Interdependent infrastructure systems: criteria for integrity

International Conference on Energy Systems Integration

December 5-6 , 2017

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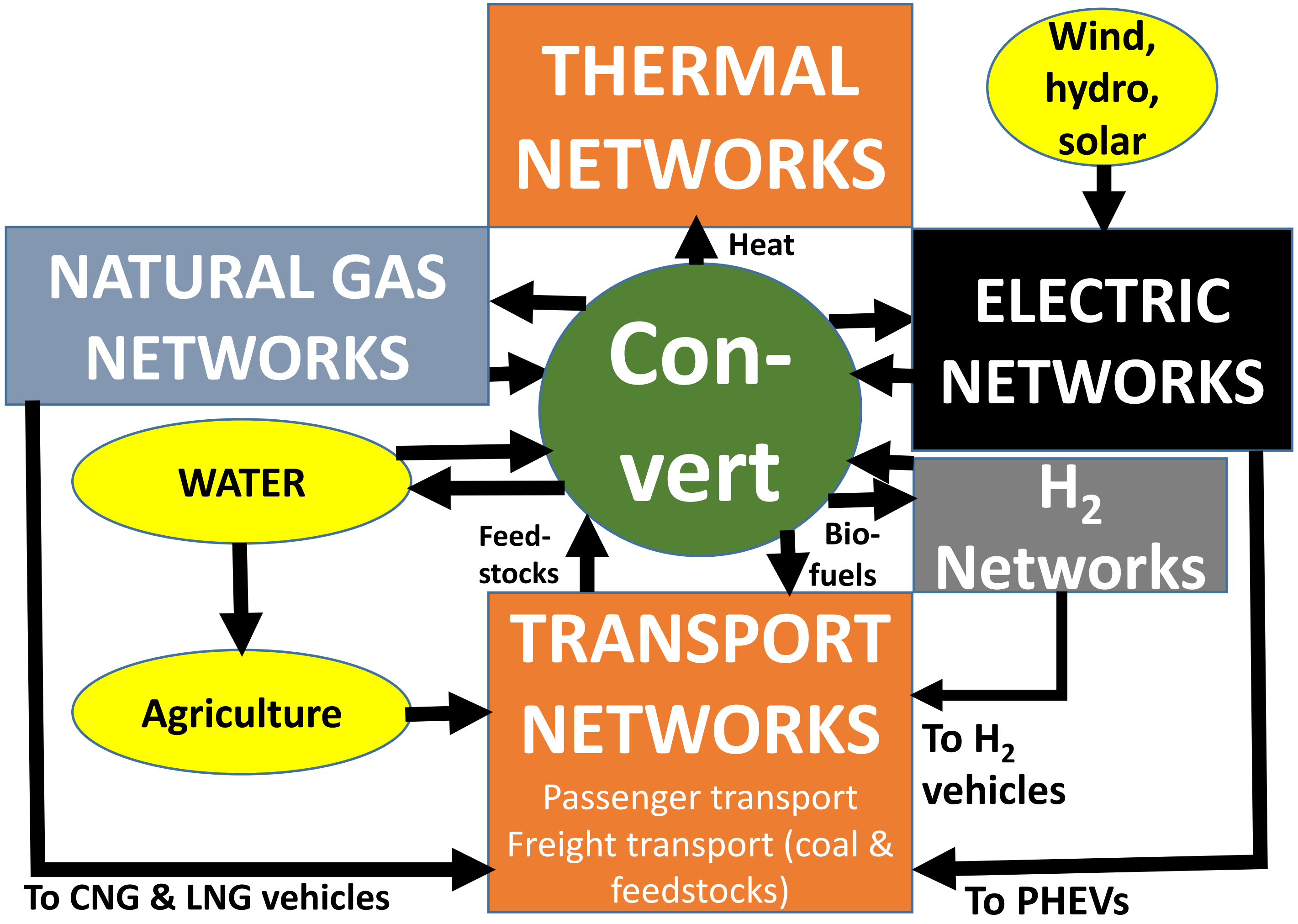
Overview

1. Interdependent infrastructure systems
2. Infrastructure criteria
3. Cost vs. recovery time for various event types
4. Infrastructure criteria
5. What maximizes infrastructure integrity?
6. Macrogrid & MIMO energy plants
7. Conclusions

Interdependent infrastructure systems

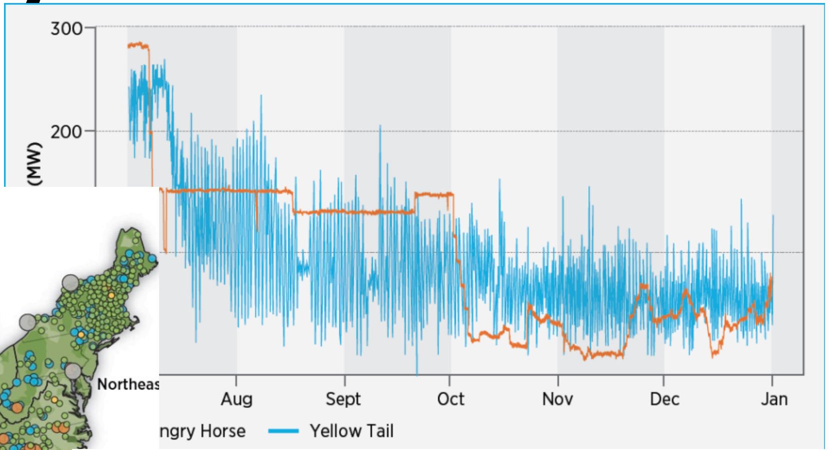


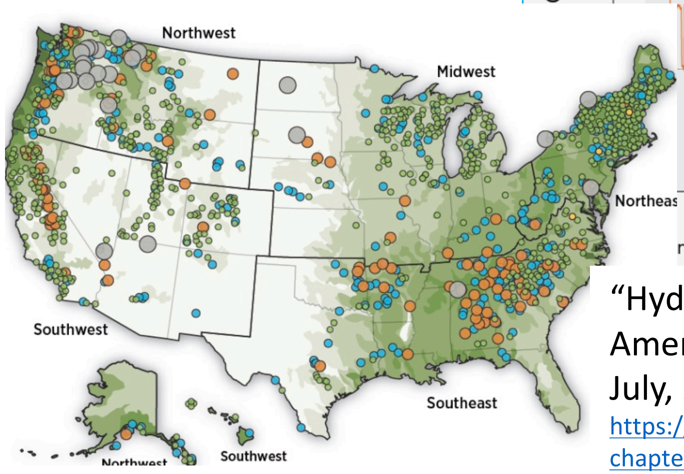
Energy services:

- Electric
- Non-electric
  - heating/cooling including process heating
  - transportation

Flexibility:

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





"Hydropower vision," A new chapter for America's 1rst renewable electricity source," July, 2016, https://energy.gov/eere/water/articles/hydropower-vision-new-chapter-america-s-1st-renewable-electricity-source.

- 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
- SAIDI, SAIFI

NERC Disturbance-Performance Table:

- SS performance
- Dynamic performance

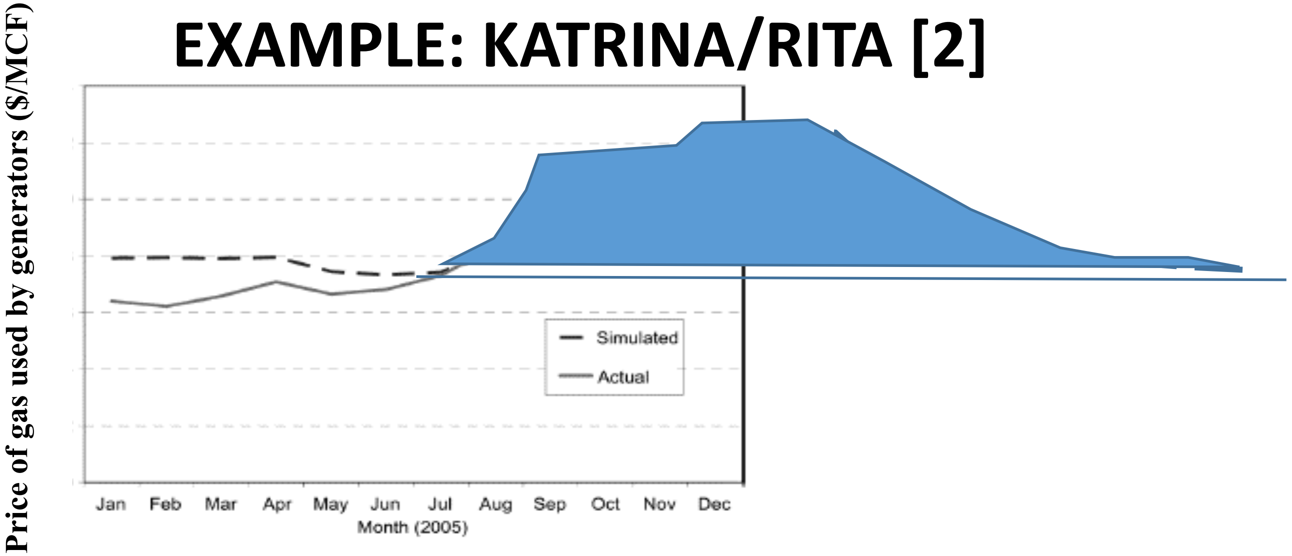
http://www.nerc.com/files/tpl-004-1.pdf

Category	Contingencies	System Limits or Impacts		
	Initiating Event(s) and Contingency Element(s)	System Stable and both Thermal and Voltage Limits within Applicable Rating [a]	Loss of Demand or Curtailed Firm Transfers	Cascading Outages
A No Contingencies	All Facilities in Service	Yes	No	No
B Event resulting in the loss of a single element.	Single Line Ground (SLG) or 3-Phase (3Ø) Fault, with Normal Clearing: 1. Generator 2. Transmission Circuit 3. Transformer Loss of an Element without a Fault.	Yes Yes Yes Yes	No [b] No [b] No [b] No [b]	No No No No
	Single Pole Block, Normal Clearing [e]: 4. Single Pole (dc) Line	Yes	No [b]	No
C Event(s) resulting in the loss of two or more (multiple) elements.	SLG Fault, with Normal Clearing [e]: 1. Bus Section 2. Breaker (failure or internal Fault)	Yes Yes	Planned/ Controlled [c] Planned/ Controlled [c]	No No
	SLG or 3Ø Fault, with Normal Clearing [e], Manual System Adjustments, followed by another SLG or 3Ø Fault, with Normal Clearing [e]: 3. Category B (B1, B2, B3, or B4) contingency, manual system adjustments, followed by another Category B (B1, B2, B3, or B4) contingency	Yes	Planned/ Controlled [c]	No
	Bipolar Block, with Normal Clearing [e]: 4. Bipolar (dc) Line Fault (non 3Ø), with Normal Clearing [e]: 5. Any two circuits of a multiple circuit towerline [f]	Yes Yes	Planned/ Controlled [c] Planned/ Controlled [c]	No No
	SLG Fault, with Delayed Clearing [e] (stuck breaker or protection system failure): 6. Generator 7. Transformer 8. Transmission Circuit 9. Bus Section	Yes Yes Yes Yes	Planned/ Controlled [c] Planned/ Controlled [c] Planned/ Controlled [c] Planned/ Controlled [c]	No No No No
D [d] Extreme event resulting in two or more (multiple) elements removed or Cascading out of service	3Ø Fault, with Delayed Clearing [e] (stuck breaker or protection system failure): 1. Generator 3. Transformer 2. Transmission Circuit 4. Bus Section 3Ø Fault, with Normal Clearing [e]: 5. Breaker (failure or internal Fault) 6. Loss of towerline with three or more circuits 7. All transmission lines on a common right-of way 8. Loss of a substation (one voltage level plus transformers) 9. Loss of a switching station (one voltage level plus transformers) 10. Loss of all generating units at a station 11. Loss of a large Load or major Load center 12. Failure of a fully redundant Special Protection System (or remedial action scheme) to operate when required 13. Operation, partial operation, or misoperation of a fully redundant Special Protection System (or Remedial Action Scheme) in response to an event or abnormal system condition for which it was not intended to operate 14. Impact of severe power swings or oscillations from Disturbances in another Regional Reliability Organization.	Evaluate for risks and consequences. ▪ May involve substantial loss of customer Demand and generation in a widespread area or areas. ▪ Portions or all of the interconnected systems may or may not achieve a new, stable operating point. ▪ Evaluation of these events may require joint studies with neighboring systems.		

Resilience

<u>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.

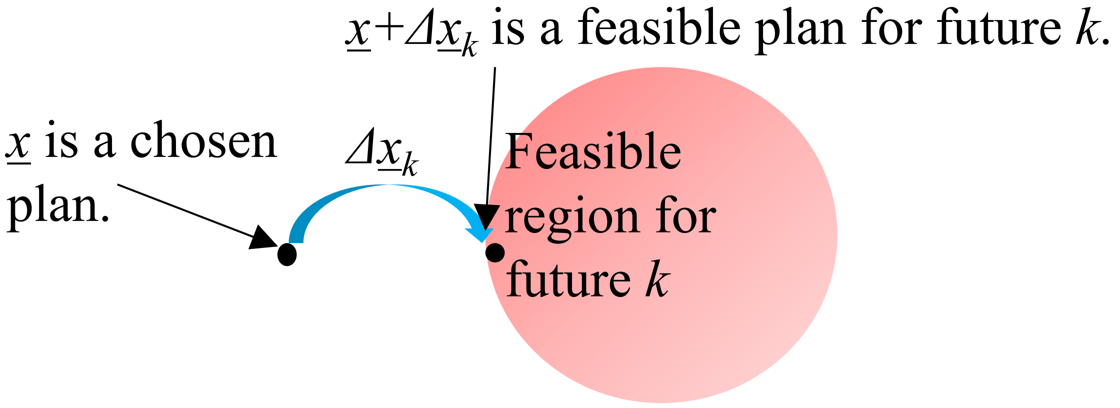
<u>Examples</u>:

- **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.



Adaptability [1,2]

<u>Co-optimized expansion planning with adaptation</u>:

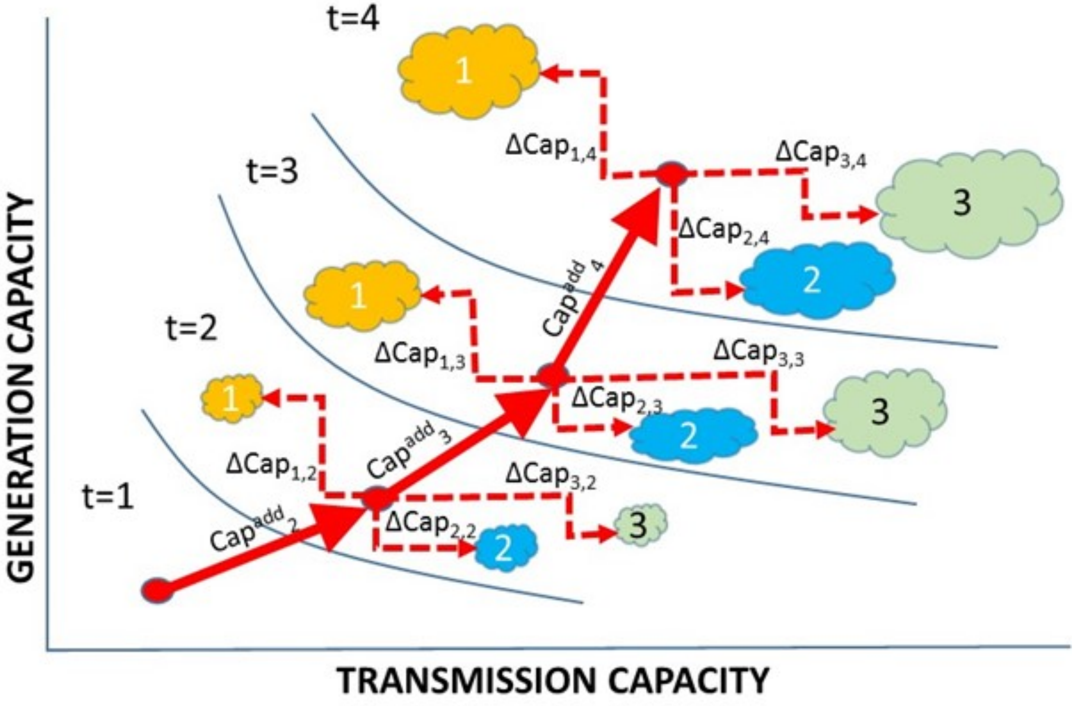
Minimize:

NPW{CoreCosts($\underline{x}$)

+ Σ_k Pr_k × {OpCost($\Delta\underline{x}_k$)} + AdaptationCost($\Delta\underline{x}_k$)}

Subject to:

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



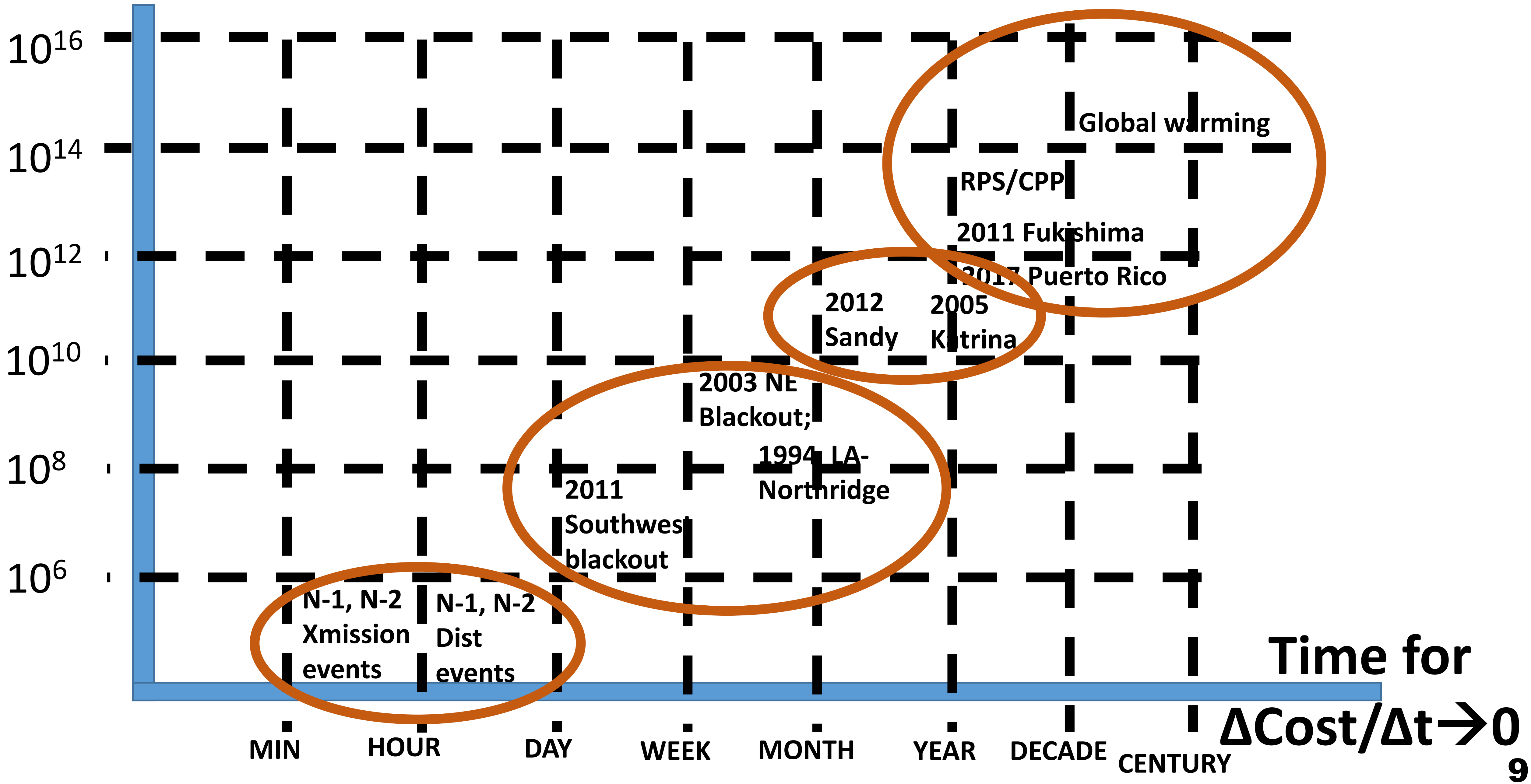
$\underline{x}$: Core investments, to be used by all futures k

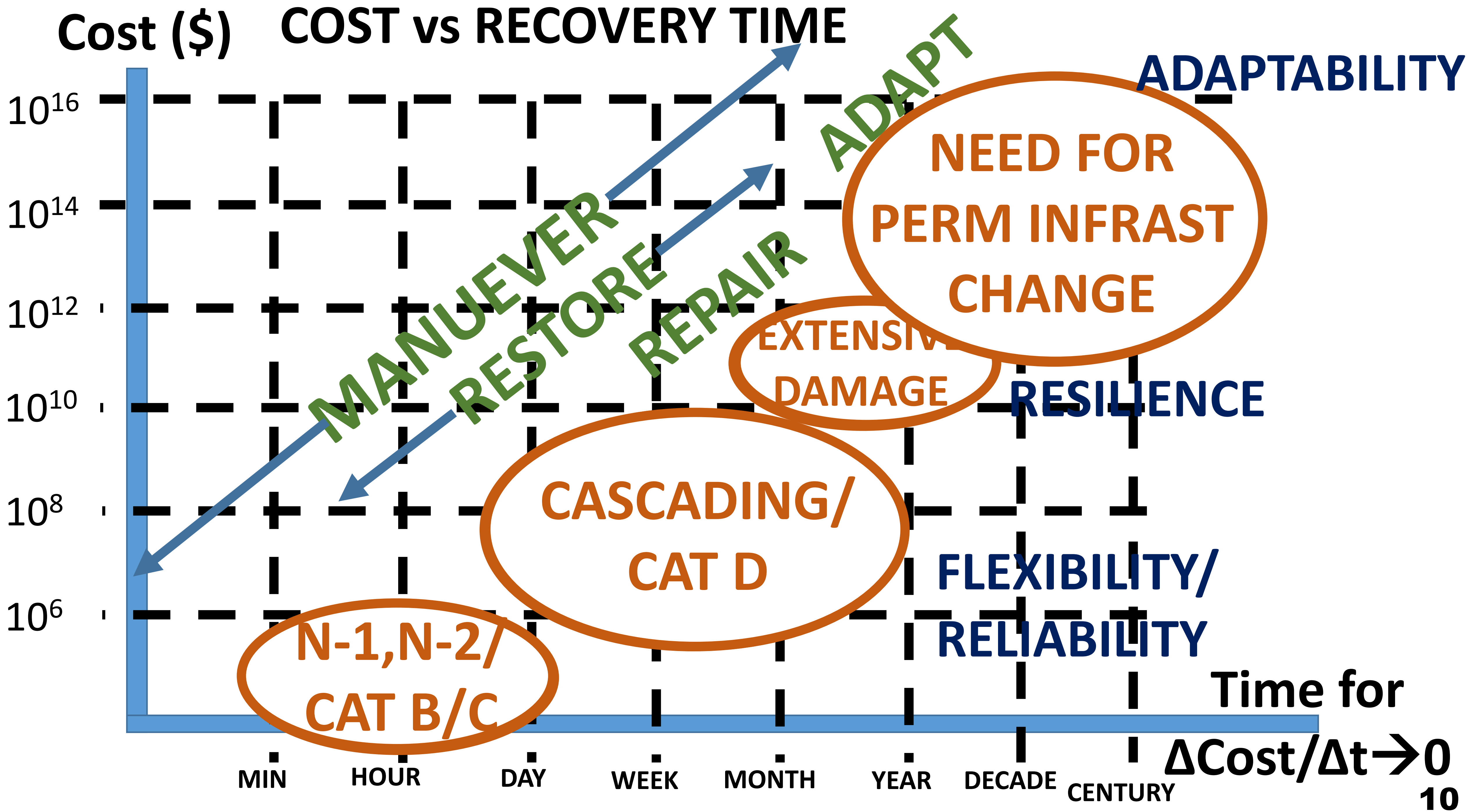
$\Delta\underline{x}_k$: Additional investments needed to adapt to future k

[1] D. Mejia-Giraldo and J. McCalley, “Maximizing future flexibility in electric generation portfolios," *IEEE Trans on Pwr Sys*, Vol. 29, Issue 1, 2014, pp. 279-288.

[2] P. Maloney, O. Olatujoye, A. Jahanbani, D. Mejia-Giraldo, J. McCalley, B. Hobbs, “A comparison of stochastic and adaptation programming methods for long-term generation and transmission co-optimization under uncertainty,” under review, North American Power Symposium, 2016.

COST vs RECOVERY TIME




Cost ($)
COST vs RECOVERY TIME
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
ADAPTABILITY
ADAPT
NEED FOR PERM INFRAST CHANGE
MANUEVER
RESTORE
REPAIR
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 criteria

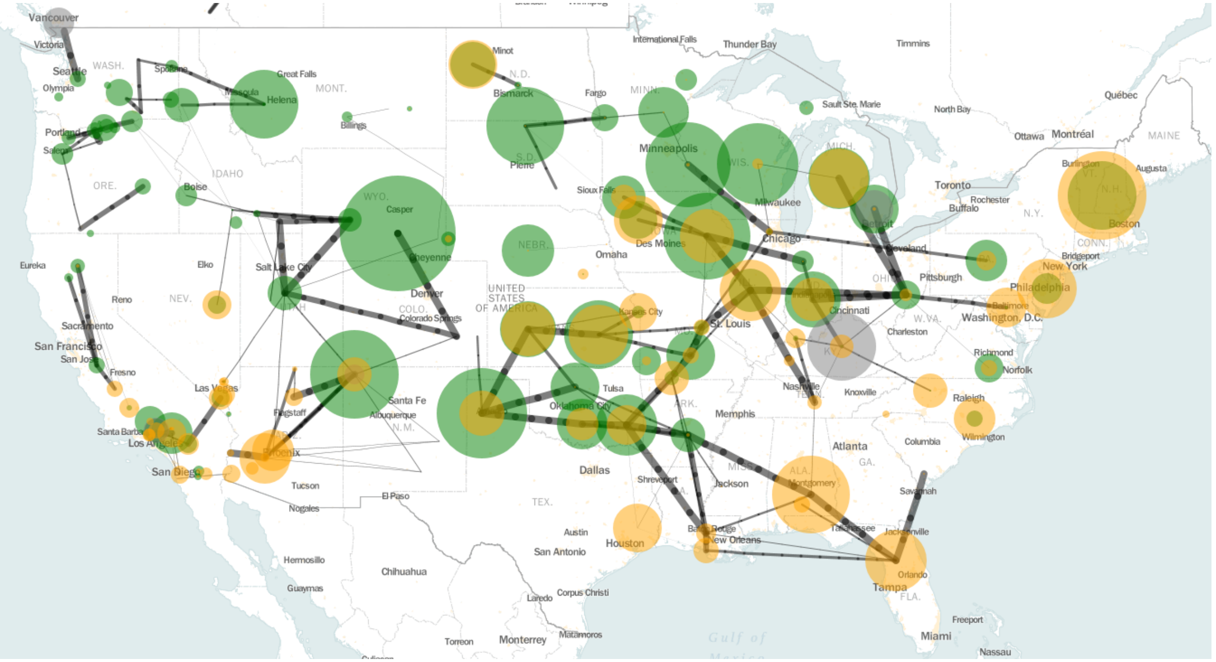
- **Sustainability criteria:**
  - **Environmental**: impact on GHG emissions; air pollutants, water pollution, runoff; and aesthetic, wildlife and social impacts of land conversion;
  - **Economic**: value & cost of services delivered in terms of aggregate effect on market efficiency;
  - **Social**: 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);
  - **Resilience**: economic service availability – ability to use operational measures to minimize & recover from the change 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.

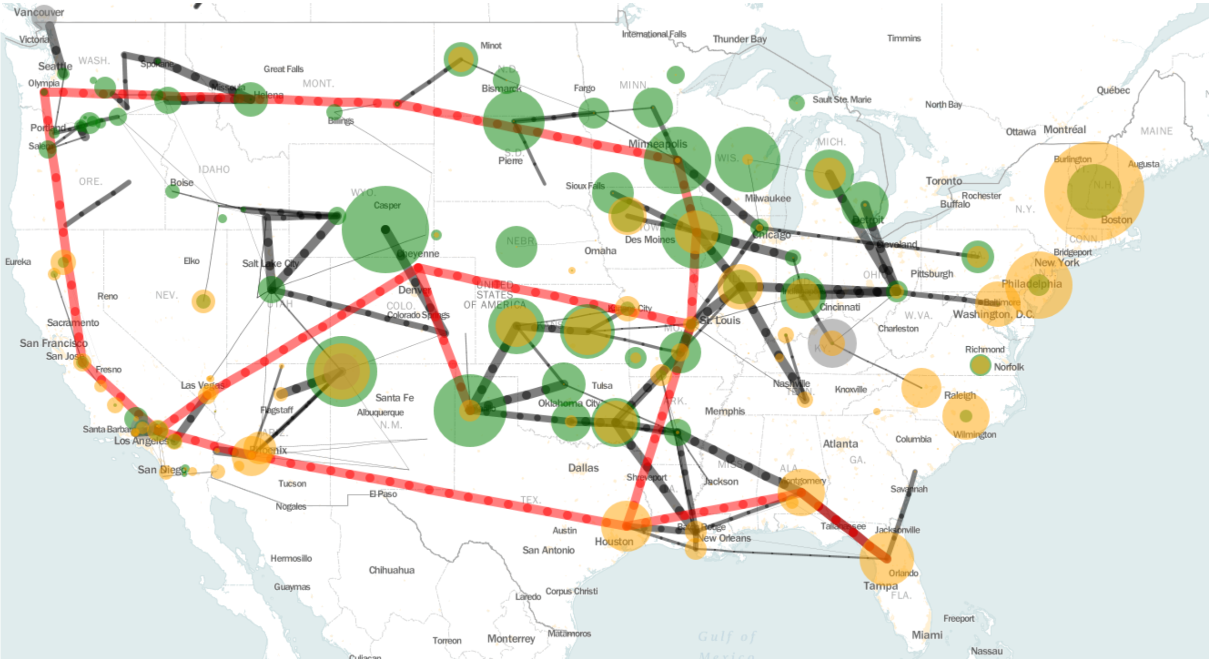
What maximizes infrastructure integrity?

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

Deliverability? = Capacity + Interconnectedness

Macrogrid: a US transmission design





Technology	MW
Transmission AC	228,853
Transmission DC	0
Wind	385,804
Solar	176,906
Gas	37,289

Technology	MW
Transmission AC	195,128
Transmission DC	125,824
Wind	392,769
Solar	169,638
Gas	37,951

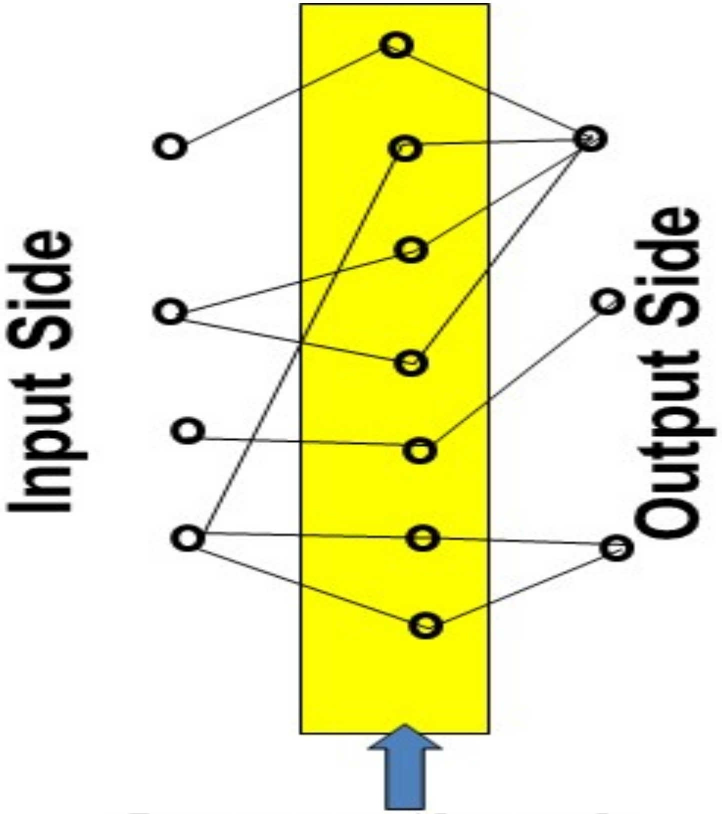
HVDC	MW
Capacity/segment	8,389.5

Macrogrid: a US transmission design

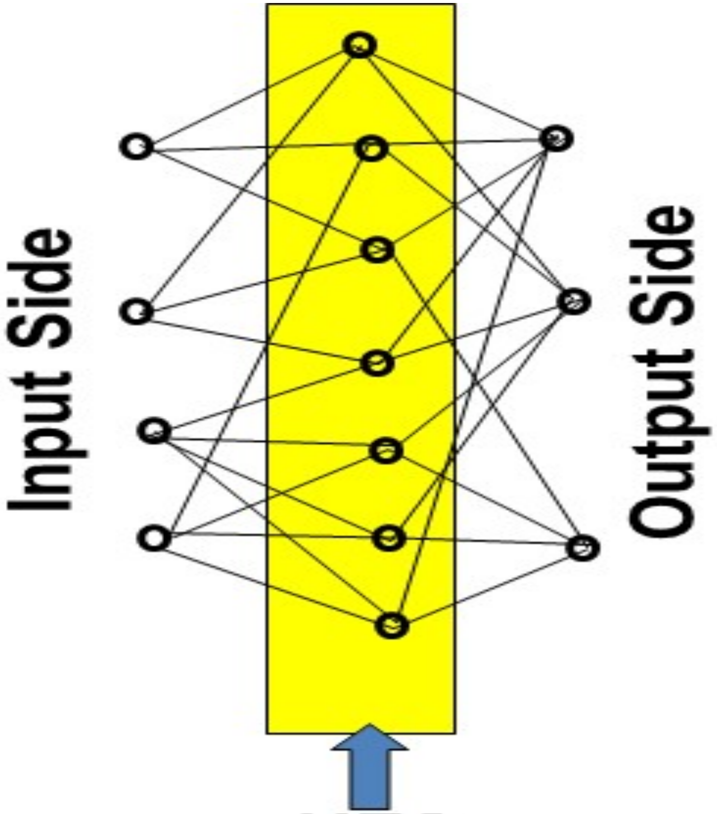
ECONOMICS, NPV $B	Design 1	Design 3	Delta
Line Investment Cost	61.21	80.1	18.89
Generation Investment Cost	704.03	700.51	-3.52
Fuel Cost	753.8	736.12	-17.68
Fixed O&M Cost	455.6	450.23	-5.37
Variable O&M Cost	64.5	64.39	-0.11
Carbon Cost	171.1	162.5	-8.6
Regulation-Up Cost	33.29	26.63	-6.66
Regulation-Down Cost	4.76	3.81	-0.95
Contingency Cost	24.41	19.52	-4.89
Total Non-Xm Cost (Orange)	2,211.49	2,163.71	-47.78
15-yr B/C Ratio (Orange/Blue)	-	-	2.52

CAPACITY, GW	Design 1	Design 3	Delta
Total gen invested (W/S/G)	600 (386/177/37)	600 (392/169/38)	0 (7/-6/1)
Total gen retired	240	294	54
Total 2024 creditable capacity	838.5	794.1	-44.4
Total AC Xm invested	228.9	195.1	-33.8
Total DC Xm invested	0	125.8	125.8

MIMO Energy Plants = Interconnectedness



Conventional:
single-input,
single-output
energy converters



HES:
multi-input,
multi-output
energy converters

Conclusions

- Infrastructure integrity:
  - Flexibility
  - Reliability
  - Resilience
  - Adaptability
- Deliverability (interconnectedness + capacity) supports all
- Transmission (& MIMO energy plants) supports deliverability
- Transmission is good for the integrity of energy systems!

Resilience

<u>Experiment</u>: For a 40 year investment strategy, simulate total failure of each of 14 generation technologies at year 25.

Did this with national transmission expansion and without.

<u>Resilience metric:</u> Averaged the 1 year operational cost increase across 14 events with respect to the no-event case.

Societal consequence

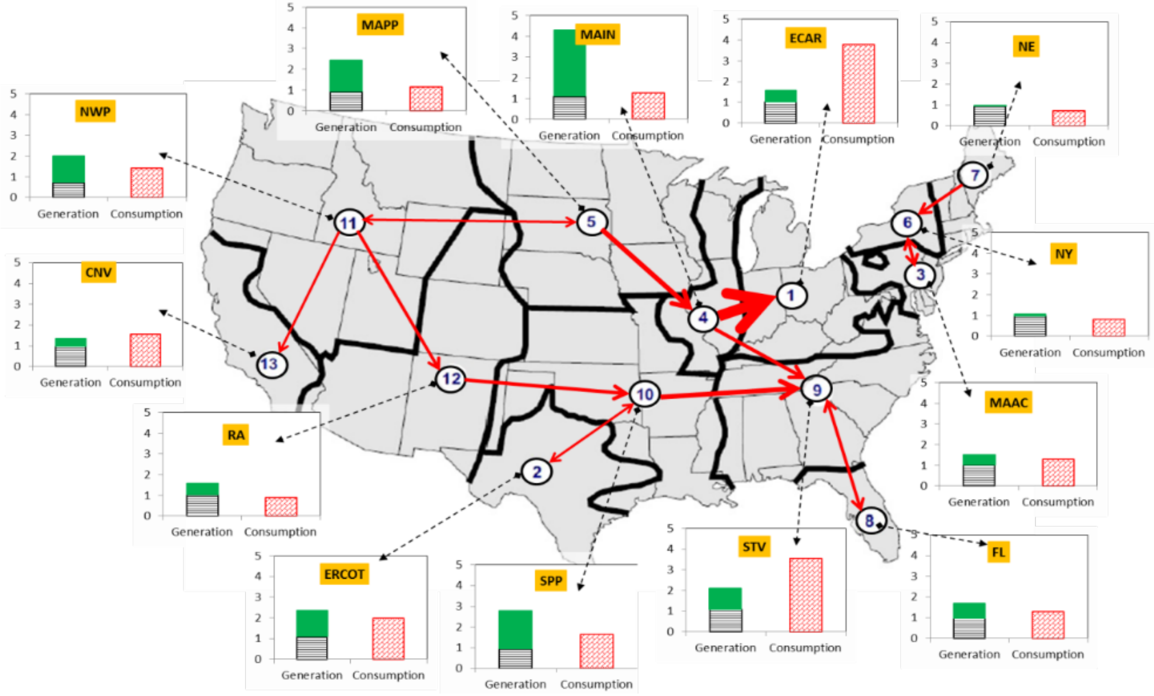
=\$5B without trans expansion

=\$450M with trans expansion

WHY?

RESILIENCE (AND ADAPTABILITY) IMPROVES WITH

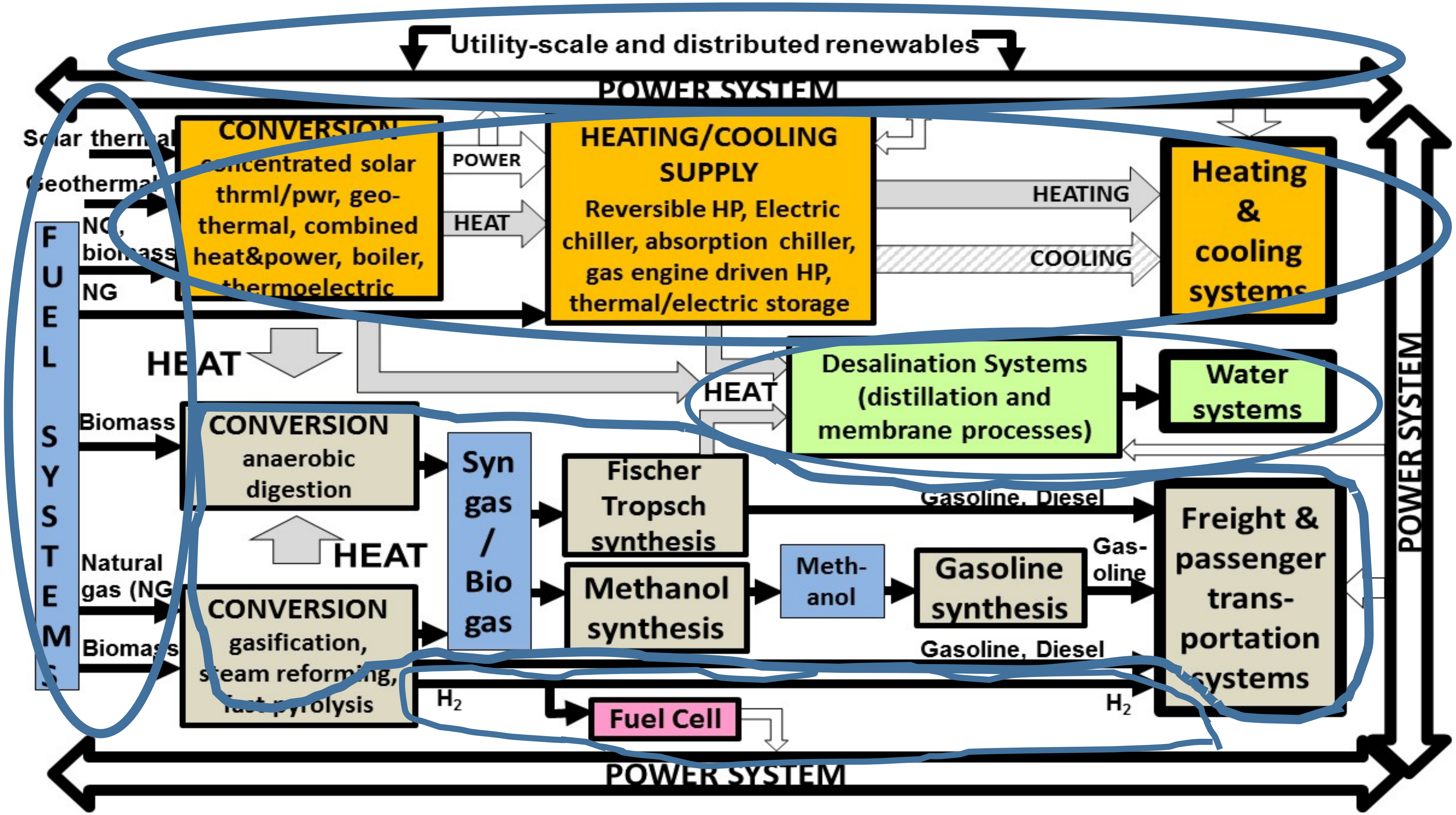
- DELIVERABILITY
- DIVERSIFICATION



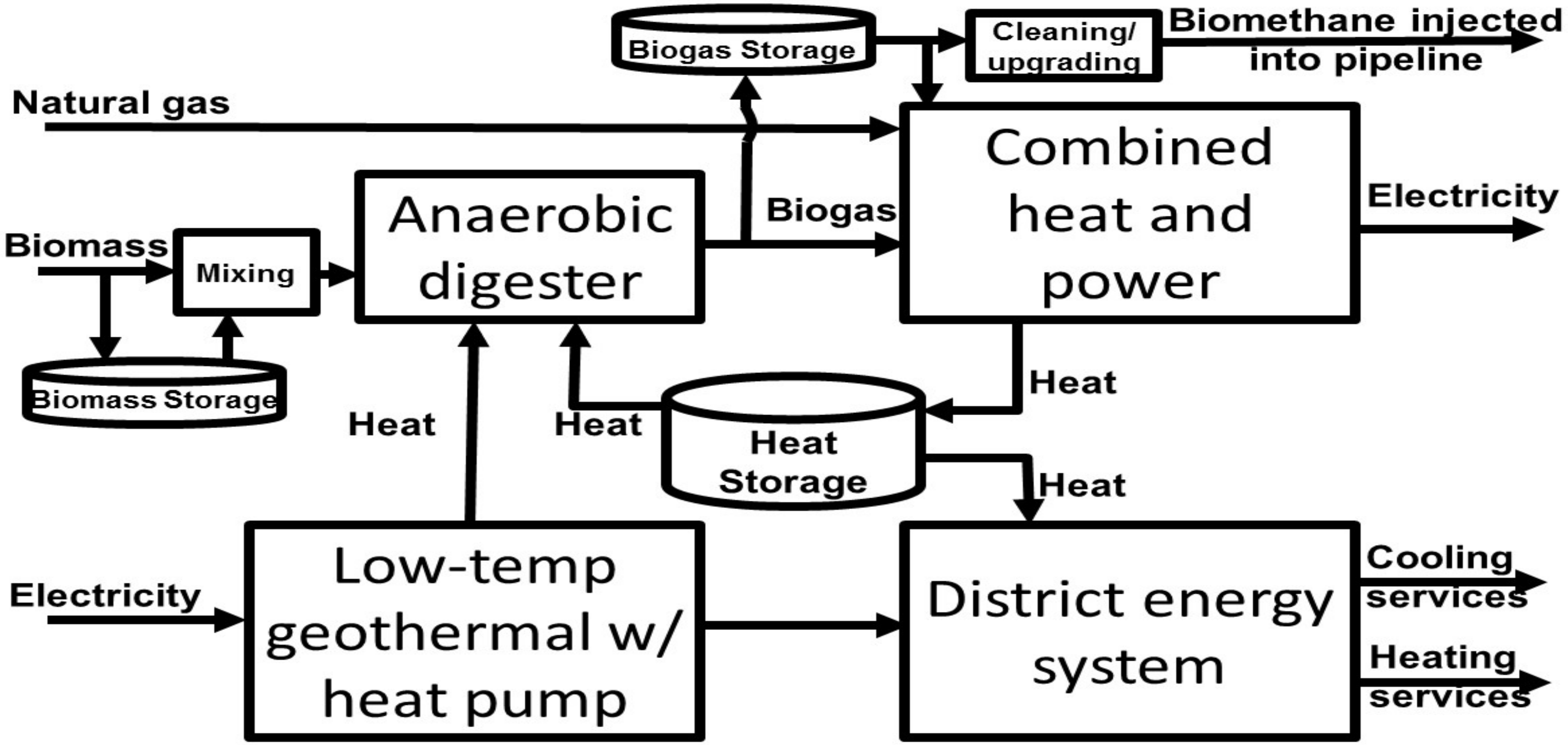
A hybrid energy conversion system template

Features:

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



A geographically-correct HES for the Midwest

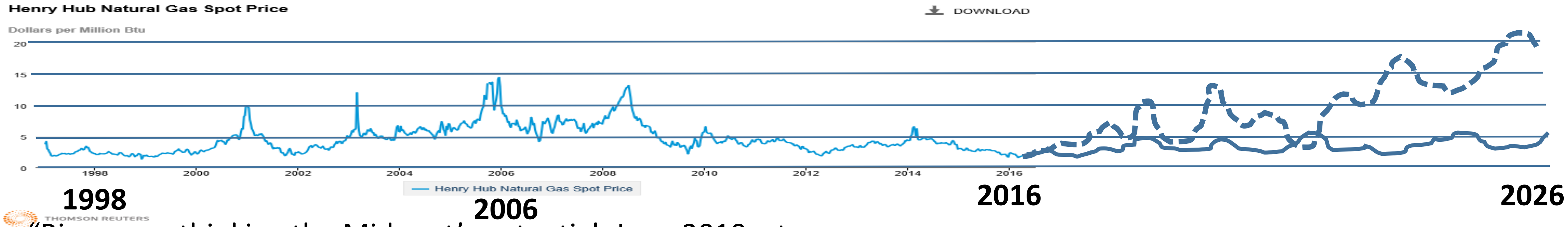


- Two heat sources
- Two uses of low temperature heat
- Three forms of storage

Effective configurations may utilize subset of these.

Why anaerobic digestion?

- Uses low temperature heat
- Midwest: biomass abundant where flexibility needed most
- Captures GHG emissions; addresses waste disposal issues
  - animal waste, grass and maize silage, and grains
- Provides partial hedge for the high risks of shale gas due to
  - Supply reduction if concerns for seismic and/or groundwater impacts intensify;
  - Combusted gas from NGCC units have 700lbs/MWhr CO_2 production.
  - Demand increase due to increased electric sector dependence, increased exports, and increased unconventional uses (e.g., transportation CNG/LNG).



P. Taglia, “Biogass: rethinking the Midwest’s potential, June 2010, at https://www.americanbiogascouncil.org/pdf/Clean%20Wisconsin%20MidwestBiogasPotential.pdf.