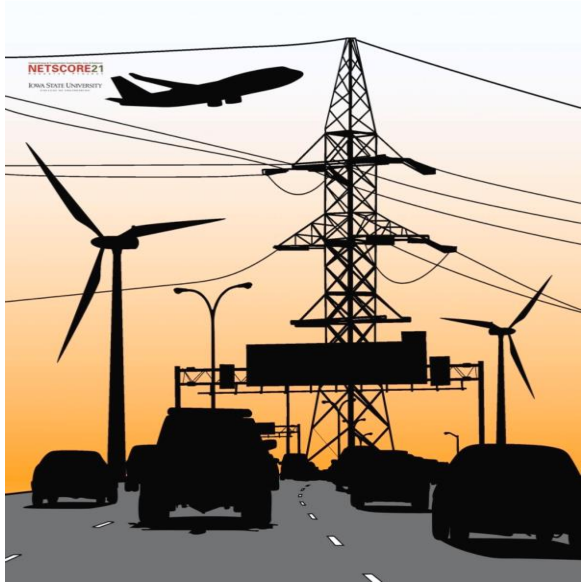
Planning in Energy Systems Integration

Utility Variable-Generation Integration Group



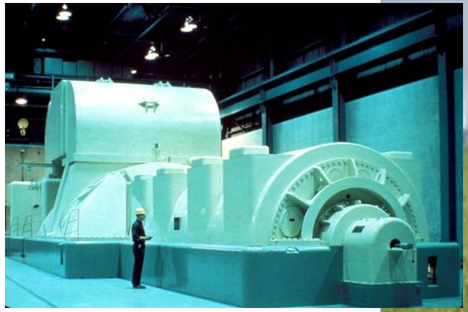
March 13, 2018

Tucson, Arizona

James McCalley

London Professor of Power Systems Engineering

Iowa State University



Overview

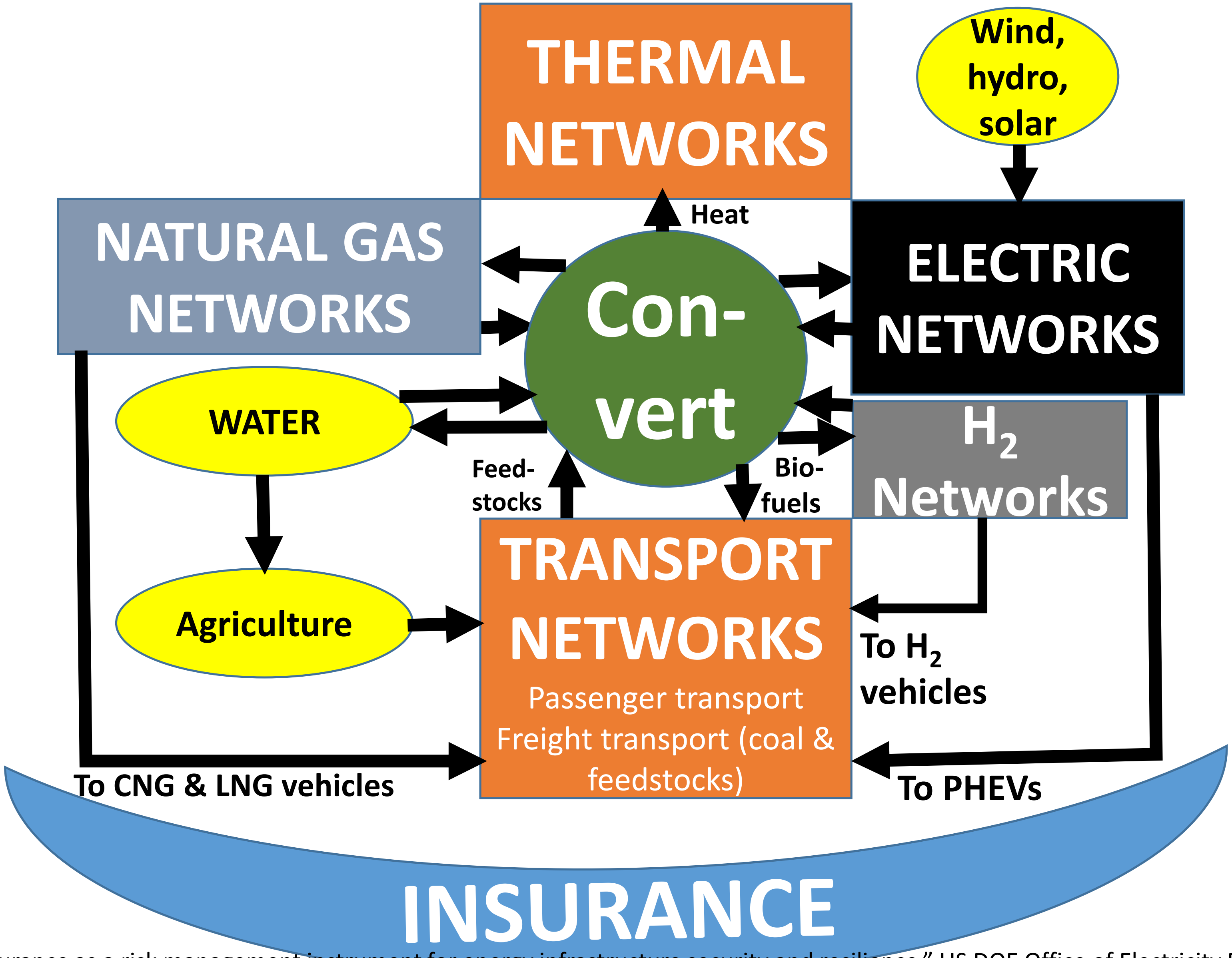
1. Energy system integration: system & technology views
2. ESI planning concepts
3. Design tools
4. Example studies
5. Conclusions

16 critical infrastructure sectors

1. Chemical sector
2. Commercial facilities
3. Communications
4. Critical manufacturing
5. Dams
6. Defense industrial base
7. Emergency services
8. Energy
9. Financial services
10. Food and agriculture
11. Government facilities
12. Healthcare & public health
13. Information technology
14. Nuclear reactors, materials & waste
15. Transportation systems
16. Water & wastewater systems

Reference: https://www.dhs.gov/critical-infrastructure-sectors

ESI: system view



<u>Energy services</u>:

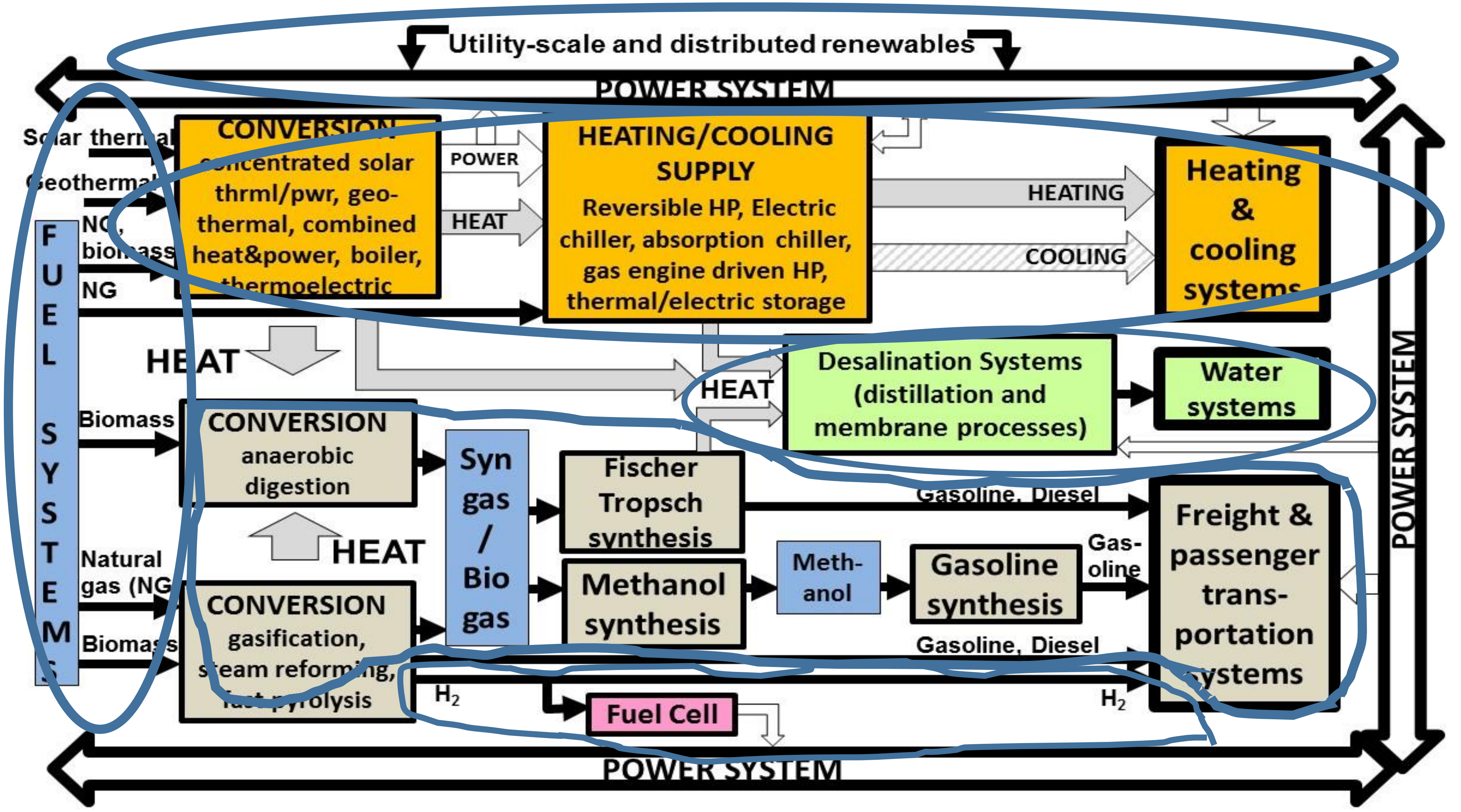
- Electric
- Non-electric
  - Heating/cooling including process heating
  - Transportation
  - Water

"Insurance as a risk management instrument for energy infrastructure security and resilience," US DOE Office of Electricity Delivery & Energy Reliability, Infrastructure Security and Energy Resotration, March, 2013., developed by T. Choi of ICF International.

ESI: technology view

Features:

- A better DG
  - At dist sub
  - 10-100MW
- Modular
  - built quickly
  - region-specific configurations
- Efficient
- Flexible
  - fast
  - storage
- MIMO



A Hybrid Energy System (HES)

ESI: technology view

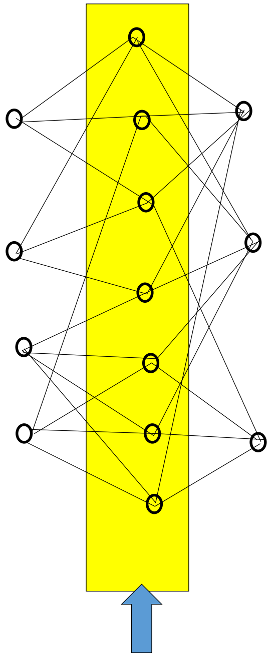
Coal
Natural gas
Biomass
Wind
Solar
Geothermal
Hydrogen

→

HES: Flex Fuel Poly-generation Plant

→

Power
Heat
Syngas
Liquid Fuels



Multi-input, multi-output energy converters

FFPG power plants are multiple input, multiple output energy converters; in the multi-grid network, they are nodes with multiple connections, increasing the density of the multigrid network; thus enhancing resilience.

ESI planning concepts

- **Interdependencies**
  - **vs boundaries**
  - **discovery through modeling**
- **Technical understanding**
- **Portfolios & geo-correctness**
- **The future:**

  ➔prediction vs. exploration
- **Infrastructure design criteria:**

  ➔Flexibility; Reliability;

  Cost resilience; Adaptability
- **Nuts and bolts**

Identify least-cost designs subject to imposed constraints that specify desired directions of exploration.

Flexibility:

Deliverable regulation, load following, contingency reserves to give high response speed for balancing energy service supply & demand.

- CTs and CCs
- Demand response
- Wind & solar control
- CHPs
- Water systems
  - Existing hydropower
  - New small-scale hydro power
  - Conventional pumped storage
  - Wastewater/water treatment plants
  - Irrigation systems
  - Aquifer storage & recovery
  - Virtual pumped storage
- Other storage:
  - Gas
  - Thermal
  - Batteries, flywheels, etc.

Reliability: energy service availability (Adequacy, security level, cascading risk);

Adequacy indices:

- LOLE, EUE
- SAIFI, SAIDI

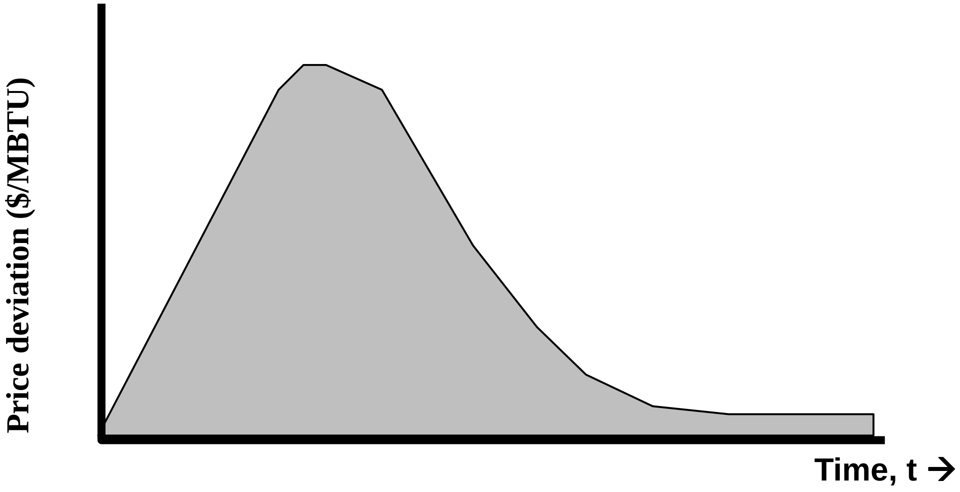
NERC Disturbance-Performance Table:

- SS performance
- Dynamic performance

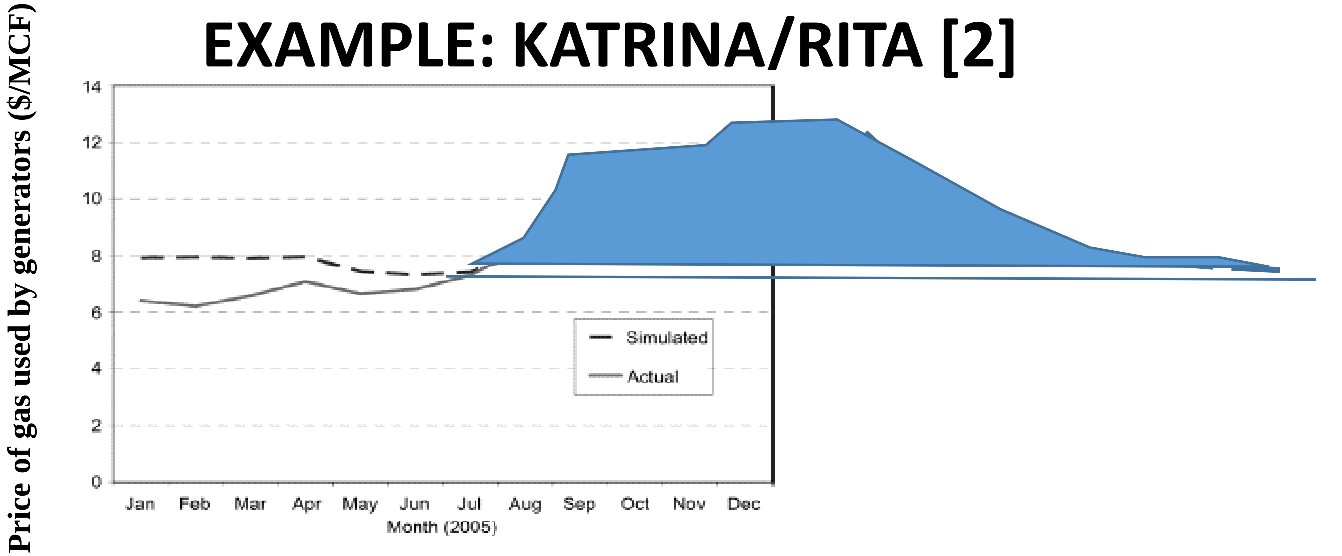
http://www.nerc.com/files/tpl-004-1.pdf

Cost resilience

<u>C-Resilience</u>: ability to use operational measures to minimize & recover from the change in cost of service following extreme events[1]



EXAMPLE: KATRINA/RITA [2]



<u>Possible extreme events</u>:

- **2-yr 50% reduction of nuclear supply;**
- **2-yr 50% reduction of hydro due to extreme drought;**
- **2-yr 50% reduction of shale gas supply;**
- **1-yr loss of rail access to Powder River Basin coal;**
- **Sustained flooding in Midwest destroying crops, reducing biofuel production, interrupting E-W rail system.**

[1] E. Ibanez, V. Krishnan, S. Lavrenz, D. Mejia, K. Gkritza, J. McCalley, & A. Somani, "Resilience and robustness in long-term planning of the national energy and transportation system," *International Journal of Critical Infrastructures*, 2014.

[2] E. Gil and J. McCalley, "A US Energy System Model for Disruption Analysis: Evaluating the Effects of 2005 Hurricanes," *IEEE Transactions on Power Systems*, Volume: 26 , Issue: 3, 2011, pp. 1040 – 1049.

Adaptability

<u>Adaptability</u>: A long-term version of resilience – ability to use investment to adapt infrastructure to provide continuous low-cost energy services.

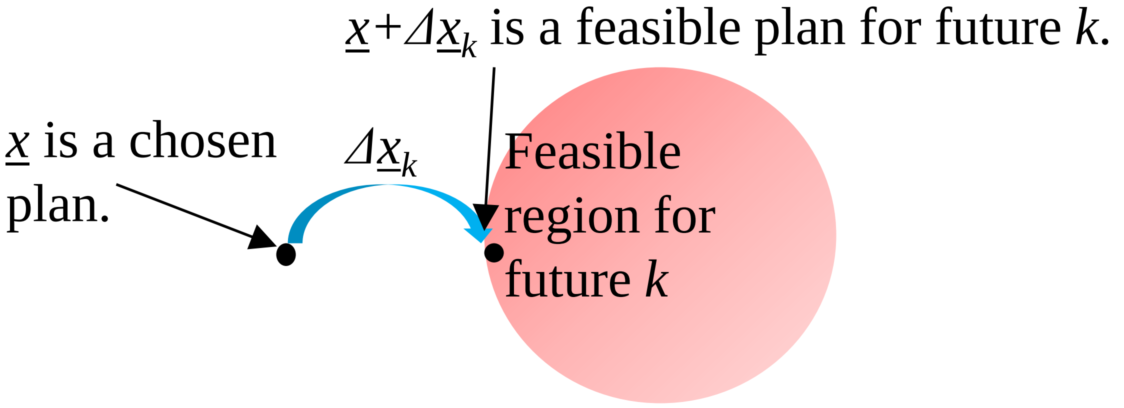
<u>Examples</u>:

- **Permanent loss of nuclear supply, like Fukushima**
- **Permanent loss of shale gas supply;**
- **Government-imposed extreme reduction of GHG-emitting electric resources**

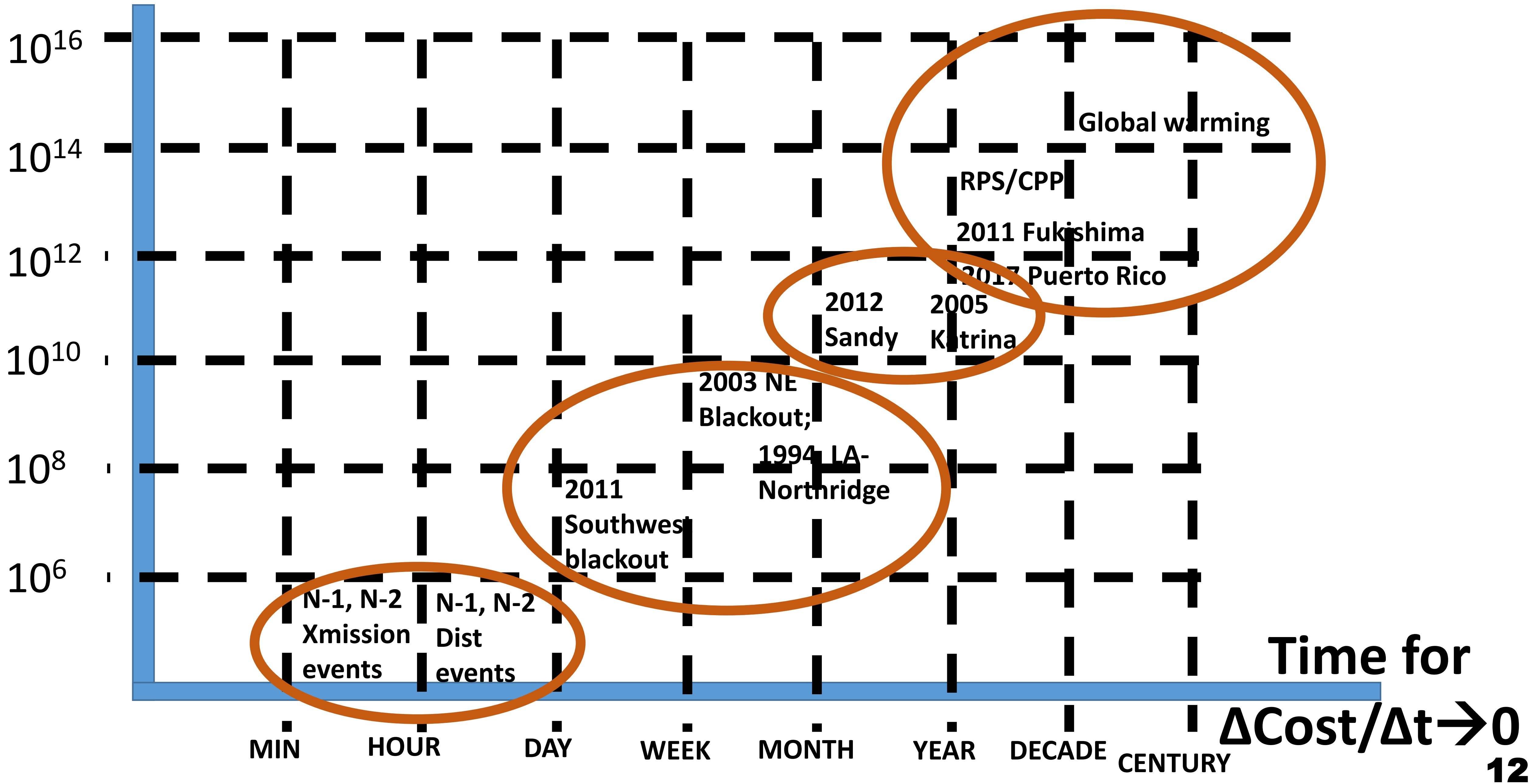
Adaptation is the additional *<u>investment</u>* necessary for plan $\underline{x}$ to acceptably perform under future *k*:

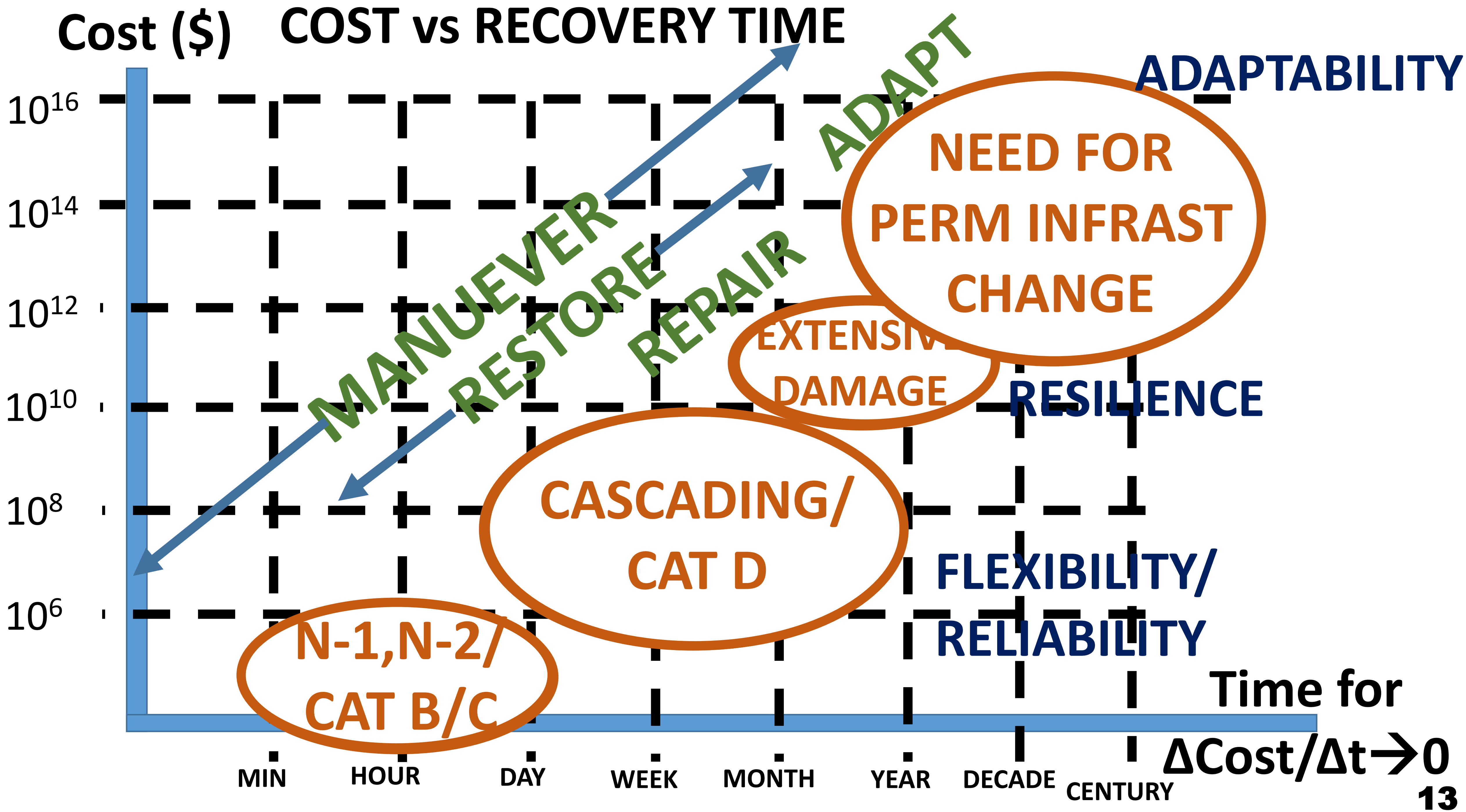
- **the adaptation cost of additional investment is $AdaptationCost(\Delta \underline{x}_k)$**
- **$\Delta \underline{x}_k = 0$ if plan $\underline{x}$ is designed under future *k***

The <u>adaptation cost</u> of $\underline{x}$ to future *k* is the minimum cost to move $\underline{x}$ to a feasible design in future *k*.
It measures the additional cost of plan $\underline{x}$ if future *k* happens.



COST vs RECOVERY TIME




Cost ($)
COST vs RECOVERY TIME
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
MANUEVER
RESTORE
REPAIR
ADAPT
ADAPTABILITY
NEED FOR PERM INFRAST CHANGE
EXTENSIVE DAMAGE
RESILIENCE
CASCADING/ CAT D
FLEXIBILITY/ RELIABILITY
N-1,N-2/ CAT B/C
Time for $\Delta Cost/\Delta t \rightarrow 0$
MIN
HOUR
DAY
WEEK
MONTH
YEAR
DECADE
CENTURY

Infrastructure design criteria

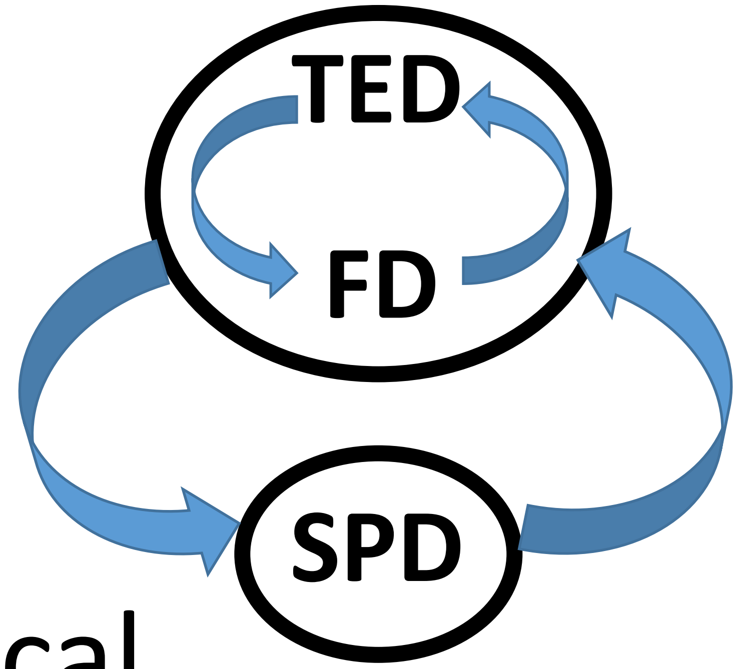
- **Sustainability criteria:**
  - **Environmental**: impact on GHG emissions; air pollutants, water pollution, runoff; and aesthetic, wildlife and social impacts of land conversion;
  - **Economic**: value & cost of services delivered in terms of aggregate effect on market efficiency;
  - **Social**: benefit & cost distribution among societal groups, together with extent to which constituent groups actively support the technologies.
- **Integrity criteria:**
  - **Flexibility**: speed of response to balance energy service supply & demand;
  - **Reliability**: energy service availability (SAIDI/SAIFI, security level, cascading risk);
  - **C-Resilience**: economic service availability – ability to use operational measures to minimize & recover from changes in cost of service following extreme events;
  - **Adaptability**: A long-term version of resilience – ability to use investment to adapt infrastructure to provide continuous low-cost energy services.

What maximizes infrastructure integrity?

- **Flexibility:**
  - reserve availability
  - reserve response speed
  - deliverability
- **Reliability:**
  - equipment availability
  - repair speed
  - deliverability
- **Cost resilience:**
  - resource diversity
  - operational response time
  - deliverability
- **Adaptability:**
  - design diversity
  - Infrastructure development time
  - deliverability

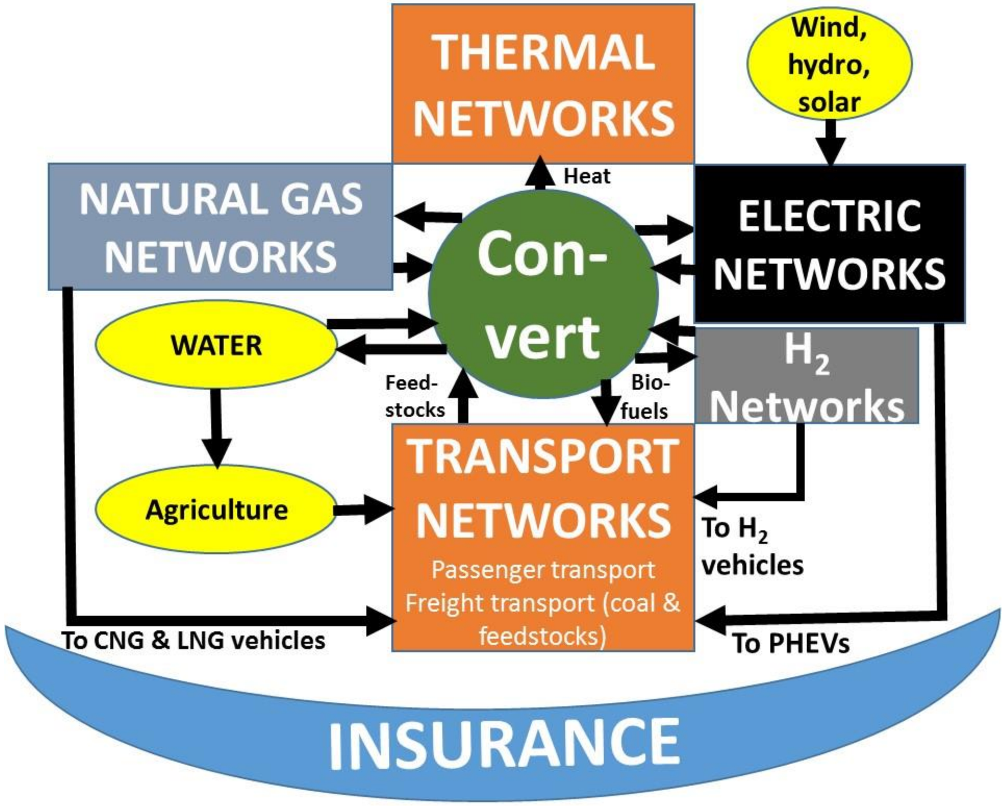
Deliverability? = Capacity + Interconnectedness

Nuts and bolts: design tools



- Techno-economic design, TED
  - Expansion planning
  - Production costing
  - Technology, e.g., Homer
- Functional design, FD
  - Power flow
  - Transient stability
  - Fault analysis
  - Technology, Aspen Plus
- Socio-political development, SPD
  - Stakeholder focus groups
  - Regulatory hearings
  - Negotiated settlements

Nuts and bolts: co-optimized expansion planning



MINIMIZE PRESENT WORTH

Investment costs
+ Fixed O&M Costs
+ Var O&M Costs + Fuel Costs
+ Service reduction costs
+ Environmental Costs
+ Insurance cost
+ Resilience cost
+ Adaptation cost

SUBJECT TO:

Operational & environmental constraints, investment and planning constraints flexibility, reliability, & resiliency constraints.

Year 1 **Year 2** **•••** **Year N**

Nuts and bolts: data needs

NETWORK

OPERATING (LOAD) BLOCKS

RESOURCES

TRANSMISSION/DISTRIBUTION

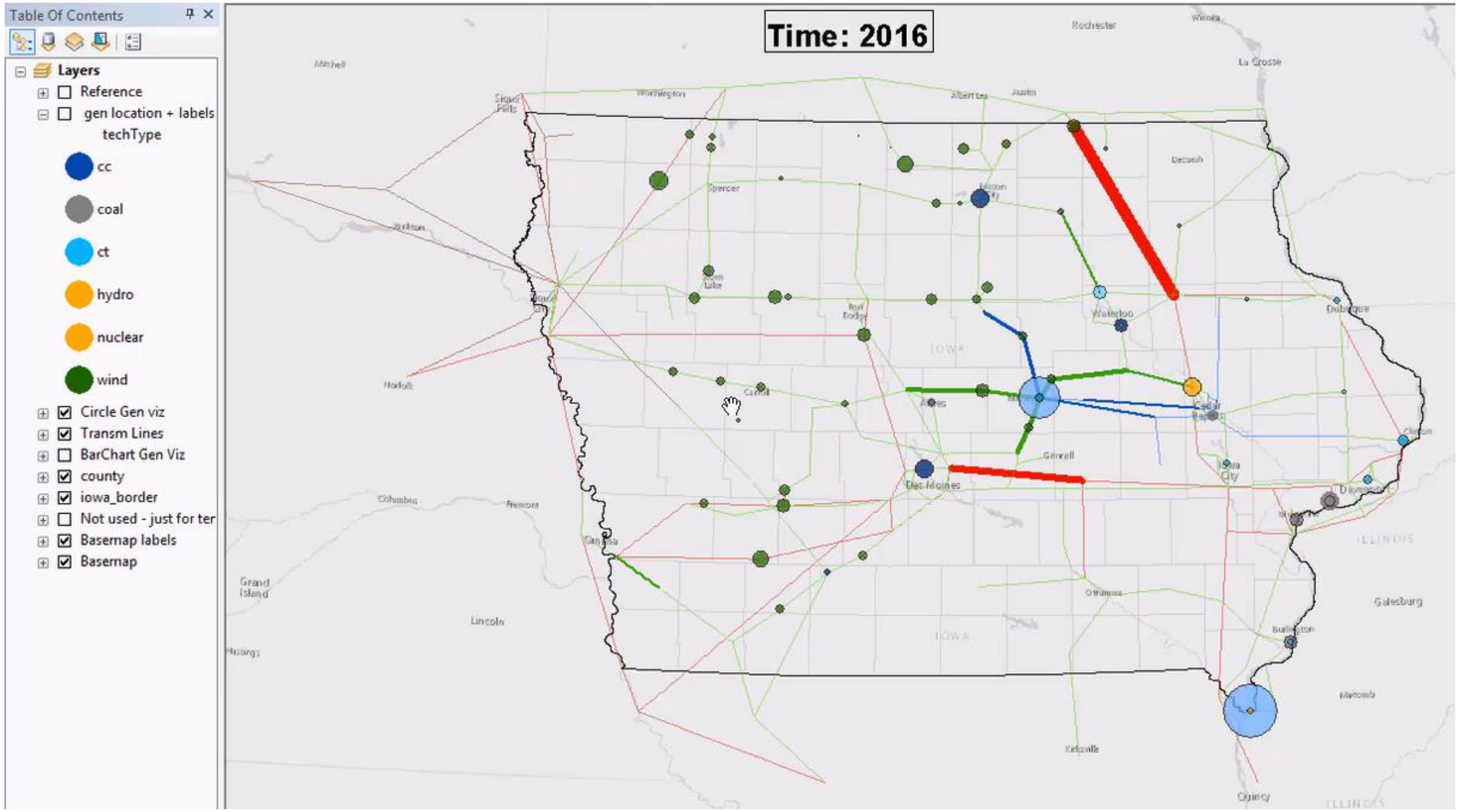
Nuts and bolts: data needs

1. **<u>Reduced network is represented using DC power flow, with “normal condition” flow limits. N-1 analysis not done (yet).</u>**
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 additional years of final year operation cost.
5. **Load is modeled for each of 4 seasons using multiple 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. Investments can be focused for only a single “subgrid;” resources should include utility-scale resources and DER.
11. **Planning/operating reserves modeled regionally, interconnection-wide. Reserve sharing requires deliverability constraints.**
12. **Operating reserve modeled as function of variability; variability a function of load & wind/solar penetration.**
13. **Load, hydro, wind, solar resources characterized meteorologically via climate models.**
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 T&D modeled w/ impedances. Candidate T&D modeled continuously or disjunctively (integers).**
19. Multiple DC & AC transm technologies with cost a function of technlgy, length, subs, terminals.
20. AC transm capacity a function of length between substations per St Clair curve; substations separated by < 200miles.
21. Line losses approximated as linear function of flows.

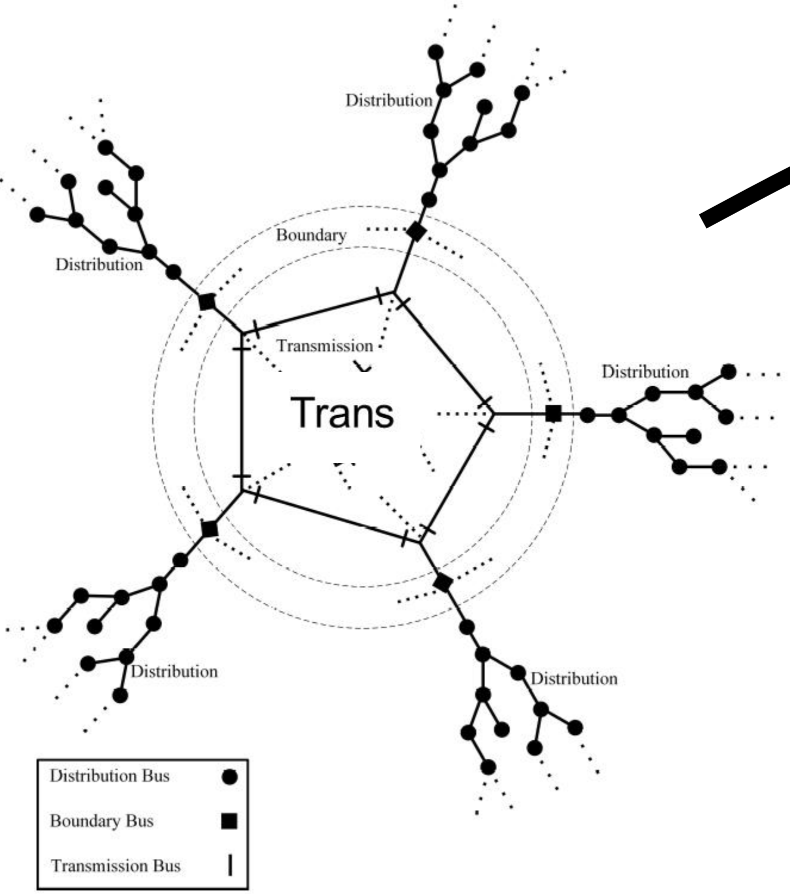
Illustrations of Expansion Planning Problems

1. <u>G</u>eneration and <u>T</u>ransmission
2. G, T, and DER
3. G, T, DER, Water
4. G, T, Water, Insurance
5. G, T, under uncertainty
6. G, T, Gas network
7. G, T, Long-distance transportation including HSR

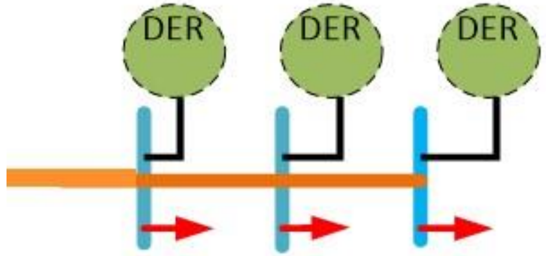
ESI planning: Ex 1a - G & T



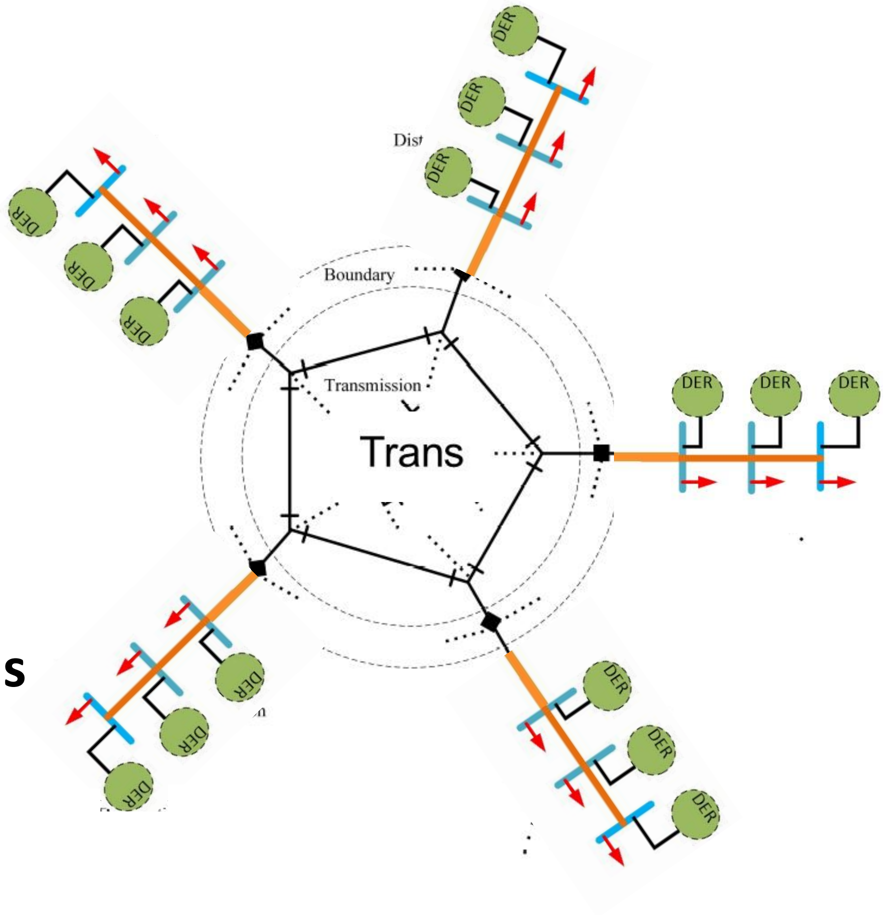
ESI planning: Ex 2 - G, T, DER



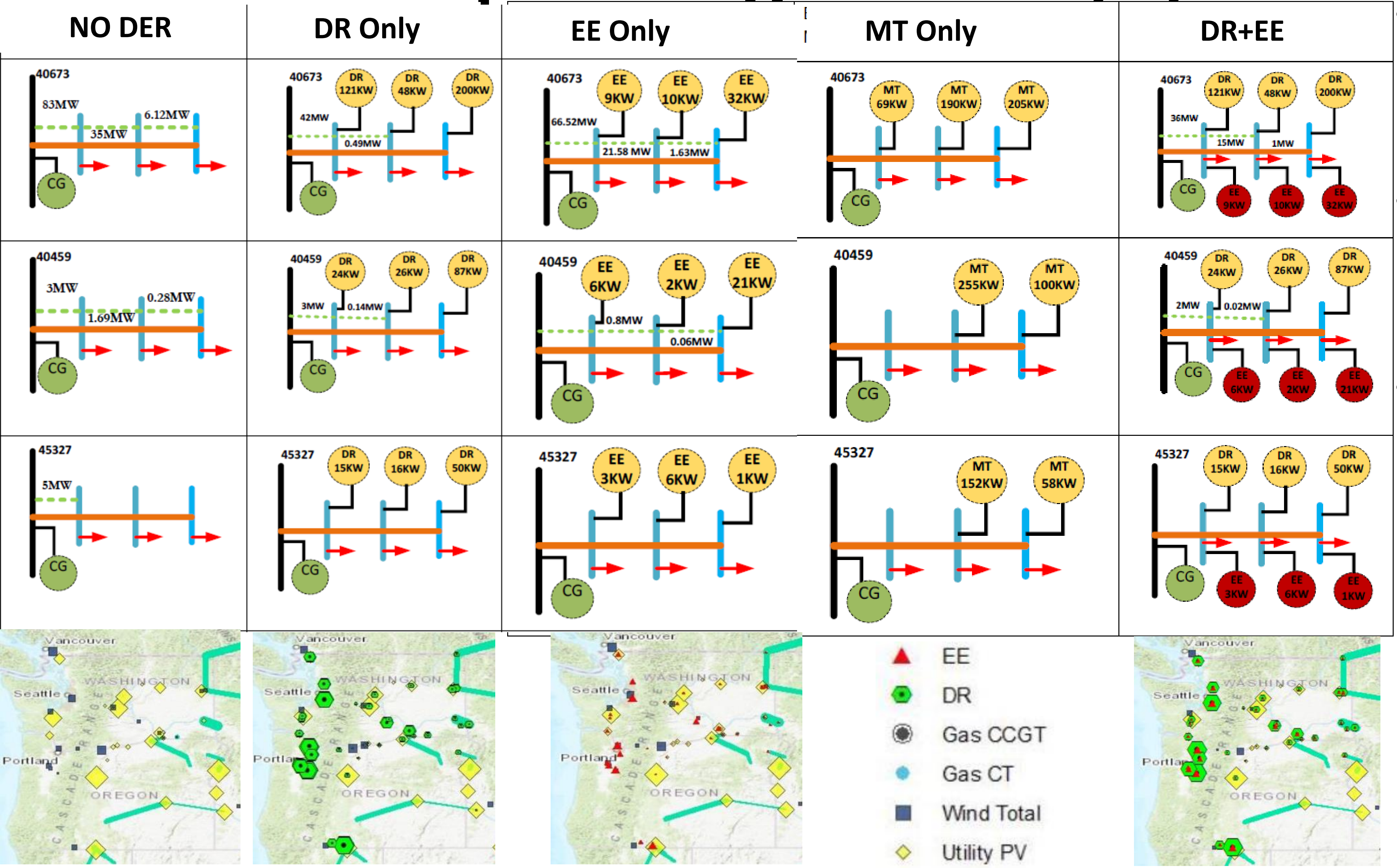
Model one 3-seg feeder at each trans load bus.



Enables multisegment loss analysis & investment without increasing model size too much.

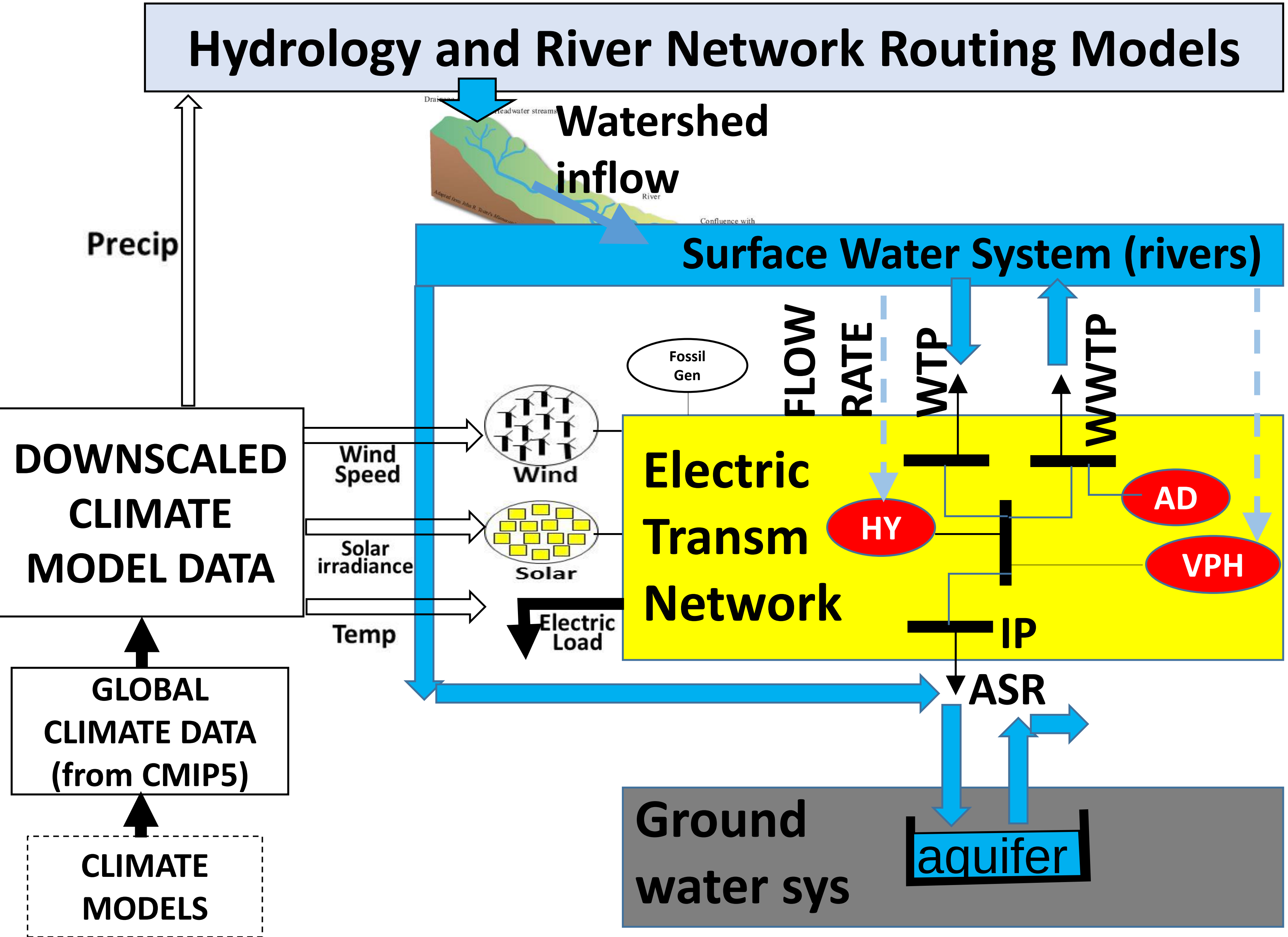


ESI planning: Ex 2 - G, T, DER



- EE, DR highly attractive to reduce energy, capacity needs
- D-PV capex inhibits investment w/o subsidy;
- D-PV looks better with Cheap storage, microturbines, loss modeling, hi load growth, hi-cost feeder expansion.

ESI planning: Ex 3 - G, T, DER, Water



➔**Water-related electric injections (±):**

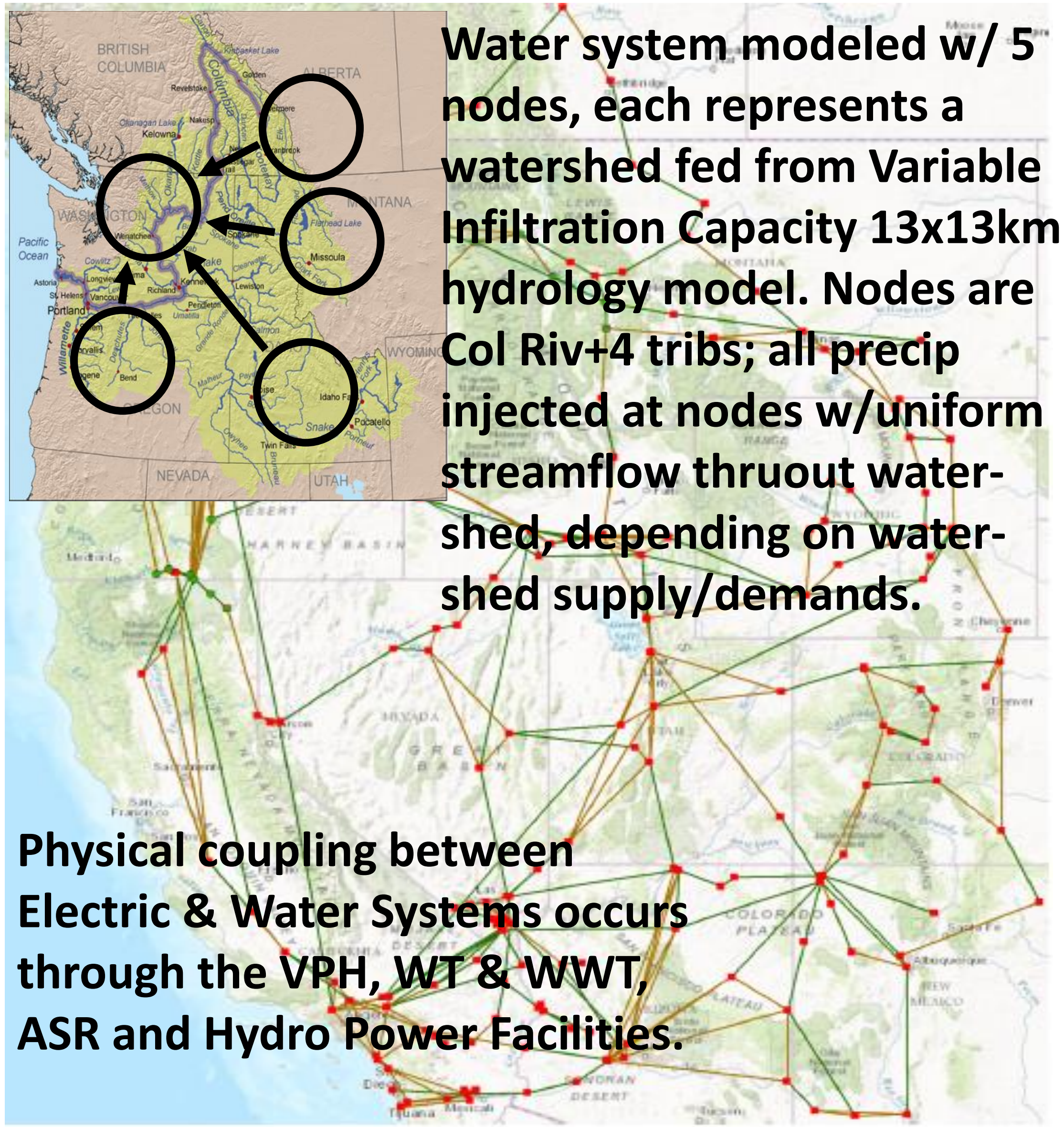
- For WWTP, WTPs, irrigation pumping (IP), ASR pumping/gen;
  - electric demand;
  - demand response capability.
- Existing and potential anaerobic digesters (AD) at WWTP;
- Hydroelectric output as function of surface water systems.

Water injections (±):

- For irrigation, public supply, thermal power plants, ASR, precipitation (including snowpack/runoff):
  - Flow change in surface water systems
  - Discharging and charging of aquifers

ESI planning: Ex 3 - G, T, DER, Water, Ins

ELECTRIC & WATER SYSTEM



Water system modeled w/ 5 nodes, each represents a watershed fed from Variable Infiltration Capacity 13x13km hydrology model. Nodes are Col Riv+4 tribs; all precip injected at nodes w/uniform streamflow thruout water-shed, depending on water-shed supply/demands.

Physical coupling between Electric & Water Systems occurs through the VPH, WT & WWT, ASR and Hydro Power Facilities.

MIN NET PRESENT VALUE

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

SUBJECT TO:

Electric & Water Infrastructure Investment constraints
Electric & Water Operational, planning, environmental constraints
WT & WWT working level limits, Stream Flow Balance, ASR Charge/Discharge, VPH storage & release constraints

Decision Variables:

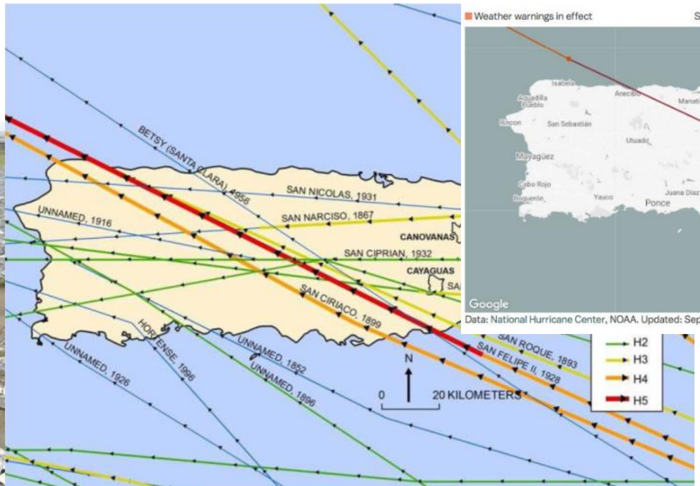
Investment variables for Electric & Water infrastructure
Operational levels for Electric & Water infrastructure

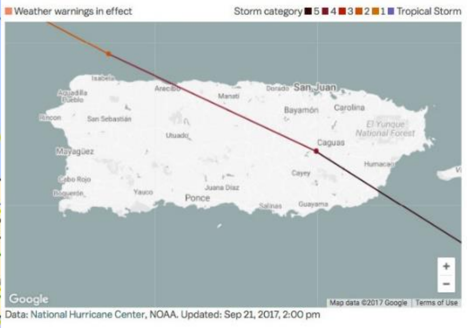
Year 1 | **Year 2** | ••• | **Year 20**

ESI planning: Ex 4 - G, T, DER, Water, Insurance

Why G, T, DER, Water, Insurance?

- Resilience: High-consequence events create very large liabilities;
- Tradeoffs:
  - Design ultra-resilient infrastructure to withstand all events, forgo insurance;
  - Design infrastructure-lite, pay very high insurance premiums;
  - Something in between?
- Climate change may make such events more frequent, more severe;
- Puerto Rico is illustrative, but other regions share similar features





ESI planning: Ex 4 - G, T, DER, Water, Ins

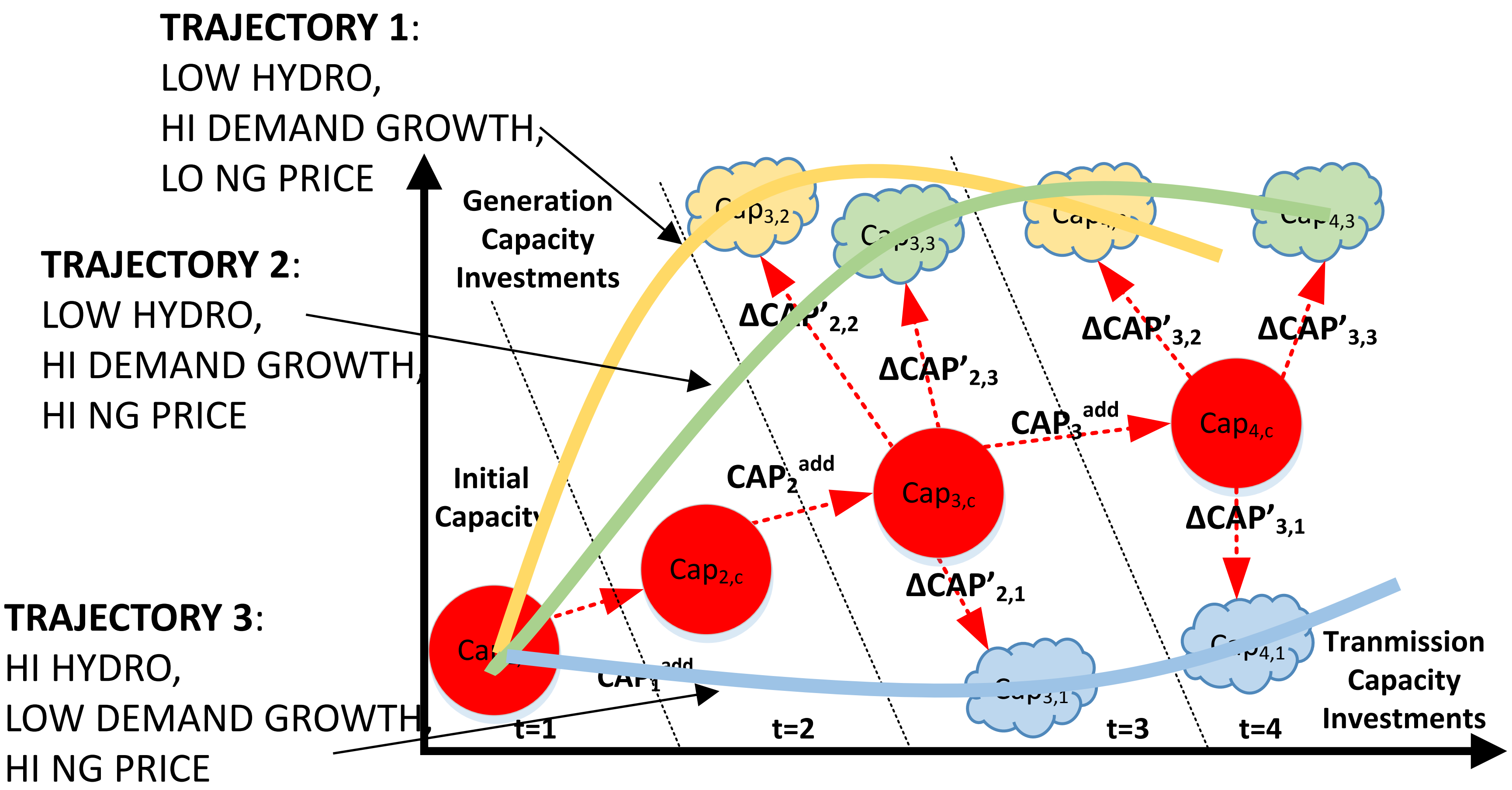
Minimize $c(\underline{x})+f_k(p(\underline{x}))$

Total cost *c* of investment plan $\underline{x}$.

Cost of insurance associated with investment plan $\underline{x}$ resulting in performance p.

- When infrastructure plan is expensive (high $c(\underline{x})$),
- the performance is good (low $p(\underline{x})$), and
- the insurance cost is inexpensive (low $f_k(p(\underline{x}))$).

ESI planning: Ex 5 - G & T under uncertainty



Each trajectory represents a deterministic investment plan. The computed core (red circles) is an investment plan that is "most robust" to those trajectories.

ESI planning: Ex 5 - G & T under uncertainty

β: Robustness parameter:

- Low ➔ Adaptation is cheap, wait & see!
- High ➔ Adaptation is expensive, invest in core here & now..

Minimize:

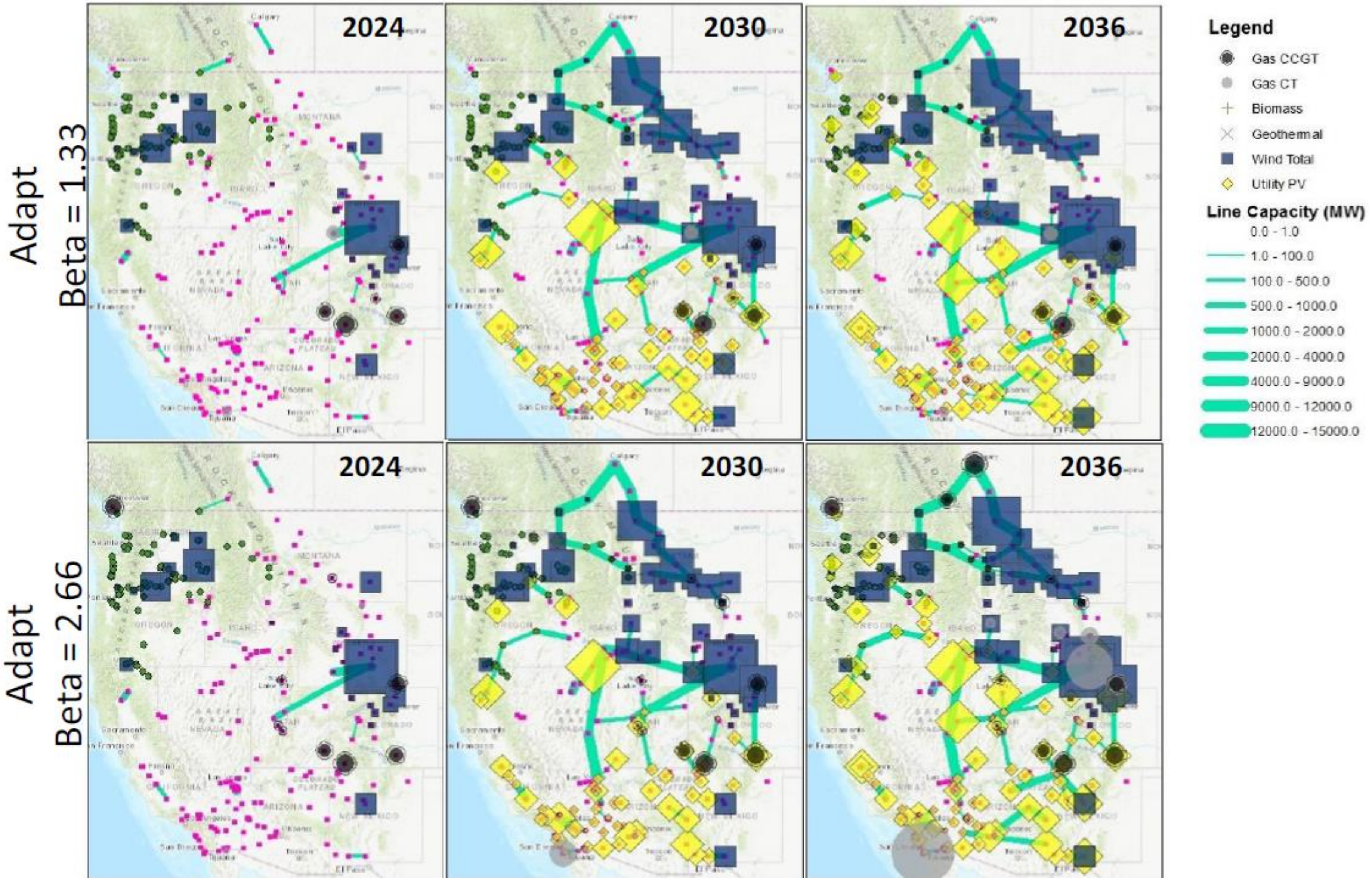
$$\mathrm{NPW}\{\mathrm{CoreCosts}(\underline{x})$$
$$+ \beta\ \{\Sigma_k\ \mathrm{Pr}_k \times \mathrm{AdaptationCost}(\Delta\underline{x}_k)\}$$
$$+ \quad \Sigma_k\ \mathrm{Pr}_k \times \{\mathrm{OpCost}(\Delta\underline{x}_k)\}$$

Subject to:

Operational constraints for each future k=1,…,n

ESI planning: Ex 5 - G & T under uncertainty

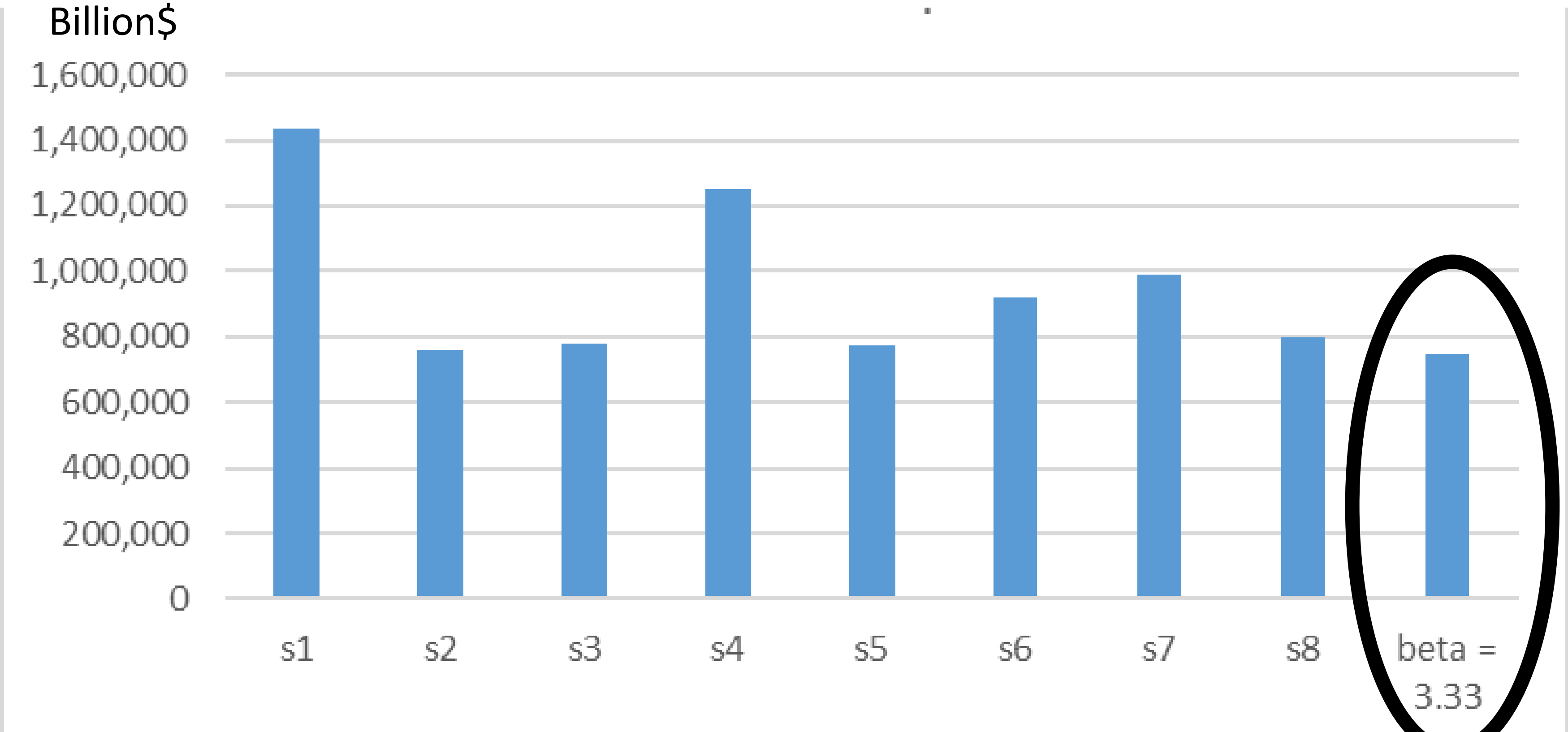
“Core” investments resulting from adaptation optimization.



ESI planning: Ex 5 - G & T under uncertainty

Once the core is designed, compare it to other deterministic plans via repeated simulation through the same 20 years exposing it to the same 5 randomly selected realizations of uncertainties. The design based on uncertainty has lowest average cost.

Cost of investments + operations + load shedding penalties.



ESI planning: Ex 6 - G, T, Gas Network

ELECTRIC vs. GAS TRANSMISSION MODELING

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

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

$X_{i,j}$ → **The reactance defines the transmission line characteristics**

$K'_{i,j}$ → **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.

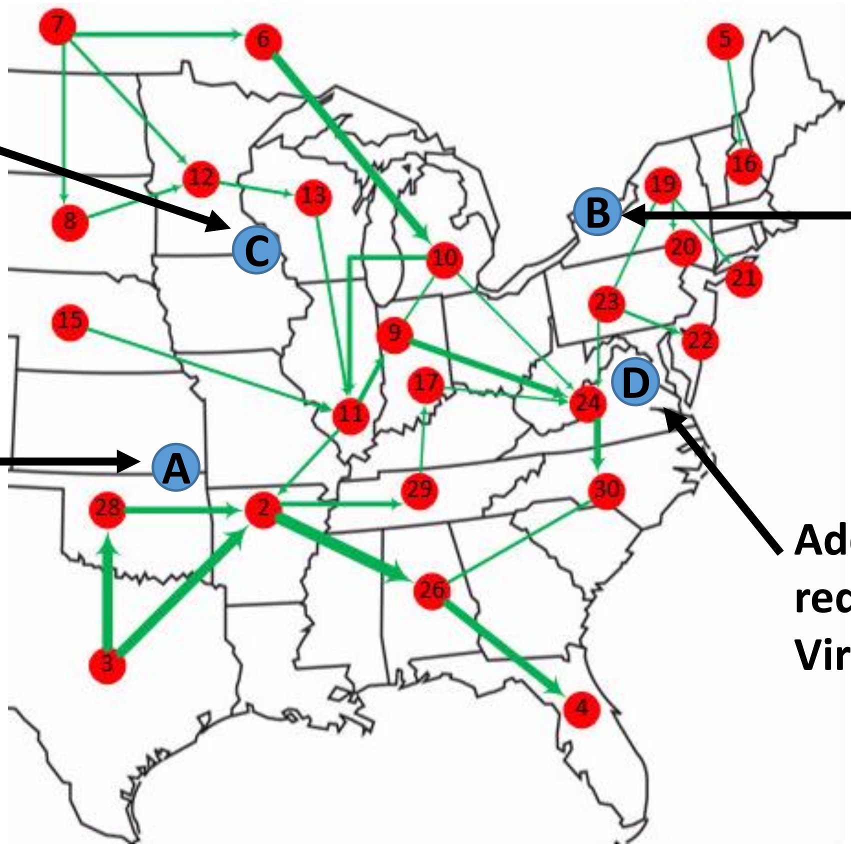
Important difference: Linearized power flow equations are pretty good for MW flows. However, in linearized gas flow equations, constants c_i and c_j are sensitive to pressures, so a piecewise linear gas pipeline model is necessary.

ESI planning: Ex 6 - G, T, Gas Network

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

Natural gas flows in 2035

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

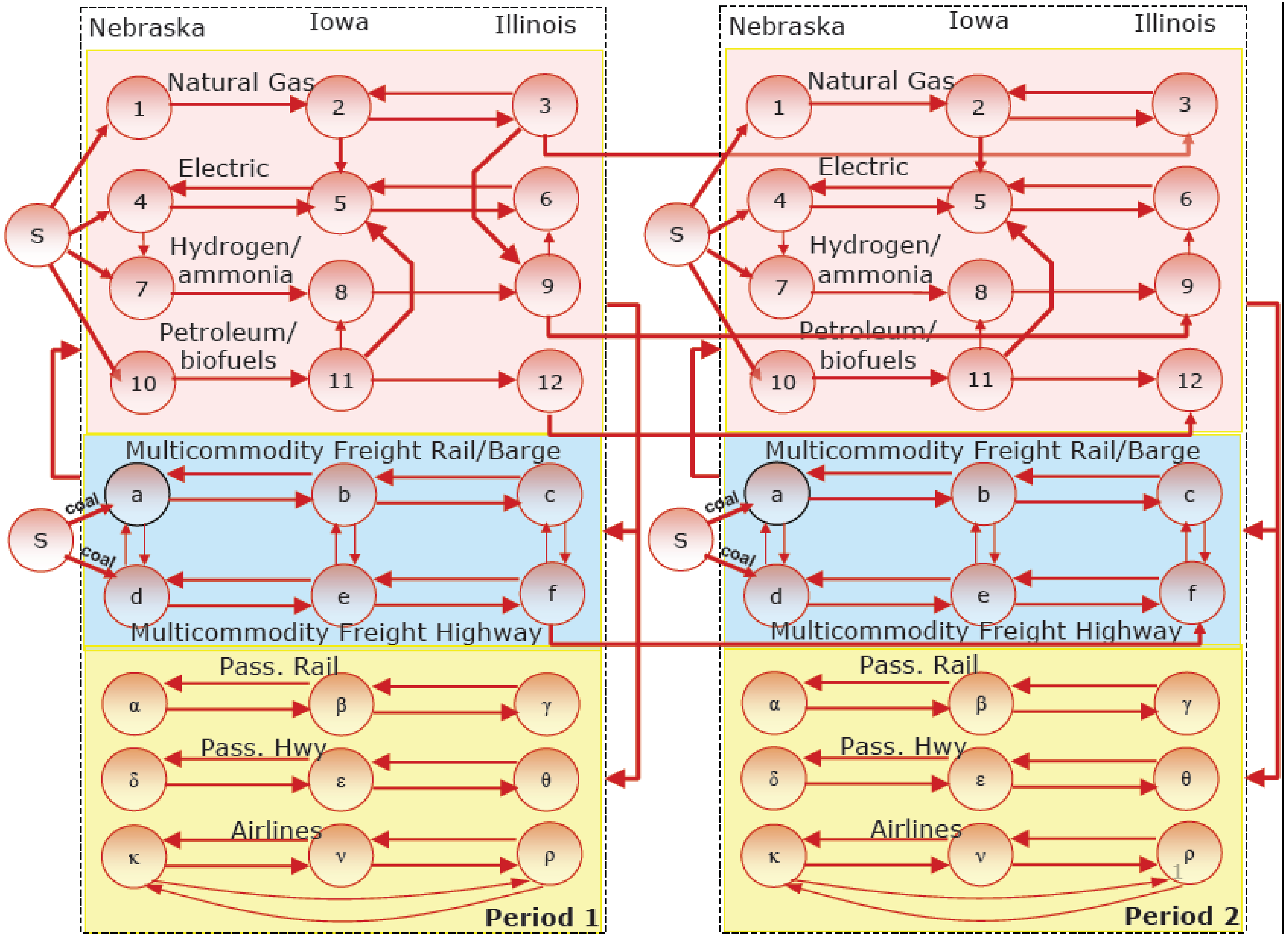


Reduction in electricity and gas imports from Canada to the Northeast, and additional investments in gas-fired units in NY area because of increase in Marcellus gas production.

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

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

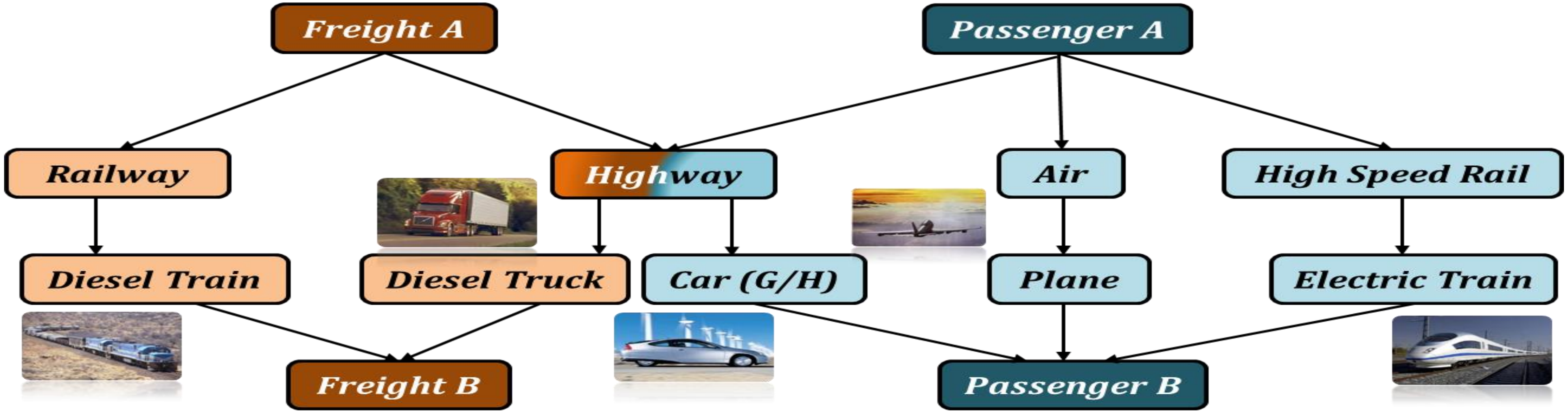
ESI planning: Ex 7 - G, T, long-distance transport

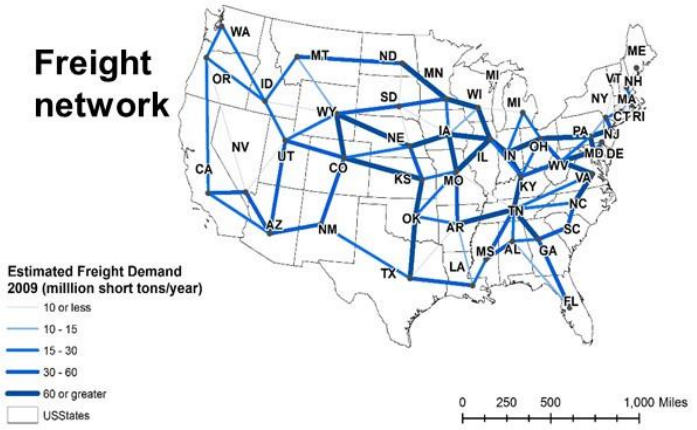


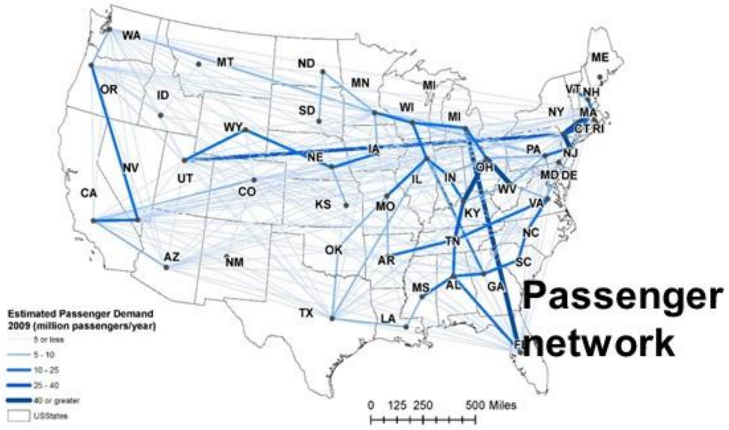
ESI planning: Ex 7 - G, T, long-distance transport

Long-distance transportation facilities:

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



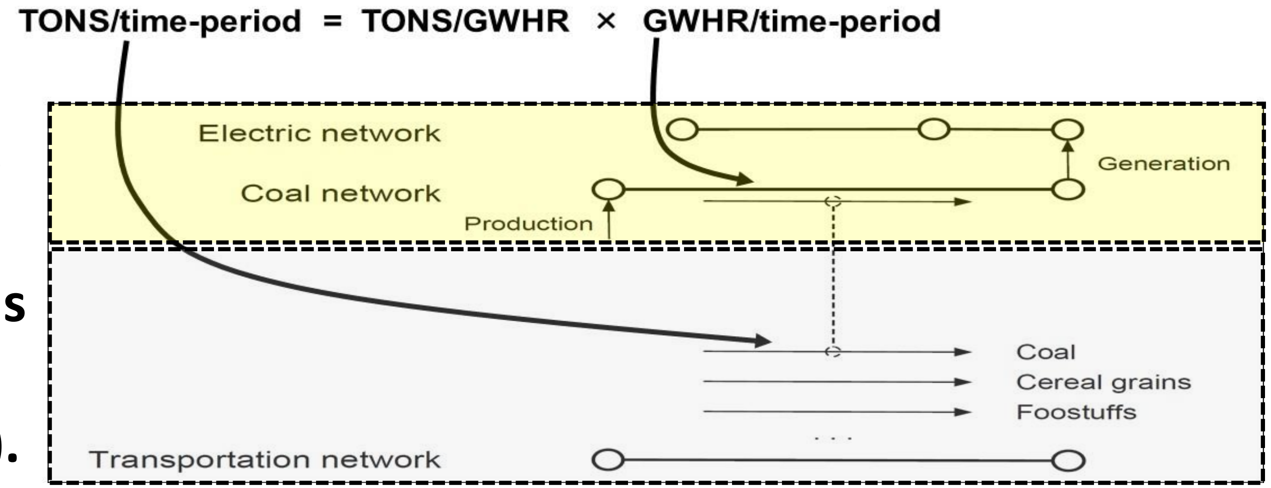




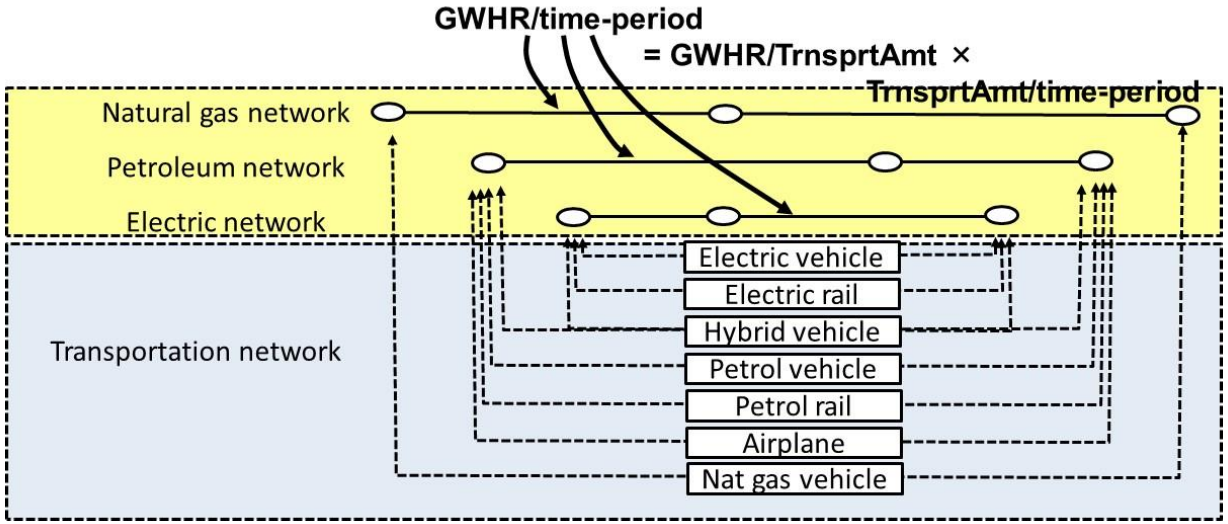
Transportation demand is specified node-to-node, except for *energy commodities*.

ESI planning: Ex 7 - G, T, long-distance transport

"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.



ESI planning: Ex 7 - G, T, long-distance transport

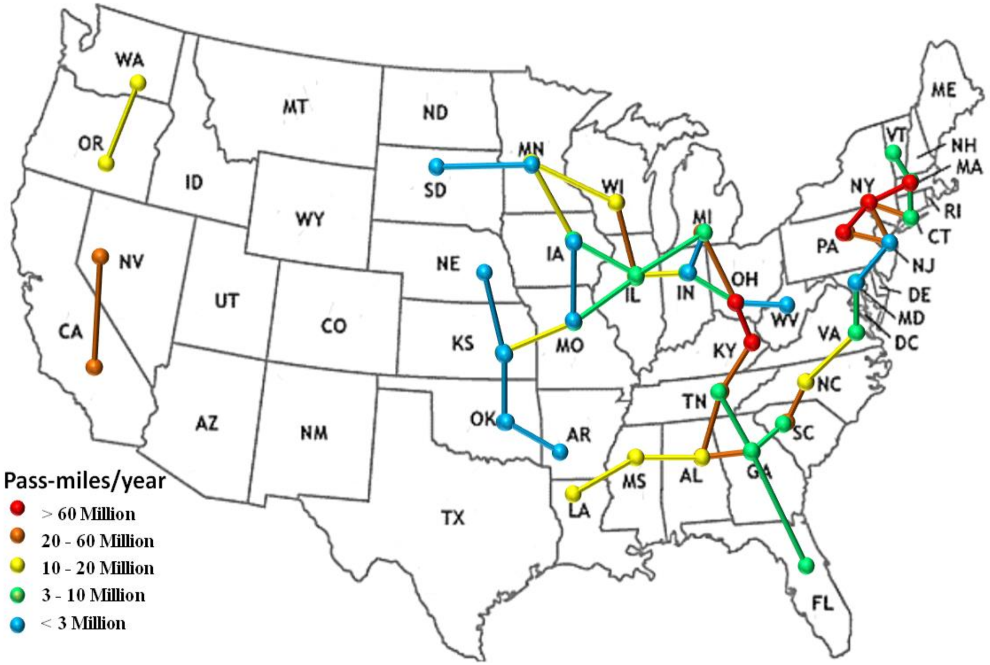
HSR diversifies transportation sector, and, under a low carbon electric portfolio, leads to a reduction in GHG emissions by 10% over a 40-yr period.

HSR investment results in long-term cost savings assuming a petroleum price increase of 3% per yr, and travel time valued at average hourly wages.

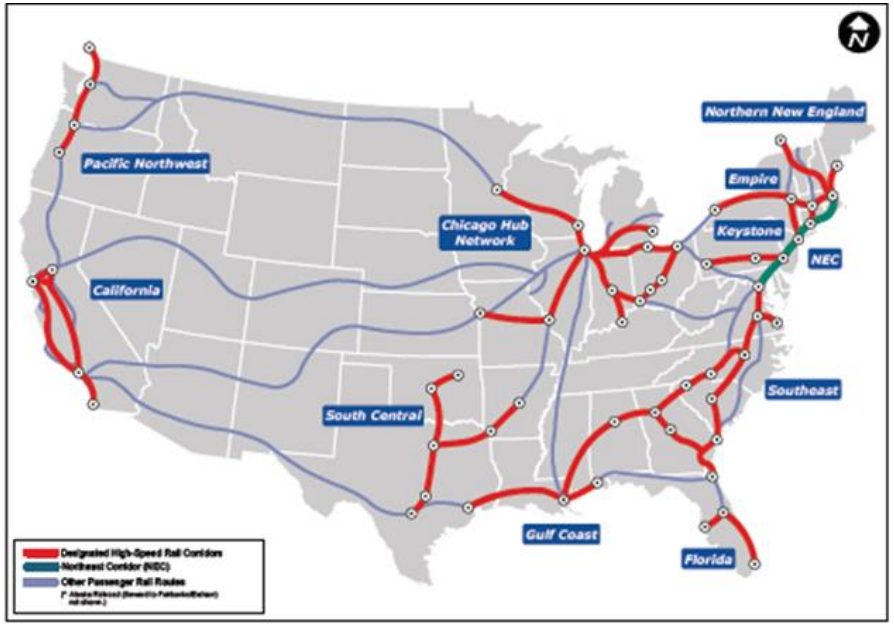
Attractive because

- expansive US travel distances;
- HSR travel convenience
- HSR total electric dependence

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



Netplan Results



DOT Designations

Conclusions

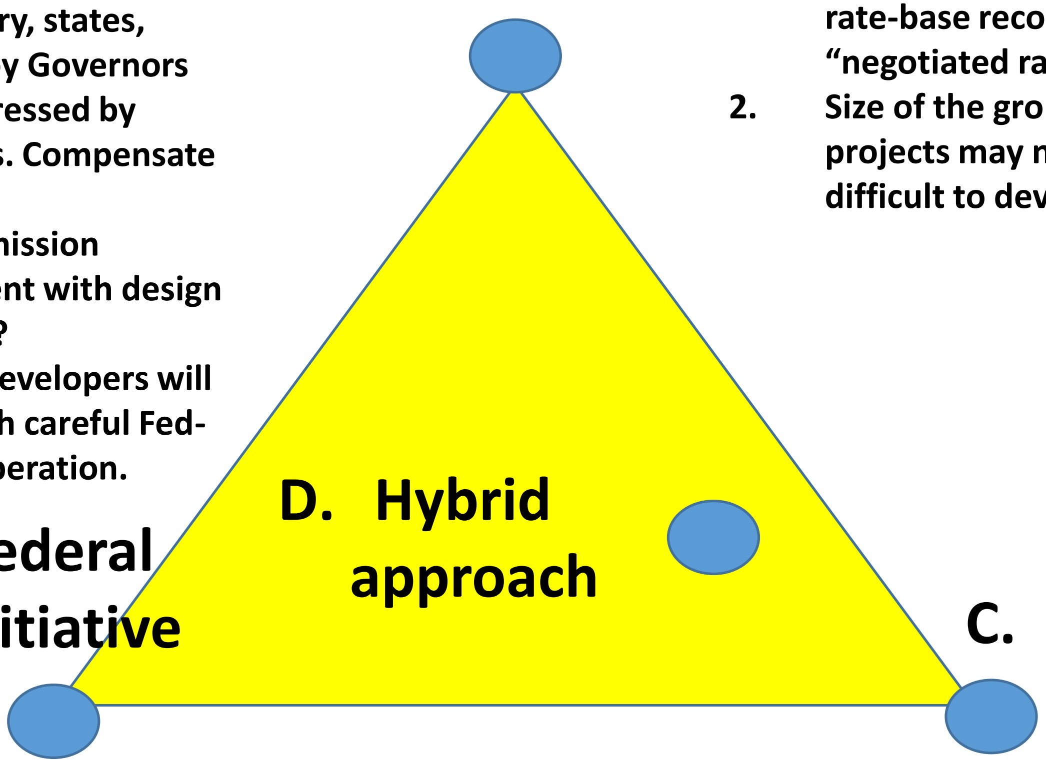
- **Infrastructure integrity:**
  - Flexibility
  - Reliability
  - Cost resilience
  - Adaptability
- **Deliverability (interconnectedness + capacity) supports all**
- **Transmission & MIMO energy plants support deliverability**
- **Infrastructure systems should be designed**
- **Interdependencies motivate new design tools**
- **Building infrastructure needs social/political development**

Paths forward: frameworks

A. Market-driven investment

1. Market (merchant)-driven investment: no rate-base recovery, costs recovered through "negotiated rates."
2. Size of the groups to form for overlay projects may need to be very large and difficult to develop/manage.

1. Design it using multiregional collaborative stakeholder group of industry, states, advocacy, DOE, supported by Governors Associations. Impasses addressed by federally-appointed arbiters. Compensate losers.
2. Incentivize merchant transmission developers to build consistent with design ➔A "transmission market"?
3. Federalize what merchant developers will not or cannot build, but with careful Fed-State coordination and cooperation.



B. Federal initiative

1. Similar to interstate highway system, where Feds paid 90% via gasoline tax, states 10%. States managed program for location, design, ROW acquisition, construction, O&M.
2. Differences: (a) Transmission "pass-through" feature is not shared with interstate highway system; (b) Economic development more at sending end.

C. Multiregional coordination

1. Establish permanent multiregional stakeholder group consisting of industry, state governments, advocacy groups to address:
2. States need to see benefit for taking multiregional view; consider compensating those who benefit least.

Resource Parochialism?

"One problem," he said, is "resource nationalism," in which individual states want to use local resources, whether they are coal or yet-to-be-built offshore wind, rather than importing from neighbors in a way that could be more economical.

James Hoecker,
FERC Commissioner 1993-2001,
FERC Chair 1997-2001

in Matthew L. Wald, "Ideas to Bolster Power Grid Run Up Against the System's Many Owners," NY Times, July 12, 2013, www.nytimes.com/2013/07/13/us/ideas-to-bolster-power-grid-run-up-against-the-systems-many-owners.html?emc=eta1&_r=1&