Interconnections Seam Study

Aaron Bloom

TransGrid-X Symposium

Ames, Iowa

NREL is Objective, Integrated, Scientific Analysis

Renewable Generation

Wind
Solar
Geothermal
Hydro
Biomass
Hydrogen

Buildings

Residential
Commercial
Devices

Vehicles

Electrification
Light duty
Heavy duty
Fuel Cell

Data

Foundational Datasets
Visualization
High Performance Computing

People

1,700 employees
$872M annual economic impact
750 Partnerships

We’ve been imagining a modern grid for 40 years.


Now is the time to
Make it Happen
Meet your EV match

The Interconnections Seam Study

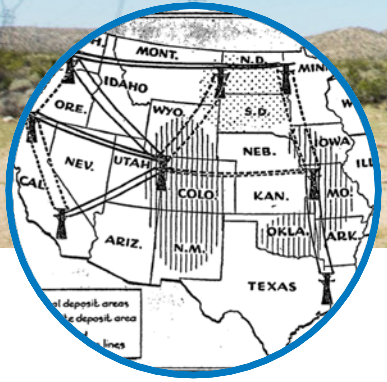
Continental Power Systems

Continental Transmission Studies

Chicago Tribune

1923

Tying the Seasons to Industry



Bureau of Reclamation

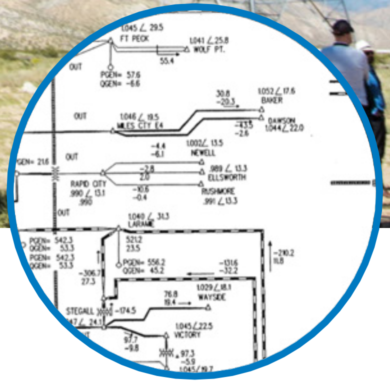
1952

Super Transmission System

Bonneville Power Administration

1979

Interconnection of the Eastern and Western Interconnections



Western Area Power Administration

1994

East/West AC Intertie Feasibility Study

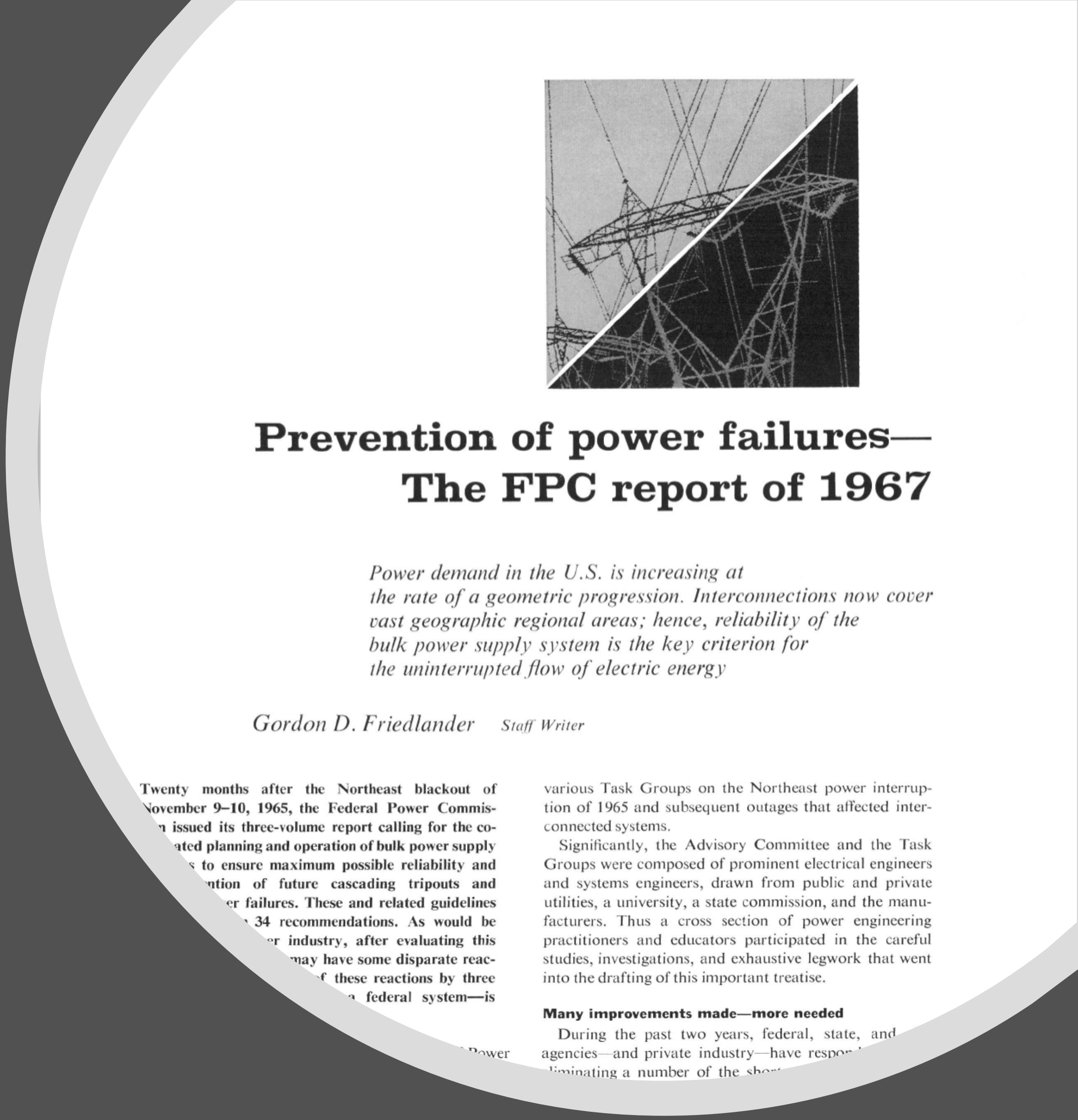
Department of Energy

2002

National Transmission Study

Transmission Principles

- Long distance transmission enables diversity, diversity lowers the cost of maintaining planning reserves.
- Optimal use of generating resources lowers costs for rate payers.
- Lower costs and shared risk make it easier to maintain reliability.



**Prevention of power failures—
The FPC report of 1967**

Power demand in the U.S. is increasing at the rate of a geometric progression. Interconnections now cover vast geographic regional areas; hence, reliability of the bulk power supply system is the key criterion for the uninterrupted flow of electric energy

Gordon D. Friedlander *Staff Writer*

Twenty months after the Northeast blackout of November 9–10, 1965, the Federal Power Commis- issued its three-volume report calling for the co- ated planning and operation of bulk power supply to ensure maximum possible reliability and ntion of future cascading tripouts and er failures. These and related guidelines 34 recommendations. As would be er industry, after evaluating this may have some disparate reac- f these reactions by three federal system—is

various Task Groups on the Northeast power interruption of 1965 and subsequent outages that affected interconnected systems.

Significantly, the Advisory Committee and the Task Groups were composed of prominent electrical engineers and systems engineers, drawn from public and private utilities, a university, a state commission, and the manufacturers. Thus a cross section of power engineering practitioners and educators participated in the careful studies, investigations, and exhaustive legwork that went into the drafting of this important treatise.

Many improvements made—more needed

During the past two years, federal, state, and agencies—and private industry—have respon

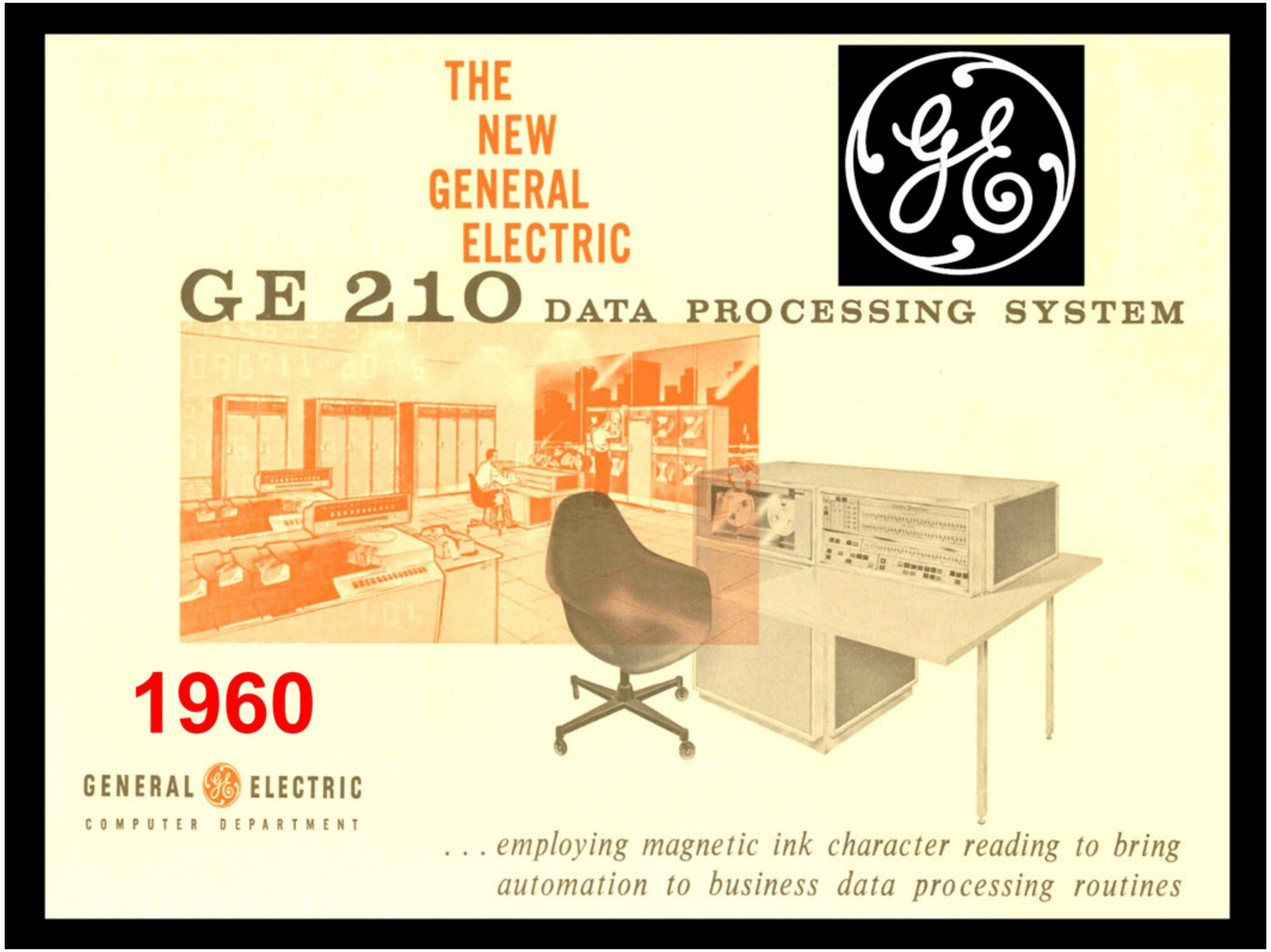
https://ieeexplore.ieee.org/document/5214771/

Great Engineering Schools

"The industry should make young people cognizant of the full challenge of modern power systems engineering. Utilities should work more closely with educational institutions to develop and sponsor appropriate research..." FPC, 1967

Early Computer Models

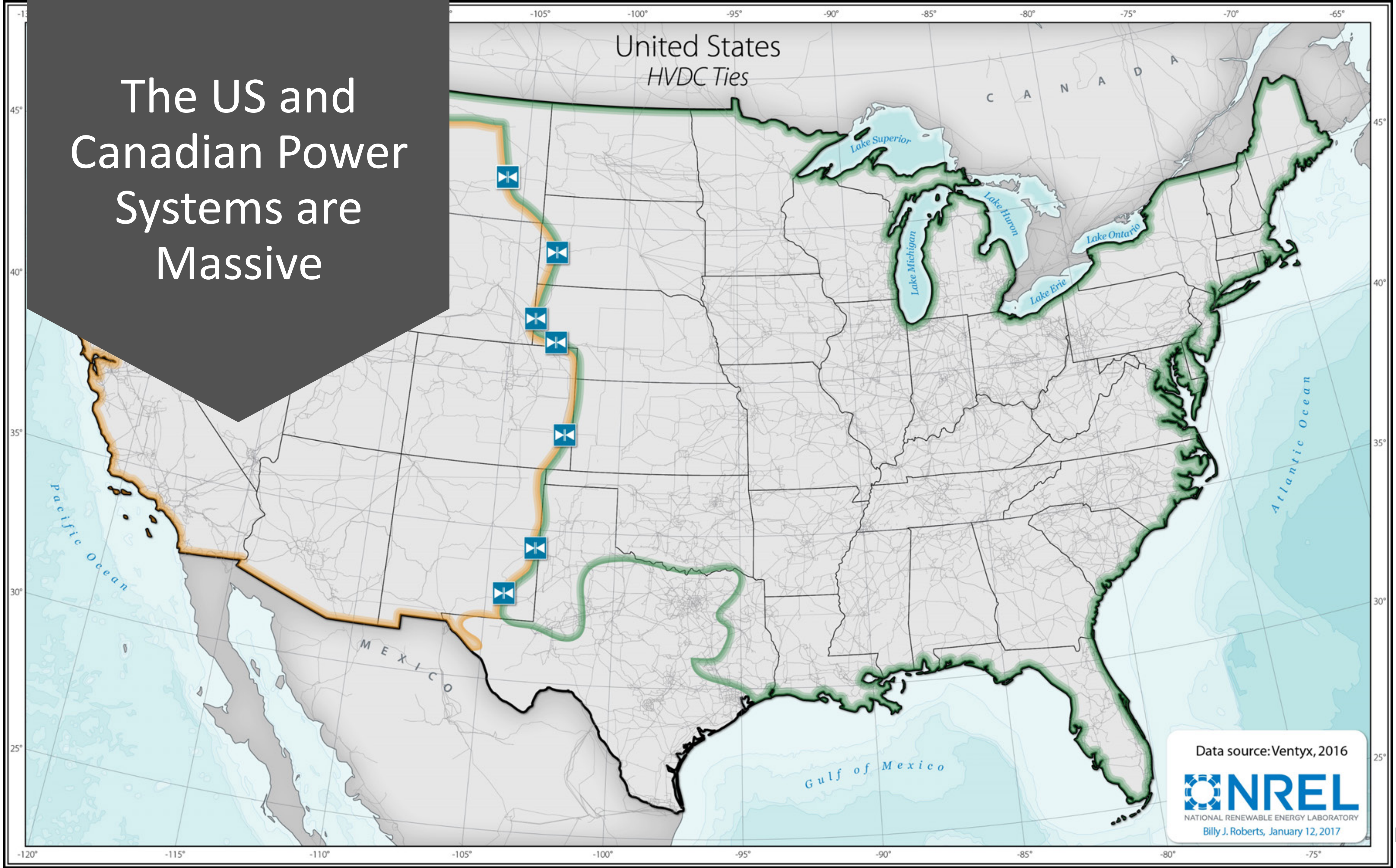
"Digital computers and sophisticated computer programs now make practicable the study of large interconnections, and permit extensive analyses that were impossible only a few years ago." FPC, 1967



Regional Coordination

"Strong regional organizations should be established for the coordination of planning, construction, operation, and maintenance of individual bulk power supply systems." FPC, 1967

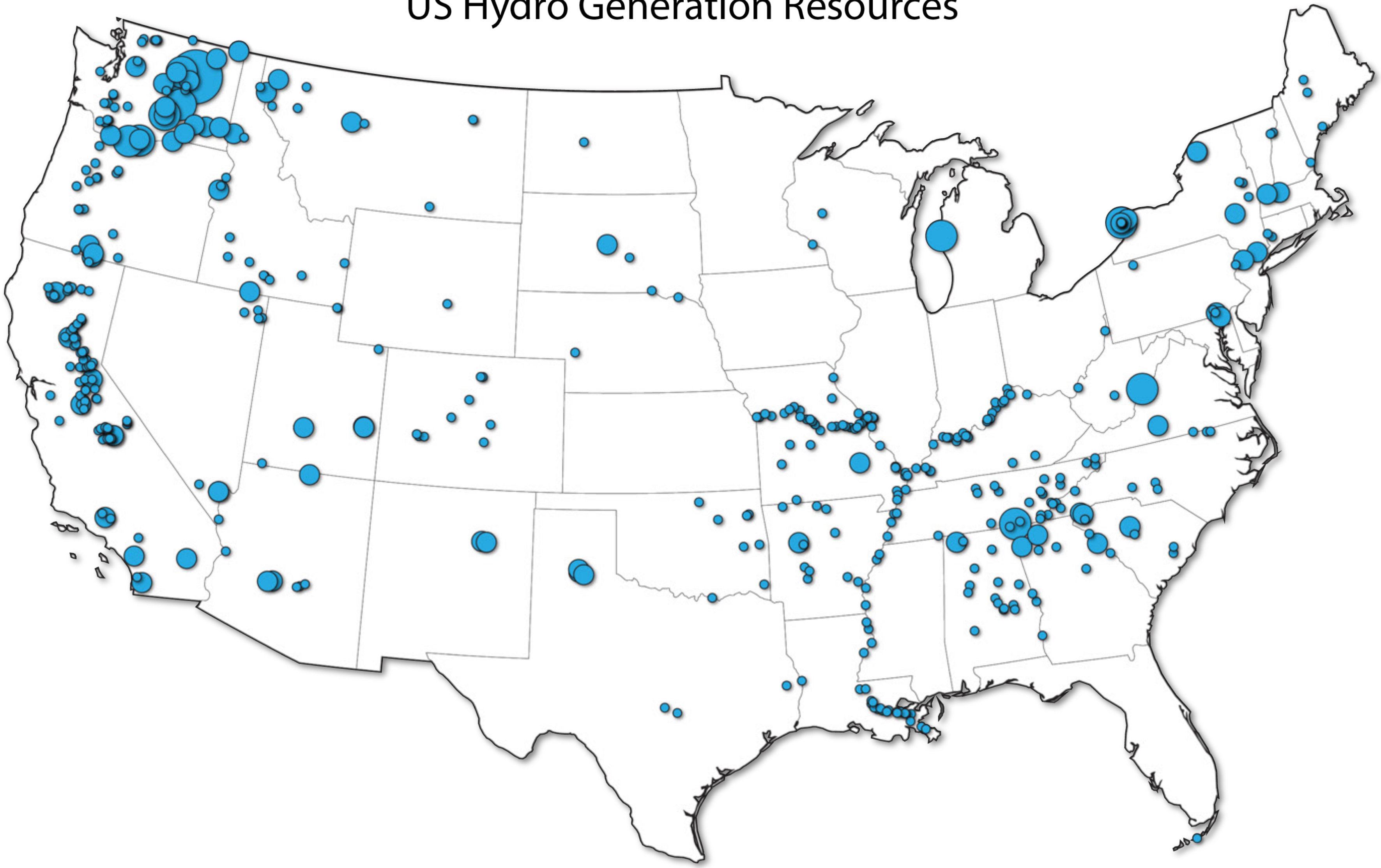
The US and Canadian Power Systems are Massive



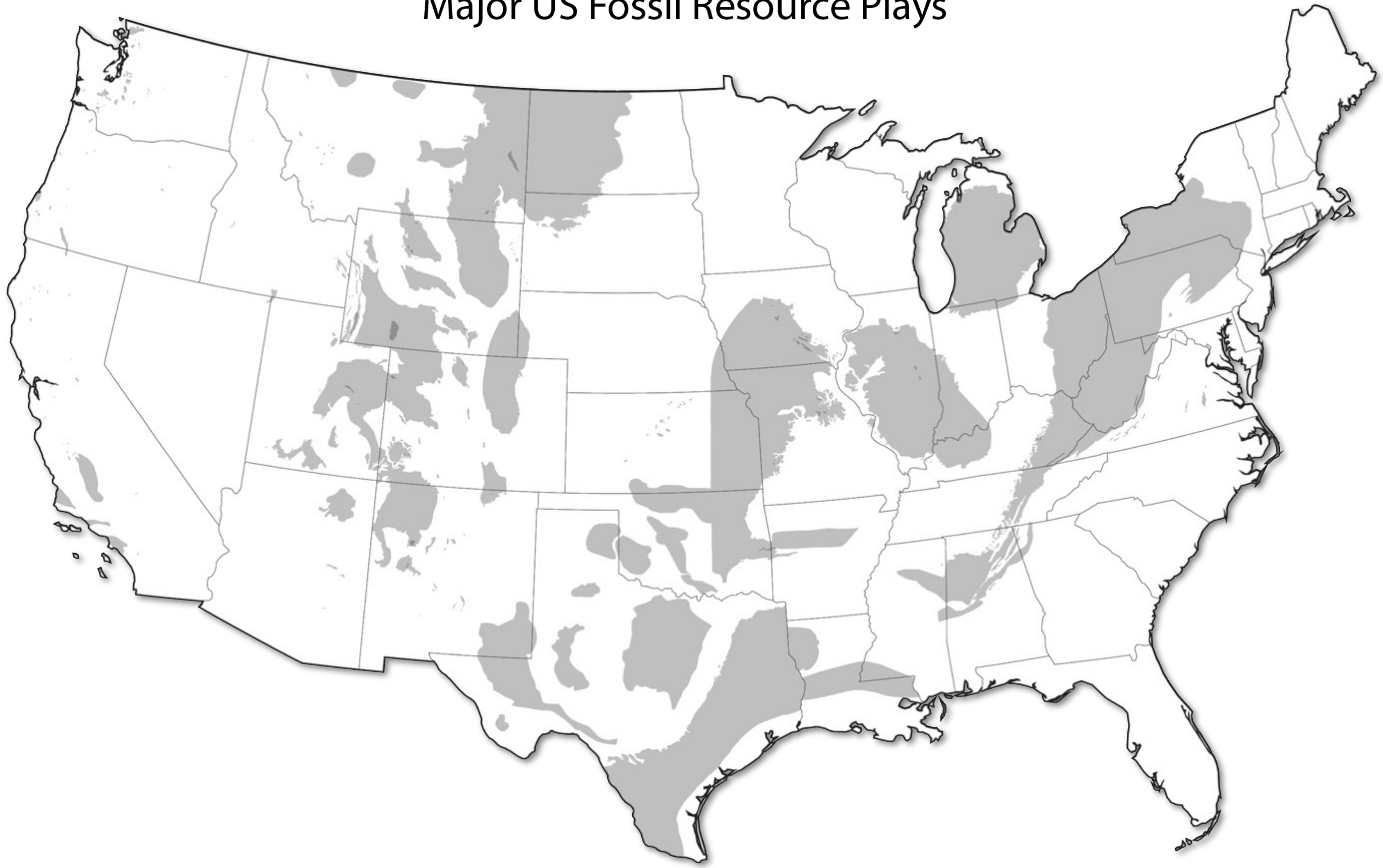
If the value looked that good back then

What about today?

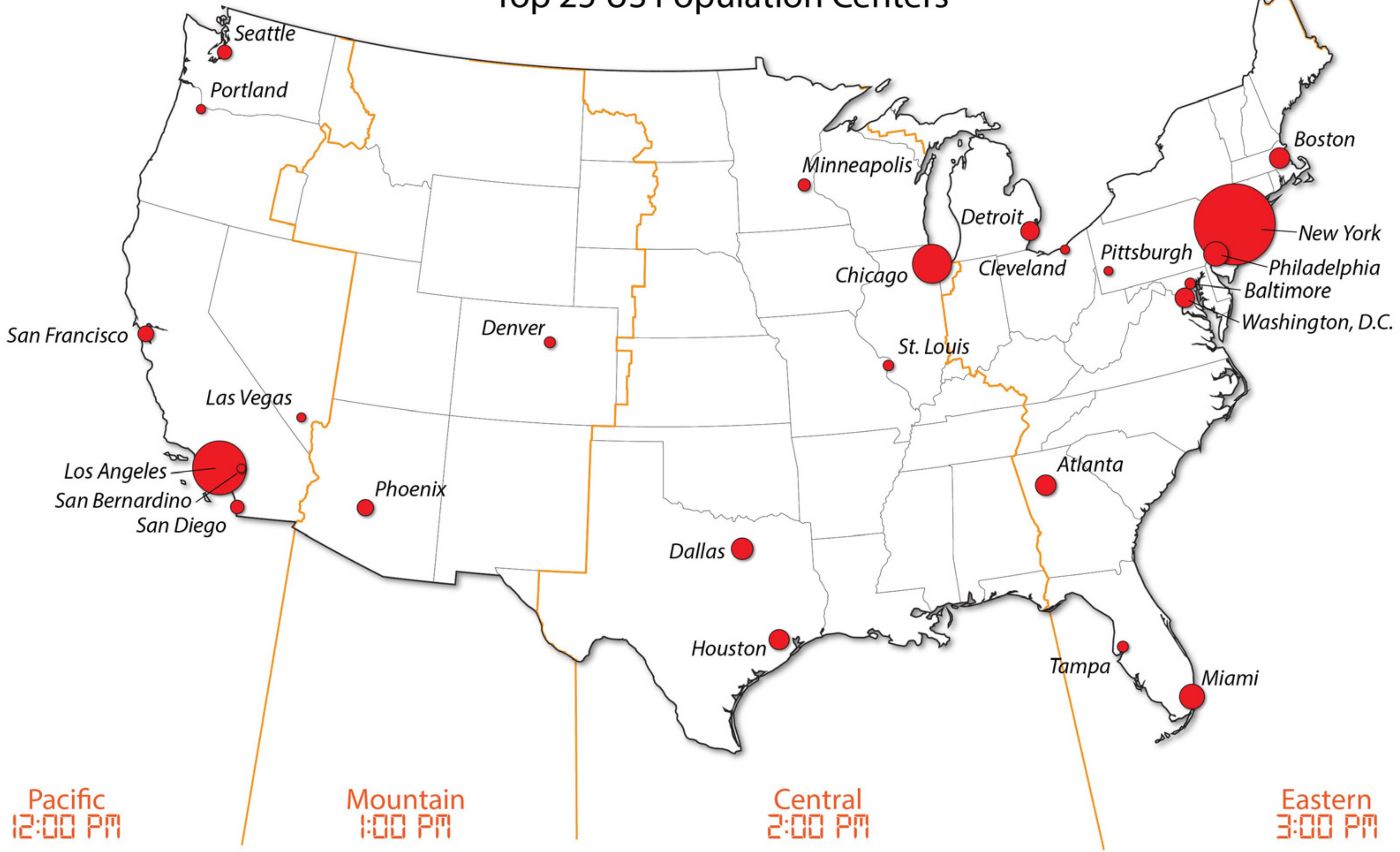
US Hydro Generation Resources



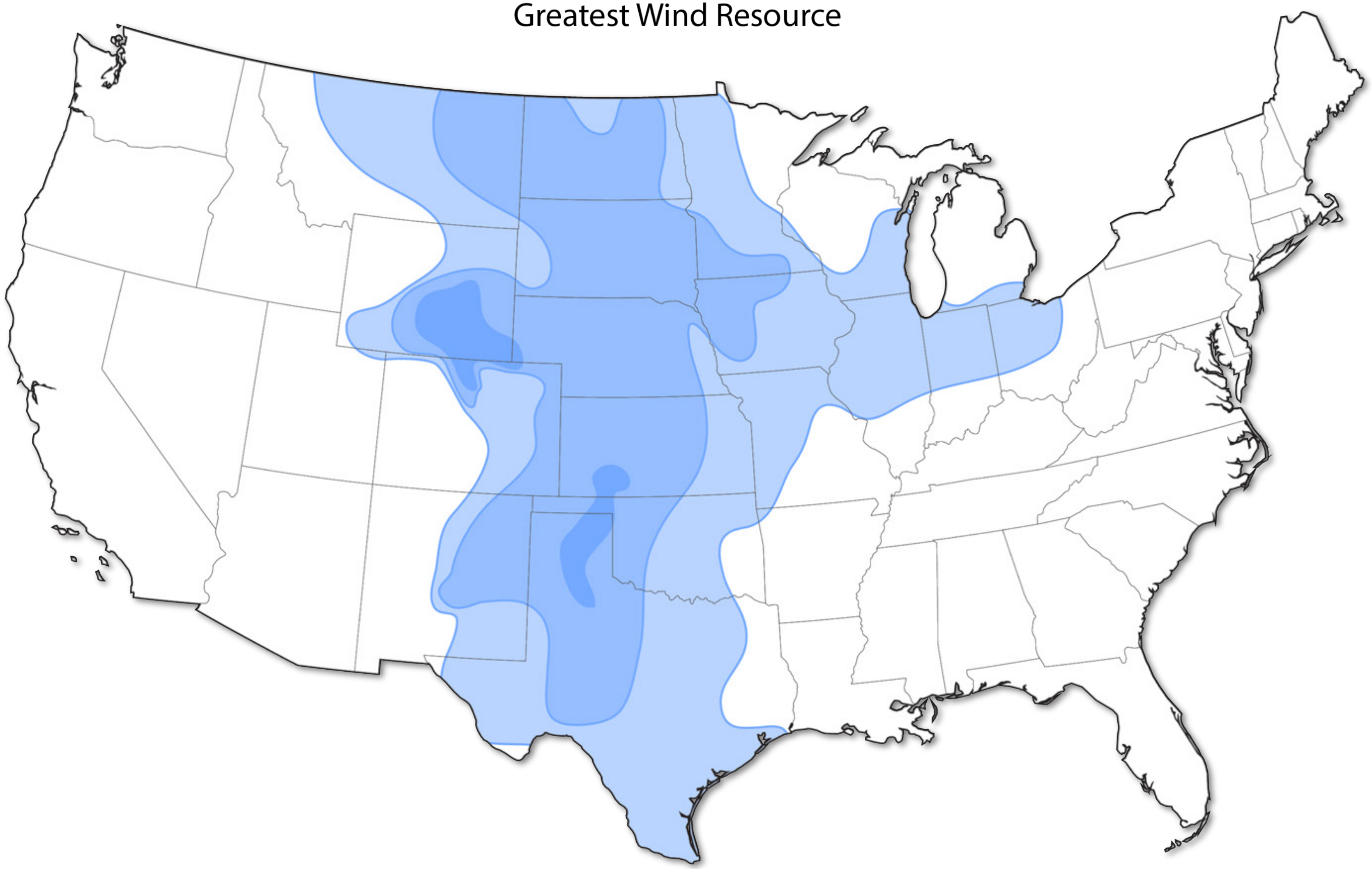
Major US Fossil Resource Plays



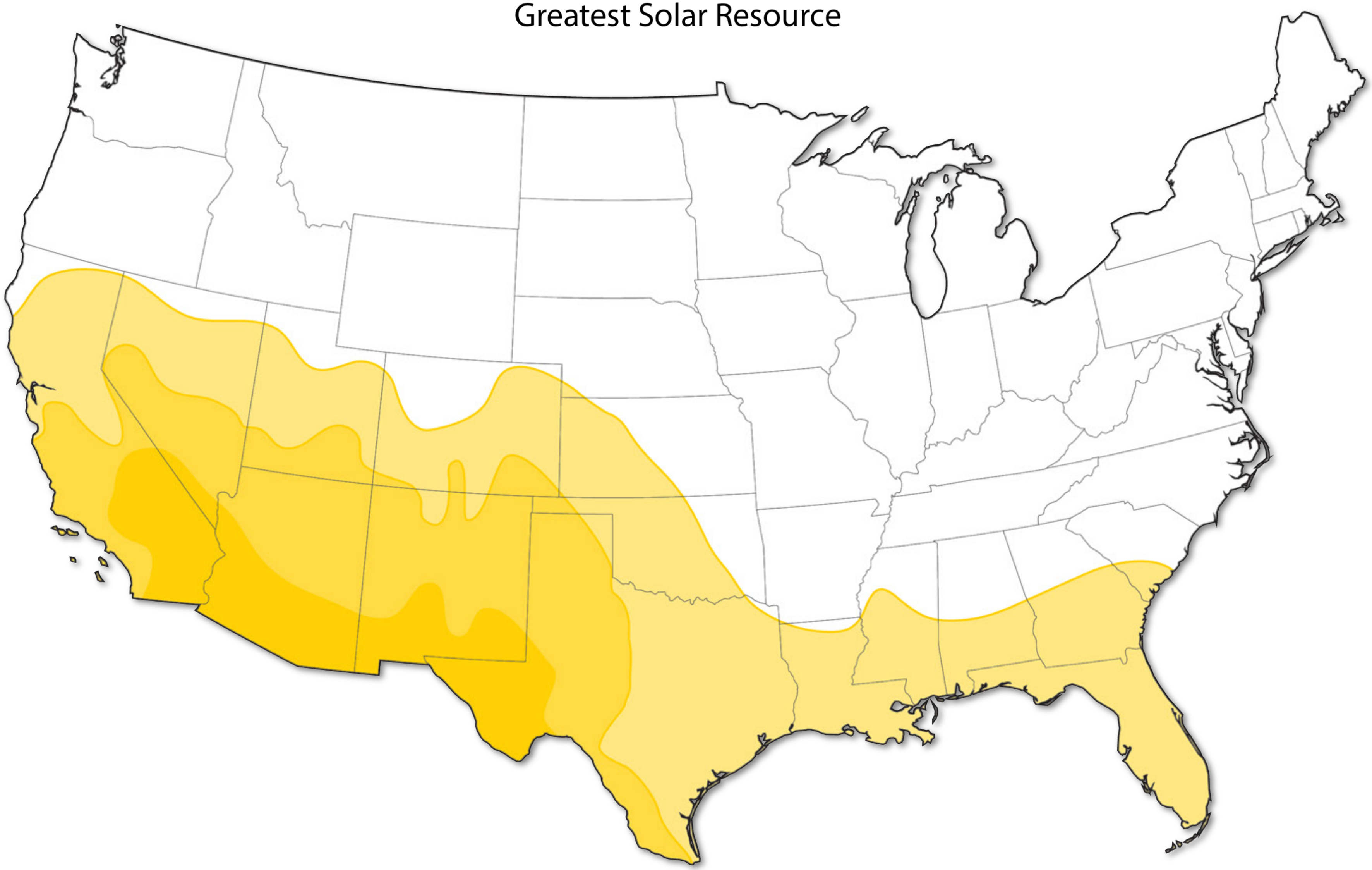
Top 25 US Population Centers

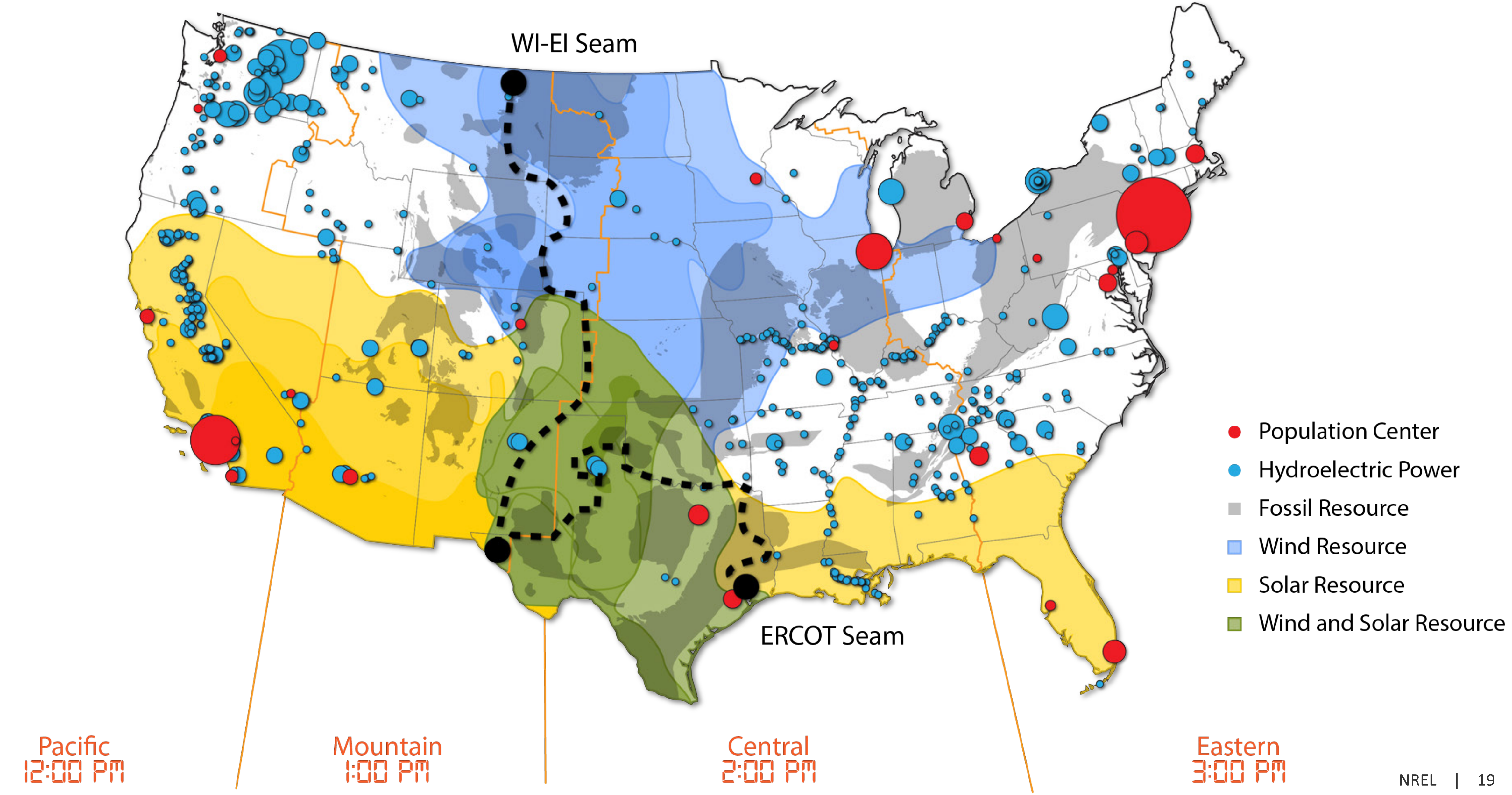


Greatest Wind Resource



Greatest Solar Resource

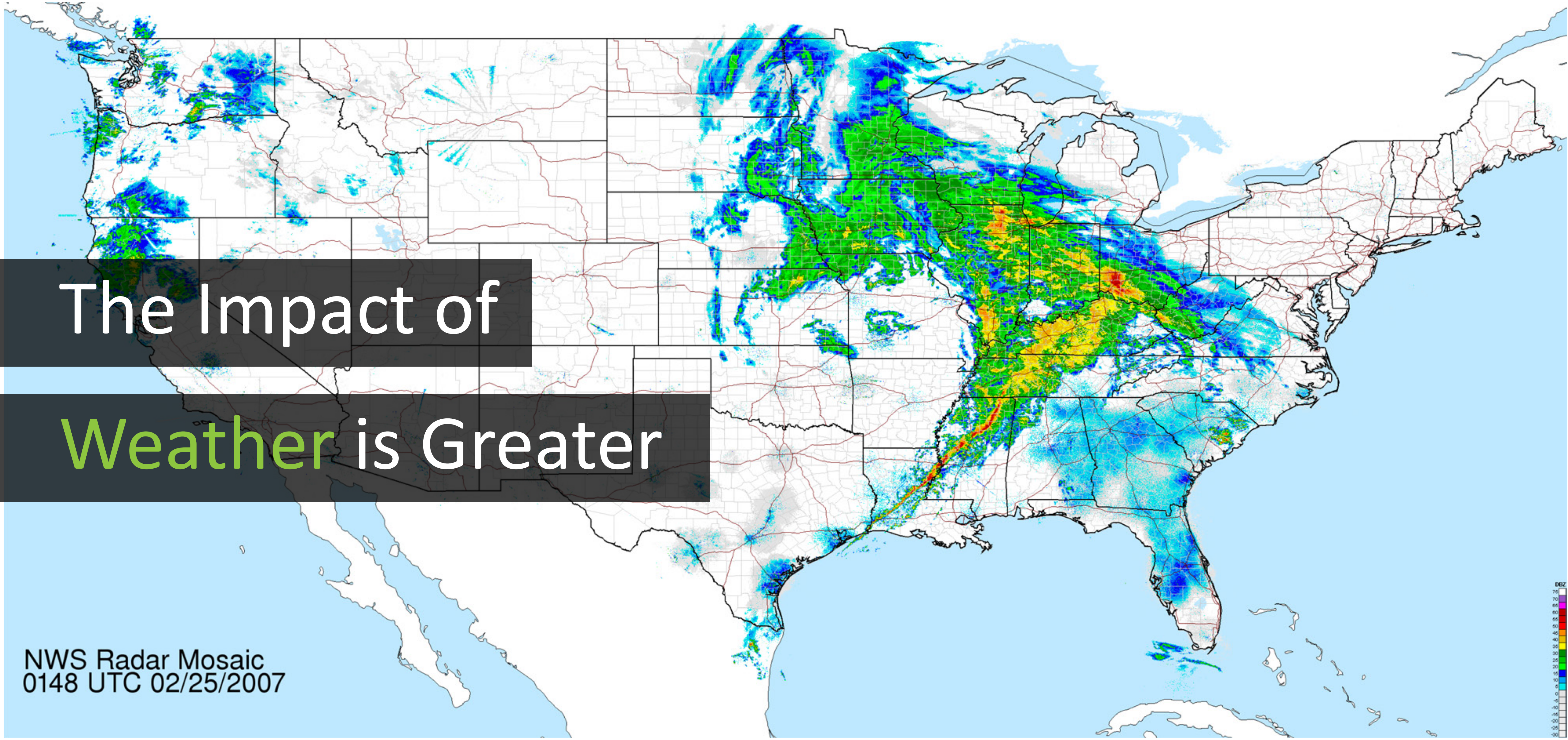



WI-EI Seam
ERCOT Seam
Population Center
Hydroelectric Power
Fossil Resource
Wind Resource
Solar Resource
Wind and Solar Resource
Pacific
12:00 PM
Mountain
1:00 PM
Central
2:00 PM
Eastern
3:00 PM

It's Different

This Time

The Impact of Weather is Greater



Daily patterns drive demand and supply

https://www.youtube.com/watch?v=hVymyJ9q5a0

Energy Needs and Supply Change with the Seasons

https://svs.gsfc.nasa.gov/4452

Unimaginable Computation

- Parallel computing environments, complex algorithms, and artificial intelligence offer new capabilities.
- 100,000 node transmission models can be simulated for an entire year, in a single day.
- The dawn of Exa-scale computing

New Technologies

Wind

The single largest source of renewable energy capacity in the US

Solar PV

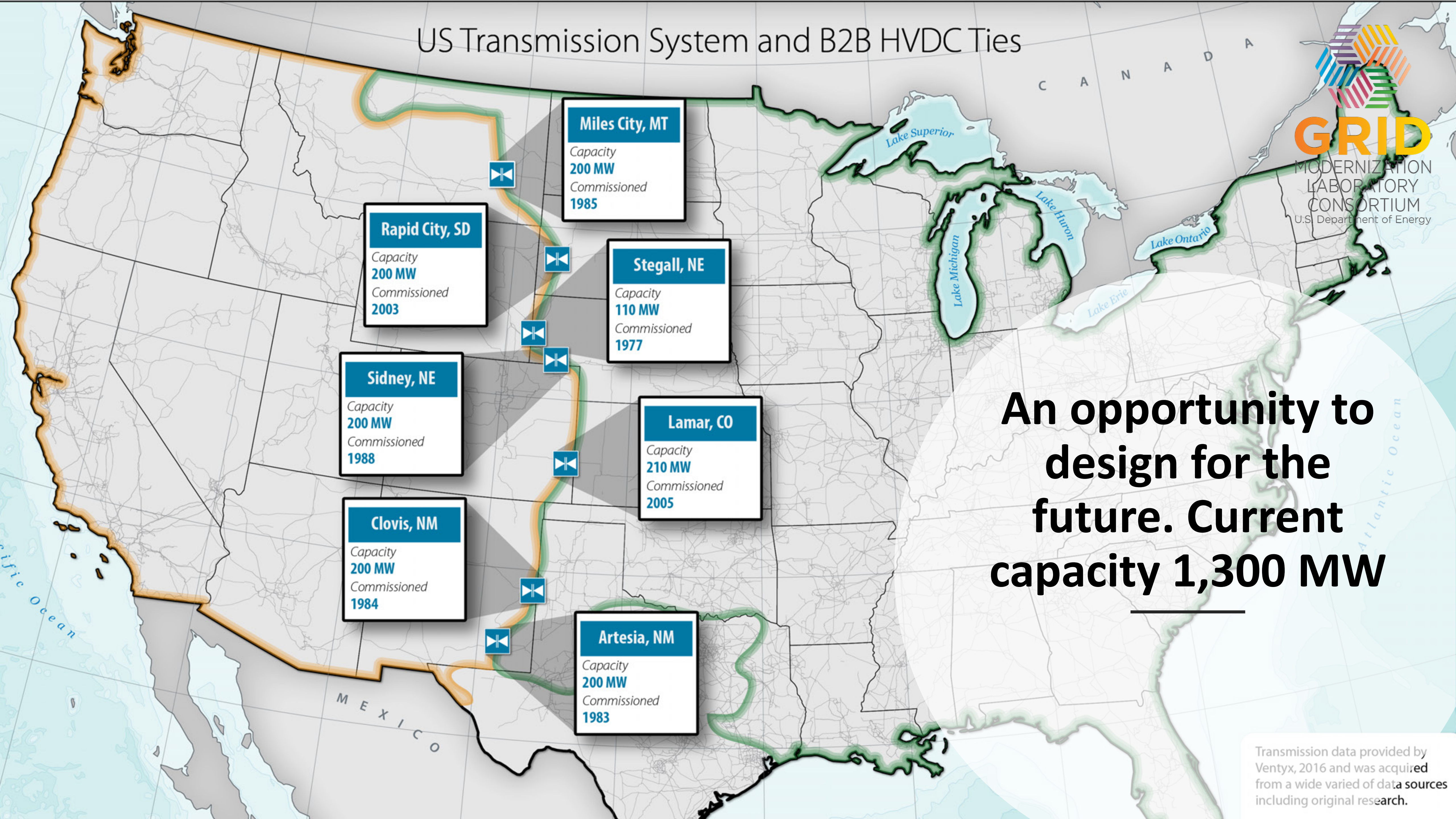
The fastest growing renewable energy resource

HVDC

Controllable, directional, electricity transmission, with large scale deployment worldwide

HVAC

The backbone of existing American Transmission



An opportunity to design for the future. Current capacity 1,300 MW

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

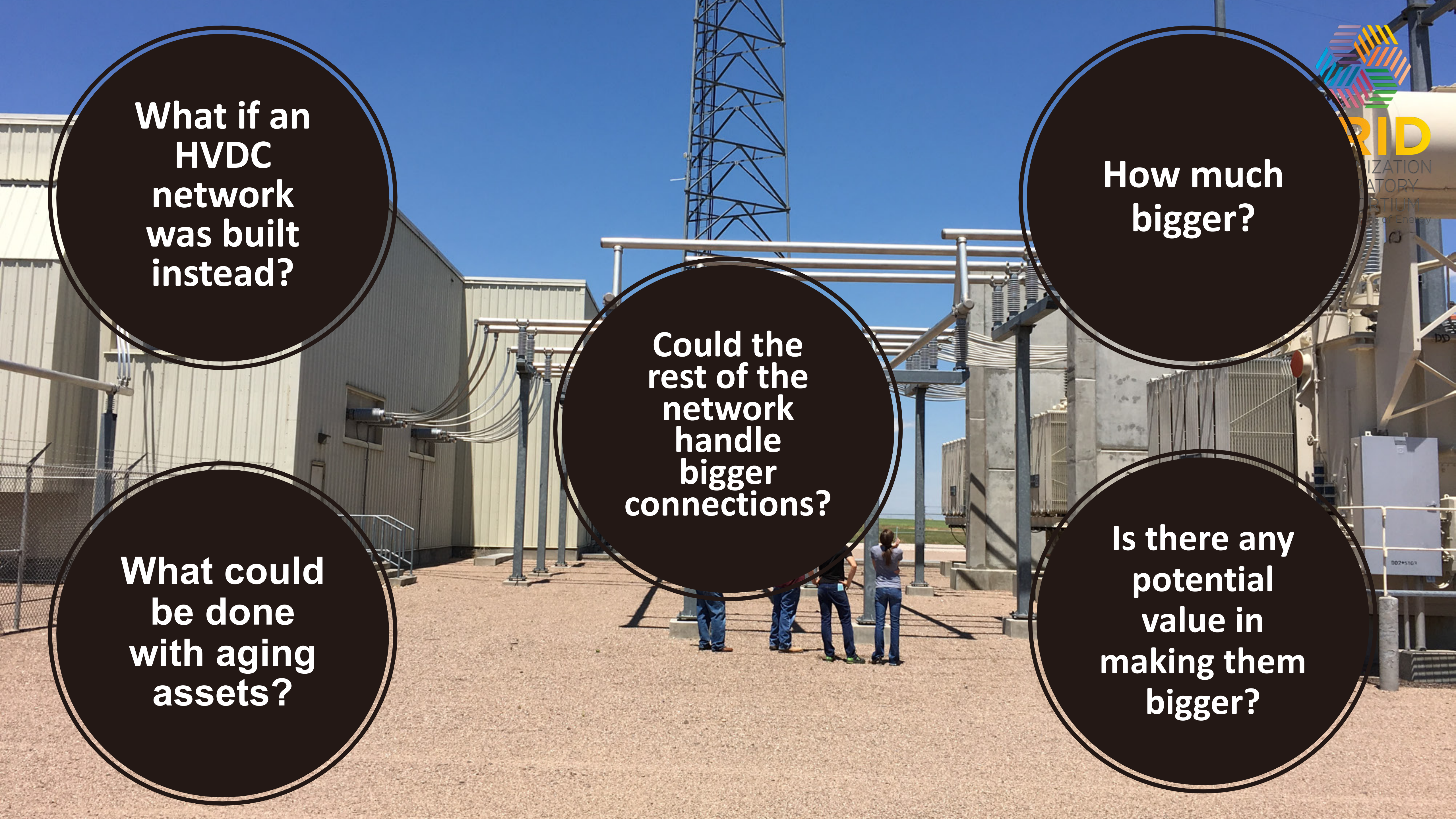

What could be done with aging assets?

What could be done with aging assets?

Is there any potential value in making them bigger?


How much bigger?
What could be done with aging assets?
Is there any potential value in making them bigger?


What if an HVDC network was built instead?
How much bigger?
What could be done with aging assets?
Is there any potential value in making them bigger?

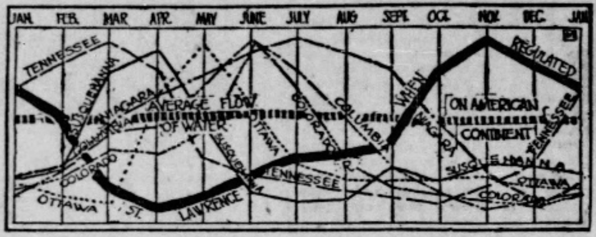

What if an HVDC network was built instead?
How much bigger?
Could the rest of the network handle bigger connections?
What could be done with aging assets?
Is there any potential value in making them bigger?


Top 5 Quotes from 95 years of
National Transmission Planning

TRIBUNE OFFERS HYDRO-ELECTRIC SYSTEM FOR U. S.

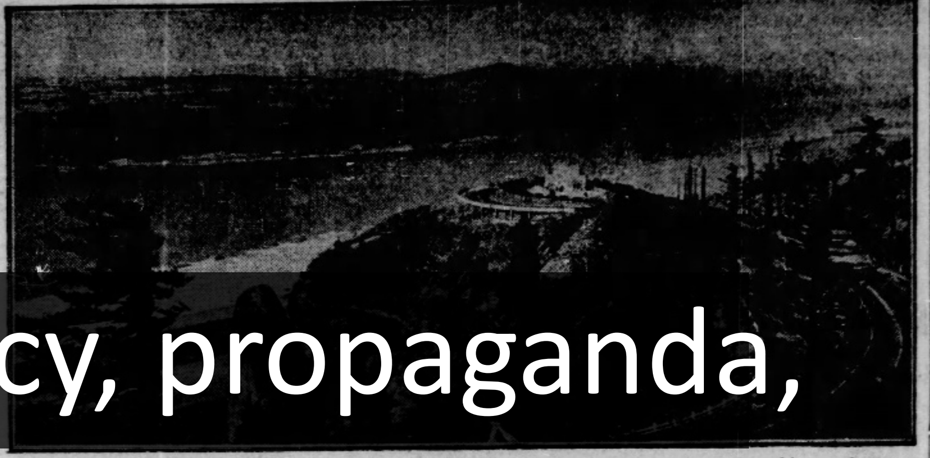
Would Hitch Seasons to All Industries.

Making Rivers Work Together



This chart shows how flood waters in different water sheds occur in different months. The artist has drawn a line showing the St. Lawrence river under artificial regulation.

ONE OF THE POWER RESERVOIRS



Among the great American rivers which it is proposed to harness to produce the white coal to run industrial enterprises and to light cities is the Columbia. This picture was taken at one of the famous scenic points along the Columbian highway during the visit of the late President Harding to the northwest.

PACIFIC STATES PLAN FIGHT ON PITTSBURGH PLUS

"This is neither prophecy, propaganda, nor rhapsody, but **the assured goal** of the scientific and economic forces at work."

Chicago Tribune, 1923

COAL MAY PROVIDE POWER FOR WEST

Reclamation Bureau Pictures Super Transmission System Operated by Steam Plants

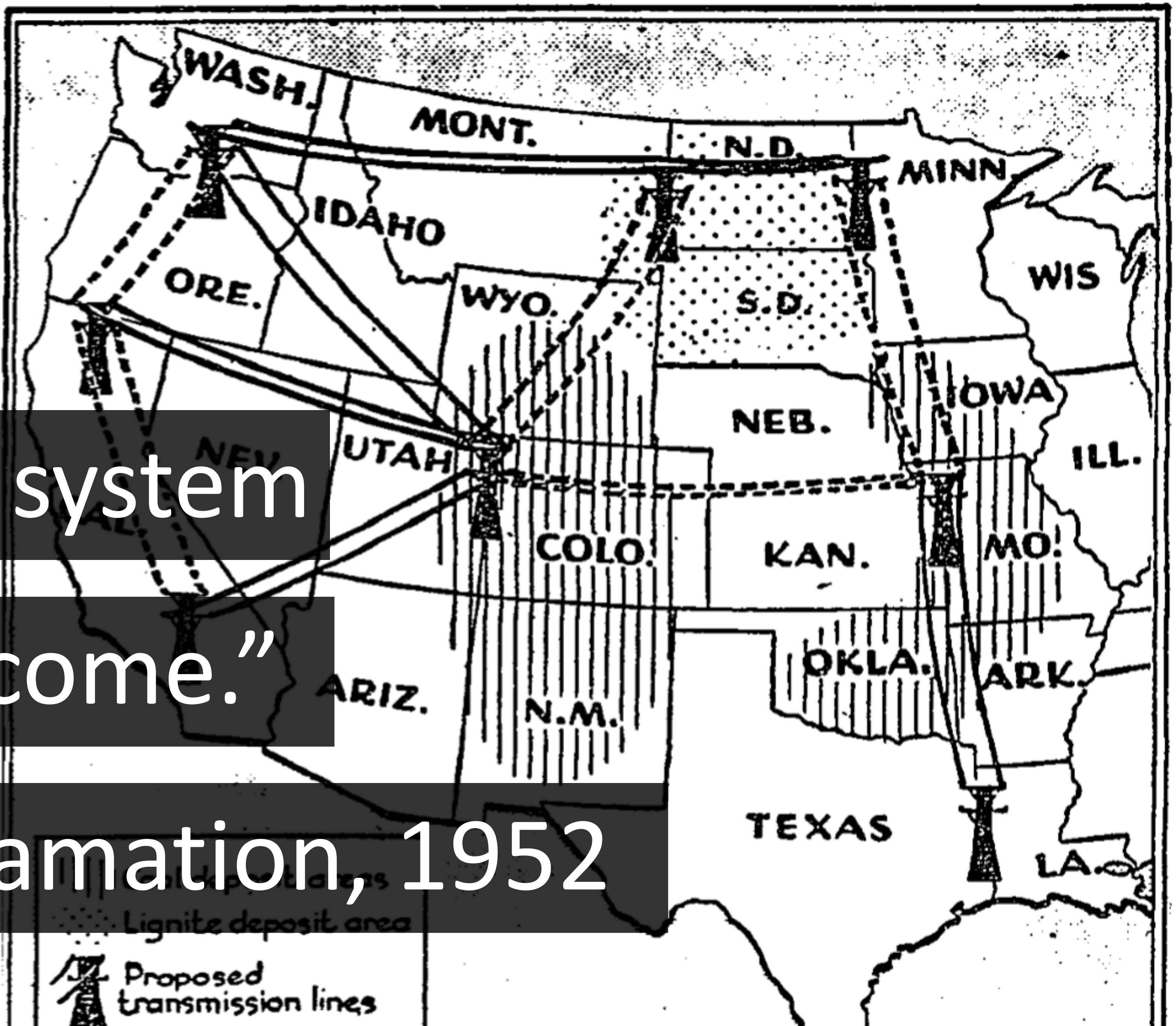
The Reclamation Bureau today pictured the West's future power needs being supplied in large part

long distance transmission system. More than half now is supplied by hydroelectric plants.

The bureau made public a study

Minnesota and Louisiana to the west, and proposing long range planning to fill them.

Michael W. Straus, Reclamation



"Such a power system will *inevitably* come."

Bureau of Reclamation, 1952

“The results to date indicate that if there are substantial benefits to east-west reclosure…”

Bonneville Power Administration, 1979

UNITED STATES GOVERNMENT

Memorandum

UNITED STATES DEPARTMENT OF THE INTERIOR
BPA
BONNEVILLE POWER ADMINISTRATION

DATE : JUL 6 1979

In reply refer to : EOGB

TO : Branch of System Engineering - EO

FROM : R. L. Cresap

SUBJECT: Report -- Interconnection of Eastern and Western North American Power Systems in the Early 1980's

Attached is a report pertaining to reclosure of interconnections between the eastern and western North American power systems. Although automatic generation control performance is briefly discussed, the study basically is limited to transient stability performance with 500 MW power transfer across the ties (both east to west and west to east).

WESTERN

AREA POWER ADMINISTRATION

“The systems as they exist today…

are more robust than…

the late 1960s and 1970s”

WAPA, 1994

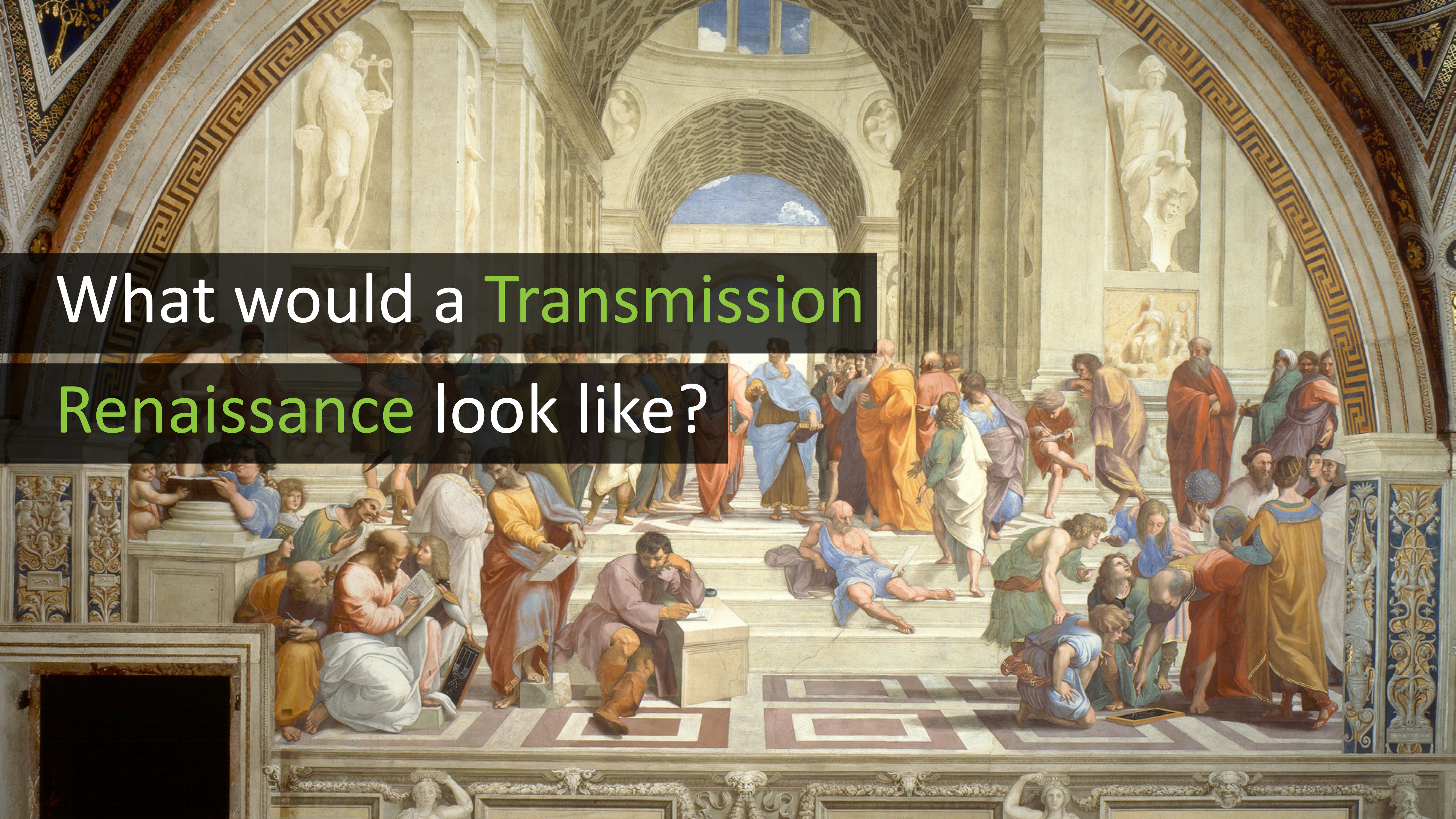
EAST/WEST AC INTERTIE

FEASIBILITY STUDY

Discussion Time

1) What is the biggest opportunity today?
2) What challenges do you see to continental planning?
3) What was the biggest obstacle to these visions?

What would a Transmission Renaissance look like?



Partners are Everything

SPP Southwest Power Pool

MISO

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Western Area Power Administration

IOWA STATE UNIVERSITY

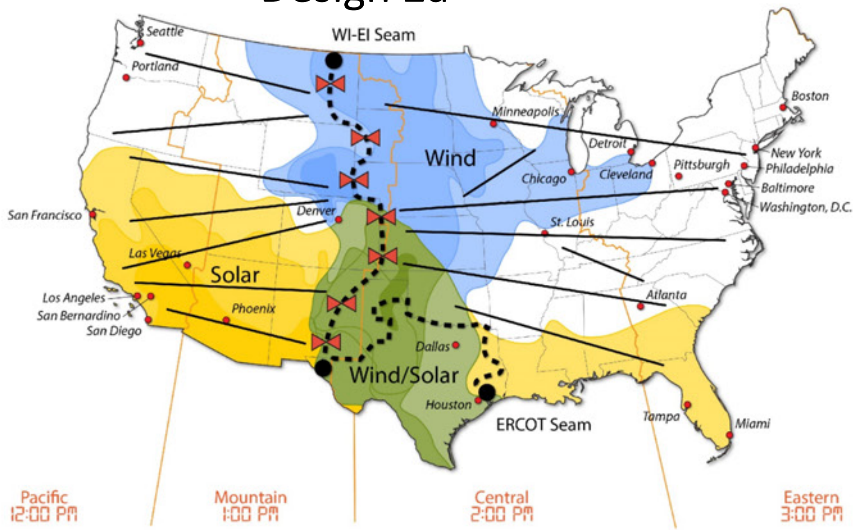
Pacific Northwest NATIONAL LABORATORY

Technical Review Committee

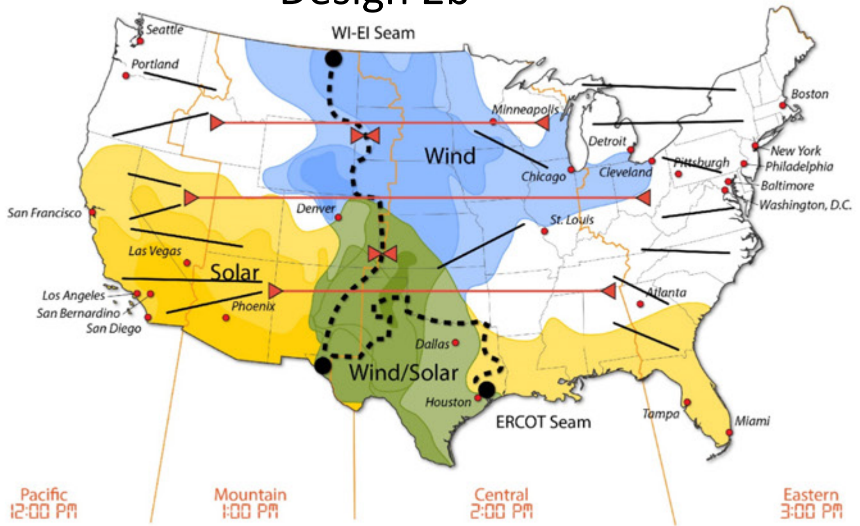
Design Concepts

Design 1

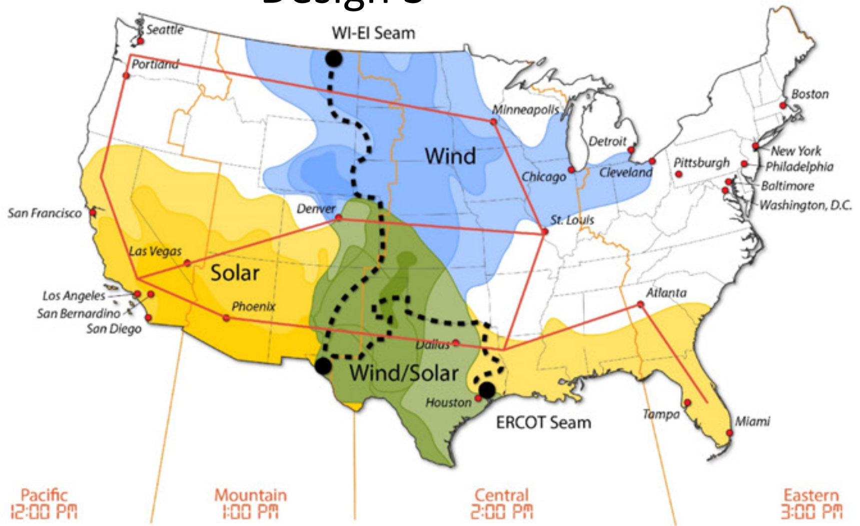
Design 2a

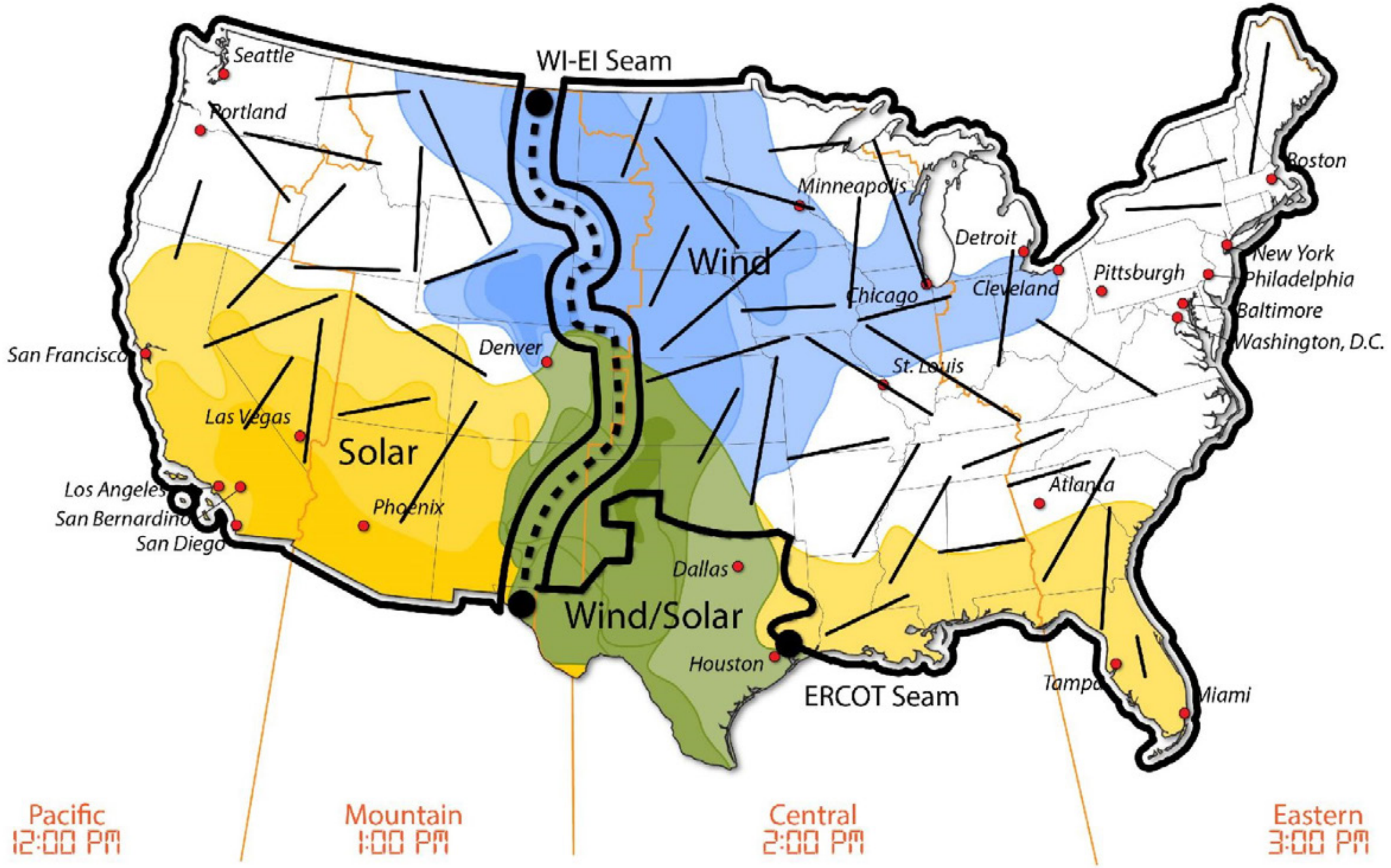


Design 2b



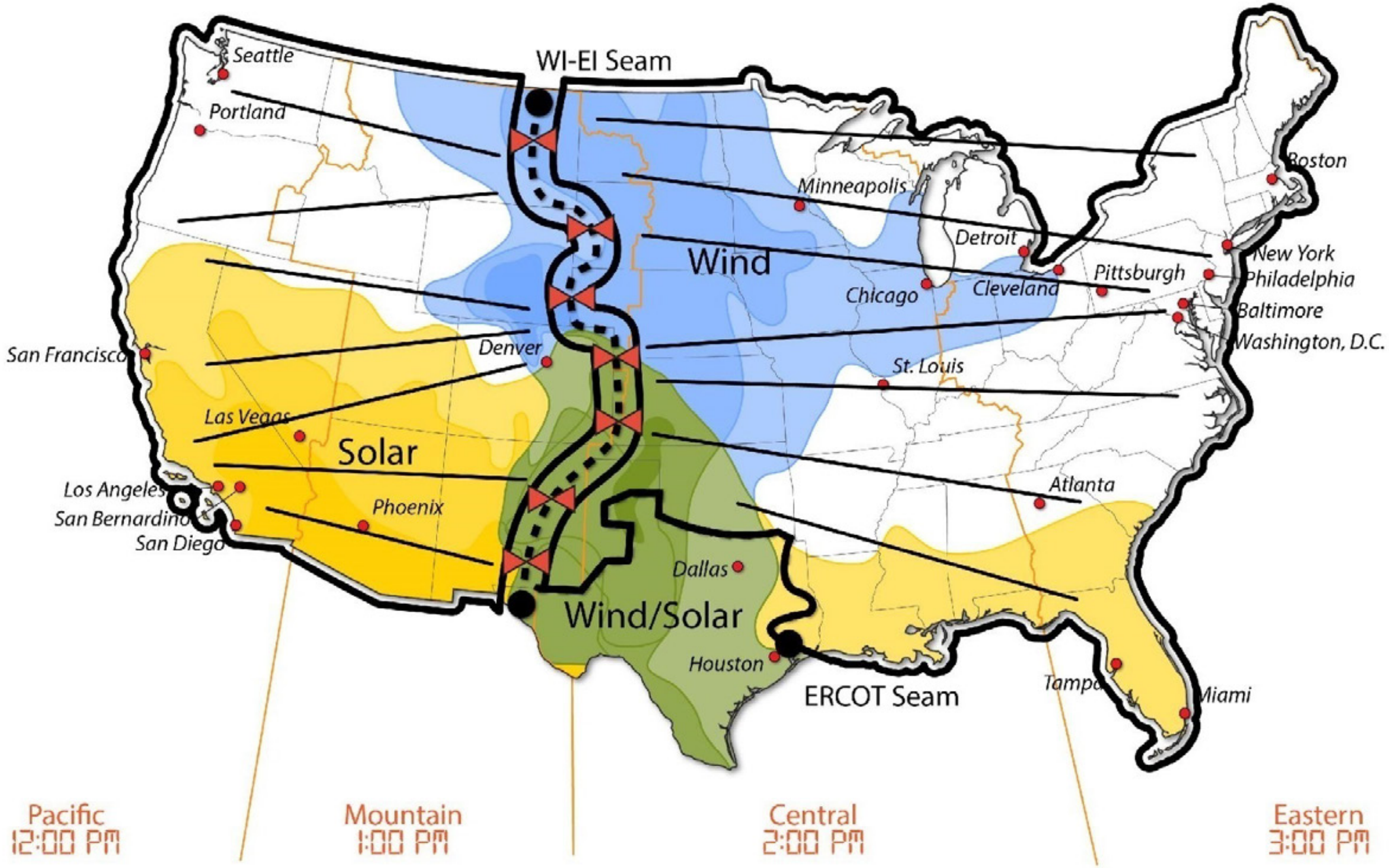
Design 3





Design 1

Existing B2B facilities are replaced at their current (2017) capacity level and new AC transmission and generation are co-optimized to minimize system wide costs.

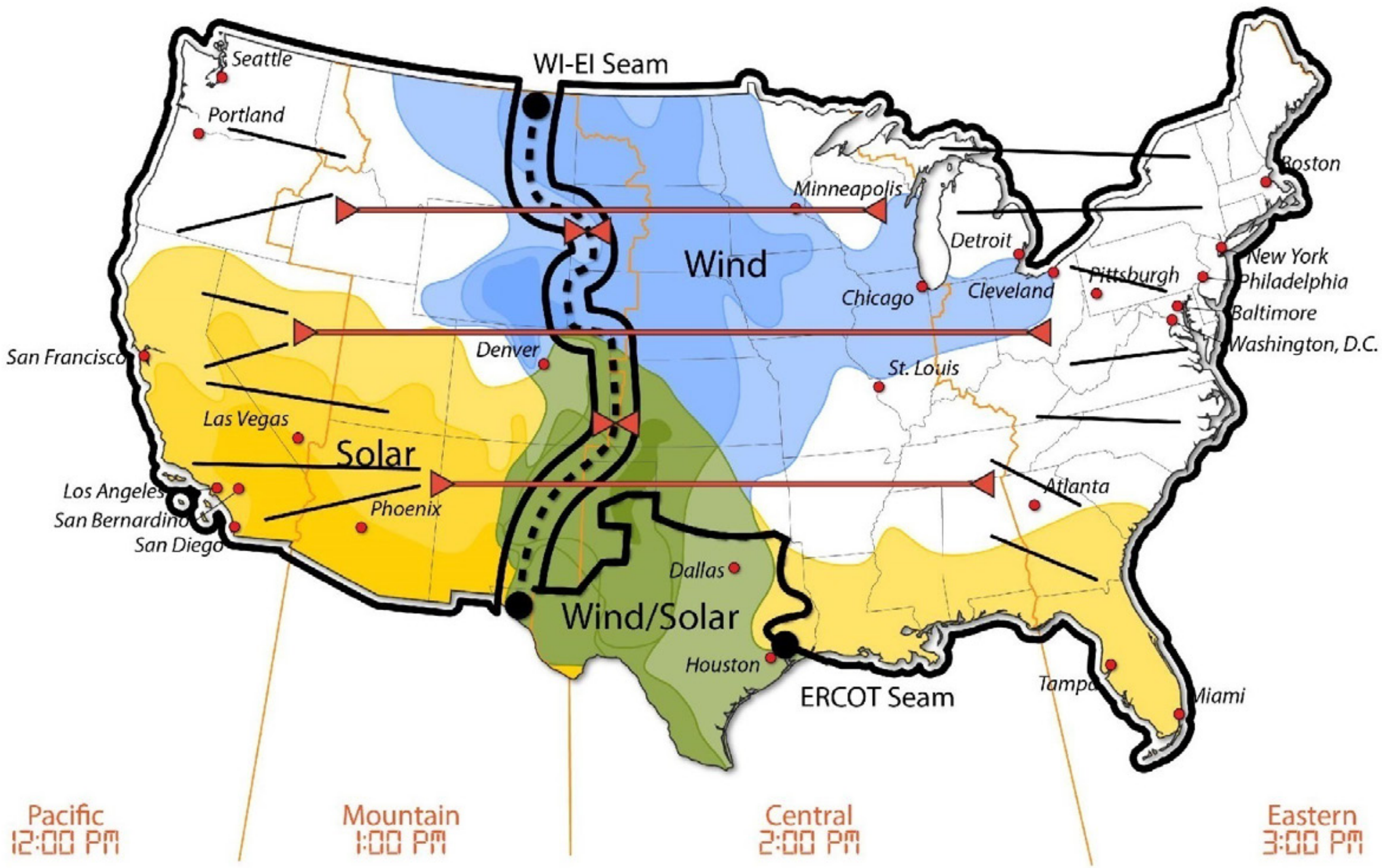


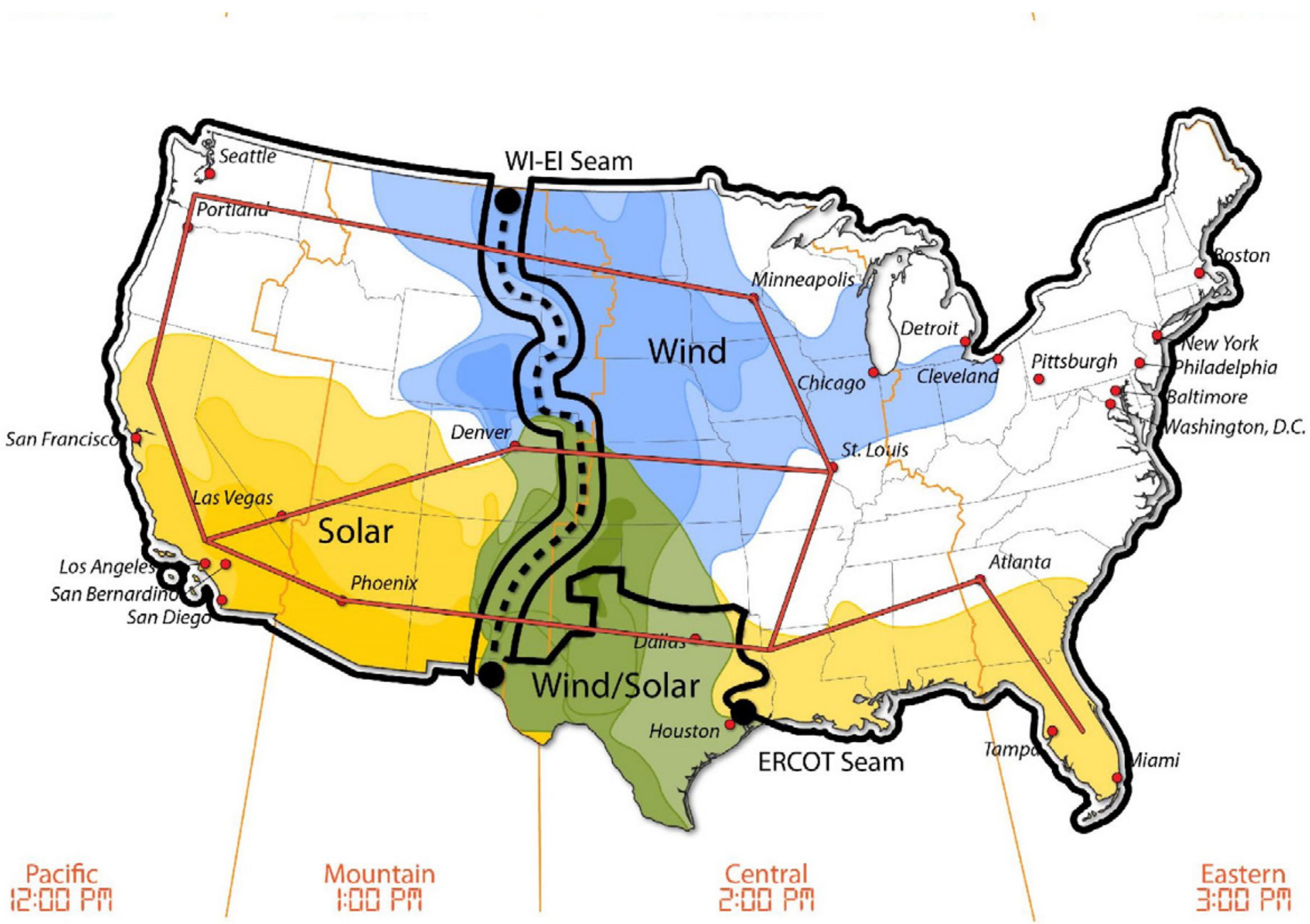
Design 2a

Existing B2B facilities are replaced at a capacity rating that is co-optimized along with other investments in AC transmission and generation.

Design 2b

Three HVDC transmission segments are built between the Eastern and Western Interconnections and existing B2B facilities are co-optimized with other investments in AC transmission and generation.





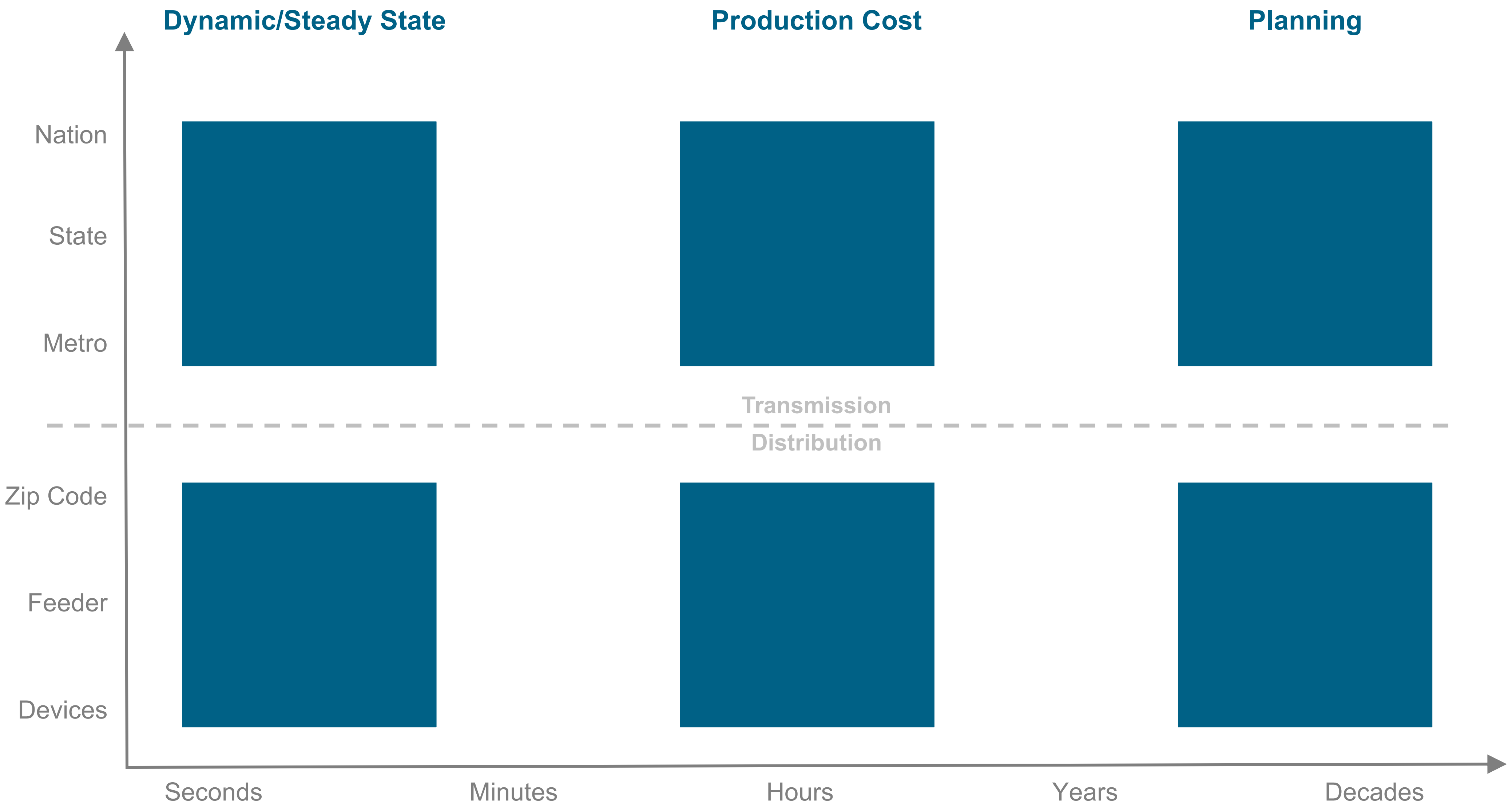
Design 3

A national scale HVDC transmission network, Macro Grid, is built and other investments in AC transmission and generation.

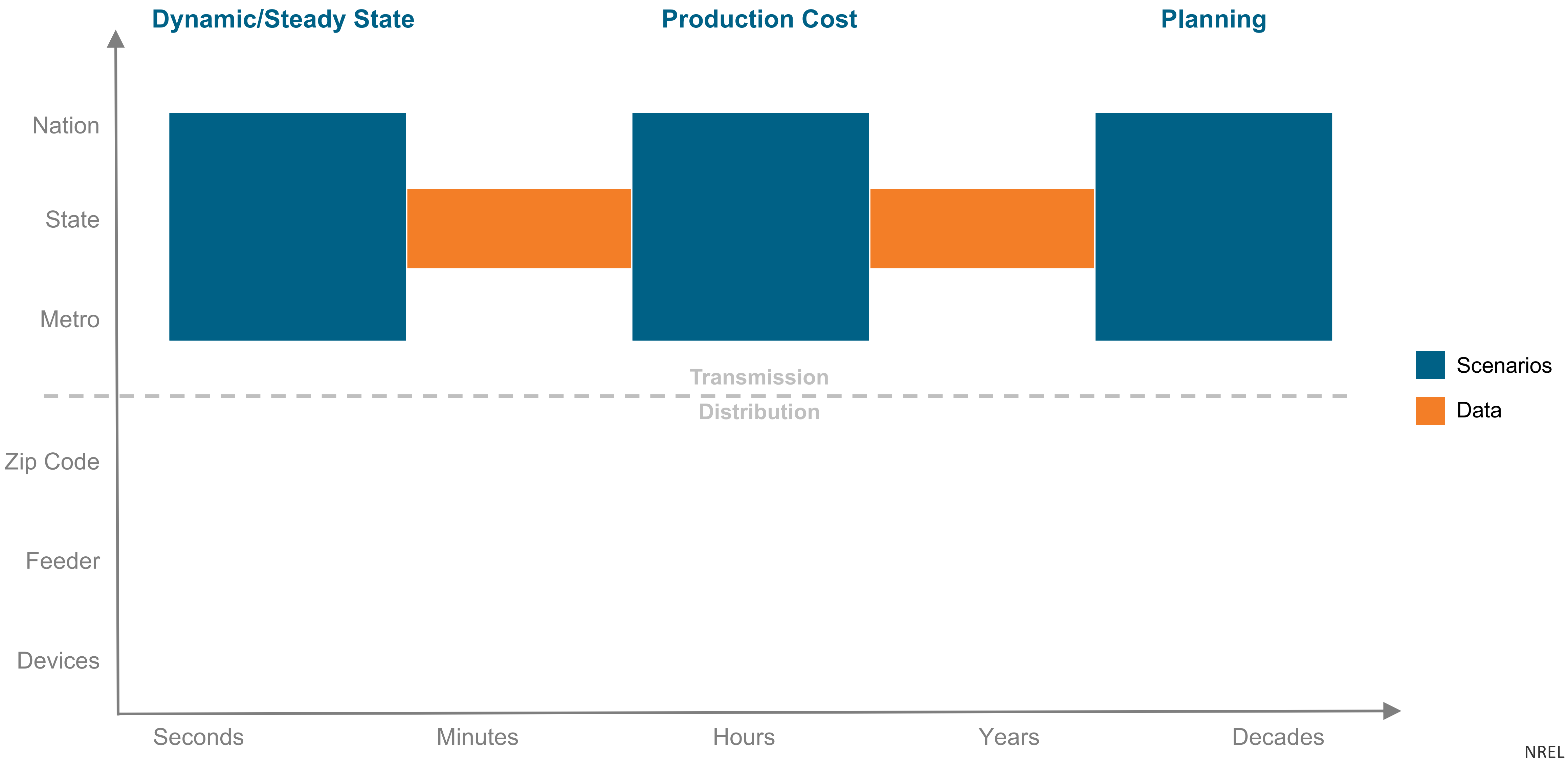
Here is our Research Methodology

Spatial and Temporal Scales of Reliability

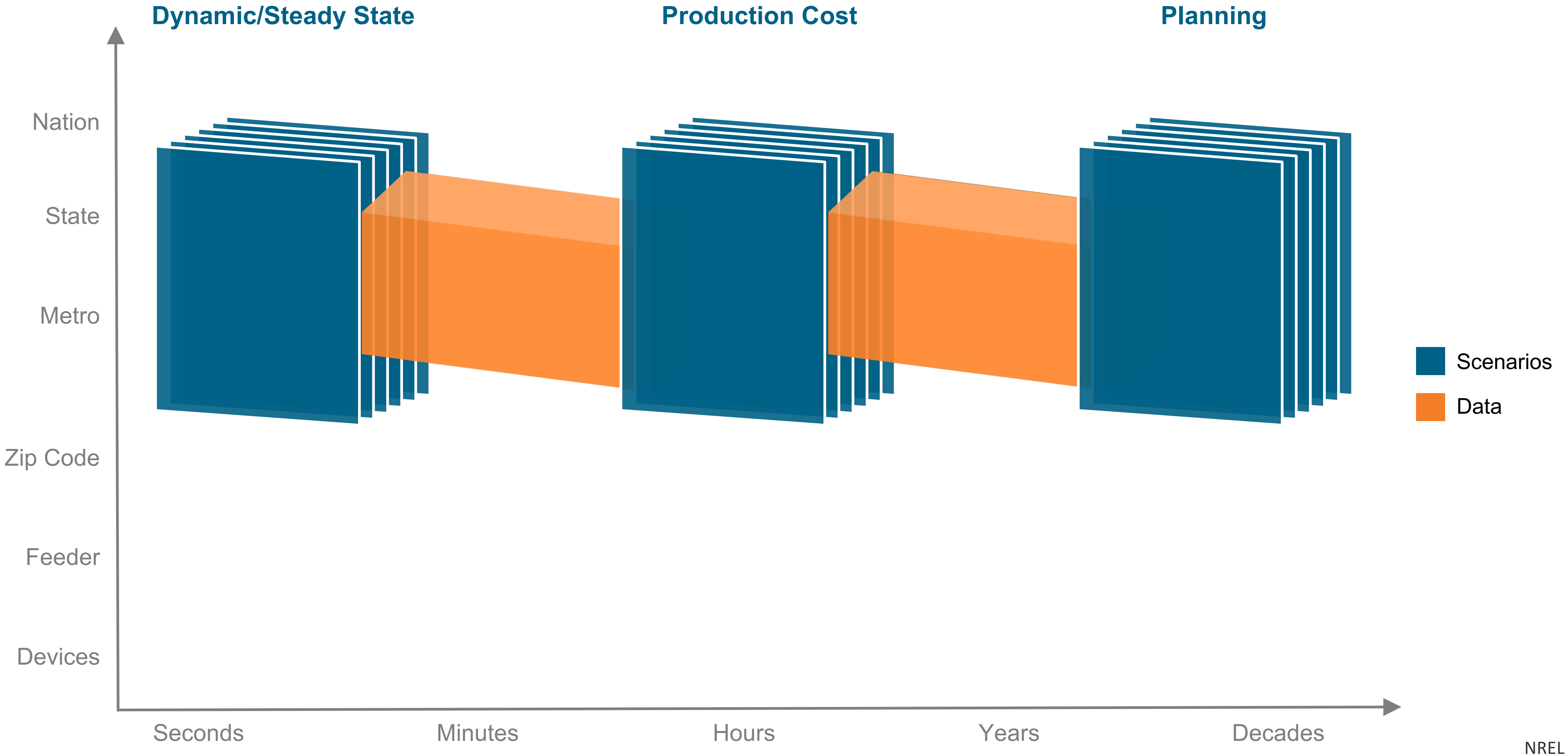
Scale Separation Problems and Solutions



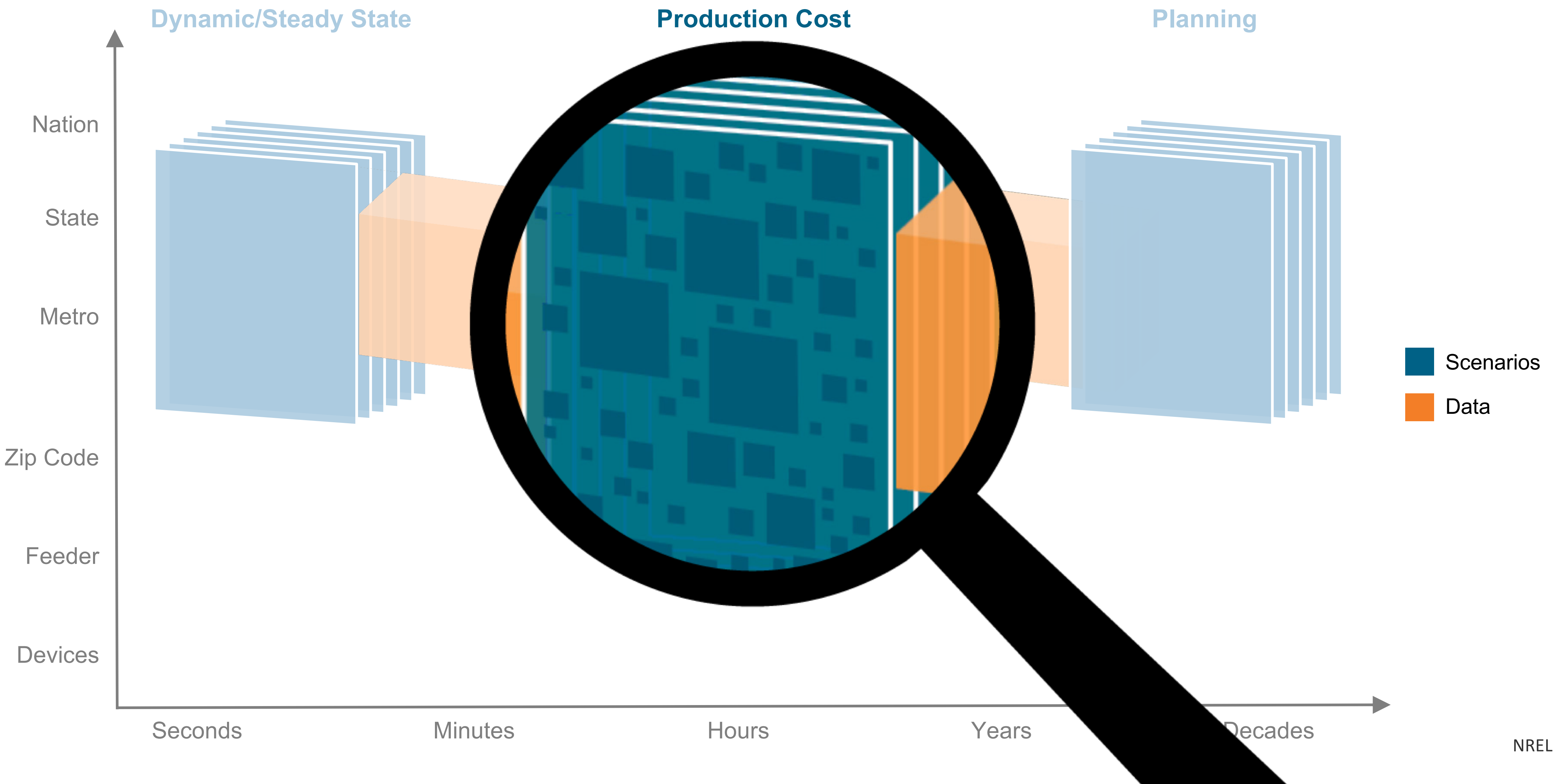
Bulk Power Focus



Scenarios, Data, Uncertainty

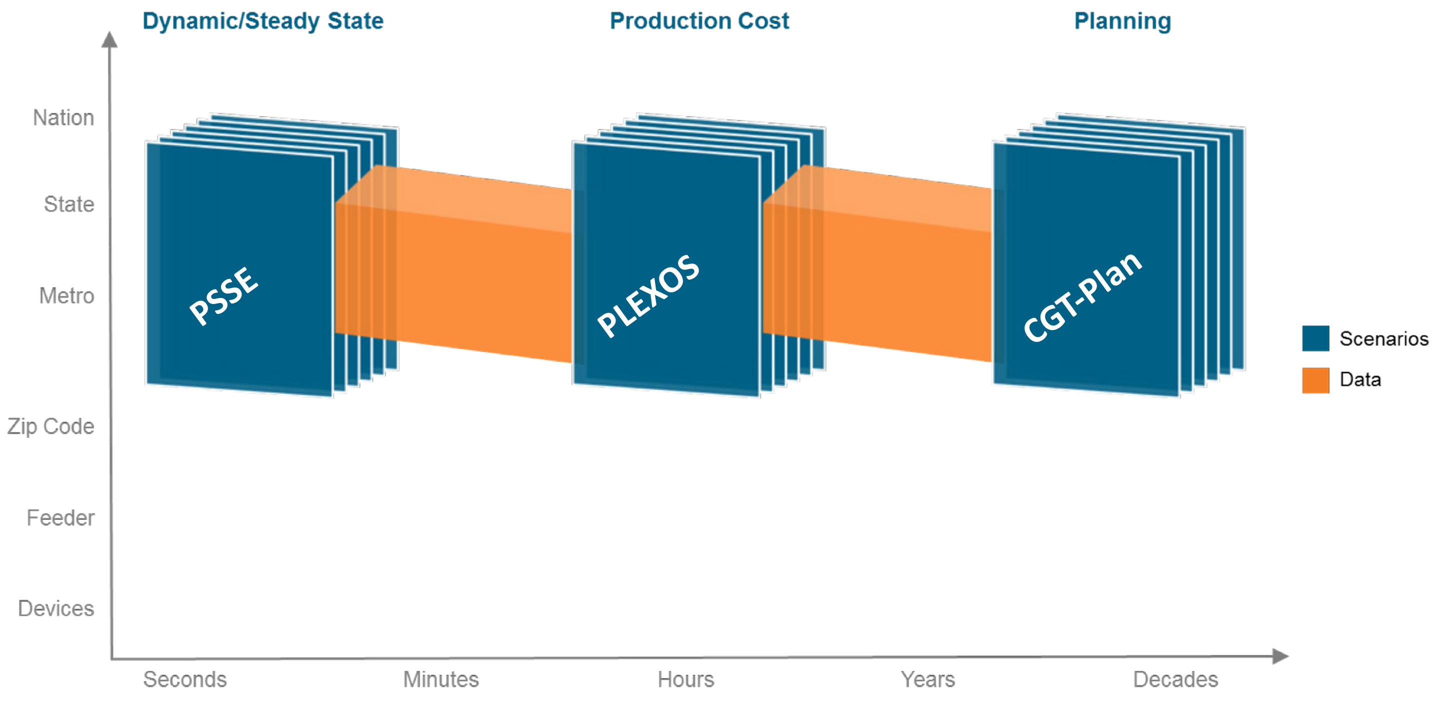


Unprecedented Resolution

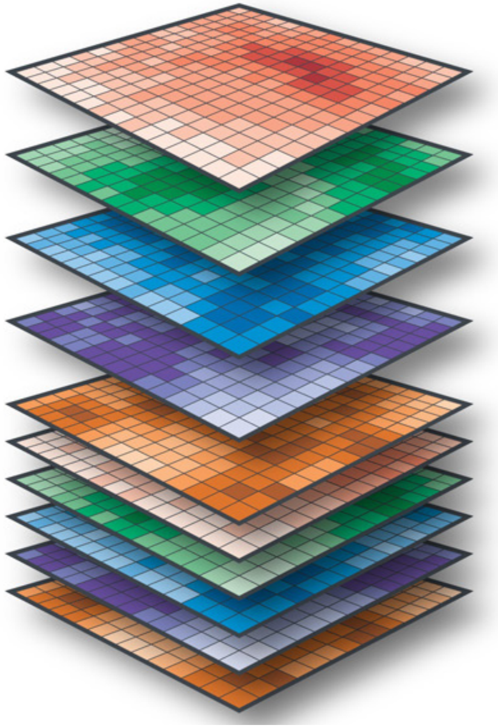


Comprehensive Economic and Reliability Analysis

- CGT-Plan
  - Iowa State University
  - Capital and operating costs 2024-2038
  - Generation and transmission system for 2038
- PLEXOS
  - NREL
  - Operating costs 2038
  - Hourly unit commitment and economic dispatch
- PSSE
  - PNNL
  - Develop a capability for future work
  - Preliminary analysis of AC power flow impacts



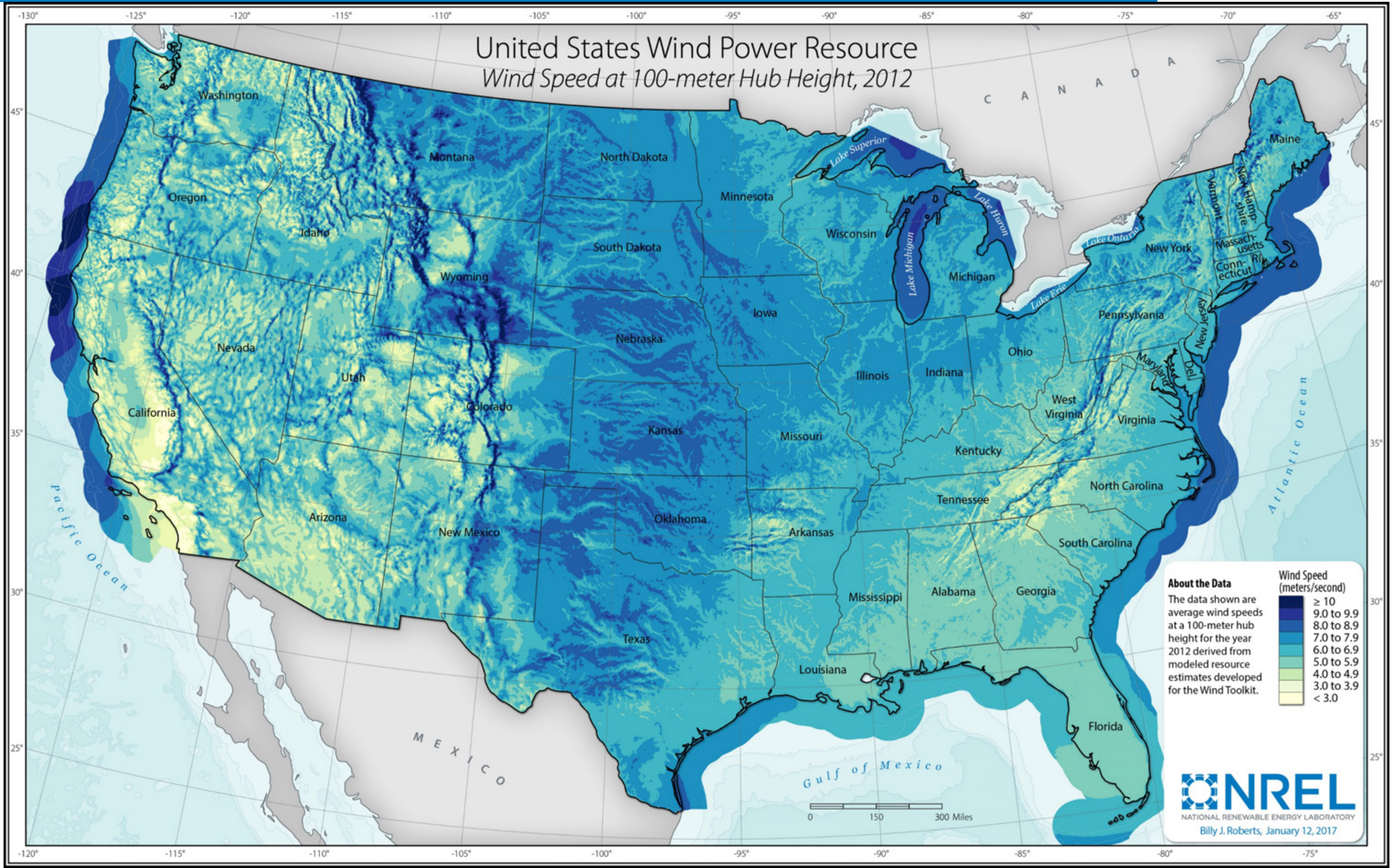
Integrated Data



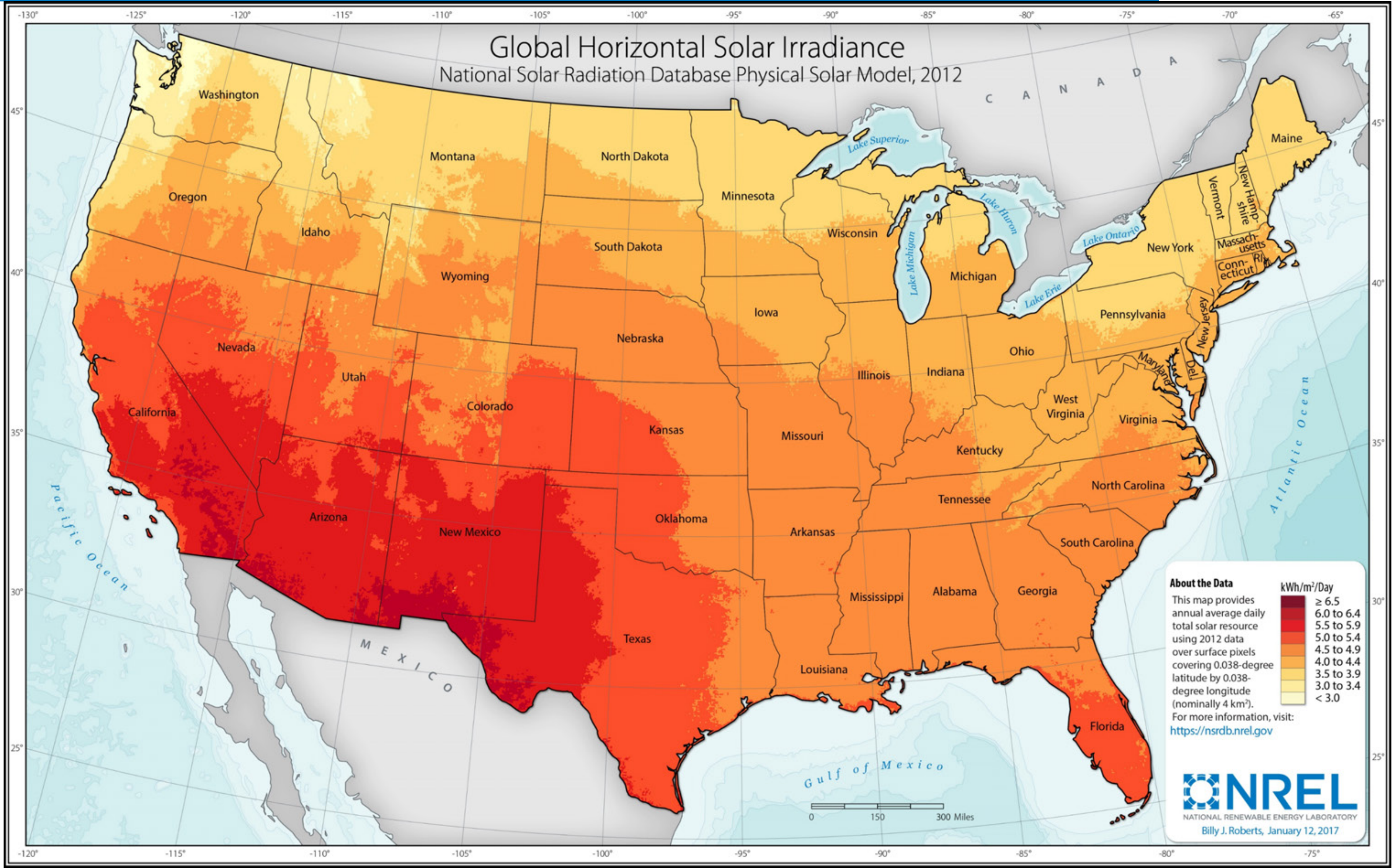
Solar resource
Thermal generation
Wind resource
Load
Hydro
Transmission
Fuel prices

- Consistent data between modeling domains
  - Wind
    - 2012 WIND Toolkit
    - https://www.nrel.gov/grid/wind-toolkit.html
  - Solar
    - 2012 NSRDB
    - https://nsrdb.nrel.gov/
  - Transmission and Generation
    - WECC TEPPC 2024*-Western Interconnection
    - MMWG 2026-Eastern Interconnection
  - Load
    - 2012 FERC Form 714 and RTO websites

Wind Data


United States Wind Power Resource
Wind Speed at 100-meter Hub Height, 2012
Washington
Oregon
California
Idaho
Nevada
Montana
Wyoming
Utah
Colorado
Arizona
New Mexico
North Dakota
South Dakota
Nebraska
Kansas
Oklahoma
Texas
Minnesota
Iowa
Missouri
Arkansas
Louisiana
Wisconsin
Illinois
Michigan
Indiana
Ohio
Kentucky
Tennessee
Mississippi
Alabama
Georgia
Florida
South Carolina
North Carolina
Virginia
West Virginia
Pennsylvania
New York
Maryland
Del.
New Jersey
Conn-ecticut
RI
Massach-usetts
Vermont
New Hamp-shire
Maine
Lake Superior
Lake Michigan
Lake Huron
Lake Erie
Lake Ontario
C A N A D A
M E X I C O
Pacific Ocean
Atlantic Ocean
Gulf of Mexico
0
150
300 Miles
About the Data
The data shown are average wind speeds at a 100-meter hub height for the year 2012 derived from modeled resource estimates developed for the Wind Toolkit.
Wind Speed (meters/second)
≥ 10
9.0 to 9.9
8.0 to 8.9
7.0 to 7.9
6.0 to 6.9
5.0 to 5.9
4.0 to 4.9
3.0 to 3.9
< 3.0
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Billy J. Roberts, January 12, 2017

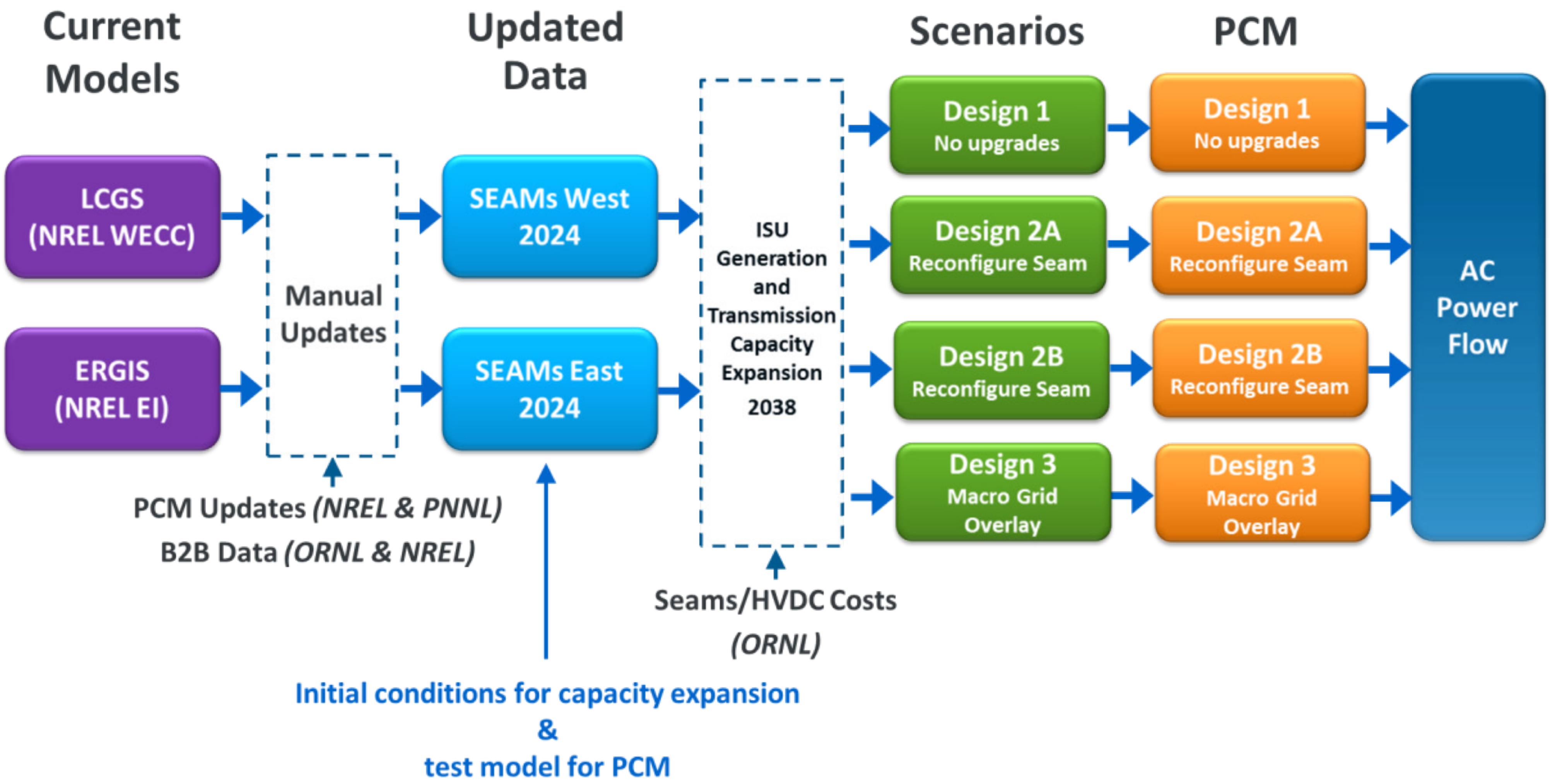
Solar Data


Global Horizontal Solar Irradiance
National Solar Radiation Database Physical Solar Model, 2012
About the Data
This map provides annual average daily total solar resource using 2012 data over surface pixels covering 0.038-degree latitude by 0.038-degree longitude (nominally 4 km²).
For more information, visit:
https://nsrdb.nrel.gov
kWh/m²/Day
≥ 6.5
6.0 to 6.4
5.5 to 5.9
5.0 to 5.4
4.5 to 4.9
4.0 to 4.4
3.5 to 3.9
3.0 to 3.4
< 3.0
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Billy J. Roberts, January 12, 2017
0
150
300 Miles
Washington
Oregon
California
Nevada
Idaho
Montana
Wyoming
Utah
Arizona
Colorado
New Mexico
North Dakota
South Dakota
Nebraska
Kansas
Oklahoma
Texas
Minnesota
Iowa
Missouri
Arkansas
Louisiana
Wisconsin
Illinois
Michigan
Indiana
Ohio
Kentucky
Tennessee
Mississippi
Alabama
Georgia
Florida
South Carolina
North Carolina
Virginia
West Virginia
Pennsylvania
New York
Maryland
Del.
New Jersey
Conn-ecticut
RI
Massach-usetts
Vermont
New Hamp-shire
Maine
CANADA
MEXICO
Pacific Ocean
Atlantic Ocean
Gulf of Mexico
Lake Superior
Lake Michigan
Lake Huron
Lake Erie
Lake Ontario

This is a Resource Adequacy and Cost Study

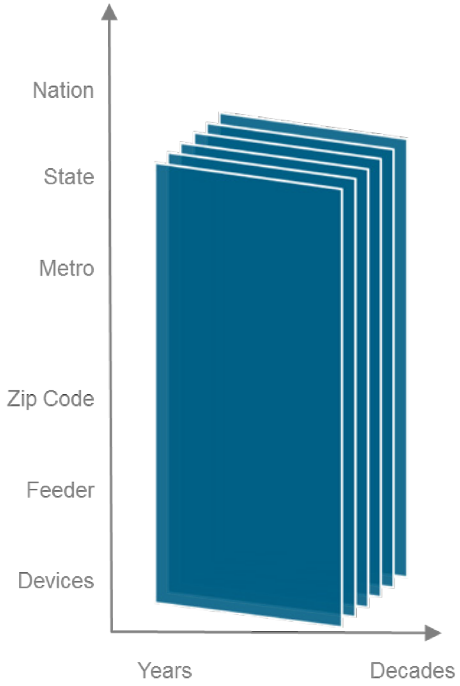
- Given a defined resource adequacy constraint, how does the cost of meeting that constraint change as a function of the HVDC scenarios?
- We setup a framework for security and stability analysis, but do not conduct comprehensive contingency and stability analysis.
- **Goal:** Determine if there is significant economic value associated with these transmission futures. If there is significant value, then do economic, reliability and resiliency analysis.

Modeling Approach



What is an Expansion Planning Tool?

- Conducted by ISU
- Many names, similar general purpose
- Used to determine the optimal build of generation and transmission to meet a defined objective function
- Informs <u>some</u> Resource Adequacy questions
- Sometimes used in concert with other tools
- Creates expansion scenarios that are designed to meet the same Reliability/Resource Adequacy Metrics
- Calculates investments and retirements for generation and transmission



CGT-Plan

- Linear Program
- Zonal Representation created using two reduction methods
- High computational requirements require approximations
- Simulates every two years of investments and retirements from 2026-2038
- It is not a crystal ball
- Assumes central planning, this is a shortcoming, and an optimal goal

Objective Function

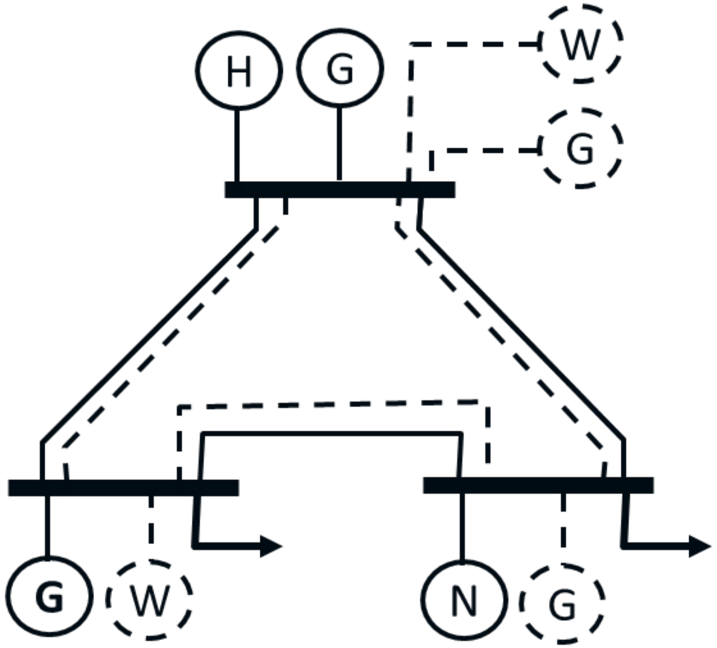
Identify investment & retirement decisions to MINIMIZE

NET PRESENT VALUE

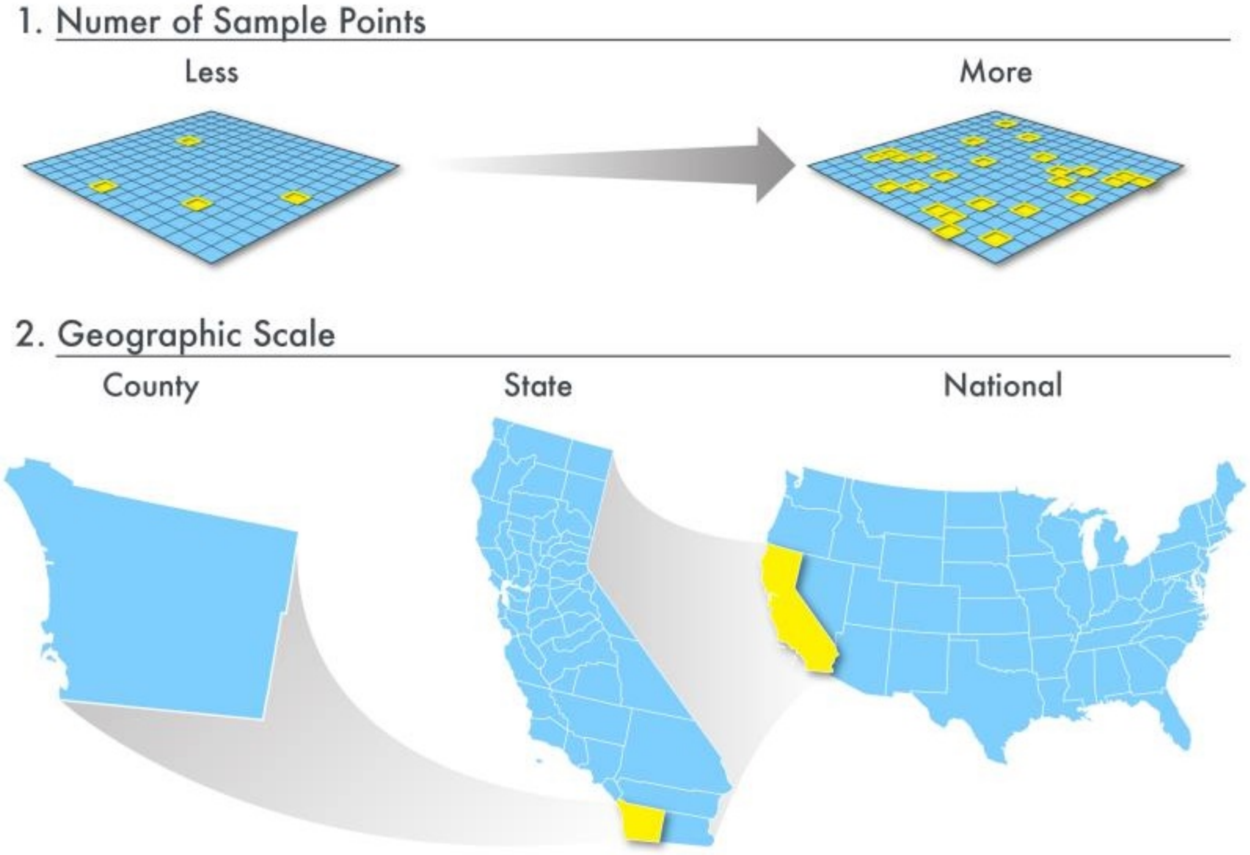
G&T Investment Costs
+ Fixed O&M Costs
+ Var O&M Costs
+ Fuel Costs
+ Reserve Costs
+ Environmental Costs

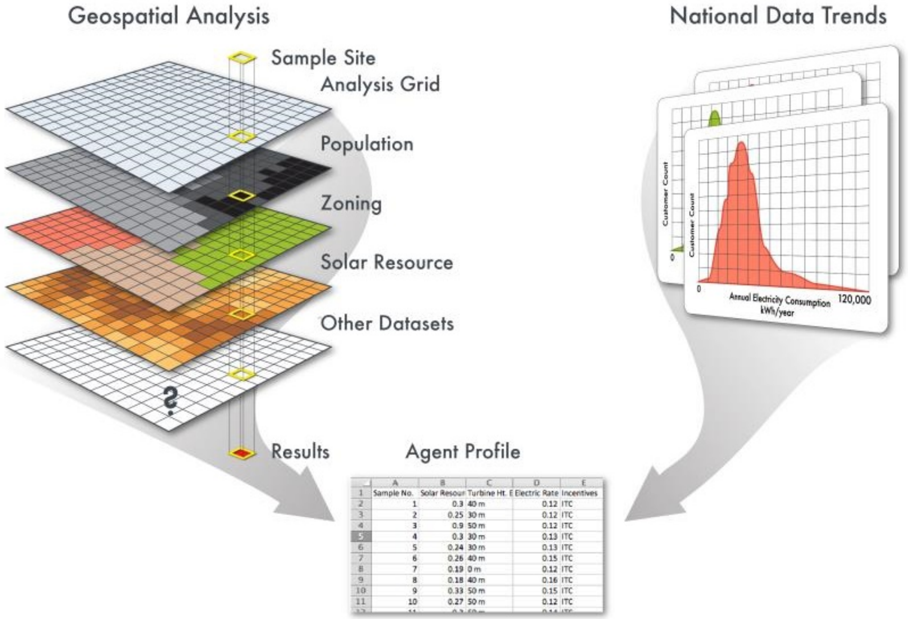
SUBJECT TO:
Investment constraints
Operational, planning, environmental constraints

Year 1 | Year 2 | • • • | Year 15



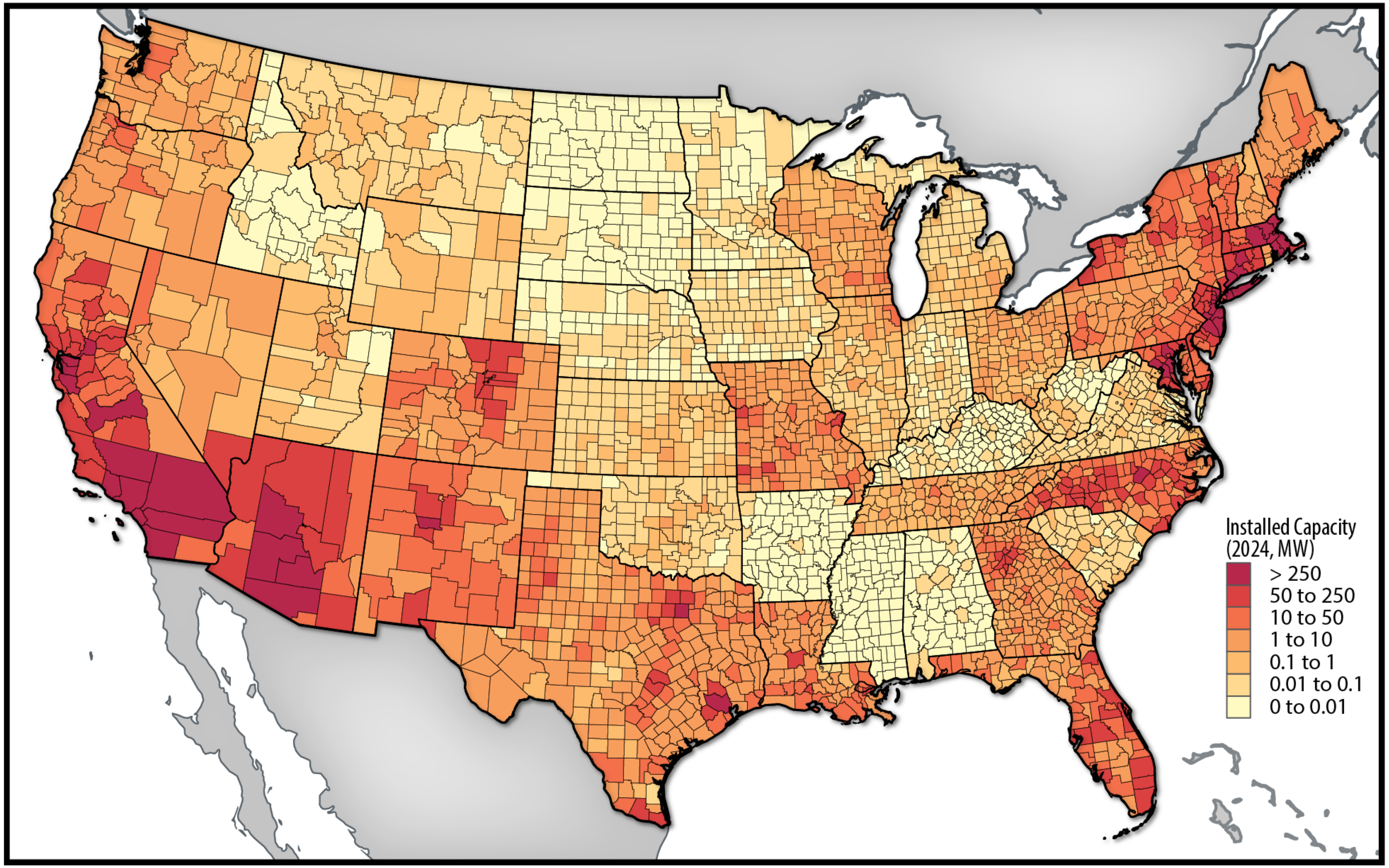
Consumer level understanding of DERs





https://www.nrel.gov/analysis/dgen/

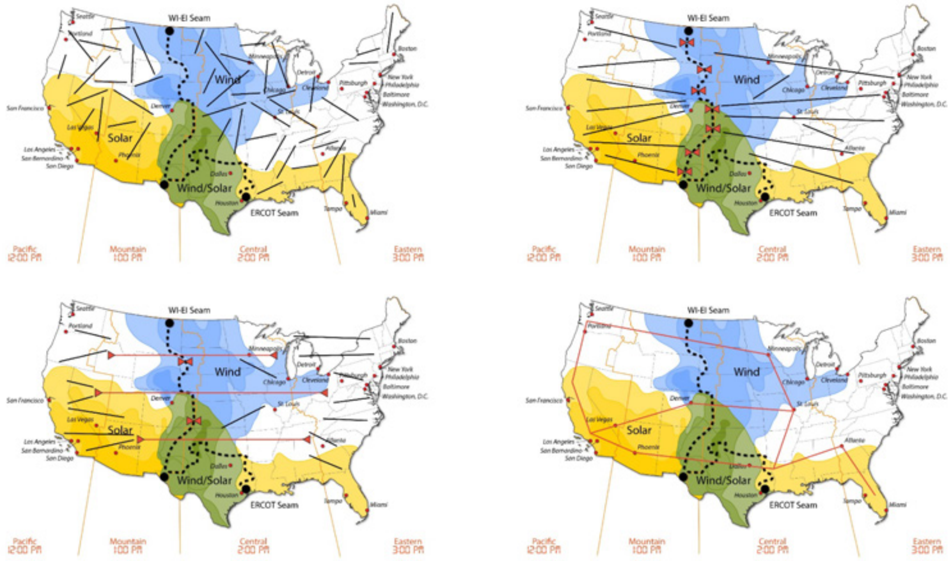
Distributed Generation



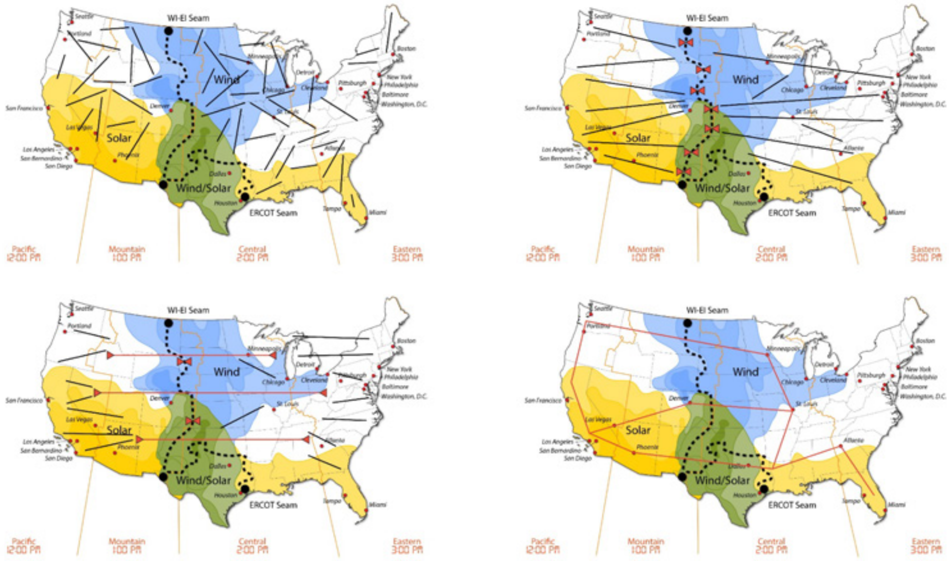
Policy Environments

The four conceptual transmission designs were studied under two different policy environments

Current Policy



Carbon Policy



TRC Requested Policy Assumptions

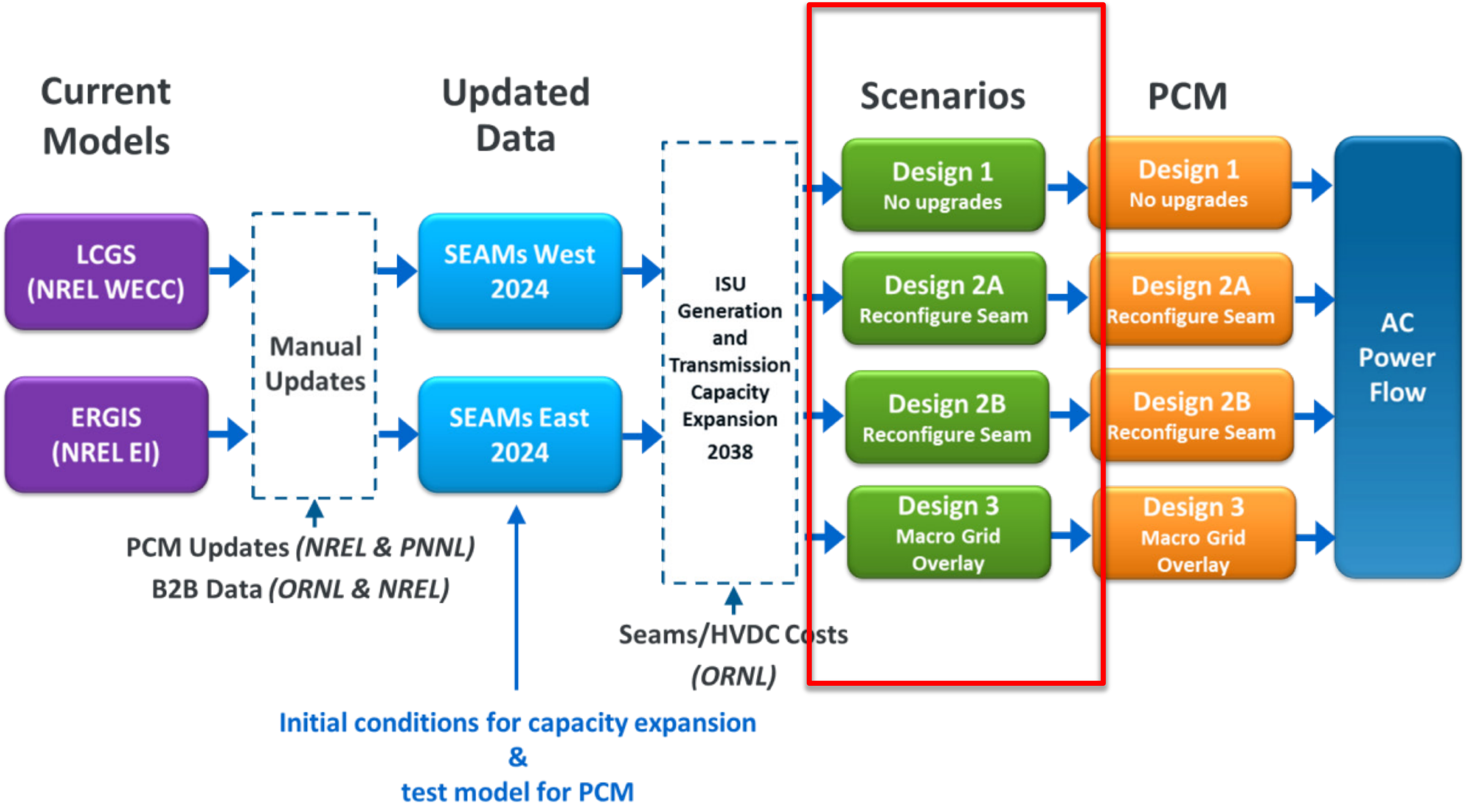
- Current Policy scenarios assume existing renewable portfolio standards as of 2017

- Carbon Policy scenarios assume a carbon tax that grows at a rate of $3/metric ton (CO2) per year to a price of $40/metric ton by 2038

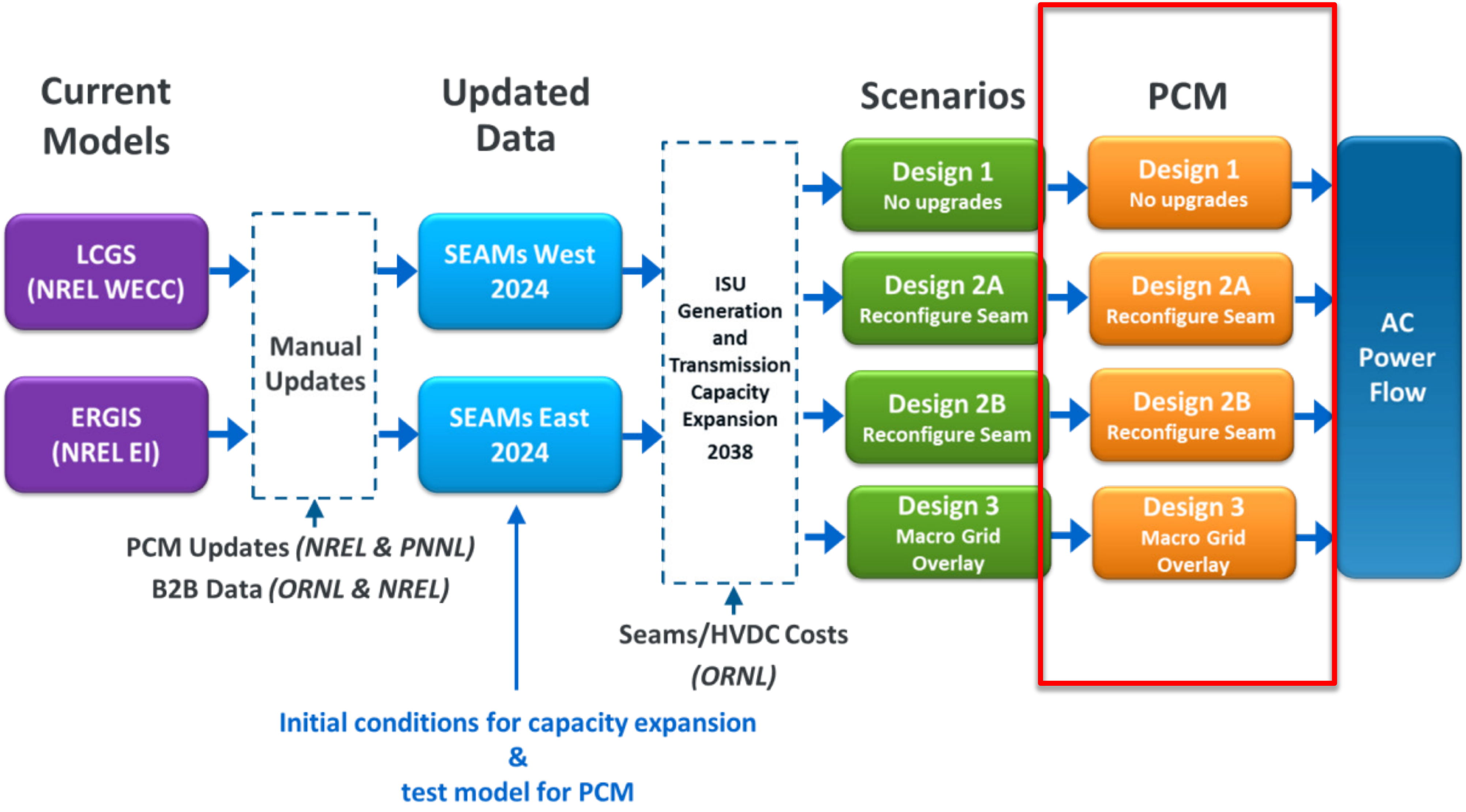
Other Assumptions

- North American Eastern and Western Interconnections
- Retire generation based on economic performance
- Run for 15 years, with 7 investment periods
- Fuel cost forecasts according to AEO 2017 (med-gas)
- Gen investment base costs & maturation rates from NREL ATB 2016
- Transmission base costs according to EIPC/B&V
- Gen & trans regional cost multipliers from EIPC/WECC
- Use of 169 bus model (68 EI, 101 WI)
- 4 regions: West, Northwest, Midwest, East
- Wind uses 100-m tower CFs ~ 0.45-0.50
- Gen capacity investment limited to 40GW/yr
- Demand growth per NEEM & WI (E3) per state
- DG growth per AEO 2016, 3% per yr
- New nuclear, offshore wind, geothermal, concentrating solar power, and carbon capture technologies were not studied

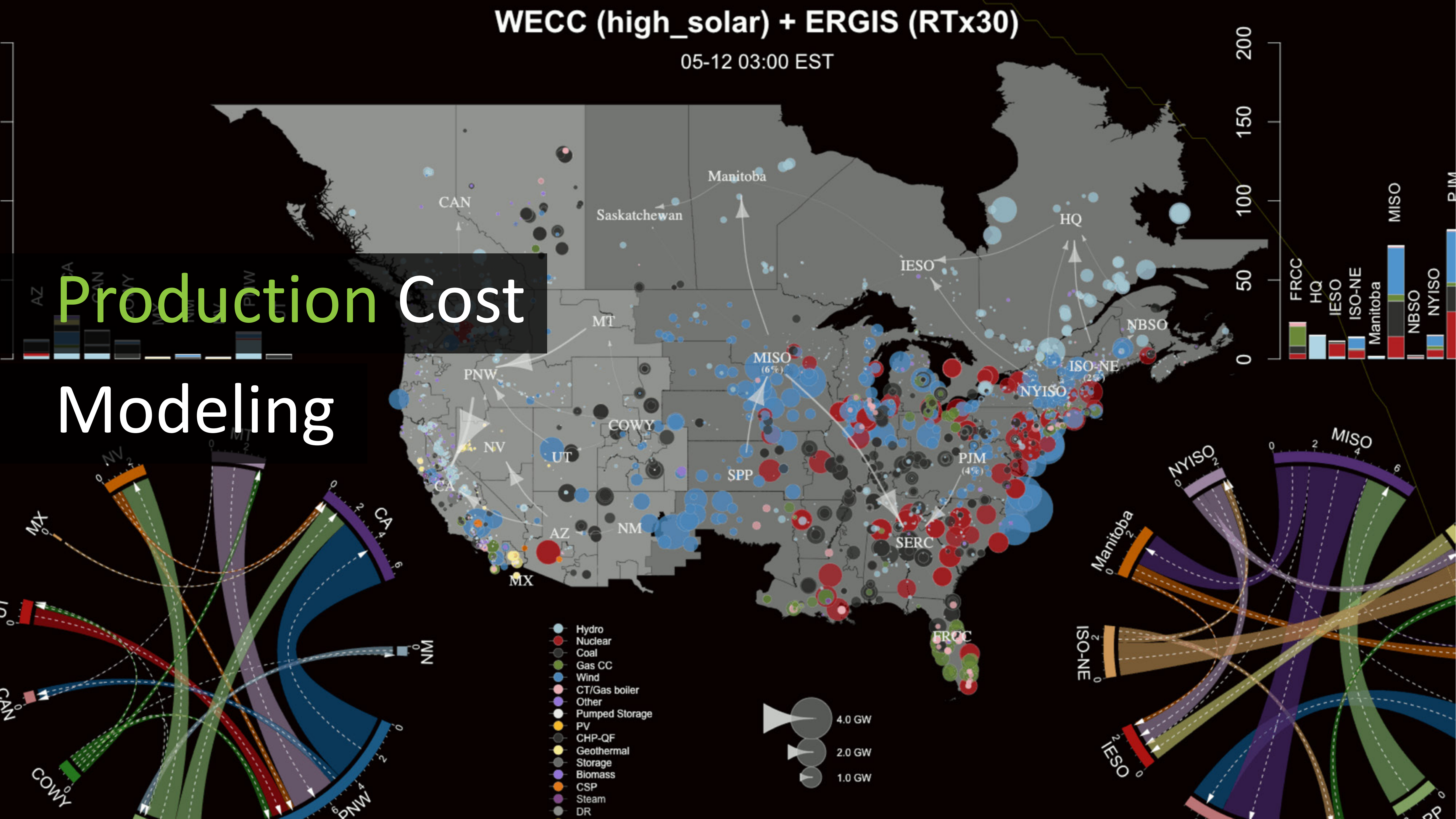
Modeling Approach



Modeling Approach

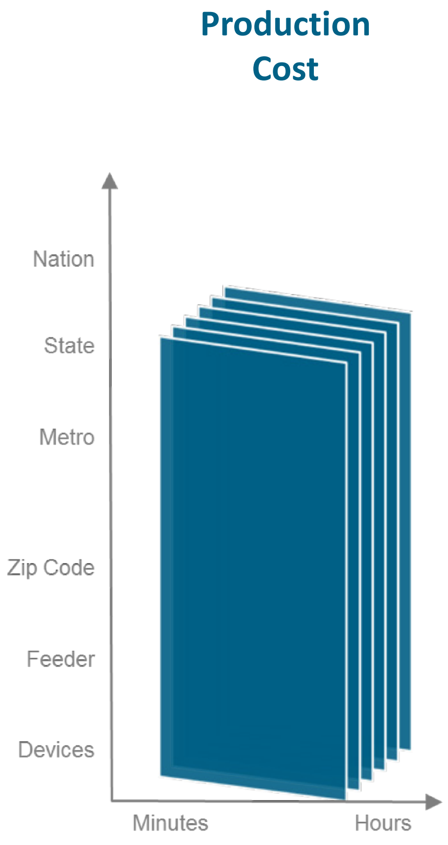


Production Cost Modeling



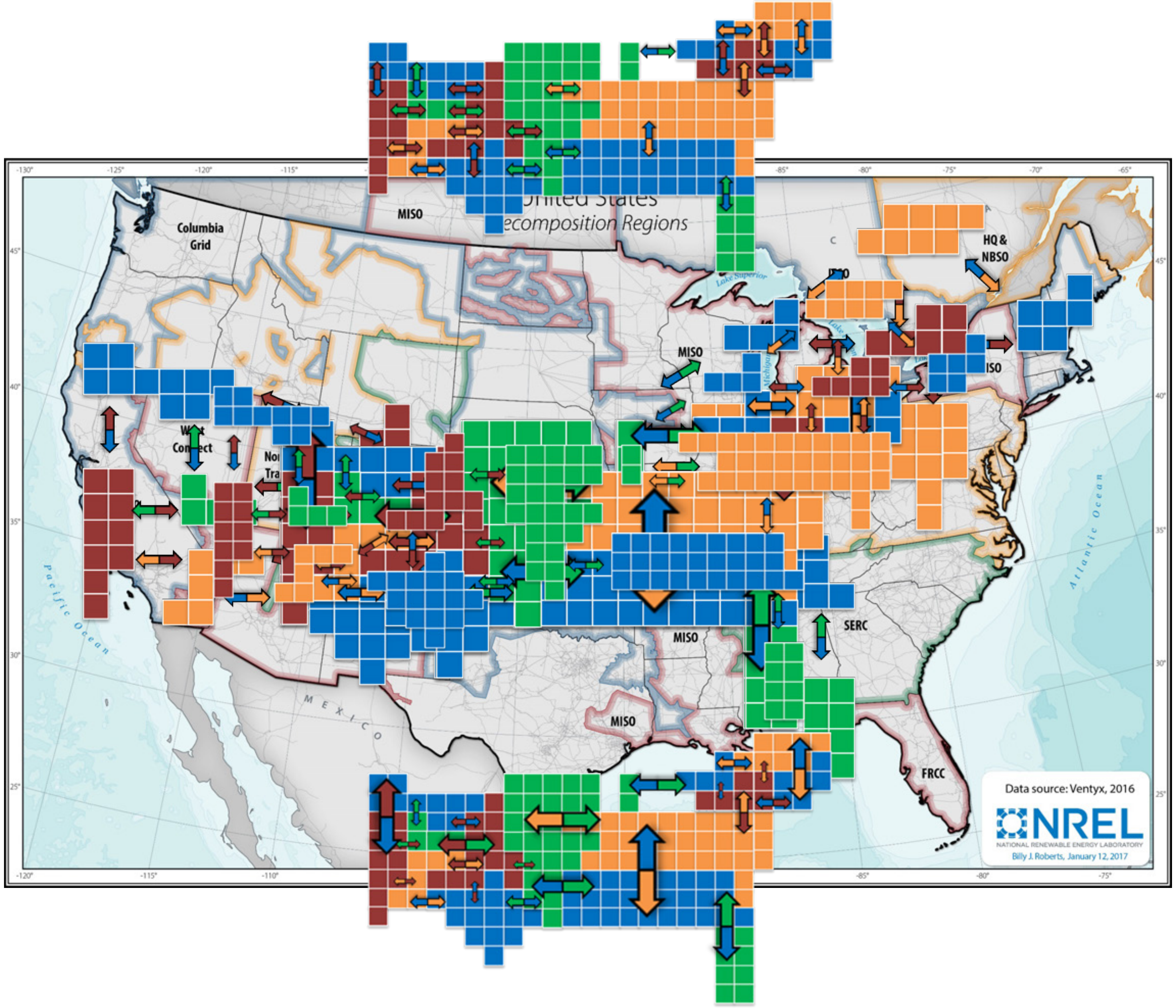
Production Cost Models

- Conducted by NREL
- Simulate the unit commitment and economic dispatch of a power system
- Approximate the daily operations of an IOU or RTO/ISO (Day ahead and Real Time)
- Used to simulate an entire year of hourly operations
- Calculates the cost of producing electricity
- Linearized DC Power flow



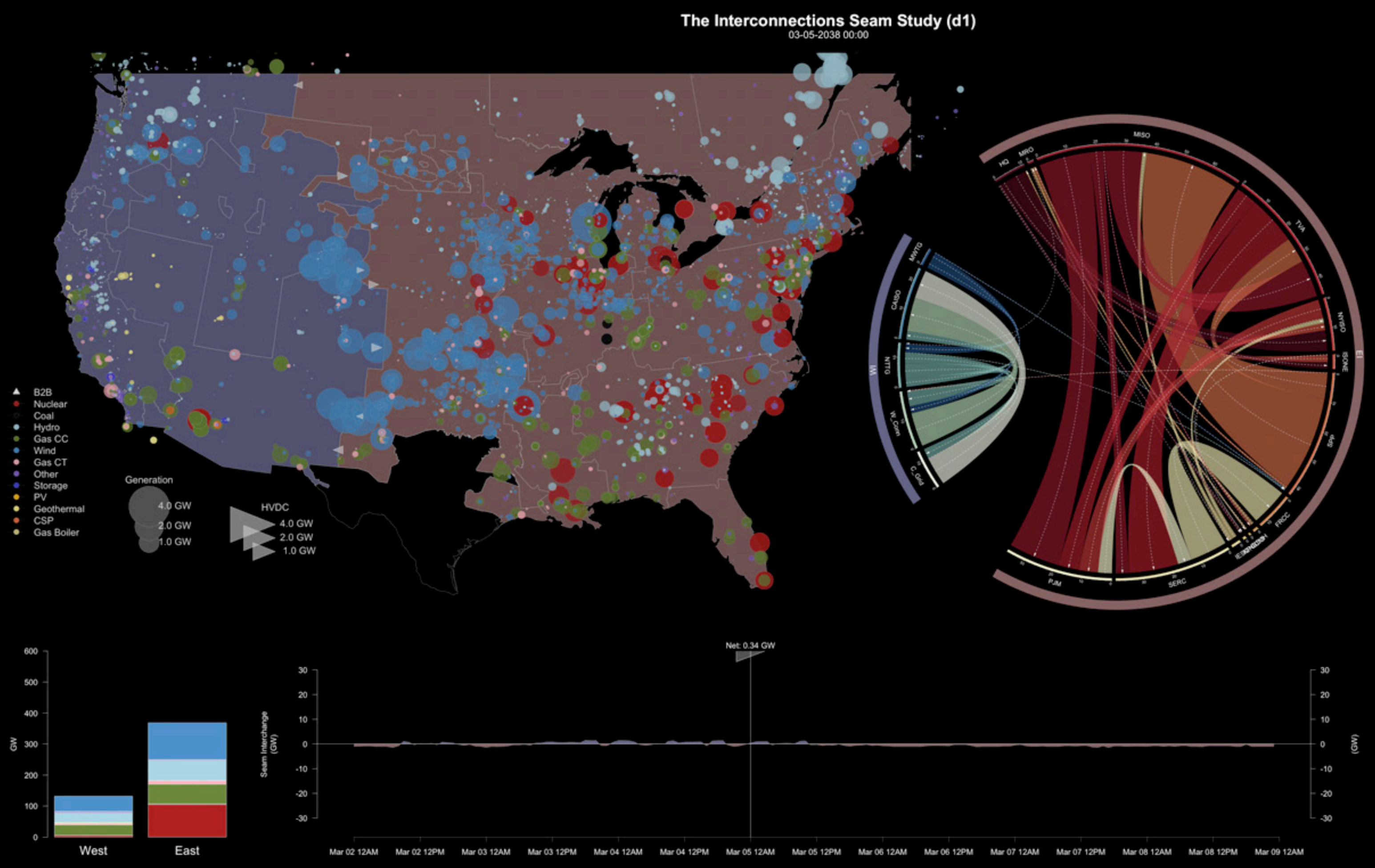
Geographic Decomposition

- Respects regional operating borders
- Advanced computation methods solve in days, not years
- Represents information asymmetries between operators



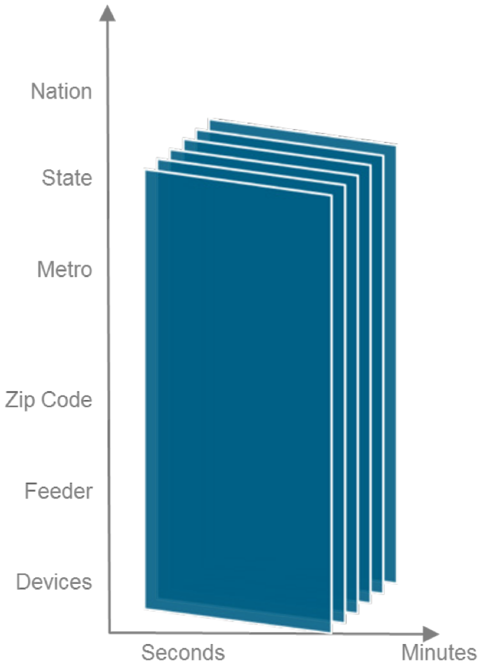
Production Cost Model: PLEXOS

- Mixed Integer Program
- Full nodal representation: 98,000
- First production cost model to simulate nodal Eastern and Western Interconnections at the same time
- Every generator and every transmission line



Steady State Analysis

- Conducted by PNNL
- Steady state analysis of 2038 cases was not studied
- Used to simulate probable contingencies
- CGT-Plan and PLEXOS modeling were conducted with an eye towards enabling future work
- If significant value is identified, subsequent analysis may be merited

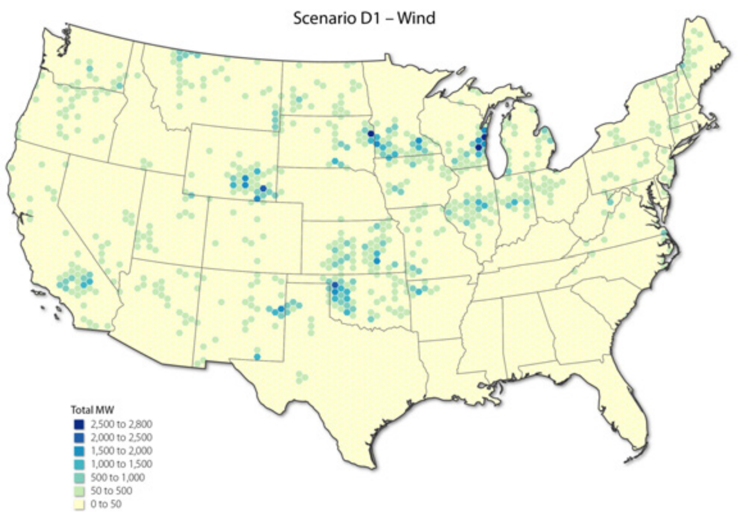


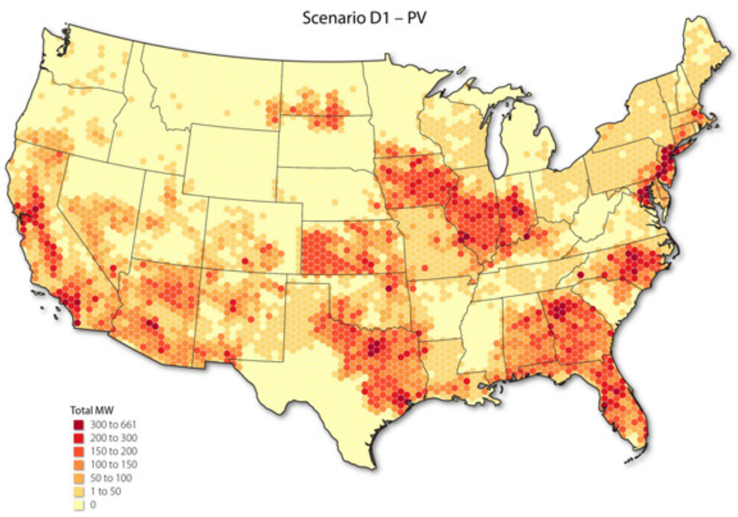
Discussion Time

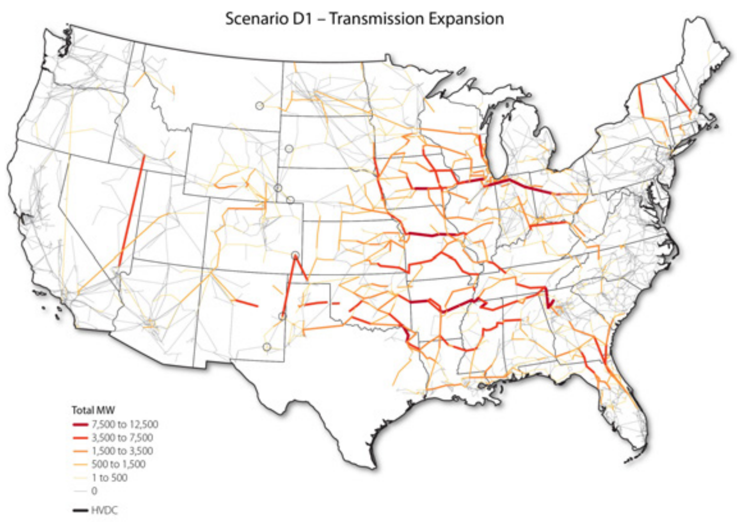
1) Is it clear how we are using the modeling tools in this study?
2) Do you have any questions about the benefits and drawbacks of these tools?
3) What are other ways we could use these tools (HPC) to answer transmission planning questions?
4) What other value streams should we investigate? Resiliency?

Here are the results

System Characteristics And Performance

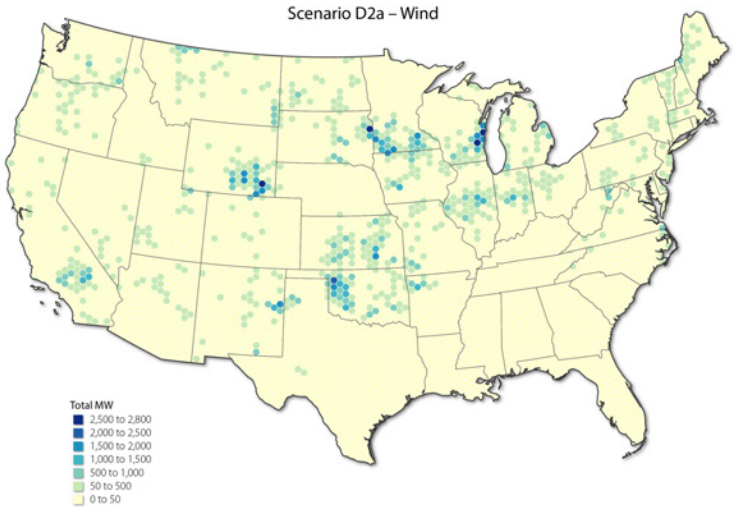


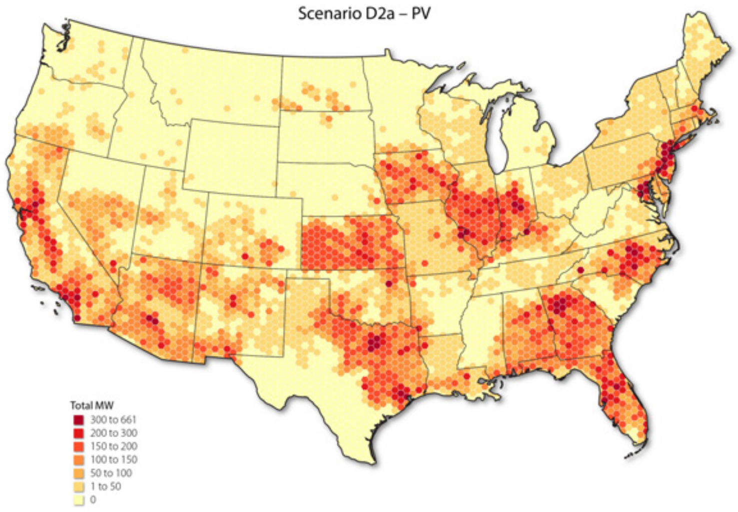


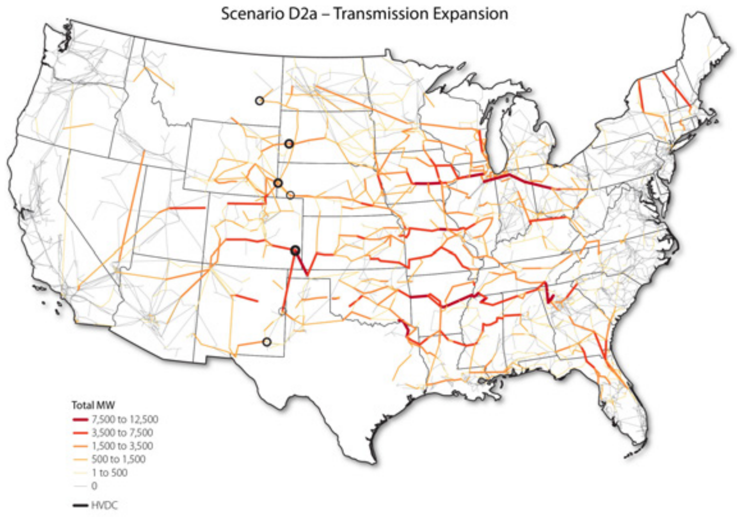


Design 1

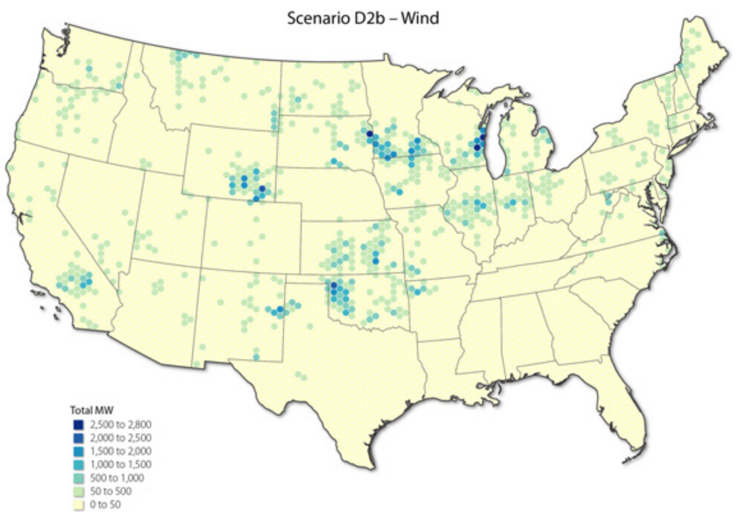
Current Policy

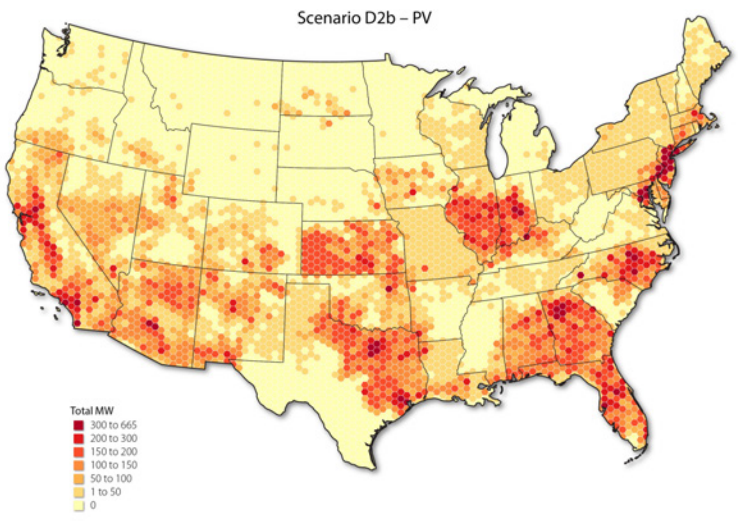


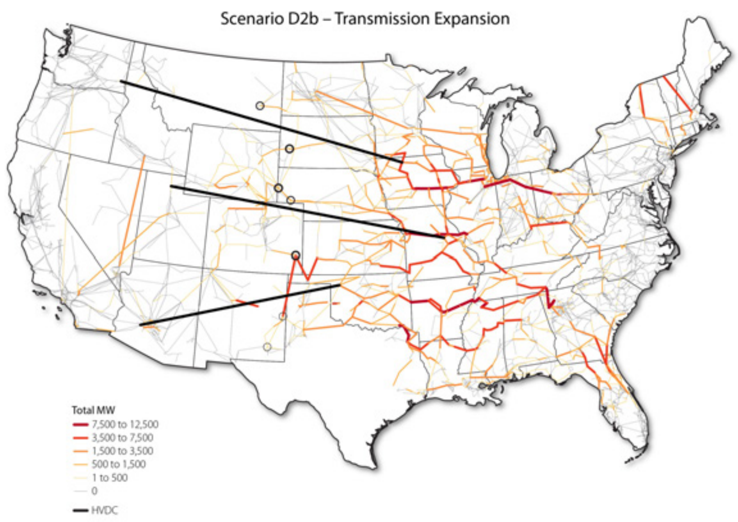




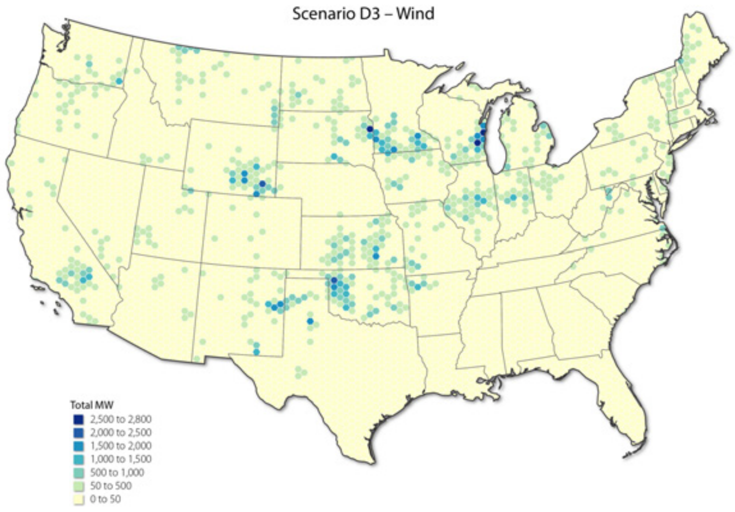
Design 2a
Current Policy

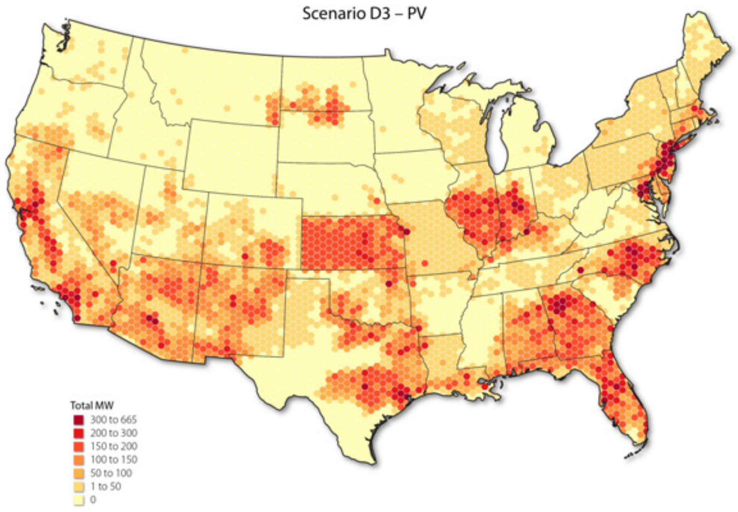


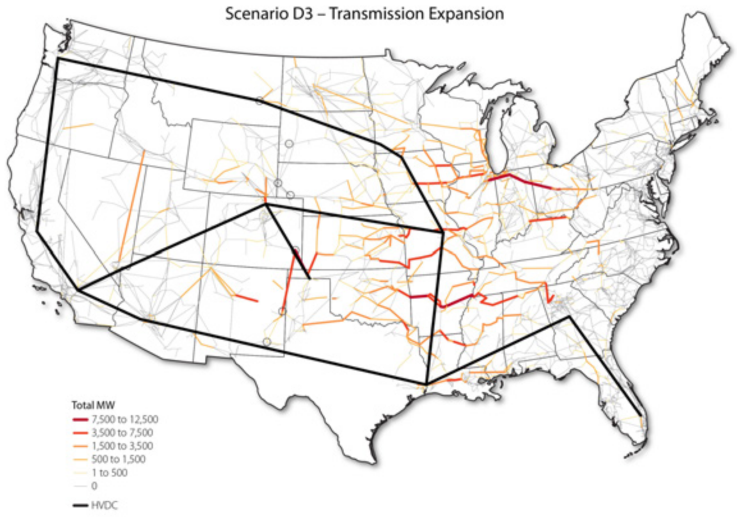




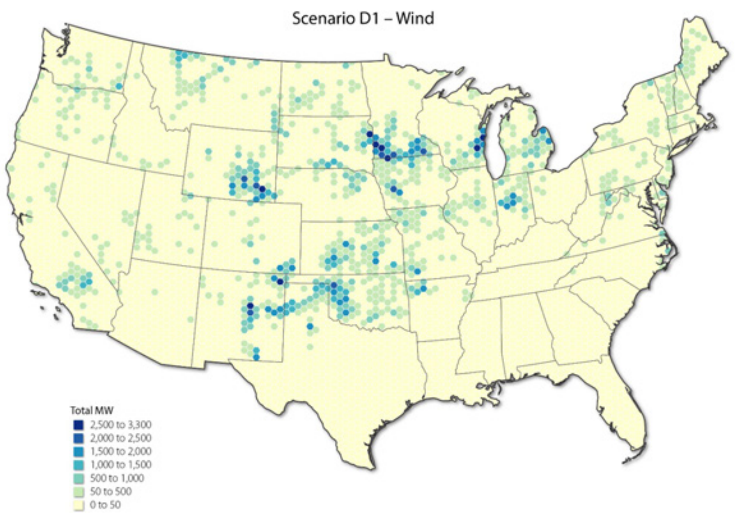
Design 2b
Current Policy

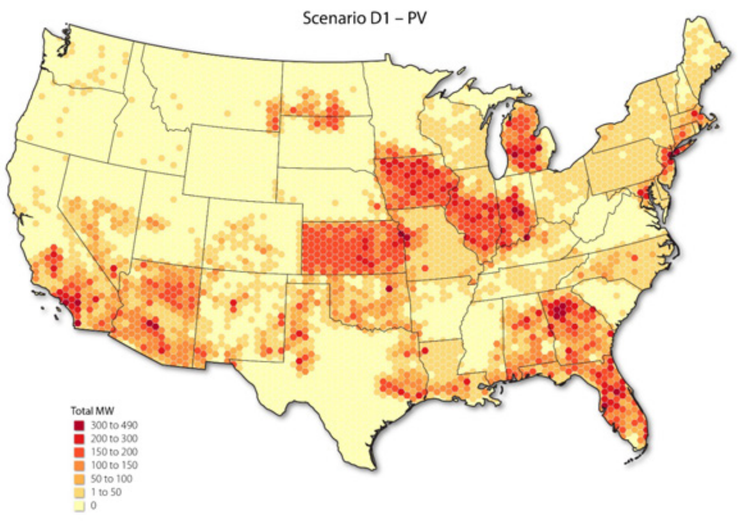


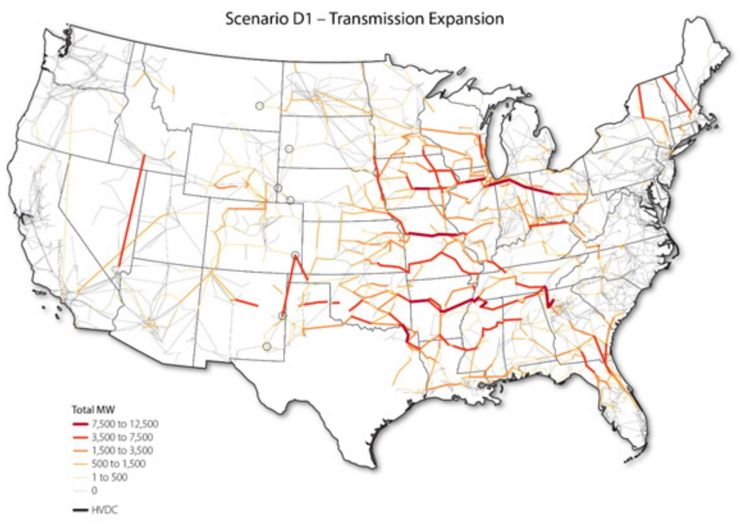




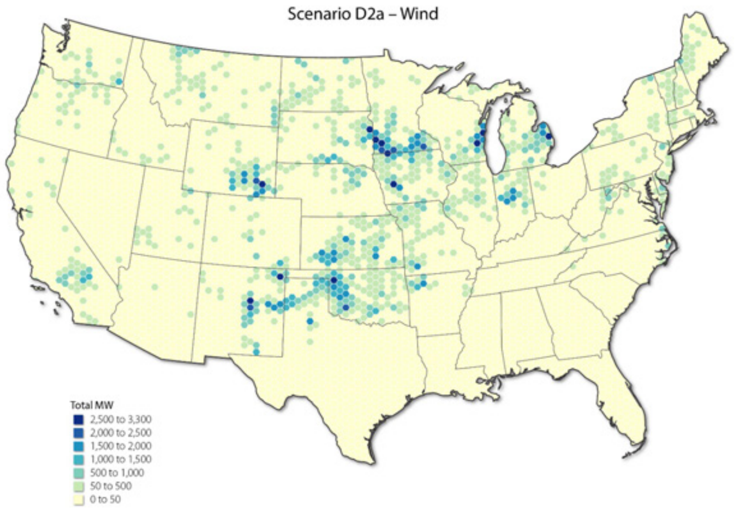
Design 3
Current Policy

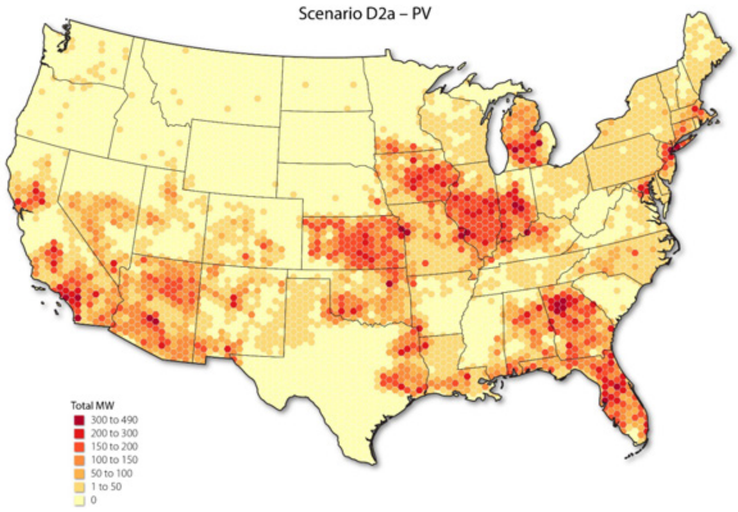


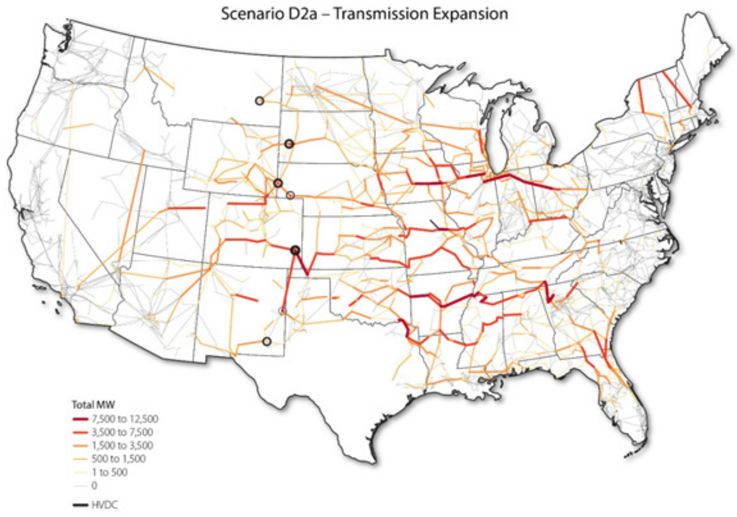




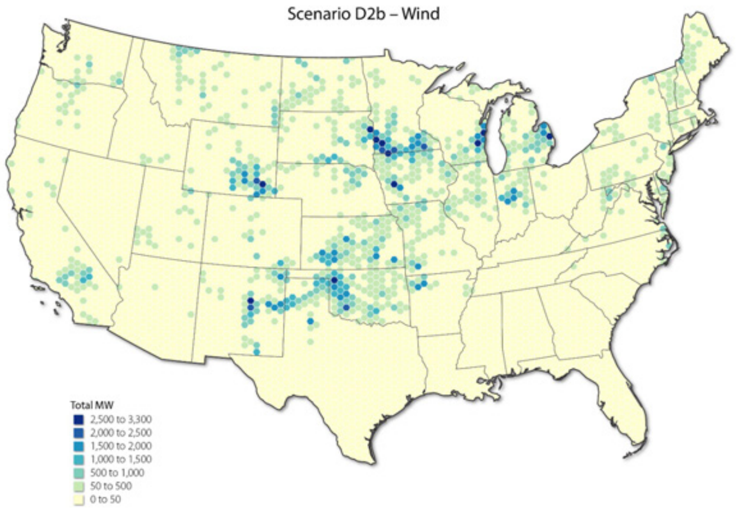
Design 1
Carbon Policy

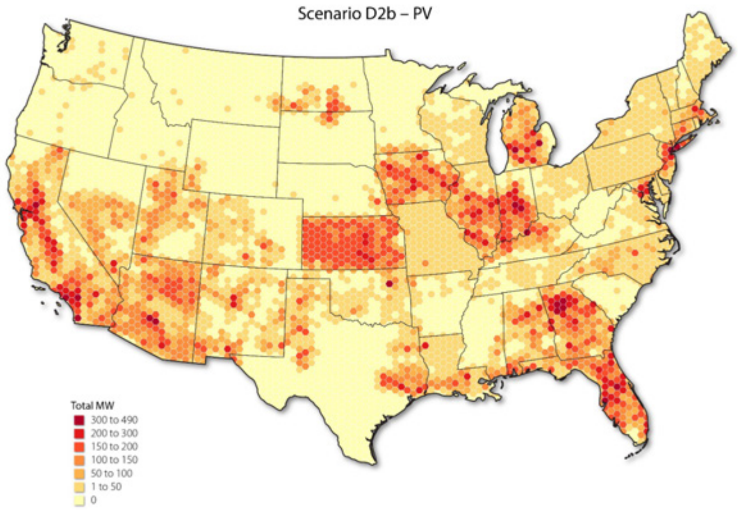


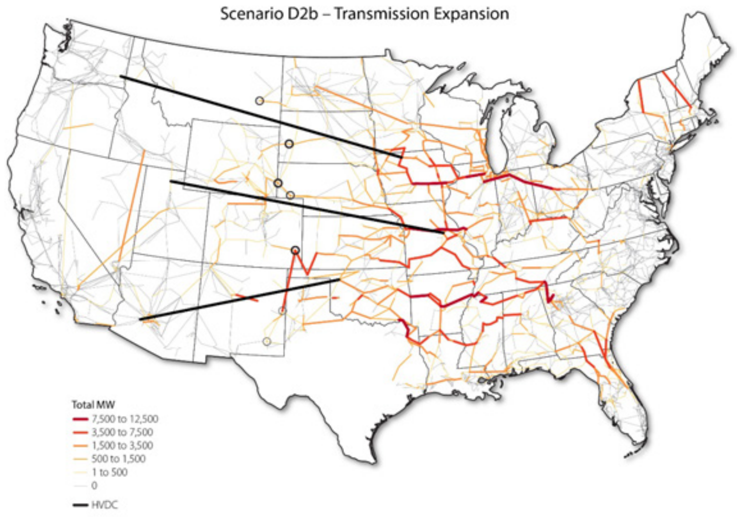




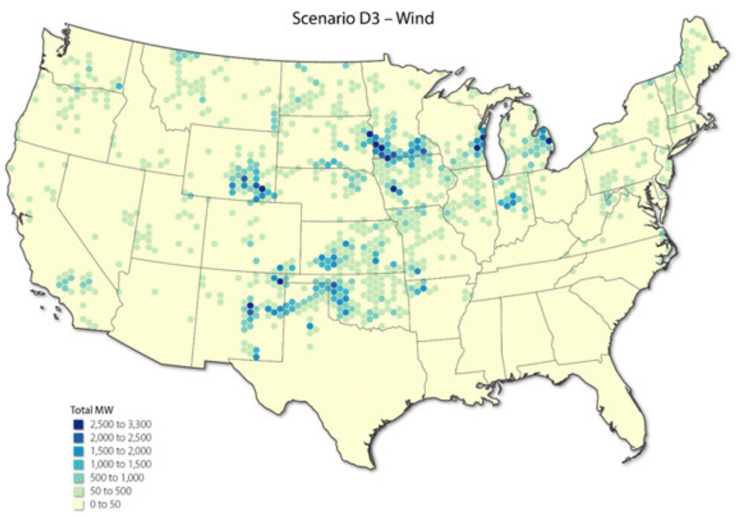
Design 2a
Carbon Policy

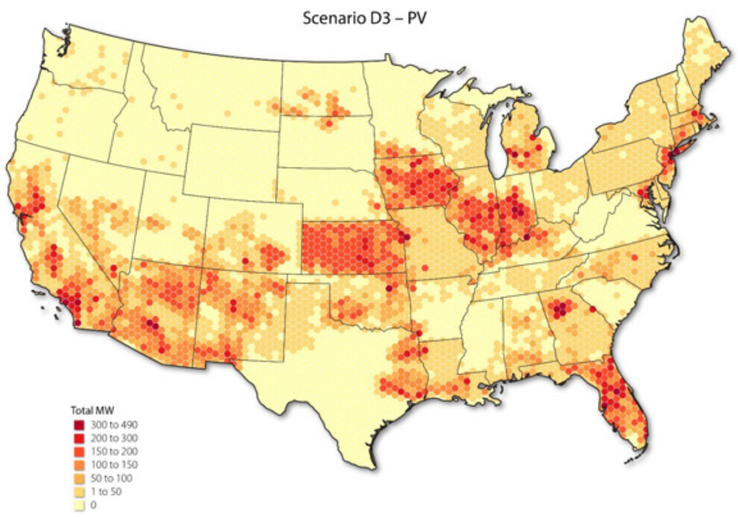


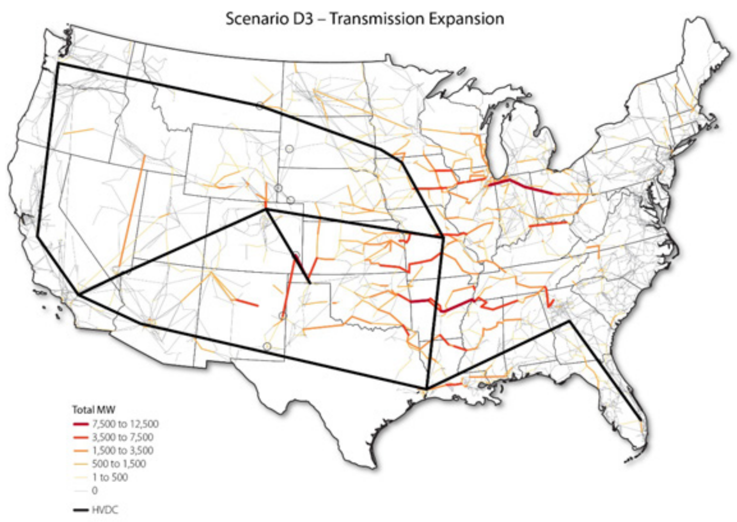




Design 2b
Carbon Policy







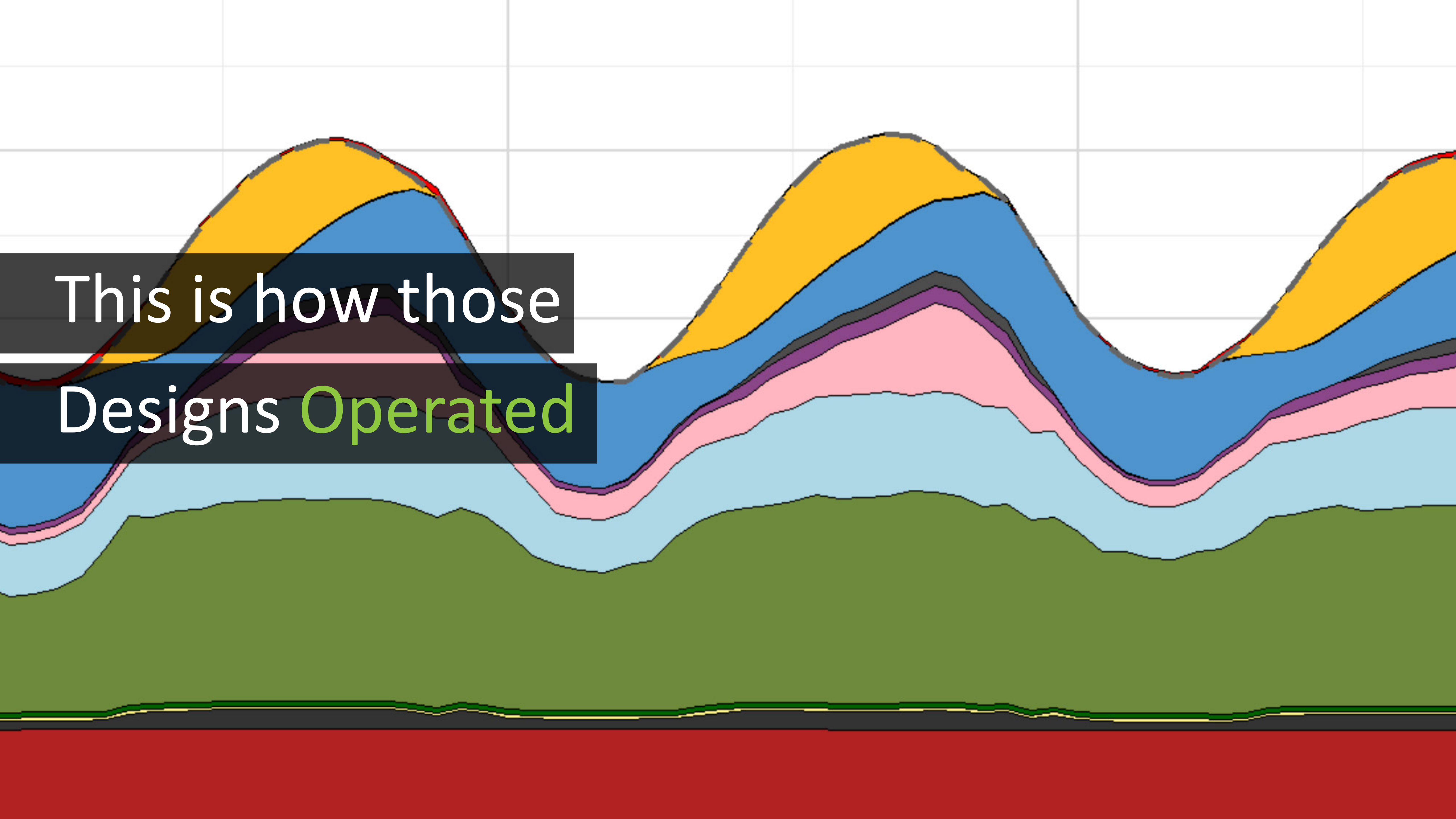
Design 3
Carbon Policy

Installed Capacity (GW)

	2024	Current Policy				Carbon Policy			
		D1	D2a	D2b	D3	D1	D2a	D2b	D3
Coal	266	120	113	111	115	65	37	29	32
Hydro	198	198	198	198	198	198	198	198	198
Natural Gas	443	437	431	418	421	467	453	450	448
Nuclear	132	132	132	132	132	132	132	132	132
Solar	64	281	277	271	278	246	241	241	239
Wind	94	320	324	326	324	450	487	488	487

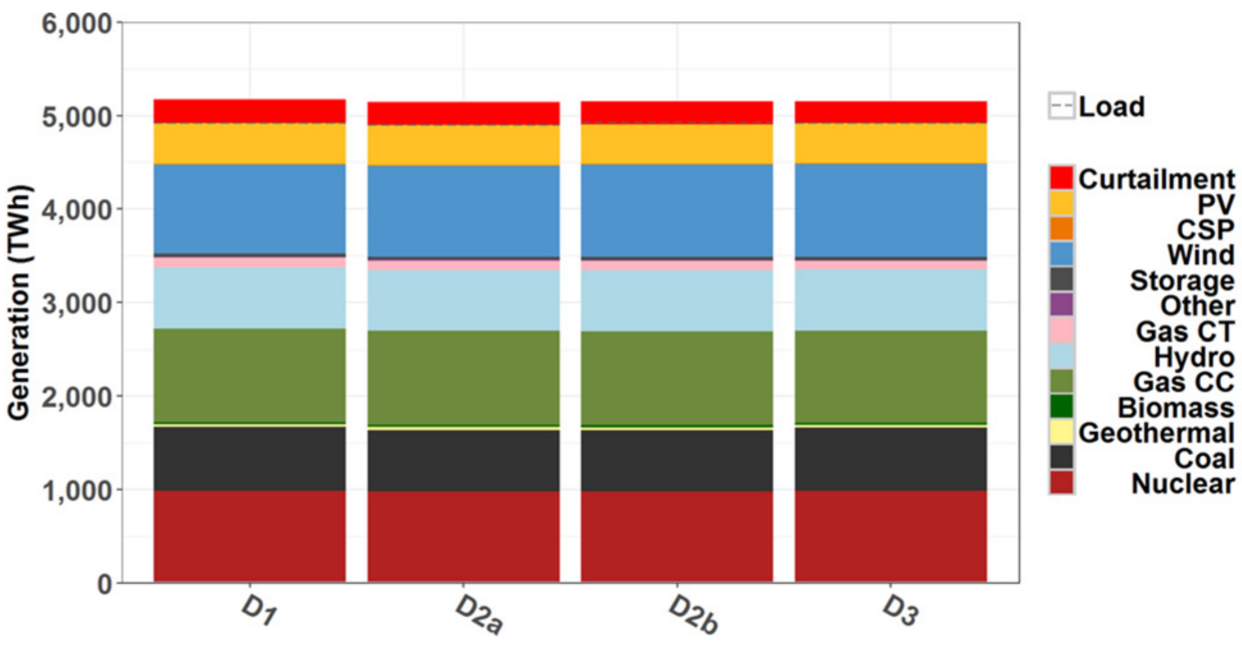
Expansion Overview

- All cases imagine a future where it is feasible to build multi-region transmission
- Design 1 is the only case without new HVDC and without new transmission across the Seam
- The generation mix changes substantially in all cases
- Results are known to be imperfect, yet informative
- Substantial AC transmission is added in all cases
- All cases meet the same Resource Adequacy target (15% planning reserve margin). Details here: https://lib.dr.iastate.edu/etd/16128/

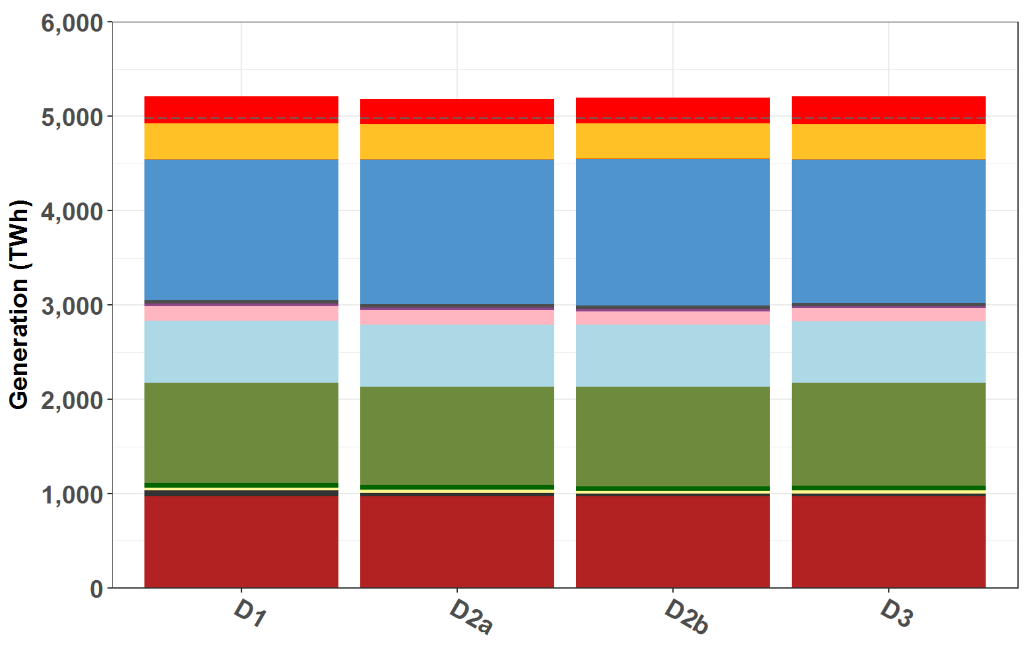

This is how those
Designs Operated

Annual Generation

- Current Policy



- Carbon Policy

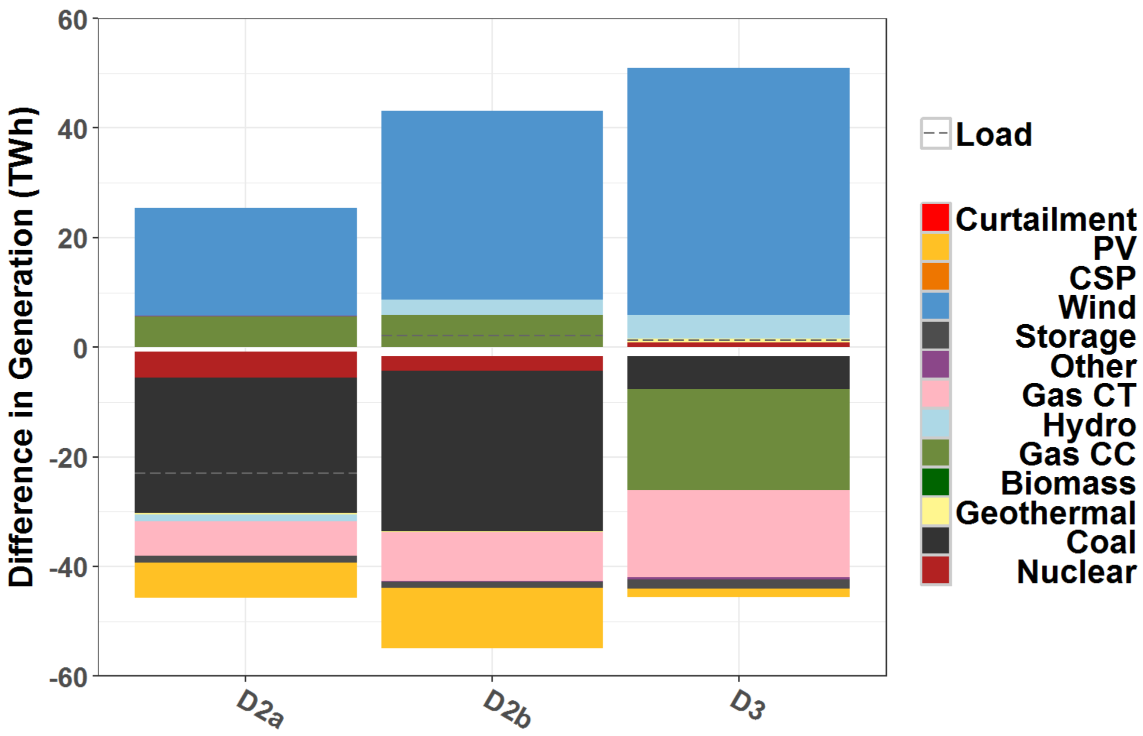


Percent of Total Generation

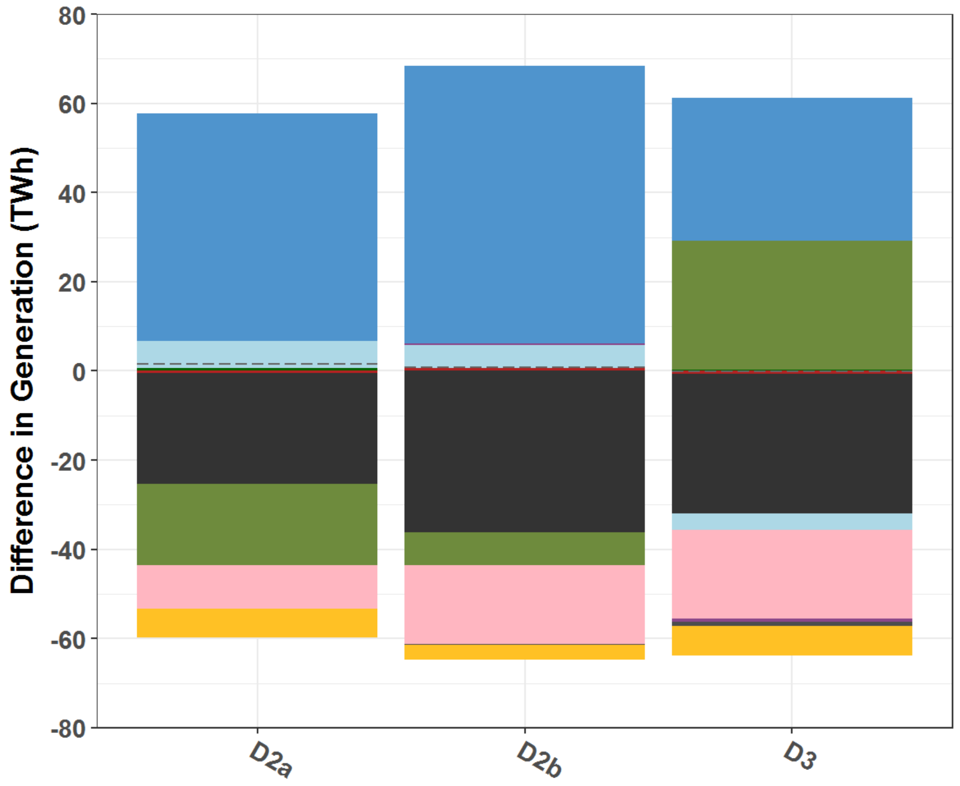
	Current Policy				Carbon Policy			
	D1	D2a	D2b	D3	D1	D2a	D2b	D3
Fossil Fuel	36%	36%	36%	36%	26%	25%	25%	25%
Wind and Solar	28%	29%	29%	29%	38%	39%	39%	39%
CO_2 Free	63%	63%	63%	64%	73%	74%	74%	73%

Generation Difference

- Current Policy

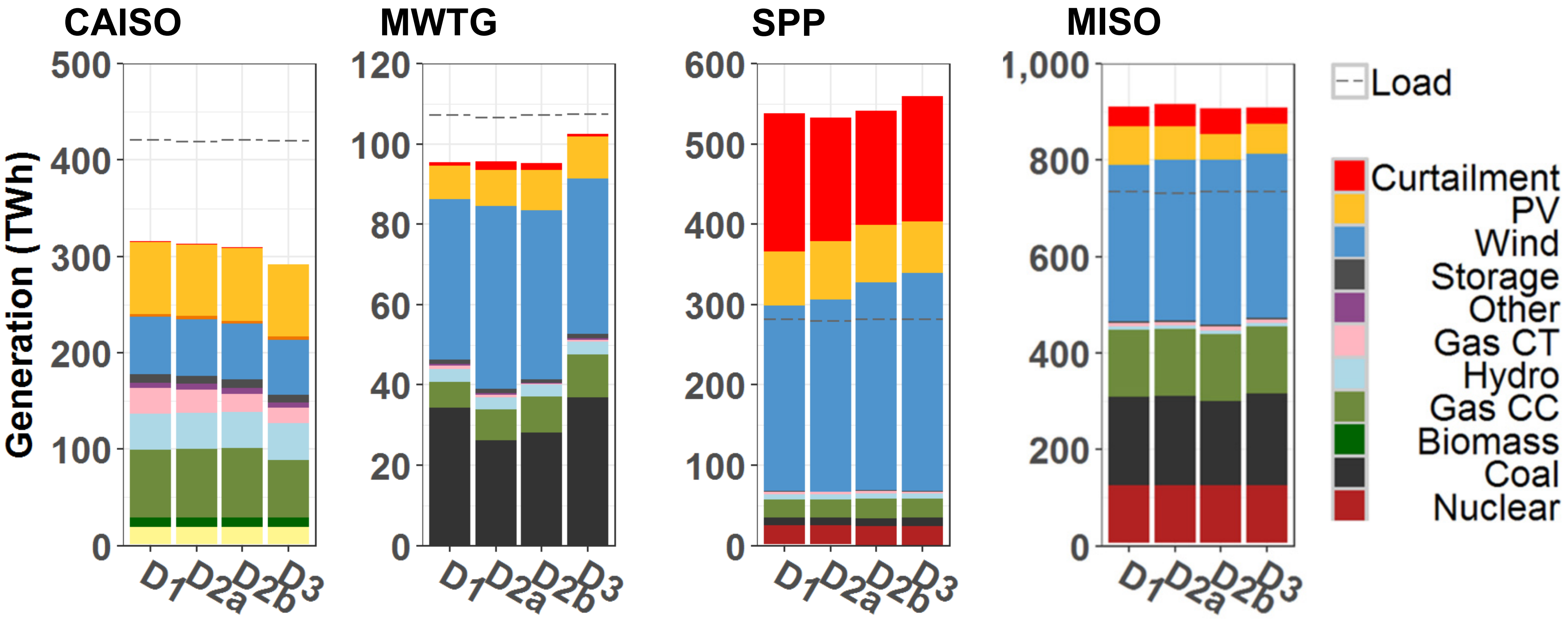


- Carbon Policy

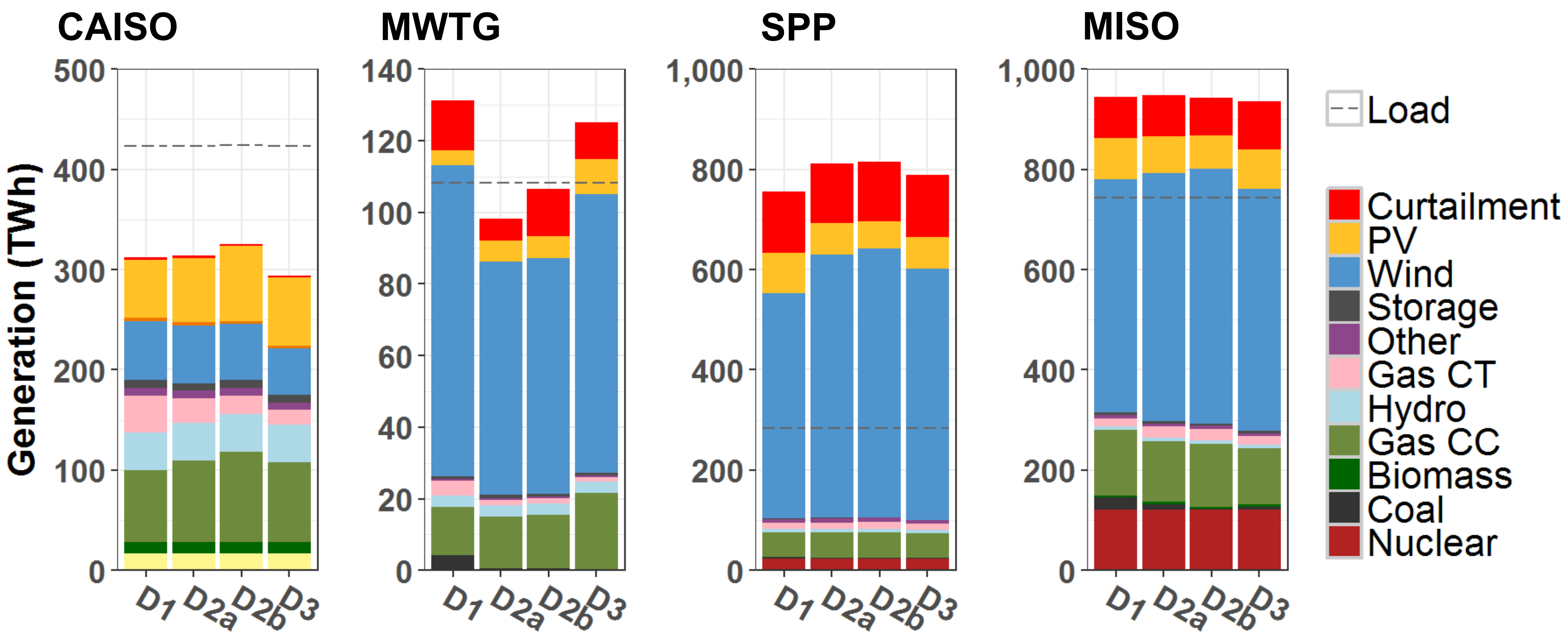


- Note smaller scale of the Current Policy plot
- Nuclear changes under Current Policy are an artifact of outage schedules.

Regional Generation Current Policy



Regional Generation Carbon Policy



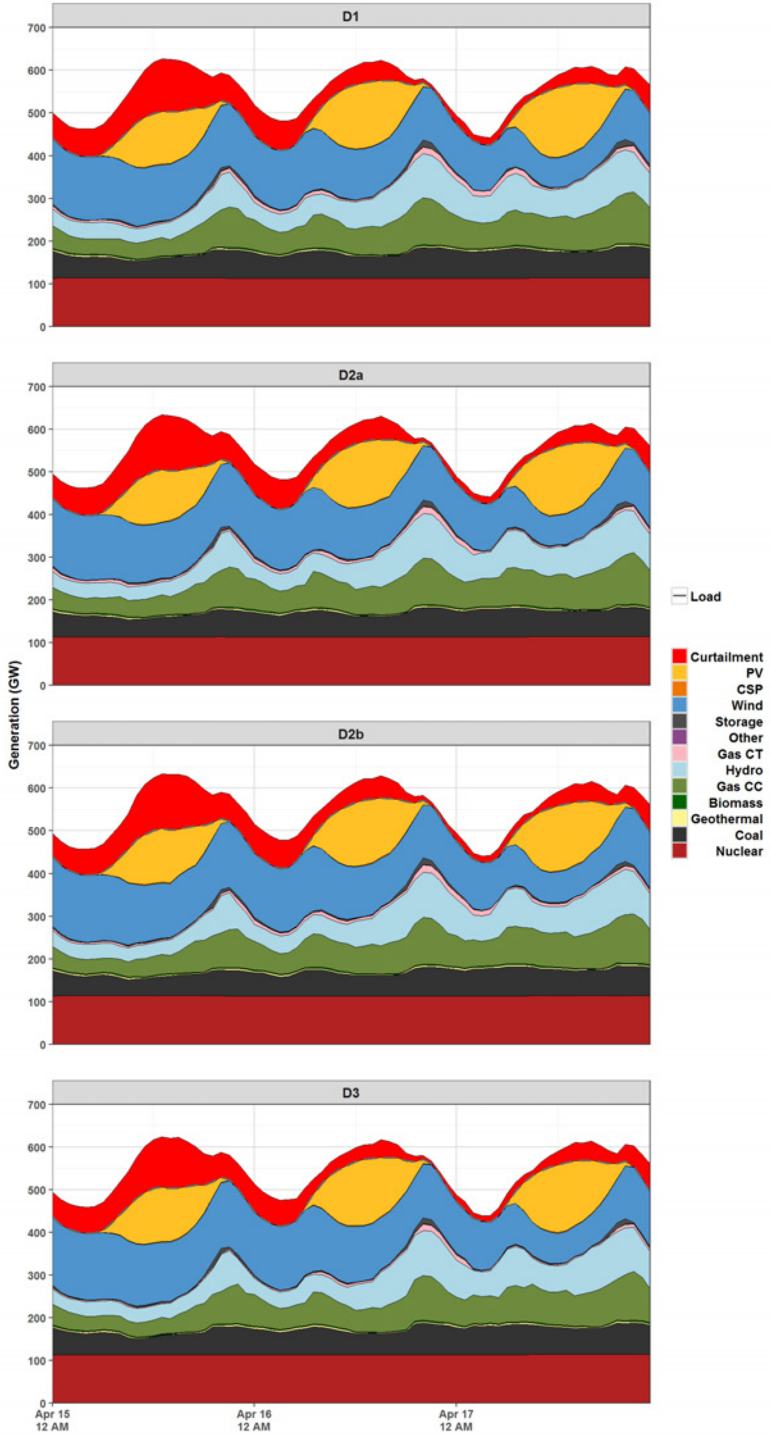
Variable Generation Curtailment

	Current Policy	Carbon Policy
D1	15.6%	13.6%
D2a	15.0%	12.2%
D2b	15.0%	12.2%
D3	13.9%	13.5%

- Curtailment is high and largely driven by congestion in both cases
- AC transmission is similar across Current Policy scenario
- D3 AC transmission expanded ~40% more than other scenarios

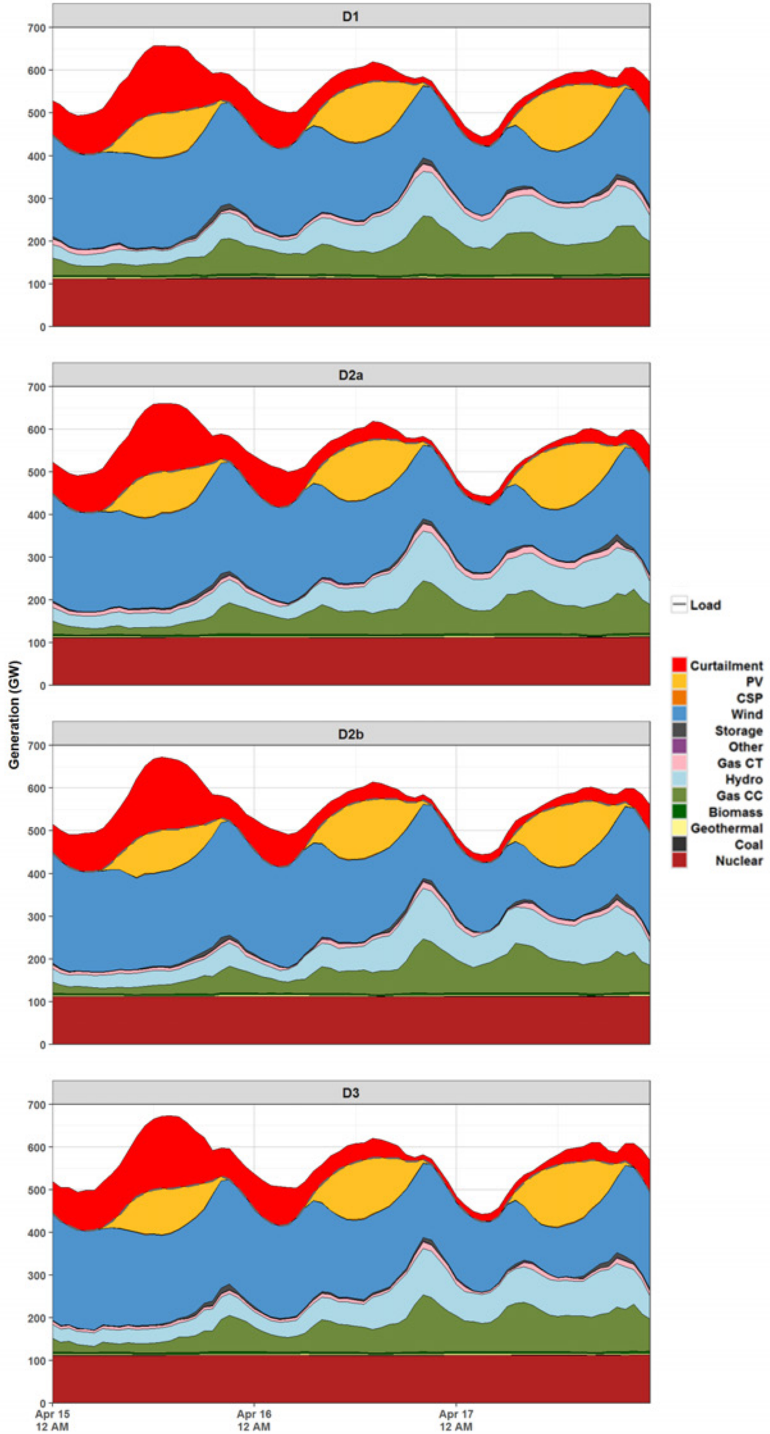
Current Policy High VG

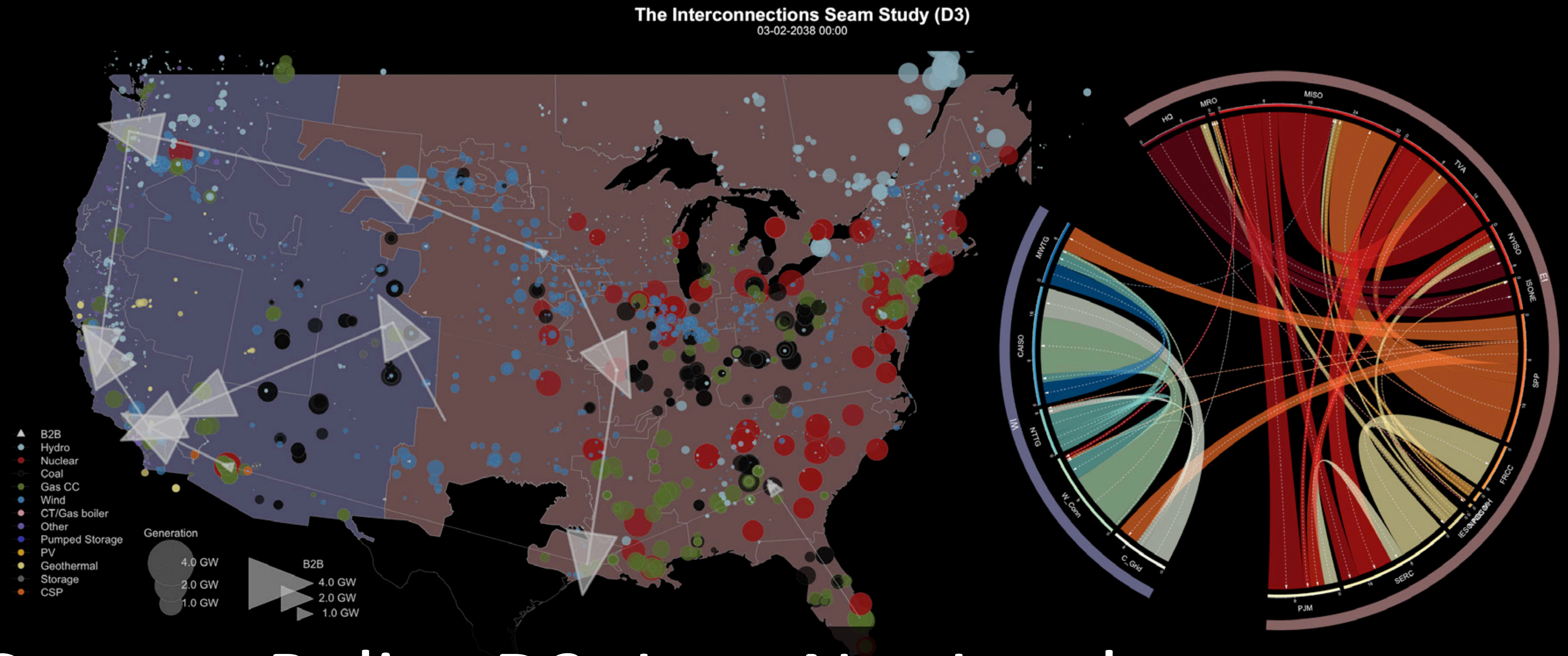
- Low levels of carbon dioxide emissions
- High curtailment
- Low levels of CT use



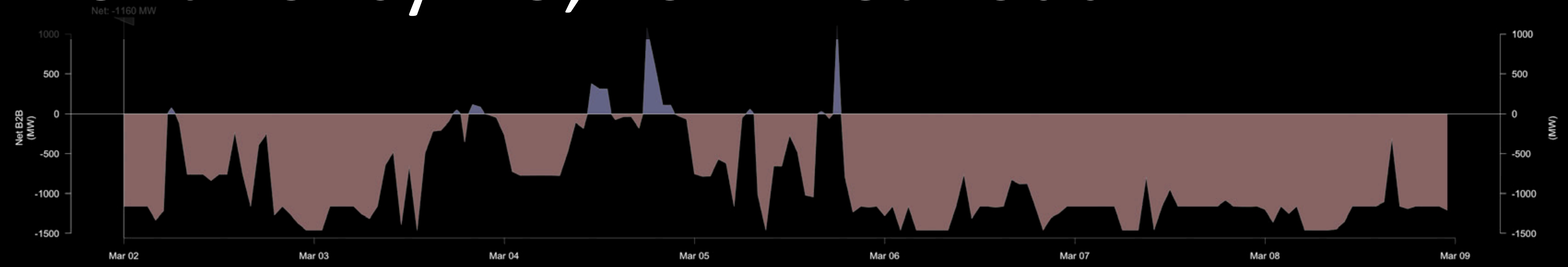
Carbon Policy High VG

- Very low levels of carbon dioxide emissions
- Very high curtailment
- Modest levels of CT use

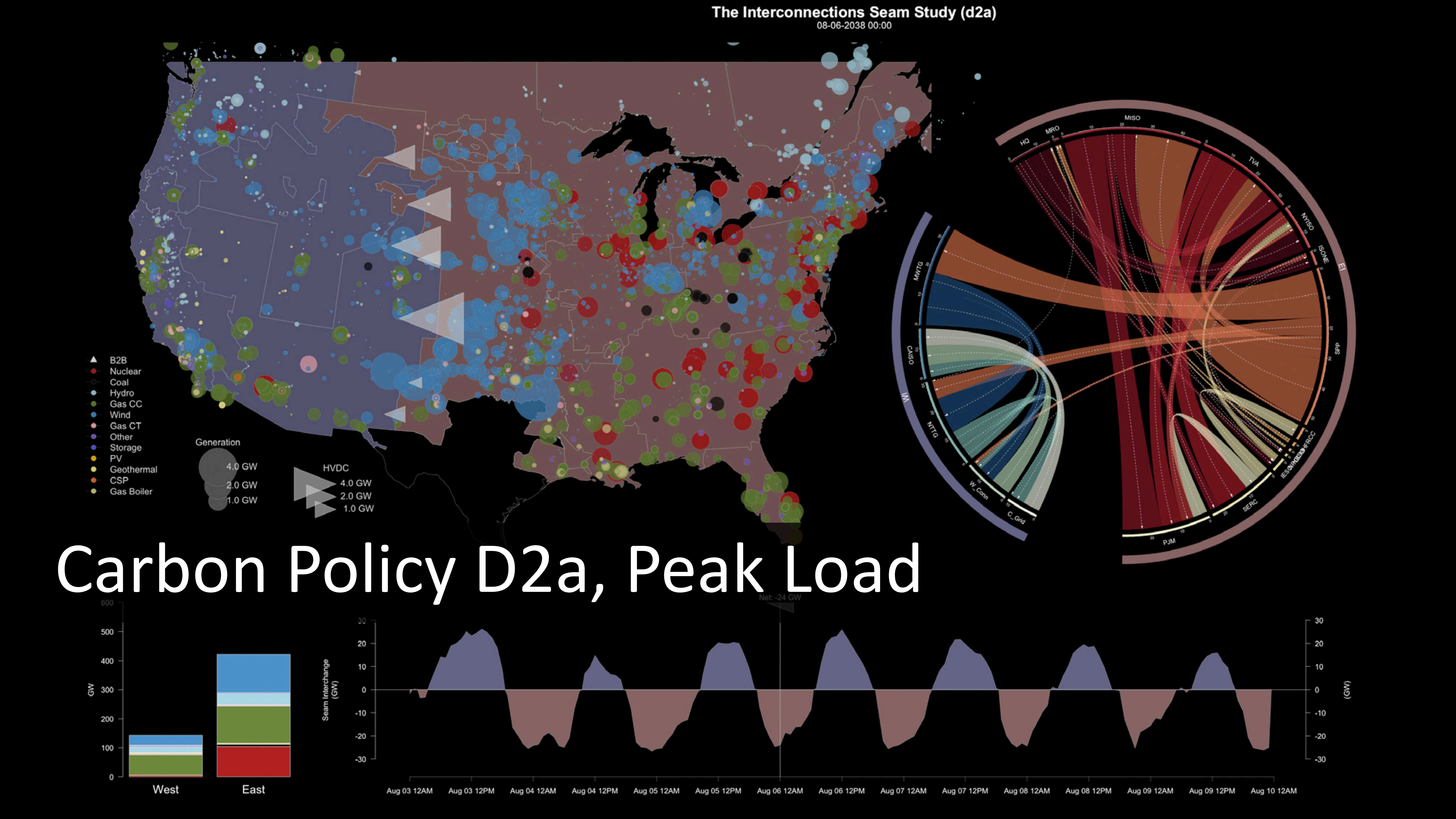




Current Policy D3, Low Net Load



Carbon Policy D2a, Peak Load



Takeaways

- Each design is Reliable from a Resource Adequacy perspective for the single year we studied.
- All load is met while respecting reserve and transmission constraints that approximate N-1.
- Increase transmission results in opportunities for expanded and more efficient capacity and energy markets.
- Increased cross seam transmission enables efficient energy sharing.

What could it cost?

What are the benefits?

Total Costs 2024-2038 (NPV $B)

$$BCR = \frac{\text{Change in Total non-Transmission Costs}}{\text{Change in Transmission Investment Costs}}$$

Example, D1 vs D2a Current Policy: 4.01/3.19= 1.26

	Current Policy							Carbon Policy						
ECONOMICS, NPV $B	**D1**	**D2a**	**Delta**	**D2b**	**Delta**	**D3**	**Delta**	**D1**	**D2a**	**Delta**	**D2b**	**Delta**	**D3**	**Delta**
Line Investment Cost	23.5	26.69	3.19	31.5	8	37.7	14.2	61.21	73.89	12.68	74.88	13.67	80.1	18.89
Generation Investment Cost	493.6	494.7	1.1	492.5	-1.1	494.2	0.6	704.03	703.32	-0.71	696.99	-7.04	700.51	-3.52
Fuel Cost	855.1	852.7	-2.4	851.2	-3.9	845.6	-9.5	753.8	738.98	-14.82	737.3	-16.5	736.12	-17.68
Fixed O&M Cost	416.4	415.6	-0.8	413.7	-2.7	413.8	-2.6	455.6	450.2	-5.4	448.95	-6.65	450.23	-5.37
Variable O&M Cost	81	81.1	0.1	81.2	0.2	81.2	0.2	64.5	63.9	-0.6	64.27	-0.23	64.39	-0.11
Carbon Cost	0	0	0	0	0	0	0	171.1	164.2	-6.9	162.6	-8.5	162.5	-8.6
Regulation-Up Cost	31.6	30.97	-0.63	31.13	-0.47	30.02	-1.58	33.29	31.63	-1.66	29.96	-3.33	26.63	-6.66
Regulation-Down Cost	45.1	44.2	-0.9	44.42	-0.68	42.85	-2.26	4.76	4.52	-0.24	4.29	-0.47	3.81	-0.95
Contingency Cost	23.9	23.42	-0.48	23.54	-0.36	22.71	-1.2	24.41	23.19	-1.22	21.97	-2.44	19.52	-4.89
Total Non-transmission Cost (Orange)	1,947.00	1,943.00	-4.01	1,937.70	-9.01	1,930.00	-16.34	2,211.49	2,179.94	-31.55	2,166.33	-45.16	2,163.71	-47.78
15-yr B/C Ratio (Orange/Green)			1.26		1.13		1.15			2.48		3.3		2.52

2038 Production Costs ($B)

	Current Policy				Carbon Policy			
Type	D1	D2a	D2b	D3	D1	D2a	D2b	D3
Emissions	0	0	0	0	25.1	23.6	23.5	23.9
Fuel	70.3	69.7	69.5	68.1	61.5	59.9	59.8	61.3
Start & Shutdown	2.8	2.7	2.7	2.5	2.7	2.3	2.2	2.2
VO&M	6.5	6.4	6.4	6.4	4.9	4.8	4.8	4.8
Total	79.6	78.8	78.5	77	94.1	90.7	90.3	92.2
Annual Savings	-	-0.8	-1.1	-2.5	-	-3.5	-3.8	-1.9

Benefits

- All designs produce benefits that exceed costs.
- Results should be viewed directionally, not definitively.
- Comparisons are made to D1, which includes significant AC expansion, but no cross seam expansion.
- Full asset life is assumed to be 35 years, over the long run, the benefit may be significantly higher.
- Not appropriate to assume 2038 savings will stay the same until retirement, they may increase or decrease depending on the rest of the system.

	Benefit-to-Cost Ratio 2024-2038	
	Current Policy	Carbon Policy
D1	-	-
D2a	1.26	2.48
D2b	1.13	3.3
D3	1.15	2.52

	Production Cost Savings 2038 ($B)	
	Current Policy	Carbon Policy
D1	-	-
D2a	-0.8	-3.5
D2b	-1.1	-3.8
D3	-2.5	-1.9

Areas for Improvement

- Refine multi-model integration to remove modeling seams, e.g. capacity and network translation, and retirements.
- Study more designs: no new transmission, synchronize systems, all of North America
- Analyze multiple weather years of simulation to inform resilience to weather.
- Conduct comprehensive stability and contingency analysis

Findings

- There is substantial value to increasing the transfer capability between the interconnections, status quo on the existing B2Bs is the least desirable.

- Cross seam transmission has a substantial impact on the location, size, and type of wind and solar.
  - The “best” wind (Eastern Interconnection) and “best” solar (Western Interconnection).

- Cross-seam transmission enables substantial energy & operating reserve sharing on diurnal and seasonal basis.

- Additional benefits (and costs) may exist, i.e. frequency response and resilience to extreme events.

Discussion Time

- Next Steps:
  - Download the slide deck
  - Send your comments to: aaron.bloom@nrel.gov
  - Submit to Peer-reviewed Journal in 3 months or less.