



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

The Interconnections Seam Study

Continental Power Systems



KEY

- EXISTING STEAM GENERATING STATION — OR — ◊
- EXISTING HYDRO GENERATING STATION — OR — ○
- PROPOSED HYDRO GENERATING STATION — OR — ○

EXISTING TRANSMISSION LINES:

- 26,000 to 44,000 VOLTS ————
- 44,000 to 90,000 VOLTS ————

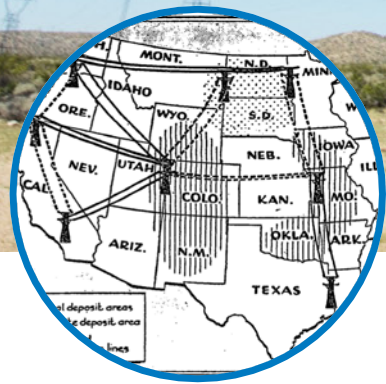
Continental Transmission Studies



Chicago Tribune

1923

Tying the Seasons to Industry



Bureau of Reclamation

1952

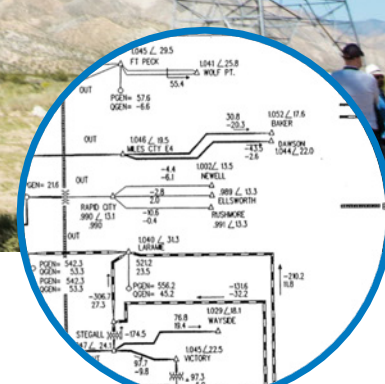
Super Transmission System



Bonneville Power Administration

1979

Interconnection of the Eastern and Western Interconnections



Western Area Power Administration

1994

East/West AC Intertie Feasibility Study



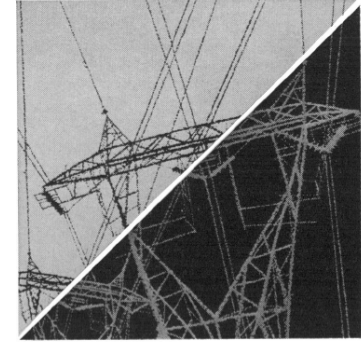
Department of Energy

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 Commission issued its three-volume report calling for the coordinated planning and operation of bulk power supply systems to ensure maximum possible reliability and prevention of future cascading trippouts and power failures. These and related guidelines comprise 34 recommendations. As would be expected, the power industry, after evaluating this report, may have some disparate reactions. These reactions by three federal system—is

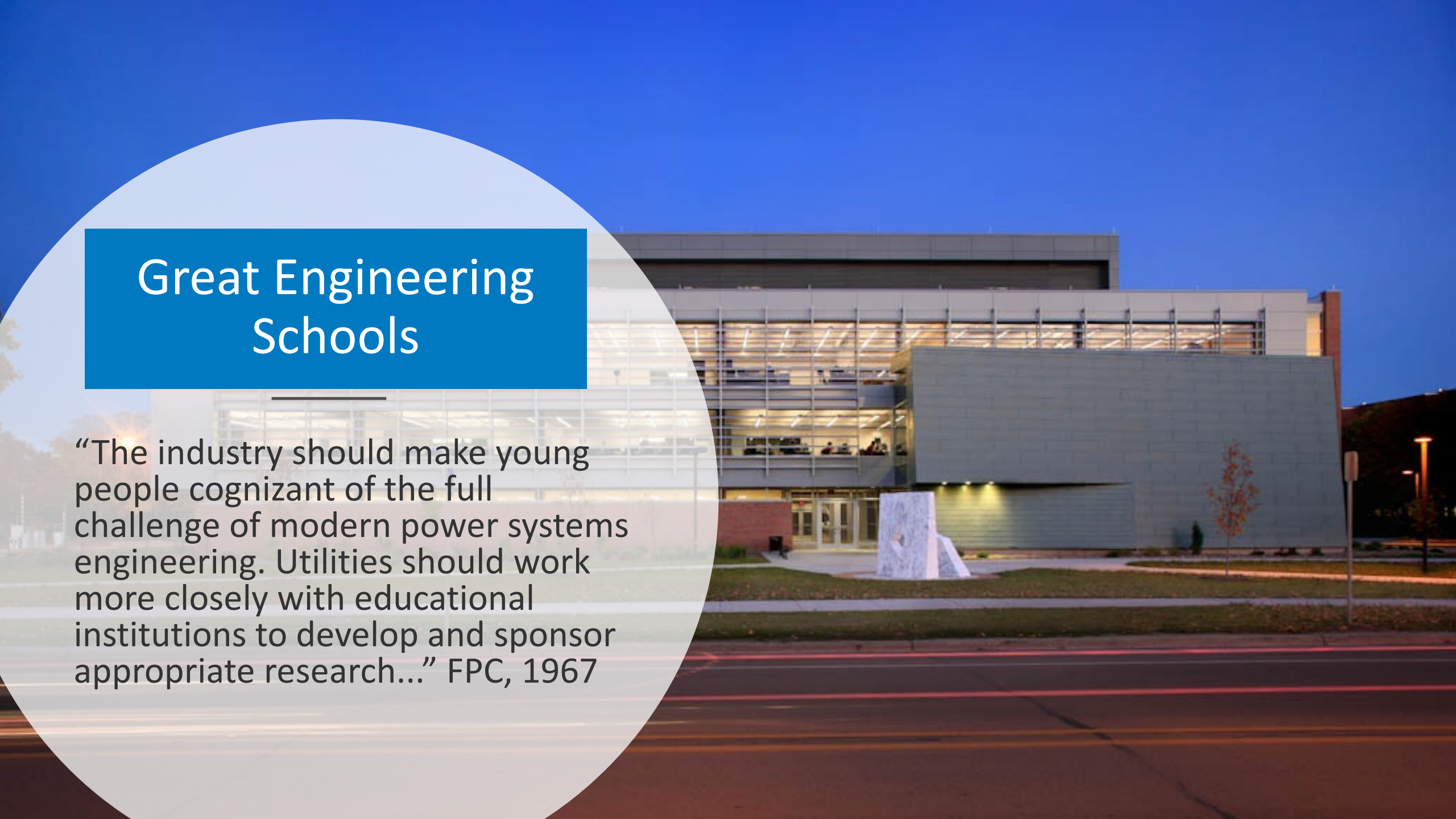
various Task Groups on the Northeast power interruption of 1965 and subsequent outages that affected interconnected systems.

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 local agencies—and private industry—have responded by eliminating a number of the short-

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

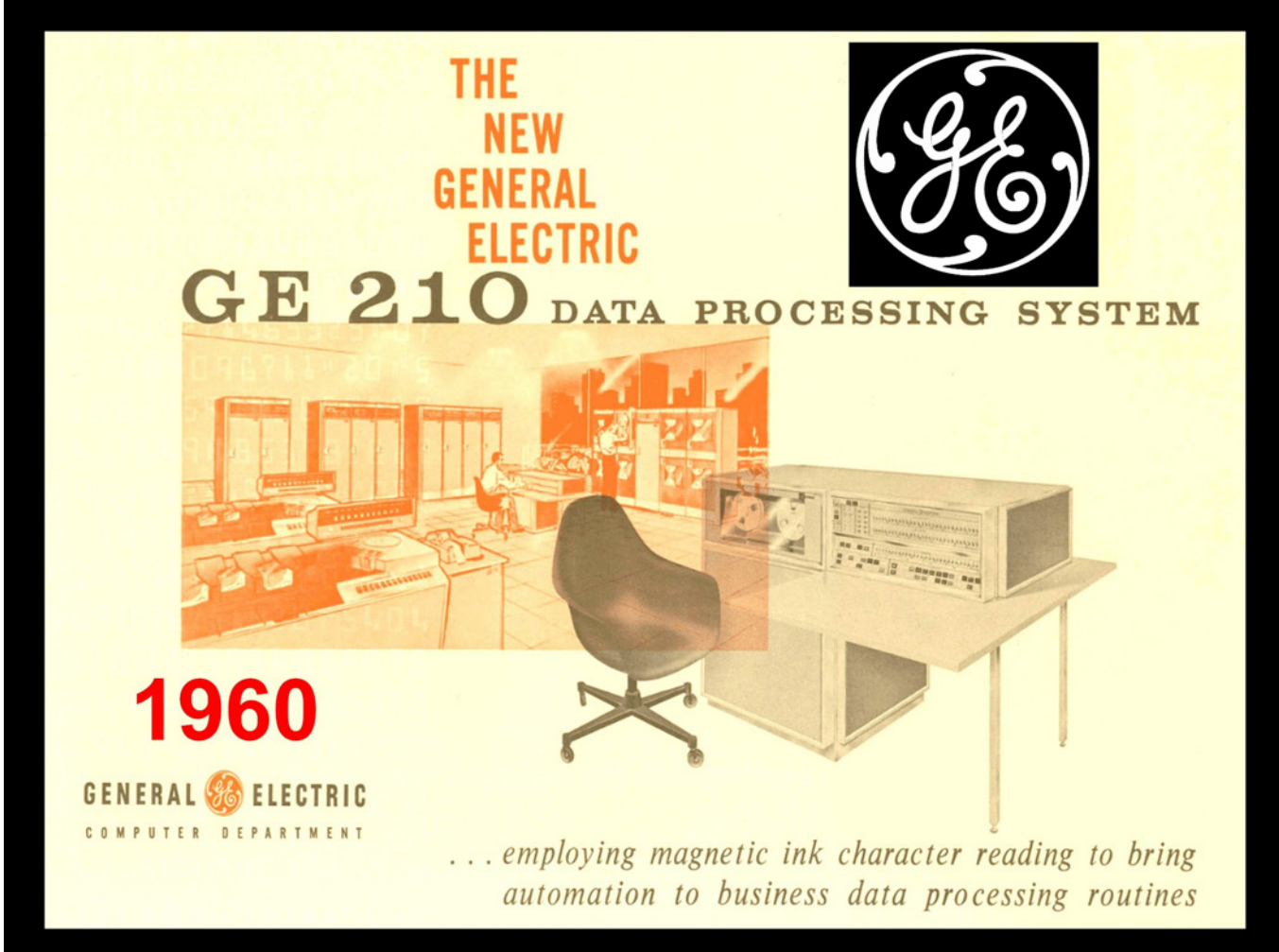


Great Engineering Schools

“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



THE
NEW
GENERAL
ELECTRIC

GE 210 DATA PROCESSING SYSTEM

1960

GENERAL  ELECTRIC
COMPUTER DEPARTMENT

... employing magnetic ink character reading to bring automation to business data processing routines

The advertisement features a large photograph of the GE 210 Data Processing System, which includes a console with a keyboard and a magnetic ink character reader (MICR) unit. A black office chair is positioned in front of the console. The background of the photograph shows a control room with multiple consoles and a person operating the system. The GE logo is prominently displayed in the top right corner, and the year 1960 is written in large red letters below the photograph. The text 'THE NEW GENERAL ELECTRIC' is written in orange above the product name, and 'GE 210 DATA PROCESSING SYSTEM' is written in black below it. The GE logo is a white stylized 'GE' inside a black circle. The text 'GENERAL ELECTRIC' is in a serif font, and 'COMPUTER DEPARTMENT' is in a smaller sans-serif font. The tagline at the bottom is in a cursive font.

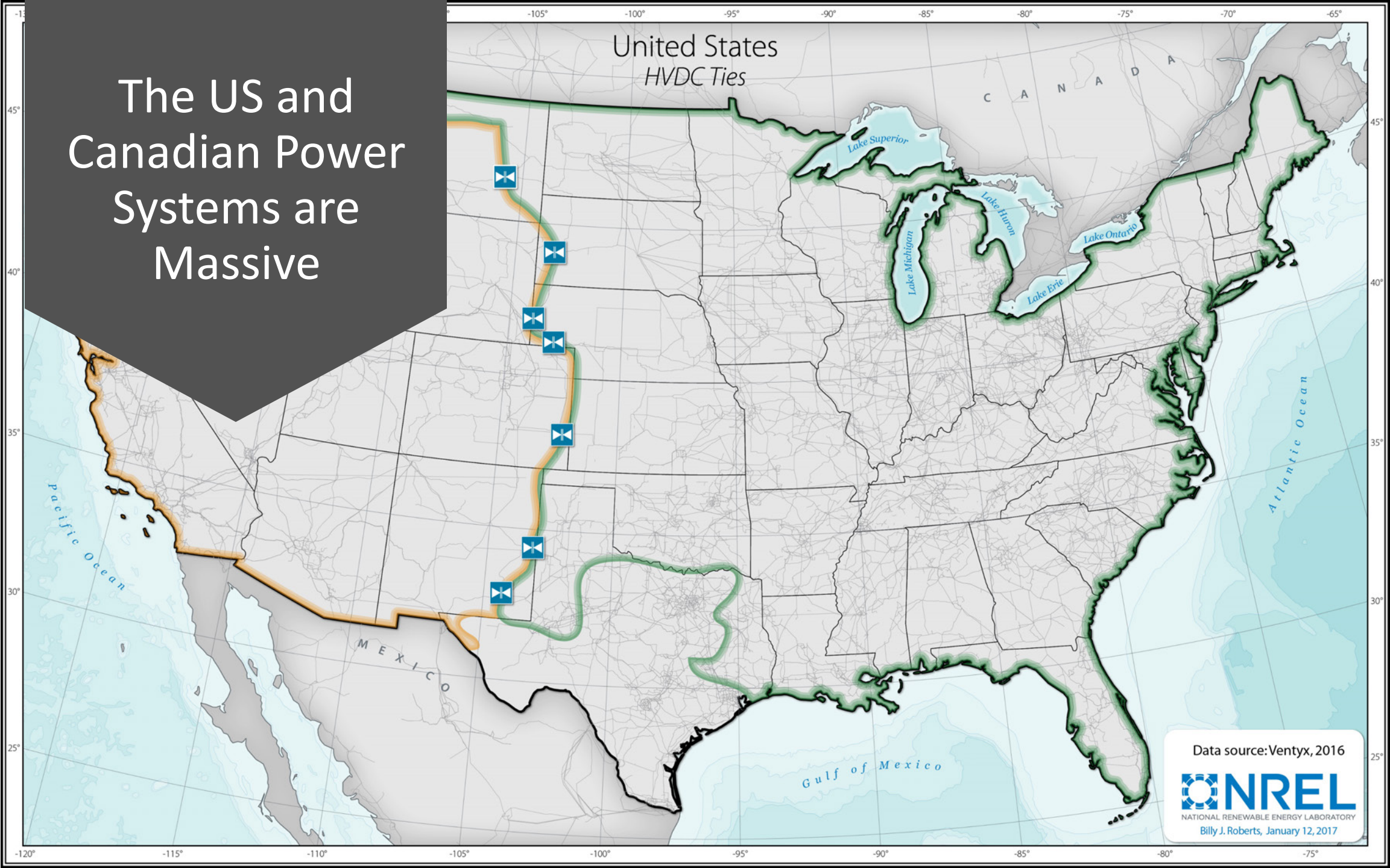


Regional Coordination

“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

United States
HVDC Ties



Data source: Ventyx, 2016



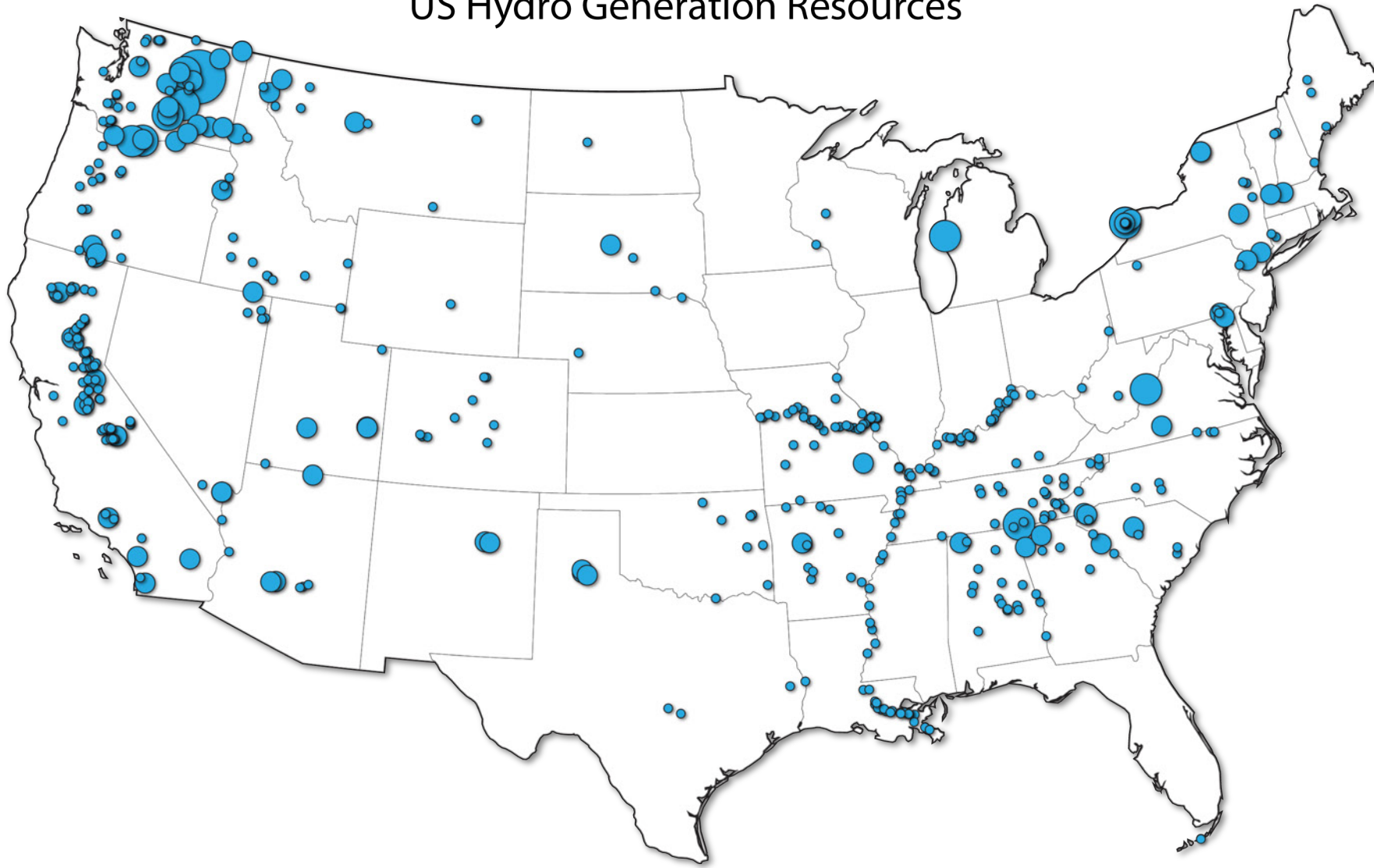
NATIONAL RENEWABLE ENERGY LABORATORY

Billy J. Roberts, January 12, 2017

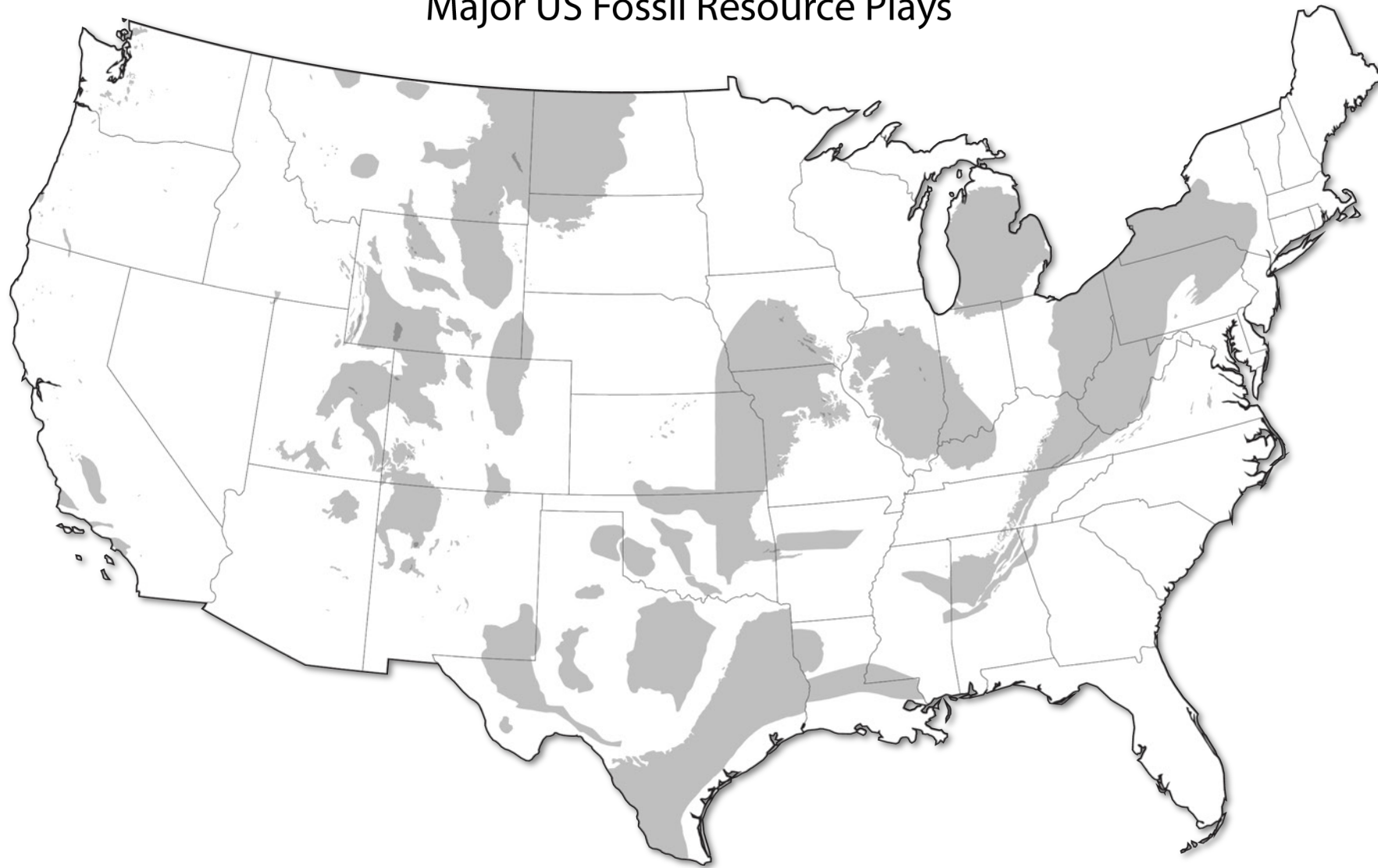
If the value looked that good back
then

What about today?

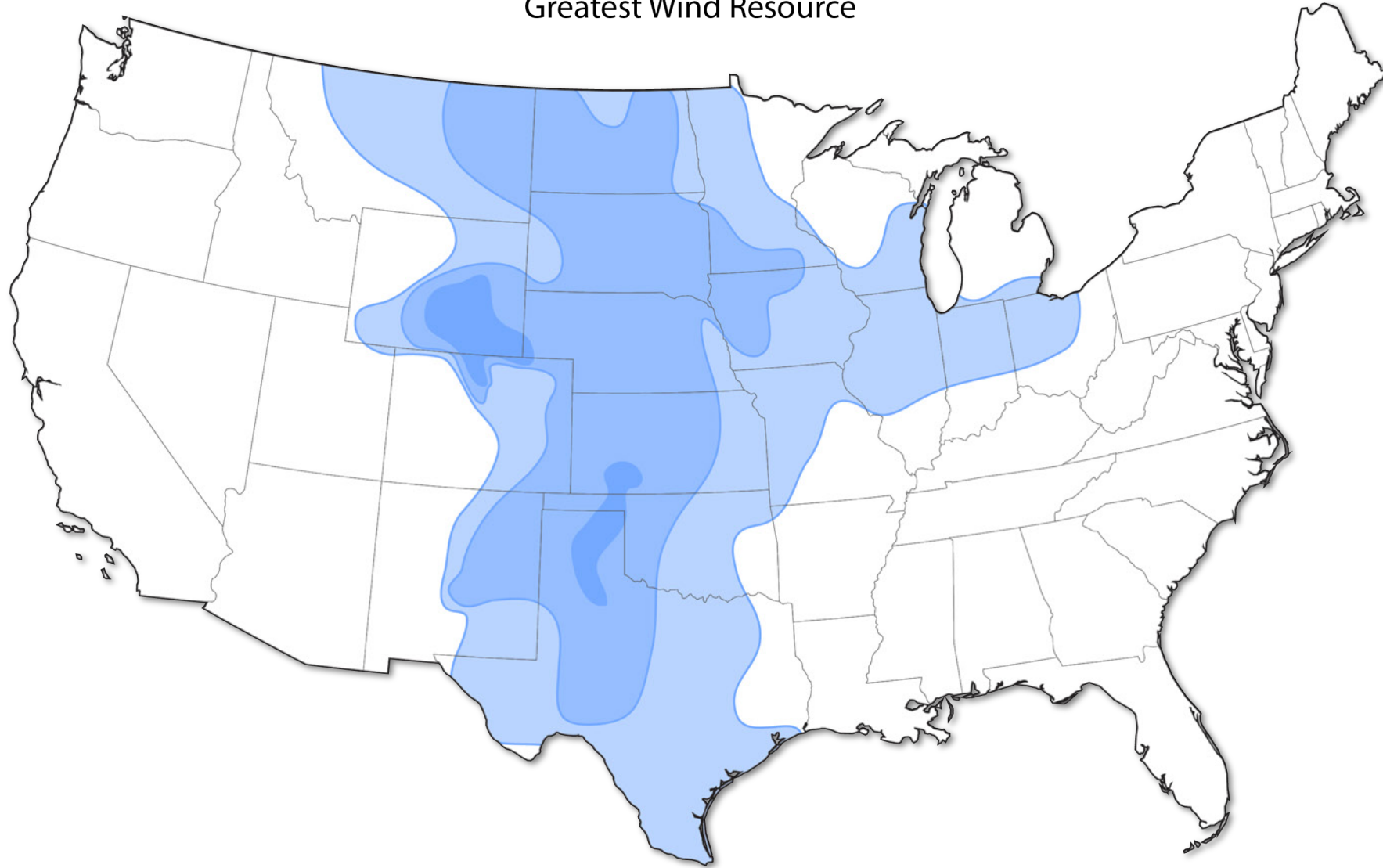
US Hydro Generation Resources



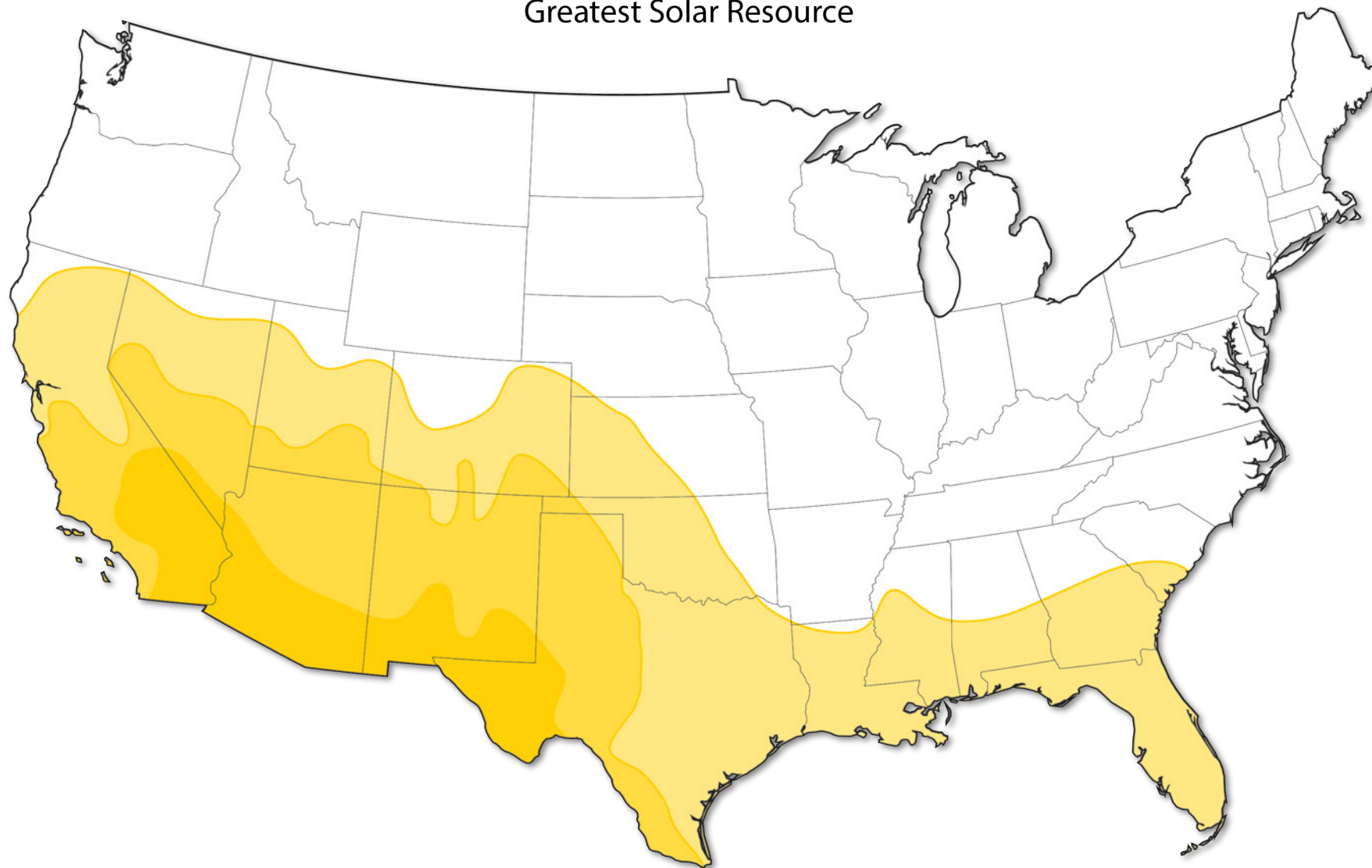
Major US Fossil Resource Plays

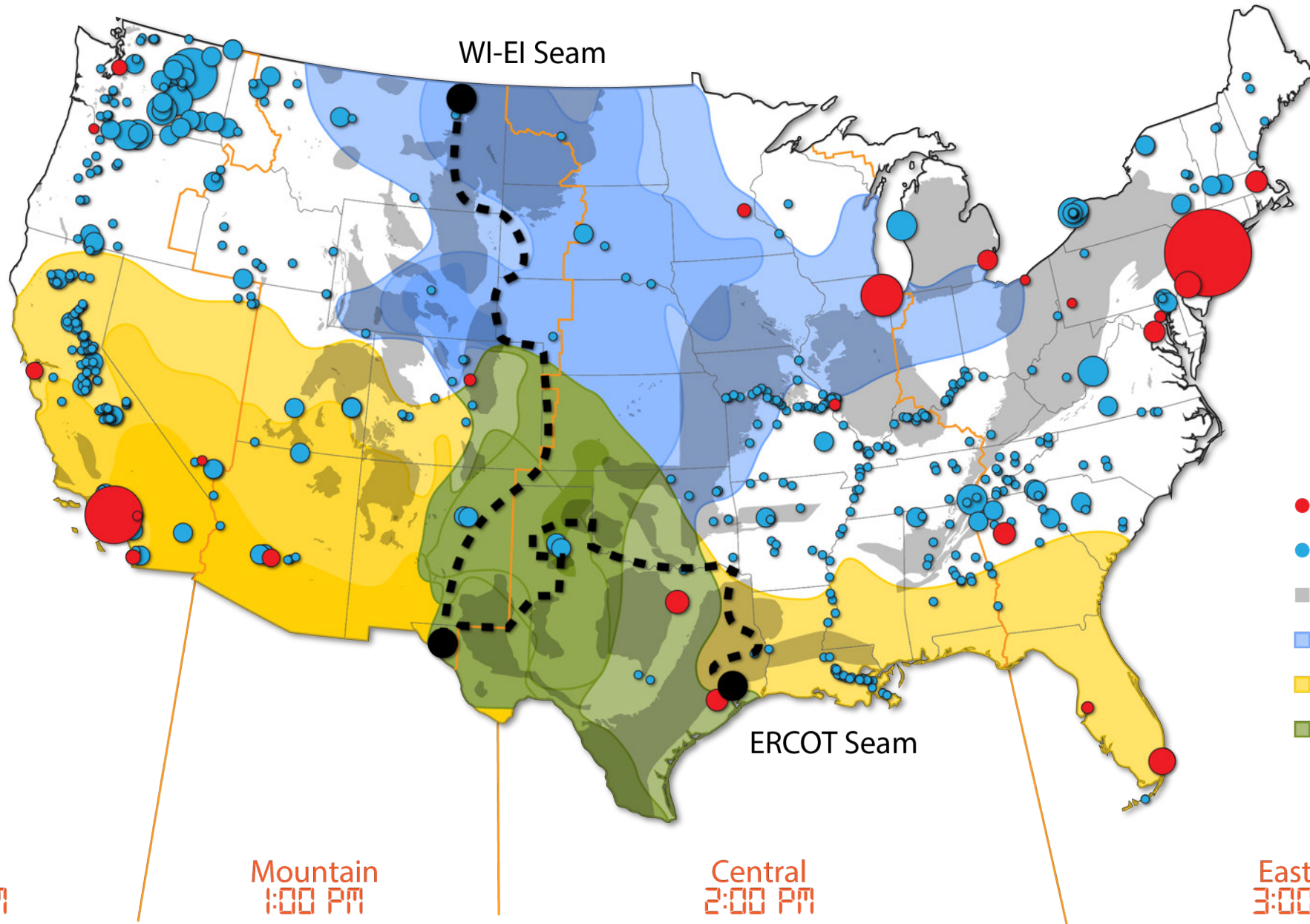


Greatest Wind Resource



Greatest Solar Resource





- 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

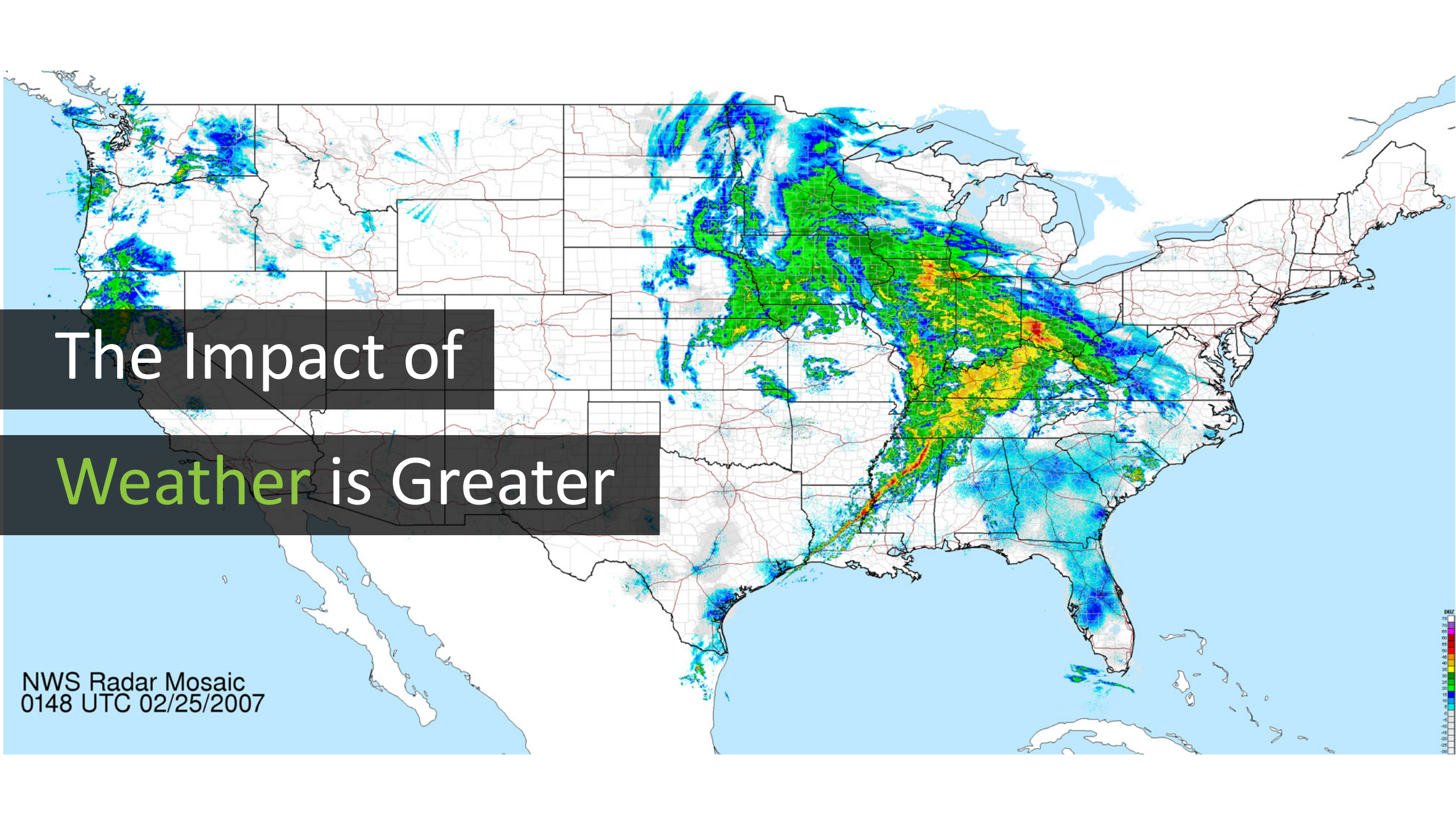
Eastern
3:00 PM



It's Different

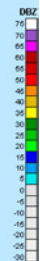
This Time





The Impact of Weather is Greater

NWS Radar Mosaic
0148 UTC 02/25/2007



Daily patterns drive demand and supply



A satellite view of Earth from space, showing the Americas. North America is in the upper left, and South America is in the lower right. The oceans are a deep blue, and the landmasses are green and brown. The Earth is set against a black background of space.

Energy Needs and Supply Change with the Seasons



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

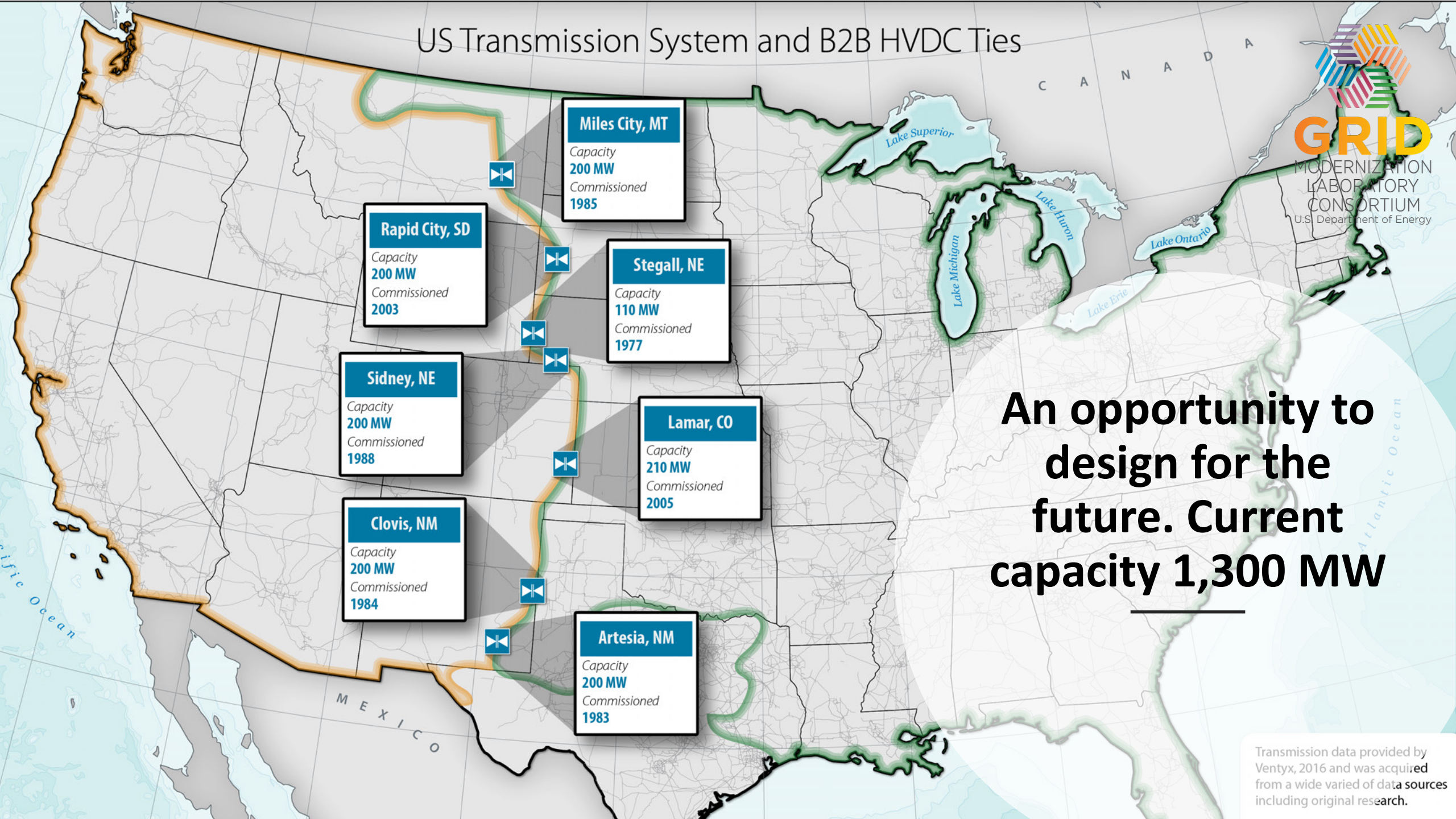
Controllable, directional, electricity transmission, with large scale deployment worldwide



HVAC

The backbone of existing American Transmission

US Transmission System and B2B HVDC Ties



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

Transmission data provided by Ventyx, 2016 and was acquired from a wide varied of data sources including original research.

**What could
be done
with aging
assets?**



**What could
be done
with aging
assets?**

**Is there any
potential
value in
making them
bigger?**






GRID
INNOVATION
LABORATORY
STIUM
of Energy

How much bigger?

Is there any potential value in making them bigger?

What could be done with aging assets?



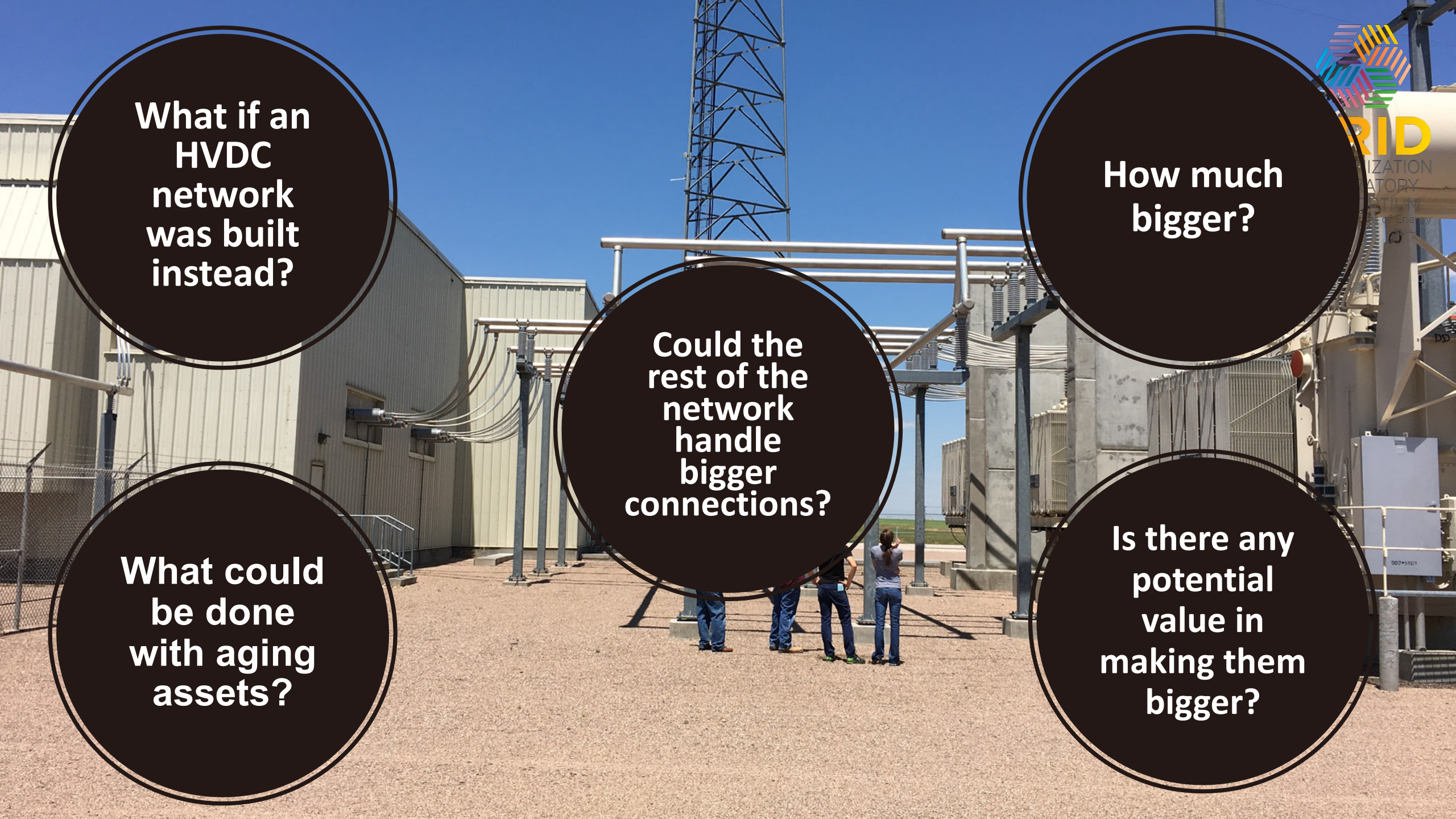


**What if an
HVDC
network
was built
instead?**

**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?**

**Is there any
potential
value in
making them
bigger?**

**What could
be done
with aging
assets?**



A group of approximately 15 people are gathered in a desert landscape, looking at a large metal transmission tower. The tower is a lattice structure made of steel, with several power lines extending from it. The ground is dry and sandy with some sparse vegetation. In the background, there are rolling hills and a clear blue sky. The text "Top 5 Quotes from 95 years of National Transmission Planning" is overlaid on the image in white and green font.

Top 5 Quotes from 95 years of National Transmission Planning

TRIBUNE OFFERS HYDRO-ELECTRIC SYSTEM FOR U. S.

Would Hitch Seasons to All Industries.

(Continued from first page.)

In the great water power system all day enhanced by skin the stations into a common system and the taking of the diversity factor of their flood stages.

Practice seems to have leaped ahead in theory here. Already we know that in such cases the whole develops more power than the sum of the parts—developed as parts, but as it was for the Tennessee first to hint at such a possibility.

The streams made by the Tennessee are yet fragmentary, but already they warrant the belief that when the streams of the entire continent are linked it will be profitable to develop the flood capacity of them all, because the floods are distributed throughout a great portion of a year. As more districts are developed, the water interest will be in the valley by a wide margin.

horizontal curve, or a constant power load—whatever one may choose to call it.

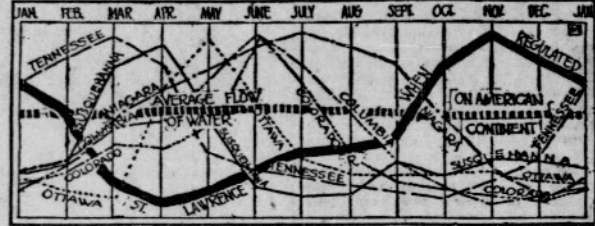
But in addition to this the studies of the consumption side of the power problem appear to show that hitherto untapped economies are possible, because the daily peaks of electric consumption from the Atlantic side are from the gulf to the Pacific waters are distributed through the continent.

The differences in time from east to west are supplemented by the varying lengths of the winter and summer day from north to south. The possibilities revealed by the Tribune's investigations are derived not so much from the nature and technique of hydro-electric generation as from the additional productivity and distributive economies made possible by pooling its transmission on a thoroughly continental scale.

Power of Four Rivers.

How the linking of the rivers for power purposes will increase the horse

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. The accompanying table of figures shows the volume of that flow at points where it can be measured.

The story itself tells how these rivers can be met so the rivers can be electric power transmission and industrial use as well as a city and a city.

COLORADO RIVER AT YUMA. Mean monthly flow—1904, 1905, 1907, 1908.

Month	Flow
January	10,000
February	12,000
March	15,000
April	18,000
May	20,000
June	22,000
July	25,000
August	28,000
September	30,000
October	32,000
November	35,000
December	38,000
Average	24,000

NIAGARA RIVER. Mean monthly flow—1922 and 1923 to 1916, inclusive.

Month	Flow
January	10,000
February	12,000
March	15,000
April	18,000
May	20,000
June	22,000
July	25,000
August	28,000
September	30,000
October	32,000
November	35,000
December	38,000
Average	24,000

OTTAWA RIVER. Mean monthly flow for 1905 and 1904.

Month	Flow
Jan.	35,000
Feb.	38,000
March	40,000
April	42,000
May	45,000
June	48,000
July	50,000
August	52,000
September	55,000
October	58,000
November	60,000
December	62,000
Average	50,000

TENNESSEE RIVER. Forty-eight years' monthly mean.

Month	Flow
January	85,000
February	100,000
March	110,000
April	120,000
May	130,000
June	140,000
July	150,000
August	160,000
September	170,000
October	180,000
November	190,000
December	200,000
Maximum	450,000
Minimum	8,500

stage that hinders navigation from the gulf to the heart of the continent. Because of the vast surface of the lakes, such impounding and releasing operations would alter their level by only a few inches, while the mass of water involved would mean additions to power and effective enhancement of the flow of navigable streams.

nomics of the case. The market for power and the price are balanced against the cost of the transmission system—that is all.

Sketches Trans-U. S. Plan.

Frank G. Baum of San Francisco, one of the engineers responsible for the development of superpower lines in California, has sketched in considerable detail a proposed national transmission system to connect up water power and steam generating plants from coast to coast. Such plans contemplate interchange of power over 220,000 volt power lines, such as are now coming into use in California, although it may be necessary to build lines up to 350,000 volt capacity to make the water power of the Sierras available to the prairie states.

As far as THE TRIBUNE'S investigations have gone, it appears that the trunk lines for such a system as it contemplated will probably be of greater voltage than either of these figures. The technique of even higher voltage lines is being developed in California.

Production of 1,000,000 and 2,000,000 volts for test insulation systems is an accomplished fact. Interesting experiments are said to be under way.

Inspired by the prospect of transforming very high voltage alternating current into direct current of much greater potential.

Charging 1,000,000 Volts.

It is said that the size of enormous high voltage power lines is being advanced, about the strain and breaking effect which is one of the problems of transmission. Direct current of a million volts obtained from alternating currents is an alluring prospect in the consideration of the continental power system, but not of prime importance.

Plans of this sort are too technical for discussion here. THE TRIBUNE'S conception of the continental power system based on maximum hydro-electric development synchronized in operation with seasonal floods, must necessarily be based on a survey of the hydroelectric resources of the continent.

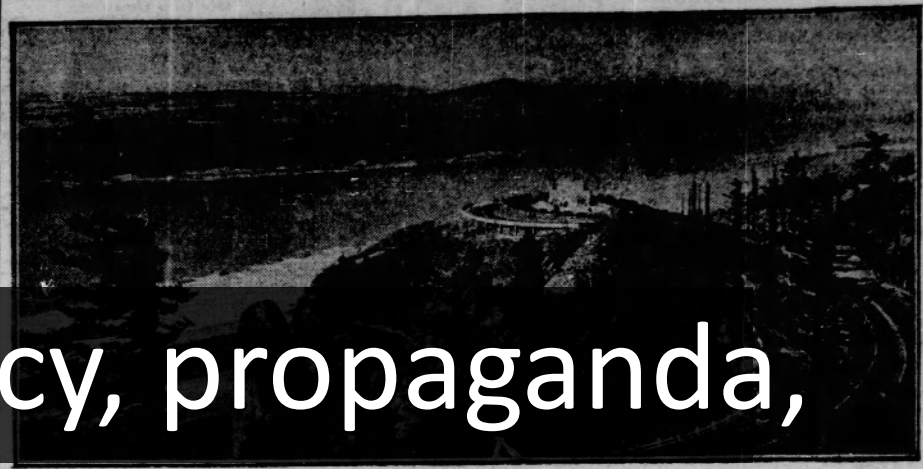
Plans of this sort are too technical for discussion here. THE TRIBUNE'S conception of the continental power system based on maximum hydro-electric development synchronized in operation with seasonal floods, must necessarily be based on a survey of the hydroelectric resources of the continent.

of government, states, and individual engineers when assembled all tend to raise the estimates of water power available for the American people.

More Rivers, More Power.

The more streams that are considered together, the higher the potential horse power becomes. In a limited exposition of this sort it has been practical only to cite small scale examples, but not only does the total amount of our potential water power under government, states, and individual engineers when assembled all tend to raise the estimates of water power available for the American people.

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 Columbia highway during the visit of the President to the northwest.

possible to impound the floods from melting snow and ice for regulated discharge over the period in which the streams of the south reach their low level. The southern streams begin to rise as freezing begins in the north. The Alaskan and Canadian streams seem destined to play a most important part in continental power. It is not extravagant to entertain the hope that the continental power system will be able to harness the floods from melting snow and ice for regulated discharge over the period in which the streams of the south reach their low level.

Every mile of electrical power line built reduces the haulage of coal by railway, both in autumn and the year round. Power can now be delivered for hundreds of miles at one-half of the freight charges on coal transported for the manufacture of power.

A rough idea of the power available on this continent from the utilization of the flood capacities of its streams may be obtained by approaching the problem through the variation from low to high water. From extreme low to peak—the variation of most rivers is enormous. The Mississippi at Keokuk goes from 20,000 cubic feet per second to 300,000, a ratio of 1 to 15. The ratio for the Connecticut is 1 to 40, the Missouri 1 to 29, the Delaware 1 to 175, the Merrimack, 1 to 69.

The variation of rivers appears to range from the Niagara's 1 to 2 up to the zero to thousands ratio of some western "streams." There are indications that a general survey of North American streams may disclose a ratio of 1 to 25. But, assuming that this is enormous, the variation of most rivers is enormous. The Mississippi at Keokuk goes from 20,000 cubic feet per second to 300,000, a ratio of 1 to 15.

While the proposed system will be able to deliver power in quantities now only imaginable, at far less cost than at present, its installation will reduce the amount of power required and lead to the more efficient use of that employed.

heat direct to many metallurgical operations. The unique economy of the continental system will come from the rotation of the earth and its inclination upon its axis. The great problem of the electric industry today is the load factor. Electrical engineers have said that the life of the industry is diversity of load, which means a diversity of uses for electrical current to avoid the waste of capital, labor, and fuel involved in providing current to meet isolated peak demands, daily or seasonally.

An All-Performing Giant.

It is probably unnecessary to point out that the greatest diversity of load can only be attained by a continental system, embracing all industrial tasks. Merely to enumerate the sorts of installed power that the hydro electric system will displace is to indicate the multiplicity of new work to be imposed on it, and its distribution in space and time.

But the peak load caused by the demand for lighting and the related power demand for electric railways and the commercial and industrial uses, associated with work done under artificial light will be profoundly modified by the integration of the industry into a continental system. The big daily peak for all city electric systems, which must be provided for by adequate investment, comes about 5 or 6 o'clock in winter evenings, when homes and stores are lighted up, and the transit systems call for maximum power to take the workers home, while many factories are still running.

Flattening Peak Load.

Due to the four hour difference in time from Halifax to Tacoma, and the varying length of the day which finds casually folk in summer playing ball hours after New Orleans has passed through her brief subtropical twilight, the evening peak will be flattened out on a continental power system.

The peak load will start in the northeast of the continent at Halifax and sweep south and west in slow waves across to the Pacific and the gulf. By the time San Francisco and New Orleans are calling for the maximum of power, New York's workers have arrived at home, and Montreal has gone to bed.

With a continental power system, power can be applied at any moment anywhere—power that travels 150,000 miles per second, moves itself, and pays its own freight.

PACIFIC STATES PLAN FIGHT ON PITTSBURGH PLUS

Colorado and other states of the Mountain Pacific group are soon to enter the fight against "Pittsburgh plus" recently invigorated by concerted action in the middle west, according to announcement made yesterday at Salt Lake City by J. W. Coverdale, executive secretary of the American Farm Bureau federation.

Gov. Mabey of Utah, as well as chief executives of other western states, has already actively entered the fight. Mr. Coverdale declared. Other states mentioned as vigorously opposing the present practice under which steel

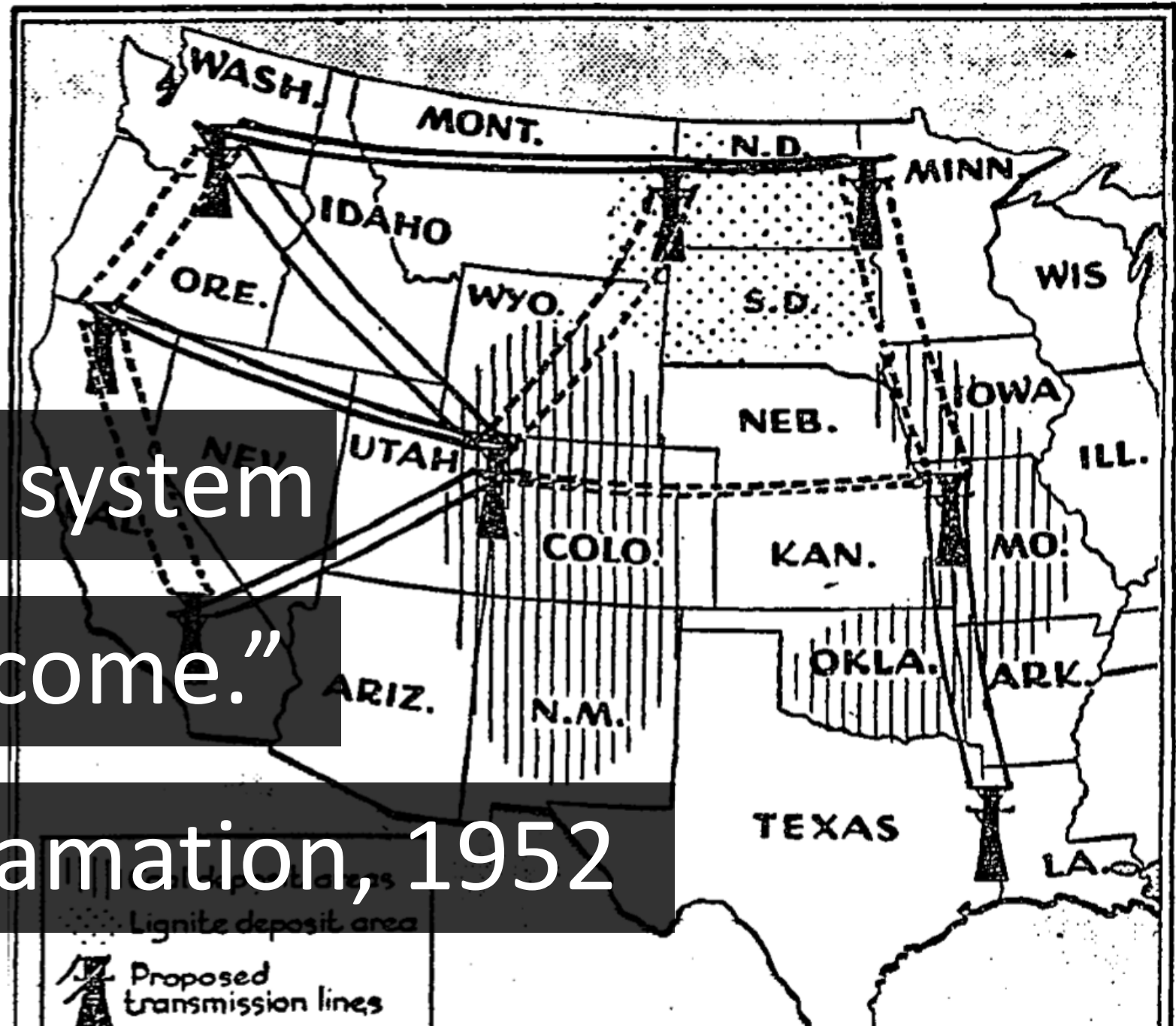
"This is neither prophecy, propaganda, nor rhapsody, but the assured goal of the scientific and economic forces at work." Chicago Tribune, 1923

COAL MAY PROVIDE POWER FOR WEST

Reclamation Bureau Pictures
Super Transmission System
Operated by Steam Plants

“Such a power system
will inevitably come.”

Bureau of Reclamation, 1952



WASHINGTON, D.C. (AP) — The Reclamation Bureau today pictured the West's future power needs being supplied in large part by coal over a eventually long distance transmission system. More than half now is supplied by hydroelectric plants.

The bureau made public a study estimating the power needs of 13 of the 15 states from Minnesota and Louisiana to the west, and proposing long range planning to fill them.

Michael W. Straus, Reclamation

UNITED STATES GOVERNMENT

Memorandum



DATE : JUL 6 1979
In refer to : EGGD

“The results to date indicate

that if there are **substantial benefits**

to east-west reclosure...”

FROM : R. L. Cresap

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

Bonneville Power Administration, 1979

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”

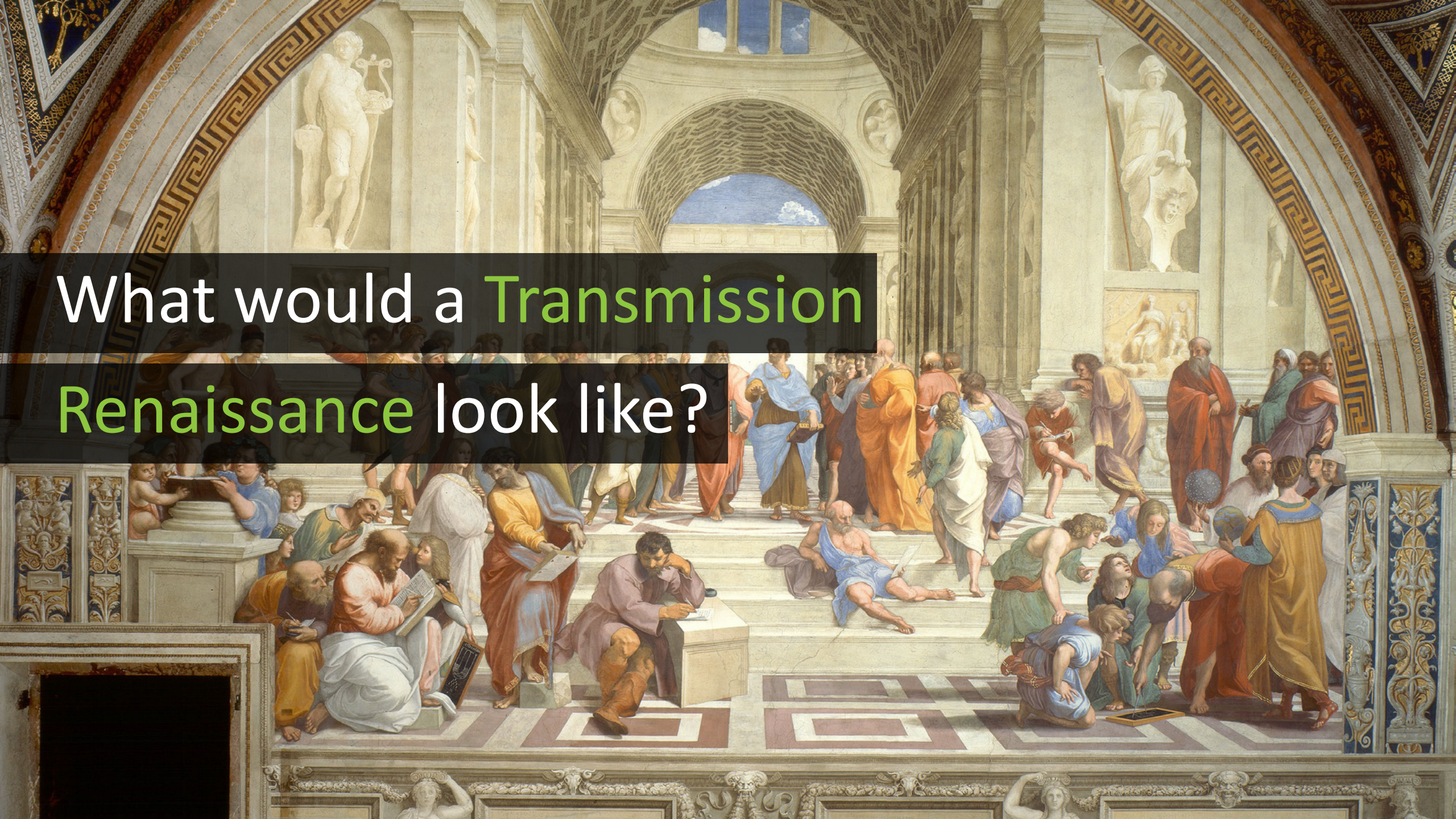
WAPA, 1994

**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

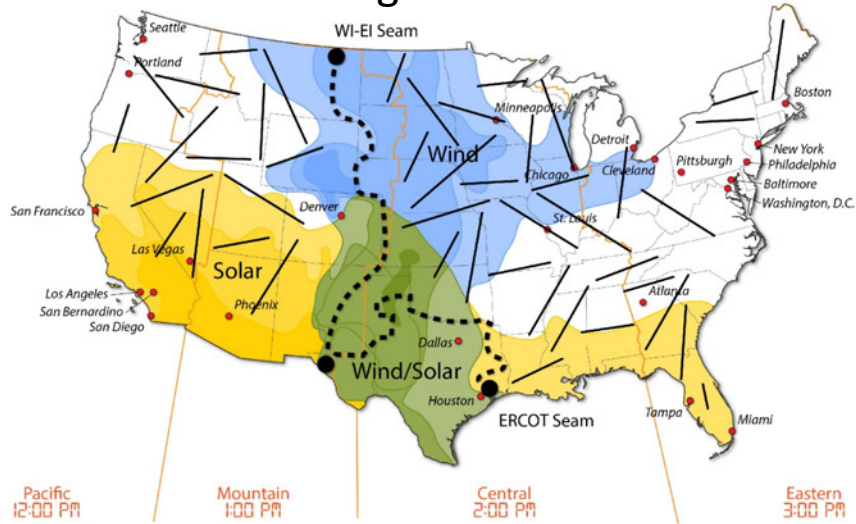




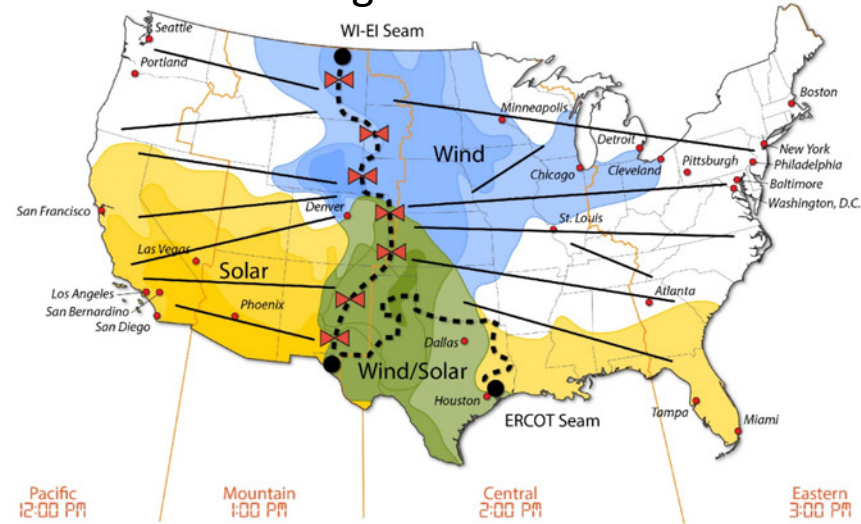
Technical Review Committee

Design Concepts

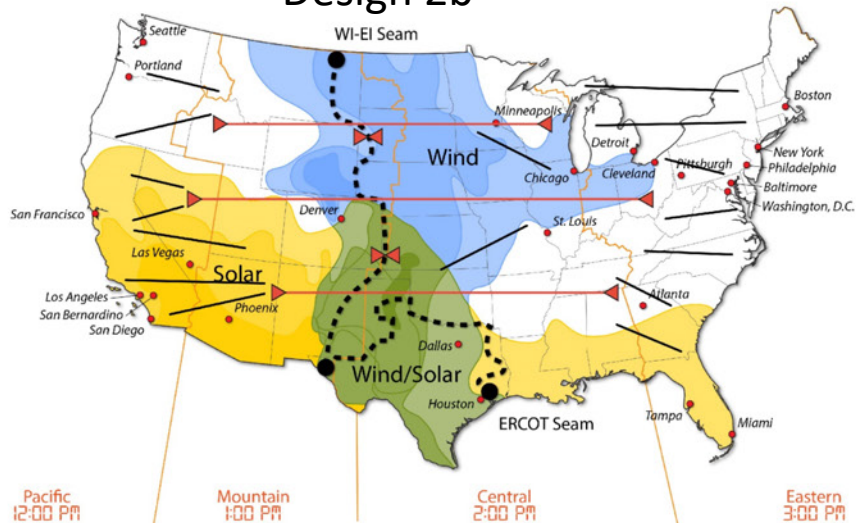
Design 1



Design 2a



Design 2b



Design 3

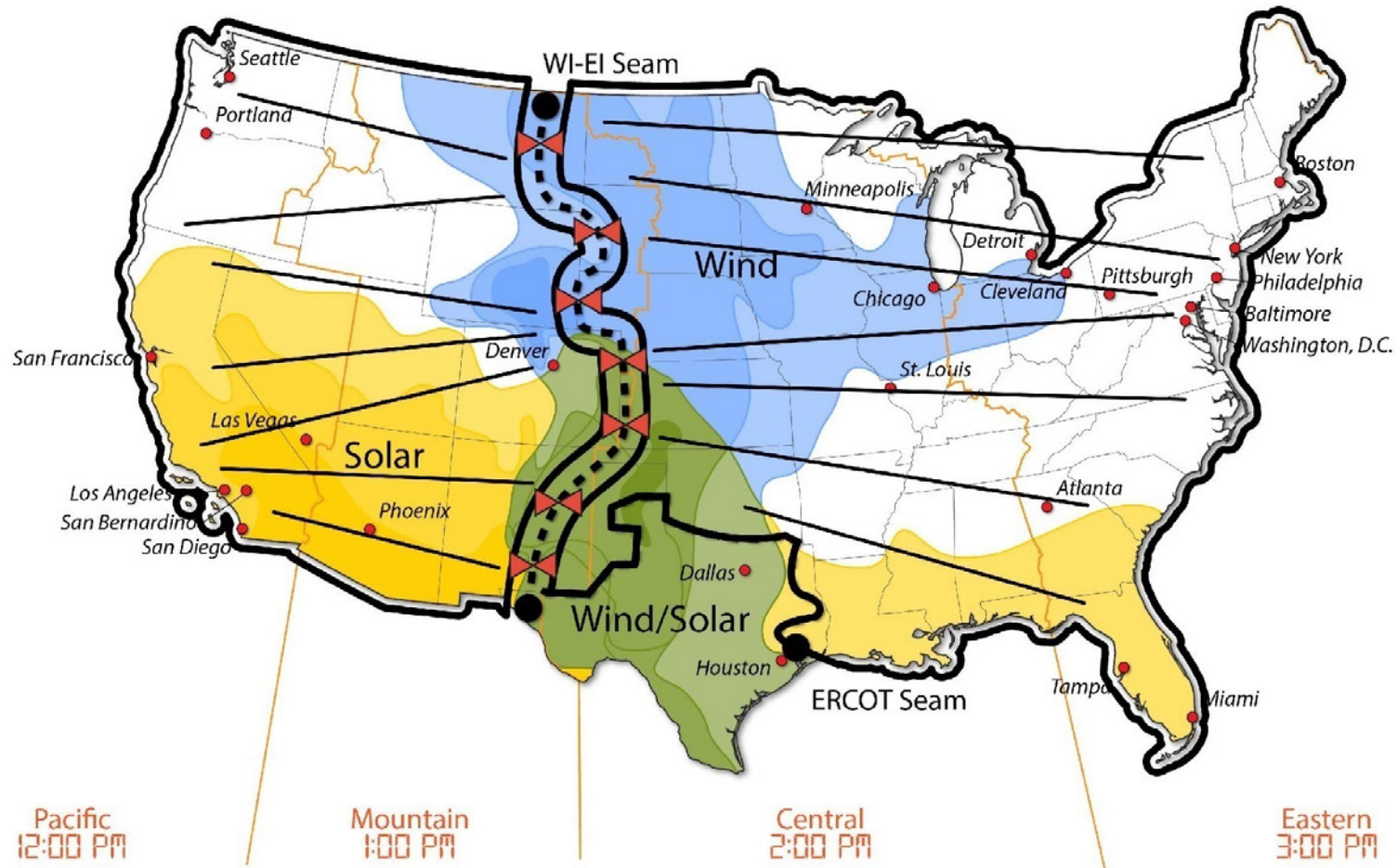


Design 1



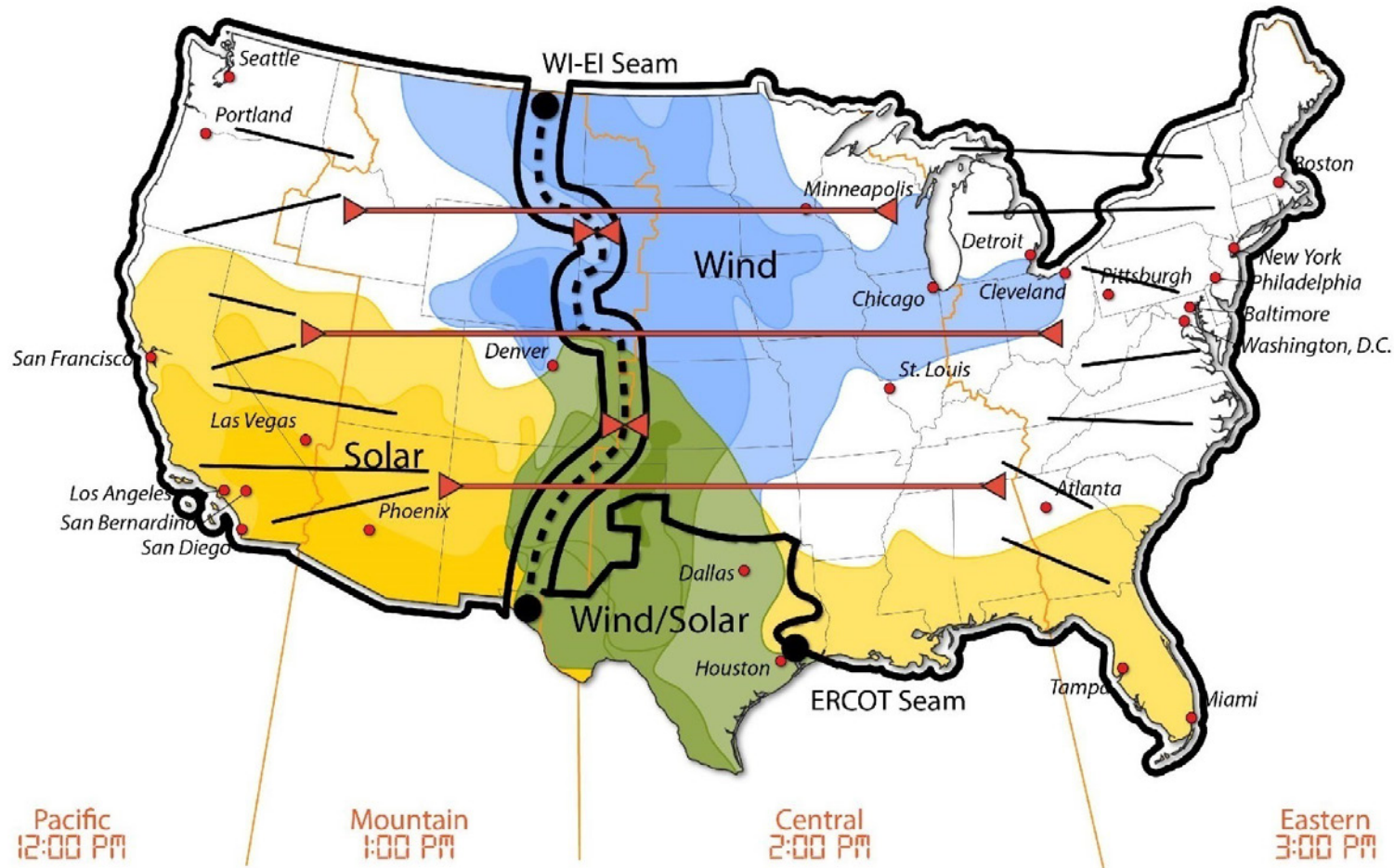
Existing B2B facilities are replaced at their current (2017) capacity level and new AC transmission and generation are co-optimized to minimize system wide costs.

Design 2a



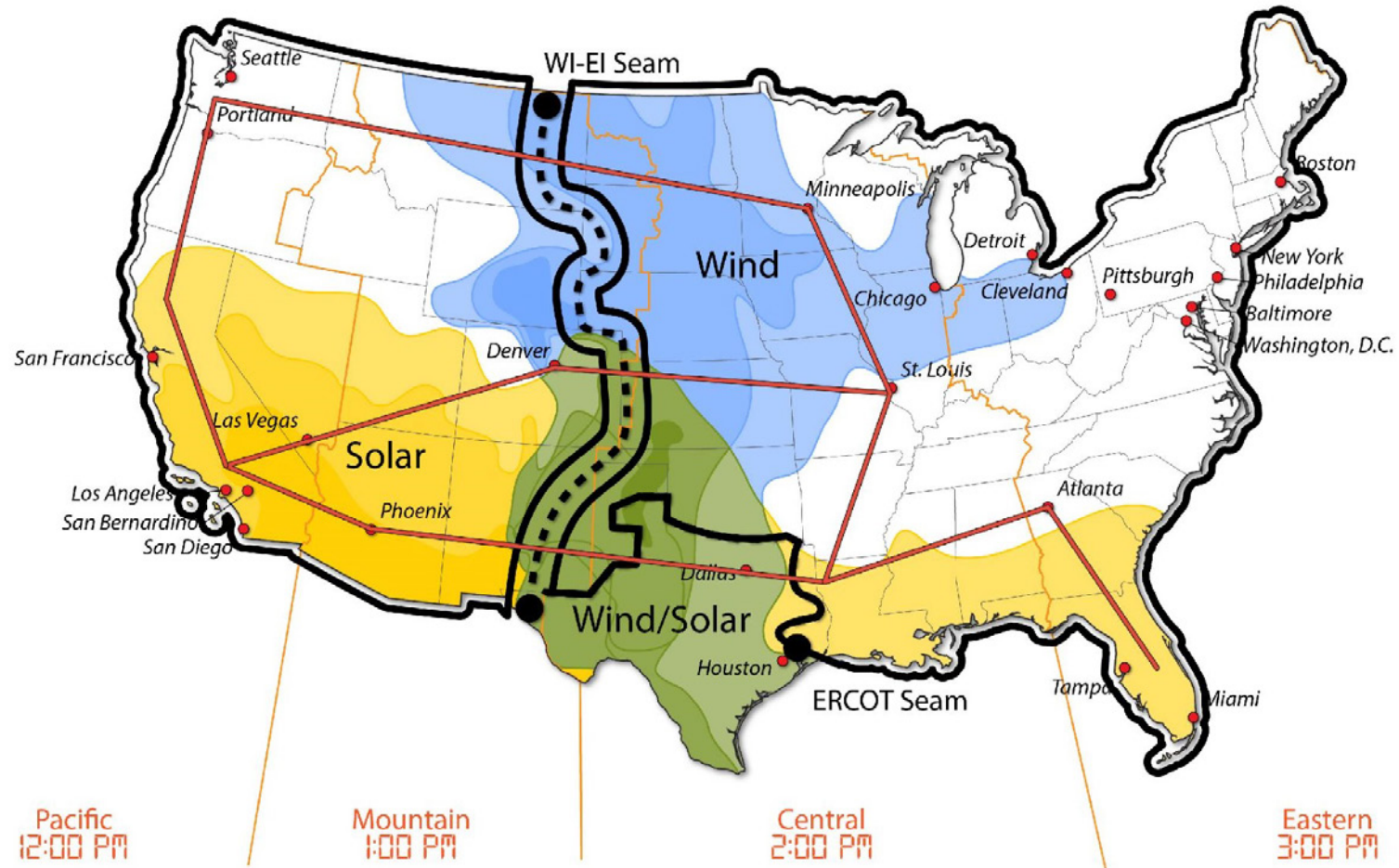
Existing B2B facilities are replaced at a capacity rating that is co-optimized along with other investments in AC transmission and generation.

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.



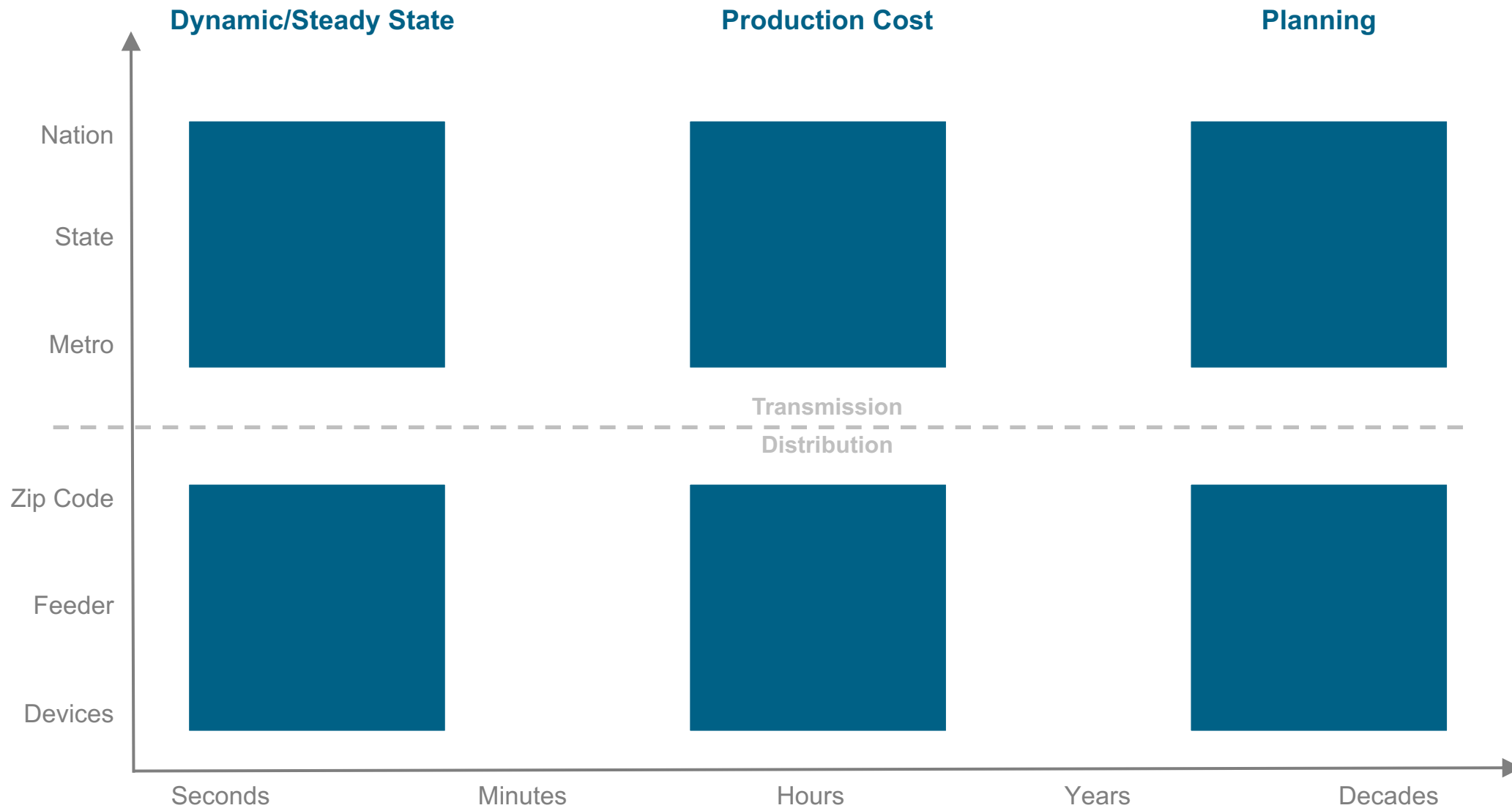
Here is our

Research Methodology

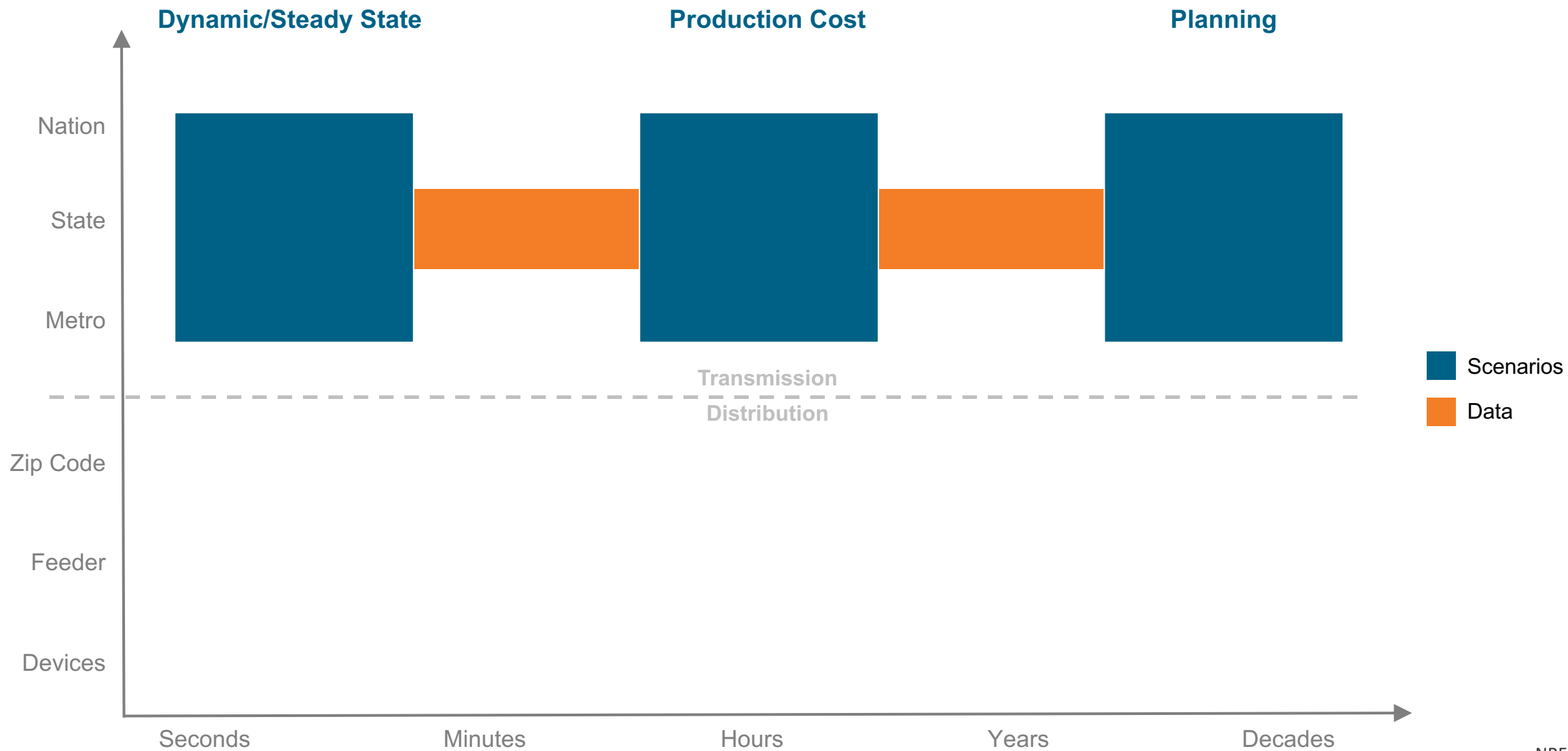
Spatial and Temporal Scales of Reliability



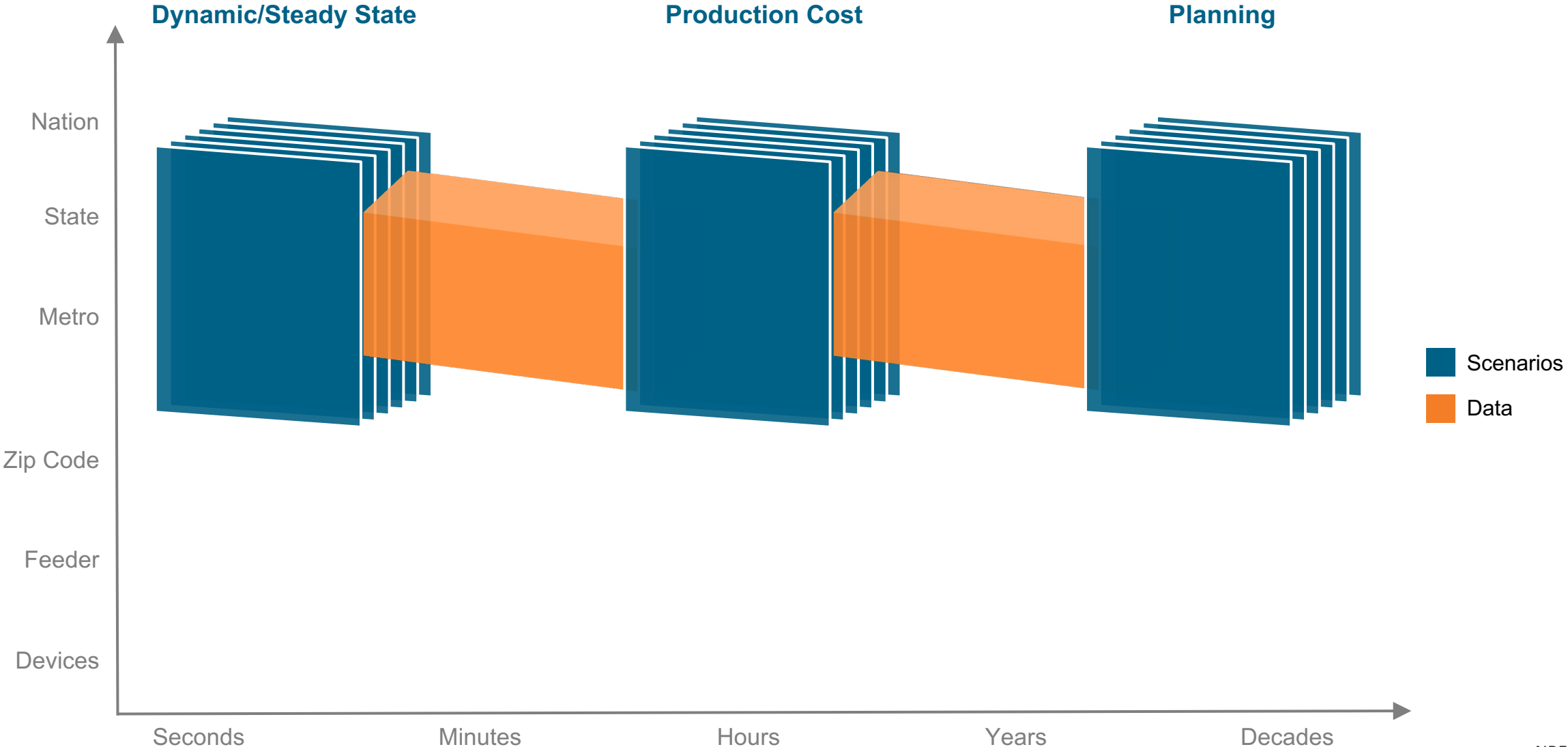
Scale Separation Problems and Solutions



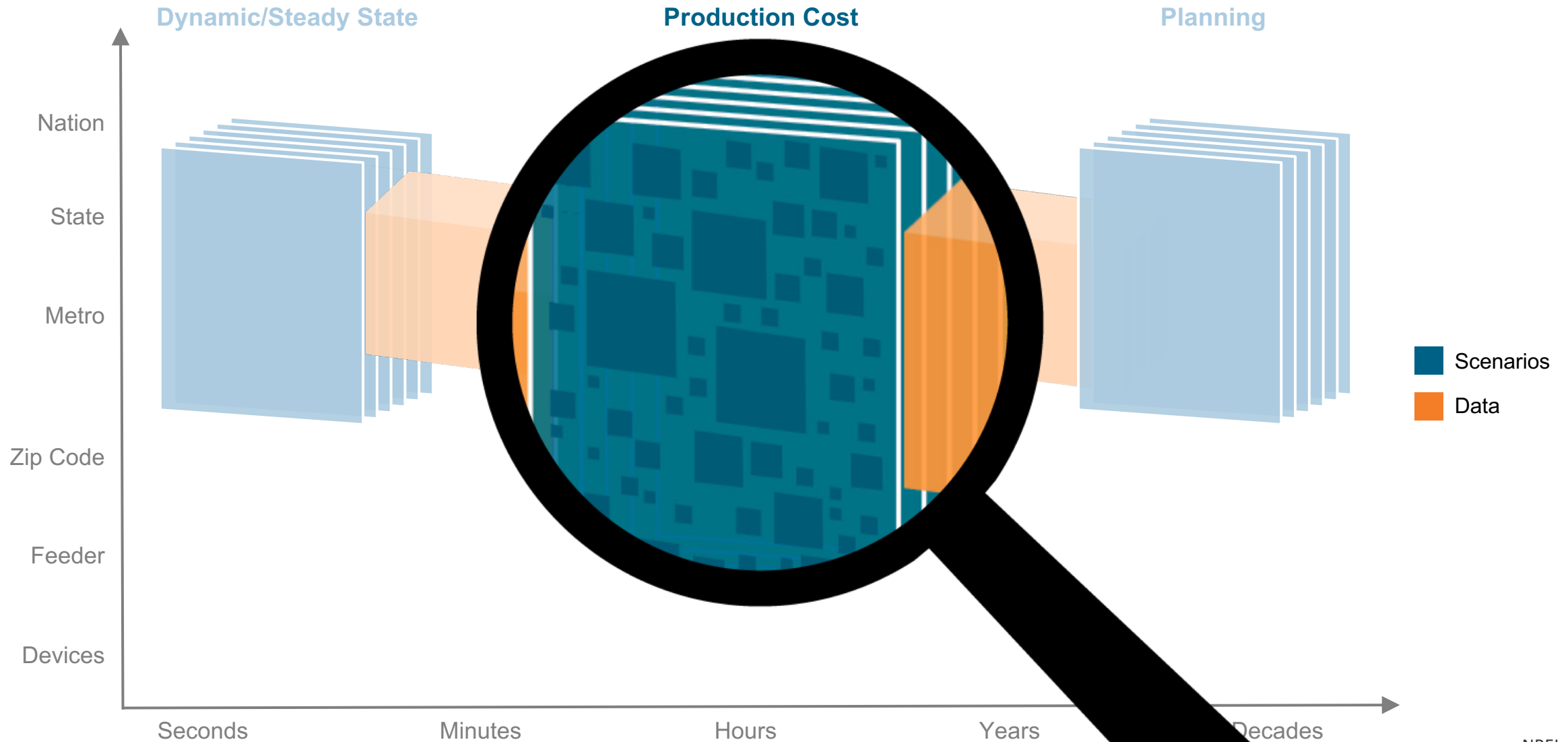
Bulk Power Focus



Scenarios, Data, Uncertainty

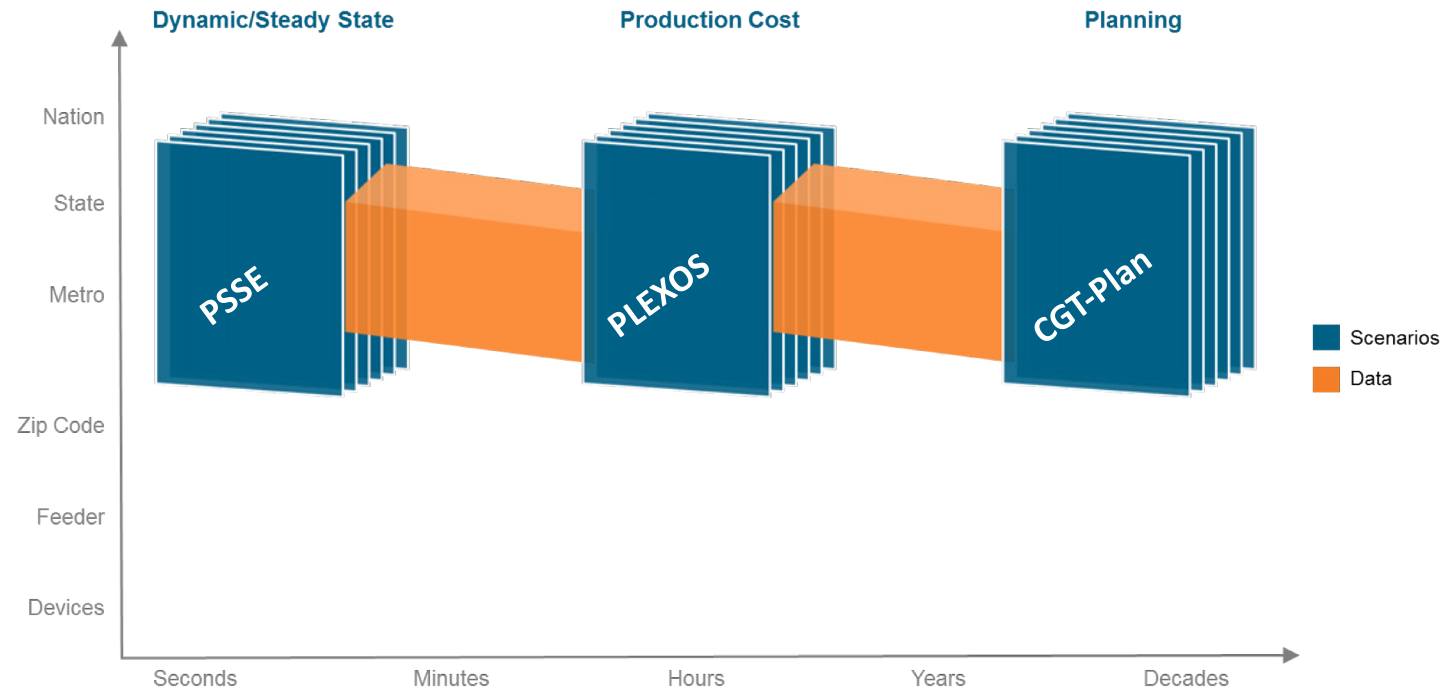


Unprecedented Resolution

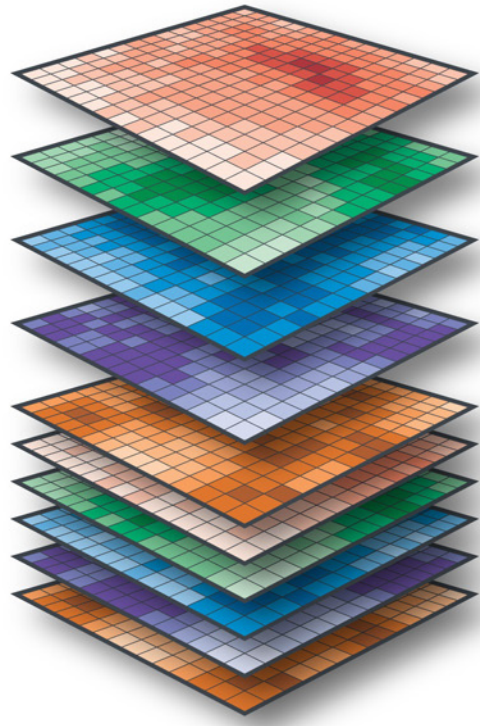


Comprehensive Economic and Reliability Analysis

- 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

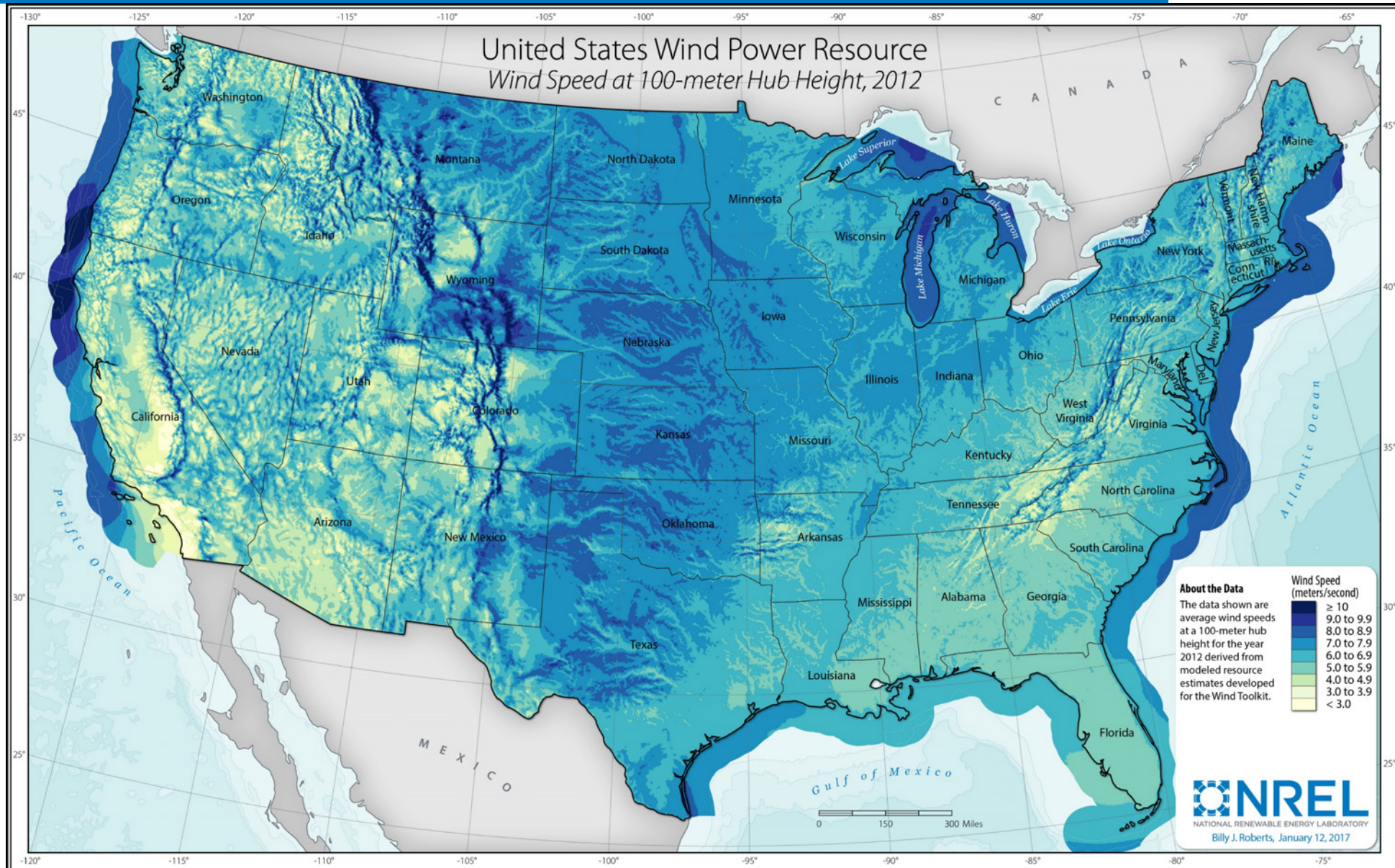
Hydro

Transmission

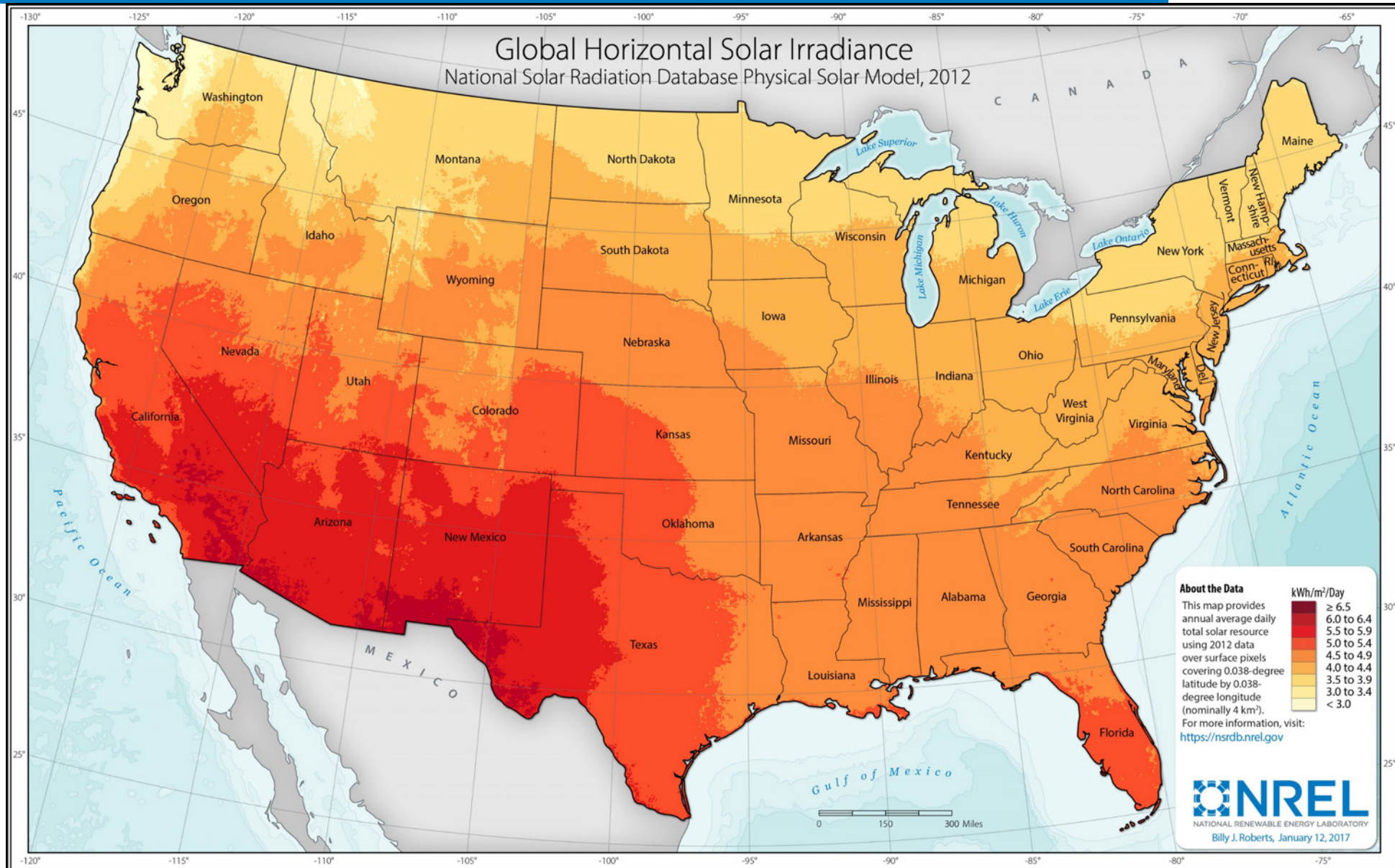
Fuel prices

- 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



Solar Data

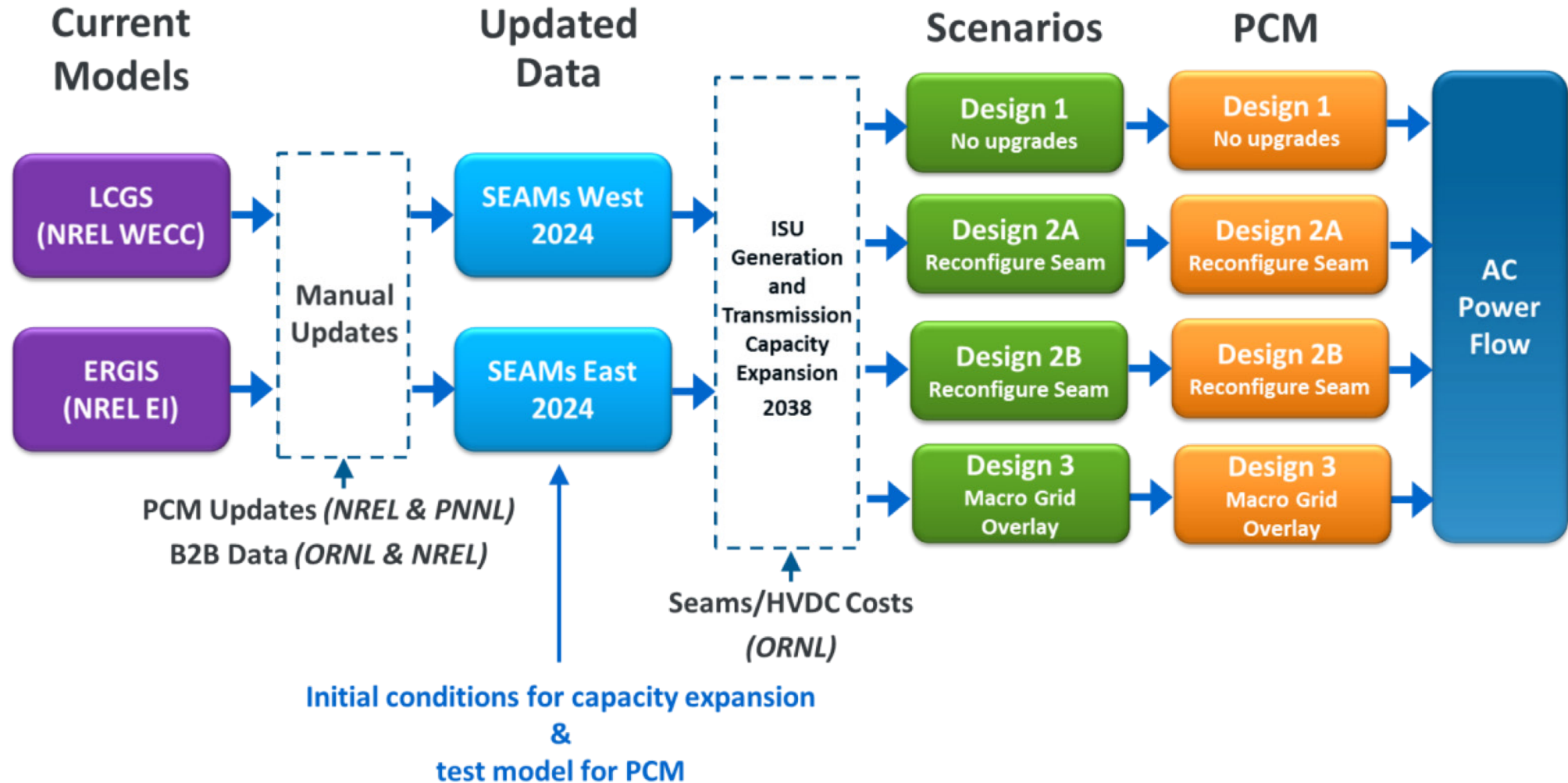




This is a Resource Adequacy and Cost Study

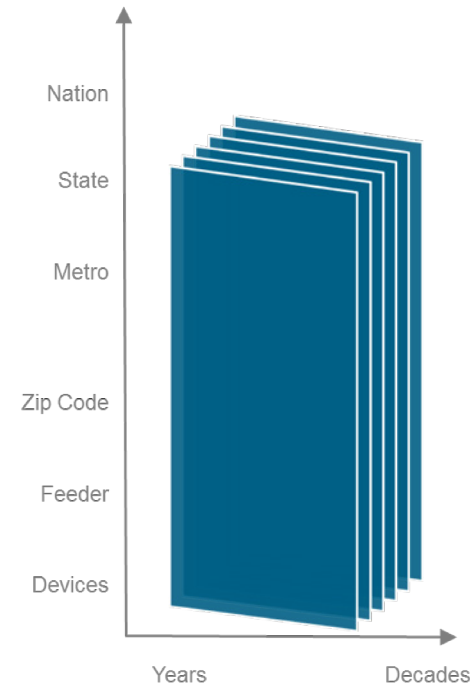
- Given a defined resource adequacy constraint, how does the cost of meeting that constraint change as a function of the HVDC scenarios?
- We setup a framework for security and stability analysis, but do not conduct comprehensive contingency and stability analysis.
- **Goal:** Determine if there is significant 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 some 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

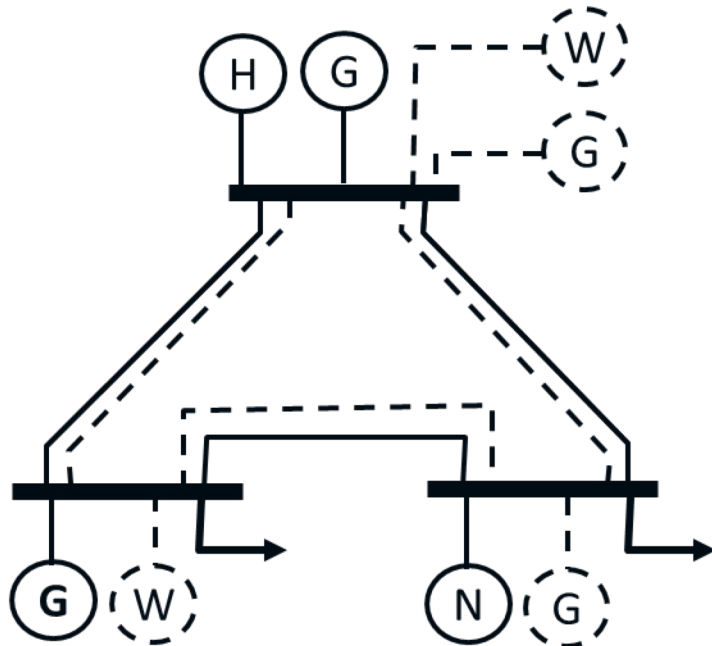


CGT-Plan

- 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

...

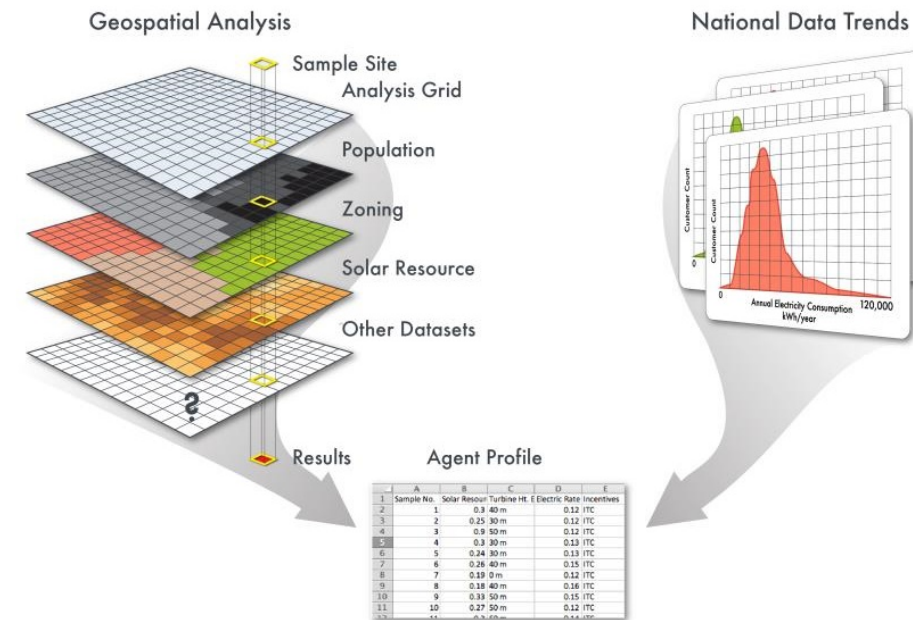
Year 15

Consumer level understanding of DERs

1. Numer of Sample Points

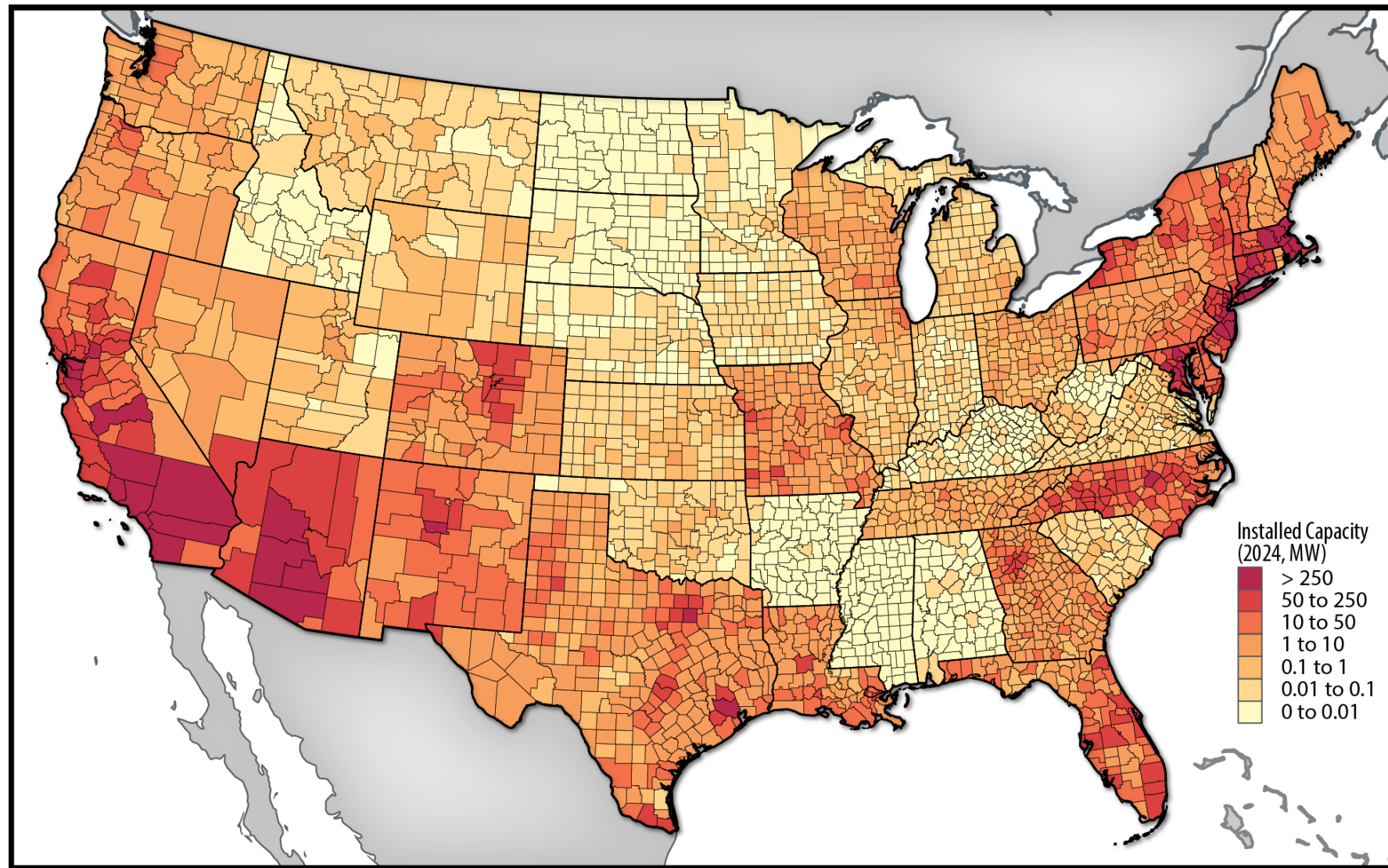


2. Geographic Scale



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

Distributed Generation

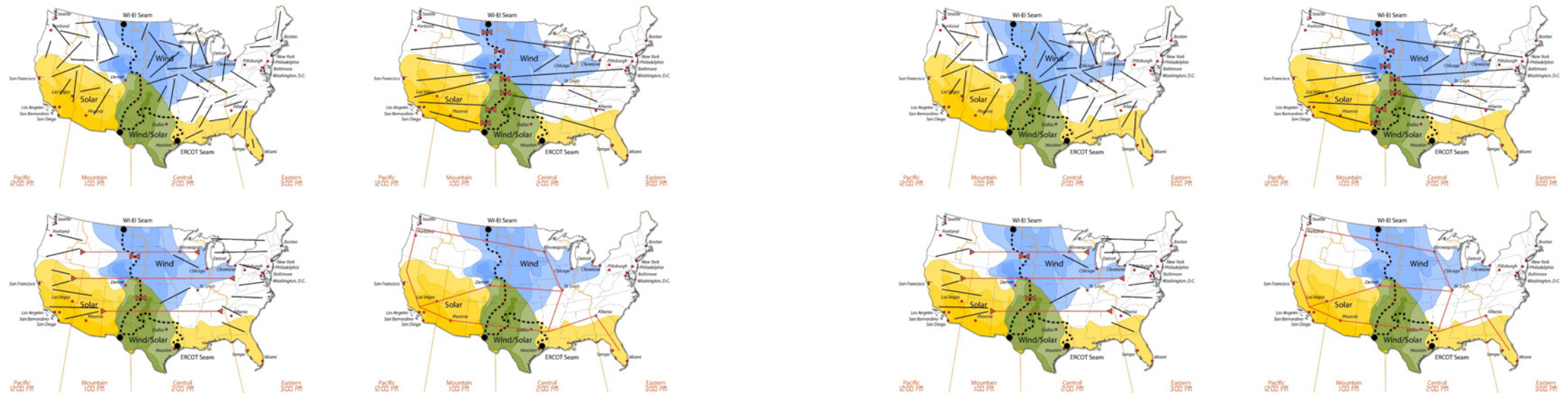


Policy Environments

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

Current Policy

Carbon Policy



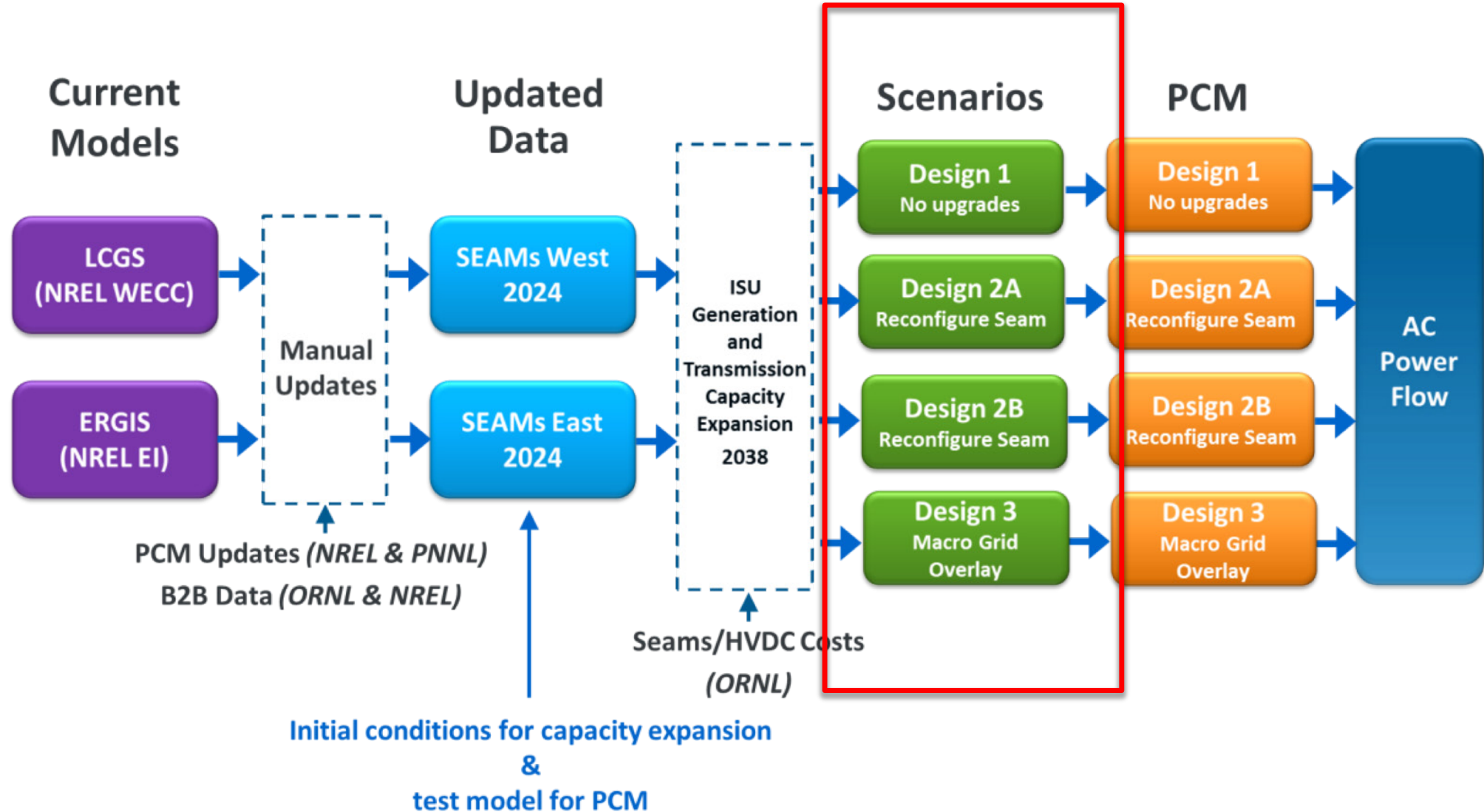
TRC Requested Policy Assumptions

- 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

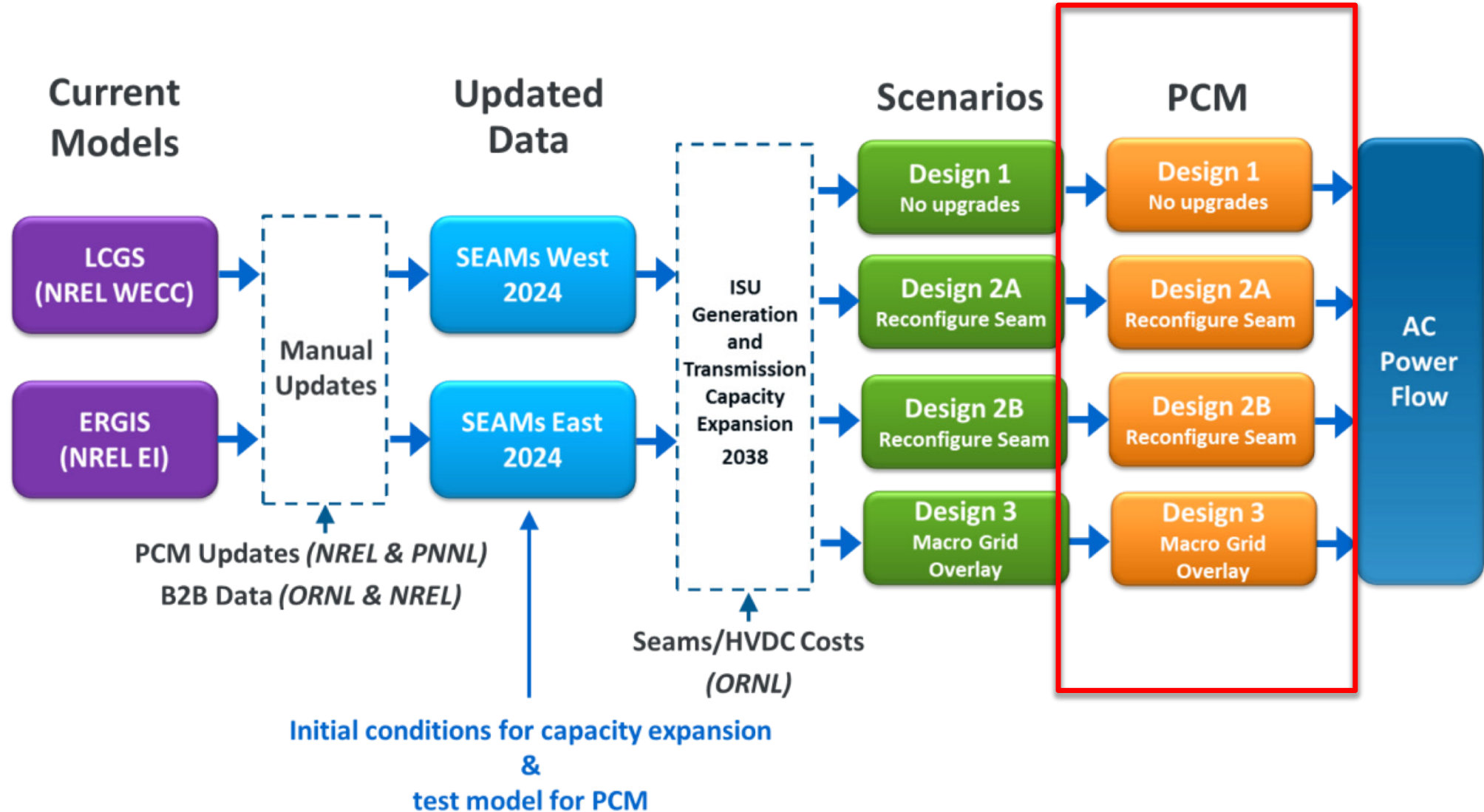
Other Assumptions

- 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

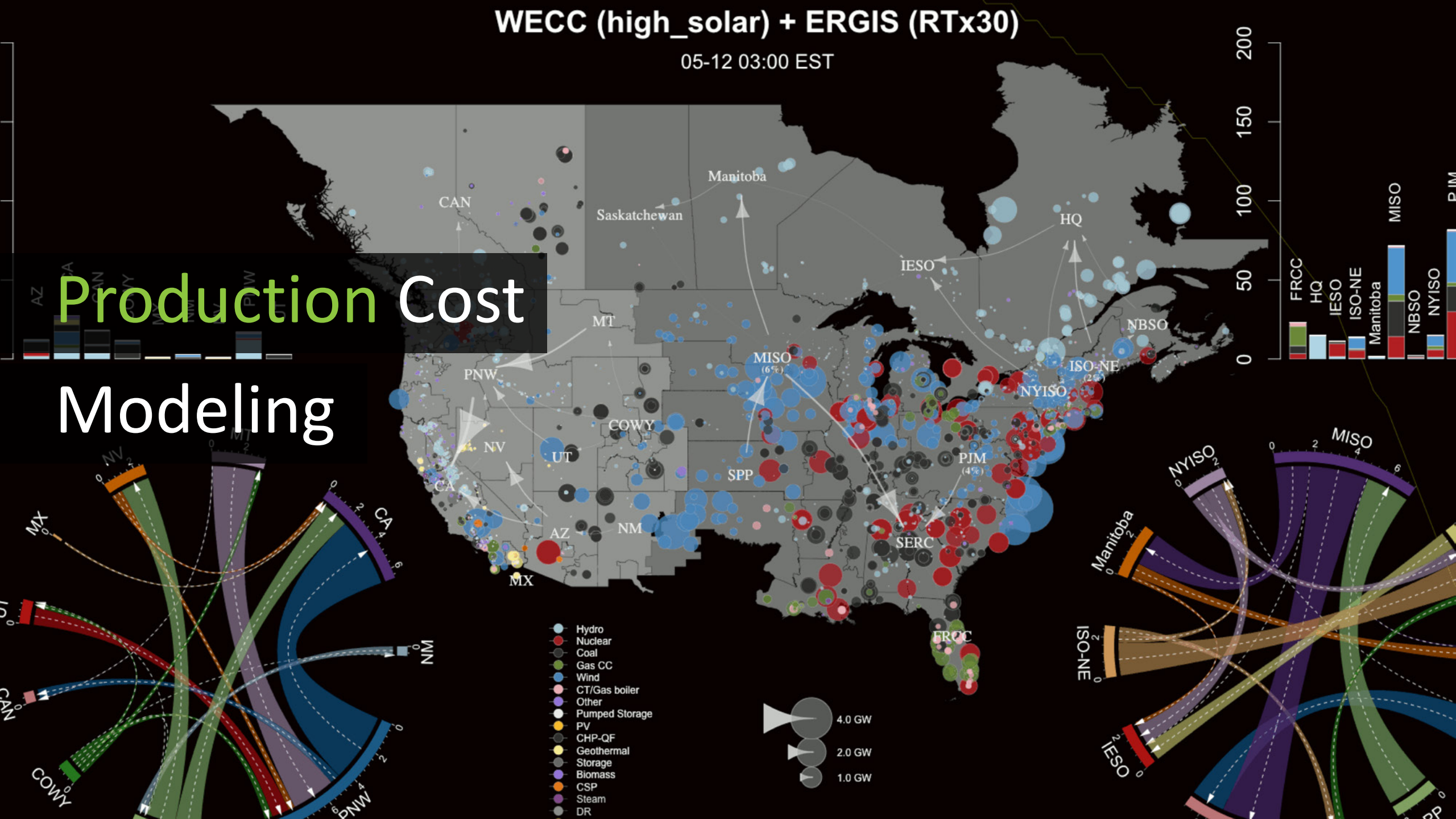


WECC (high_solar) + ERGIS (RTx30)

05-12 03:00 EST

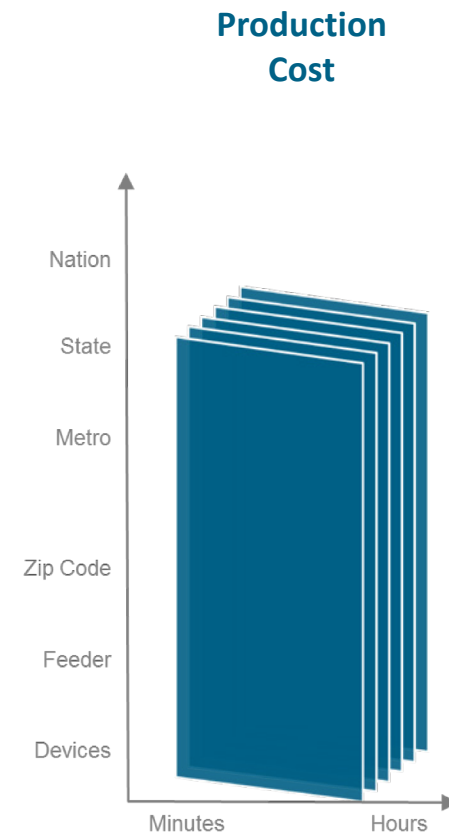
Production Cost

Modeling



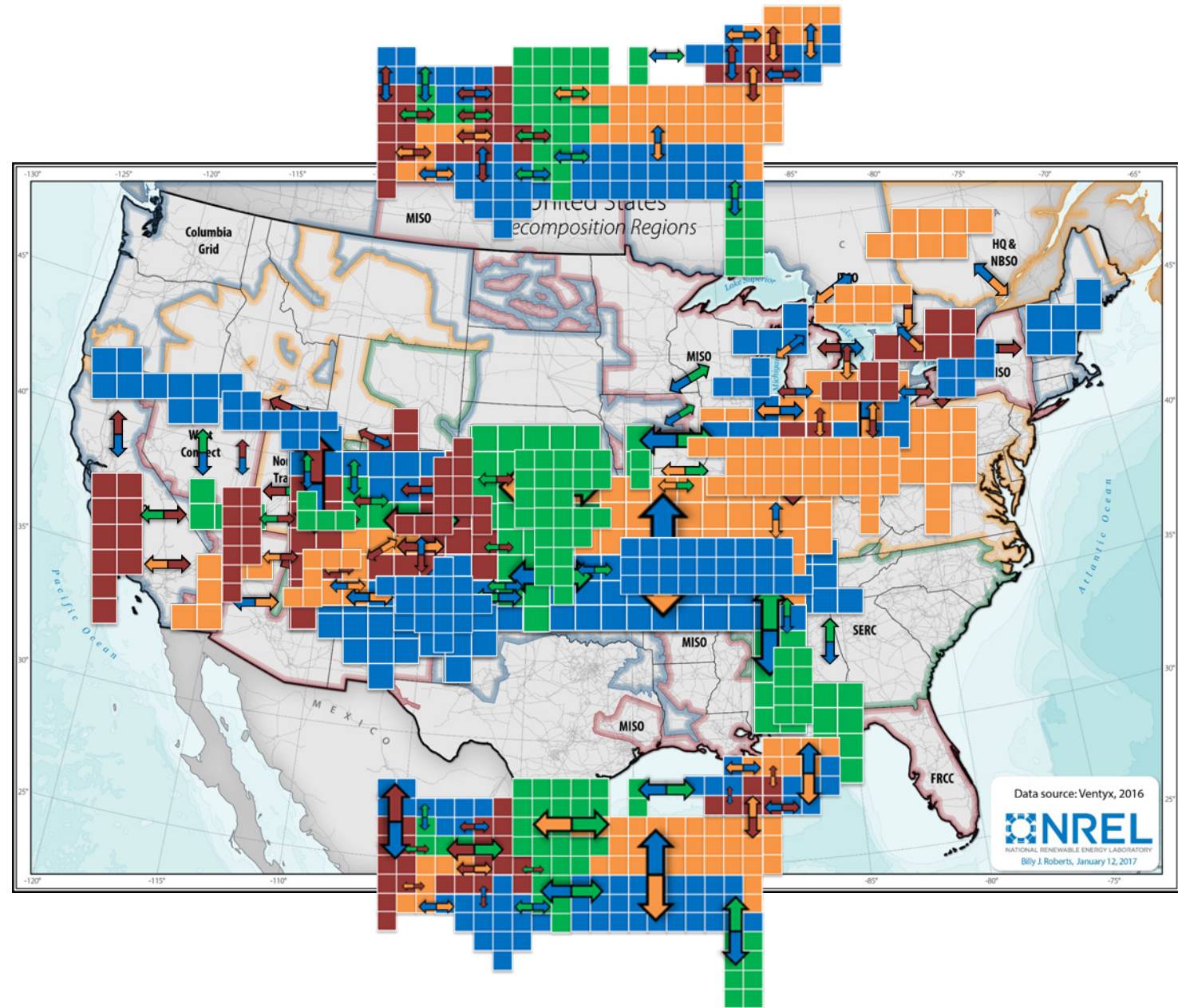
Production Cost Models

- 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



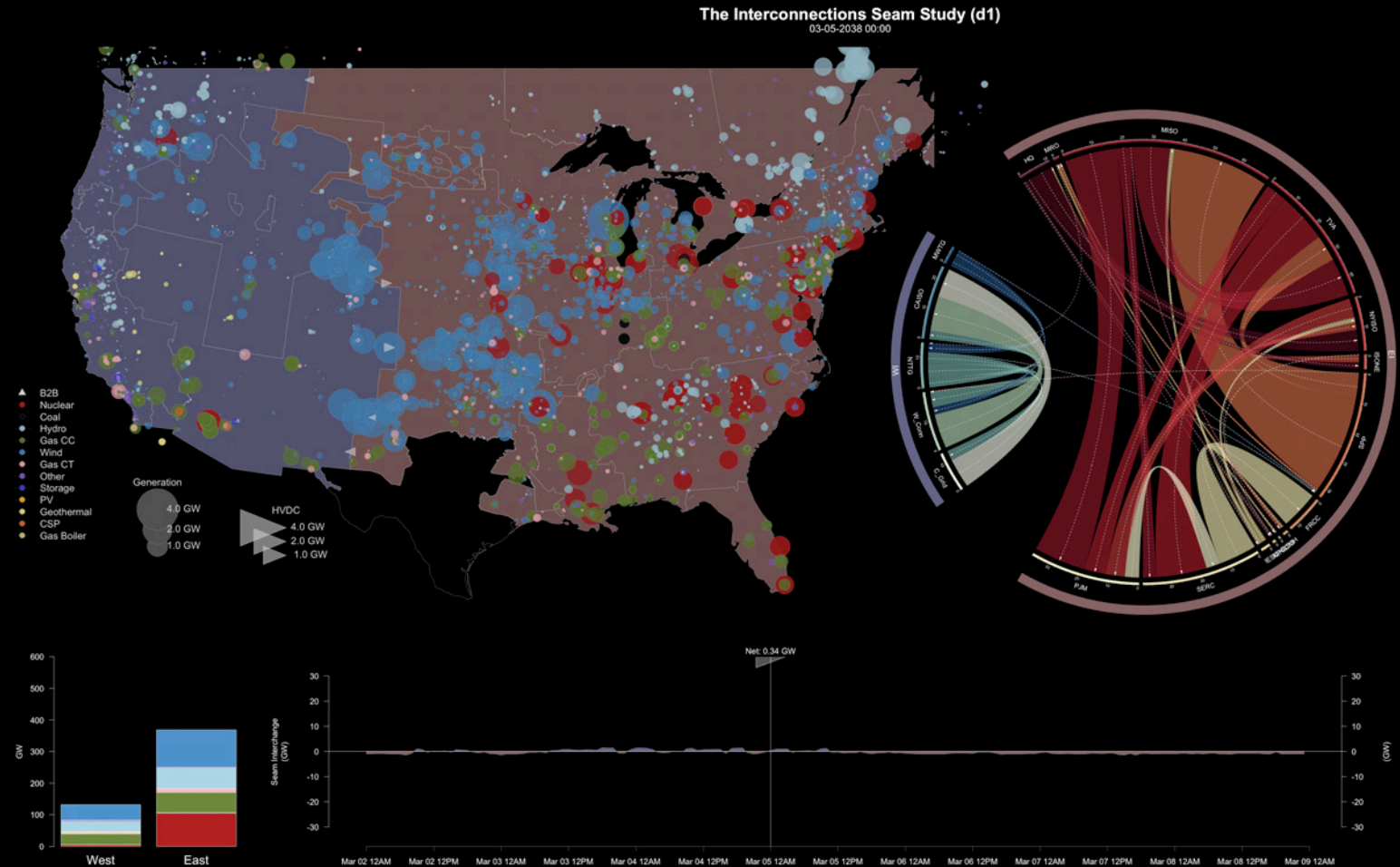
Geographic Decomposition

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



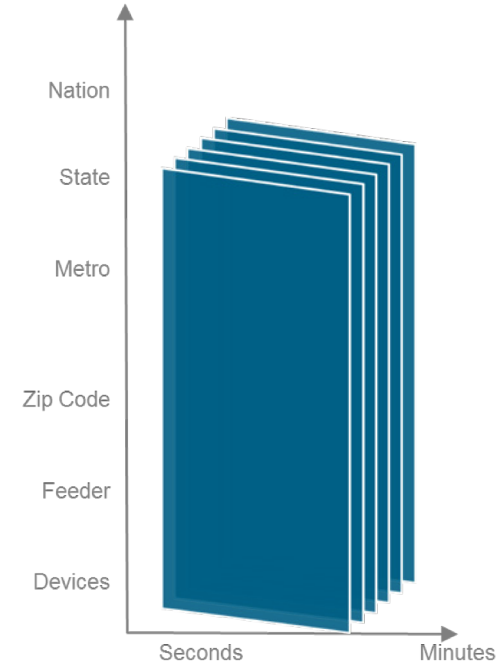
Production Cost Model: PLEXOS

- 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?

A man wearing a red hard hat with a headlamp, safety glasses, and a dark blue jacket is smiling. He is standing in a field with several wind turbines in the background under a clear blue sky.

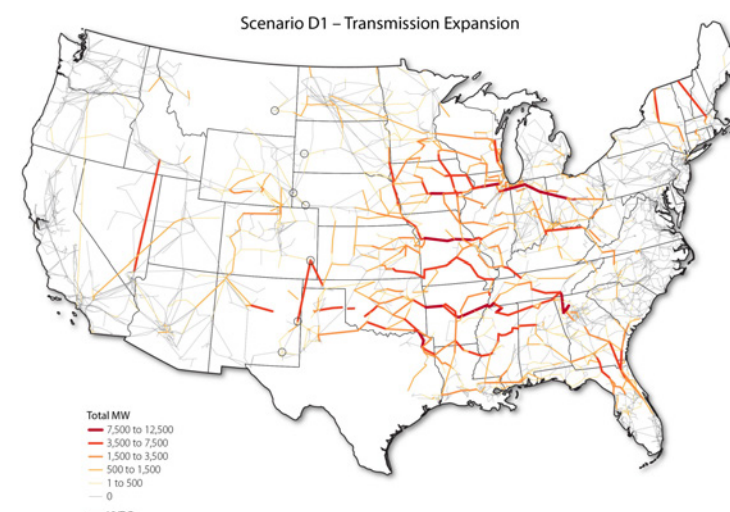
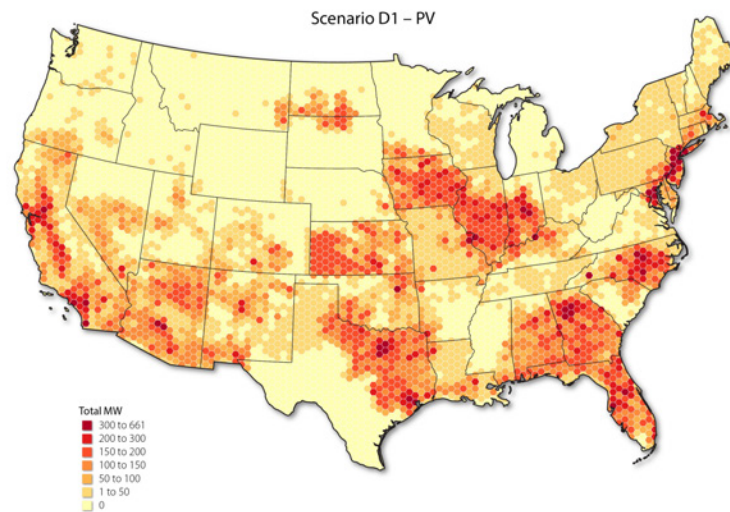
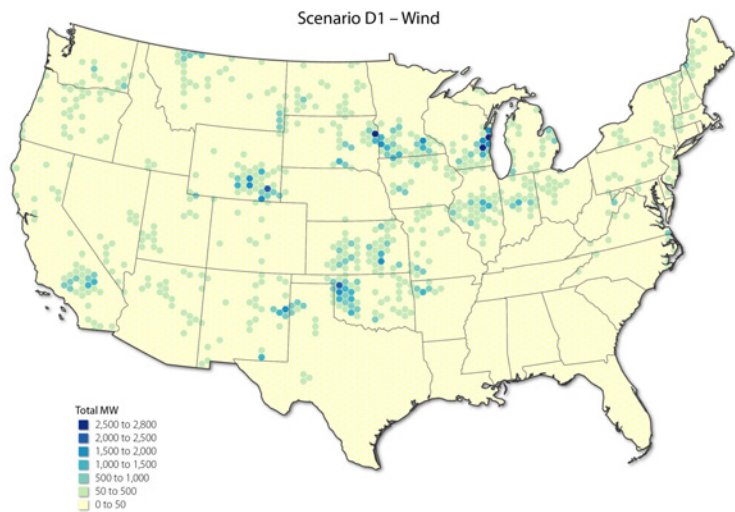
Here are

the results



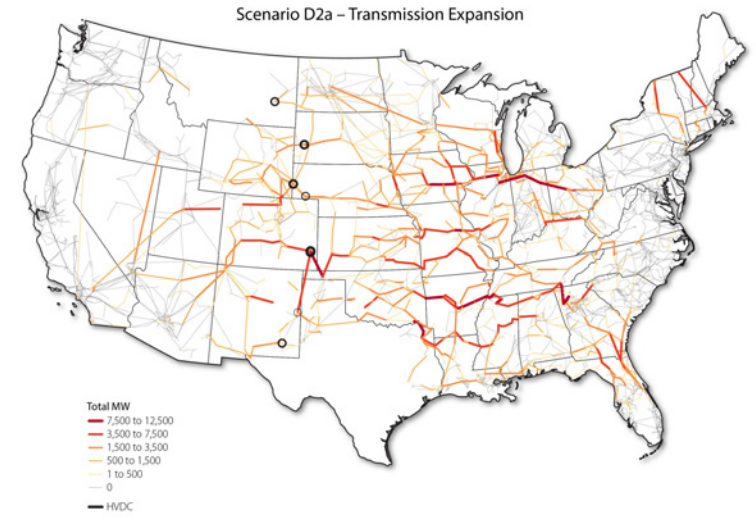
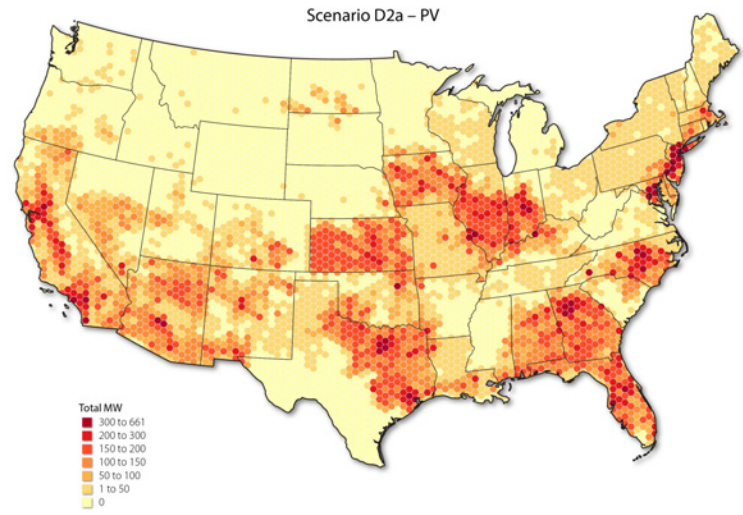
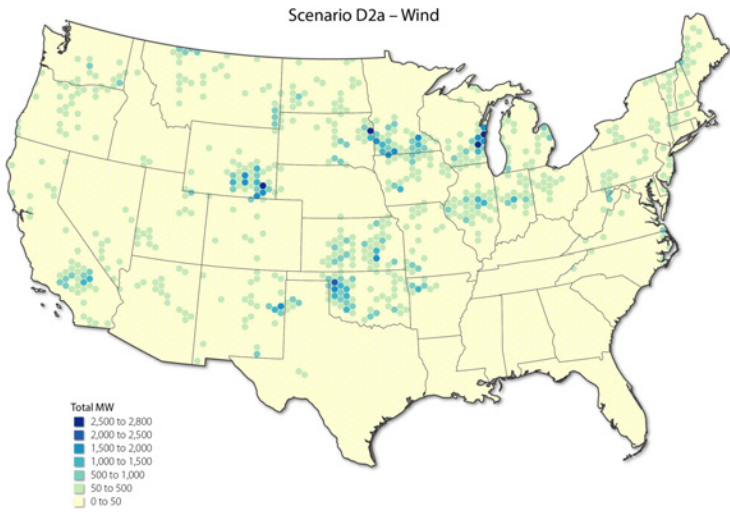
System Characteristics

And Performance

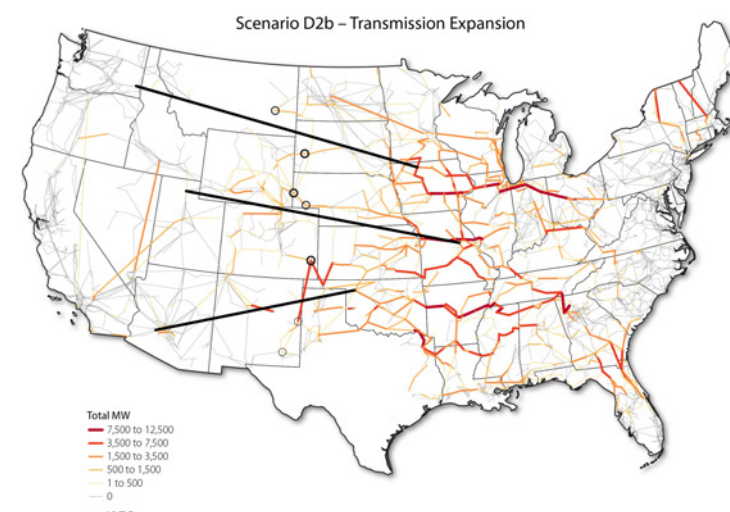
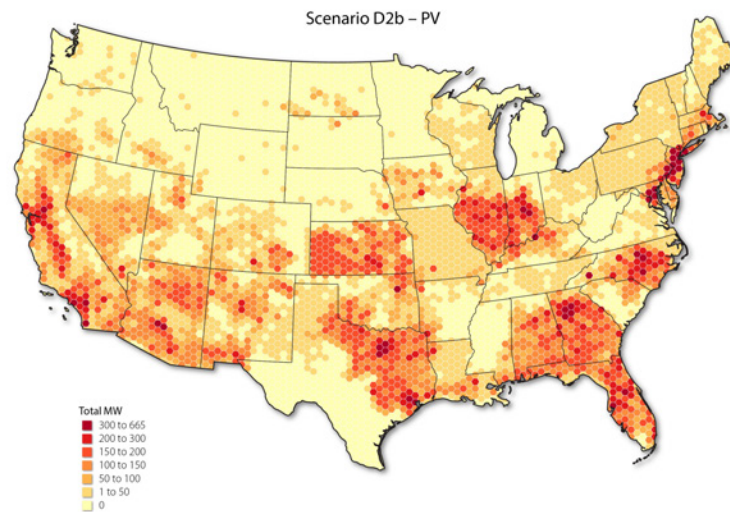
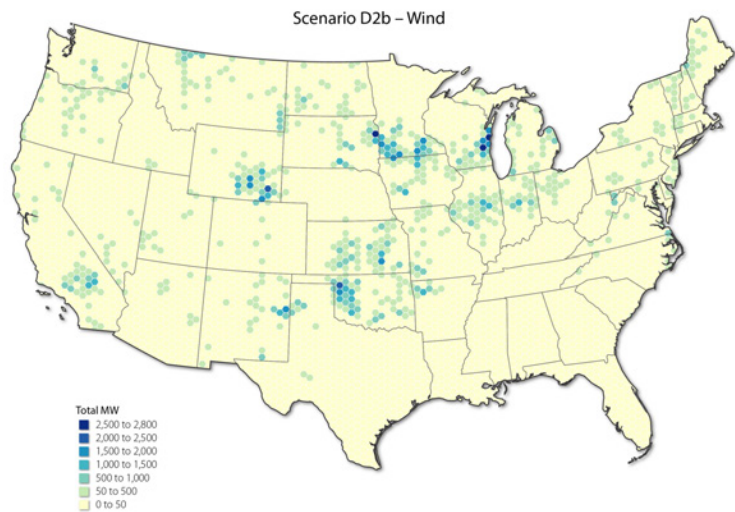


Design 1

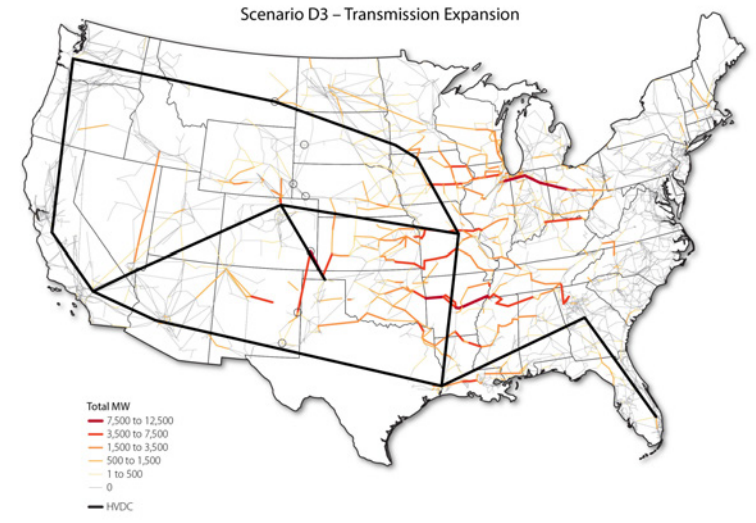
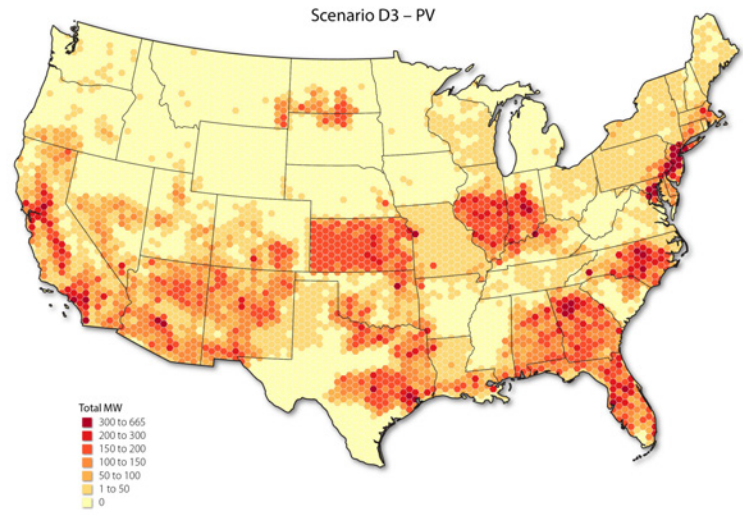
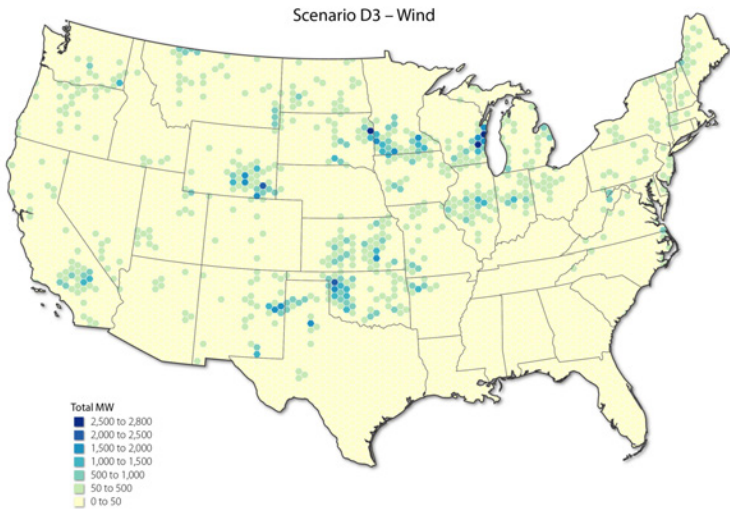
Current Policy



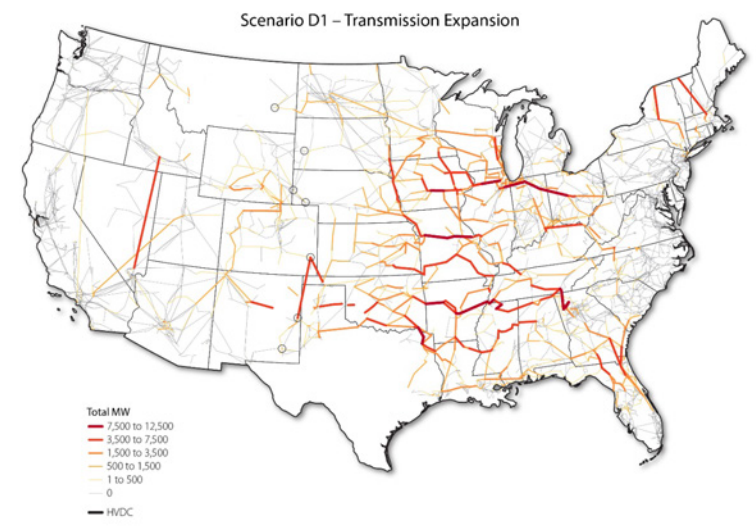
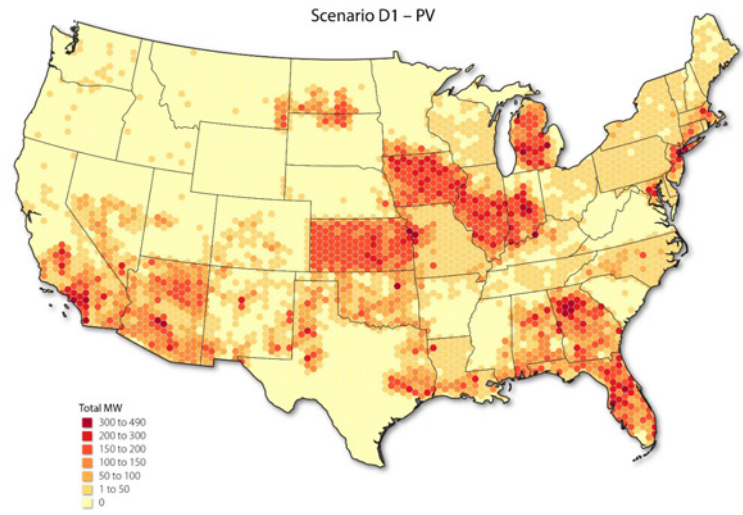
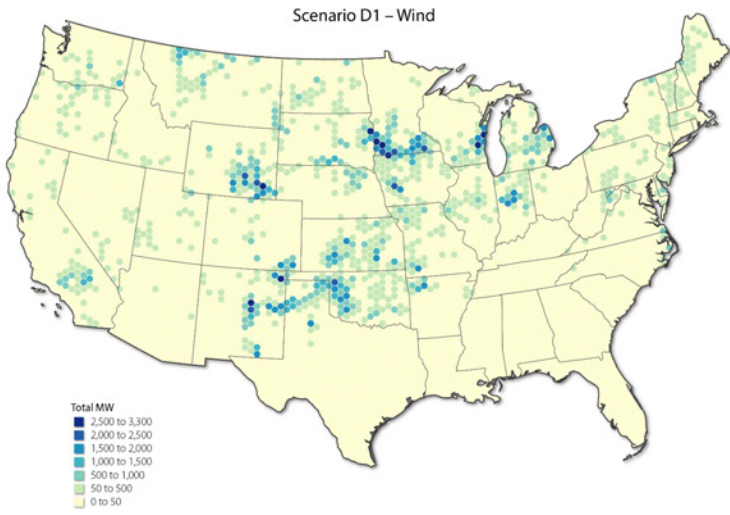
Design 2a Current Policy



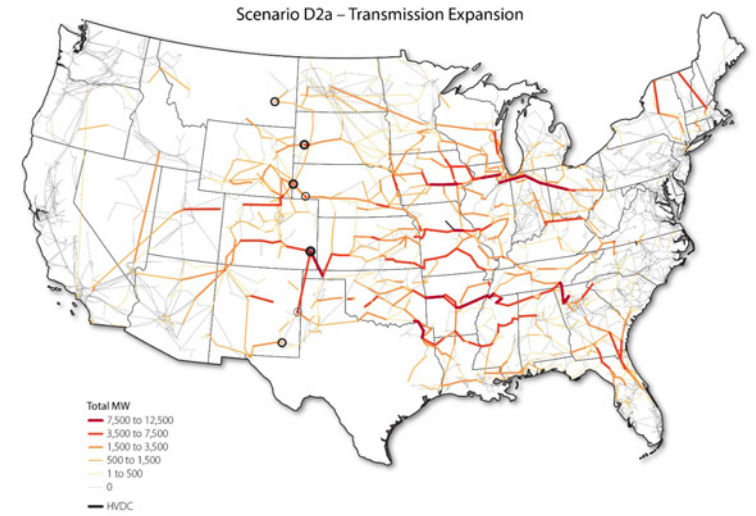
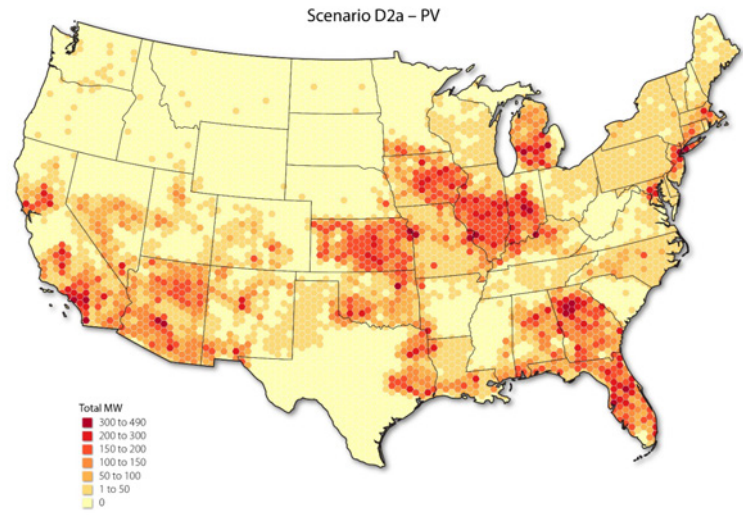
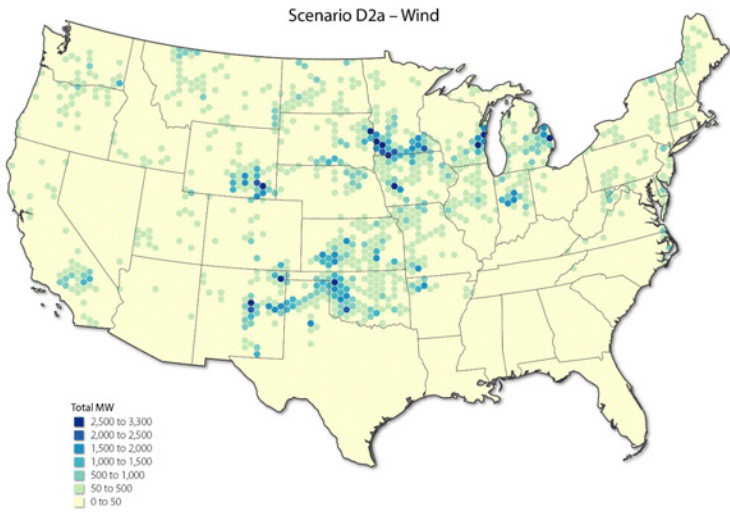
Design 2b Current Policy



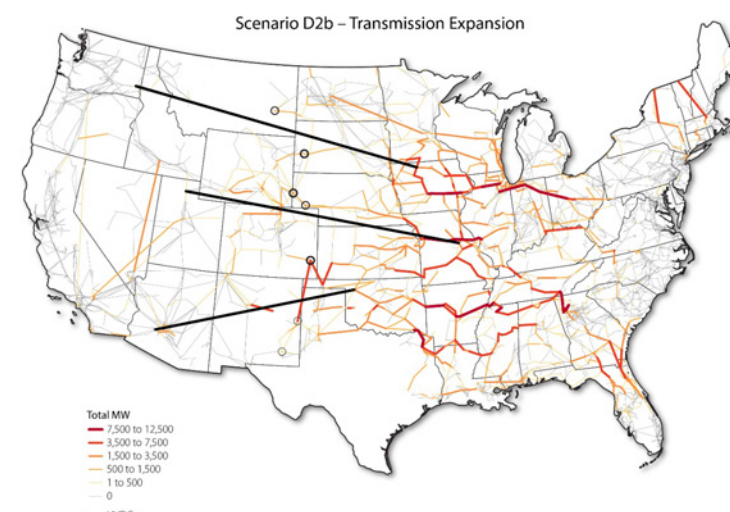
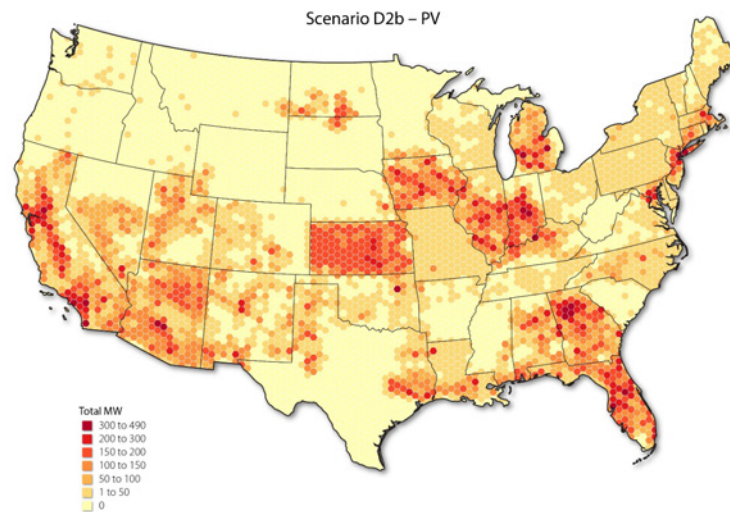
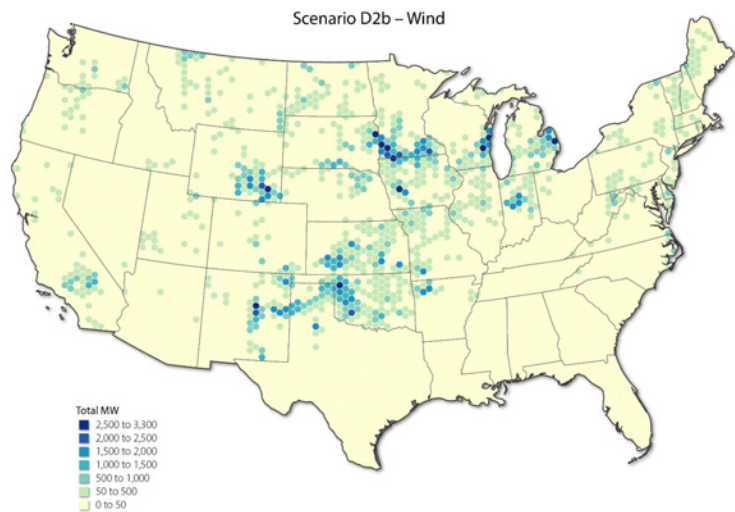
Design 3 Current Policy



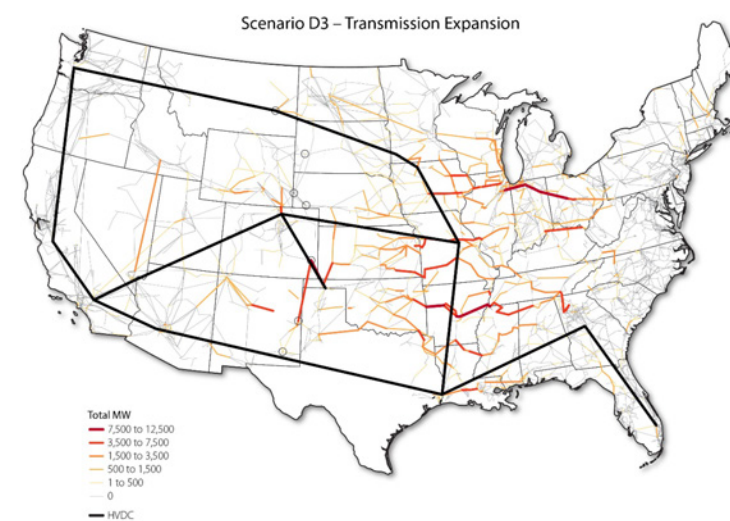
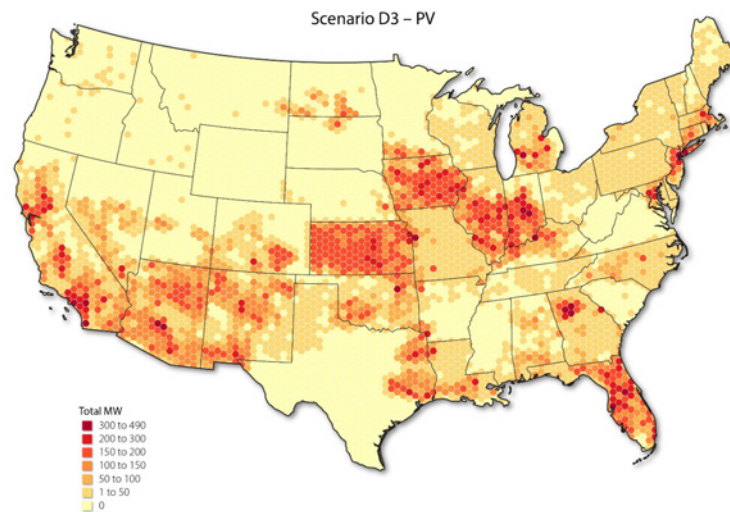
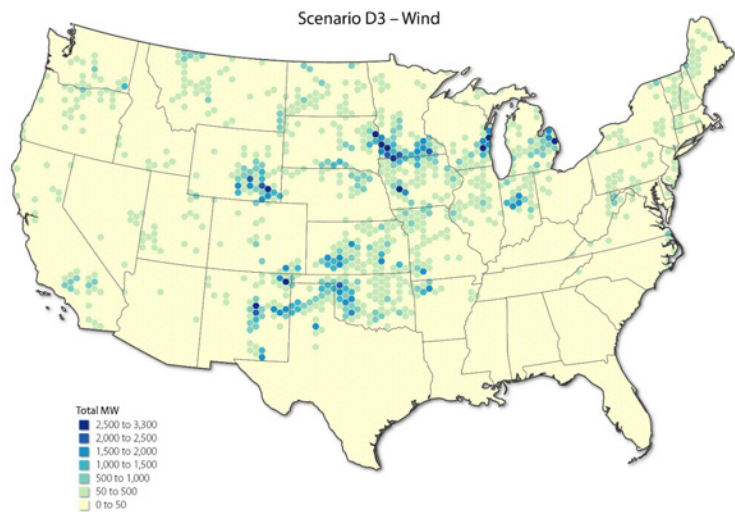
Design 1 Carbon Policy



Design 2a Carbon Policy



Design 2b Carbon Policy



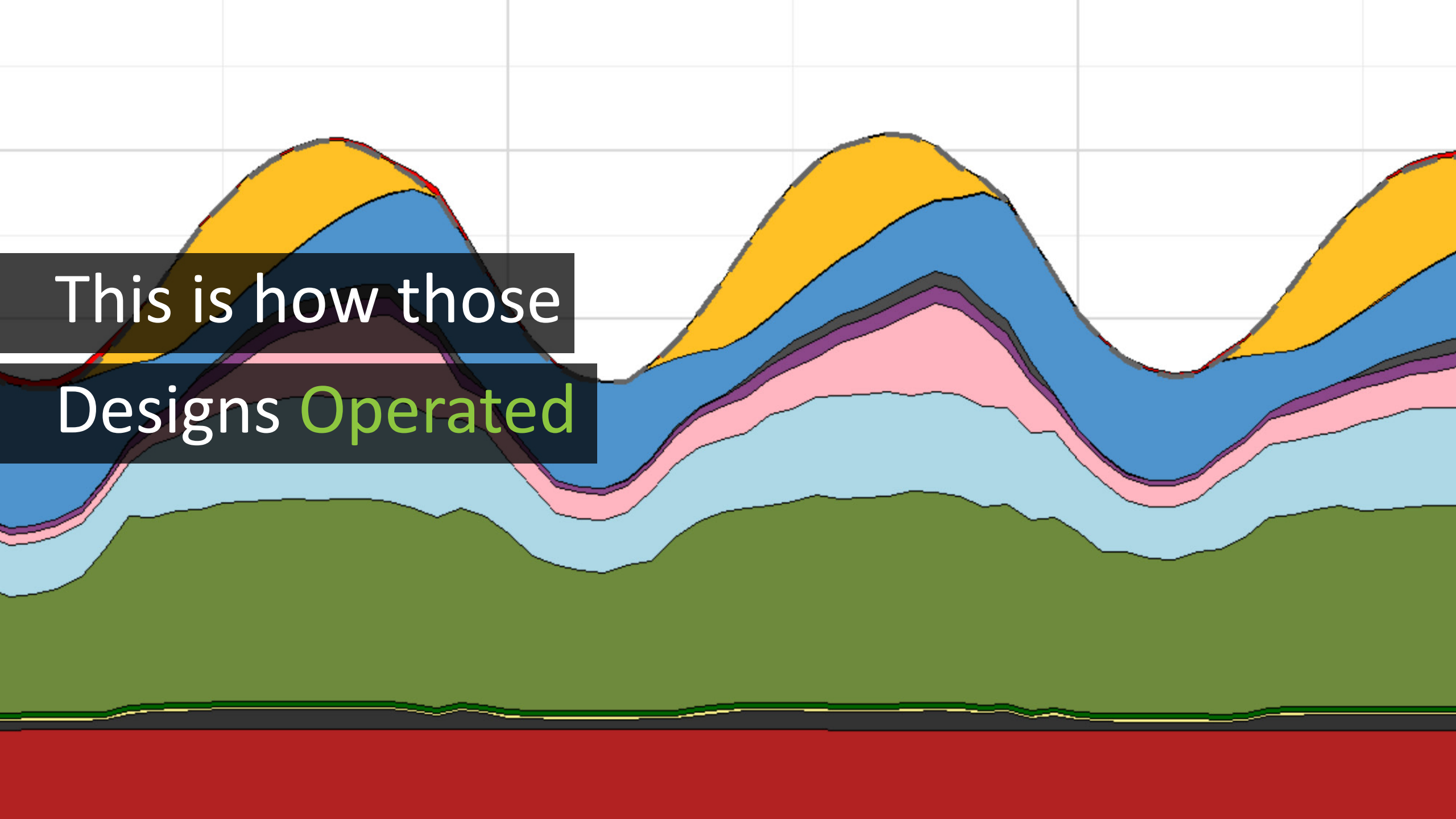
Design 3 Carbon Policy

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

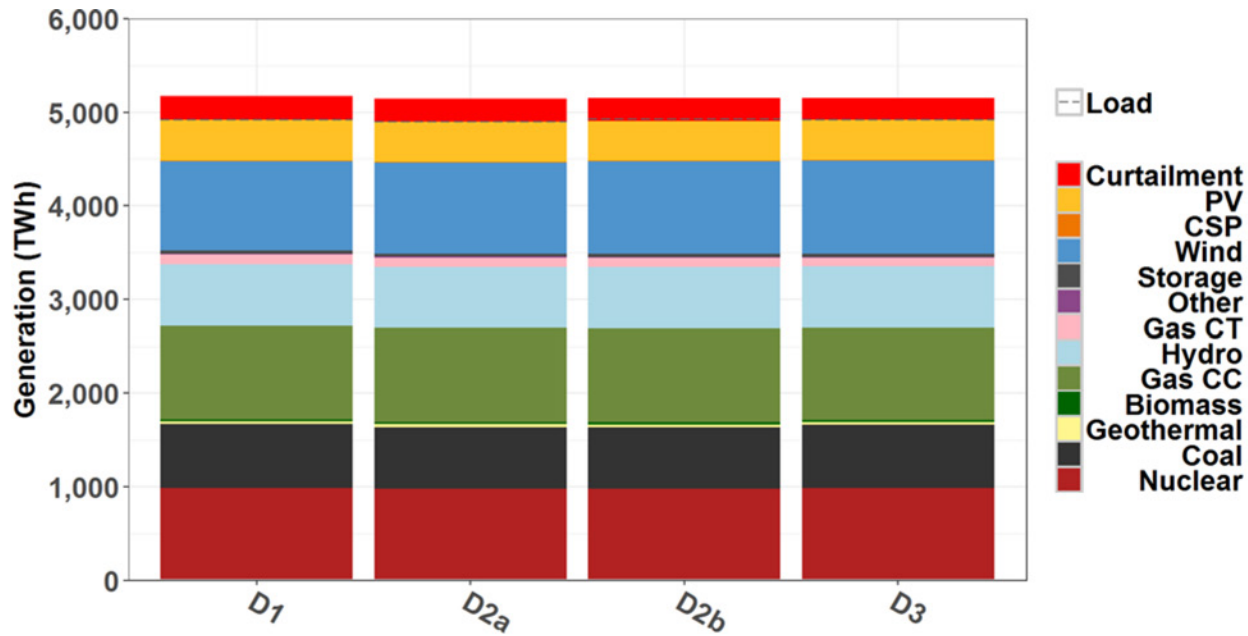
- All cases imagine a future where it is feasible to build multi-region transmission
- Design 1 is the only case without new HVDC and without new transmission across the Seam
- The generation mix changes substantially in all cases
- Results are known to be imperfect, yet informative
- Substantial AC 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/>



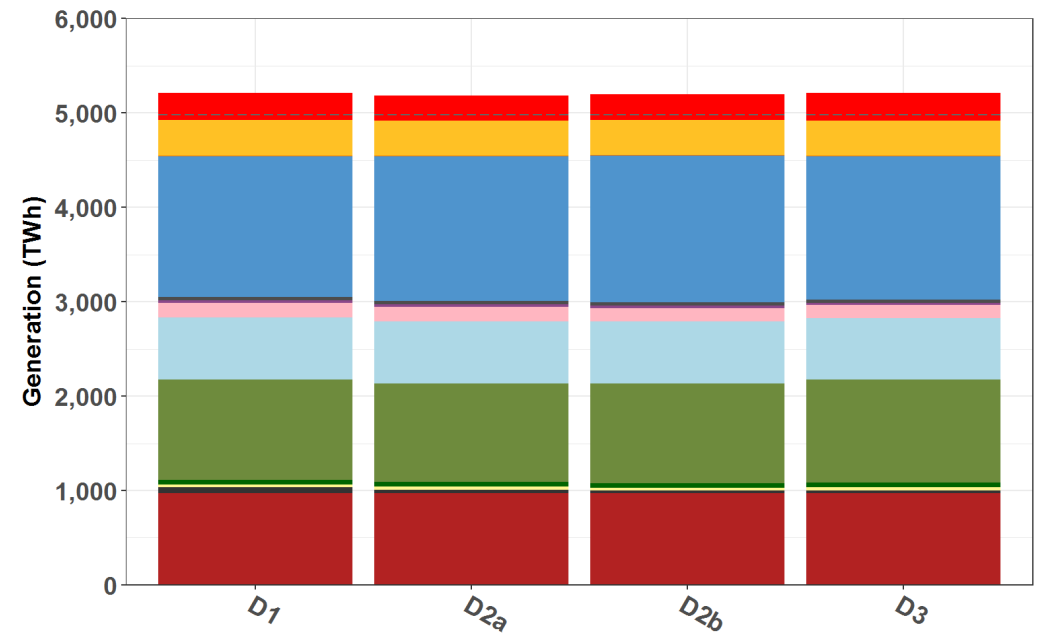
This is how those
Designs Operated

Annual Generation

- Current Policy



- Carbon Policy

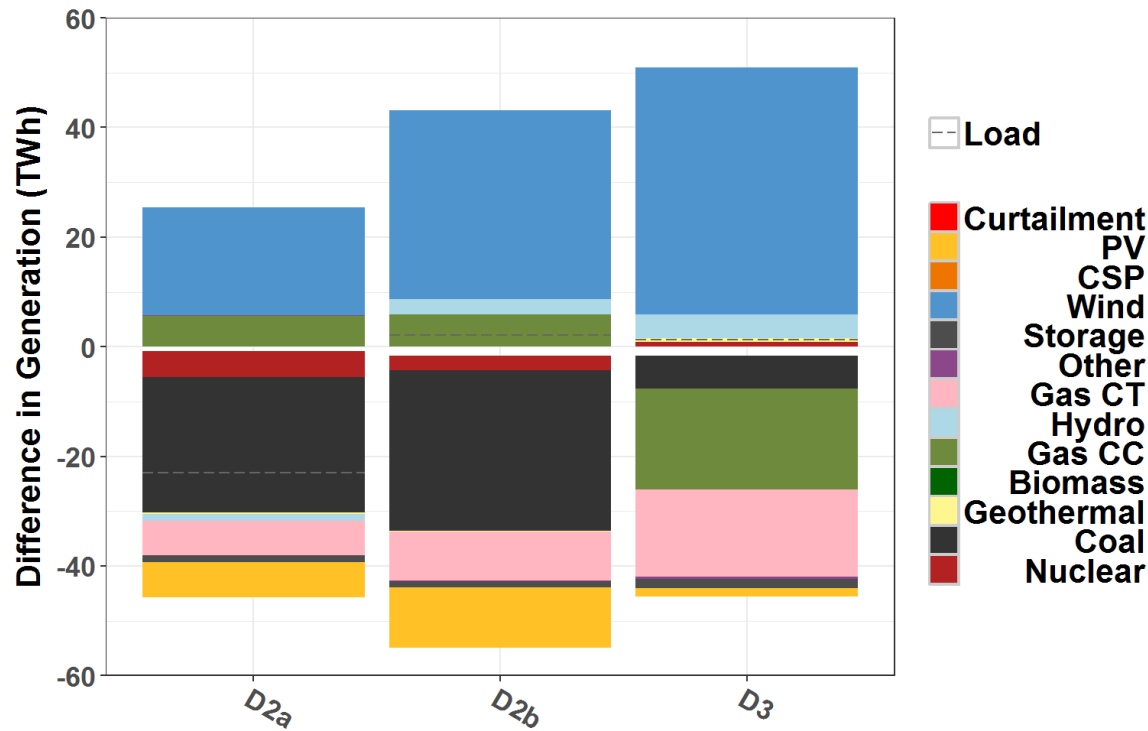


Percent of Total Generation

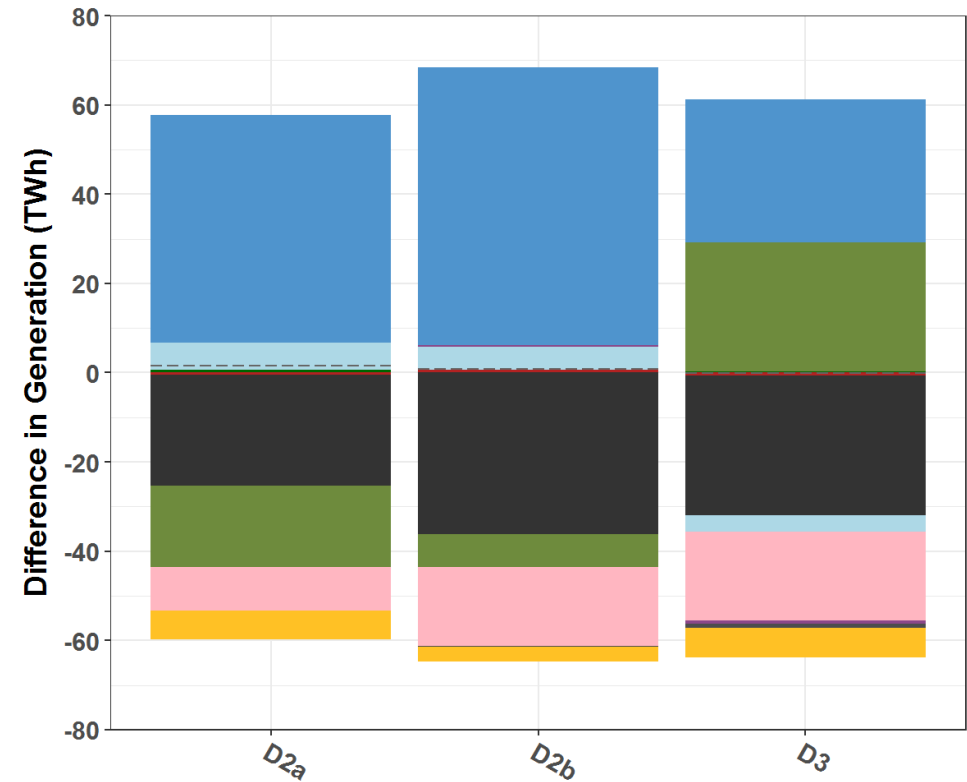
	Current Policy				Carbon Policy			
	D1	D2a	D2b	D3	D1	D2a	D2b	D3
Fossil Fuel	36%	36%	36%	36%	26%	25%	25%	25%
Wind and Solar	28%	29%	29%	29%	38%	39%	39%	39%
CO ₂ Free	63%	63%	63%	64%	73%	74%	74%	73%

Generation Difference

- Current Policy

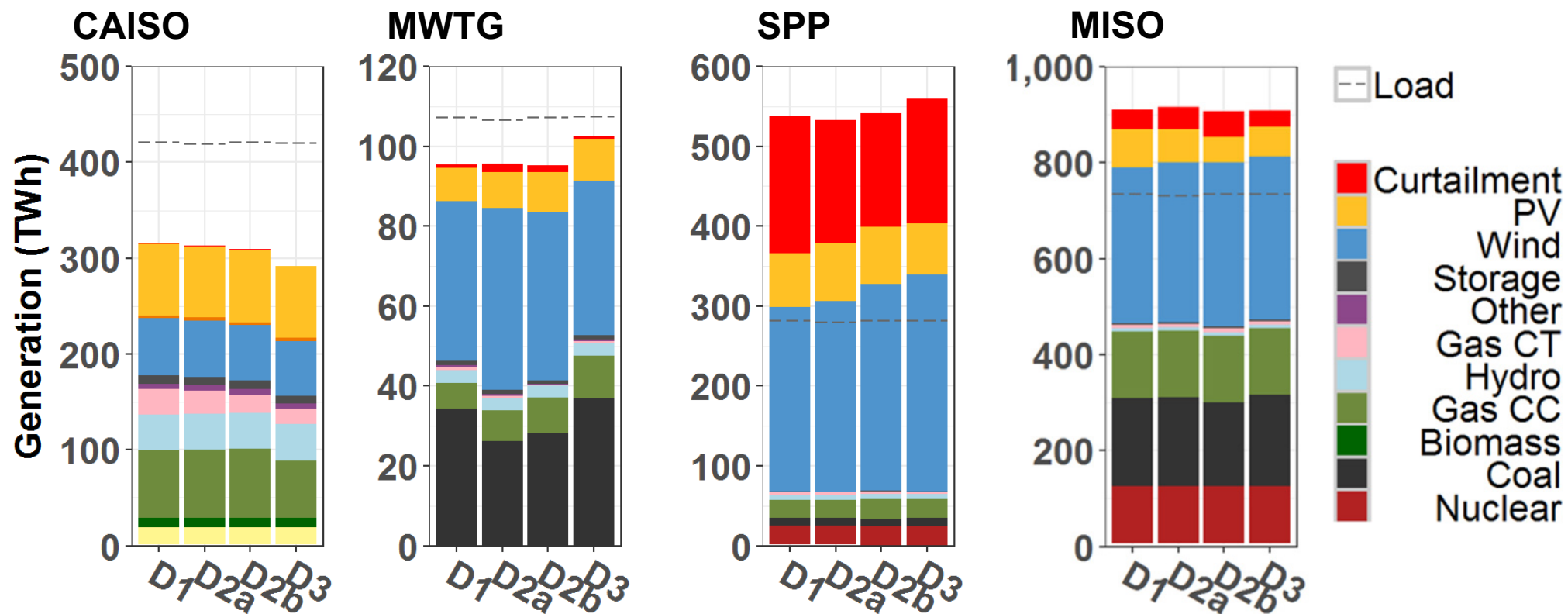


- Carbon Policy

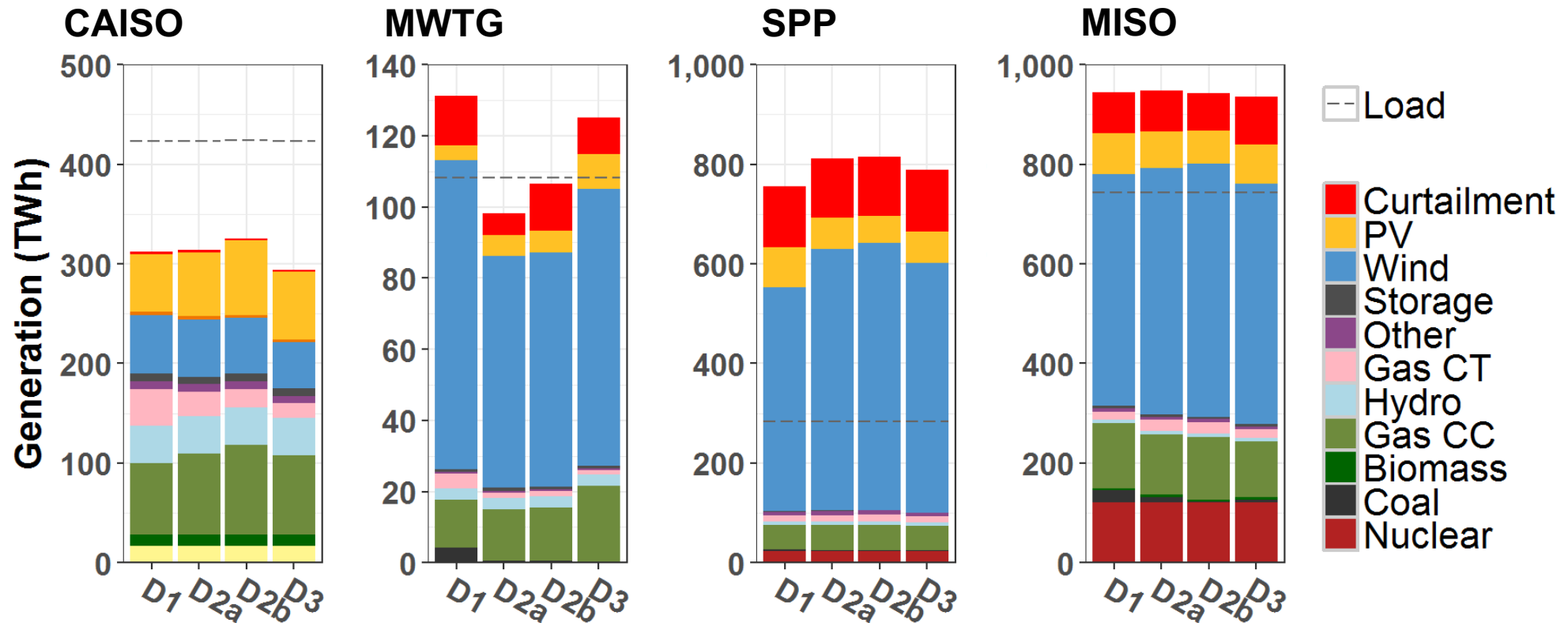


- Note smaller scale of the Current Policy plot
- Nuclear changes under Current Policy are an artifact of outage schedules.

Regional Generation Current Policy



Regional Generation Carbon Policy



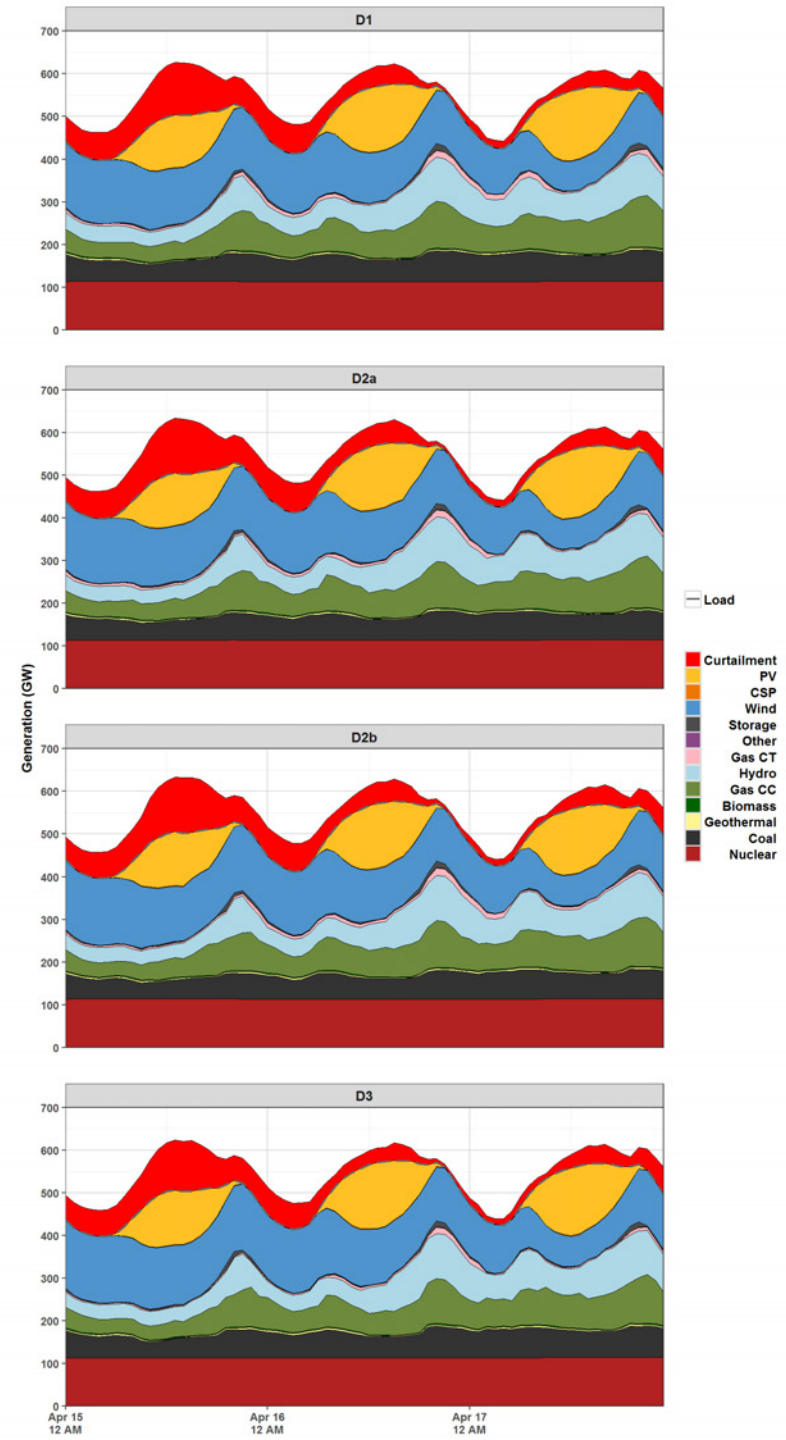
Variable Generation Curtailment

	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

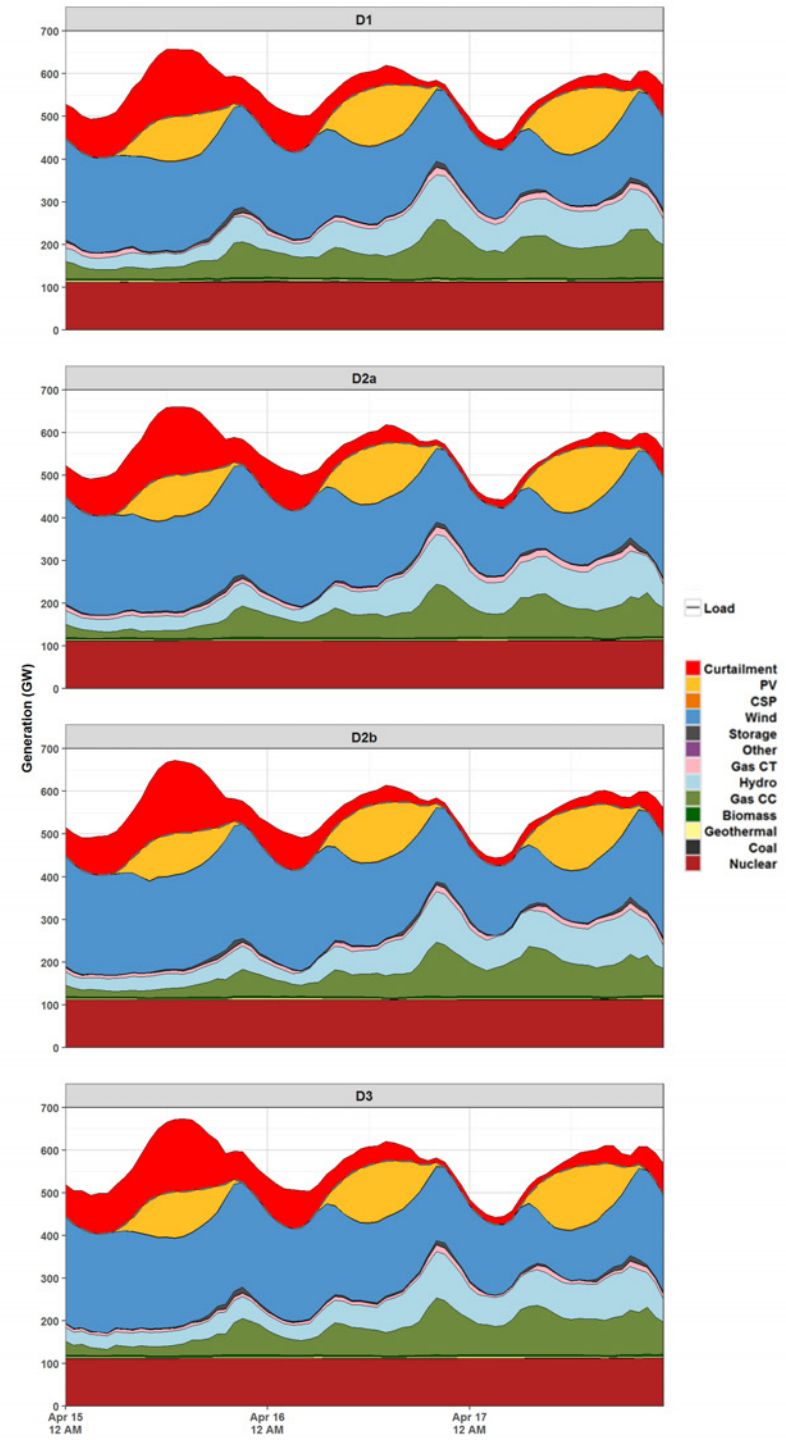
Current Policy High VG

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



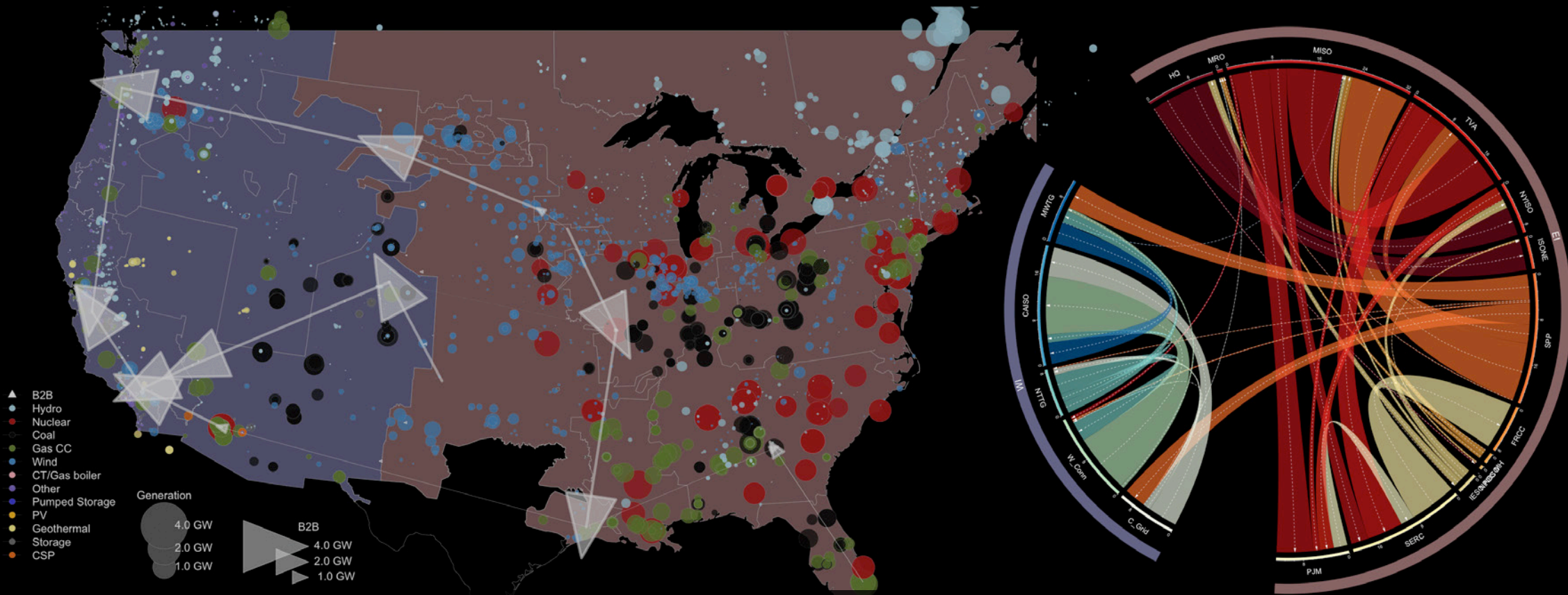
Carbon Policy High VG

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

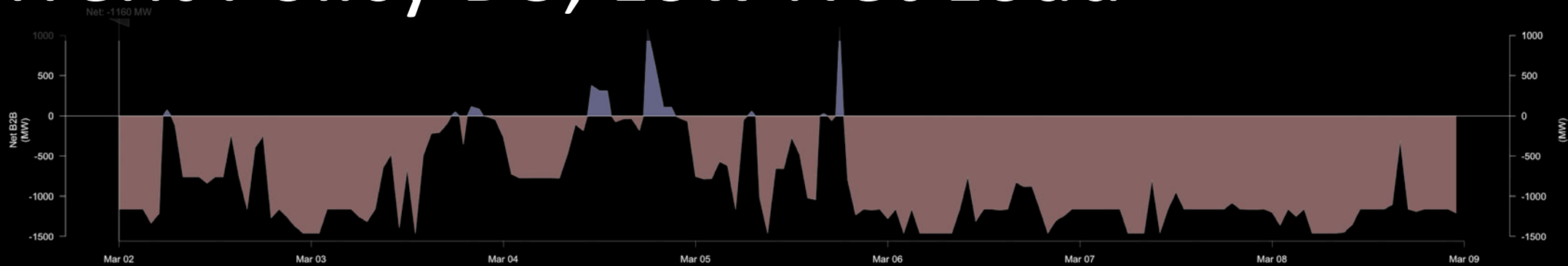


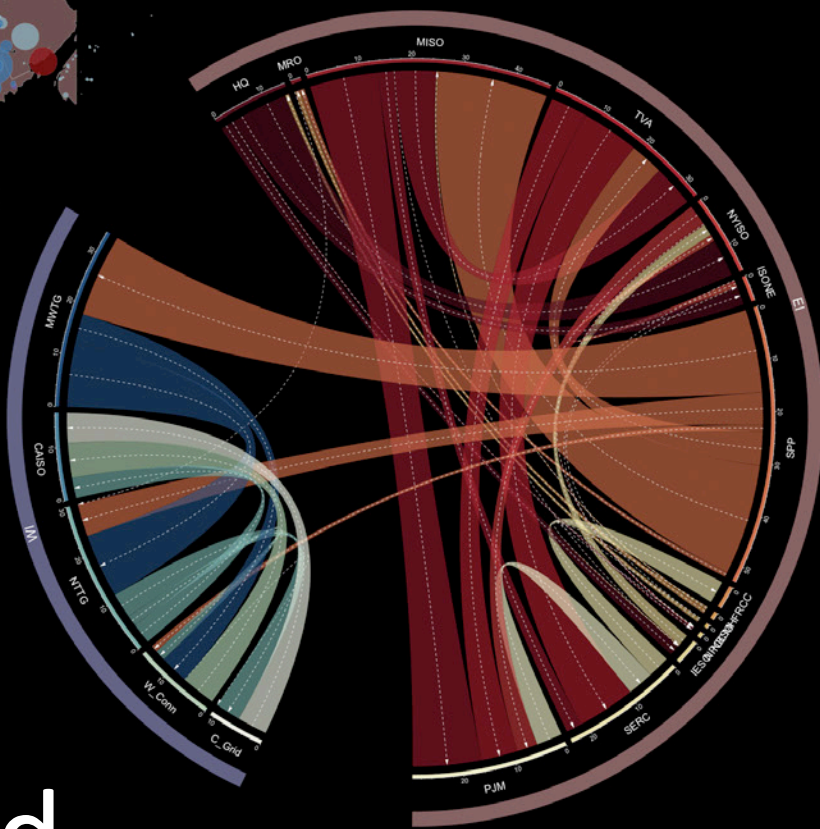
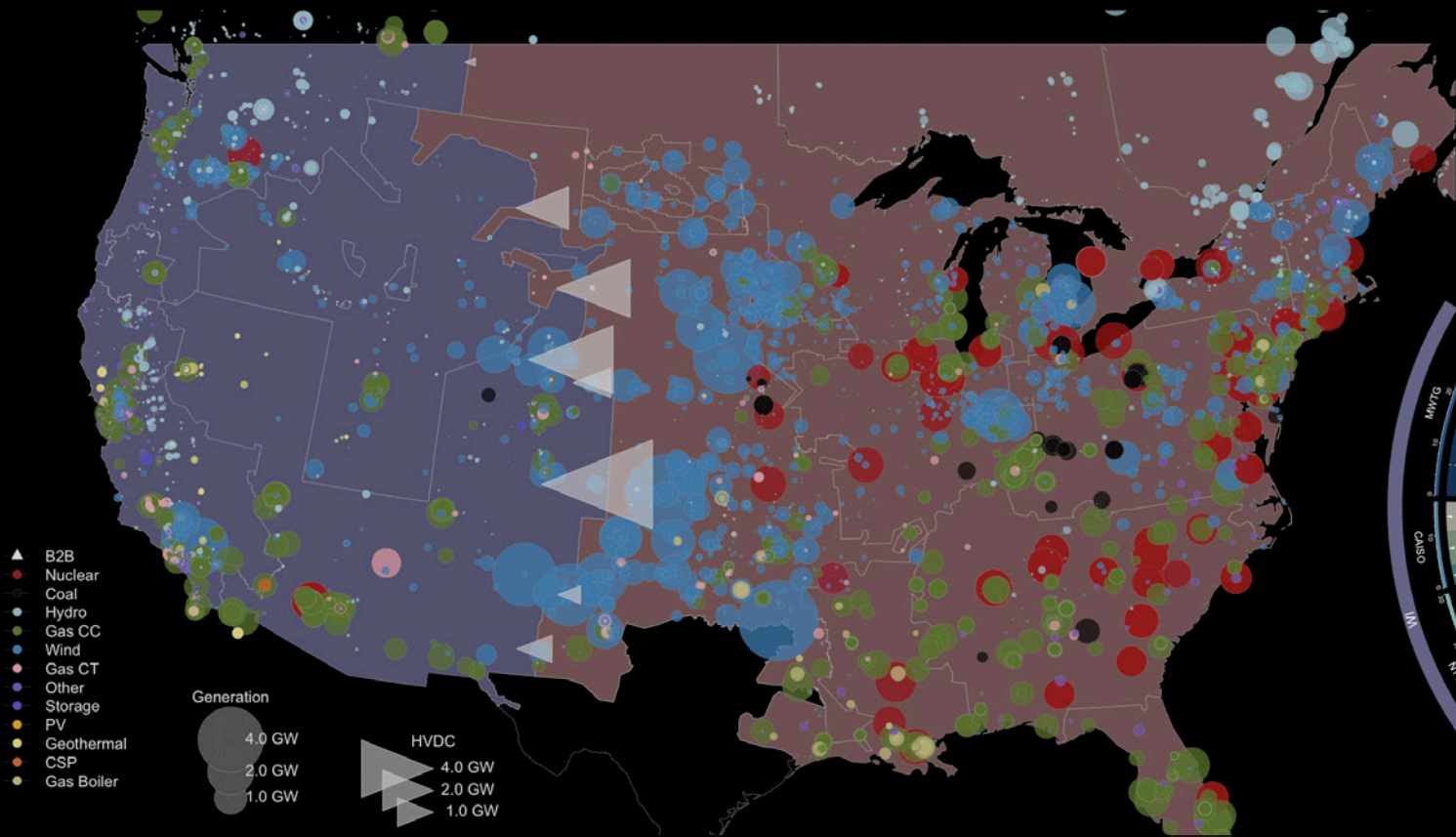
The Interconnections Seam Study (D3)

03-02-2038 00:00

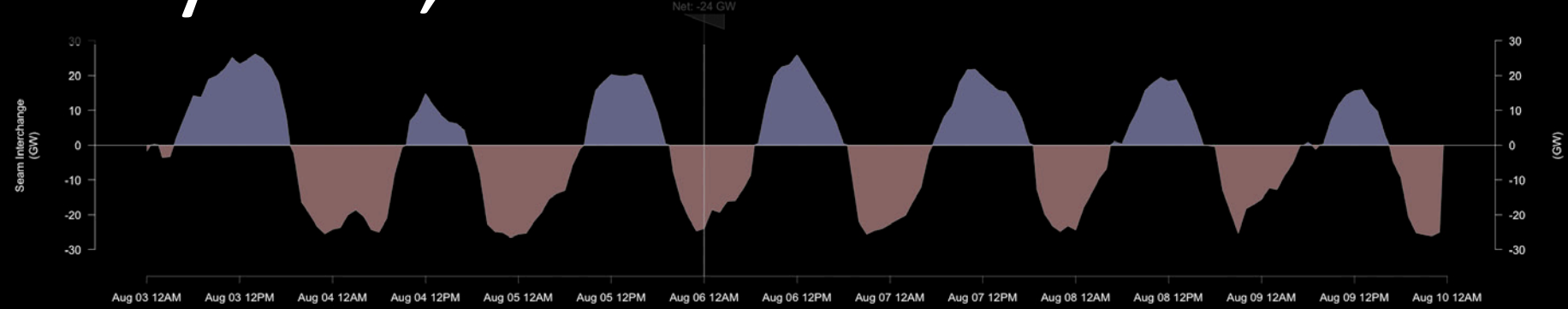
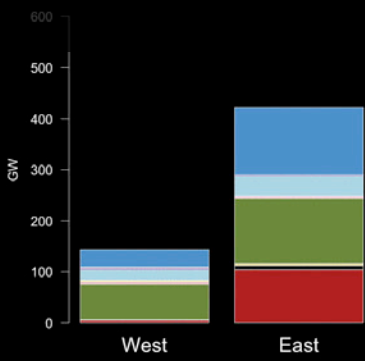


Current Policy D3, Low Net Load





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)

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

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)

Type	Current Policy				Carbon Policy			
	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.