Energy Systems Orientation and Electric Systems Expansion Planning

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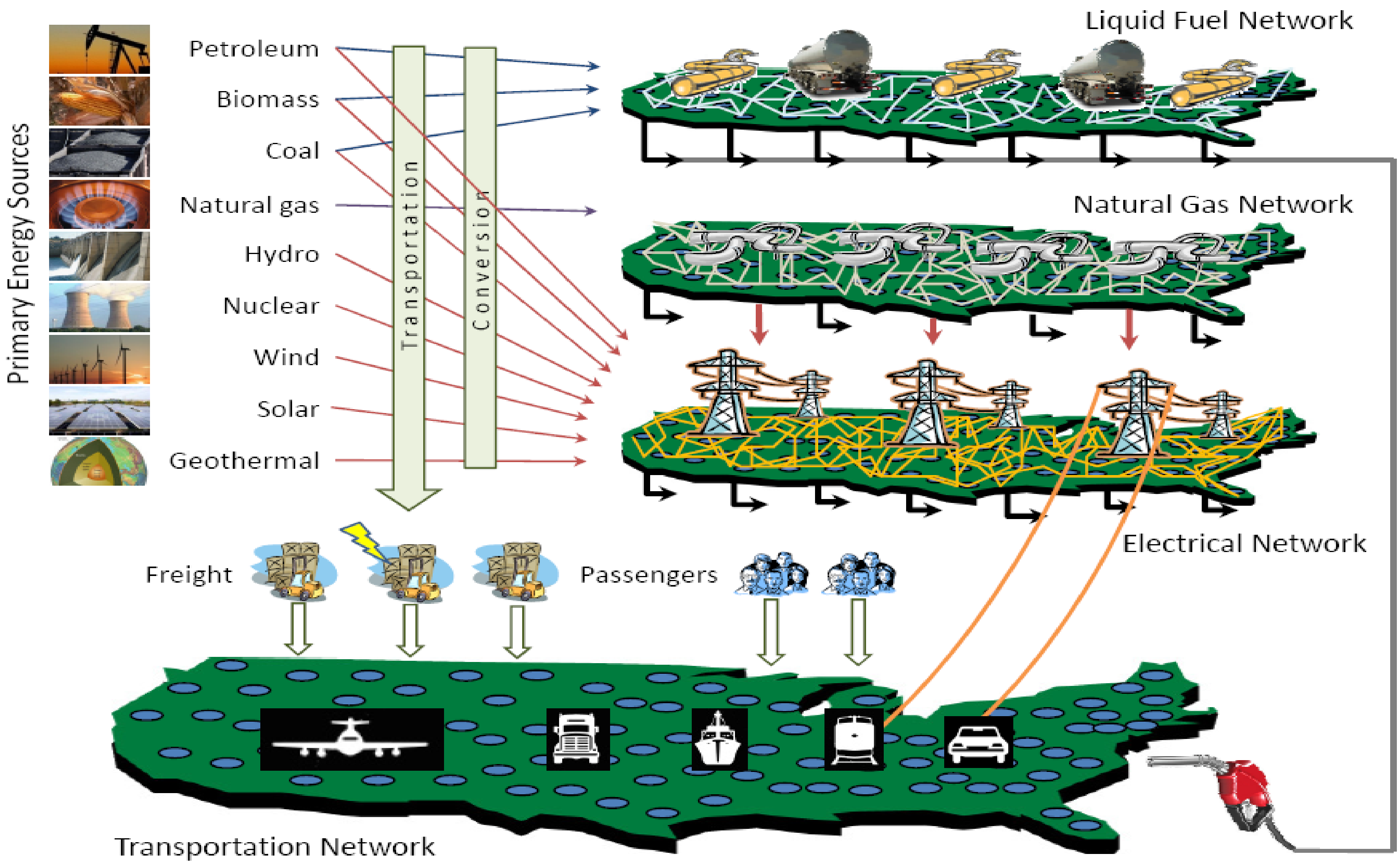
Overview

1. **Energy system orientation**
   a. **Infrastructure view**
   b. **Energy view**
   c. **Socio-political and technical tensions**
   d. **Attributes of a "good" energy system**
2. **Electric system investment planning**
   a. **Processes & systems**
   b. **Expansion planning models: GEP & TEP**
   c. **GTEP modeling issues**
   d. **Continent-wide transmission design**
   e. **Adaptation**
   f. **Ways forward**

To do to these slides:
1. Put in resilience evaluation?
2. Add thoughts from transmission forum
3. Add more transmission designs at end
4. Consider comments on additional transmission benefits (Armando)

1. **Energy system orientation**
    a. **Infrastructure view**
    b. **Energy view**
    c. **Socio-political and technical tensions**
    d. **Attributes of a “good” energy system**

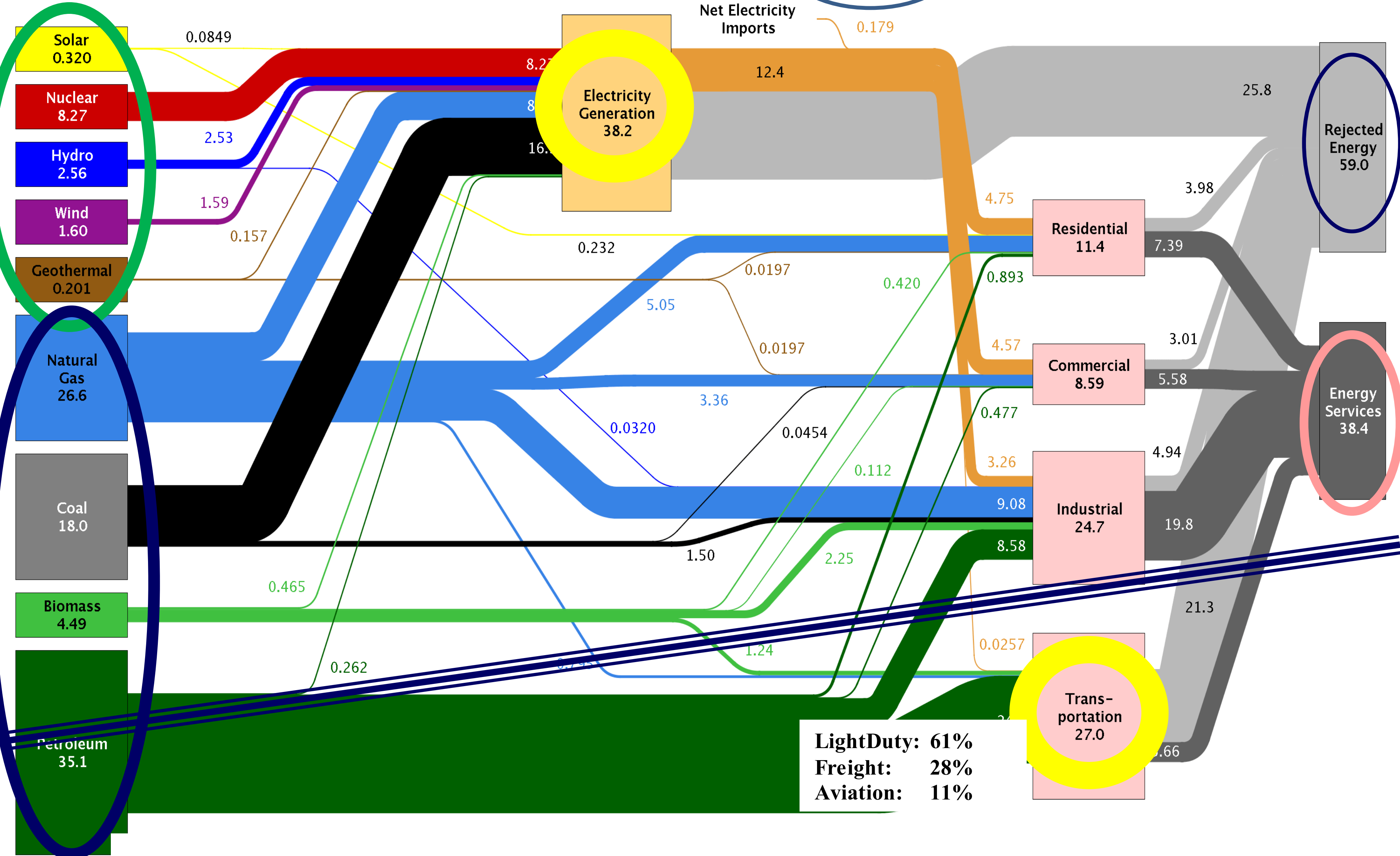
Infrastructure view: <u>Multi-sector</u> (fuel, electric, transportation), <u>national</u>, long-term planning



Energy View

Estimated U.S. Energy Use in 2013: ~97.4 Quads

Lawrence Livermore National Laboratory



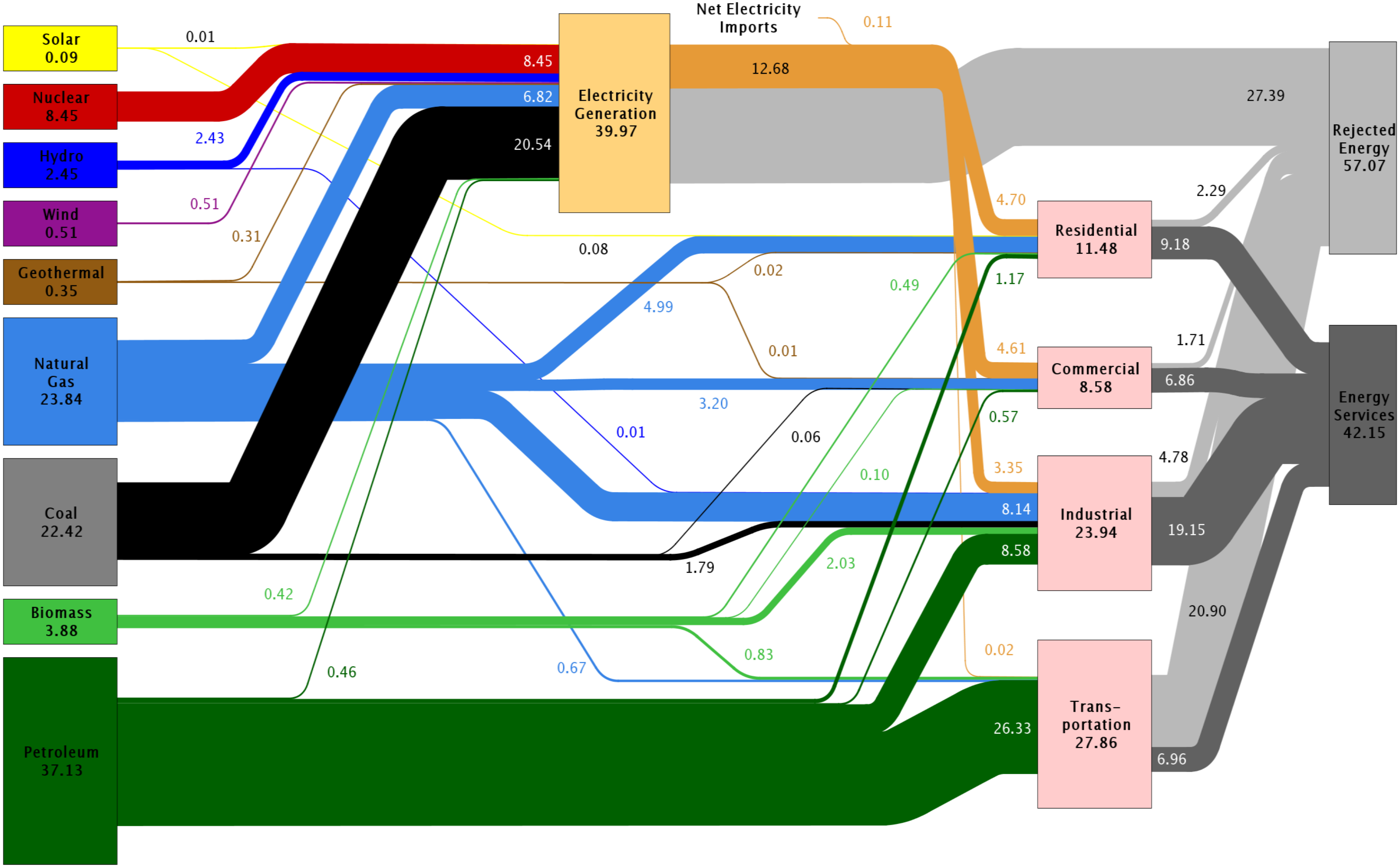
2013

https://flowcharts.llnl.gov/index.html

Energy View

Estimated U.S. Energy Use in 2008: ~99.2 Quads

Lawrence Livermore National Laboratory

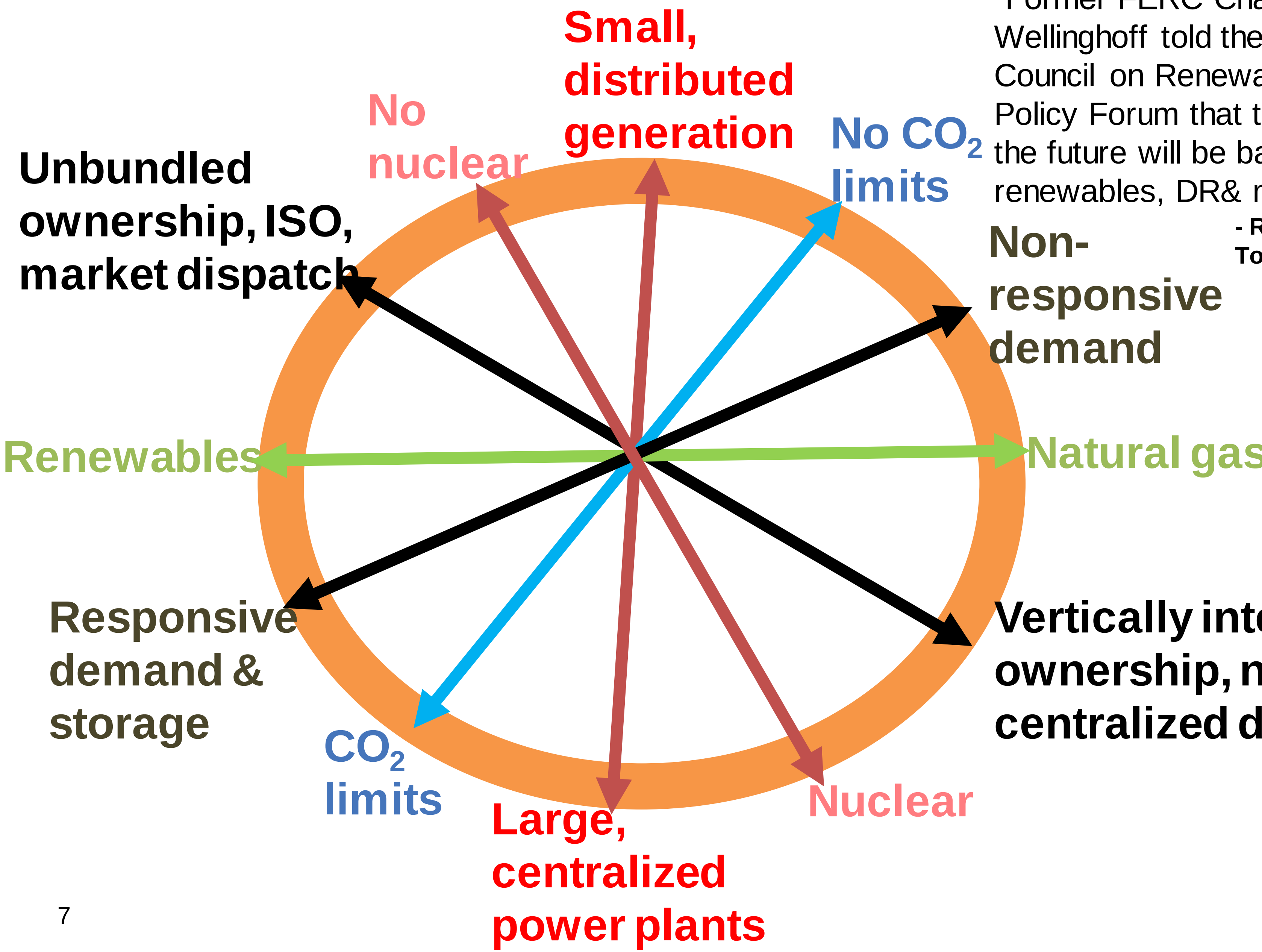


2008 – For Comparison Only

Socio-political & technical tensions

"Former FERC Chairman Jon Wellinghoff told the American Council on Renewable Energy Policy Forum that the grid of the future will be based on renewables, DR& natural gas"

- Restructuring Today, 3/31/2014



Attributes of a “Good” Energy System

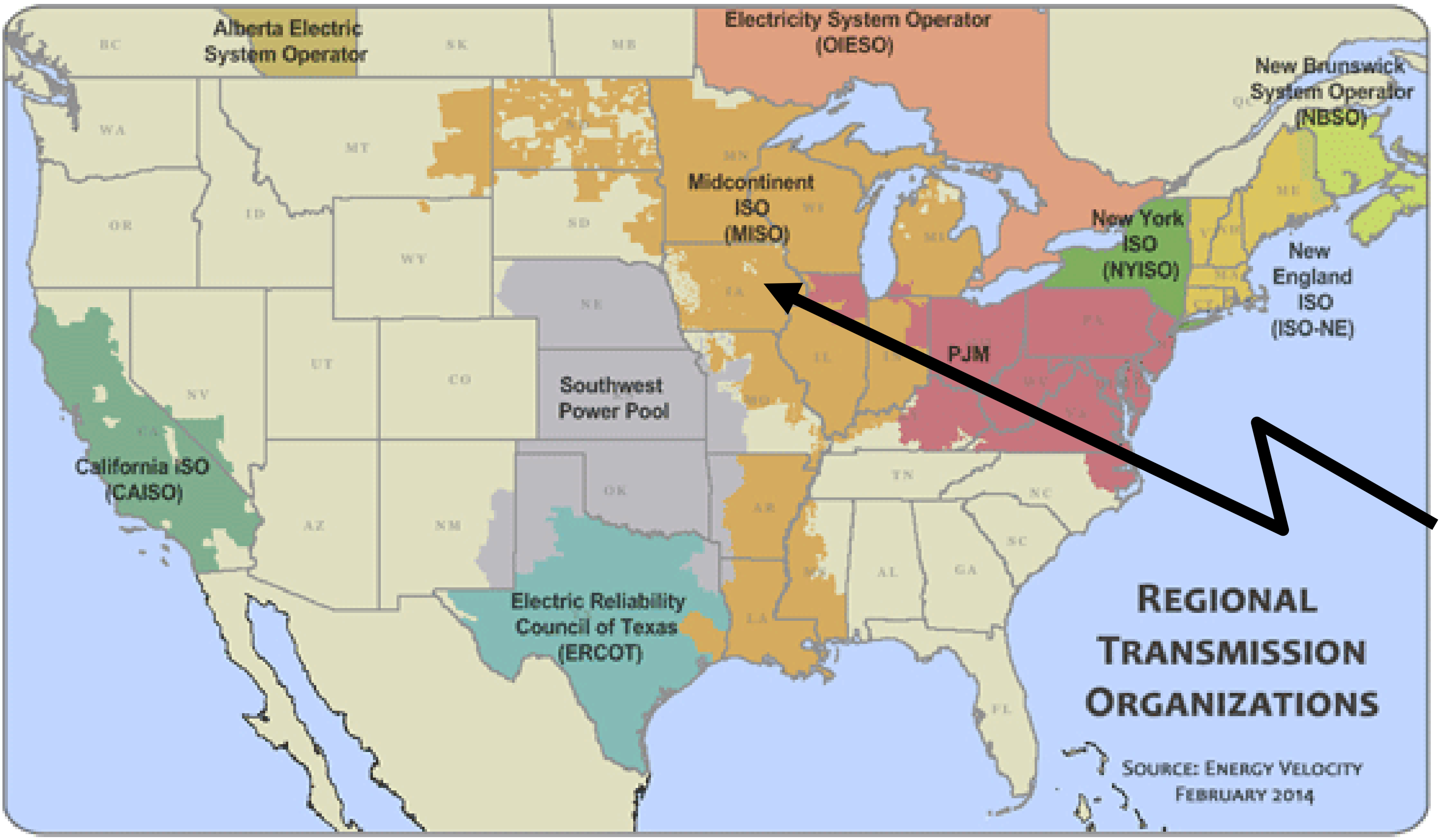
• Reliable	Percentage of time that the energy-service (with necessary quality) is available is high.
• Economic	Price of the energy-service paid by consumers is low.
• Sustainable	Short/long-term adverse environmental impacts are minimal.
• Resilient	Extreme events cause small impact (peak and duration) on energy-service prices.
• Adaptable	The cost of adapting to the future is low.

Overview

2. **Electric system investment planning**
   a. **Processes & systems**
   b. **Expansion planning models: GEP, TEP, GTEP**
   c. **GTEP modeling issues**
   d. **Continent-wide transmission design**
   e. **Adaptation**
   f. **Ways forward**

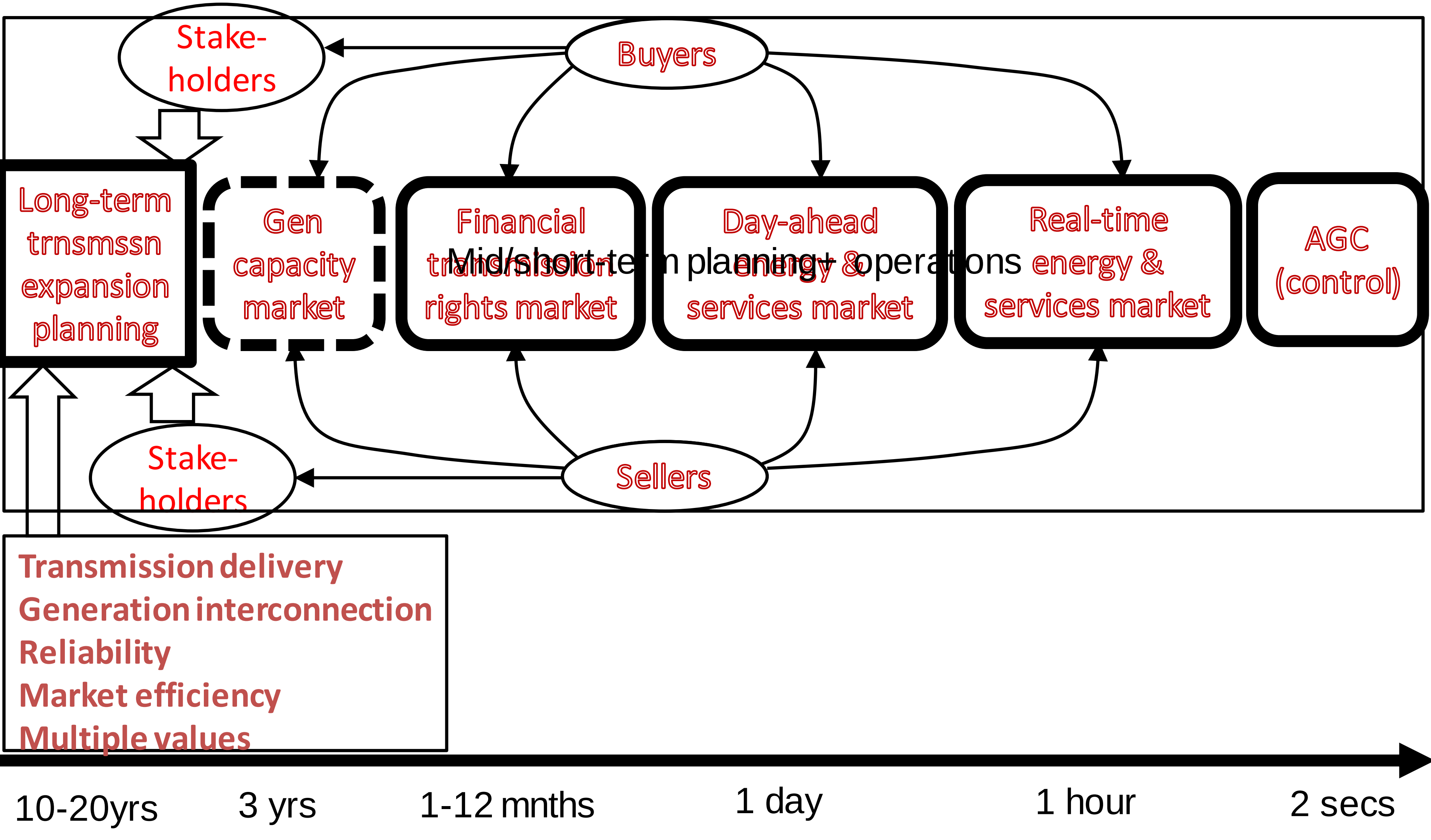
Regional Transmission Organizations/Independent System Operators

- The regional system operator: monitors and controls grid in real-time
- The regional market operator: monitors and controls the electricity markets
- The regional planner: coordinates 5 and 10 year planning efforts
- They own no electric power equipment.
- None of them existed before 1996.
- They are central to electricity production and transmission today.

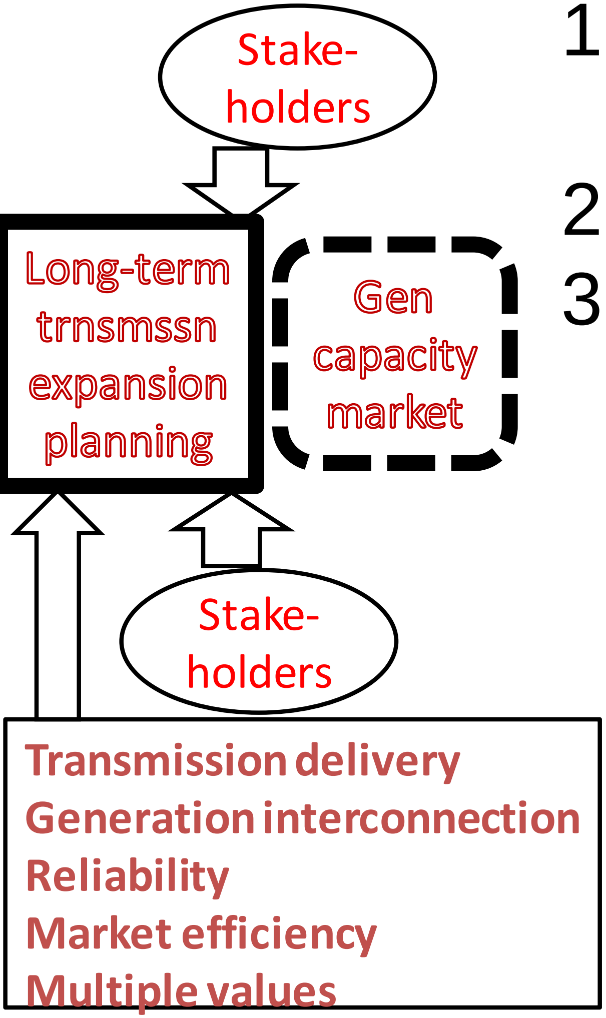


- $18.4 billion annual gross market charges (2012)
- 1,948 pricing nodes
- Five-minute dispatch
- Offers locked in 30 minutes prior to the scheduling hour
- Spot market prices calculated every five minutes
- 362 Market Participants who serve 41.7 million end-use customers

Systems & processes for electric power planning for unbundled structures with ISOs and markets



Focus on Expansion Planning



Features:

1. Performed by ISO engineers; investors are part of stakeholders
2. Mainly regional, mainly incremental
3. Gen is predicted, not planned: gen & transmission investments performed separately

We want to explore:

- inter-regional solutions
- derived from integrated gen & transmission optimization;

Generation & Transmission Expansion Planning (GTEP) problem for multiple periods

$$\min \underbrace{\sum_t \zeta^{t-1} \sum_i \sum_j I_{i,j} Cap^{add}_{i,j,t}}_{GenInvestmentCosts} + \underbrace{\sum_t \zeta^{t-1} \sum_i \sum_j FC_{i,j} H_j P_{i,j,t} T}_{OperationalCosts} + \underbrace{\sum_t \zeta^{t-1} \sum_{a=1,\dots,n} \sum_{\substack{l=(a,b);\\ \forall b \in \Omega_a^+}} K_l Z_{l,t}}_{TransInvestmentCosts}$$

subject to

$$Cap_{i,j,t} = Cap_{i,j,t-1} + Cap^{add}_{i,j,t} - Cap^{ret}_{i,j,t} \quad \forall i,j,t$$

Update capacity of Gen technology j

$$0 \le P_{i,j,t} \le CC_{i,j} Cap_{i,j,t} \quad \forall i,j,t$$

Gen must be within limits

$$\sum_i \sum_j CC_{i,j} Cap_{i,j,t} \ge (1+r) \sum_i d_{i,t} \quad \forall t$$

Reserve requirement

$$\sum_{l=(a,b),b\in\Omega_a} P_{l,t} - \sum_j P_{a,j,t} = d_{a,t} \quad a=1,\dots,n \quad \forall t$$

Power balance

$$P_{l,t} - b_l(\theta_{a,t} - \theta_{b,t}) = 0; \quad l=(a,b); \quad b \in \Omega_a^0; \quad a=1,\dots,n \quad \forall t$$

Power flow for existing circuit l

$$-P_l^{\max} \le P_{l,t} \le P_l^{\max} \quad l=(a,b); \quad b \in \Omega_a^0; \quad a=1,\dots,n, \quad \forall t$$

Flow limits for existing circuit l

$$\boxed{\begin{aligned} &-M_l(1-S_{l,t}) \le P_{l,t} - b_l(\theta_{a,t}-\theta_{b,t}) \le M_l(1-S_{l,t}); \\ &\qquad l=(a,b);\ b\in\Omega_a^+;\ a=1,\dots,n, \quad \forall t \\ &-P_l^{\max} S_{l,t} \le P_{l,t} \le P_l^{\max} S_{l,t} \\ &\qquad l=(a,b);\ b\in\Omega_a^+;\ a=1,\dots,n \quad \forall t \end{aligned}}$$

Power flow for candidate circuit l

Flow limits for candidate circuit l

$$S_{l,t} = \sum_{n=1}^{t} Z_{l,t}$$

A disjunctive constraint: prevents nonlinearity, but at the cost of integer variables → a MILP.

GTEP Modeling Issues

- Multi-period
- Discount factor
- Capacity credit & reserves
- Disjunctive circuit representation
- Multiple areas

These are modeled on the previous slide.

- Multiple load levels
- Capacity factor
- Retirements
- Impact of renewables
- Multiple gen & trans technologies
- AC capacity dependence on distance
- Cost of AC substations
- Loss representation
- End effects
- Technology maturation
- Multiple parallel circuits

These are not modeled on the previous slide.

GTEP modeling issues

15 gen technologies, M nodes, N candidate lines
And some extensions were required:

- 40 years, 4 load levels per year
- 4 transmission technologies
- up to 31 “bundles” of parallel circuits

Binary variables: N candidates*4 technologies*31 bundles*40periods=4960N
Continuous variables:

- Flows: 383candidates*4technologies*31bundles*4steps/yr*40yrs=19840N
- Gen investment: M nodes*15technologies*4steps/yr*40yrs=2400M
- Gen value: M nodes*15technologies*4steps/yr*40yrs=2400M

4960N binaries, 24800M continuous
N=383, M=62 → 1.9million binaries, 7.9million continuous

GTEP modeling issues

Ways to reduce computation time.

- Use faster or more hardware;
- Employ strategies to reduce dimensionality, e.g., use bundles only for selected candidate lines, etc.
- Utilize faster algorithms: decomposition
- Solve GEP and TEP separately, and iterate
- Do not enforce KVL

GTEP problem: transportation model

$$\min \underbrace{\sum_t \zeta^{t-1} \sum_i \sum_j I_{i,j,t} Cap^{add}_{i,j,t}}_{GenInvestmentCosts} + \underbrace{\sum_t \zeta^{t-1} \sum_i \sum_j FC_{i,j} H_j P_{i,j,t} T}_{OperationalCosts} + \underbrace{\sum_t \zeta^{t-1} \sum_{a=1,\ldots,n} \sum_{\substack{l=(a,b);\\ \forall b \in \Omega_a}} K_{l,j} Tcap^{add}_{l,j,t}}_{TransInvestmentCosts}$$

subject to

$$Cap_{i,j,t} = Cap_{i,j,t-1} + Cap^{add}_{i,j,t} - Cap^{ret}_{i,j,t} \quad \forall i,j,t$$

Update capacity of Gen technology j

$$0 \le P_{i,j,t} \le CC_{i,j} Cap_{i,j,t} \quad \forall i,j,t$$

Gen must be within limits

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Reserve requirement

$$\sum_{l=(a,b), b \in \Omega_a} P_{l,t} - \sum_j P_{a,j,t} = d_{a,t} \quad a = 1,\ldots,n \quad \forall t$$

Power balance

$$\cancel{P_{l,t} - b_l(\theta_{a,t} - \theta_{b,t}) = 0; \quad l=(a,b); \quad b \in \Omega^0_a; \quad a=1,\ldots,n \quad \forall t}$$

Power flow for existing circuit l

$$\cancel{-P^{\max}_l \le P_{l,t} \le P^{\max}_l \quad l=(a,b); \quad b \in \Omega^0_a; \quad a=1,\ldots,n, \quad \forall t}$$

Flow limits for existing circuit l

$$-P^{\max}_l - \sum_t \sum_j Tcap^{add}_{l,j,t} \le P_{l,t} \le P^{\max}_l + \sum_t \sum_j Tcap^{add}_{l,j,t}$$

Power flow for candidate circuit l

$$l=(a,b); \quad b \in \Omega_a; \quad a=1,\ldots,n \quad \forall t$$

Flow limits for candidate circuit l

$$\cancel{S_{l,t} = \sum_{n=1}^{t} Z_{l,t}}$$

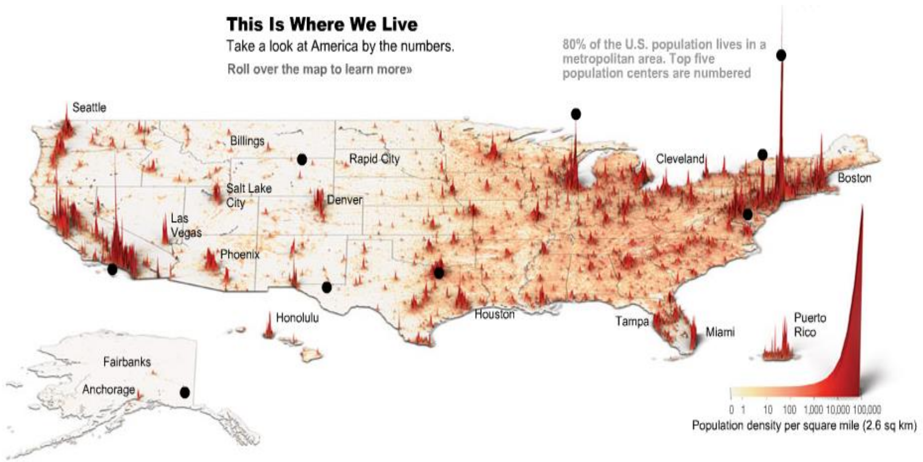
➔Replaces wires with pipes

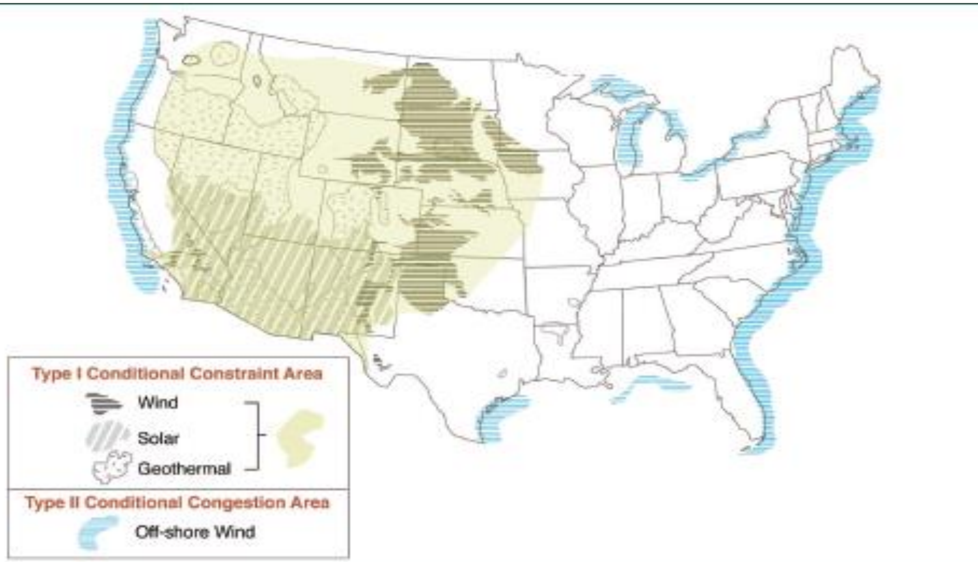
➔Eliminates binary variables.

Continent-wide transmission design

High-capacity interregional transmission is motivated by high renewable penetration because…

- **Location dependence.**
- **Renewable energy can be moved only by electric transmission.**
- **Transmission costs comprise a relatively small percent of long-term electric infrastructure cost.**



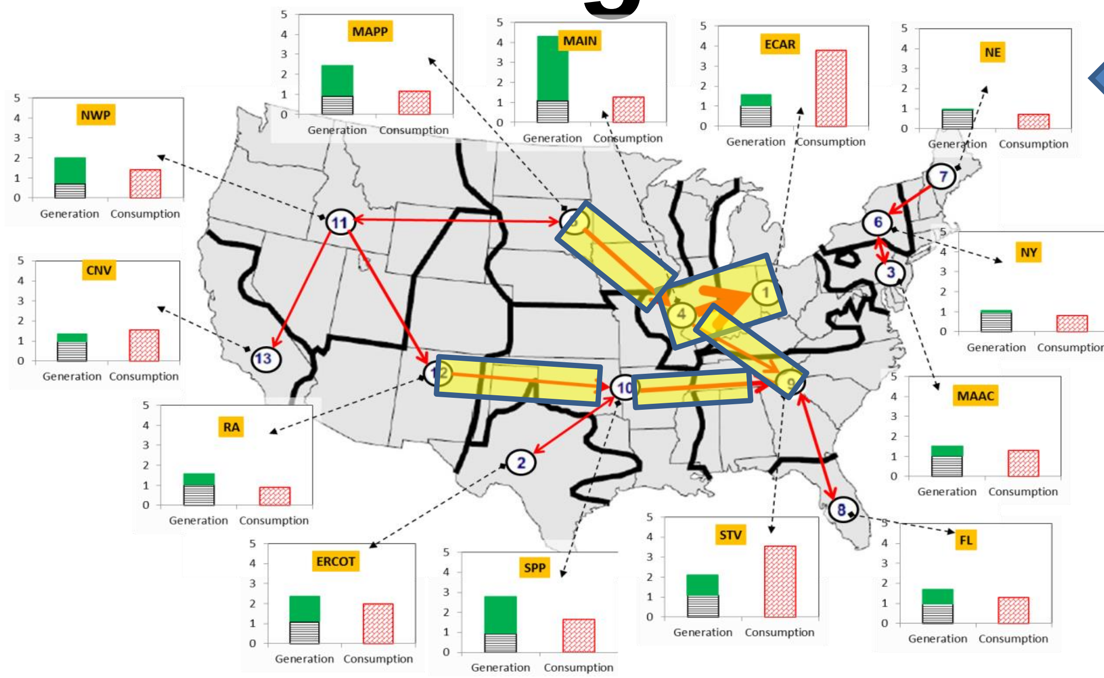


A First Analysis: 13 nodes

- Existing gen & interregional transmission capacity represented as arcs with expandable capacities.
- New gen: nuclear, wind, solar, geothermal
- Optimization problem, 40 yrs, 1 mnth periods:
  - Choose gen & trans capacities to minimize: NetPresentValue{Investments+ProdCosts}
  - Subject to: Meet energy demand in each mnth
  - Renewable CFs represented geographically
  - Generation retirements represented
  - Trans cost is $1.5B/GW/1000miles

J. McCalley, J. Bushnell, V. Krishnan, and S. Lemos, “Transmission Design at the National Level: Benefits, Risks, and Possible Paths Forward,” prepared for the PSERC/DOE project “The Future Grid to Enable Sustainable Energy Systems,” January, 2012. file:///C:/Users/jdm.IASTATE/Downloads/McCalley_PSERC_White_Paper_Transmission_Overlay_Jan_2012.pdf

Results: gen/trans investments



Case B1 (renewable & nuclear, geothermal-light)

➔Flow is west to east.

➔Highest trans cap investment is MAIN (4) to ECAR (1) because:

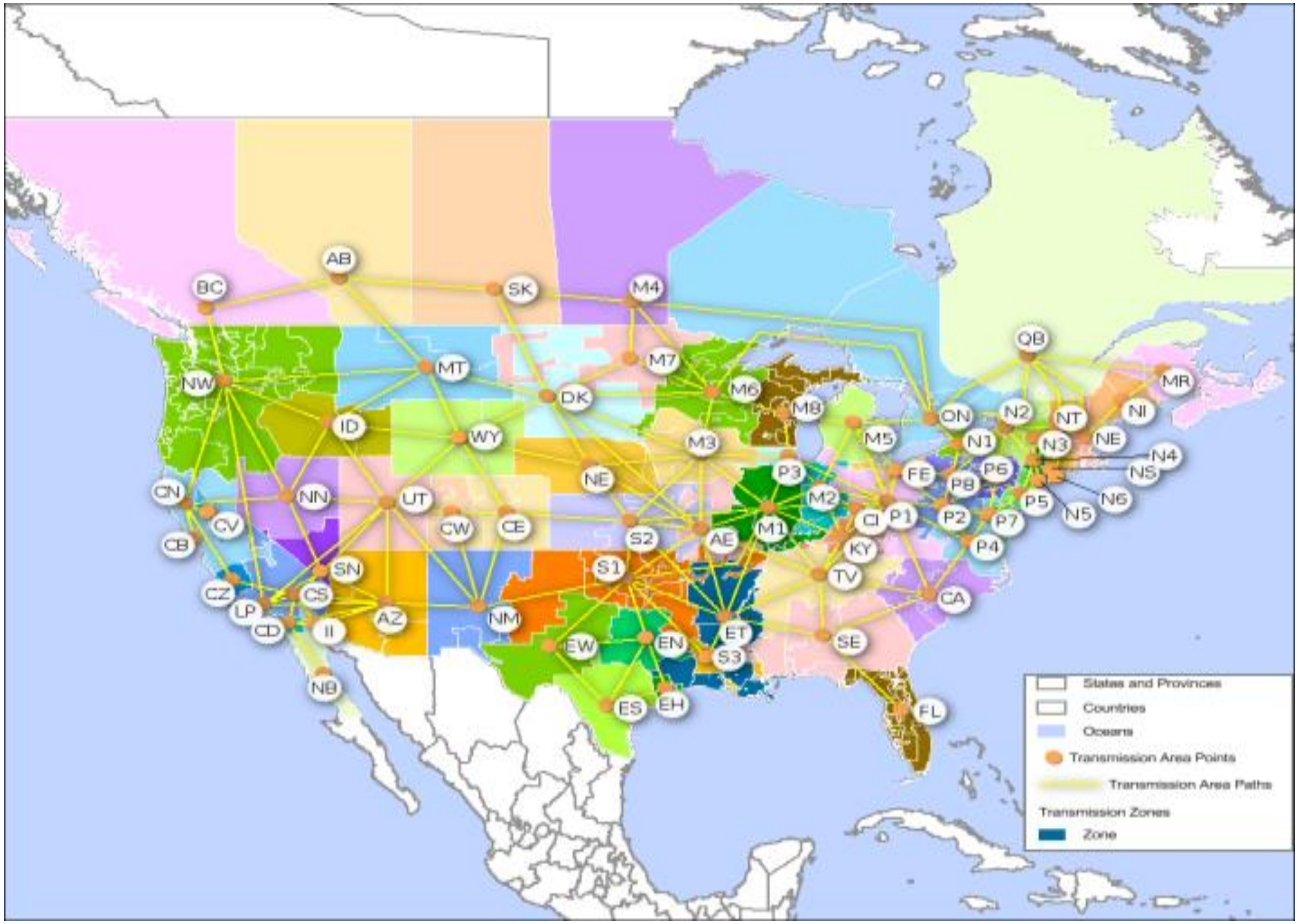
- CF (0.5 in MAIN, 0.3 in ECAR)
- Load is very high in ECAR

➔High trans cap investment from SPP (10) to STV (9) because:

- CF (0.4 in SPP, 0.1 in STV)
- Load is very high in STV

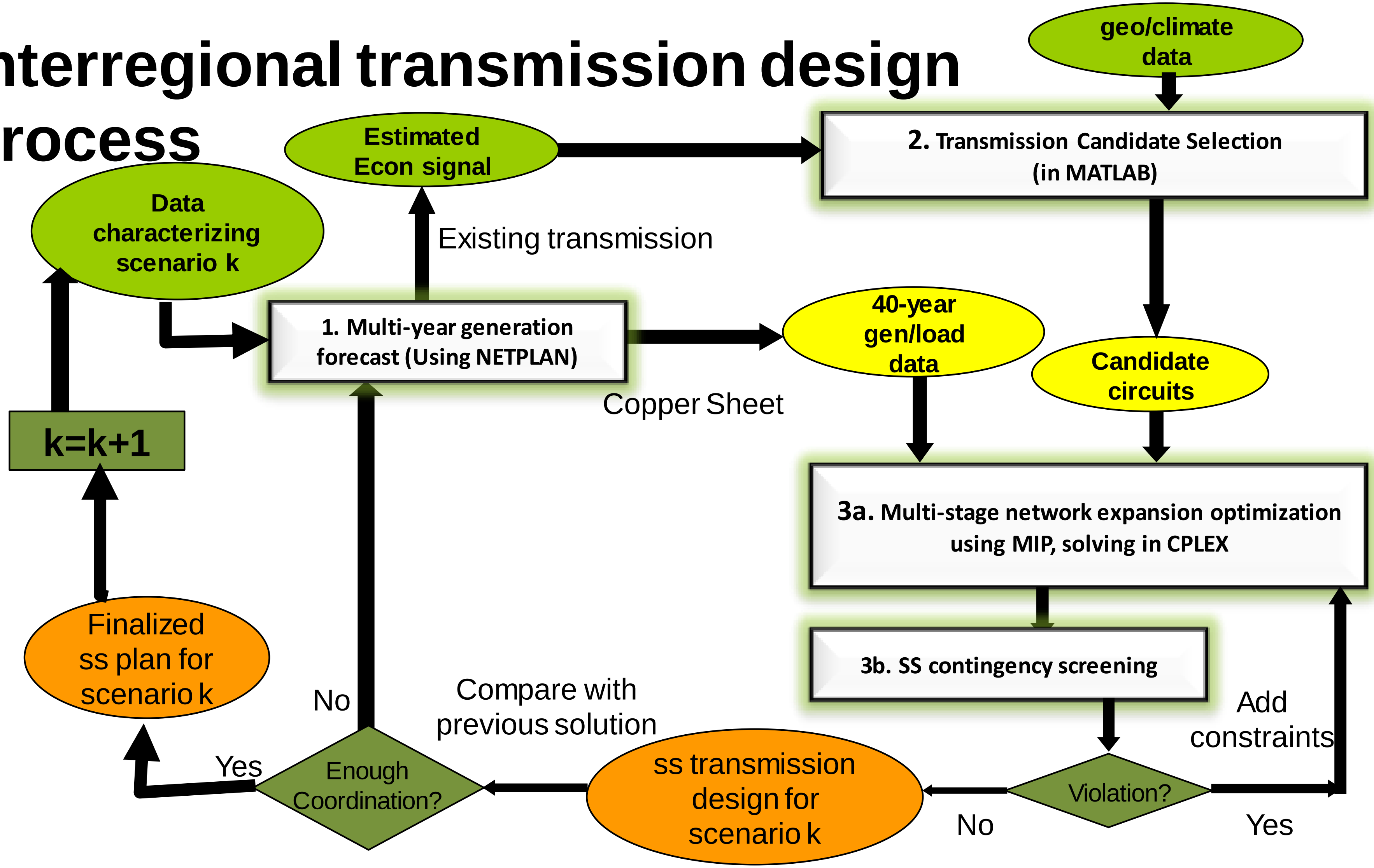
Cases	Case description	Transmission	Cost (Billion$)	
			Present worth (2010 dollars)	Annualized over 40 years
A1	Mostly renewable, geothermal-light	Fixed	5013.12	376.03
B1		Expanded	4773.96	358.09
		Difference	**239.16**	**17.94**

A second analysis: 62 nodes

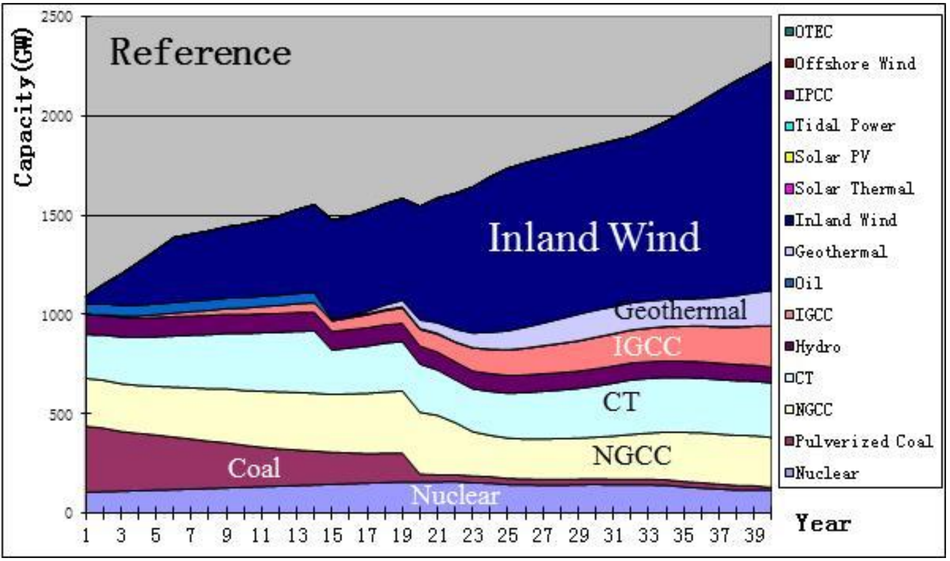


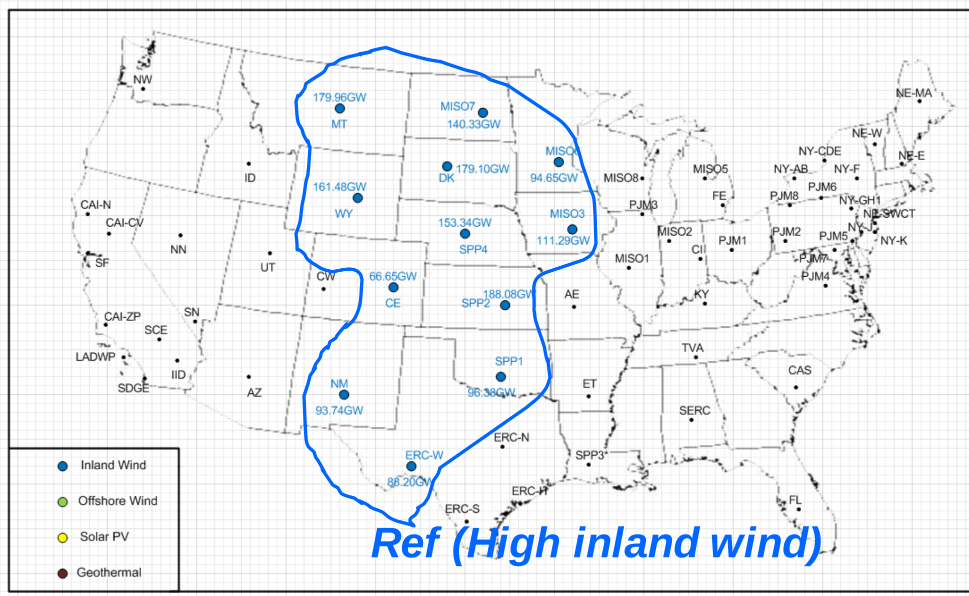
Accurate representation of existing gen; new gen chosen from 15 types.
Existing transmission modeled between nodes.
NERC's regional reserve requirements imposed.
Used iterative GEP/TEP formulation.

Interregional transmission design process



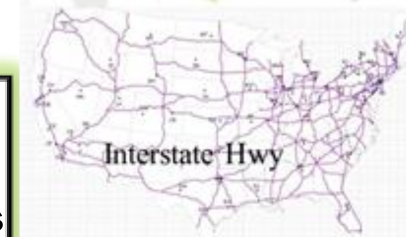
Step 1: Generation forecast



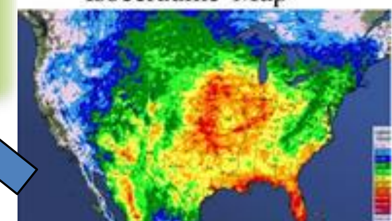


- 62 node model, infinite transmission capacity
- Accurate representation of existing generation
- 15 candidate generation technologies
- Invested generation based on technology and location
- Complied with NERC's regional reserve requirements.

Step 2: Xmission Candidates



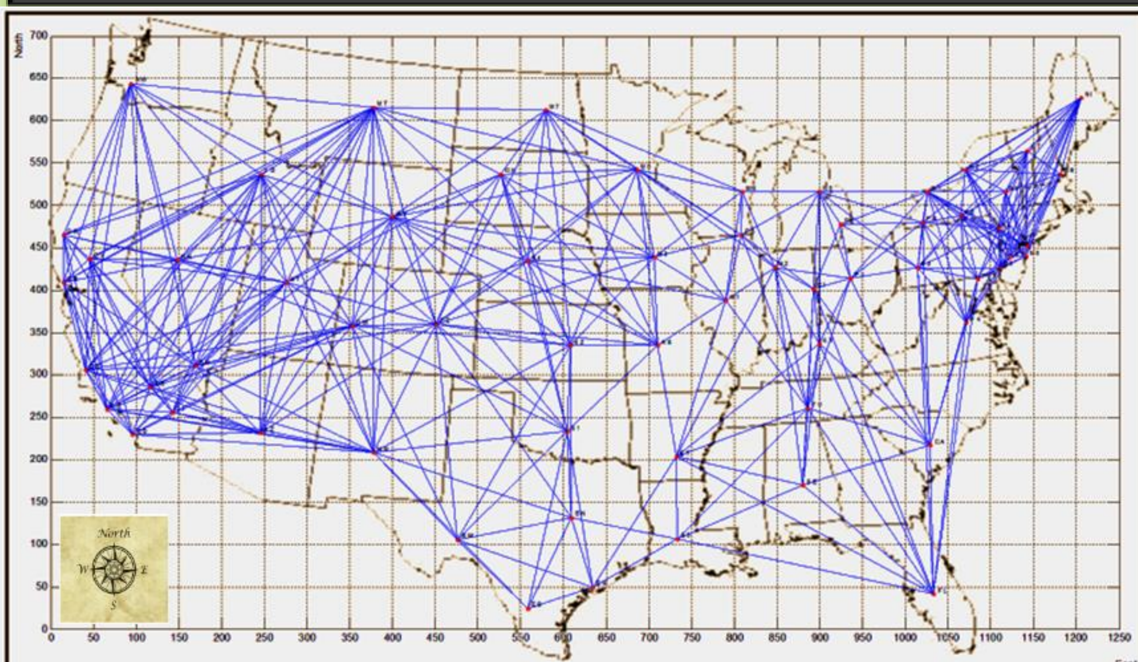
Isoceraunic Map



Iterative Reweighting Minimum Distance Spanning Tree Algorithm

a. Eliminates infeasible paths (reserve land, national parks, lightning areas…)
b. Finds minimum "distance" tree which connects all nodes; stores selected arcs
c. Develops weighted distance on selected arcs, where weights reflect
   - <u>attributes facilitating transmission</u>: existing trans, interstate hwy, rail;
   - <u>attributes inhibiting transmission</u>: terrain, pop density, forest, wind/ice;
   - <u>economic impact</u>;
d. Repeat steps a-c, each time storing selected arcs

➔ **Captures any arc which is "good" in any iteration.**



383 Candidates, N-1 connected set

Step 3: Network Expansion Optimization

A multi-period, mixed-integer linear program

➔Chooses from candidate arcs considering:
HVDC (600 kV, 800 kV) and EHVAC (500 kV, 765 kV)

MINIMIZE NPW { T-investment + G-production costs }
➔*T-investment is function of technology, distance, & substation, terminals.*

SUBJECT TO:

- ***Nodal balance constraints***
- ***DC line-flow equations, existing interregional circuits***
- ***DC line-flow equations, candidate interregional circuit***

➔*Maintains linearity using disjunctive model extended to allow multiple parallel circuits*

- ***Transmission capacity constraints***

➔*AC capacities a function of distance per St Clair Curves*

- ***Generation constraints***

Step 3: Network Expansion Optimization

Cost expressions:

$$765\text{kV AC: } CT_{1t} = 3.49 l_{at} m_t + 16.14 \times [\frac{l_{at} + 2l_0}{l_0}] + 170 n_{at} TC_{1t}$$

$$500\text{kV AC: } CT_{2t} = 2.75 l_{at} m_t + 12.57 \times [\frac{l_{at} + 2l_0}{l_0}] + 155 n_{at} TC_{2t}$$

$$600\text{kV DC: } CT_{3t} = 1.8 l_{at} m_t + 2 \times 155 TC_{3t} + 155 n_{it} TC_{3t}$$

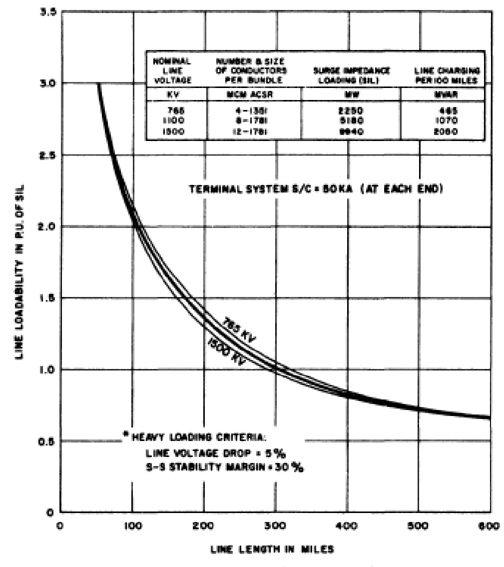
$$800\text{kV DC: } CT_{4t} = 1.95 l_{at} m_t + 2 \times 170 TC_{4t} + 170 n_{it} TC_{4t}$$

Weighted line cost

Substation or terminal cost

Additional DC terminal costs

Technology	765kV	500kV	600kV	800kV
Typical Rating(GW)	SIL=2.25 @300mile	SIL=1 @300mile	3GW	6GW
Circuit Breaker(M$)	2.88	2.27	–	–
Transformer(M$)	9.02	6.8	–	–
Voltage Control(M$)	4.24	3.5	–	–
Converter(M$/MW)	–	–	0.155	0.17
Line Cost (M$/mile)	3.49	2.75	1.8	1.95
ROW (ft.)	200	200	250	270
$(w_k l_{at})$ losses@SIL(10^{-5})	$6.47 l_{at}$	$12.6\ l_{at}$	$6.58\ l_{at}$	$4.58\ l_{at}$



Capacity expressions:

$$765\text{kV AC: } TC_{1t} = SIL_1 f(l_{at})$$

$$500\text{kV AC: } TC_{2t} = SIL_2 f(l_{at})$$

$$600\text{kV DC: } TC_{3t} = 3$$

$$800\text{kV DC: } TC_{4t} = 6$$

$$f(l_{at}) \approx 43.261 l_{at}^{-0.6678}$$

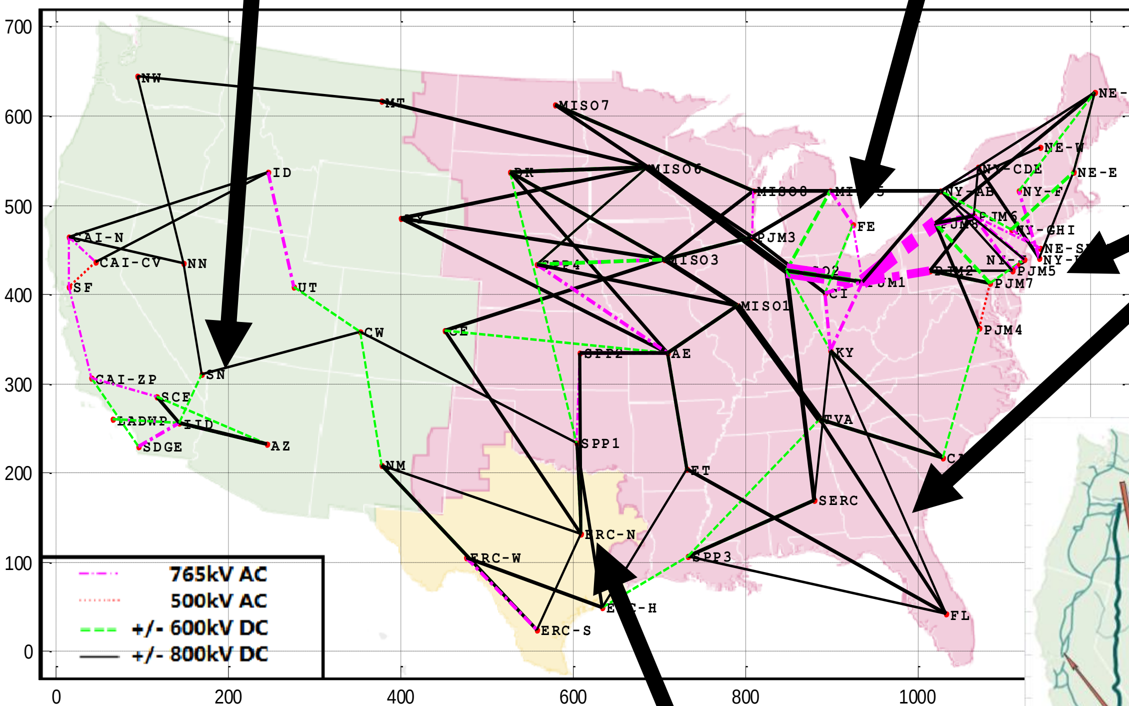
R. Dunlop, R. Gutman, and P. Marchenko, "Analytical development of loadability characteristics for EHV and UHV transmission lines," IEEE Transactions on Power Apparatus and Systems, vol. PAS-98, No. 2 March/April 1979.

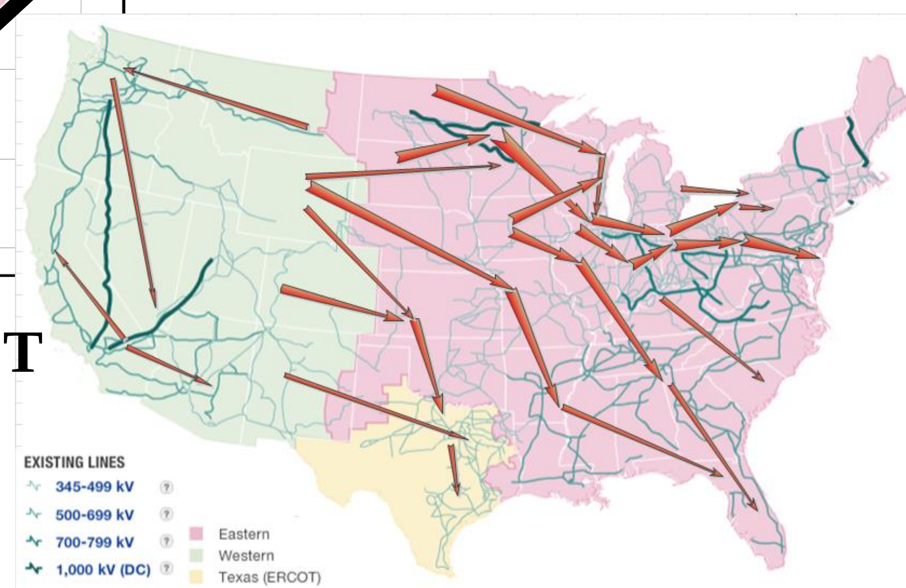
Design result for “Ref” case

800kV DC lines supply SW, where limited renewable resources are available.

Major investments around Great Lakes, consistent with MISO-MTEP2010 results

Investments in PJM & SERC move renewable gen to load centers.





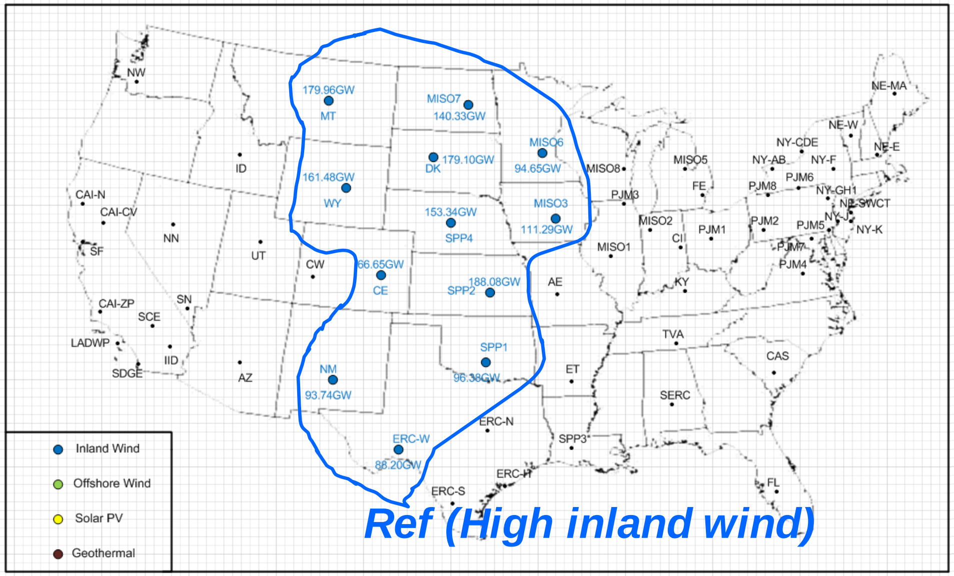
WECC, EI, and ERCOT interconnected near SPP.

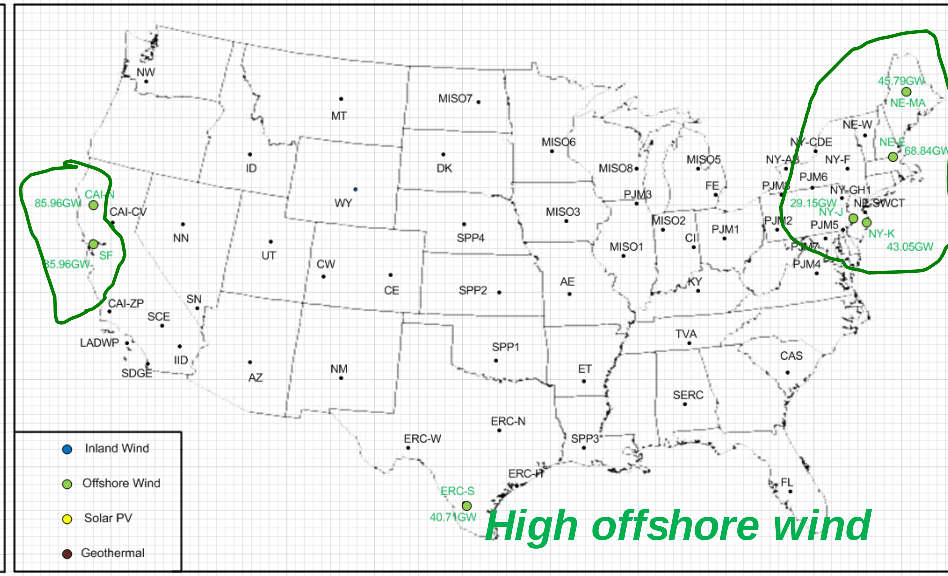
Design result for "Ref" case: major transmission investments

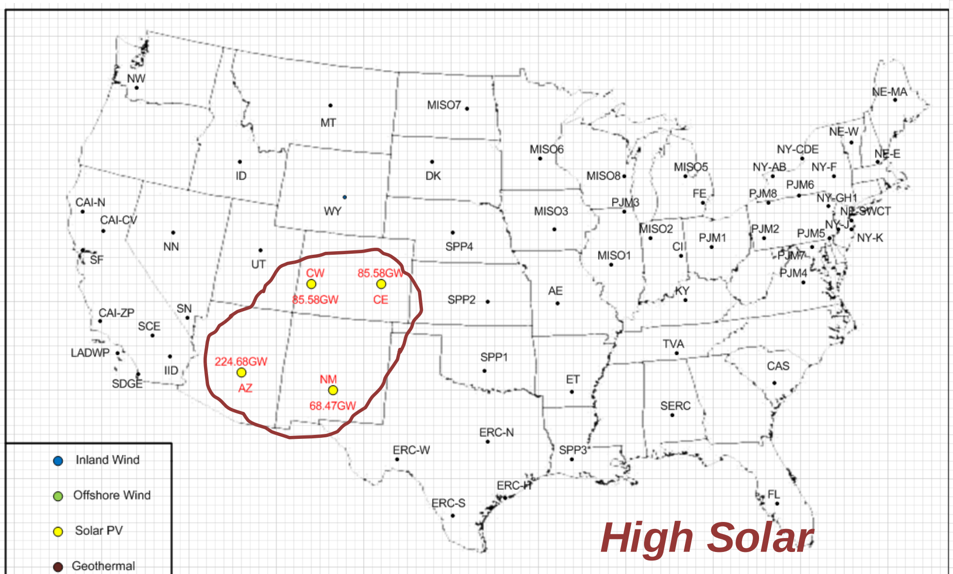
M1-M8: MISO
P1-P8: PJM
CI: Central Indiana
N1-N3: New York
NW: Northwest
NN,SN: N., S. Nevada
S1-S4: SPP
EN, EW, ES: Ercot N, W, S
EH: Ercot southeast
NE: New England
SE: Southeast
CE, CW: Colorado E, W
FL: Florida
TV: TVA
NT, NI, NS: Northeast
ET: Entergy
CA: Carolina
NM: New Mexico

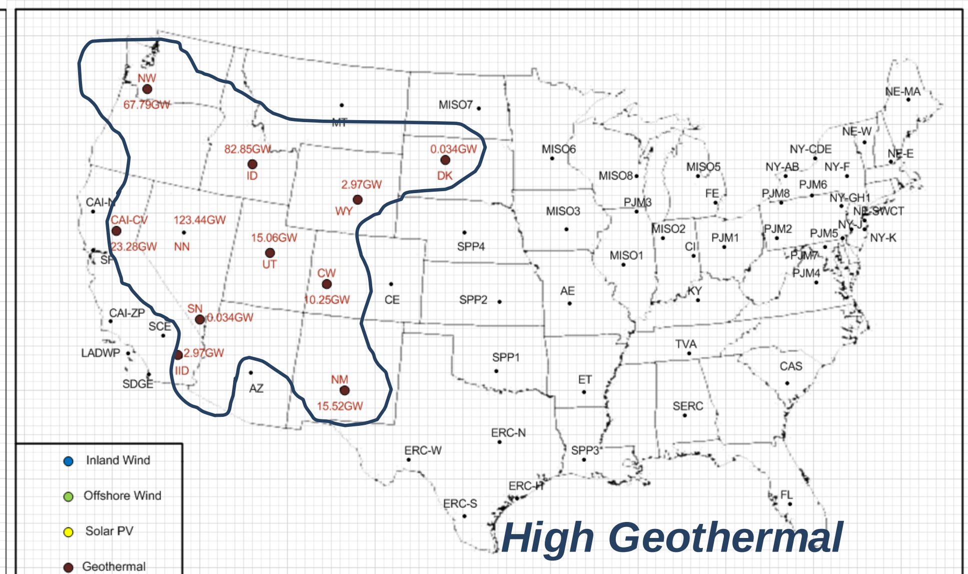
Year	Tech	From	To	# of Ckt. Added	Length (mile)	Capacity per Ckt. (GW)	Cost per Circuit (2010M$)
1	765kV	M2	P1	4	176.0	3.1	675.0
1	600kV	S3	SE	2	472.0	3.0	2240.5
1	800kV	N6	N2	2	290.0	6.0	2885.1
16	765kV	M2	P1	16	176.0	3.1	675.0
16	765kV	M2	P1	8	176.0	3.1	675.0
16	765kV	P1	P2	8	205.0	2.8	827.5
16	765kV	P1	P8	16	185.0	3.0	712.1
16	765kV	P1	P8	8	185.0	3.0	712.1
16	765kV	P8	P6	8	204.0	2.8	787.8
16	500kV	P7	P4	1	107.0	1.9	472.2
16	600kV	M1	TV	8	338.0	3.0	1,705.5
16	600kV	M2	P1	8	176.0	3.0	1,269.2
16	800kV	M1	TV	8	338.0	6.0	2,858.9
16	800kV	M3	M1	8	339.0	6.0	2,802.4
16	800kV	M6	M2	8	610.0	6.0	3,960.8
1	600kV	S3	SE	2	472.0	3.0	2,240.5

Developed 4 Gen Futures; All at 60% penetration (by energy: 2010: 3.5%; 2020: 25%; 2050: 60%)



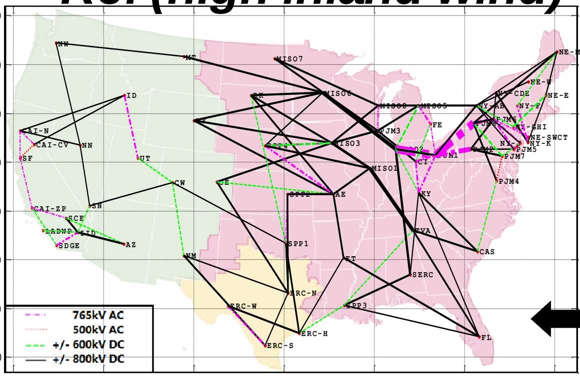


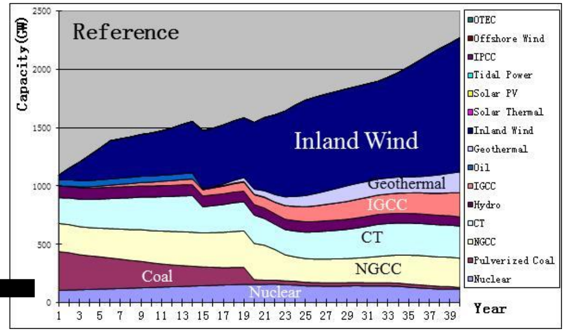




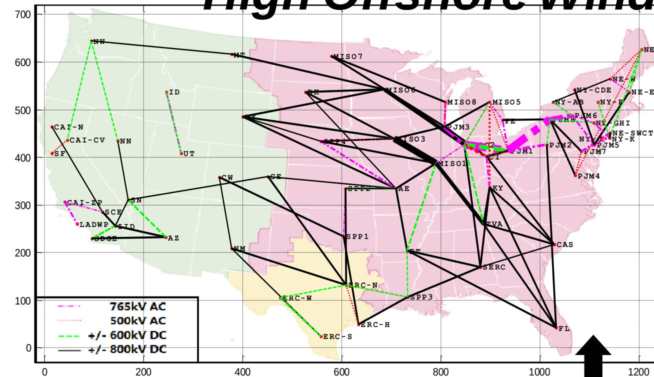
Design Results for 4 Gen Futures

Ref (high inland wind)

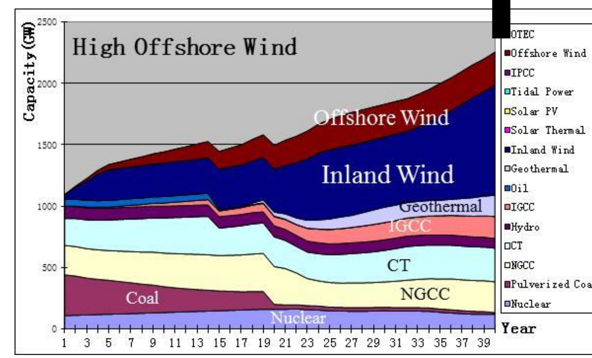


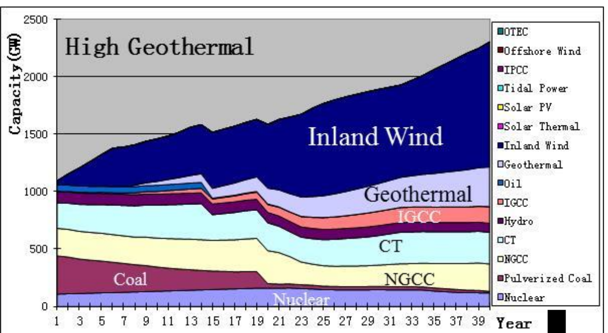


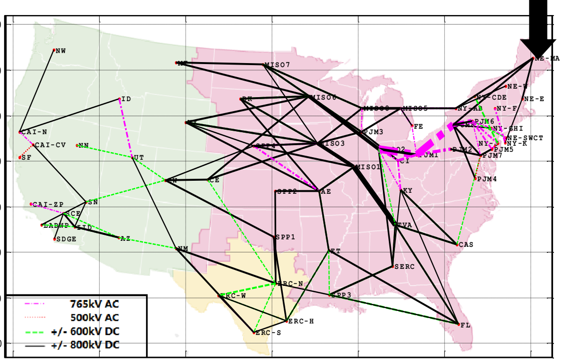
High Offshore Wind



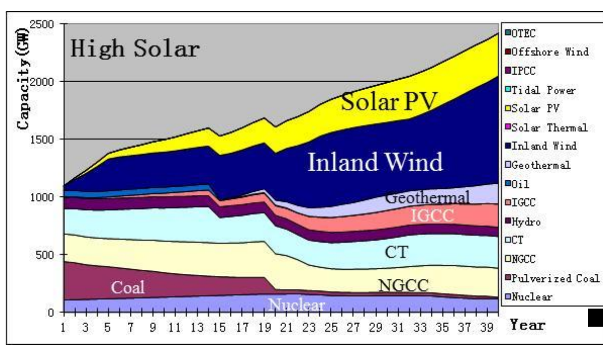
Designs selected to minimize 40yr investment+operational costs, accounting for existing transmission, terrain, population density, forest areas, elevation, wind, ice-loading, right-of-way.

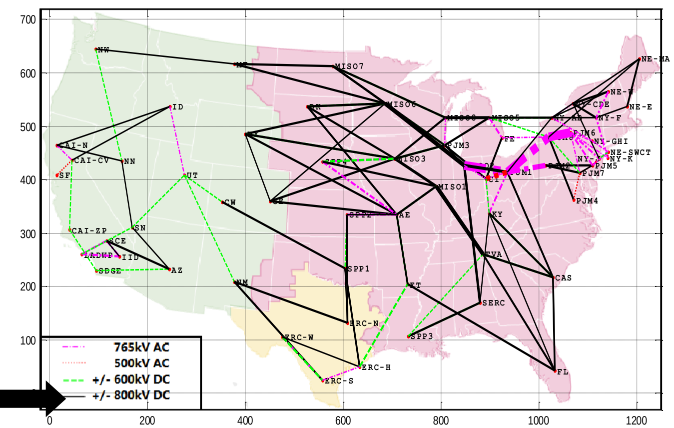






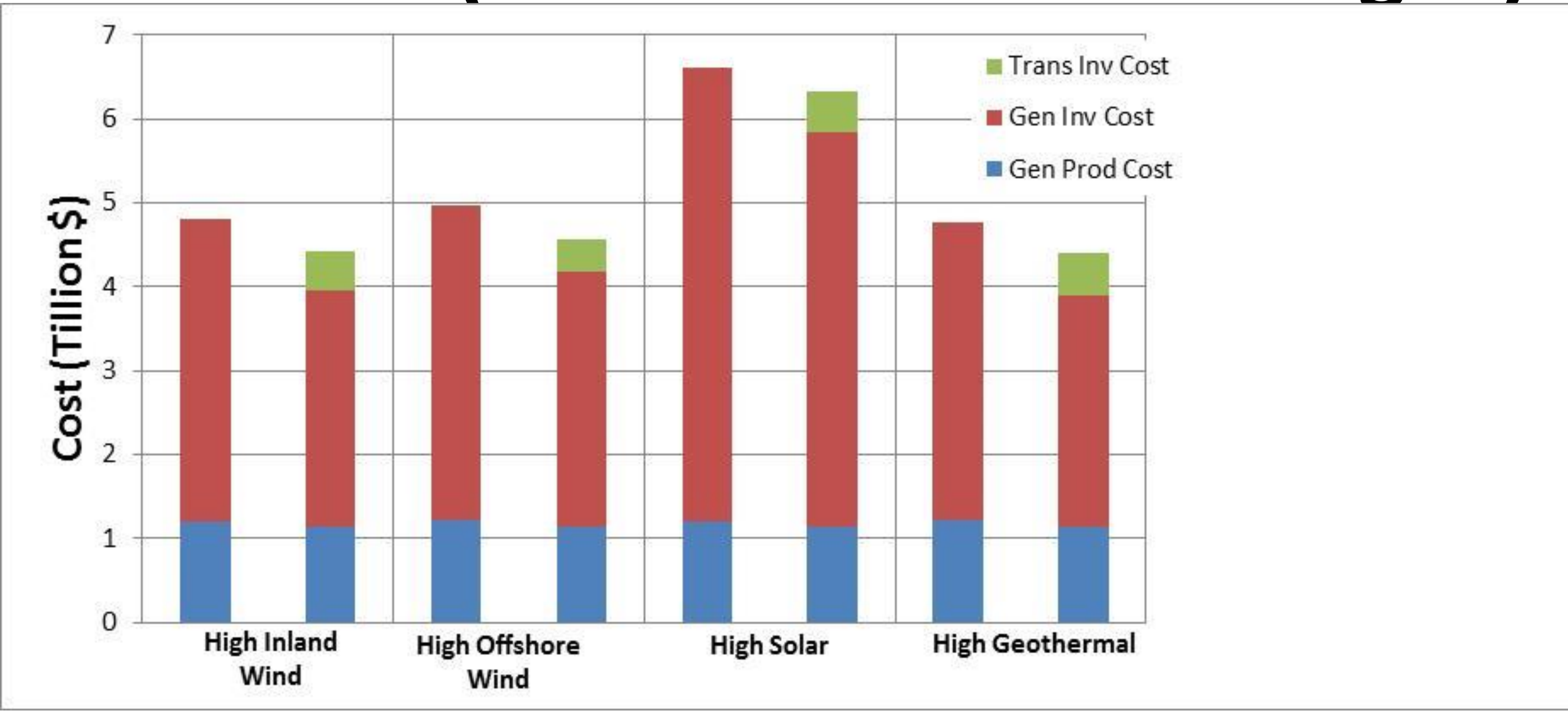
High Geothermal





High Solar

Benefits (for Each of the 4 Designs)



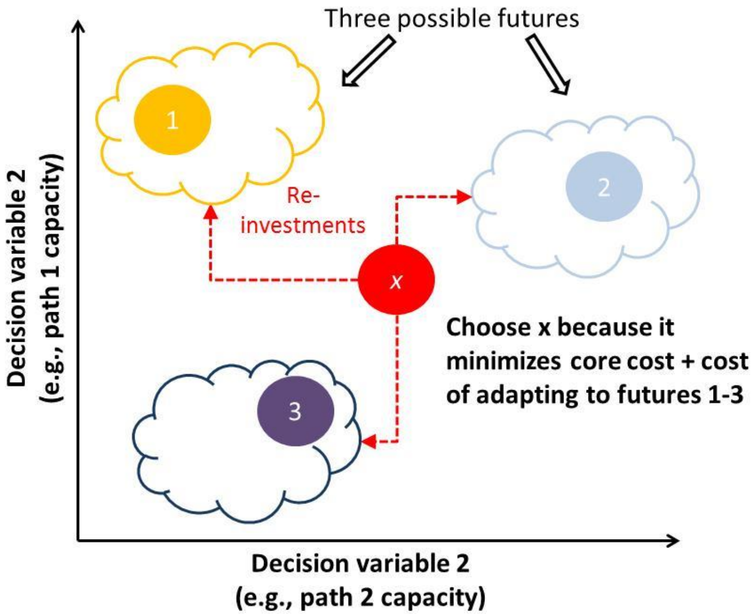
Transmission lowers total 40-year cost.

And provides 2 more benefits:

- **resilience of energy prices to large-scale events;**
- **planning adaptability.**

Planning under uncertainty

Under the 4 futures, what design to build?
➔An adaptable one!

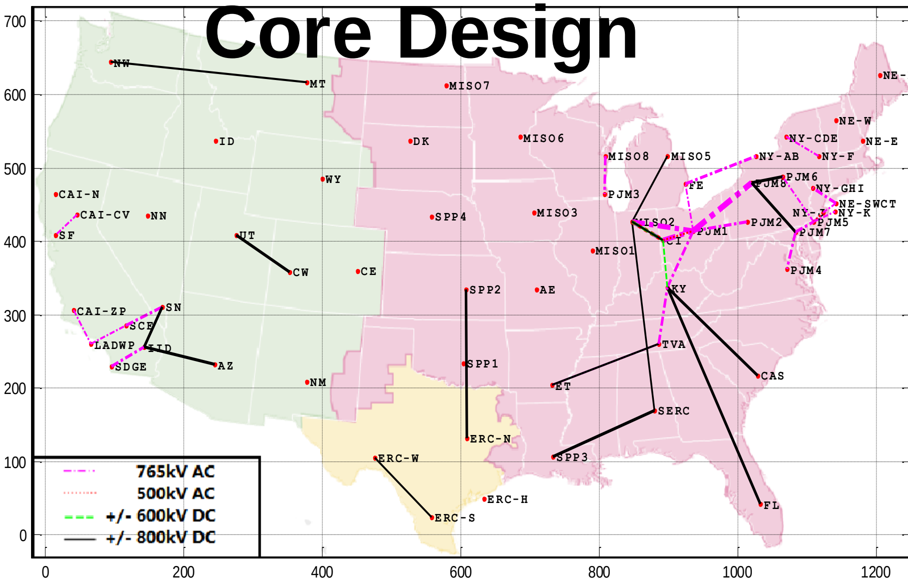


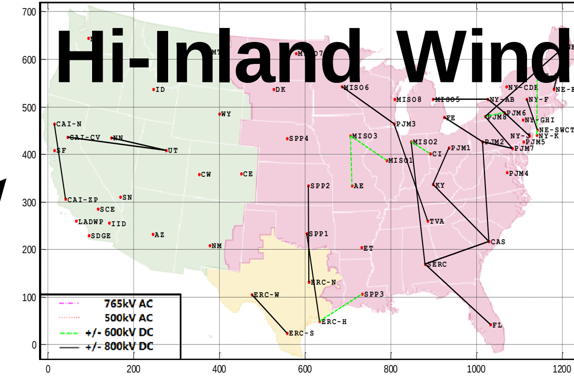
Identifies an investment that is "core" in that the total "CoreCost" plus the cost of adapting it to the set of envisioned futures is minimum.

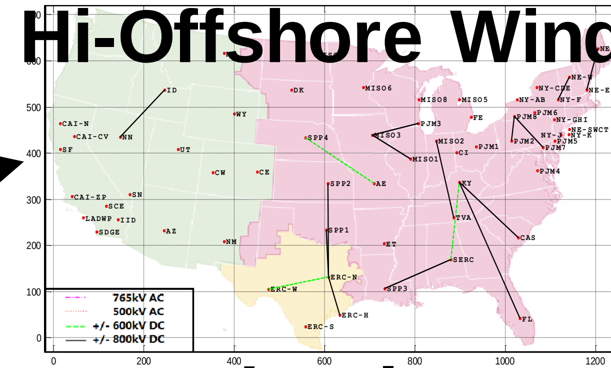
Minimize:
$\text{CoreCosts}(\underline{x}^f)+\beta[\Sigma_i \text{AdaptationCost}(\Delta\underline{x}_i)]$
Subject to:
Constraints for scenario i=1,…N: $\underline{g}_i(\underline{x}^f+\Delta\underline{x}_i)\leq\underline{b}_i$

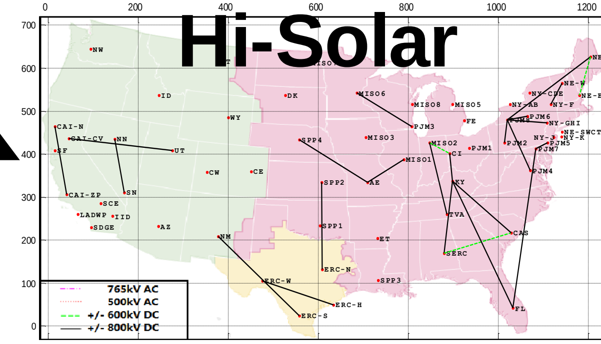
$\underline{x}^f$: Core investments, to be used by all scenarios i
$\Delta\underline{x}_i$: Additional investments needed to adapt to scenario i

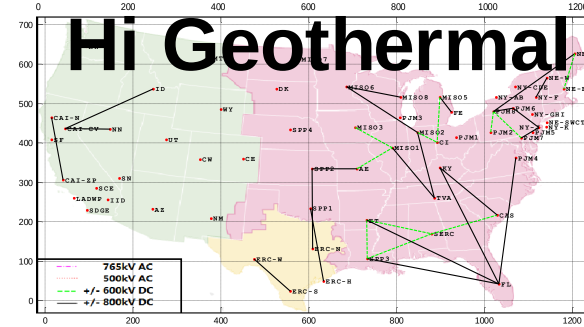
Planning under uncertainty



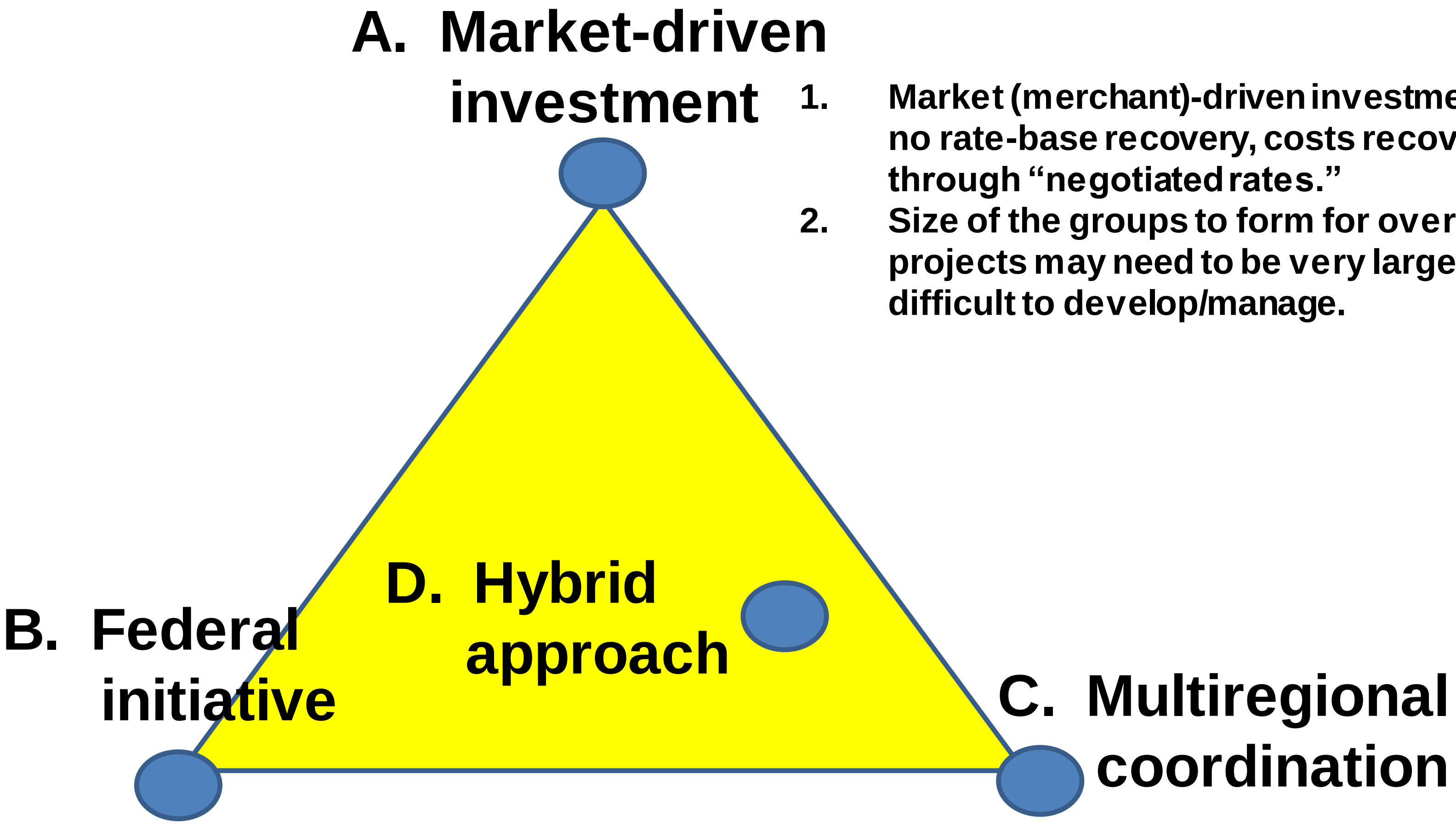








Paths forward: frameworks



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.

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.
3. The above is evolving.

Paths forward: Frameworks
D. Hybrid approach

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.**

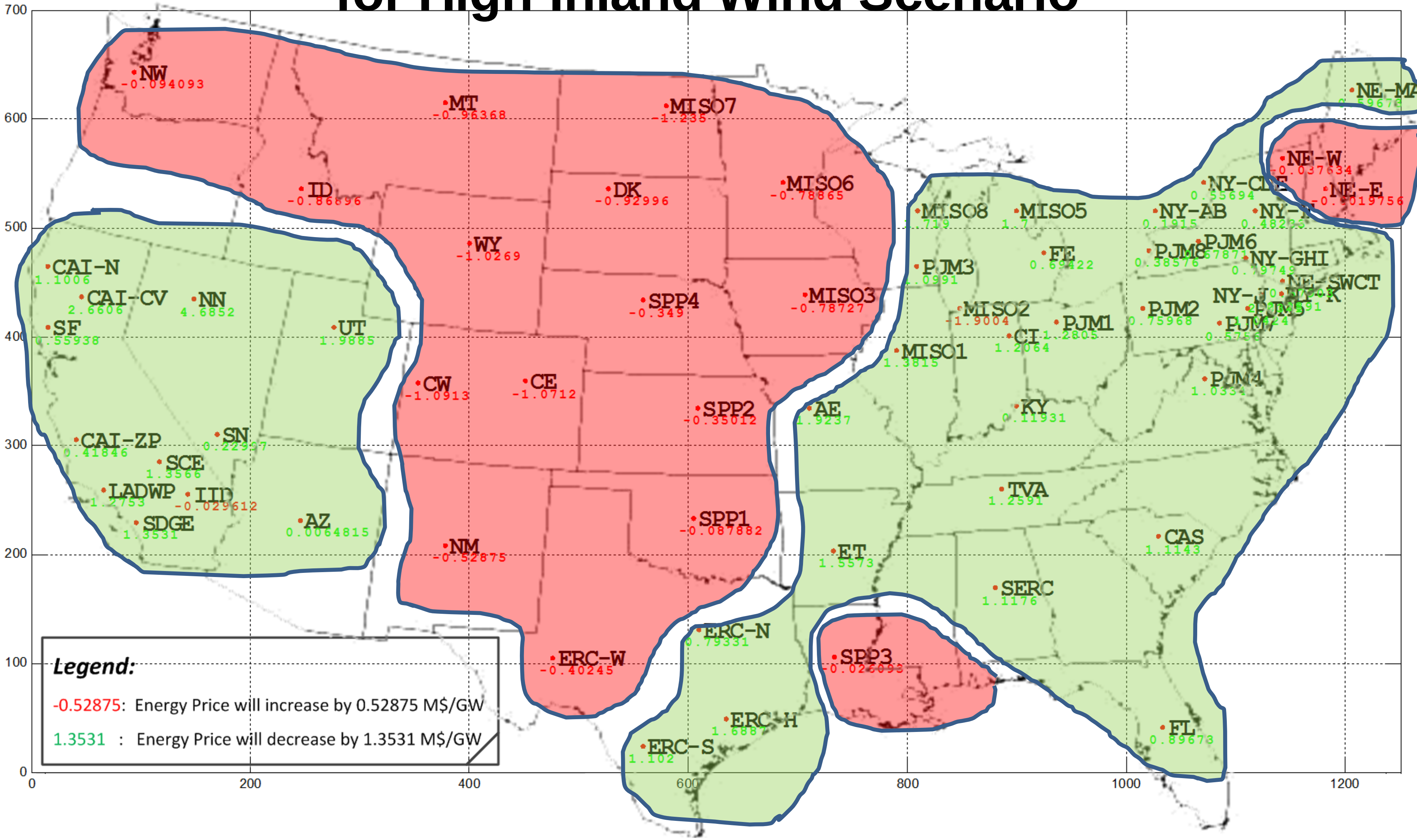
Resource Parochialism?

"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.

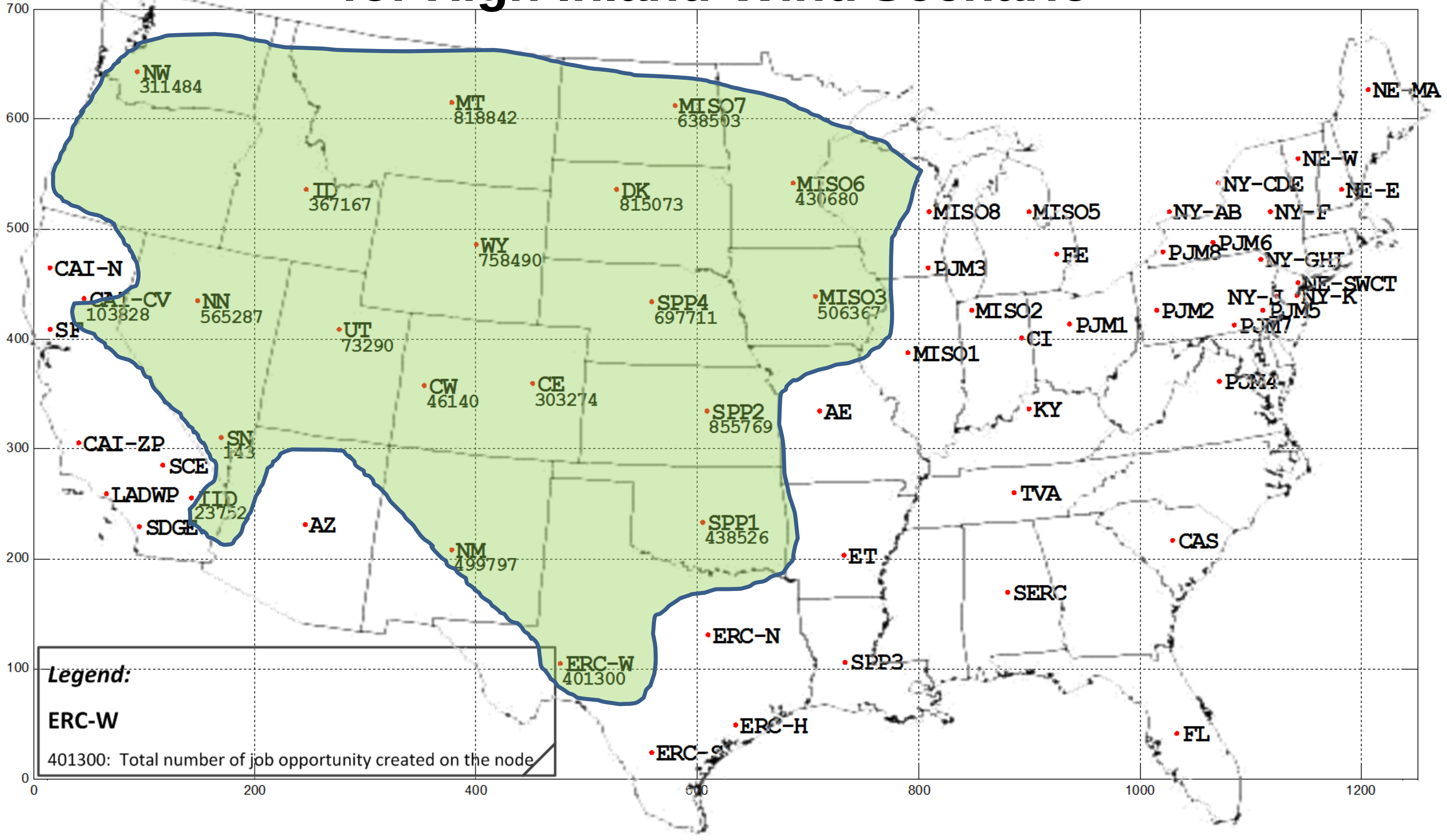
James Hoecker,
FERC Commissioner 1993-2001,
FERC Chair 1997-2001

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&

Impact of Transmission Expansion on Average LMPs for High Inland Wind Scenario



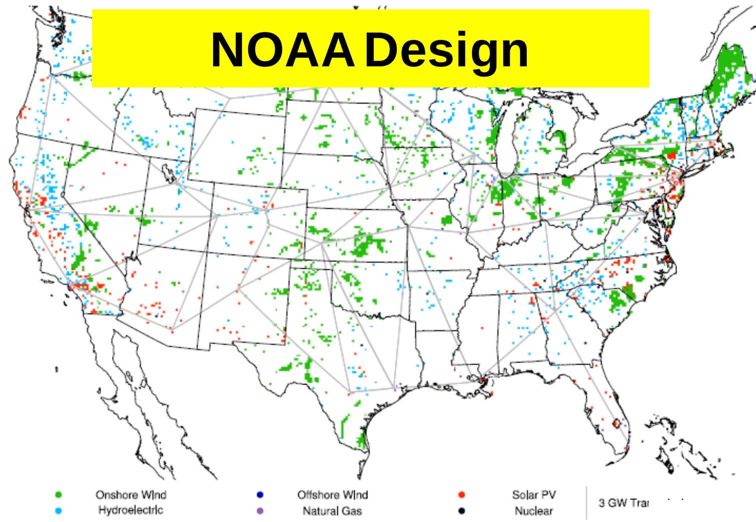
Impact of Generation Expansion on Job Creation for High Inland-Wind Scenario



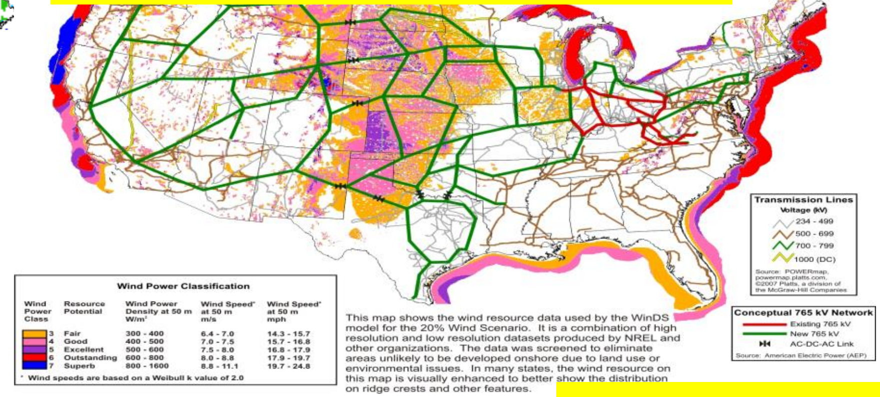
Takeaways

- "Energy system" is a multi-sector infrastructure system and should be planned accounting for interdependencies between sectors.
- There are political, social, and technical tensions today regarding directions future energy system development should take.
- Electric system expansion planning is performed incrementally (not always been so), mainly regionally; there are big benefits to centralized interregional design when resource economics vary geographically.
- GTEP is a useful tool that is not yet commercially available because of computational limitations. Handling "large" uncertainties in futures is an open research question – we think adaptation is the way to go.
- Transmission - the silver bullet: enhances economics & sustainability by lowering \$/unit-CO_2-reduced; increases resilience and adaptability.
- Incremental transmission development & associated cost-allocation - a complex, stakeholder-driven problem. Interregional transmission development and its cost-allocation seems impossible in the US (but not China or Europe!) – developing socio-political-economic processes & procedures to address the balkanization is an essential step.
- Developing interregional designs is useful even if entire design never built, because it identifies attractive transmission paths and it develops tools/approaches applicable to regional and sub-regional planning.

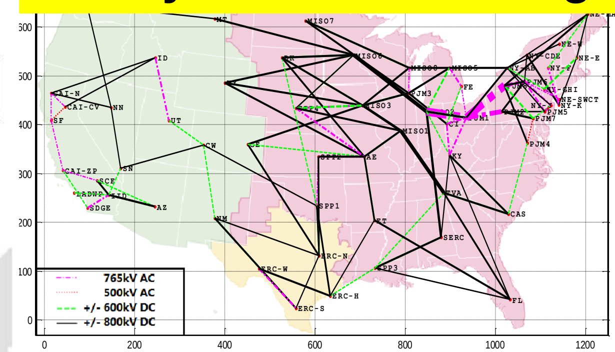
NOAA Design



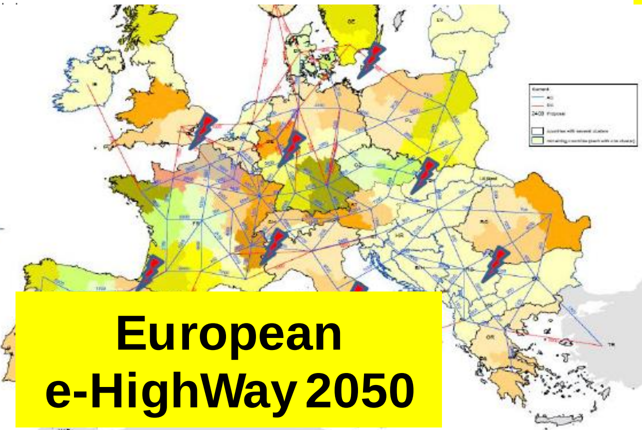
AEP 765kV Concept



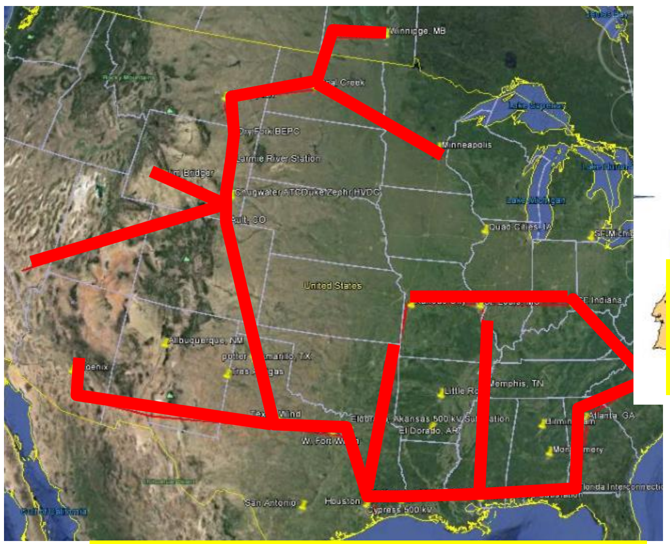
ISU Hybrid AC/DC Design



European e-HighWay 2050



MISO HVDC Design



Projects of the Clean-Line Energy Partners