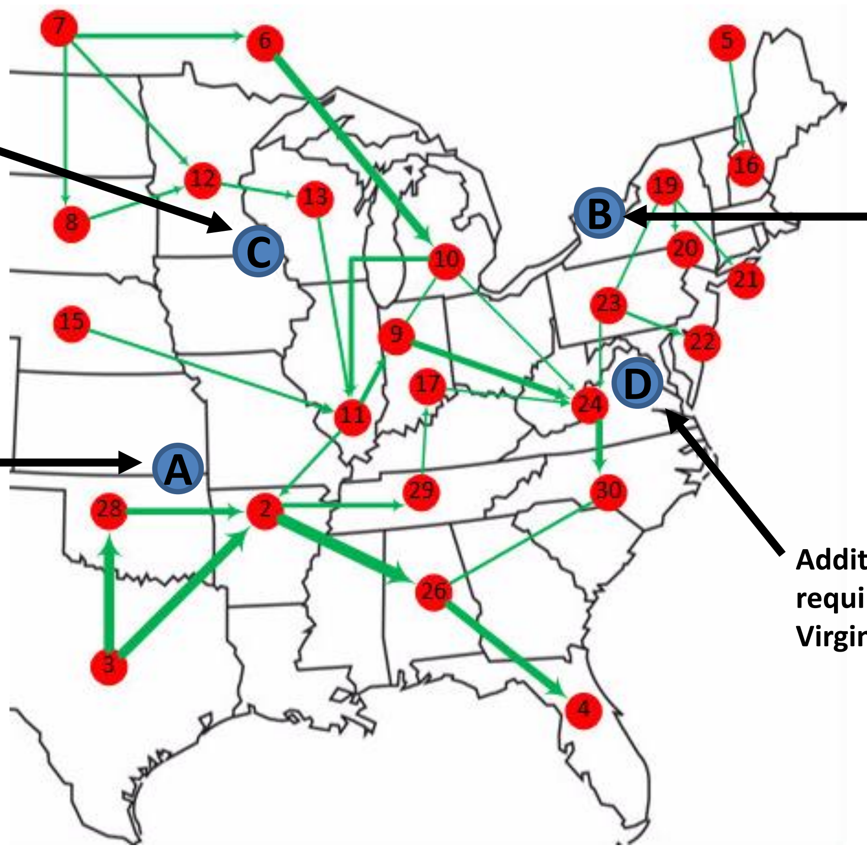
# ILLUSTRATION USING EI MODEL - RESULTS

## Comparing co-optimization solutions obtained for the model with and without a natural gas system

### Natural gas flows (MMcf/h) in 2035

**Reduction in transmission investments inside MISO resulting from pipeline investments from Canada.**

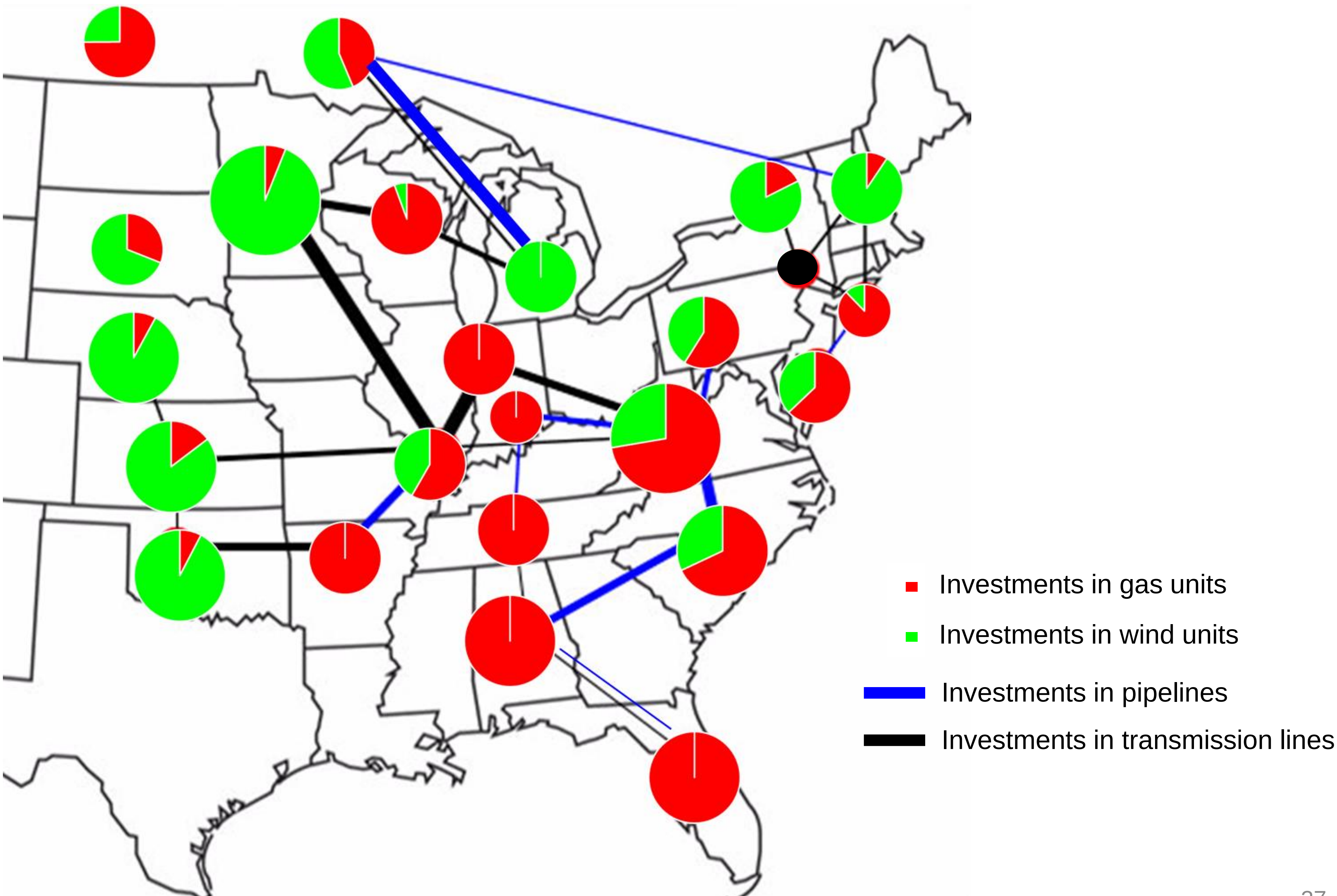
**Reduction in transmission line investments and in wind unit investments because of new pipeline investments.**



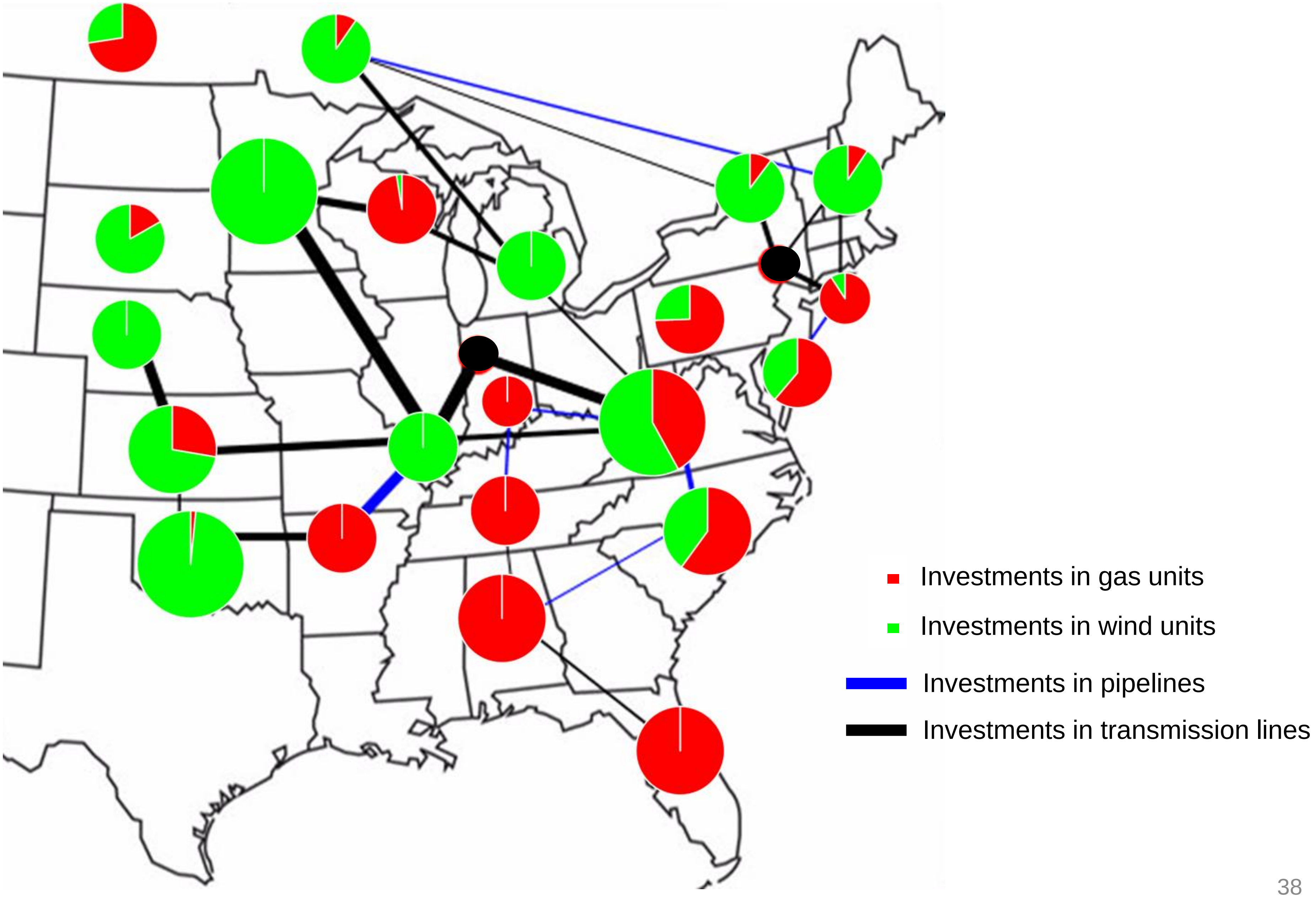

**Reduction in electricity and gas imports from Canada to the Northeast, and additional investments in gas-fired units in NY area because of increase in Marcellus gas production.**

**Additional pipeline investments required to move Marcellus gas to Virginias and Carolinas.**

# Interconnection (EI): Electric gen, trans, pipeline, $5 gas



# Interconnection (EI): Electric gen, trans, pipeline: $9 Gas



# Co-optimized Infrastructure (CI) Design

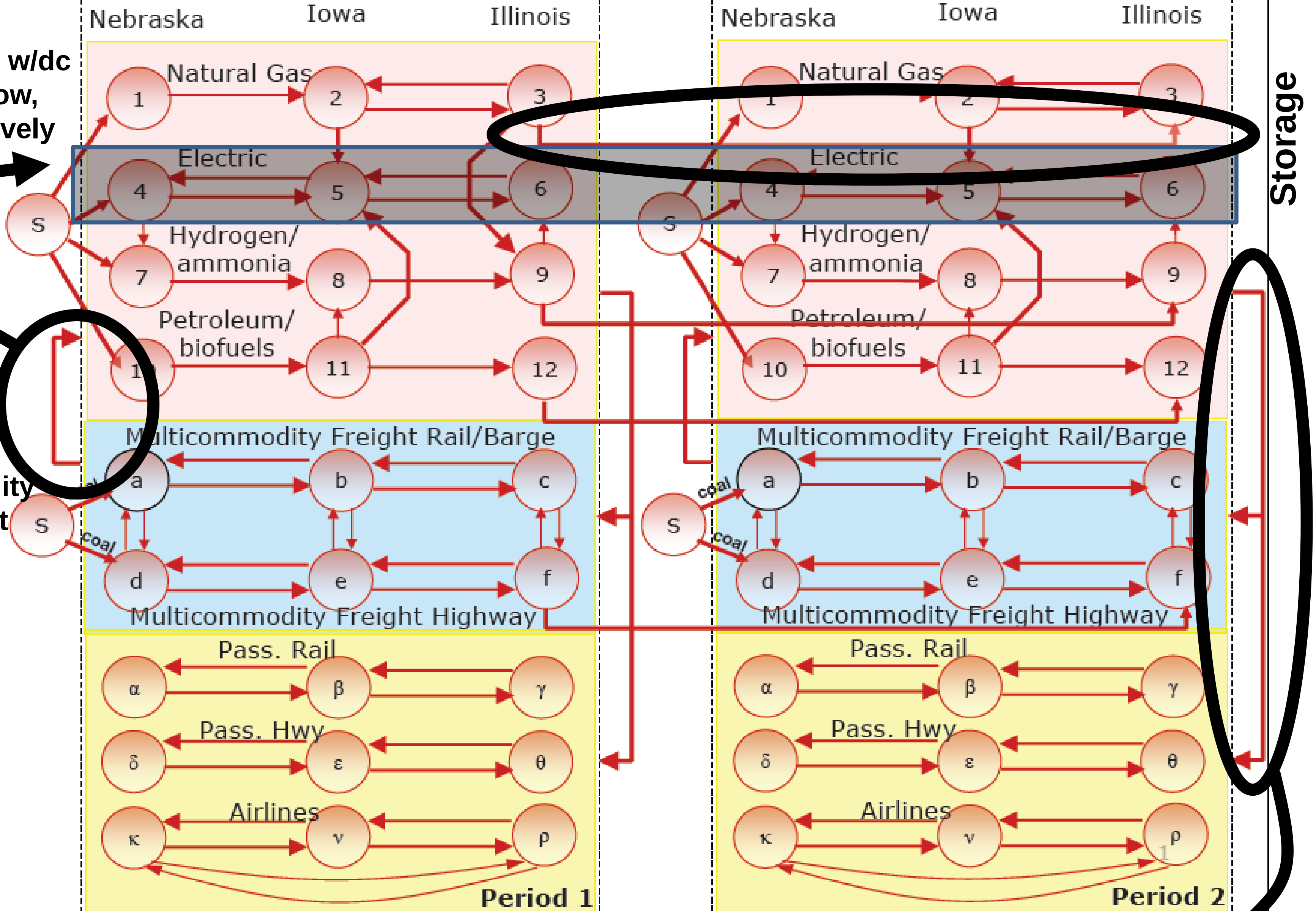
**Co-optimization: the simultaneous identification of two or more classes of infrastructure decisions within one optimization problem.**

**Can be applied to combinations of the below:**

- **Electric generation & transmission, storage, demand response**
- **Natural gas facilities (pipelines, wells, processing plants)**
- **Transportation facilities (highway, rail, air: fleets and fixed)**
- **Other fuel facilities: oil pipelines, rail for coal, fuel storage**
- **Agriculture systems (land, water, transport systems)**
- **Thermal networks for district energy systems**
- **Water systems (processing, purification, reuse)**

Electric modeled w/dc power flow, disjunctively

Energy loads commodity transport system



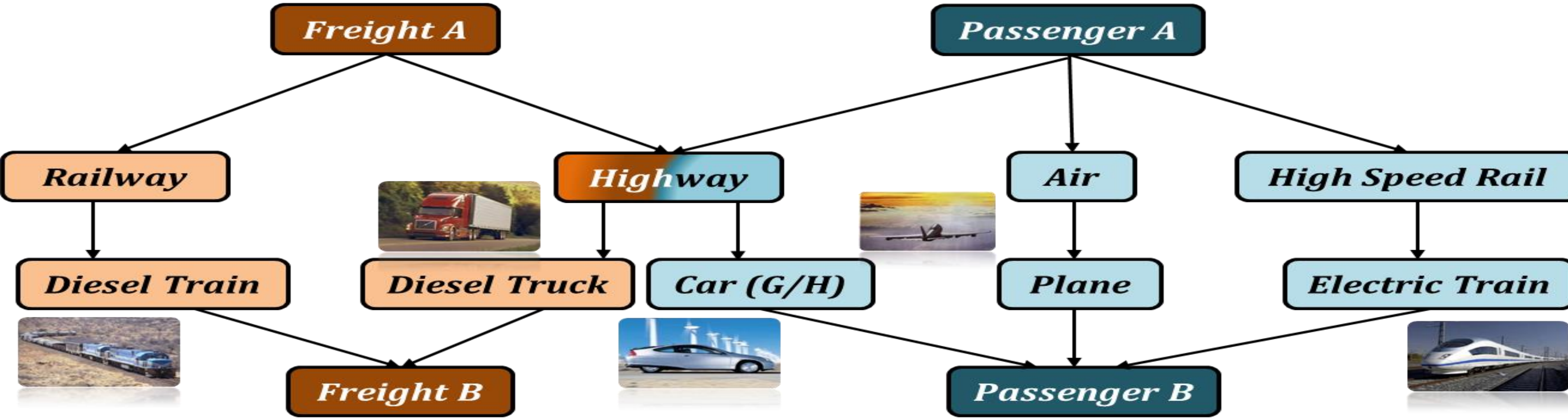

Commodity & passenger networks load energy system

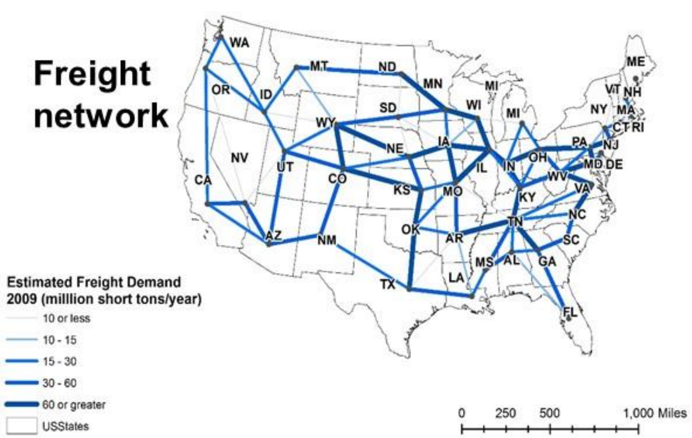
**Co-optimized cost-minimization: Multi-period w/network structure**

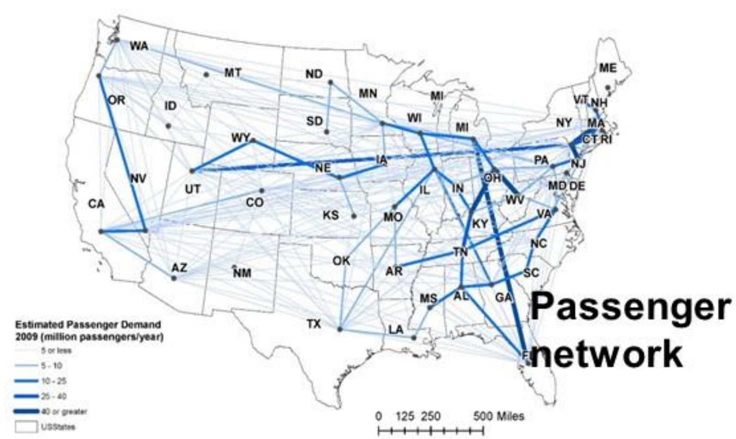
# Transportation Modeling

**Long-distance transportation facilities:**

- **commodity: freight/passenger**
- **mode: highway, air, rail, barge**
- **infrastructure: fleets & fixed**



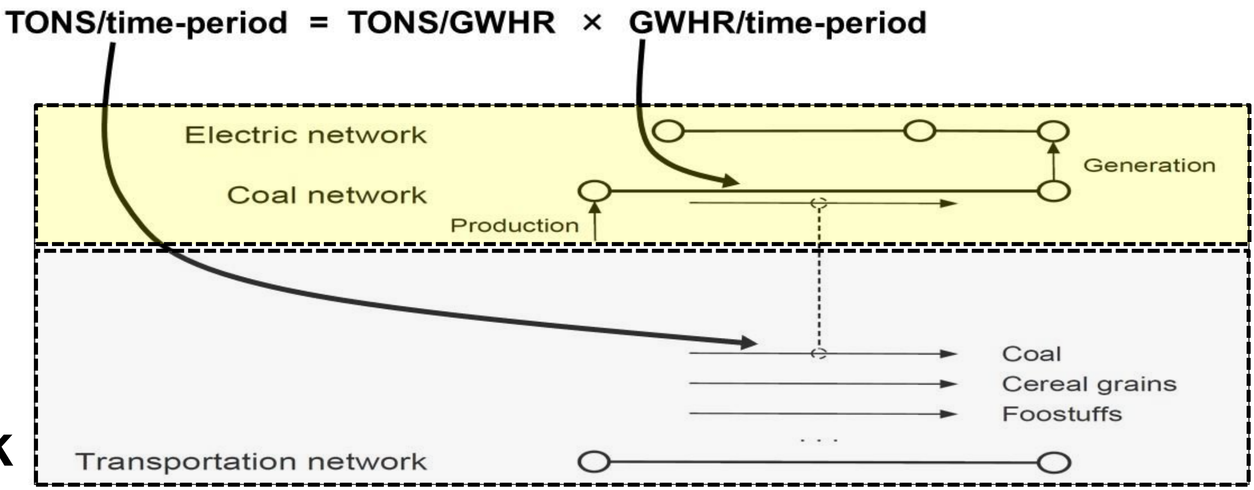

**Transportation demand is specified node-to-node, except for *energy commodities*.**

# Summary of networks represented in cost-minimization problem

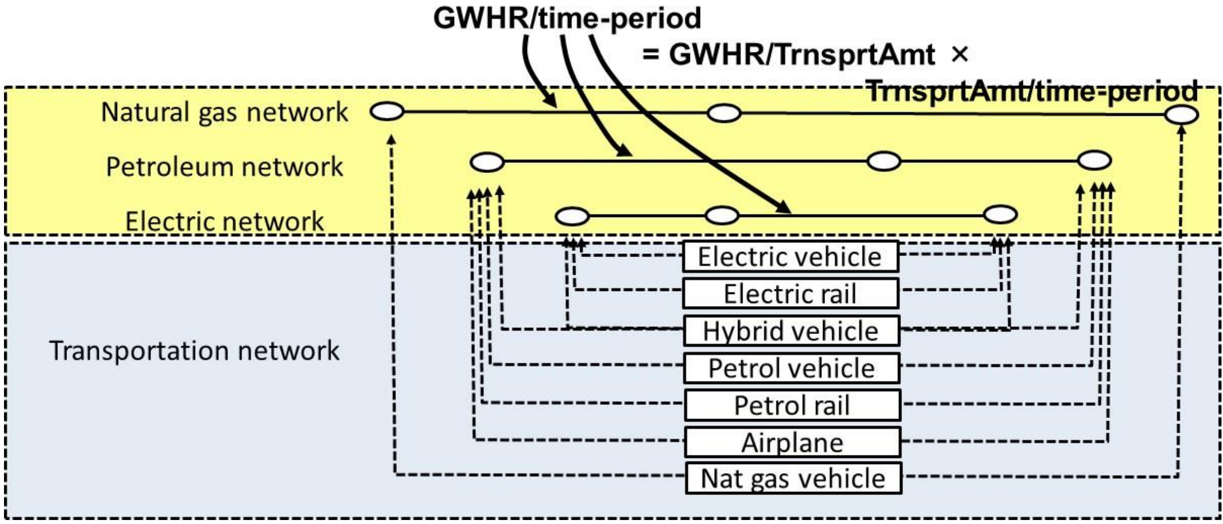
| Network | Flow | Commodities | Units | Infrast. | Fleet | Demand |
|---|---|---|---|---|---|---|
| Energy | Single comm. | Electric<br>Natural gas<br>$H_2$, $NH_3$<br>Petroleum | GWhr/ time-period | Electric<br>Pipeline<br>Pipeline<br>Pipeline | N/A | Nodes |
| Energy comm. coal & bio. | Multicomm. | Bituminous<br>Subbitmns<br>Lignite | Tons/ time-period | Rail<br>Barge<br>Highway | Diesel, elect.<br>Diesel<br>Diesel, hybrid | Nodes |
| Freight | Multicomm. | Grains<br>Chemicals<br>Gravel, etc. | Tons/ time-period | Rail<br>Barge<br>Highway | Diesel, elect.<br>Diesel<br>Diesel, hybrid | Arcs |
| Passenger | Single comm. | | Pssngrs/ time-period<br>600mph air<br>150mph HSR<br>65mph LDV | Highway<br>Rail<br>Rail<br>Air | Gasoline, elect.<br>Diesel, elect.<br>Electric<br>Petroleum | Arcs |

# Energy – transportation coordination

**“Energy commodities” (e.g., coal, feedstocks) are represented in the transportation network (as transported tons) and the energy network (as MWh). Both flows are coordinated.**




**Transportation loading on energy system: all transportation modes produce demand in energy networks.**



# Modeling: mathematical formulation for cost minimization problem

(i,j) are arcs. m is mode. k is commodity.

$$\min \quad \{CostOp^E + CostInv^E + CostOp^T + CostFleetInv^T + CostInfInv^T\} \tag{3.2}$$

Minimize operational and investment cost

**subject to:**

Meet energy demand at the appropriate nodes

$$\sum_i \eta_{(i,j)}(\mathbf{t}) e_{(i,j)}(\mathbf{t}) - \sum_i e_{(j,i)}(\mathbf{t}) = d_j^E(\mathbf{t}) + d_j^{ET}(\mathbf{t}) \quad j \in \mathcal{N}_d^E \tag{3.3}$$

Meet energy demand

**Yellow is energy commodity.**

DC power flow equations

$$e_{(i,j)}(\mathbf{t}) - e_{(j,i)}(\mathbf{t}) = b_{(i,j)} \Big(\theta_i(\mathbf{t}) - \theta_j(\mathbf{t})\Big) P_E \, \Delta(\mathbf{t}), \quad (i,j) \in \mathcal{A}_{DC}^E \tag{3.4}$$

DC power flow

Generation capacity must cover peak demand at electric nodes

$$\sum_i cf_{(i,j)}(\mathbf{t}) eCap_{(i,j)}(\mathbf{t}) \geq peakD_j^E(\mathbf{t}), \quad j \in \mathcal{N}_p^E \tag{3.5}$$

Meet electric peak demand

Transportation demand for non-energy commodities

$$\sum_m f_{(i,j,k,m)}(\mathbf{t}) = d_{(i,j,k)}^T(\mathbf{t}), \quad k \in \mathcal{K} \backslash \mathcal{K}_e \tag{3.6}$$

Transportation demand for energy commodities

$$\sum_m f_{(i,j,k,m)}(\mathbf{t}) = heatContent_k^{-1}(\mathbf{t}) \, e_{(n_{(i,k)}^E, n_{(j,k)}^E)}(\mathbf{t}), \quad k \in \mathcal{K}_e \tag{3.7}$$

Meet transportation demand

Fleet upper bound for transportation flows

$$\sum_k f_{(i,j,k,m)}(\mathbf{t}) \leq fleetCap_{(i,j,m)}(\mathbf{t}) \, \Delta(\mathbf{t}) \tag{3.8}$$

Max. fleet capacity

Infrastructure upper bound for transportation flows

$$\sum_k \sum_{m \in \mathcal{M}_l} f_{(i,j,k,m)}(\mathbf{t}) \leq infCap_{(i,j,l)}(\mathbf{t}) \, \Delta(\mathbf{t}) \tag{3.9}$$

Max. transportation infrastructure capacity

**Decision variables:**

Energy flows: $0 \leq lbe_{(i,j)}(\mathbf{t}) \leq e_{(i,j)}(\mathbf{t}) \leq eCap_{(i,j)}(\mathbf{t}) \, \Delta(\mathbf{t})$ (3.10)

Energy capacity inv.: $lbeInv_{(i,j)}(\mathbf{t}) \leq eInv_{(i,j)}(\mathbf{t}) \leq ubeInv_{(i,j)}(\mathbf{t})$ (3.11)

Energy flows and investments

Transportation flows: $f_{(i,j,k,m)}(\mathbf{t}) \geq 0$ (3.12)

Fleet inv.: $lbFleetInv_{(i,j,m)}(\mathbf{t}) \leq fleetInv_{(i,j,m)}(\mathbf{t}) \leq ubFleetInv_{(i,j,m)}(\mathbf{t})$ (3.13)

Infrastucture inv.: $lbInfInv_{(i,j,l)}(\mathbf{t}) \leq infInv_{(i,j,l)}(\mathbf{t}) \leq ubInfInv_{(i,j,l)}(\mathbf{t})$ (3.14)

Transportation flows and investments

Phase angles: $-\pi \leq \theta_i(\mathbf{t}) \leq \pi$ (3.15)

# Summary of long-distance transp/energy study results

## 1. Natural gas as transportation fuel

➔Reducing natural gas use in electric power while increasing its use as a transportation fuel (CNG and LNG) serves to diversify both sectors while decreasing both total cost of, and GHG emissions from, the energy/transportation system. This option is unattractive if natural gas use in the electric sector continues to grow.

## 2. US high-speed rail investment [1]

➔Development of a US passenger high-speed rail system diversifies the transportation sector, and, under a low carbon electric generation portfolio, leads to a reduction in GHG emissions by between 3 and 10% over a 40-year period. The investment in fixed infrastructure causes long-term cost savings to be small but positive assuming a petroleum price increase of 3% per year, and travel time valued at average hourly wages. The expansive US travel distances, the travel convenience of HSR, and HSR total electric dependence makes this option attractive.

[1] V. Krishnan, E. Kastrouni, V. Pyrialakou, K. Gkritza, and J. McCalley, "An optimization model of energy and transportation systems: assessing the impact of high-speed rail on U.S. passenger transportation investment," to appear, *Transportation Research Part C*, 2015.

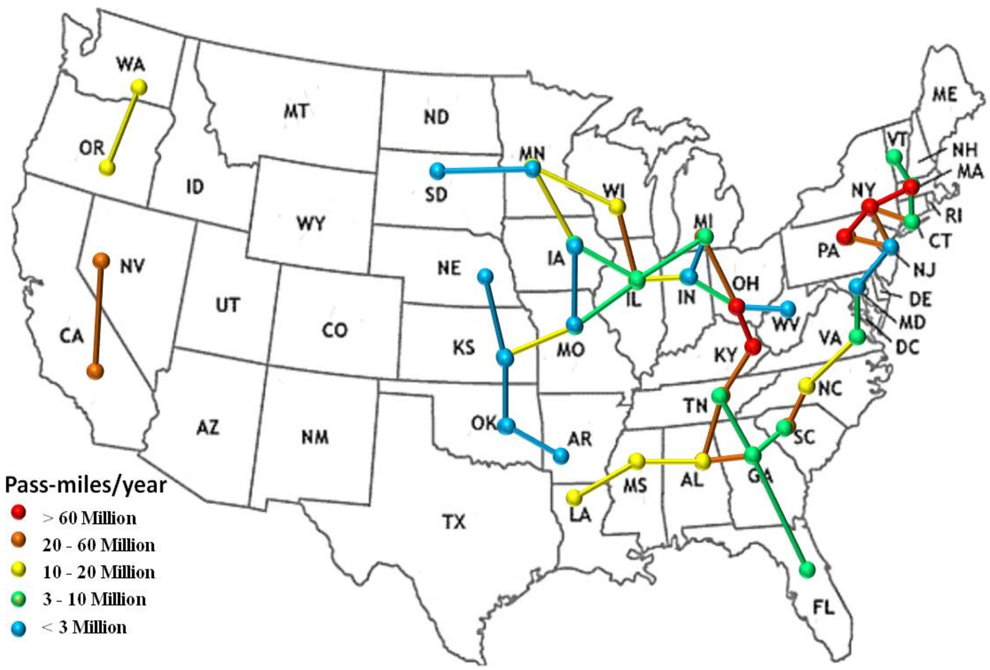
## 3. Use of biomass for biofuels & biopower [2]

➔Biomass can play a significant role in reducing GHG emissions mainly through deployment of biofuels, particularly ethanol. Although biopower may flourish in some parts of the country, its national impact will remain limited unless the investment and operational cost of biopower technologies (combustion, gasification, and anaerobic digestion) are reduced. Use of biofuels in transportation competes with food via land use and so may not be an attractive option at high penetration levels.

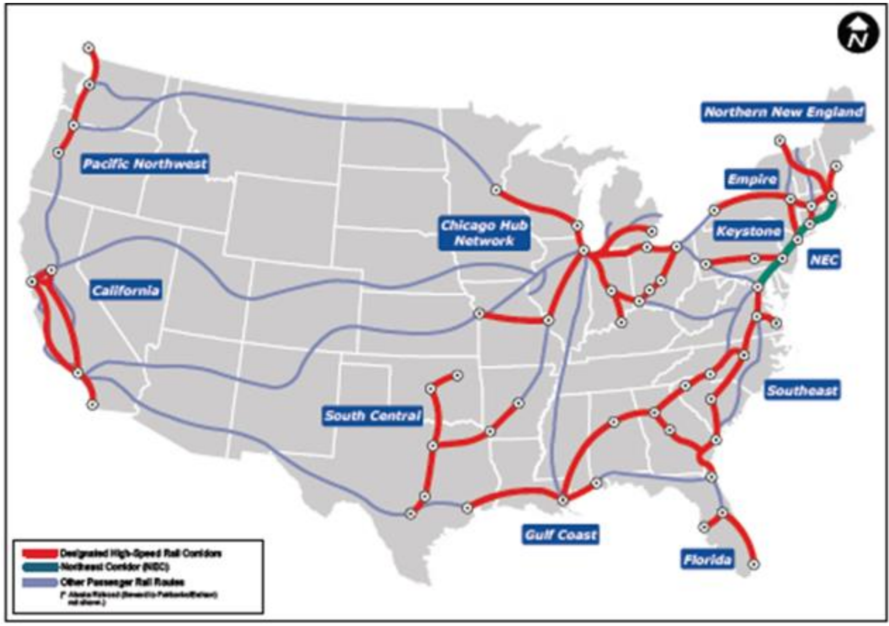
[2] V. Krishnan and J. McCalley, "The Role of Bio-renewables in National Electric and Transportation Systems Portfolio Planning for Low Carbon Economy," under review by Renewable Energy.

# Design: High-speed rail (HSR)

**Results are similar to the high-speed rail corridors designated by DOT.**




Netplan Results

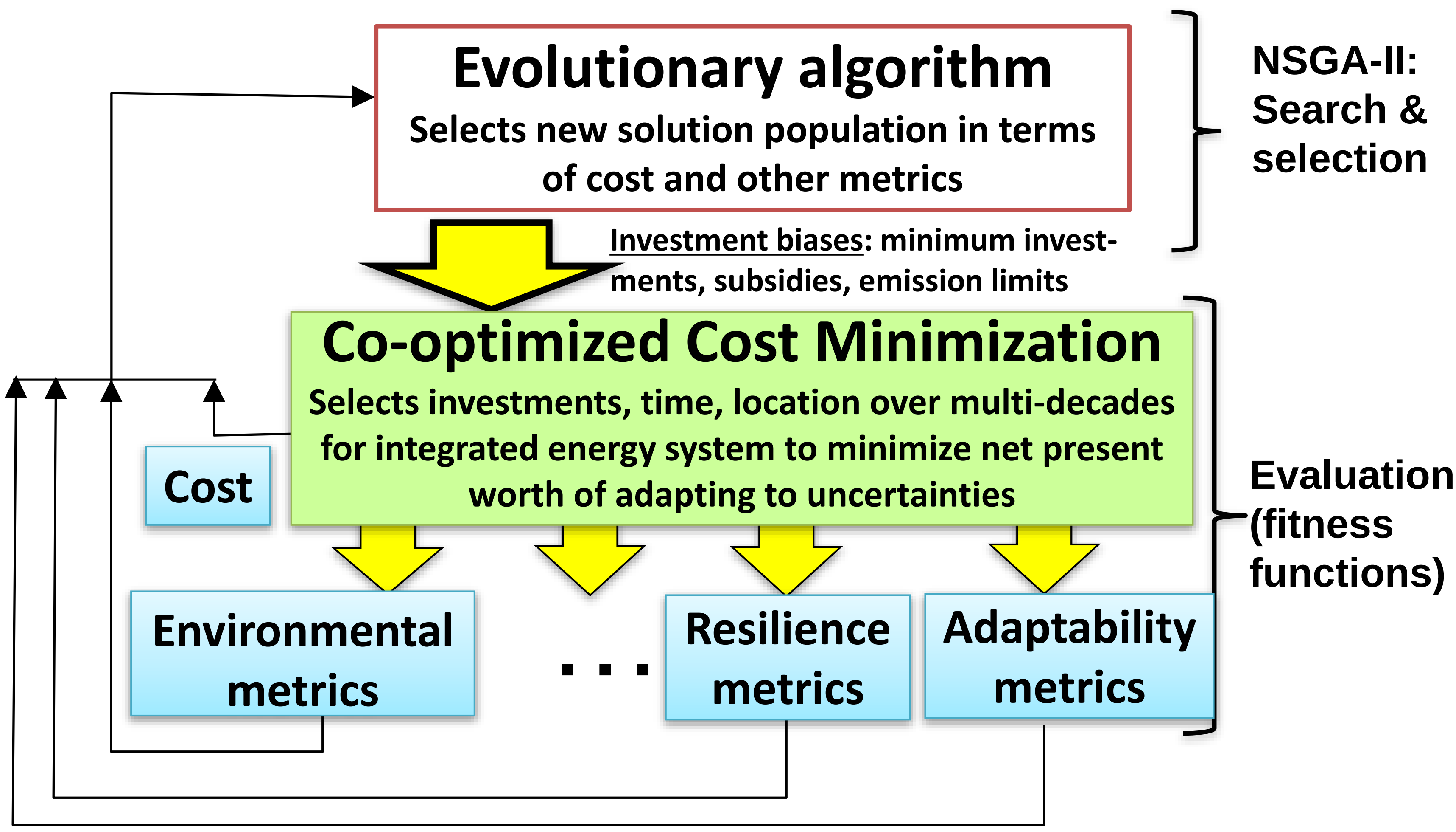



DOT Designations

# Design objectives: EES-S/FRRA

- **E: Environmental sustainability;**
- **E: Economic sustainability;**
- **S: Social sustainability;**
- **FRRA:**
  - **Flexibility: operational speed of response;**
  - **Reliability: service availability (SAIDI, SAIFI);**
  - **Resilience: economic service availability – ability to minimize & recover from price-consequences of extreme events;**
  - **Adaptability: A long-term version of resilience – ability to economically adapt infrastructure to adverse and permanent changes in technology/fuel availability or cost.**

# A design tool



# Design levels

technology — Solar PV/thermal, biofuels, fuel cells, storage, heat pumps…

cmmnty/ind — Flex-fuel poly-generation power plants
Or Energy Hub, Hybrid Energy System,
Virtual Power Plant

city — District heat/cooling systems
Local transportation systems

state

region — Local transmission & pipeline systems

intrconnctn — Long distance freight & passenger transportation

nation — Hi capacity interregional transmission

continent

**Questions:**

1. Is there a design procedure?
2. What is the decision process?
3. Should one level receive more attention than another? Why?

# Design procedure

1. Identify services:
    - electricity services (cooling, heating, lighting…)
    - fuel services (conversion, heating…)
    - transportation services (passenger, freight…)
    - water services (human needs, irrigation, power plant cooling…)
    - agricultural services (food, feedstocks…)
2. Identify technologies to provide services, energy carriers to supply technologies;
3. Characterize and model each service/technology/carrier:
    - interconnections with other subsystems,
    - costs (investment/operational),
    - performance (efficiency, environmental, FRRA);
4. Explore strengths of each service/technology/carrier within higher-level systems, temporal/geo-scales.
5. Inform/interact with decision-makers at appropriate levels.

# Decision process

<table>
<tr><th>Level</th><th>Decision-makers</th><th>Barriers</th></tr>
<tr><td>Technology</td><td>Business owners</td><td>The business case</td></tr>
<tr><td>Community or industry</td><td rowspan="2">Community/city leaders,<br>Community/city populace.<br>Or organization’s board<br><br>Local infrastructure operators,<br>Agencies & regulators of 1 state</td><td rowspan="2">- Financing infrastructure developments<br>- Interconnections to existing networks<br>- Compliance with environmental permitting<br>- Local codes and permits<br>- Local regulatory treatment</td></tr>
<tr><td>City</td></tr>
<tr><td>State/<br>region</td><td rowspan="2">Community/city leaders (many)<br>State, region, or nation populace.<br><br>Many infrastructure operators<br>Agencies & regulators of many states<br>Coordinating groups<br>Federal agencies and regulators</td><td rowspan="2">- Balkanized decision-making<br>- Parochialism, NIMBYism<br>- Lack of accepted mechanisms to achieve equitable cost/benefit allocation<br>- Uncertainties: in policy, growth in services, climate, technology maturation</td></tr>
<tr><td>Interconnection/<br>nation/<br>continent</td></tr>
</table>

# Concluding comments

- Interdependencies matter to infrastructure decisions
  - Generation ←→ Transmission
  - Generation ←→ Transmission←→ Gas pipeline
  - Energy←→ Transportation
  - Biofuels←→ Food
  - Water ←→Agriculture←→ Energy
- EES-S/FRRA are infrastructure design objectives
- Design issues:
  - Economies of scale: to be discussed tomorrow
  - Design procedure: an important "ESI community" research goal
  - Should one level receive more attention than another?

    ➔Which level has largest benefit to cost ratio where

    cost: for design, materials, labor, O&M, and …

    decision process complexity.
  - Decision process – stakeholder processes is a research focus.
  - Communication with the media is essential.

"When a reporter approaches, I generally find myself wishing for a martini."

-- Jonas Salk, Nobel Prize winner

# Concluding comments

**I prefer scientists/engineers as information sources because…**

- "I want to hear it from the horse's mouth."
- "I want to see research 'personalized'."
- "I would like to hear it from the originator, not the middleman."
- "I am drawn by scientists' enthusiasm about the work they do."

Source: Horrigan, 2008

Lulu Rodriguez: Expert on the communication of science and risk. See:

http://home.eng.iastate.edu/~jdm/wesep594/Comm%20dimension%20of%20wind%20energy.pdf

www.igert.windenergy.iastate.edu/files/2013/02/Rodriguez-Lulu-Public-perception-of-and-attitudes-toward-wind-energy.pdf