National Transmission Planning Study

Technical Review Committee Meeting #1

May 20, 2022

Study Objectives and Goals

U.S. DEPARTMENT OF
ENERGY
Office of Electricity

National Transmission Planning Study

NREL Transforming ENERGY

Pacific Northwest NATIONAL LABORATORY

May 20th, 2022

Building a Better Grid (BBG)

Engagement and collaboration

- States
- Tribal nations
- Stakeholders

Enhanced transmission planning

- Transmission Needs Study
- National Transmission Planning Study
- Atlantic Offshore Wind Transmission Study

Federal financing tools ($20+B)

- Transmission Facilitation Program ($2.5B)
- Smart Grid Investment Grant Program ($3B)
- Grid resilience grants for states, Tribes, and utilities ($10+B)
- Loan guarantee programs

Transmission permitting process

- Streamline of permitting with federal agencies
- Public private partnerships
- Designation of corridors

Transmission-related R&D

- "Next generation" electricity delivery technologies
- Supporting activities

Objectives of the study

1. Identify **interregional and national strategies** to accelerate cost-effective **decarbonization** while maintaining system reliability

2. Inform regional and interregional transmission planning processes, particularly by **engaging stakeholders** in dialogue

3. Identify **viable and efficient** transmission options that will provide broad-scale benefits to electric customers

Desired outcomes of the study

$ Results help **prioritize future DOE funding** for transmission infrastructure support

Results help **fill existing gaps** within interregional transmission planning

Study provides a framework for stakeholders to discuss **desired grid outcomes** and **address barriers** to achieving them

Scenario Analysis: What it is doing and is not

What the study will do

- Link several long-term and short-term power system models to test a number of transmission buildout scenarios
- Inform existing planning processes
- Test transmission options that lie outside current planning
- Provide a wide range of economic, reliability, and resilience indicators for each transmission scenario

What the study will not do

- Replace existing regional and utility planning processes
- Site individual transmission line routes
- Address the detailed environmental impacts of potential future transmission lines
- Provide results that are as granular as planning done by utilities
- Develop detailed plans of service

Technical Review Committee (TRC) background, structure, and process

NTP Study Public Engagement: Four Aspects

Public Workshops and Input

- Introduce project and provide updates
- Share interim and results
- Provide opportunities for public feedback via website

Existing Convenor Groups

- Validate data and input assumptions
- Discuss consistency with groups’ existing efforts
- Share project updates and interim results

Technical Review Committee

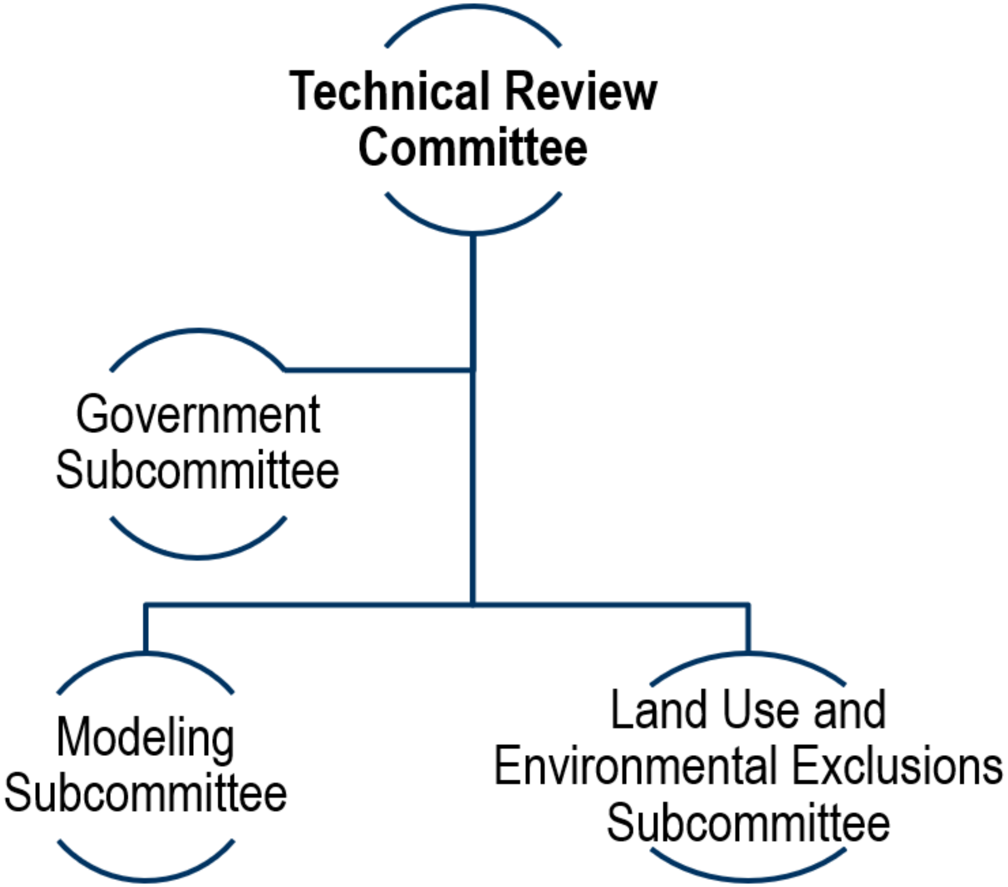
- Provide project input
- Suggest project adjustments
- Review interim results

Tribal Outreach

- Initiate broad outreach to all Tribes
- Invite statements of interest
- Incorporate Tribal input into analysis

Technical Review Committee

- **Technical Review Committee** (TRC) will constructively scrutinize and review the overall project and, where needed, will provide a forum for integrating input from all three subcommittees.
- **Government Subcommittee** will provide feedback on how to reflect federal and state policy and regulatory issues in the analysis.
- **Modeling Subcommittee** will provide technical feedback on assumptions, modeling, and data.
- **Land Use and Environmental Exclusions Subcommittee** will provide feedback on generalized issues related to constraints on locating new transmission and generation.



Technical Review Committee Members and Meetings

- TRC members were selected based on technical qualifications, prior experience in transmission planning processes, geographic and technical diversity, availability to participate in scheduled meetings, and ability to articulate the overall perspectives of the sectors in which they are active
  - Members should avoid using their participation in the TRC or its subcommittees to advance individual commercial interests
- We are also maintaining a list of subject matter experts that we may reach out to on specific topics
- Slides for this TRC meeting will be posted to DOE's National Transmission Planning (NTP) Study website

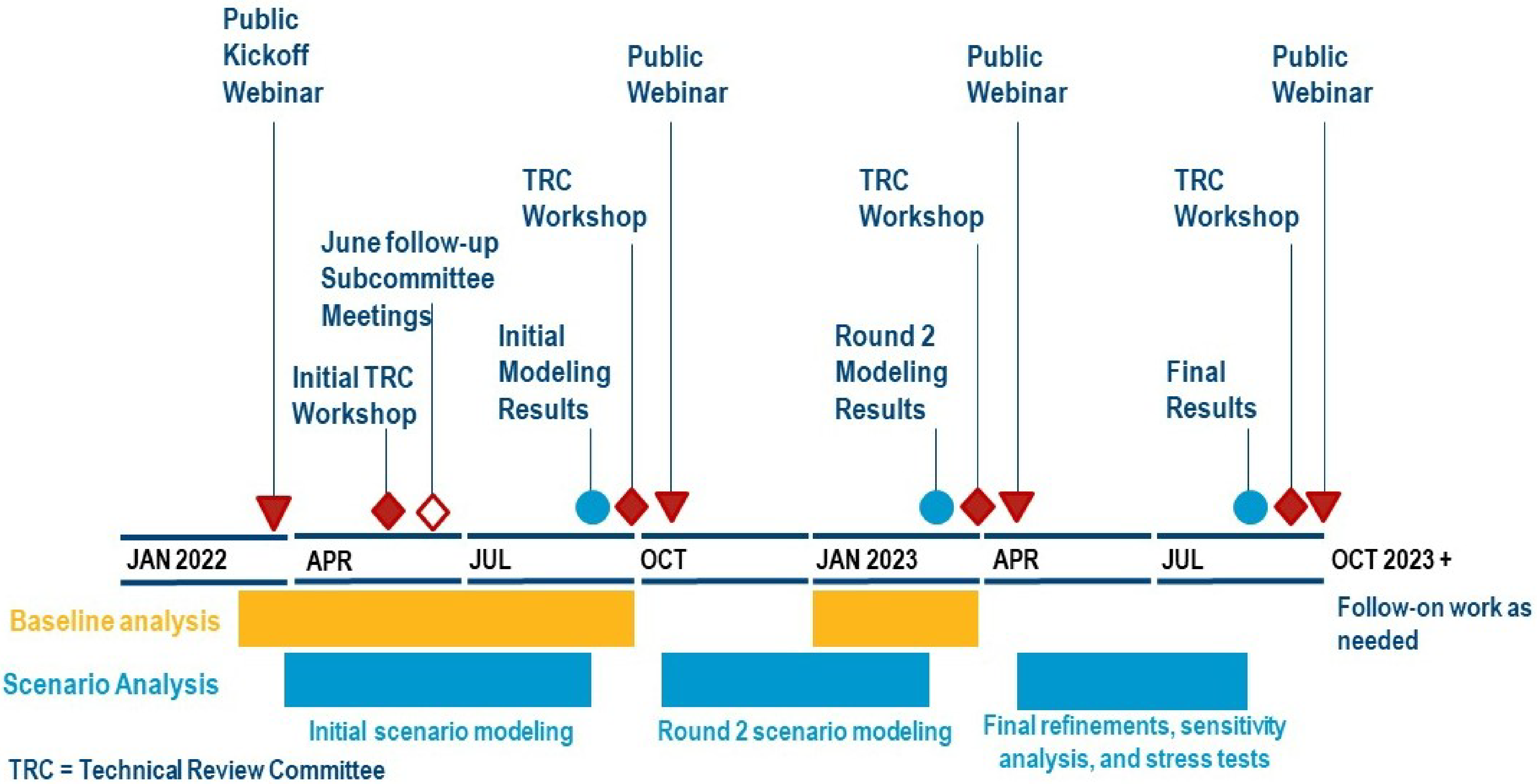
Follow-up June Subcommittee Meetings

- Follow-up June subcommittee meetings will provide an opportunity for smaller-group dialogue and questions
- No substantially new material will be presented at the June subcommittee meetings
  - **Modeling Subcommittee** – June 7th from 12:00 to 2:00 p.m. Eastern
  - **Government Subcommittee** – June 10th from 12:00 to 2:00 p.m. Eastern
  - **Land Use and Environmental Exclusions Subcommittee** – June 24th from 12:00 to 2:00 p.m. Eastern
- Additional subcommittee meetings will be held as the project progresses
- Future TRC meeting information will be posted on the public project website: https://www.energy.gov/oe/national-transmission-planning-study

Feedback areas

- Presenters today will identify questions or areas where feedback is being sought
- These will be summarized on a final slide at the end of most presentations
- Although there won't be time to go into those questions and discussion topics today, we invite you to consider these questions and:
  - Provide input via input forms
  - Come to June subcommittee meetings with ideas and questions

Public Engagement: Timeline

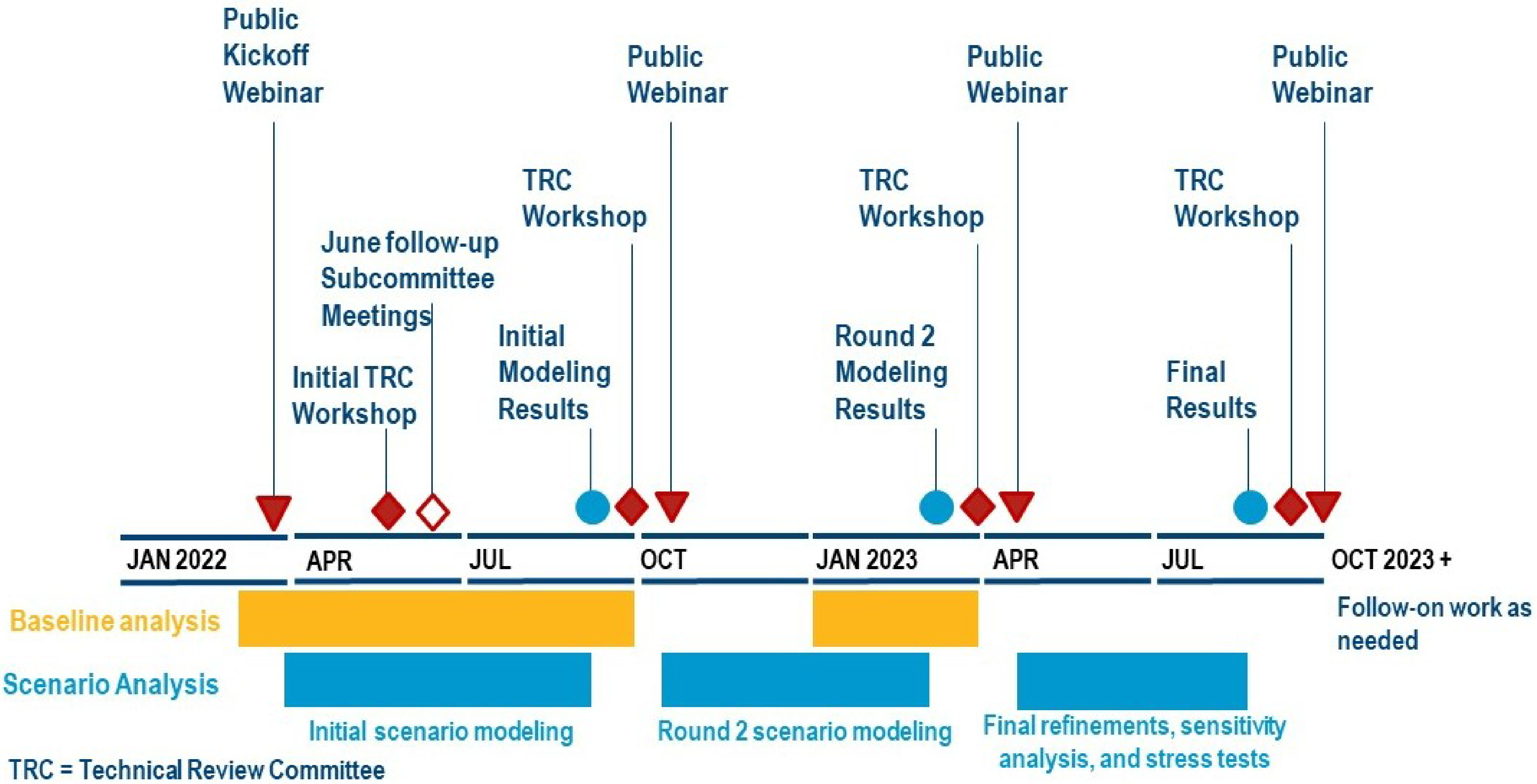


Study Overview

Next Steps

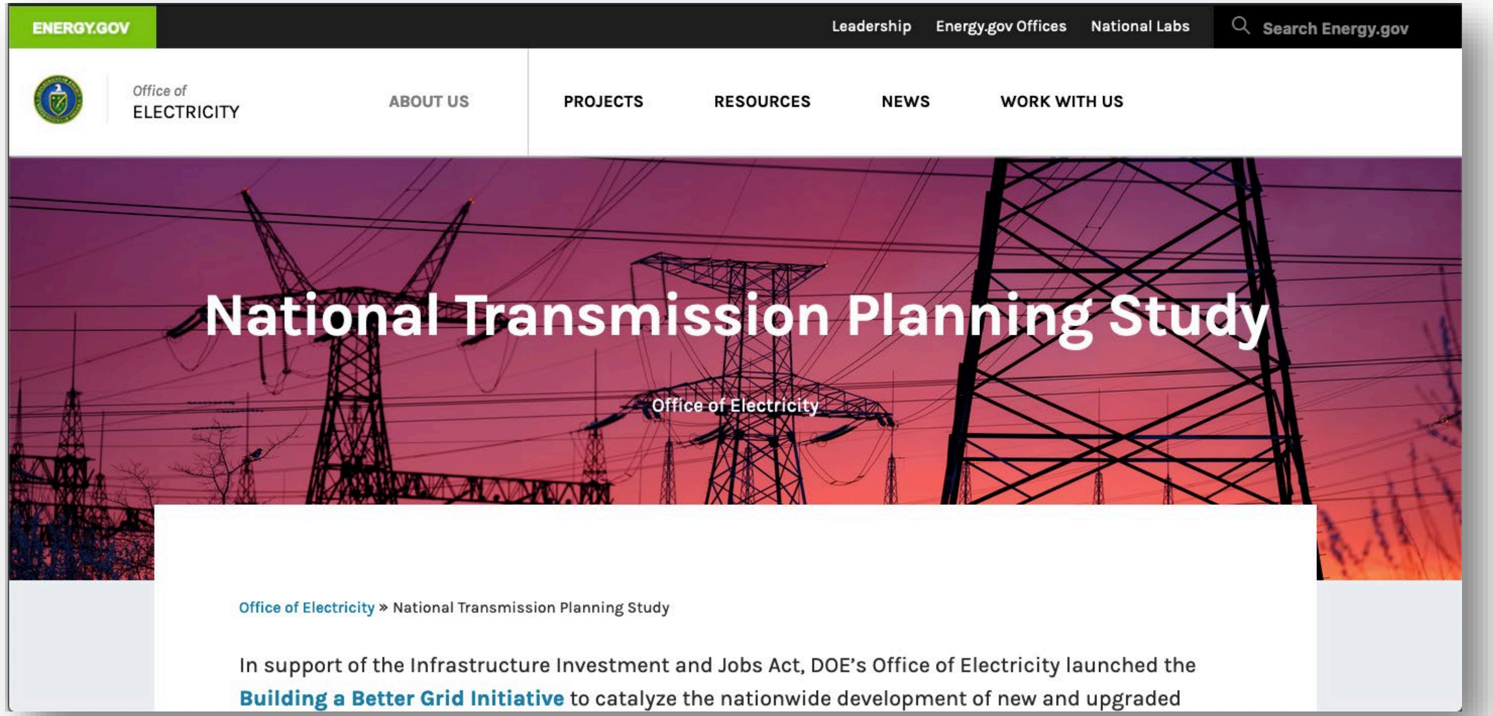
- Provide comments through the **comment form** on the NTP Study website https://www.energy.gov/oe/national-transmission-planning-study
- Interested parties sign up for email updates through the NTP Study website
- TRC members complete and submit the feedback form provided
- Follow-up June subcommittee meetings from 12:00 to 2:00 p.m. Eastern
  - **Modeling Subcommittee** – June 7th
  - **Government Subcommittee** – June 10th
  - **Land Use and Environmental Exclusions Subcommittee** – June 24th
- Lab team will continue conducting the baseline and scenario analysis
- Next TRC meeting - September
- Next public webinar will be in October 2022 to share interim results

Public Engagement: Timeline



https://www.energy.gov/oe/national-transmission-planning-study

- Overview of NTP Study goals and objectives
- Project news and milestone results
- Webinar presentations
- NTP Study mailing list
- TRC meeting schedules and presentation materials
- **Public comment form**



National Transmission Planning Study:
Introduction

Josh Novacheck
National Renewable Energy Laboratory

May 2022
Technical Review Committee Meeting

NOTICE
This presentation contains illustrative examples from preliminary modeling only; final results will differ from any results shown here.

The Transmission Grid:

What we know from **past modeling** of low-carbon futures

Photo by Dennis Schroeder / NREL 50673

Past modeling of low-carbon futures shows…

1. **Transmission has particular value in systems with high wind and solar**
2. Interregional transmission is often designed to deliver wind and solar from one region to load in another—but a new project's bidirectional operations can provide capacity value to both regions
3. Transmission-system reliability analysis should consider more time periods and connect power-systems modeling tools
4. Electrification increases the need for carbon-free generation (see #1)

Transmission has particular value in systems with high wind and solar

Interconnections Seam Study

Base Scenario
30% Wind and Solar Annual Contribution

Capacity or Cost Item	D1	ΔD2a	ΔD2b	ΔD3
Transmission Investment Cost, $B	40.03	2.57	6.76	8.19
Generation Investment Cost, $B	555.23	3.6	10.44	4.17
Operational cost, $B	2376.50	-8.79	-21.70	-15.30
35-yr Net Cost Change, $B	-	-2.62	-4.5	-2.94
35-yr B/C ratio	-	2.02	1.66	1.36

High VG Scenario
40% Wind and Solar Annual Contribution

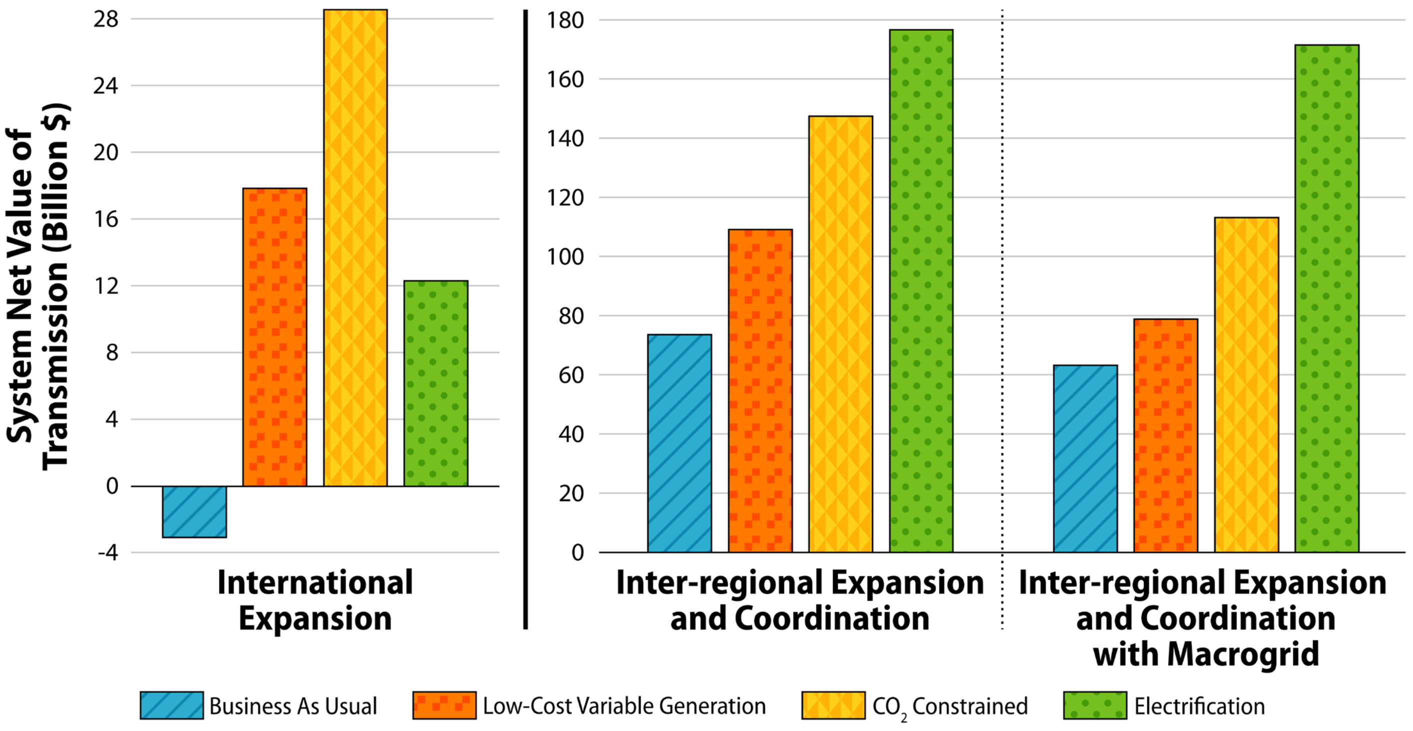
Capacity or Cost Item	D1	ΔD2a	ΔD2b	ΔD3
Transmission Investment Cost, $B	71.69	16.79	15.6	28.86
Generation Investment Cost, $B	741.38	6.83	8.02	7.95
Operational Cost, $B	2563.3	-41.97	-52.45	-59.85
35-year Net Cost Change , $B	NA	-18.35	-28.83	-23.04
35-year B/C Ratio	NA	2.09	2.89	1.80

Note: D1 results are shown as absolute costs; D2a, D2b, and D3 results are shown relative to D1.
In the High VG case, carbon costs are included in the optimization but not the net costs or B/C ratio

https://www.nrel.gov/analysis/seams.html

Transmission has particular value in systems with high wind and solar

North American Renewable Integration Study



https://www.nrel.gov/analysis/naris.html

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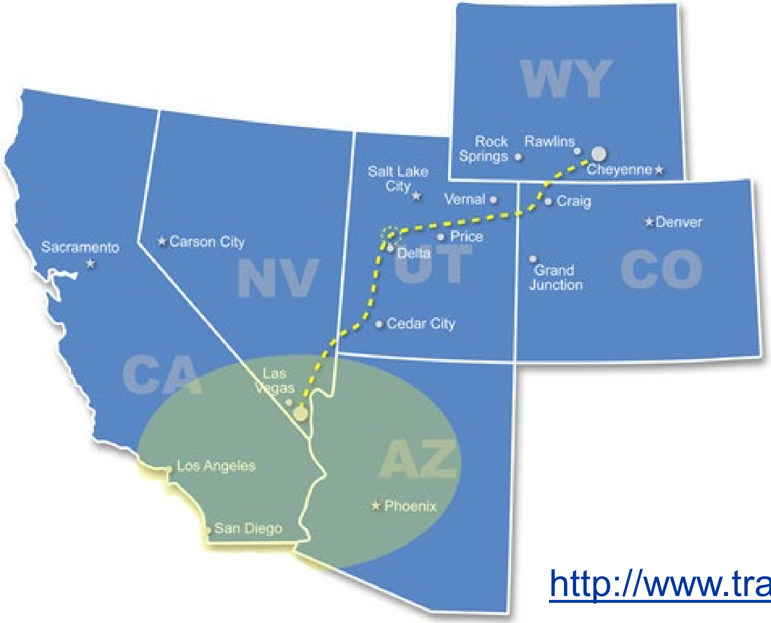
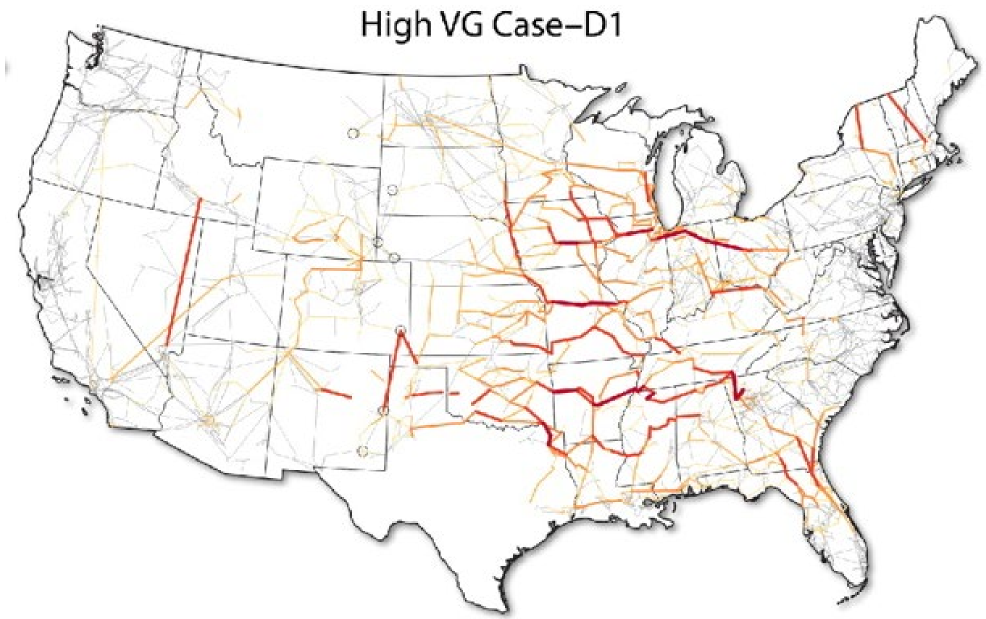
Lines are often built to connect wind and solar to load centers



http://www.transwestexpress.net

Interconnections Seam Study



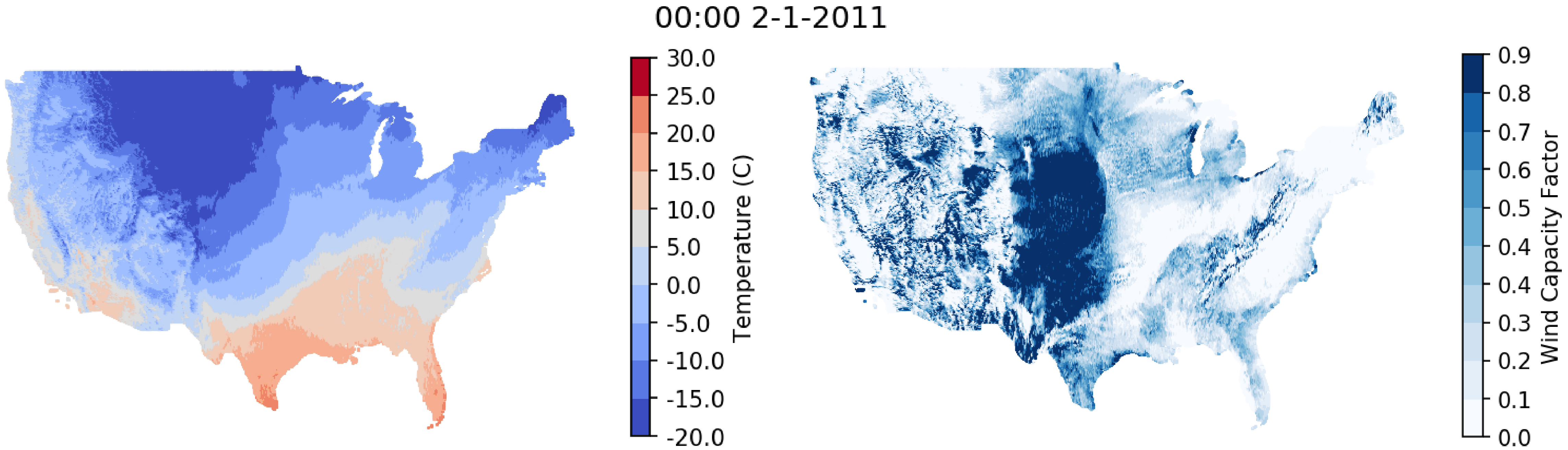
Transmission Investment Summary
High VG Scenario

Design→	D1	D2a	D2b	D3
HVDC-B2B (GW)	0	25.7	7.5	0
HVDC-Line (GW-miles)	0	0	31,300	63,200
AC Line (GW-miles)	52,700	60,100	51,000	43,200

Note: New transmission investments are identified for B2B in terms of GW increased capacity between B2B terminals, and for lines in terms of GW-miles (which is the GW capacity multiplied by the path distance).

https://www.nrel.gov/analysis/seams.html

But lines can provide capacity value to both ends



Cold waves (especially in the Eastern and Texas Interconnections) come with high wind resource as cold pushes down the Front Range of the Rocky Mountains.
How widespread and prolonged stagnant wind lasts differs between cold waves.

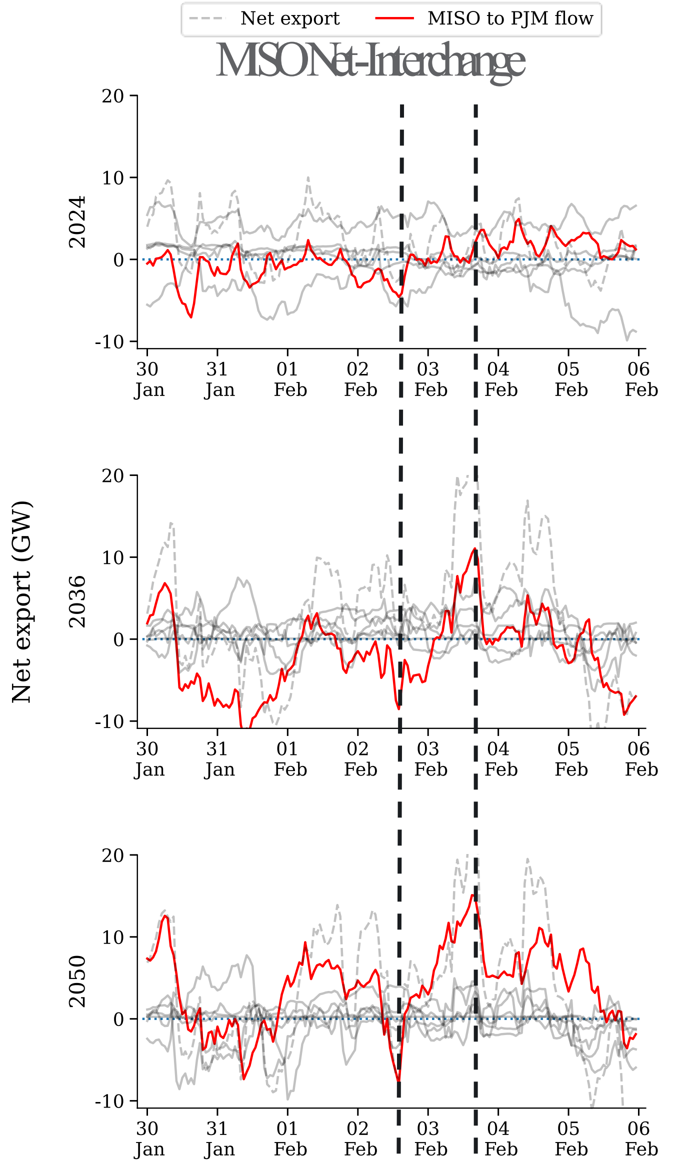
Novacheck, Sharp, et al. 2021. “The Evolving Role of Extreme Weather Events in the U.S. Power System with High Levels of Variable Renewable Energy”
https://doi.org/10.2172/1837959

But lines can provide capacity value to both ends

2011 Extreme Cold Wave

Wind and solar generation **provide >80% of generation** in the EI even as load increases as the cold front moves across the continent.

Wind and solar continues to serve ~50% of load after front moves through and load is elevated. This is enabled by **interregional interchange**.



Swing in MISO exports to PJM used to serve SERC and NYISO

Novacheck, Sharp, et al. 2021. "The Evolving Role of Extreme Weather Events in the U.S. Power System with High Levels of Variable Renewable Energy" https://doi.org/10.2172/1837959

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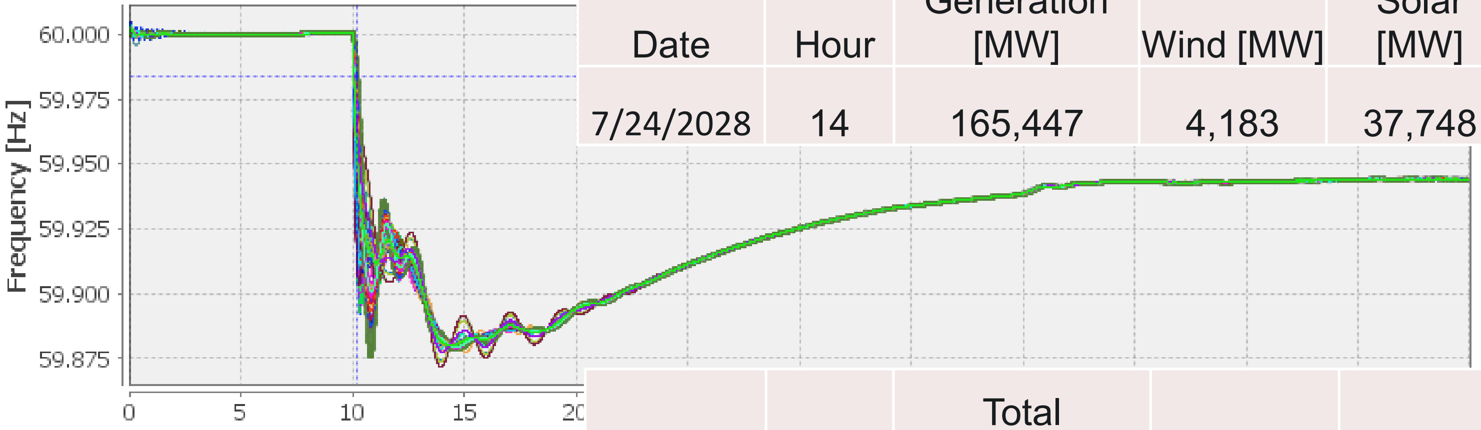
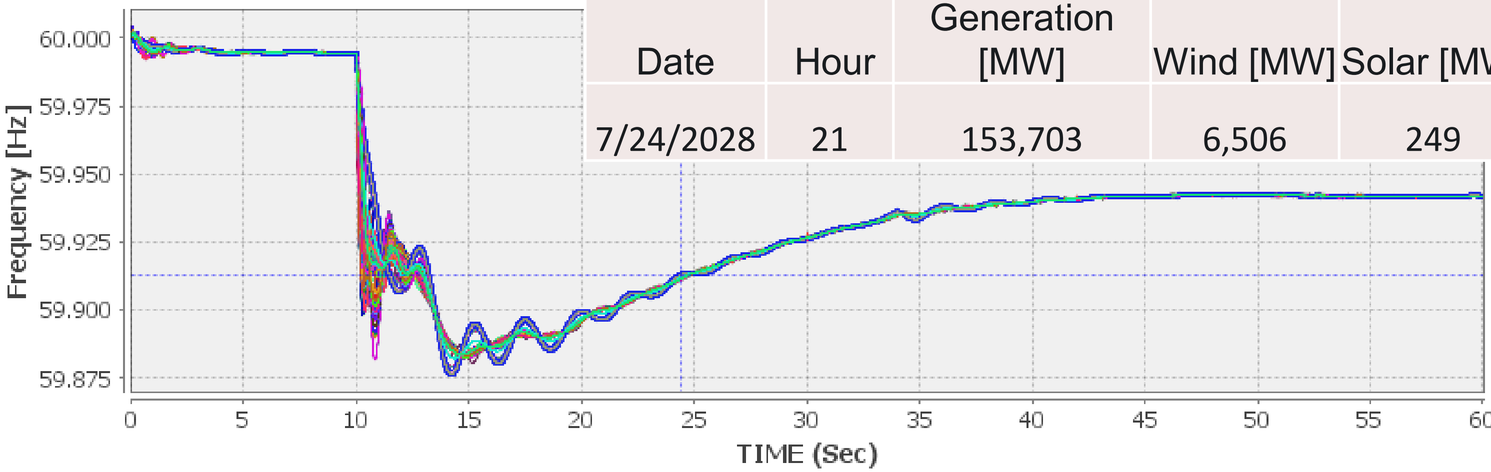
3. **Transmission-system reliability analysis should consider more time periods and connect power-systems modeling tools**
4. Electrification increases the need for carbon-free generation (see #1)

Connecting tools to ensure transmission system reliability



Date	Hour	Total Generation [MW]	Wind [MW]	Solar [MW]	renewable/ total [%]
7/24/2028	14	165,447	4,183	37,748	25%



Date	Hour	Total Generation [MW]	Wind [MW]	Solar [MW]	renewable/ total [%]
7/24/2028	21	153,703	6,506	249	4%

PNNL's C-PAGE tool

B. Vyakaranam, Q. H. Nguyen, T. B. Nguyen, N. A. Samaan and R. Huang, "Automated Tool to Create Chronological AC Power Flow Cases for Large Interconnected Systems," in ***IEEE Open Access Journal of Power and Energy***, doi: 10.1109/OAJPE.2021.3075659

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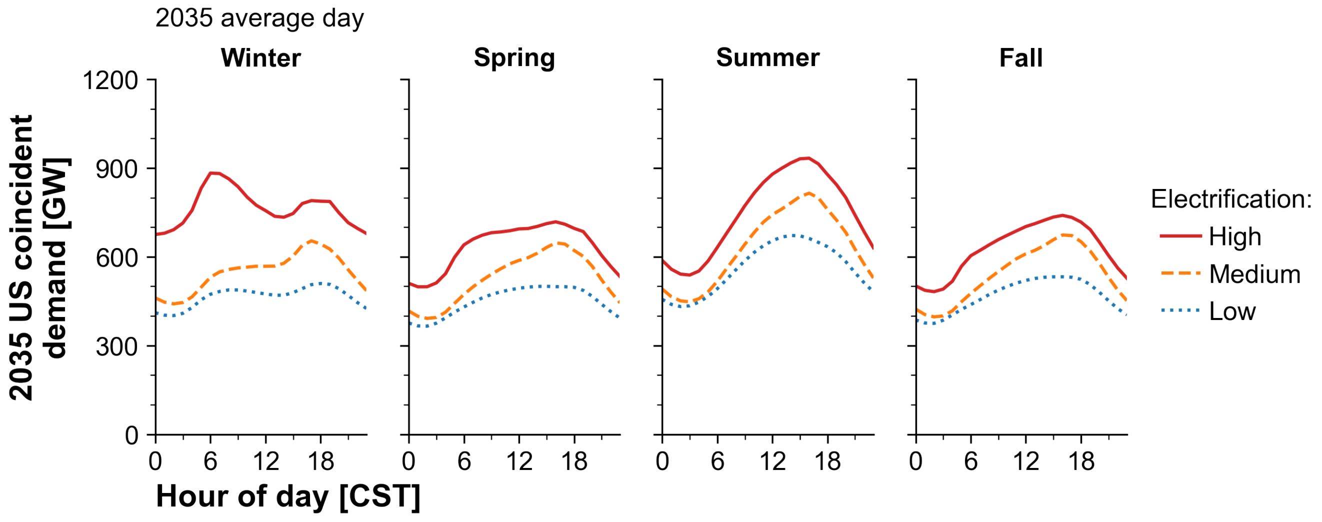
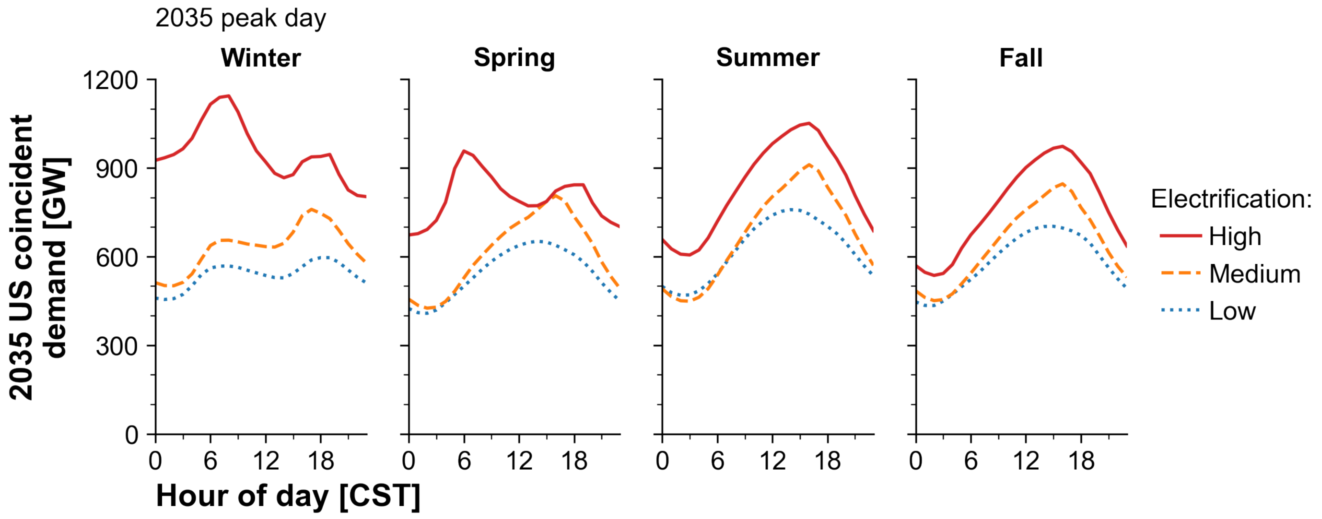
Electrification increases the need for carbon-free generation



Most U.S. regions are **summer peaking** today and expected to remain as such without significant electrification.



Electrification raises average demand throughout the year and **demand peaks could shift to winter**, particularly for electrified space and water heating.

https://www.nrel.gov/analysis/electrification-futures.html

Looking Ahead: The National Transmission Planning Study (NTPS)

To meet national targets of clean electricity by 2035 and a decarbonized economy by 2050, **the electric power transmission system needs significant enhancements** to accommodate the growth of renewable generation and electrified loads.

Photo by Dennis Schroeder / NREL 50680

Study Overview

Co-led by NREL and PNNL, the NTPS will:

Produce **transmission expansion recommendations** based on a set of planning scenarios coordinated by DOE with industry, states, and regional planning entities

Conduct **scenario analysis** to articulate national approach to upgrading the electric transmission system

With DOE involvement, facilitate **stakeholder collaboration** to fill crucial gaps in national transmission planning

Study Scope

Public Engagement

- Develop detailed public engagement plan
- Coordinate with existing convenor groups
- Form Technical Review Committee with subcommittees
- Hold public workshops and develop informational webpage

Baseline Analysis

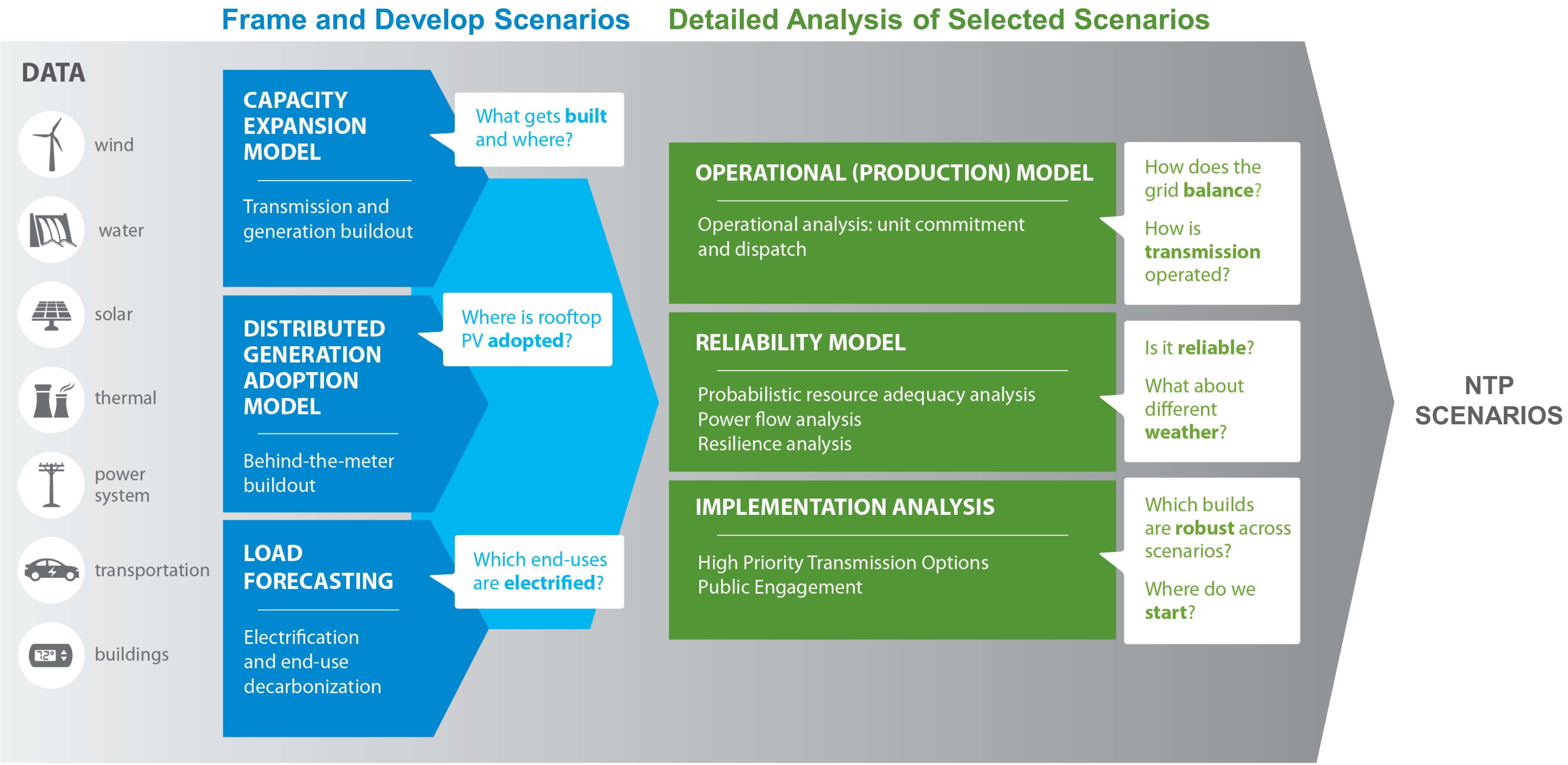
- Develop database of large, interregional transmission projects in the advanced stages of development
- Develop nodal version of best available 2030 Industry Planning cases for power flow and production cost modeling
- Evaluate baseline projects and system relative to 2035 target and identify bottlenecks

Study Scope, Continued

Scenario Analysis Key Tasks

- Define scenarios for divergent transmission pathways to achieve deep decarbonization
- Capacity expansion modeling
- Production cost modeling (zonal and nodal)
- AC power flow and dynamic reliability analysis
- Stress case and resource adequacy analysis
- Identification of high-priority transmission options
- Identify potential interregional renewable energy zones
- Economic analysis to inform cost allocation

NTPS relies on multiple linked modeling exercises



Thank you

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Acronyms and Abbreviations

AC	alternating current
B2B	back-to-back
B/C	benefit-to-cost ratio
CONUS	contiguous United States
DOE	U.S. Department of Energy
EI	Eastern Interconnection
GW	gigawatts
NREL	National Renewable Energy Laboratory
NTPS	National Transmission Planning Study
NYISO	New York Independent System Operator
MISO	Midwest Independent System Operator
PJM	PJM Interconnection
PNNL	Pacific Northwest National Laboratory
SERC	SERC Reliability Corporation
VG	variable generation

National Transmission Planning:

Baseline of U.S. Electric Power System Expansion Plans

Nader Samaan, PNNL

NOTICE

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Objectives behind Baseline Cases

1. Using 10-year outlook industry planning models, estimate the expected **power system decarbonization range**
   - Planning models include expected loads, resources, and transmission topology 10 years into the future
   - Planning models comprise Production Cost Models (PCM) and Power Flow Models (PFM)
2. Model additional new lines (in **advanced development stages**) and associated new wind and solar projects
   - Consider increased utilization of current transmission surplus
   - Quantify **additional, achievable, decarbonization**
3. **Assess realized decarbonization** against the 2035 decarbonization goal based on metrics covering transmission utilization, energy mix, emission, and grid reliability

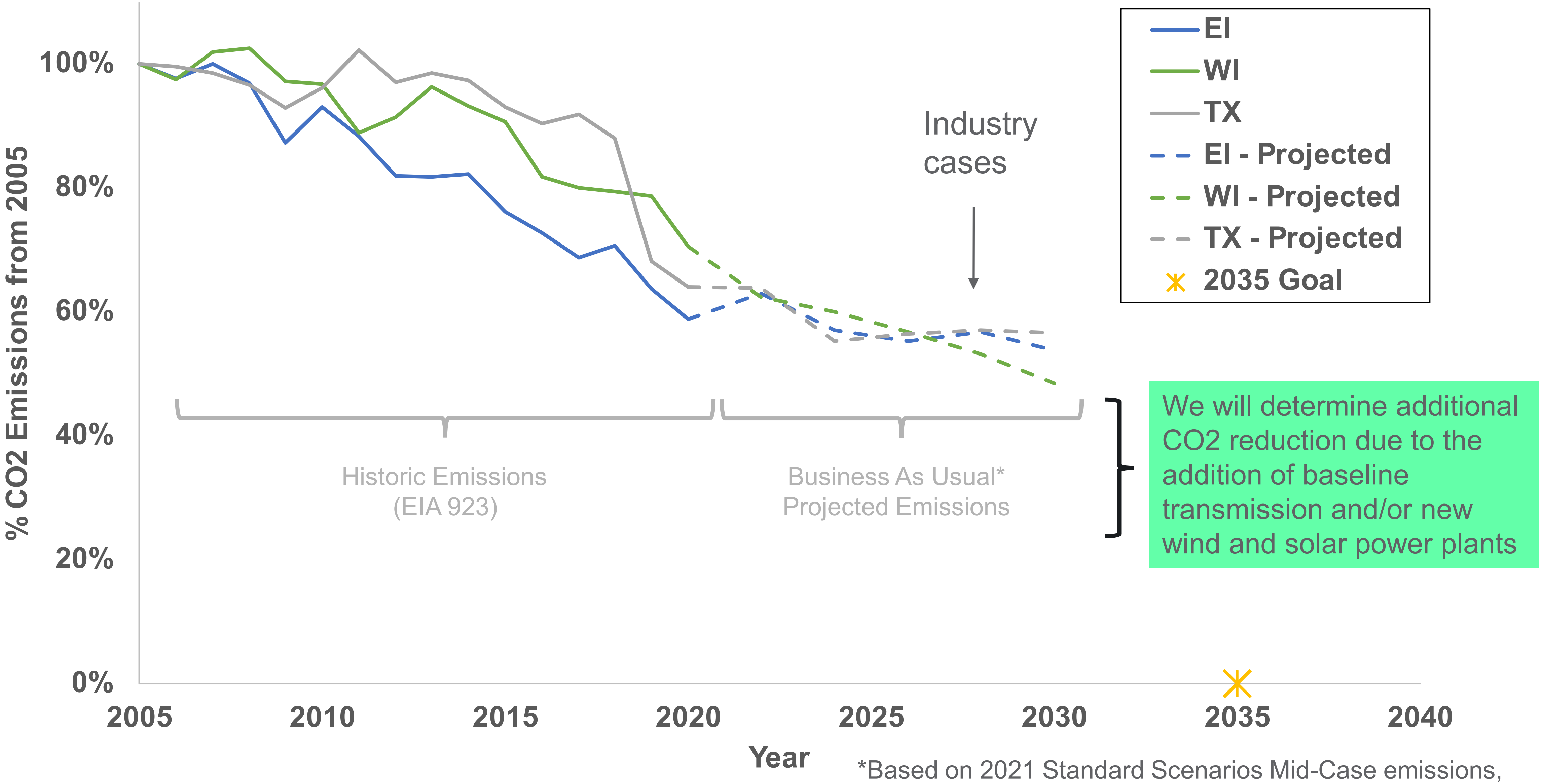
Approach for Developing Baseline Cases

1. Case 1: Establish **Industry Planning Case**
   a) Start from 10-year outlook power industry planning models (PFM and PCM)
   b) Develop PCM models if none available
2. Case 2: Establish **Baseline Transmission Case** (Industry Planning Case + New Transmission Lines)
   a) Add new transmission projects to Industry Planning Case (PFM and PCM) as most of the baseline transmission projects are not already modeled in the industry planning case.
   b) This step is to verify that the Modified Industry Planning Case correctly models identified baseline transmission projects (see slide 6)
3. Case 3: Establish **High Renewables Industry Case** (Industry Planning Case + New Renewables)
   a) Add new wind and solar projects where current transmission lines have surplus capacity
4. Case 4: Establish **High Renewables Baseline Transmission Case** (Industry Planning case + New Transmission Lines + High Renewables)
   a) Select new wind and solar project locations and add to PFM and PCM
   b) Maintain compatibility between PCM and PFMs to preserve ability to import generation dispatch from PCM to the PFM

Case 1: Industry Planning Models (10-year ahead)

- Leverage the best industry and DOE data and models available
  - West: WECC Anchor Data Set 2030 (PCM and PFM) developed by WECC stakeholders
  - East: NERC Multiregional Modeling Work Group (MMWG) 2031 (PFM),
    - ✓ A PCM base case model for the **Eastern Interconnection** does not pre-exist and is under development, leveraging the MMWG 2031 and NREL North American Renewable Integration Study (NARIS) study
  - Texas: ERCOT 2030 planning case (PFM) - *pending*, NREL North American Renewable Integration Study as starting point to develop 2030 PCM
  - US: Energy Information Administration(EIA) data sets are used to supplement the models above as needed

Case 1: Electricity CO2 Emissions Trajectory and Gap to 2035 Goal



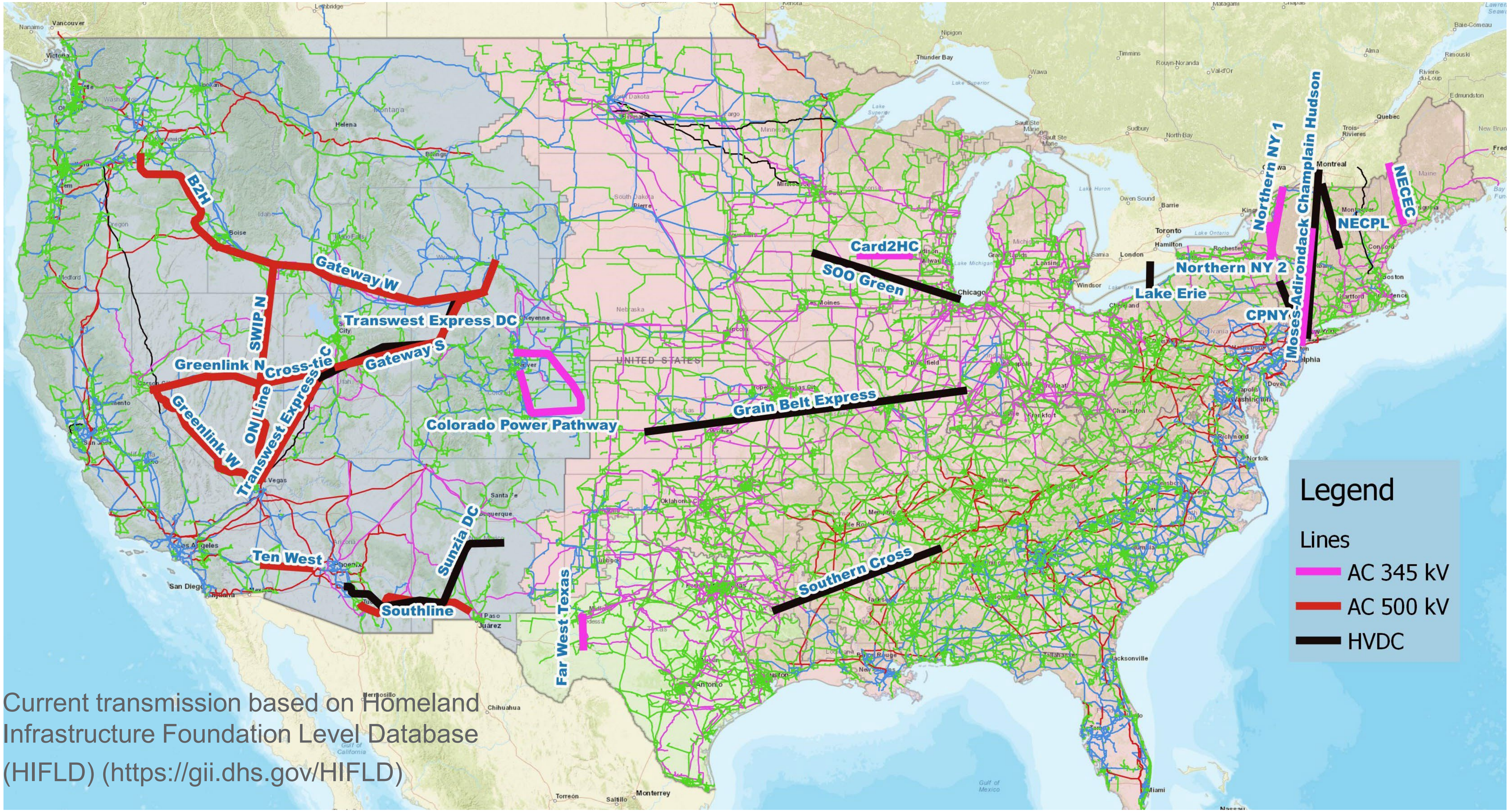
*Based on 2021 Standard Scenarios Mid-Case emissions, results are consistent with Basecase 2030 PCM results

EIA 923 Emissions (https://www.eia.gov/electricity/data.php#elecenv)

Case 2: Baseline Transmission - Selection Criteria

- We only considered large transmission projects that are 345KV or above and at least 70 miles in length
- Projects were screened based on meeting **two** or more of the following criteria:
    1. New Line construction or rebuild of an existing line is underway.
    2. New line developers are in active communications with FERC Order 1000 entities and are providing transmission line visibility/impact studies and PFM data.
    3. Developers actively / successfully acquiring federal and/or state permits
    4. Developers actively / successfully securing power purchaser commitment for proposed lines (load-serving entities, power trade in RTO, state energy commission approvals for Regulated utilities)
    5. Developers actively / successfully engaging public to address concerns and gain acceptance
- Team is collaborating with the power industry to collect baseline transmission data
    - Looking at projects in development
    - Not picking winners and losers
    - Not advocating for any of these specific lines

Baseline transmission projects at advanced development stage



Current transmission based on Homeland Infrastructure Foundation Level Database (HIFLD) (https://gii.dhs.gov/HIFLD)

Most of them have the objective of connecting renewable resources with load centers

Case 2: Baseline Transmission Lines (Western Interconnection and ERCOT)

Western Interconnection

- Boardman to Hemmingway (B2H)
- Ten West Link
- Gateway West (several segments completed, others are under construction)
- Gateway South
- SWIP North and SWIP South
- Transwest Express
- Cross-Tie
- SunZia
- Southline
- Greenlink Nevada West
- Greenlink Nevada North
- Colorado Power Pathway

ERCOT

- Far West Texas Project (one of two proposed segments completed)

ERCOT to Eastern Interconnection

- Southern Cross

Case 2: Baseline Transmission Lines Eastern Interconnection

SPP to MISO

- Grain Belt Express

MISO

- Cardinal Hickory Creek

MISO to PJM

- Soo Green HVDC Link

PJM

- Lake Erie Connector

ISO-NE

- The New England Clean Energy Connect (NECEC)
- New England Clean Power Link (NECPL)

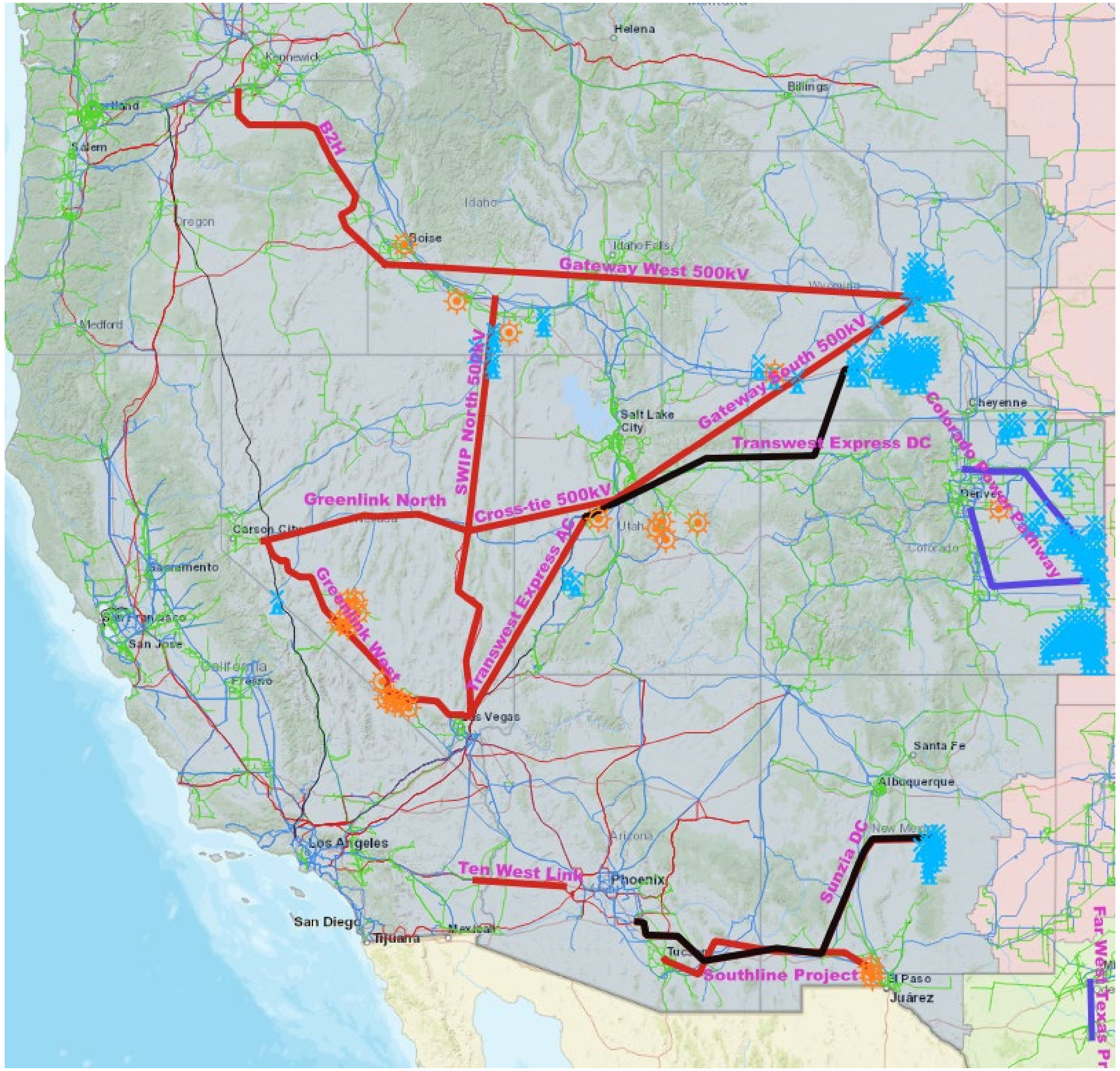
NY-ISO

- Champlain Hudson Power Express Line
- Clean Path New York
- Smart Path Connect (Northern New York Priority Transmission Project) rebuild of existing line
- Moses-Adirondack (NYPA's Moses-Adirondack Smart Path Reliability Project) rebuild of existing line

Case 3: High Renewables Industry Case

- Use Case 1 models
- Add wind and solar power plants based on the following:
  - Current transmission with available capacity, high quality wind and solar resources exist guided by interconnection queue requests, EIA 860 planned project
  - Current transmission capacity that will become available due to thermal unit retirement
- This is more of an initial estimate rather than a full comprehensive analysis to utilize all available transmission capacity as that will require additional reliability analysis

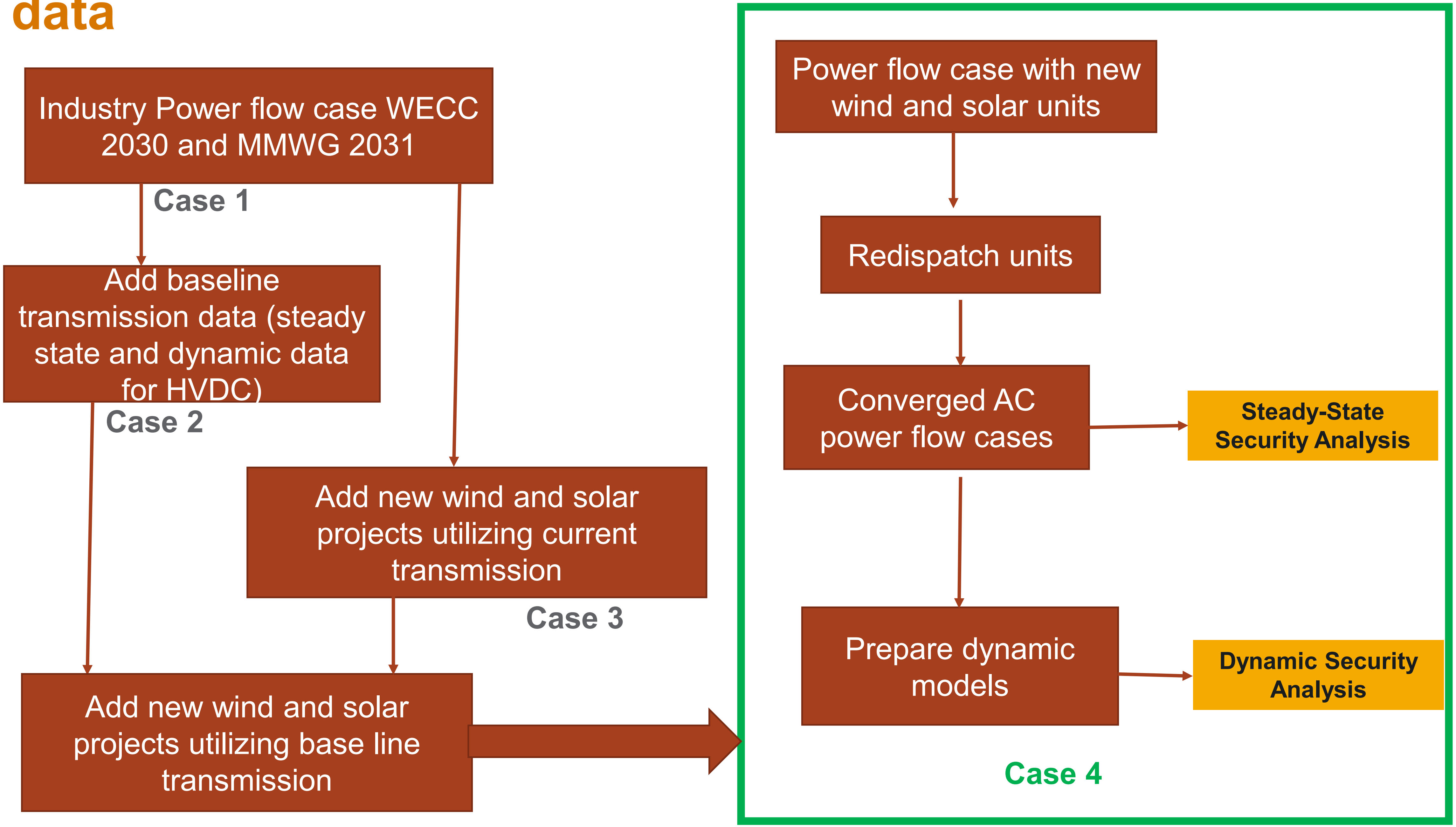
Case 4: High Renewables Baseline Transmission Case (a) Adding new wind and solar power plants



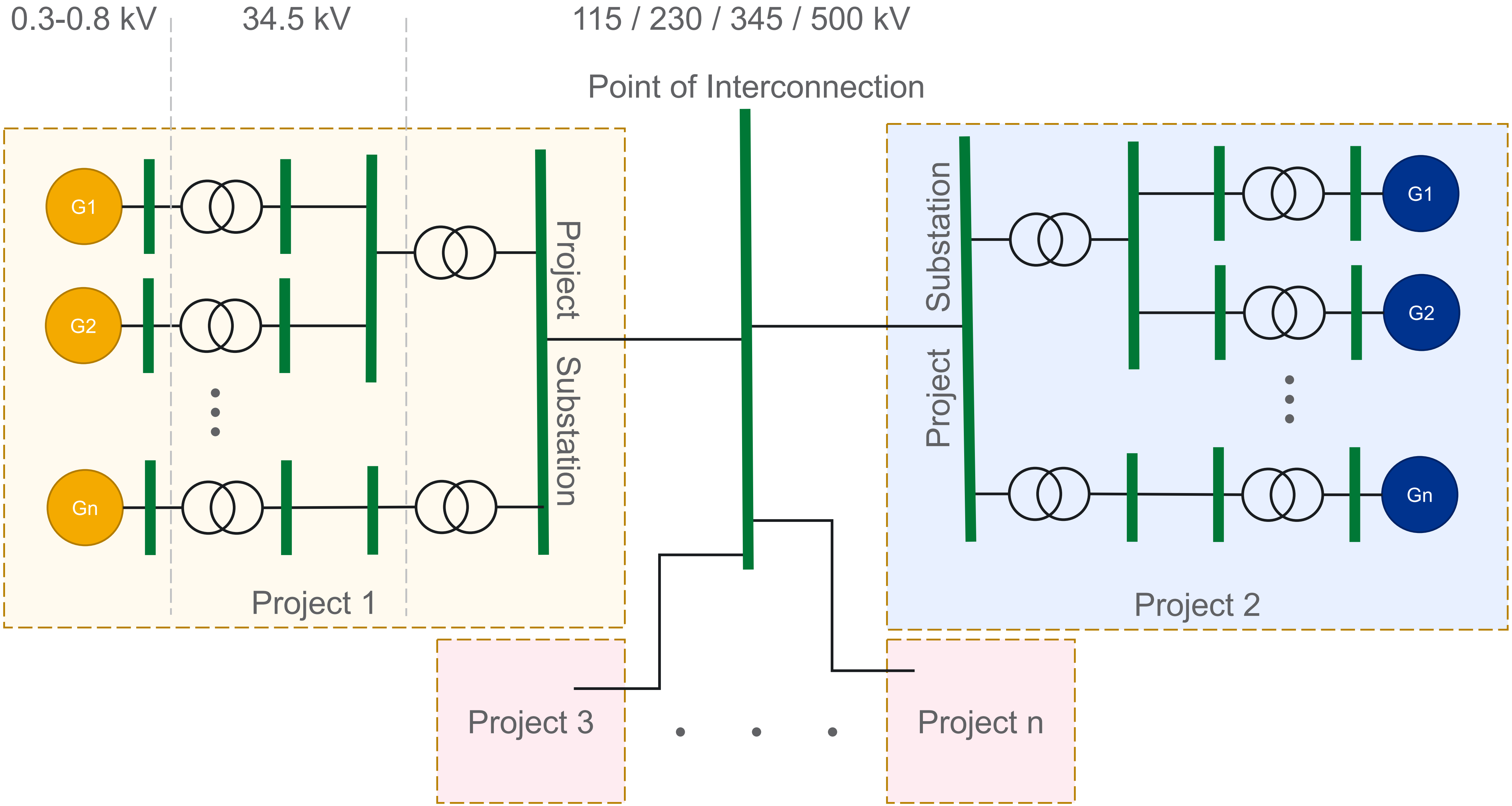
Starting from Case 3, add new baseline transmission identified in Case 2, add new wind and solar that can utilize bassline transmission with the following steps:

- **Step 1:** Identify high voltage substations based on new transmission lines: either direct connection (new transmission line substation) or adjacently branched.
- **Step 2**: Identify wind and solar candidate projects within 50 miles from identified high voltage substations. Use NREL reV tool to create generation profiles.
- **Step 3**: Identify the limits: Projects from Step 2 are added until new transmission lines are at capacity; congestion, reliability, and economic concerns may also limit additions

Case 4: (b)-Development of PFM and associated dynamic data



Case 4: (b) Typical PF model for Newly added Wind or Solar Project



Case 4: (C)-Development of PCM

Transmission Projects

Incorporate baseline transmission projects and associated components:
- HVDC lines
- AC Lines
- Series compensators
- Tap changing transformers
- Phase-shifting transformers

Interface Paths

Update PCM interface paths rating:
- Map new transmission projects to existing and new interface paths.
- Update paths' ratings based on stakeholders' inputs

Wind & Solar Projects

Incorporate new wind and solar generation:
- Import generation information from the PFM
- Import hourly time series of wind and solar generation linked to plant level weather conditions (solar intensity, wind speed)

python™

python™

python™

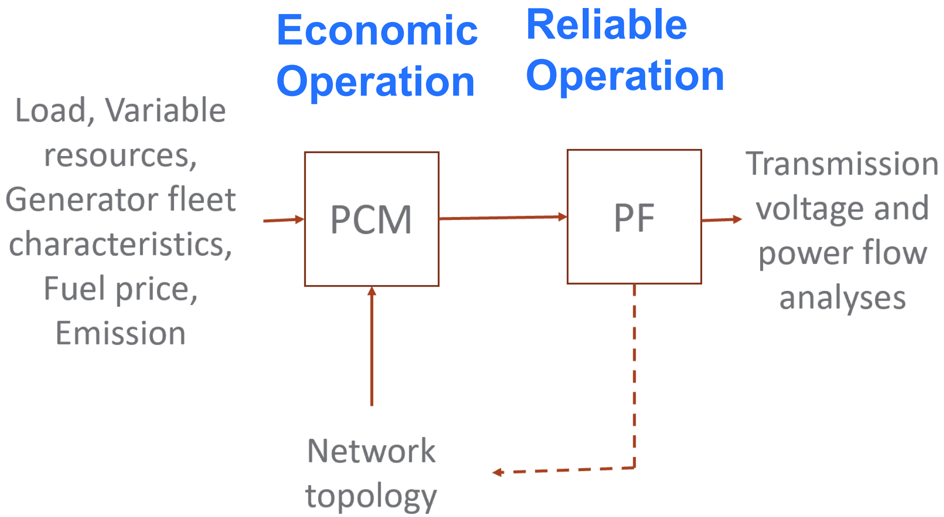
Production Cost Model
- Centrally minimizes operating costs

Benefits Evaluation

How much additional renewable generation can we integrate into the system through utilizing new transmission projects ?

Evaluate system benefits using key performance metrics:
- Interchange power flows
- Wind/solar curtailment
- Unserved energy
- Paths' utilization & congestion
- Operating costs
- GHG emissions
- Locational marginal prices

Case 4: (D) PCM to PFM round trip for reliability analysis



- **Why round trip (PCM to PFM) :** Planning issues that cannot be dealt with only PCM or PFM
  - PCM: cannot deal with voltage stability, frequency response, contingency analysis
  - PF: cannot deal with resource adequacy, flexibility requirement, wind and solar variability
- **Challenges to perform round trip**
  - DC to AC power flow conversion
  - Time consuming: Typically, it takes several days to months to create a base AC power flow case from PCM data based on how the two data sets are harmonized

- **To address this challenge, we have developed Chronological AC Power Flow Automated Generation Tool (C-PAGE) and Scalable Integrated Infrastructure Platform (SIIP)**

Summary and key points

- We are
  - Building cases that expand on analysis based on well-vetted power industry models
  - Collaborating with the power industry to collect baseline transmission data
    - ✓ Looking at other projects in development
    - ✓ Not picking winners and losers
    - ✓ Not advocating for any of these specific lines
  - Developing insights for scenario analysis based on lines that are already in the planning process
- We will perform comprehensive analysis that include production cost modeling, and AC power flow analysis, linking between these models to perform reliability analysis (contingency analysis and dynamic simulations)

We are looking forward to meeting with TRC modeling subcommittee on June 7th for more detailed technical discussions

Questions for Stakeholders

- Is the approach clear?
- Are there any comments or suggestions on the criteria for including baseline transmission projects?
- Do you have any feedback on the list of projects?
- Are there any comments or suggestions on the overall approach?
- Are there any comments or suggestions on the data sets being used?

National Transmission Planning Study

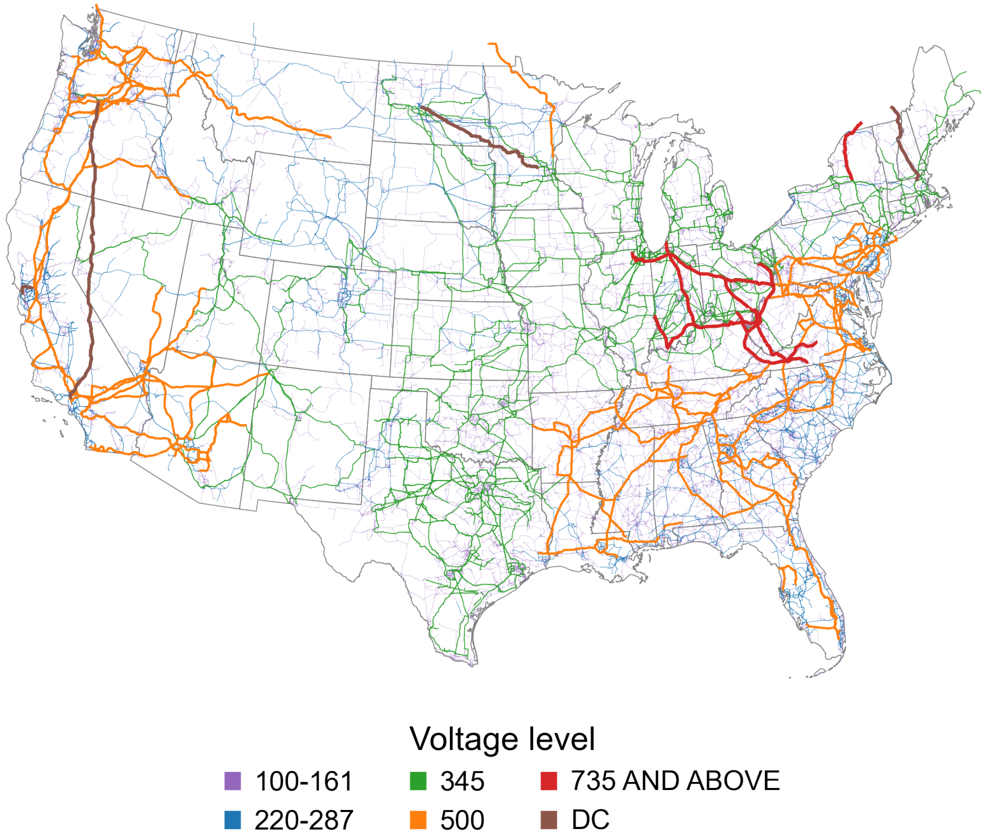
Model linkages

Jarrad Wright
National Renewable Energy Laboratory
May, 2022
Technical Review Committee Meeting

NOTICE
This presentation contains illustrative examples from preliminary modeling only; final results will differ from any results shown here.

A note on industry planning case and baseline transmission projects – a starting point

- An **industry planning case** and **baseline transmission case** are being setup (see *Baseline Methodology and Status* presentation)
- Both are **nodal representations** of the CONUS in ~2030 to obtain estimates of already progressed generation & transmission expansion and progress towards 2035 clean electricity goals
- Following this, **scenario-based analysis** begins by utilising a zonal representation of the CONUS for CEM and PCM[1]. Why zonal?
  - To improve model tractability (25+ year time horizon)
  - To establish generation mixes and zonal transmission expansion (see *"Scenario Framework"* and *"Capacity Expansion Modelling"* presentations)

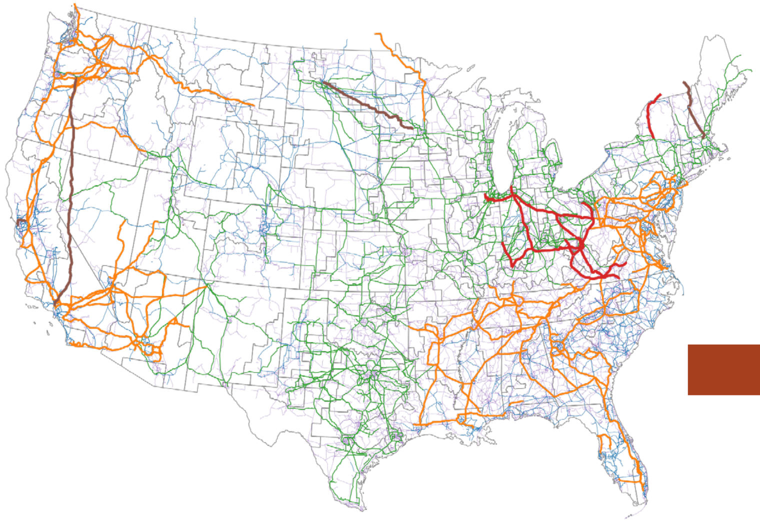


Representative nodal CONUS power system
(combined range of datasets to establish industry planning case)

[1] Supplemented by other models that inform scenario creation incl distributed generation adoption and load forecasting models;
A list of acronyms and abbreviations is available at the end of the presentation.
Sources: NREL; HIFLD

Zonal to nodal (and vice versa) - What are the benefits and drawbacks?

Nodal (PCM, PFD)
(industry planning cases with initial transmission infrastructure incl. augmentation)

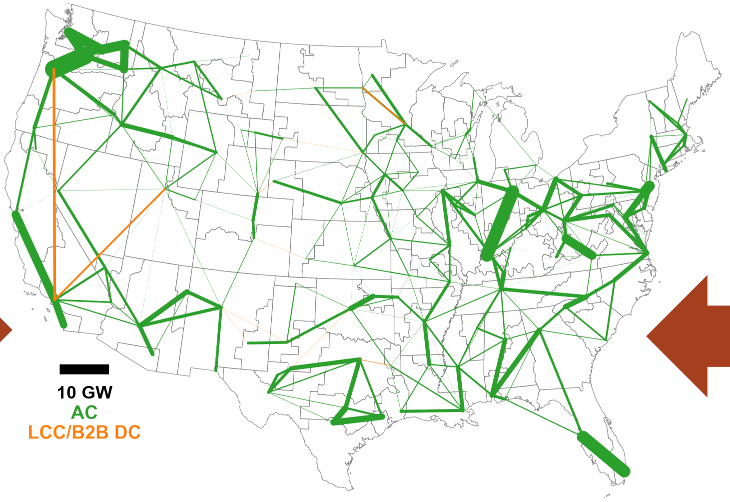


≅124 000 nodes*

≅122 000 branches

≅12 600 generators

Zonal (CEM, RA)
(lines represent transfer capacities between zones)

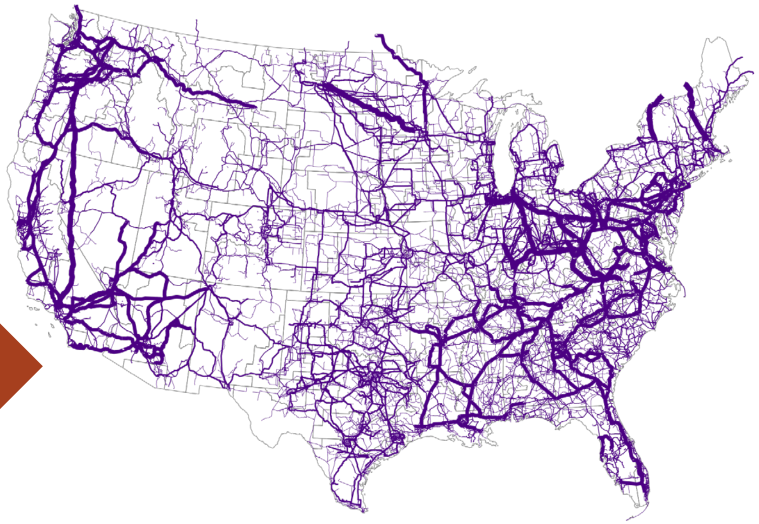


134 zones

314 branches

≅8 000 proxy generator technologies

Nodal (PCM, PFD, stress cases)
(expanded transmission infrastructure)



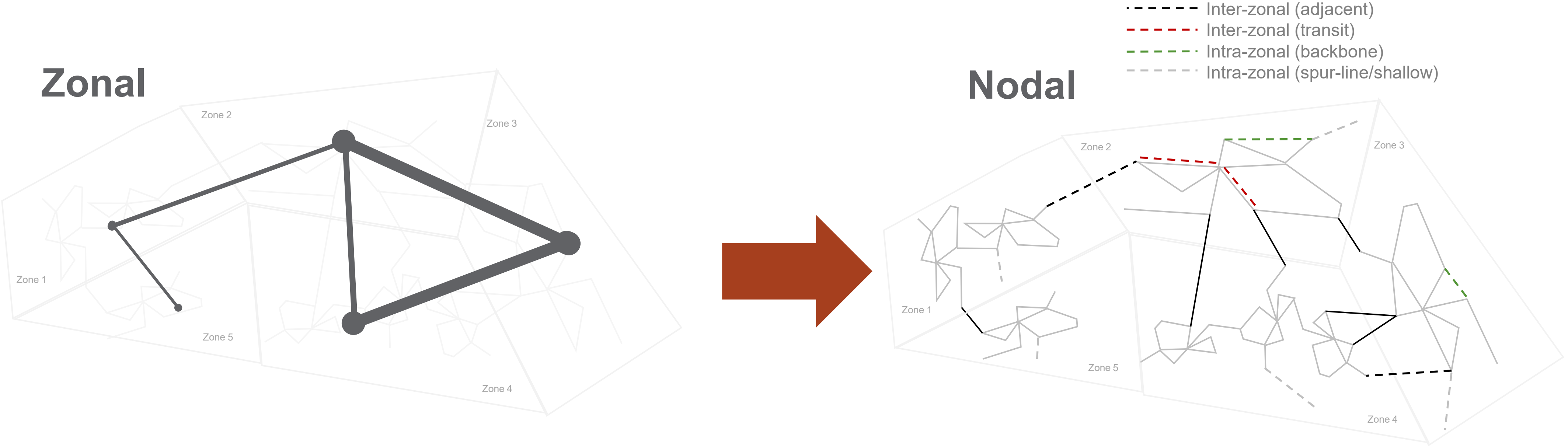
≥124 000 nodes

≥122 000 branches

≥12 600 generators

[1] ≅93,300 nodes in Eastern Interconnection, ≅23,700 nodes in Western Interconnection, ≅7,000 nodes in ERCOT
Information on how zonal representation has been established can be found in Capacity Expansion Modeling in ReEDS.
Sources: NREL; EPA eGRID

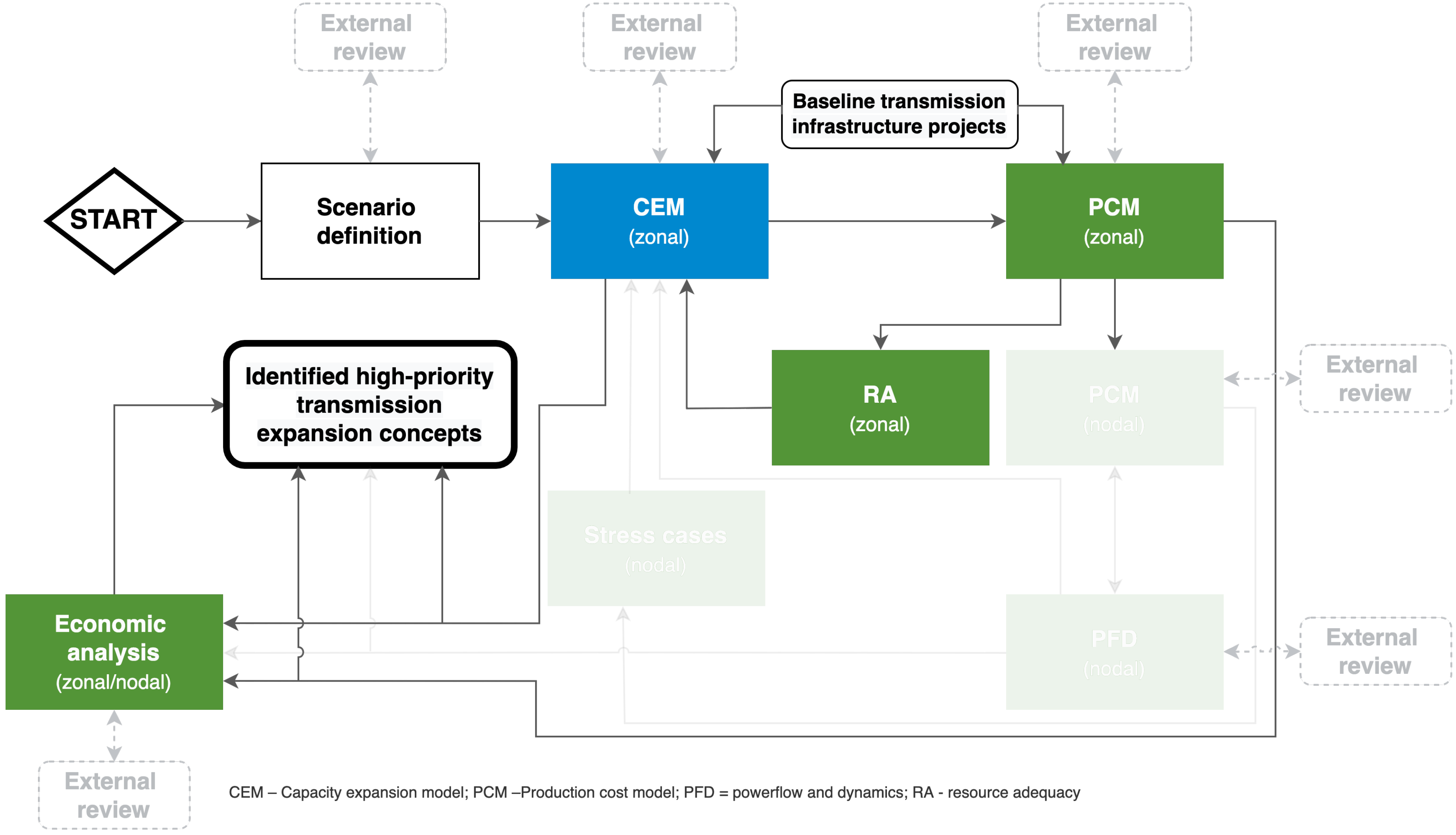
Zonal to nodal (and vice versa) - What are the benefits and drawbacks?



- Increased model fidelity and insights
- Inter-zonal transmission congestion and expansion needs (incl. transit)
- Intra-zonal transmission congestion and potential investments/upgrades
- Enabling more seamless dataflow between models (PCM and PFD)

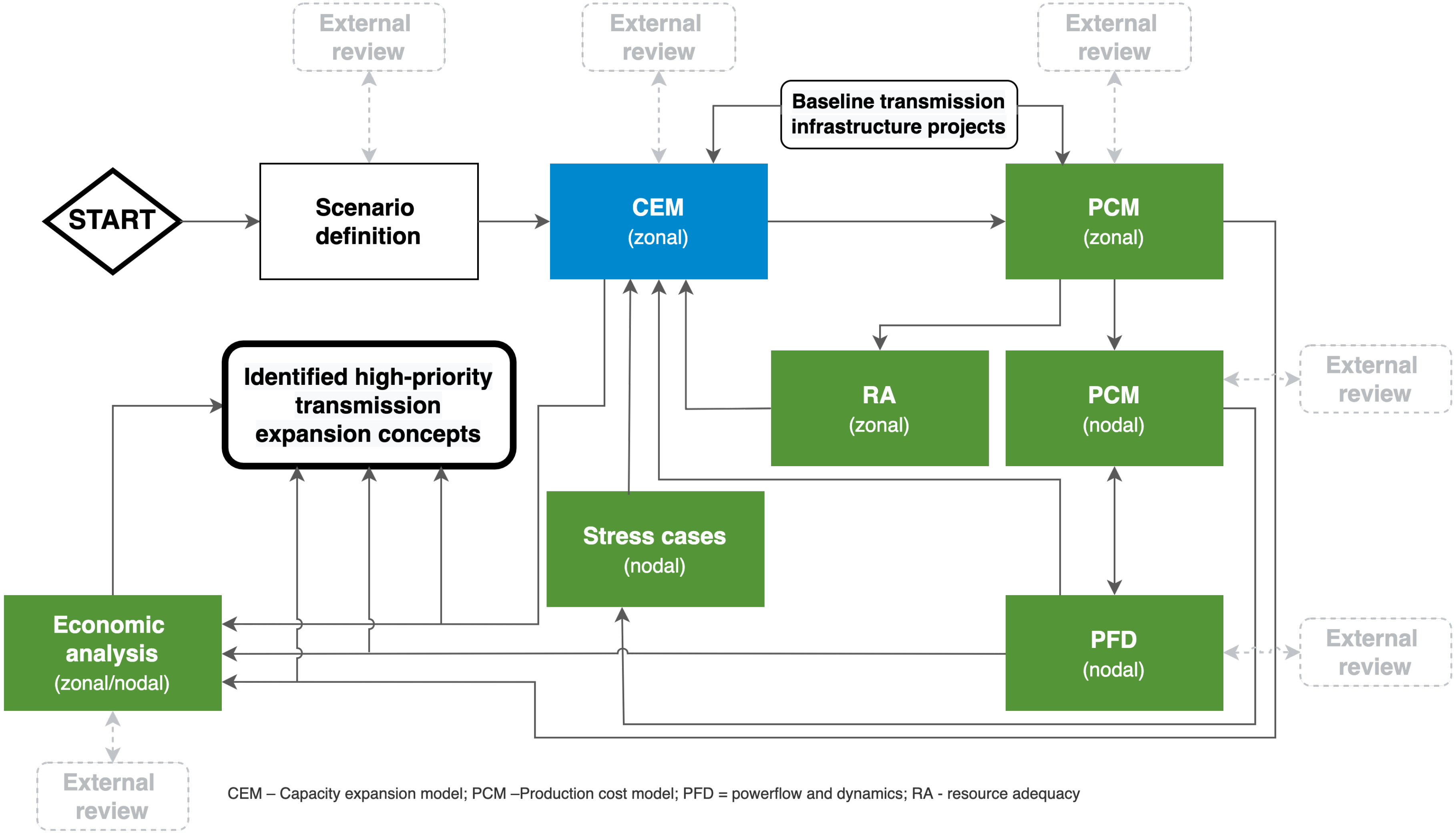
CEM – Capacity expansion model; PCM – production cost model; PFD = powerflow and dynamics

NTPS workflow links a range of data, models and methods with periodic review



CEM – Capacity expansion model; PCM –Production cost model; PFD = powerflow and dynamics; RA - resource adequacy

NTPS workflow links a range of data, models and methods with periodic review



CEM – Capacity expansion model; PCM –Production cost model; PFD = powerflow and dynamics; RA - resource adequacy

Zonal to nodal data exchanges (examples)

CEM -> PCM (zonal)

EIA	Installed Capacity (by technology, zone) + mapping
EFS	Demand profiles
ReVX	vRE profiles
EIA	Fuel prices
NREL	Reserve risk
NREL	Zonal limits

CEM -> PCM (nodal)

NARIS	Existing nodal transmission topology
EIA	Installed capacity (by technology, zone) + mapping
CEM	Decommissioned capacity (by technology, zone)
CEM	Fuel prices
CEM	Reserve risk
NARIS	Demand profiles
NARIS	Load participation factors
NARIS	Voltage
NARIS	Nodal export capacity
ReVX	vRE profiles (supply curve, CEM build-out)

PCM (nodal) <-> PFD

NARIS/MMWG/ADS	Node (bus num, bus name, voltage, area/zone)
NARIS/MMWG/ADS	Branch (node from/to, device type, status, RXB, Rate A)
NARIS/MMWG/ADS	Generator (bus num, bus name, GenID, status, MW min/max, MVAr min/max)
NARIS/MMWG/ADS	Load (bus num, bus name, area/zone, load type/ID, MW, MVAr)
NARIS/MMWG/ADS/CEM	HVDC (bus num, bus name, mode/status, DC voltage, setpoint)

Data source	*Data variable*

The data exchange shown intentionally focusses on only data exchanged between models that can aid zonal-nodal translation (a range of other data sources and variables are utilized by the CEM, PCM and PFD).
A list of acronyms and abbreviations is available at the end of the presentation.

What can be utilized from zonal to nodal translations?

Item	Data source	(S)tatic/(D)ynamic*
Economic		
Investment and operations costs	NREL ATB	D
Losses estimation	CEM/PCM/PFD	D
Demographic		
Population density	EFS	S
Electrification level	EFS	D
DER adoption	dGen	S
Siting		
Nodal export capacity	PCM/PFD (nodal), heuristics	D
Environmental constraints[1]	Numerous	S
RE specific: Resource availability, locations	NSRDB/WIND (reVX)	D
Thermals: Efficiency, fuel availability, decommissioning (technology)	EIA	(except decom.) S
Technical/Engineering		
Topology	NARIS/MMWG/ADS	D
Voltage level	NARIS/MMWG/ADS	S
Utilisation metrics and thresholds[2]	PCM (nodal)	D
Known and new critical contingencies (thermal limits, stability limits)	PFD (nodal)	D
Operational constraints from powerflow/dynamics[3]	PFD (nodal)	D

* (S)tatic/(D)ynamic – indicates unchanging/changing across scenarios

[1] Land-use, protected areas, urban settlements, existing infrastructure; [2] Lines/corridors, transformation capacity); [3] At increased RE penetration levels.

A list of acronyms and abbreviations is available at the end of the presentation.

Key model linkages questions for the TRC

Are there key reasons/drivers not listed that should be prioritized in the zonal to nodal translation methodology?

What further linkages between models are important to consider?

What additional data/information for zonal to nodal conversion would be necessary or useful (other categories, other items)?

Thank you

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Acronyms and Abbreviations

ADS	Anchor DatSet
ATB	Annual Technology Baseline
CEM	capacity expansion model
CONUS	contiguous United States
DER	distributed energy resource
dGen	Distributed Generation Market Demand model
DOE	U.S. Department of Energy
EFS	Electrification Futures Study
EIA	U.S. Energy Information Administration
eGRID	Emissions & Generation Resource Integrated Database
EPA	U.S. Environmental Protection Agency
ERCOT	Electric Reliability Council of Texas
HIFLD	Homeland Infrastructure Foundation-Level Data
HVDC	high-voltage, direct current
MMWG	Multiregional Modelling Working Group
MVAr	megavolts ampere
MW	megawatts
NARIS	North American Renewable Integration Study
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Database
NTPS	National Transmission Planning Study
PCM	production cost model
PFD	powerflow and dynamics
RA	resource adequacy
RE	renewable energy
ReEDS	Regional Energy Deployment System
reV	Renewable Energy Potential model
reVX	Renewable Energy Potential(V) eXchange Tool
RXB	Resistance, reactance, susceptance
TRC	technical review committee
VRE	variable renewable energy
WIND	Wind Integration National Dataset Toolkit

National Transmission Planning Study:
Scenario Framework for Capacity Expansion Modeling

Trieu Mai
National Renewable Energy Laboratory
May 2022
Technical Review Committee Meeting

NOTICE
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NTPS relies on multiple linked modeling exercises

Frame and Develop Scenarios

DATA

- wind
- water
- solar
- thermal
- power system
- transportation
- buildings

CAPACITY EXPANSION MODEL

Transmission and generation buildout

What gets **built** and where?

DISTRIBUTED GENERATION ADOPTION MODEL

Behind-the-meter buildout

Where is rooftop PV **adopted**?

LOAD FORECASTING

Electrification and end-use decarbonization

Which end-uses are **electrified**?

Detailed Analysis of Selected Scenarios

OPERATIONAL (PRODUCTION) MODEL

Operational analysis: unit commitment and dispatch

How does the grid **balance**?

How is **transmission** operated?

RELIABILITY MODEL

Probabilistic resource adequacy analysis
Power flow analysis
Resilience analysis

Is it **reliable**?

What about different **weather**?

IMPLEMENTATION ANALYSIS

High Priority Transmission Options
Public Engagement

Which builds are **robust** across scenarios?

Where do we **start**?

NTP SCENARIOS

The analysis *starts* with capacity expansion modeling

Frame and Develop Scenarios

DATA

- wind
- water
- solar
- thermal
- power system
- transportation
- buildings

CAPACITY EXPANSION MODEL

Transmission and generation buildout

What gets **built** and where?

DISTRIBUTED GENERATION ADOPTION MODEL

Behind-the-meter buildout

Where is rooftop PV **adopted**?

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Detailed Analysis of Selected Scenarios

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Operational analysis: unit commitment and dispatch

How does the grid **balance**?

How is **transmission** operated?

RELIABILITY MODEL

Probabilistic resource adequacy analysis
Power flow analysis
Resilience analysis

Is it **reliable**?

What about different **weather**?

IMPLEMENTATION ANALYSIS

High Priority Transmission Options
Public Engagement

Which builds are **robust** across scenarios?

Where do we **start**?

+ (human) expert judgment

NTP SCENARIOS

Schedule and iterations for scenario modeling

- **Spring 2022**: Defining the scenarios and sensitivities ← **Today**
- **Summer 2022**: Preliminary capacity expansion modeling scenarios
  - Possible revisions from: TRC feedback, new data, (zonal) PCM and RA modeling
- **Fall 2022**: Full set of capacity expansion modeled scenarios ← **Candidate Scenarios**
  - To be used for downstream modeling
  - Informs high level trends in future transmission and resource development
- **Winter 2023**: Down-selected and modified power systems ← **NTP Scenarios**
  - Adjust power system from CEM using more-detailed modeling and expert feedback
  - Informs identification of high-priority transmission options
- **Spring 2023**: Improved CEM and PCM modeling ← **Refined NTP Scenarios**
  - Revisions from: TRC feedback, updated data (nodal) PCM and PFD modeling

Objectives of scenario modeling

Perform **capacity expansion modeling** to create the generation, storage, and transmission system representation needed for follow-on operational, reliability, and economic analysis

Explore **the roles transmission might play** in achieving electricity system decarbonization

Identify and prioritize options for interregional transmission

Capacity expansion modeling: proposed scenario framework

4 transmission topologies

x

9 emissions variants = 3 grid decarbonization X 3 electrification

+

14 sensitivities = 2 emissions variants X 7 other drivers

+

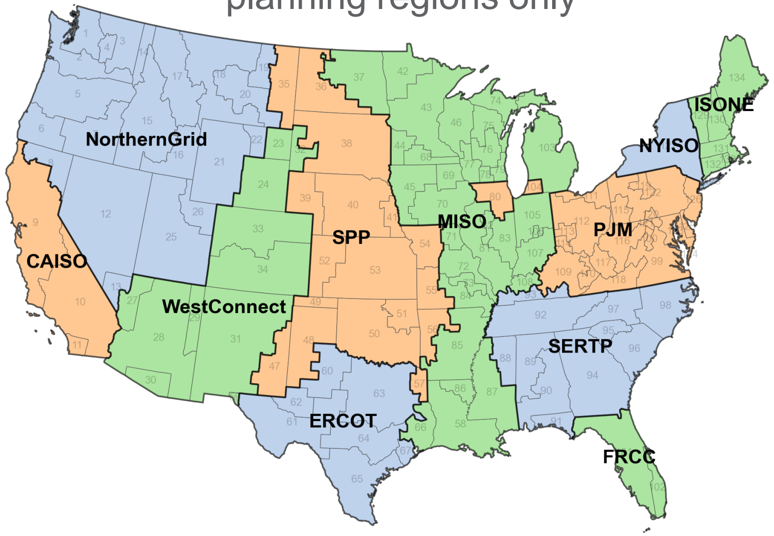
model formulation sensitivities

=

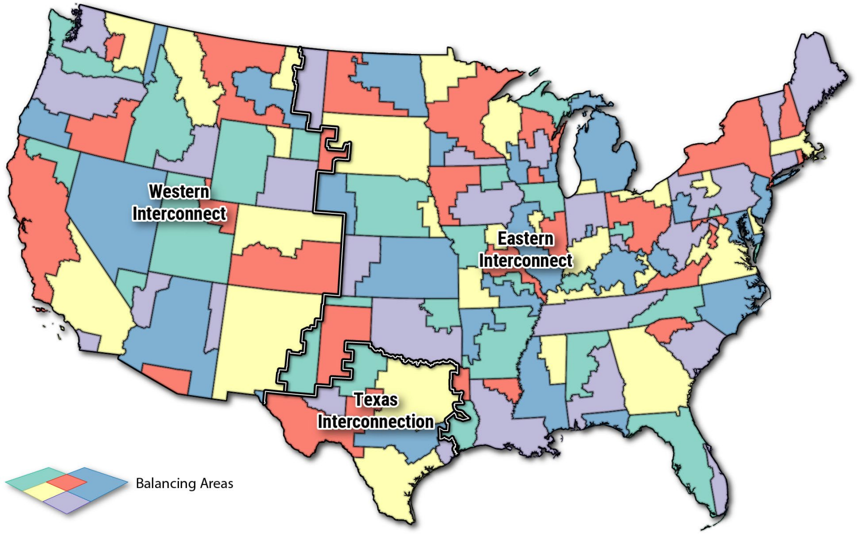
~100 total sensitivities from CEM

4 transmission topologies

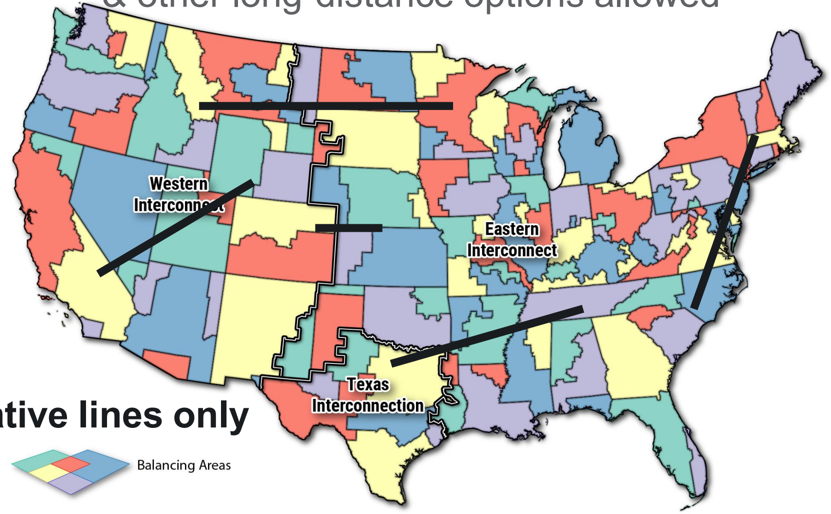
Intra-regional: expansion within 11 transmission planning regions only



Intra-interconnection: expansion between 134 model zones

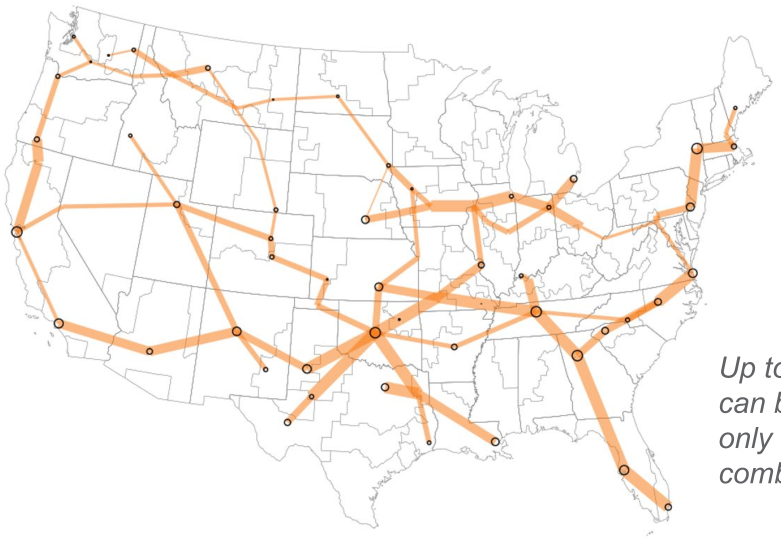


Inter-interconnection: back-to-back DC ties & other long-distance options allowed



Illustrative lines only

Macrogrid: multi-terminal HVDC-VSC



Up to 3 additional variations can be tested, but plan to only run ~4 across the full combinations of scenarios

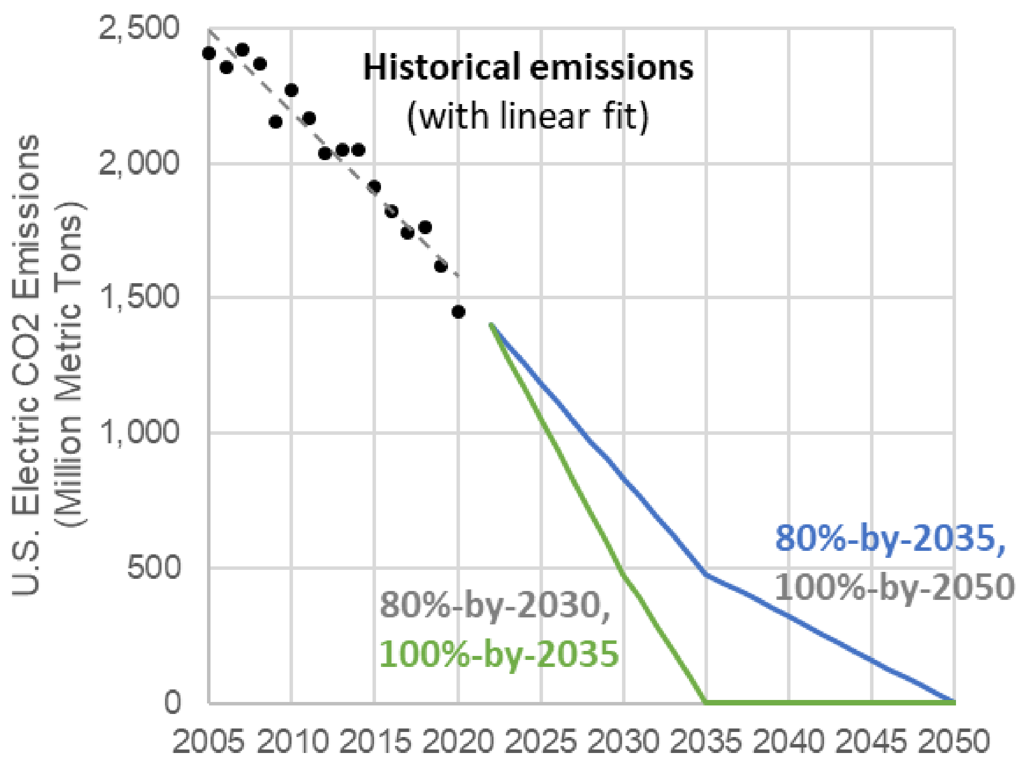
9 emissions variants = 3 grid decarbonization X 3 electrification

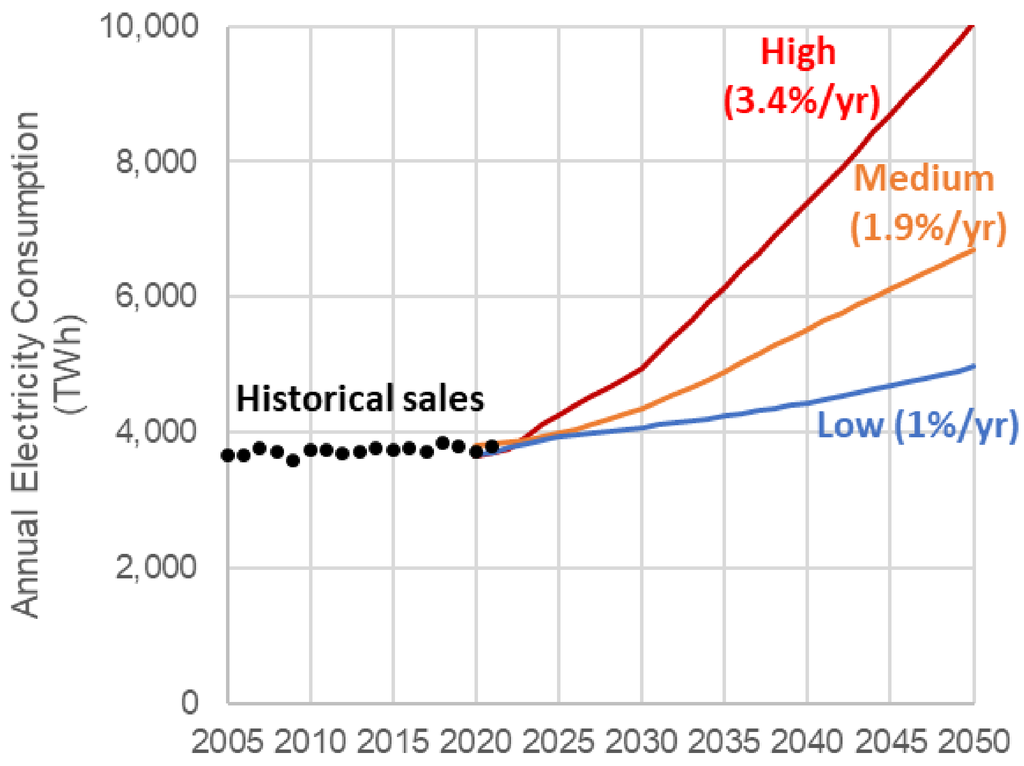
Reductions in national electric sector emissions
(from 2005 levels =2,400 MMT-CO2)

	Low electrification	**Medium** electrification	**High** electrification
Current Policies Only	X	X	X
80% by 2035, 100% by 2050	X	X	X
80% by 2030, **100% by 2035**	X	X	X

9 emissions variants = 3 grid decarbonization X 3 electrification

Emissions and electrification assumptions

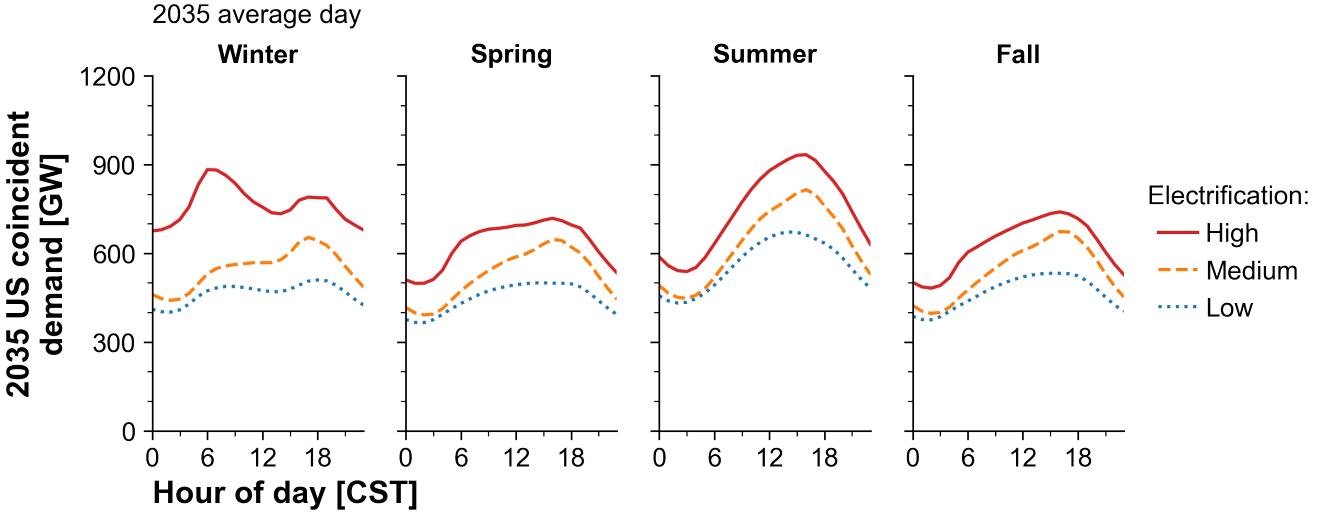




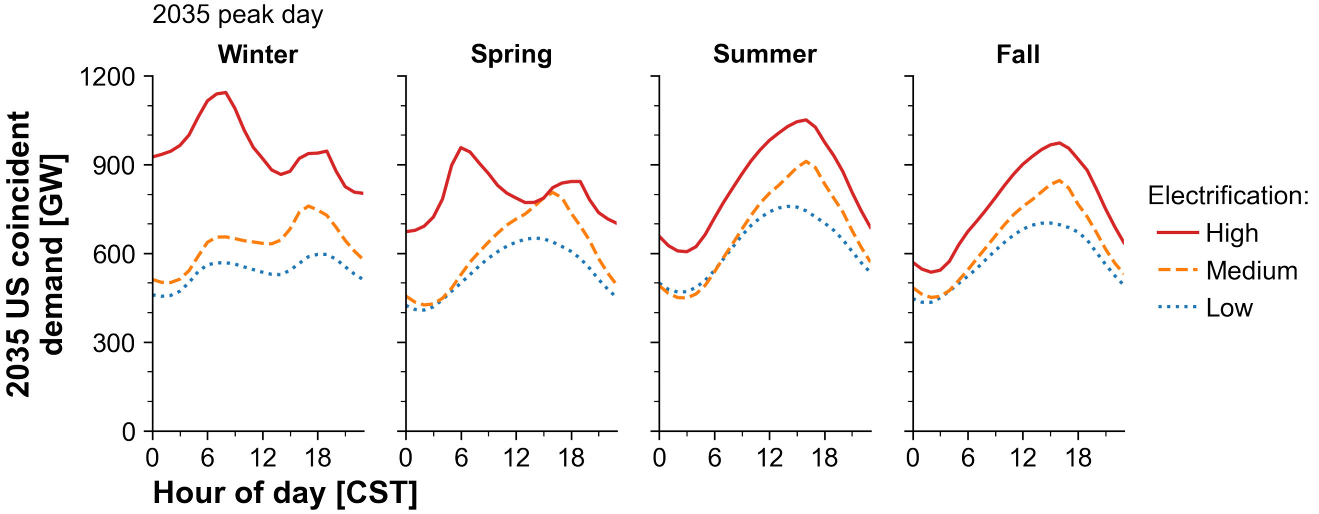
Emissions reduction targets are to be implemented as a national constraint.
Electricity (hourly, next slide) demand is an input to the model.

9 emissions variants = 3 grid decarbonization X 3 electrification

Differences between electrification assumptions affect load profiles



Electrification **raises average demand throughout the year**, due particularly to vehicle electrification.



Electrification can also cause **demand peaks to shift to winter**, from electrified space and water heating, in addition to traditional summer peaks.

14 sensitivities = 2 emissions variants X 7 other drivers

Reductions in national electric sector emissions (from 2005 levels =2,400 MMT-CO_2)

	Low electrification	**Medium** electrification	**High** electrification
Current Policies Only	**Reference**		
80% by 2035, 100% by 2050		**80% Clean** by 2035	
80% by 2030, **100% by 2035**			**100% Clean** by 2035

14 sensitivities = 2 emissions variants X 7 other drivers

The 7 other drivers include:

1. High transmission costs → 2–10x default assumptions
2. High distributed PV adoption → 170 GW in 2035 (default = 93 GW)
3. Low solar & storage costs → ATB Advanced
4. Low wind costs → ATB Advanced

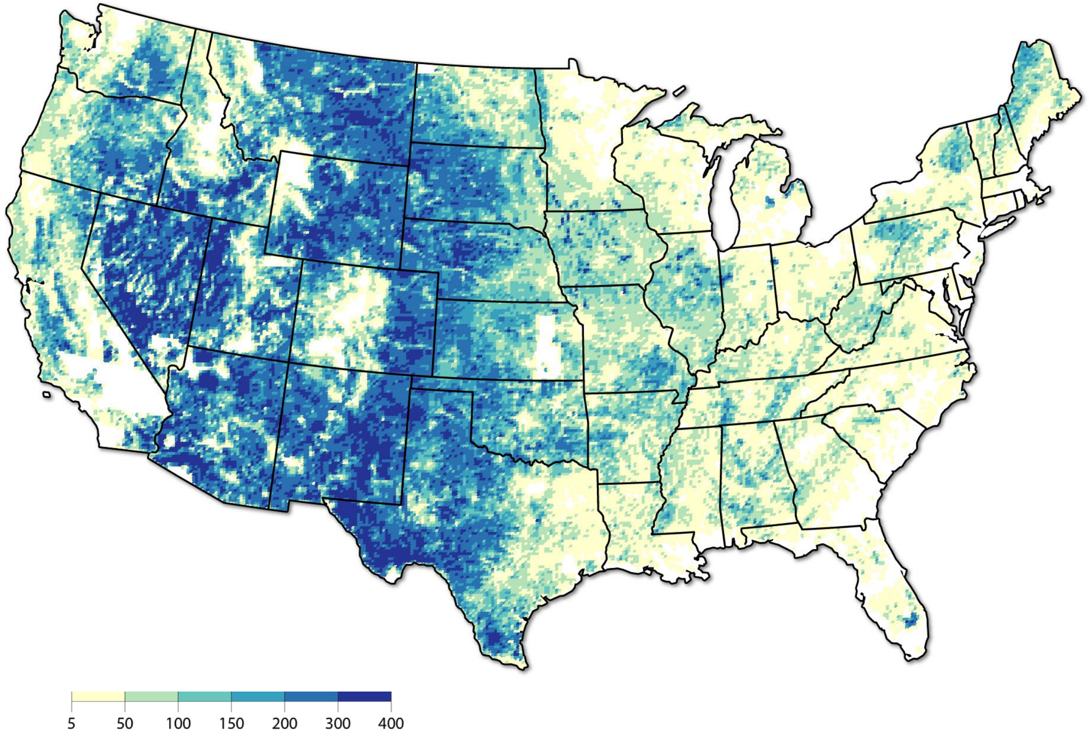
Default = ATB Moderate

5. Constrained renewable energy siting → Limited Access *(see next slide)*

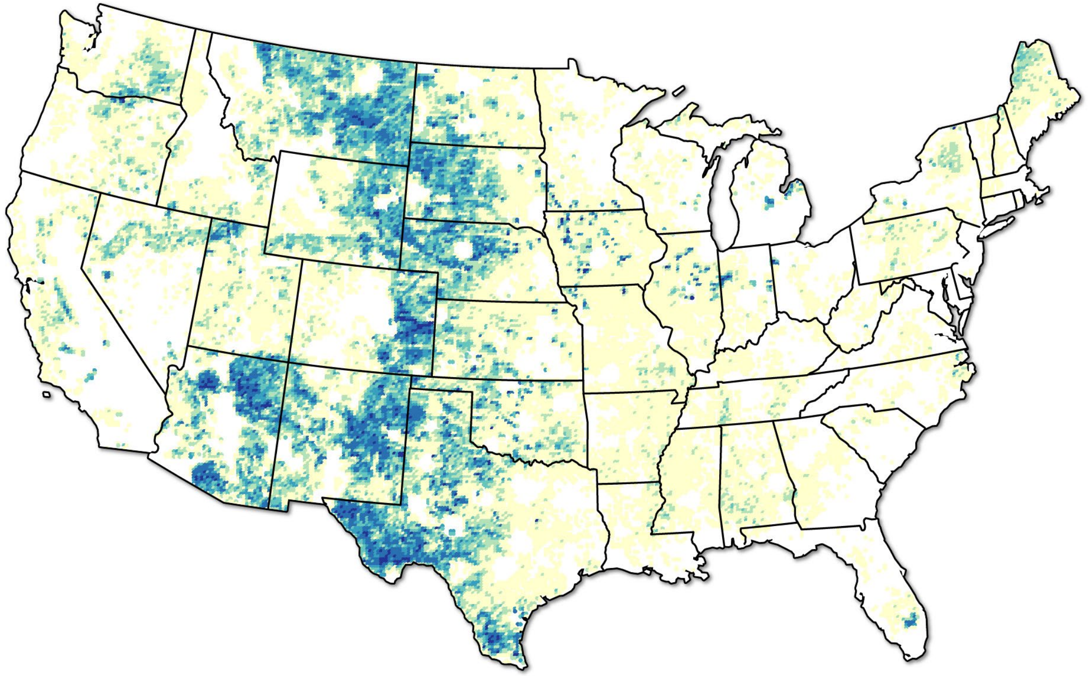
14 sensitivities = 2 emissions variants X 7 other drivers

Developable wind resource potential

Default: Reference Access (6.7 TW)



Constrained: Limited Access (2.1 TW)



Standard exclusions: federal, state, and local restrictions; complex terrain; radar, shadow flicker; setbacks to infrastructure (1.1x max tip-height to buildings, roads, railroads, transmission lines); others

Key difference between Constrained and Default is the setback: 3x max tip-height.

14 sensitivities = 2 emissions variants X 7 other drivers

The 7 other drivers include:

1. High transmission costs → 2–10x default assumptions
2. High distributed PV adoption → 170 GW in 2035 (default = 93 GW)
3. Low solar & storage costs → ATB Advanced
4. Low wind costs → ATB Advanced

Default = ATB Moderate

5. Constrained renewable energy siting → Limited Access *(see next slide)*
6. Limited non-RE techs → no CCS, no new nuclear
7. Expanded non-RE techs → incl. CO_2 removal, nuclear-SMR

Default allows new fossil CCS and conventional nuclear

Example model formulation sensitivities

- Different levels of spatial and temporal resolution
- Alternative weather years
- Alternative regional cost modifiers, reflecting long-range uncertainty
- Intra-zonal transmission costs
    - Interconnection cost estimation procedure

Capacity expansion modeling: proposed scenario framework

4 transmission topologies

x

9 emissions variants = 3 grid decarbonization X 3 electrification

+

14 sensitivities = 2 emissions variants X 7 other drivers

+

model formulation sensitivities

=

~100 total sensitivities from CEM

The following slide show **illustrative** examples of how the various drivers can impact transmission and generation expansion outcomes.

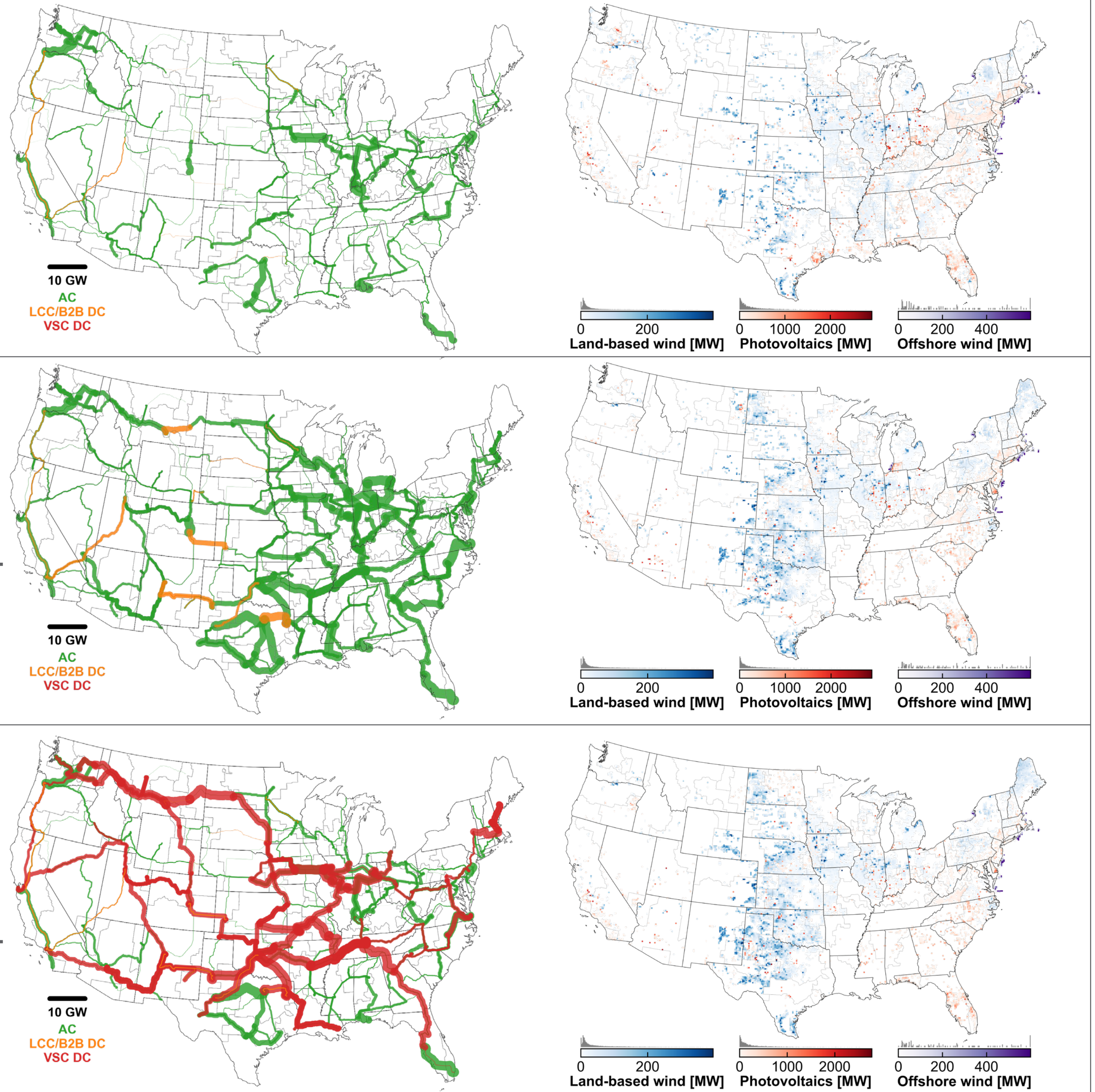
Examples are from **preliminary** modeling only; final NTPS results will differ from those shown.

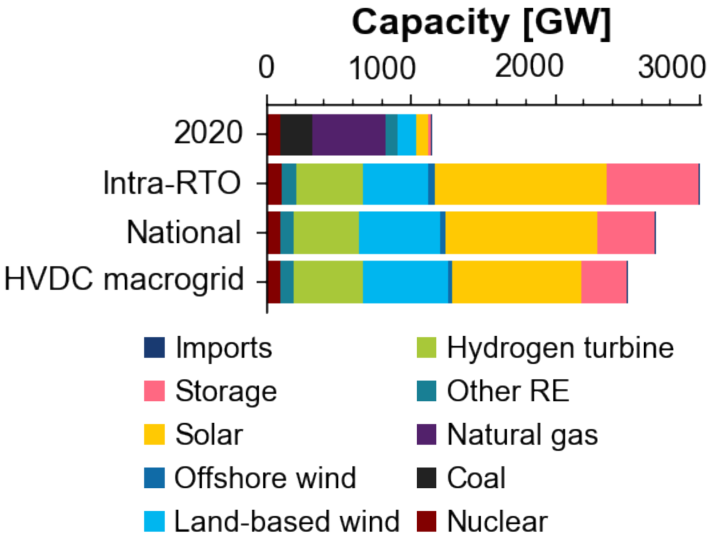
Transmission Topology Impact

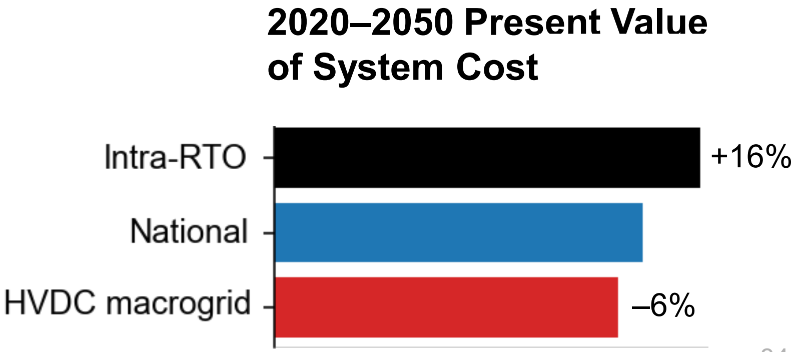
Intra-RTO only

National AC expansion

National DC (VSC) expansion

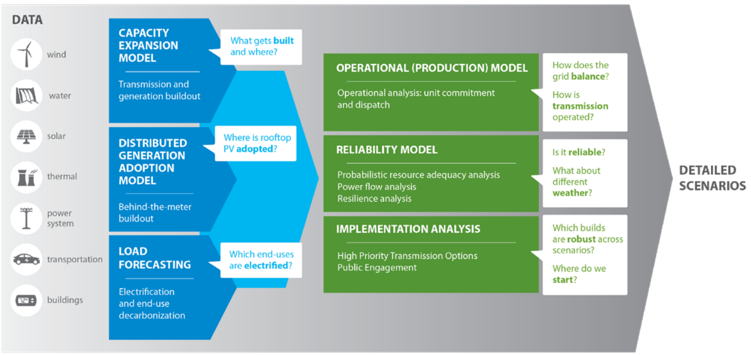






Illustrative modeling results only – do not cite

Important considerations



- **Capacity expansion modeling is only one part of the analysis**
  - Results should not be taken literally; many additional steps are needed between *modeled* transmission capacity expansion results and *real* transmission projects
  - CEM focuses on interregional transfers rather than individual lines, but downstream nodal analysis is planned
  - Non-wires options are not currently included in the CEM but will be considered in other NTPS modeling
- **Robustness of the analysis could be enhanced**
  - Proposed scenario framework is broad but not comprehensive; results can be sensitive to small perturbations to model assumptions or formulations
  - Comparisons with other modeling exercises could increase robustness
  - Non-model-based approaches need to be considered

Key scenario-design questions for the TRC

Does the proposed scenario framework capture the main drivers relevant for national transmission planning?

- Are there any missing or extraneous drivers?

Do the range of assumptions appropriately bound expectations—especially within the lens of decarbonization?

- Reactions to the electrification and demand growth assumptions would be most helpful

Are there specific variations to the transmission topologies that should be prioritized?

Thank you

trieu.mai@nrel.gov

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Acronyms and Abbreviations

ATB	Annual Technology Baseline
BAU	business as usual
CCS	carbon capture and storage
CEM	capacity expansion model
DC	direct current
DOE	U.S. Department of Energy
EFS	Electrification Futures Study
GW	gigawatts
HVDC	high-voltage direct current
MMT	million metric tons
MW	megawatts
NREL	National Renewable Energy Laboratory
NTPS	National Transmission Planning Study
PCM	production cost model
PFD	powerflow and dynamics
PNNL	Pacific Northwest National Laboratory
PV	photovoltaics
RA	resource adequacy
RE	renewable energy
RTO	regional transmission operator
SMR	small modular reactor
TRC	technical review committee
TW	terawatts
VRE	variable renewable energy
VSC	voltage source converters

National Transmission Planning Study:
Capacity Expansion Modeling in ReEDS

Patrick Brown
National Renewable Energy Laboratory

May 2022
Technical Review Committee Meeting

NOTICE
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Nationwide Capacity Expansion Modeling: ReEDS

Objective: Minimize total **capital + operational** cost of electricity system **subject to…**

Price-forming constraints: Energy balance; planning/operating reserves; RPS/carbon policies

Additional constraints: Resource availability (spatial & temporal); energy/reserve trading; generation/storage operations; fuel supply; planned builds and retirements; etc.

Inputs

- **Existing & planned** capacity
- **VRE** temporal (hourly) & spatial (11.5km×11.5km) availability
- State & federal **policies** (current and hypothetical)
- **Load** (hourly) projections for 134 zones across contiguous U.S.
- Capital, O&M, and fuel **cost** projections
- **Technology** availability & performance projections

Regional **E**nergy **D**eployment **S**ystem

ReEDS

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

Outputs

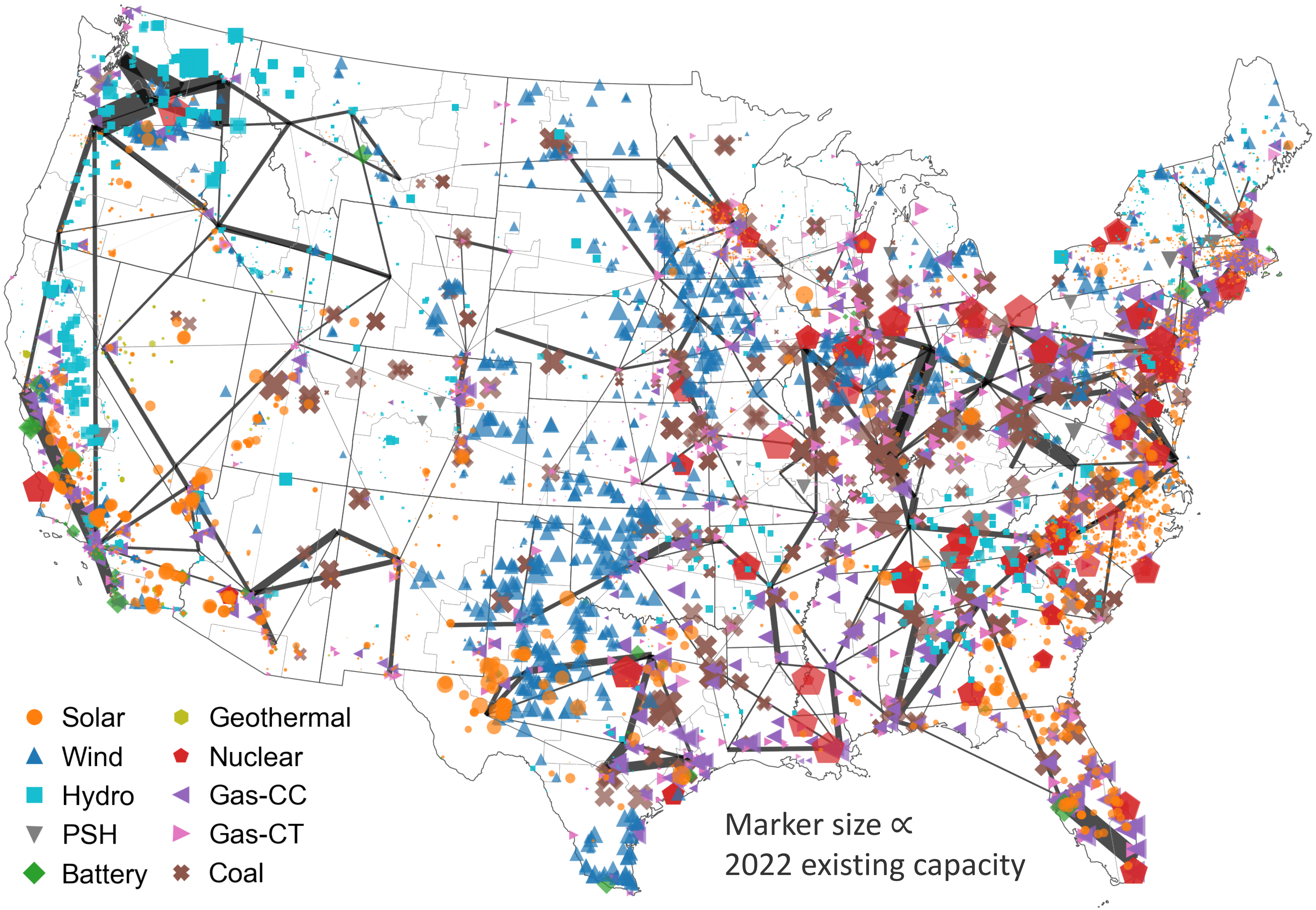
- Generation and storage **capacity** additions & retirements in each solve year
- **Transmission** capacity additions
- **Operations**: Energy generation, firm capacity, & operating reserves by tech
- CO_2, NO_x, SO_2, CH_4 **emissions**
- System **cost** [$billion], electricity **price** [$/MWh], retail **rates** [¢/kWh]

ReEDS: Key Inputs

Existing & planned capacity

- **Generation capacity:** EIA National Energy Modeling System (NEMS)
    - Updated annually
- **Transmission capacity:**
    - Initial inter-zone transfer capacities from nodal GridView analysis (currently being updated)
    - New inter-zone lines tracked individually

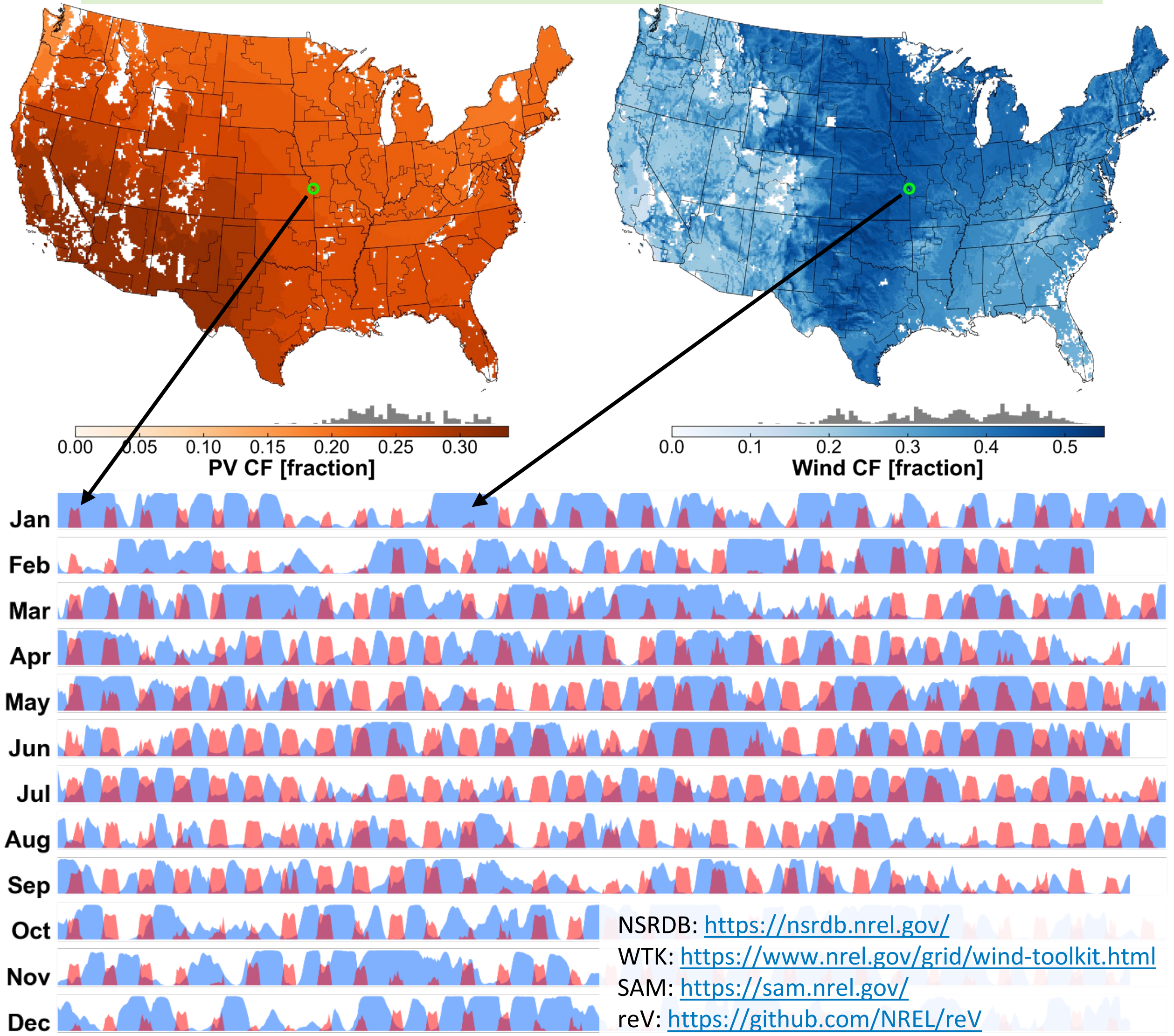
→ Maintained or retired in order to minimize total system cost



ReEDS: Key Inputs

RE temporal availability

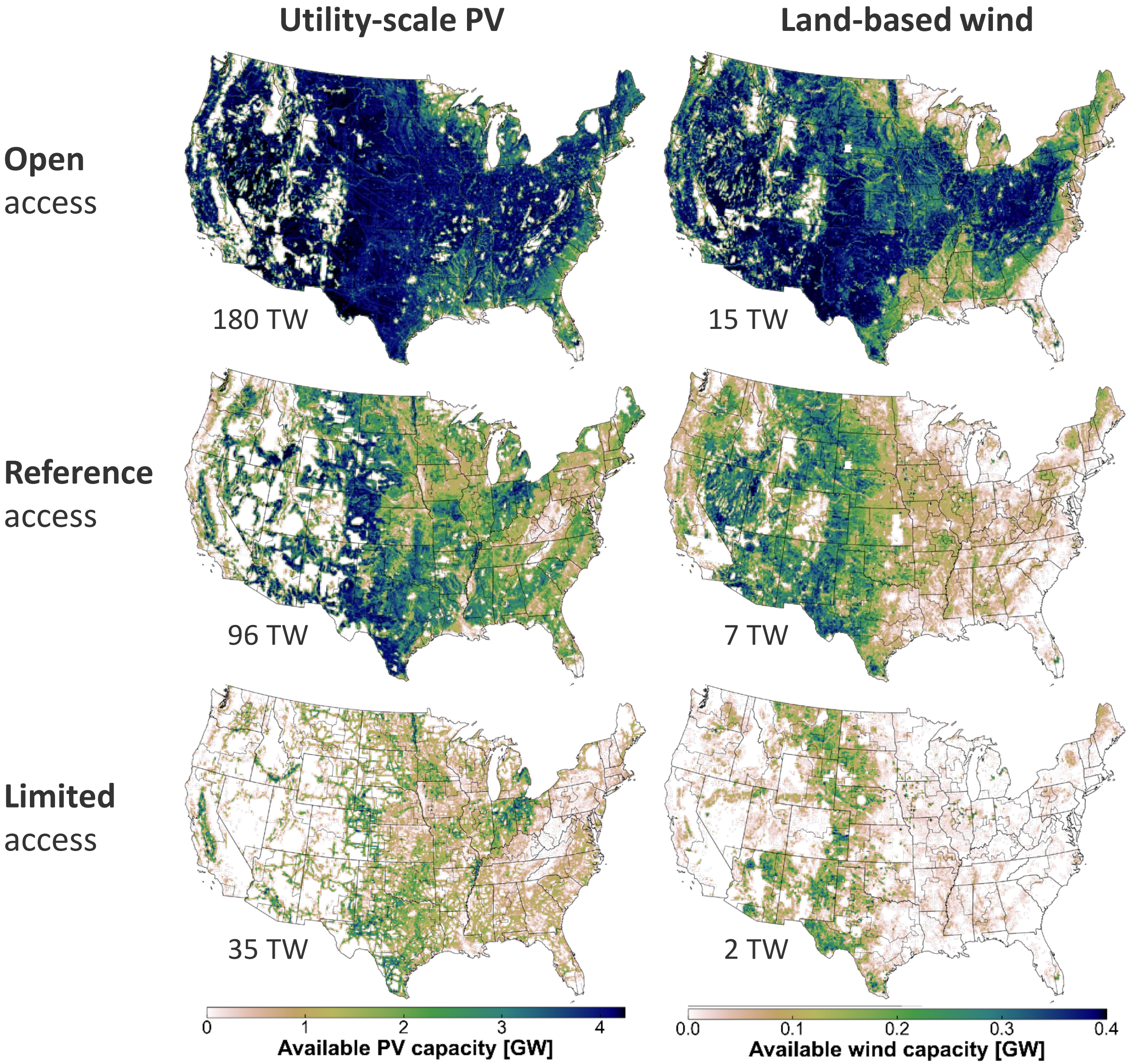
National Solar Radiation Database + WIND Toolkit → SAM → reV model → Hourly CF profiles for >50k sites across U.S.



NSRDB: https://nsrdb.nrel.gov/
WTK: https://www.nrel.gov/grid/wind-toolkit.html
SAM: https://sam.nrel.gov/
reV: https://github.com/NREL/reV

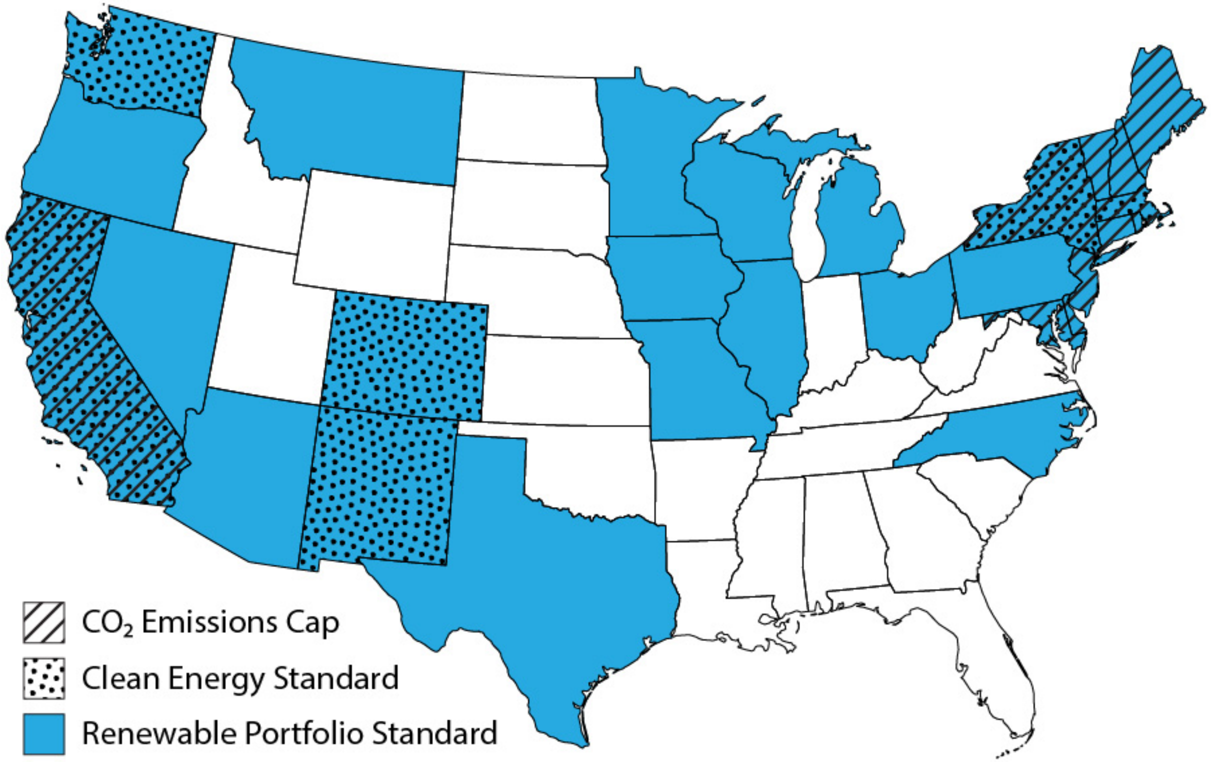
RE spatial availability

Multiple land-type exclusions → reV model → Developable wind/PV potential for same >50k sites



ReEDS: Key Inputs

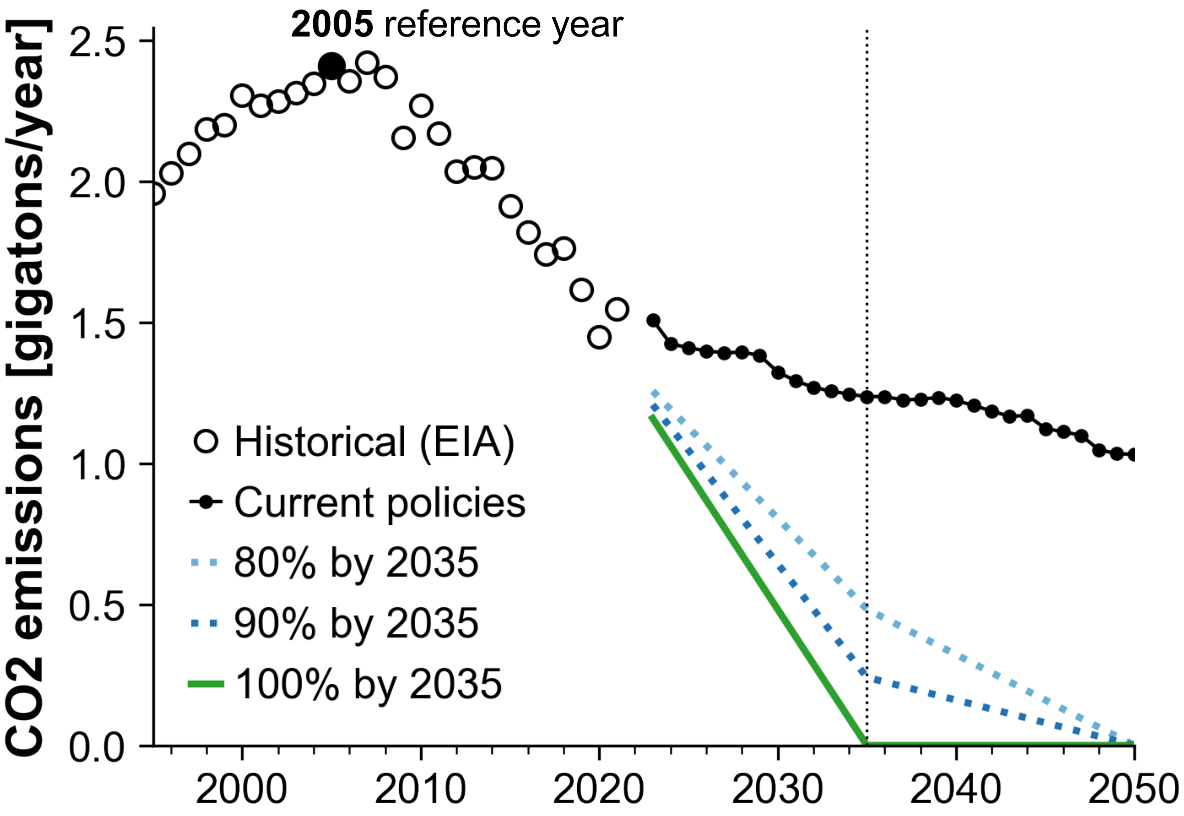
Regional and state policies
(Updated annually)



The Prospective Impacts of 2019 State Energy Policies on the U.S. Electricity System (Mai et al., 2020)

Including state-specific:
- Mandates and RPS carve-outs (e.g., offshore wind, solar)
- Technology deployment constraints (e.g., nuclear)

National policies

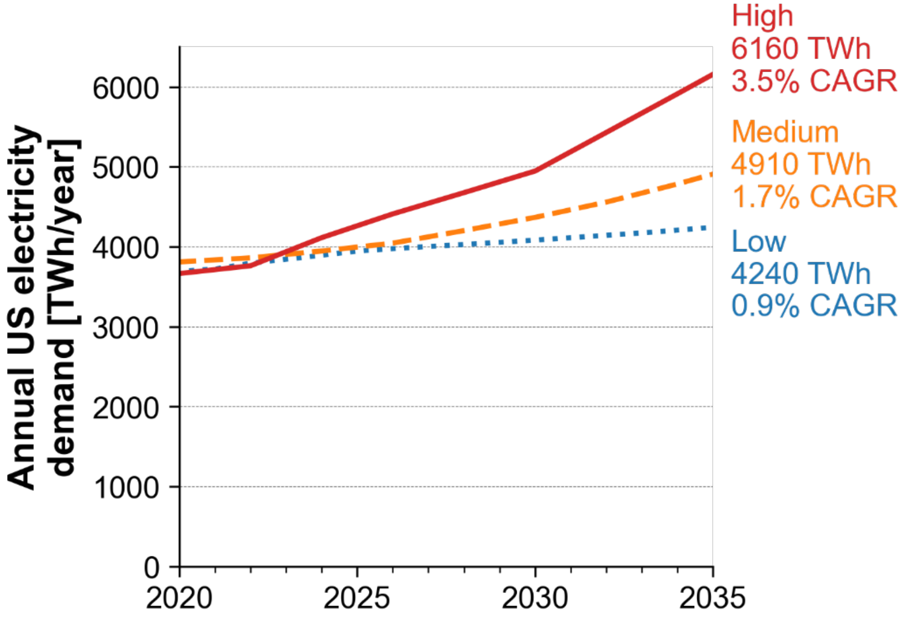


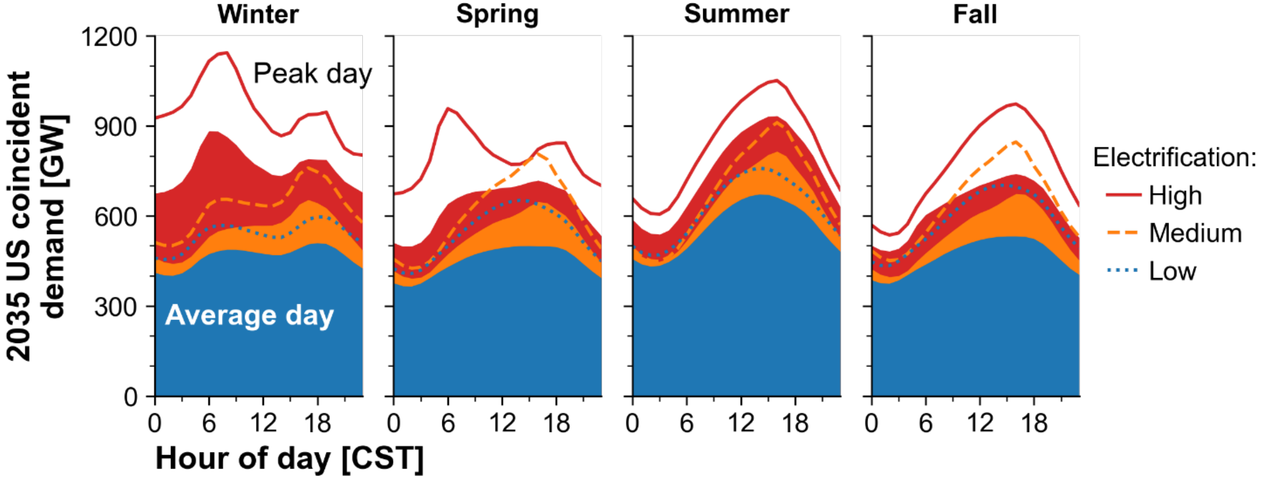
Additional options:
- Renewable Portfolio Standard / Clean Energy Standard [%]
- Emissions rate constraint [gCO_2/kWh]
- Technology-specific incentives (ITC, PTC, 45Q)

ReEDS: Key Inputs

Demand

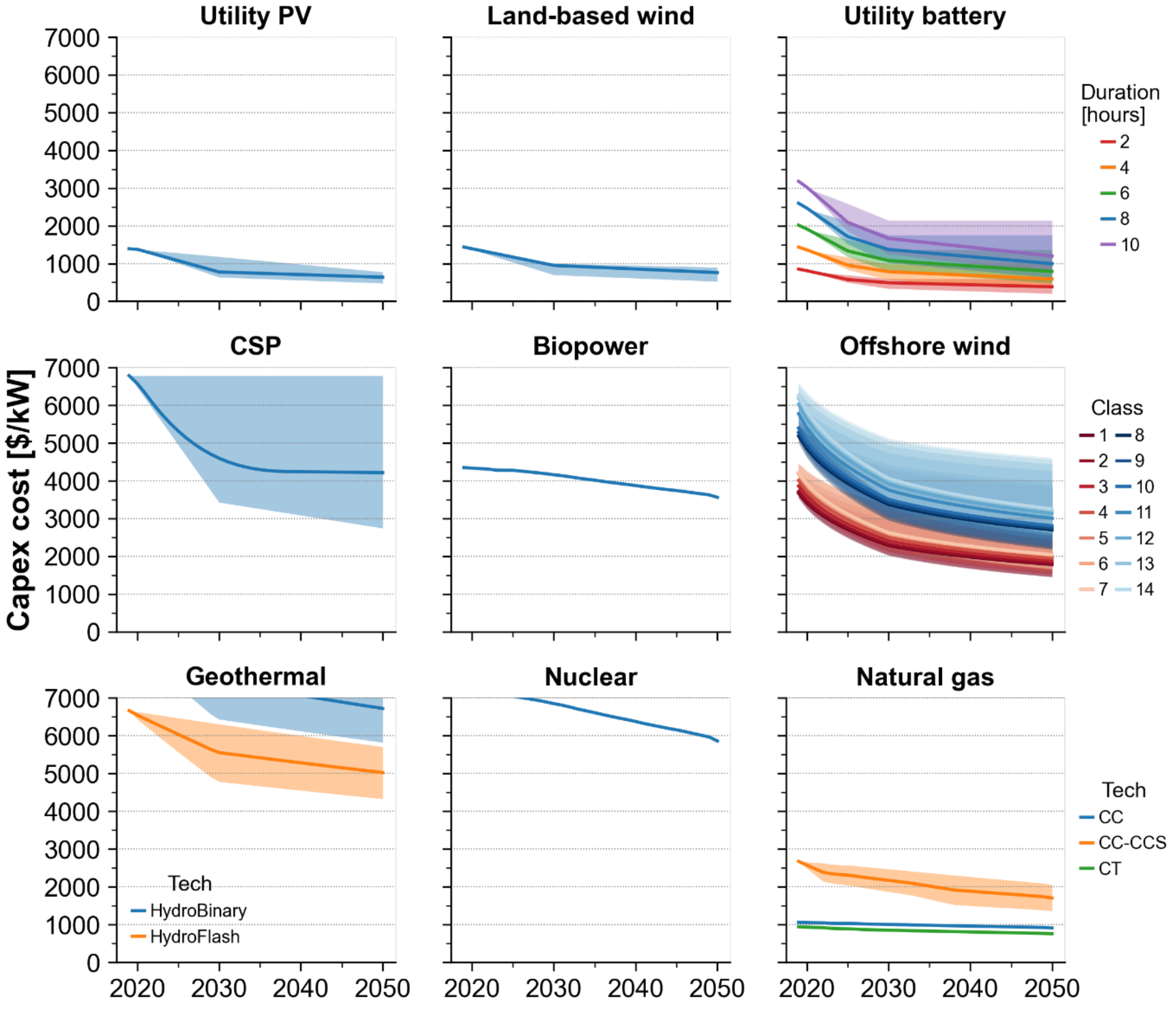
EFS: https://www.nrel.gov/analysis/electrification-futures.html
AEO: https://www.eia.gov/outlooks/aeo/





Technology cost & performance

Annual Technology Baseline (ATB) https://atb.nrel.gov/

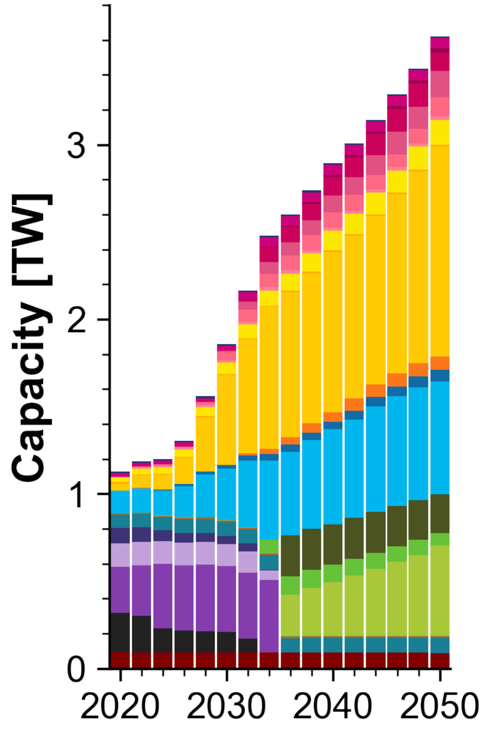


+ Fuel costs from EIA Annual Energy Outlook (AEO)
+ Interconnection spur line costs, discussed later

ReEDS: Key Outputs

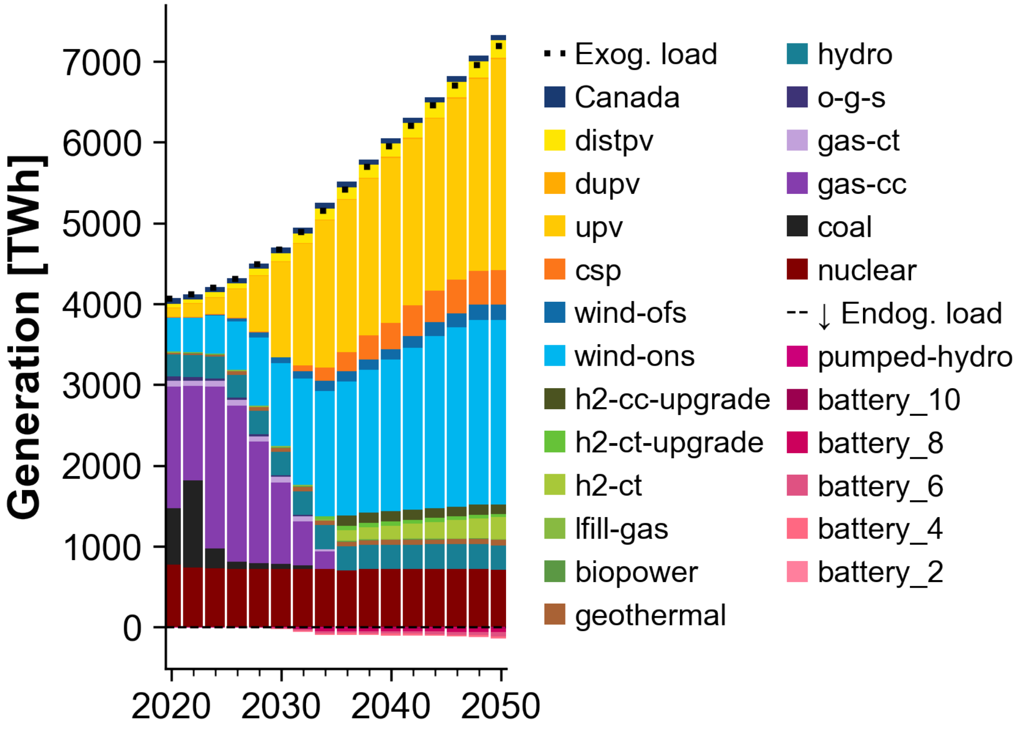
System design

Capacity

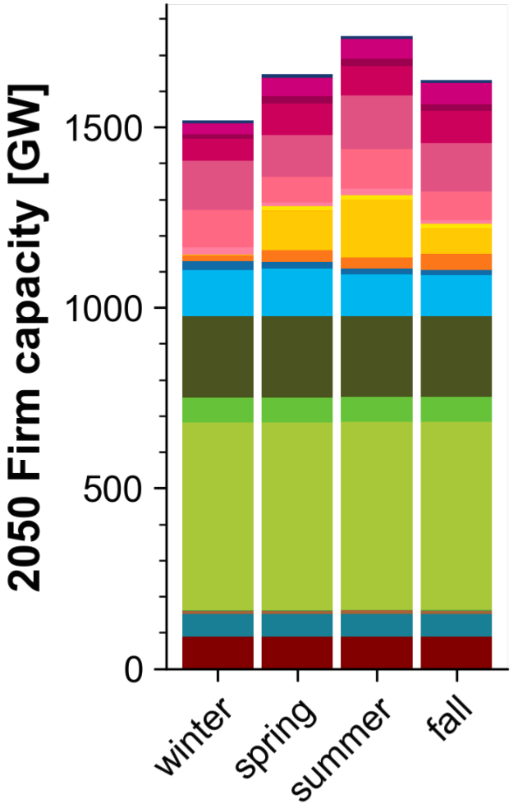


System operation & service provision

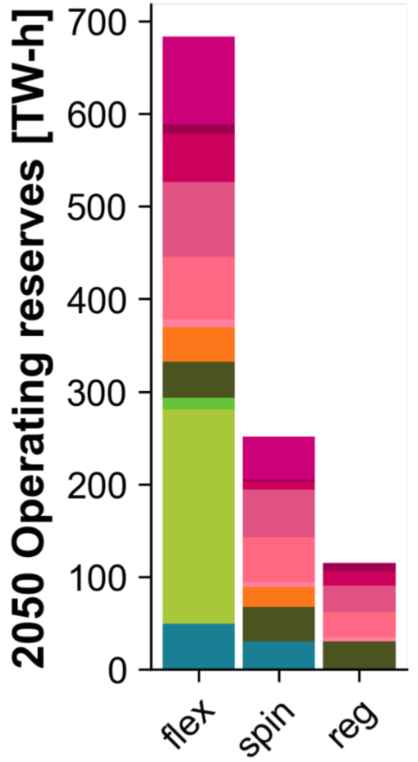
Generation



Firm capacity



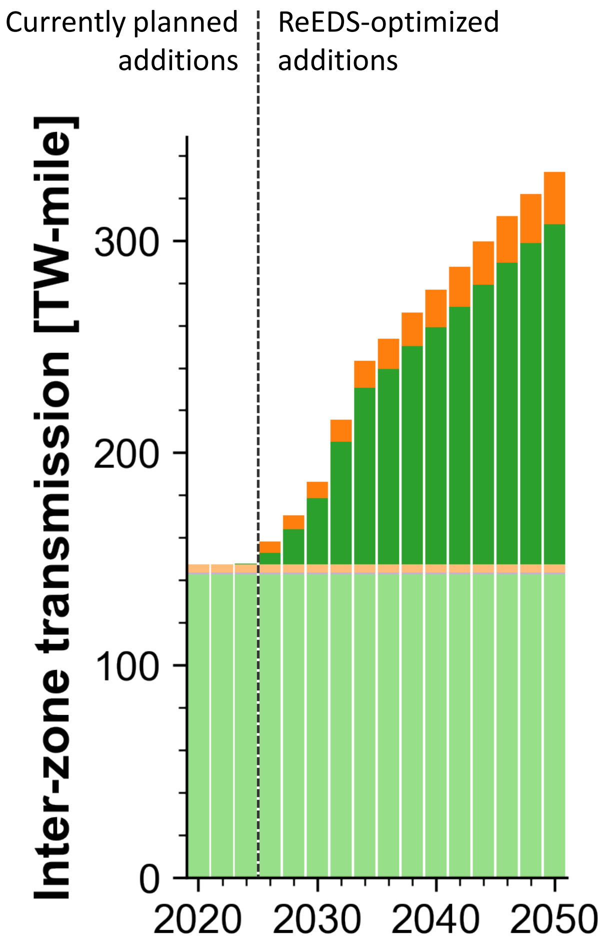
Operating reserves

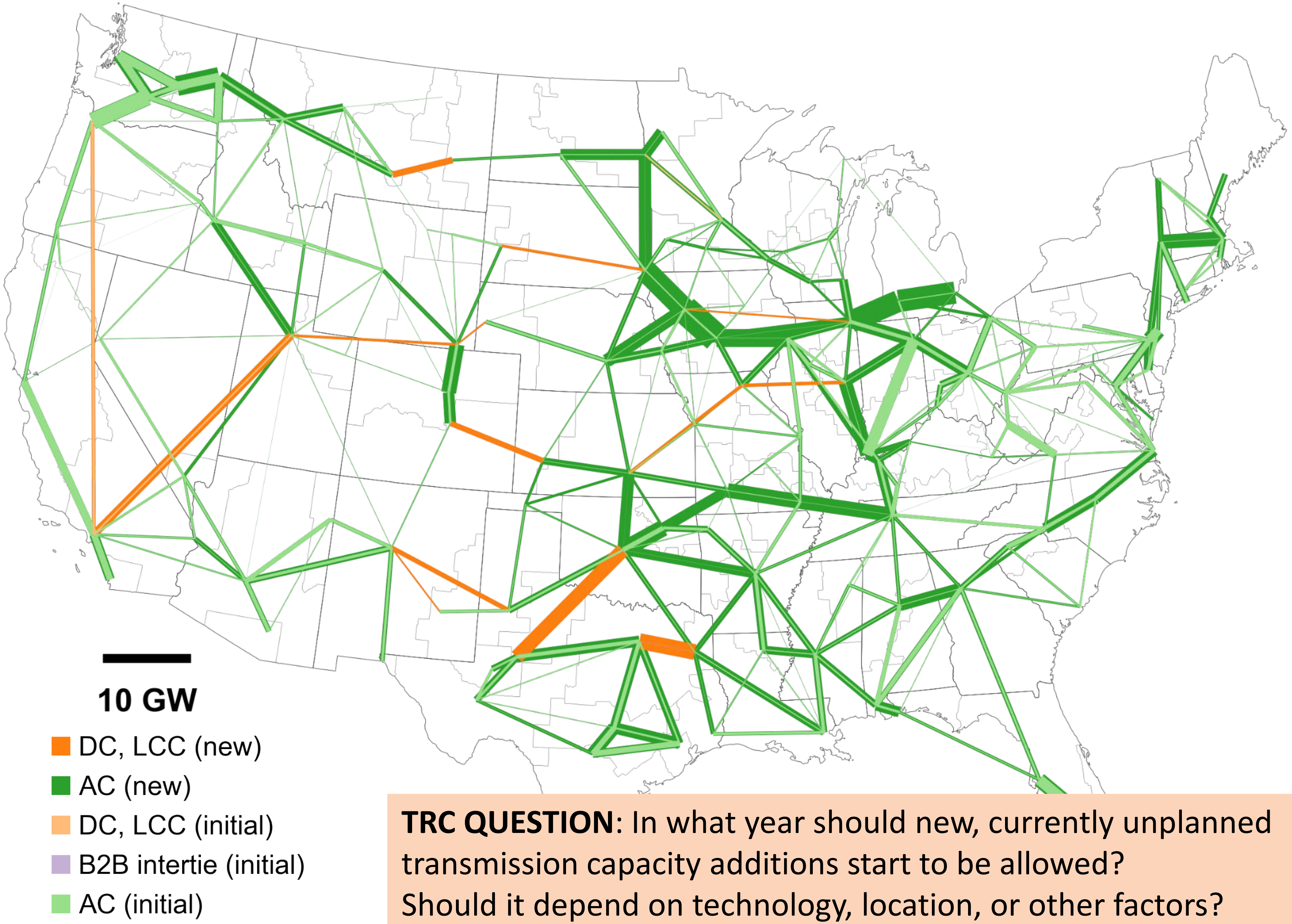


Illustrative modeling results only – do not cite

ReEDS: Key Outputs

Transmission additions



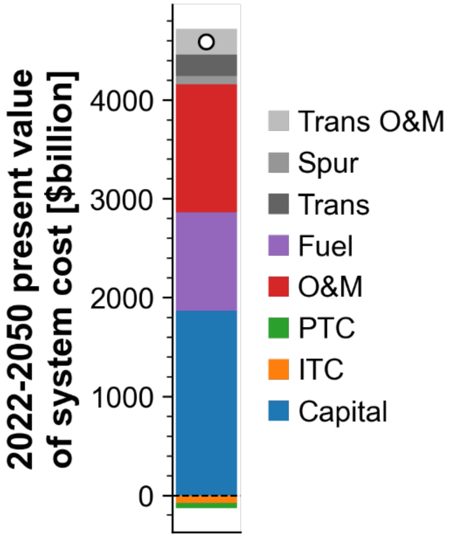


Illustrative modeling results only – do not cite

TRC QUESTION: In what year should new, currently unplanned transmission capacity additions start to be allowed?
Should it depend on technology, location, or other factors?

ReEDS: Key Outputs

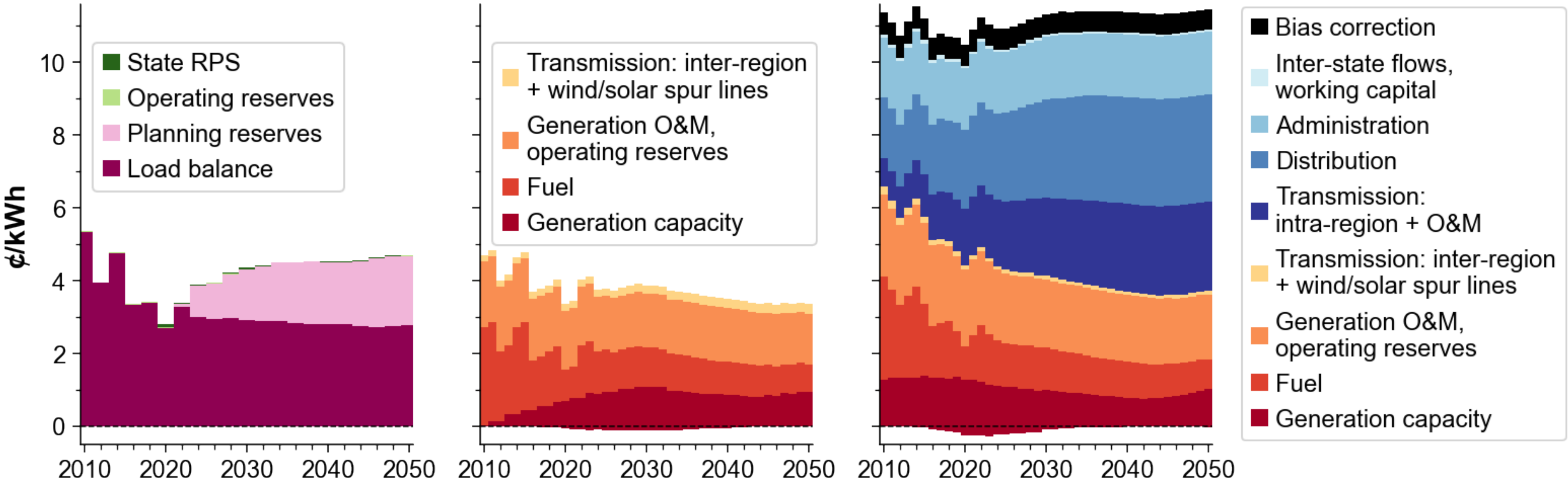
NPV of costs over full model horizon



Marginal price

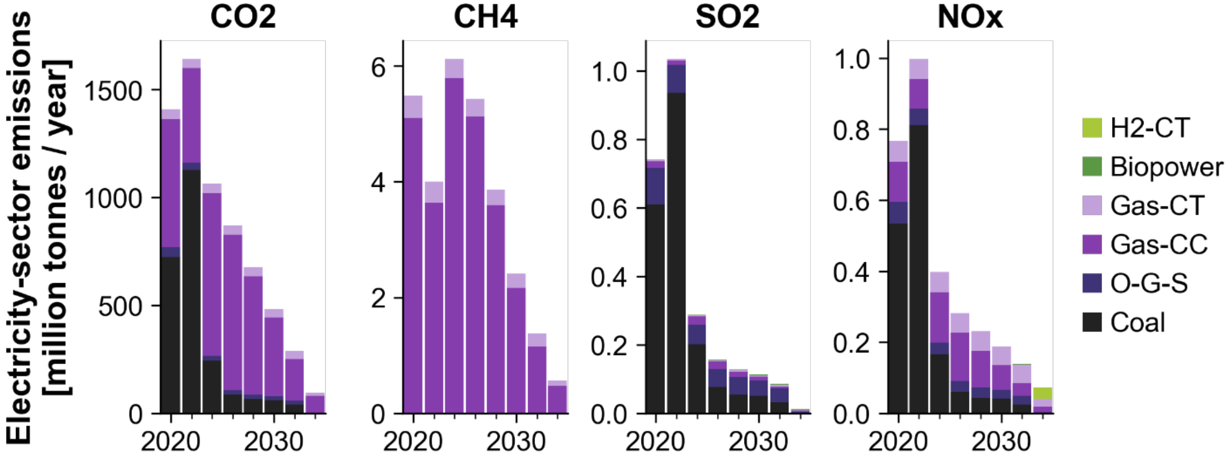
System cost

Retail rate

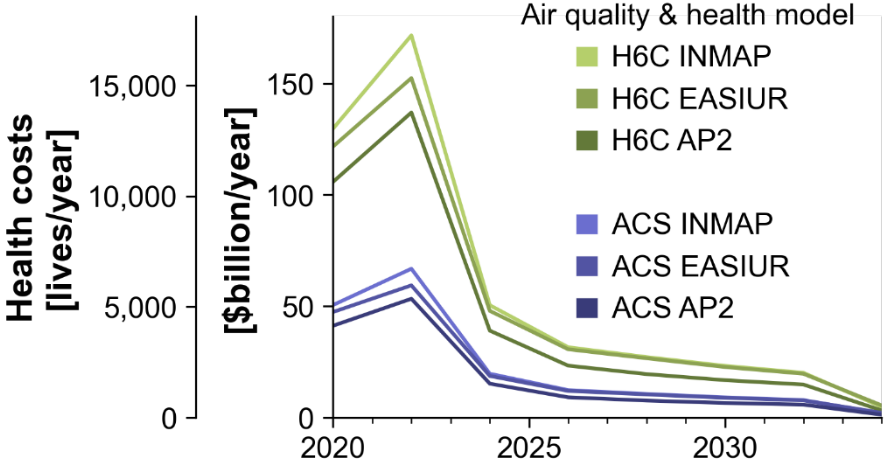


Illustrative modeling results only – do not cite

Emissions (CO_2, CH_4, SO_2, NO_x)

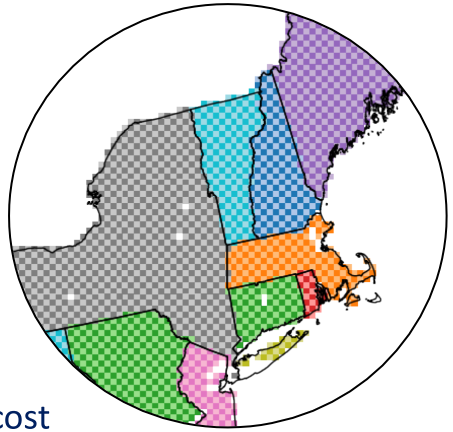


Health impacts



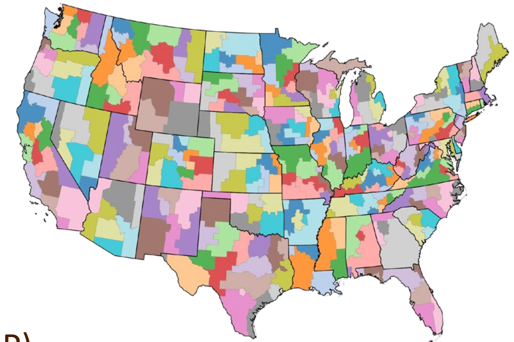
ReEDS: Spatial Resolution

>50,000 sites



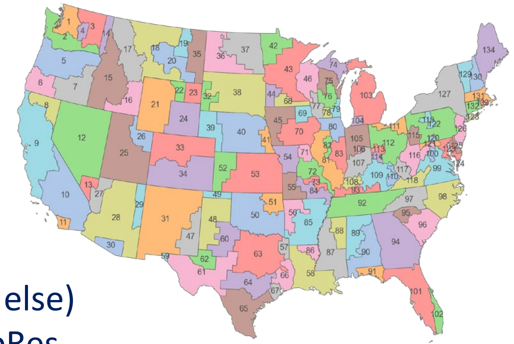
- RE availability
- Interconnection cost

356 resource regions



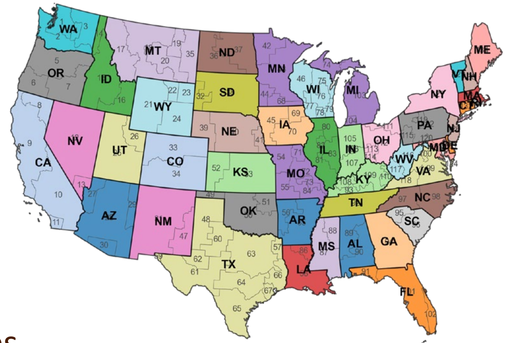
- Capacity (wind, CSP)

134 model zones



- Capacity (everything else)
- Generation, PRM, OpRes

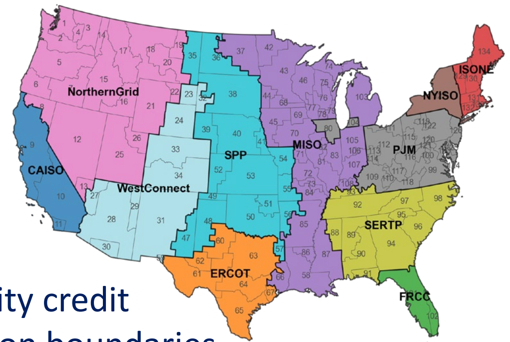
48 states



- RPS / CES policies

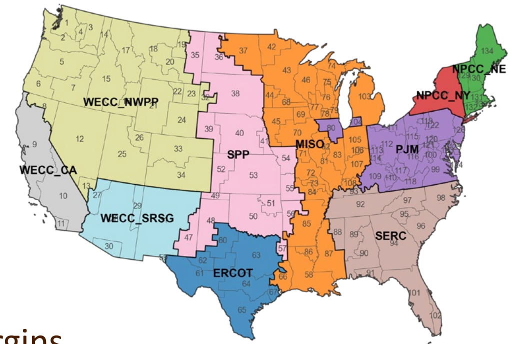
11 transmission planning regions

(approximating FERC Order 1000 regions with some modifications)



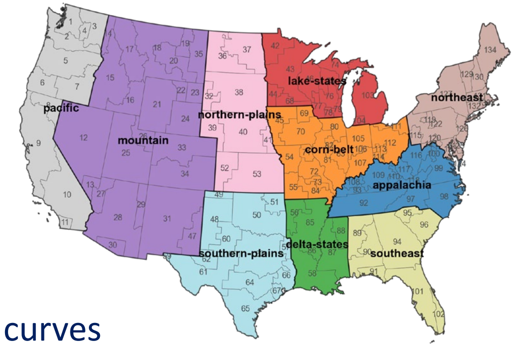
- OpRes trading
- Net load for capacity credit
- Limited-transmission boundaries

10 NERC regions



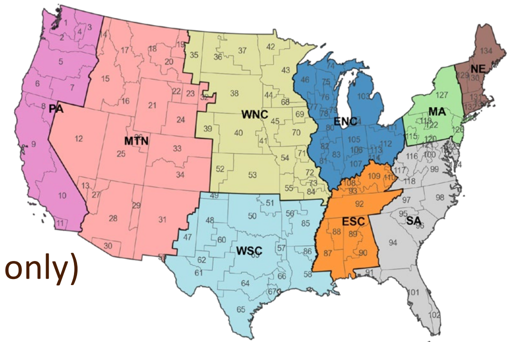
- Planning reserve margins

10 USDA regions



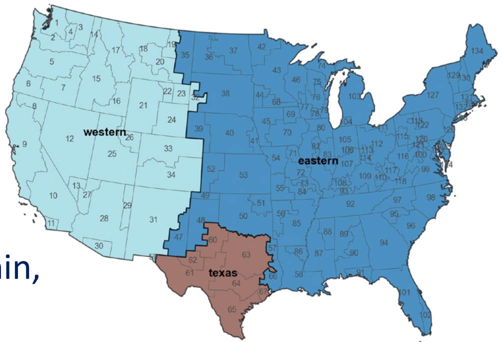
- Biomass supply curves

9 census divisions



- Load growth (AEO only)
- Gas supply curves

3 interconnections



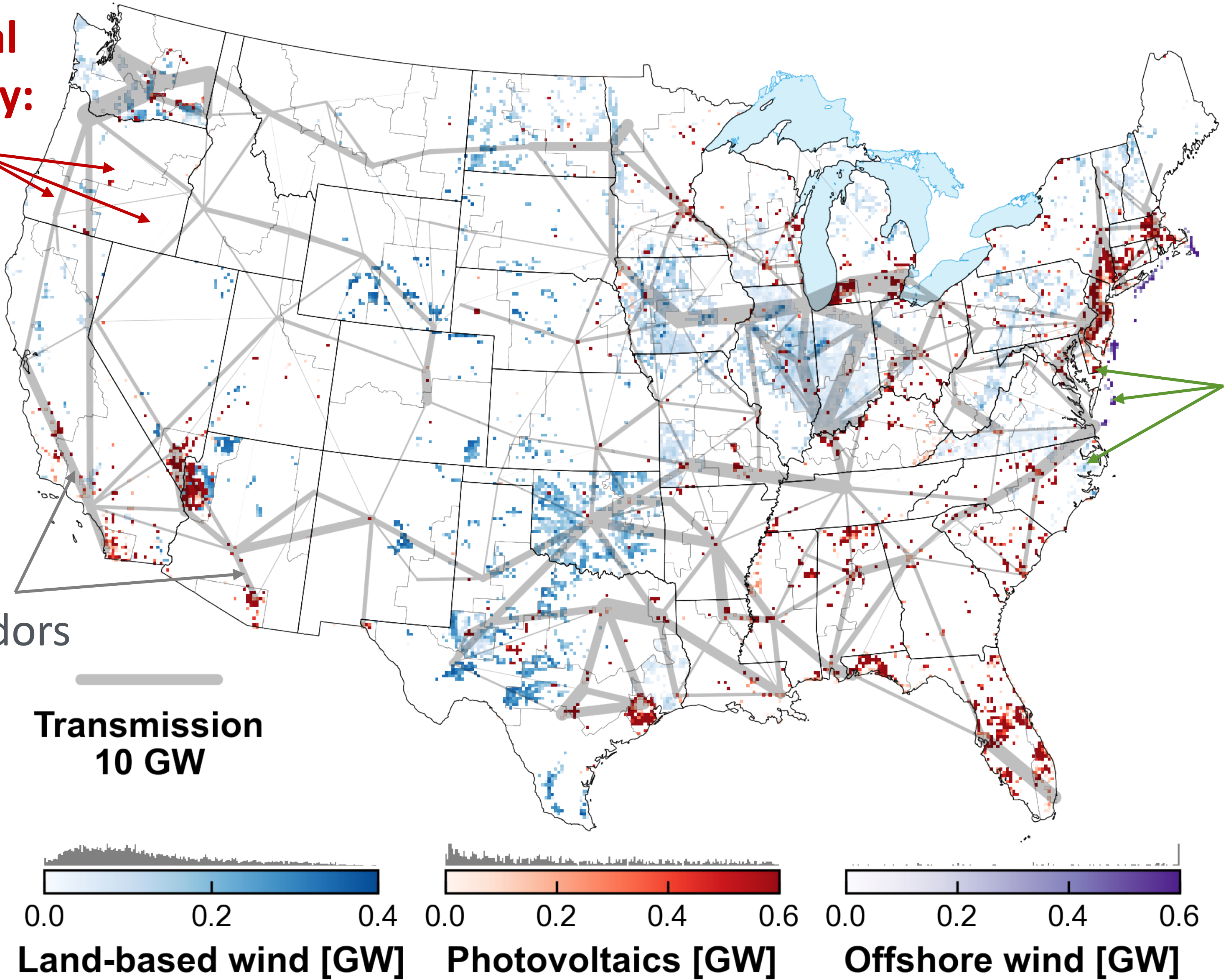
- Transmission: AC within, DC/B2B between

ReEDS: Spatial Resolution

Demand, thermal / storage capacity:
134 zones

VRE: >50k sites

Transmission:
Inter-zone corridors



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Modeled future decarbonized system

ReEDS: Temporal Resolution

Current default: 17-timeslice linear program (averaged profiles; 4 per season + summer peak) + 8760h marginal parameters

Generation, flows, reserves: 17 timeslices

Curtailment: 1y × 8760h
Capacity credit: 7y × 8760h

ReEDS LP
t = 2024

Augur
t_{cur} = 2024, t_{next} = 2026

ReEDS LP
t = 2026

Augur
t_{cur} = 2026, t_{next} = 2028

…

Capacity (gen, stor, trans) by technology and region

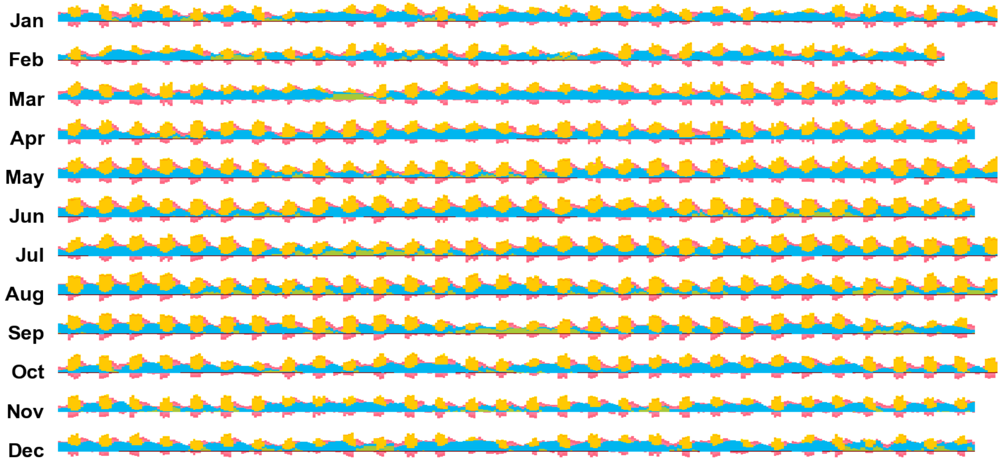
Curtailment (existing & marginal)
Capacity credit (existing & marginal)

Alternative approach: Hourly linear program

Capabilities for **full U.S.**:
- Representative days
- Representative weeks

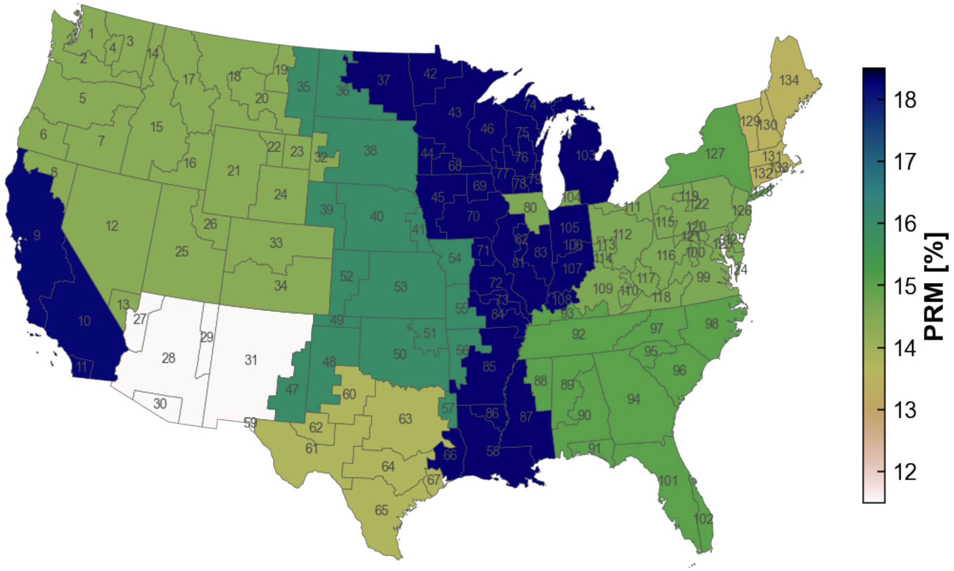
Capability for **smaller** systems (single interconnects or aggregated model zones):
- Full chronological year (1-4h steps)

Example: chronological ERCOT system at zero carbon (direct ReEDS output)



ReEDS: Planning Reserves

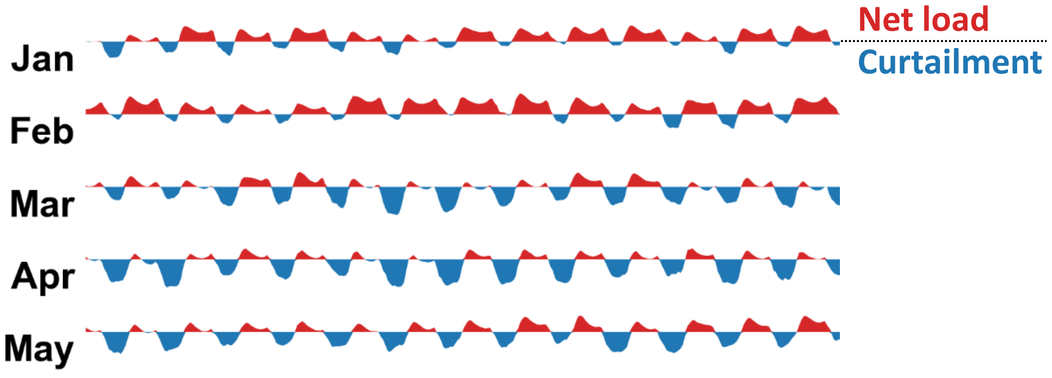
1. NERC **planning reserve margin** (PRM) requirement



2. Net load (7x8760 hours, 2007–2013; 11 regions)

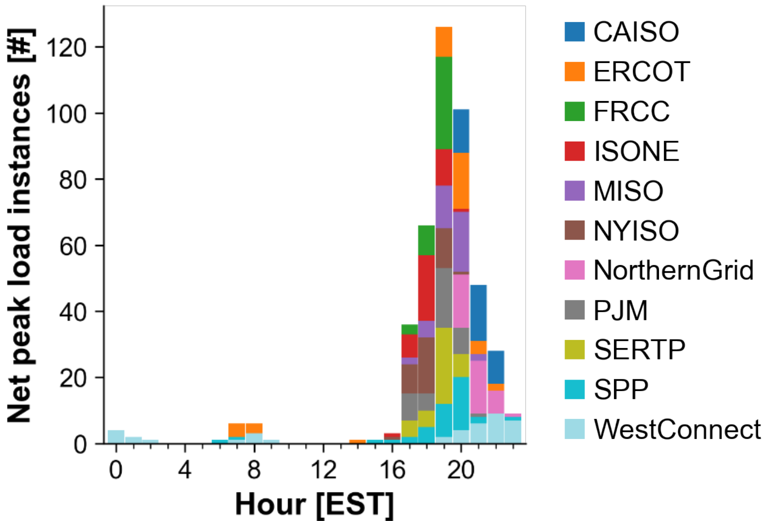
= hourly load

– hourly VRE generation



3. VRE capacity credit [%]

= capacity factor during 10 peak net load hours per season



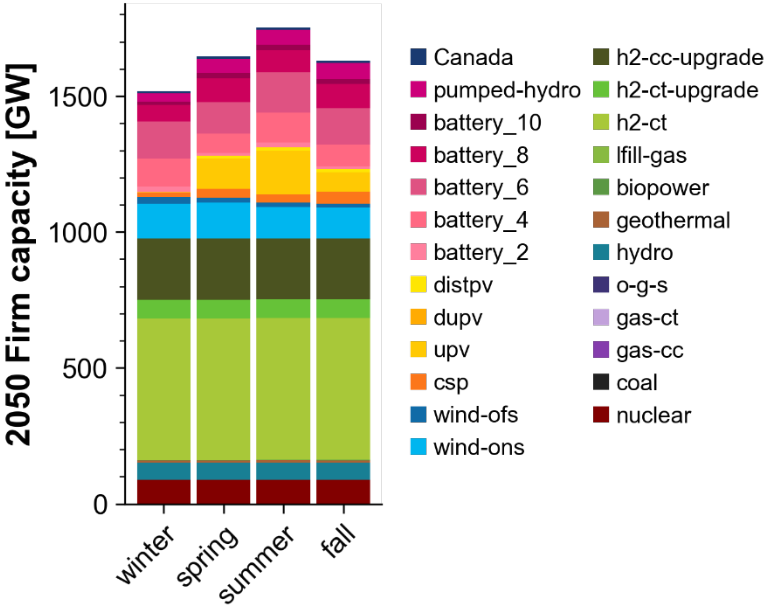
4. ReEDS constraint:

Firm capacity [MW]

≥ peak load [MW]

× (1 + PRM)

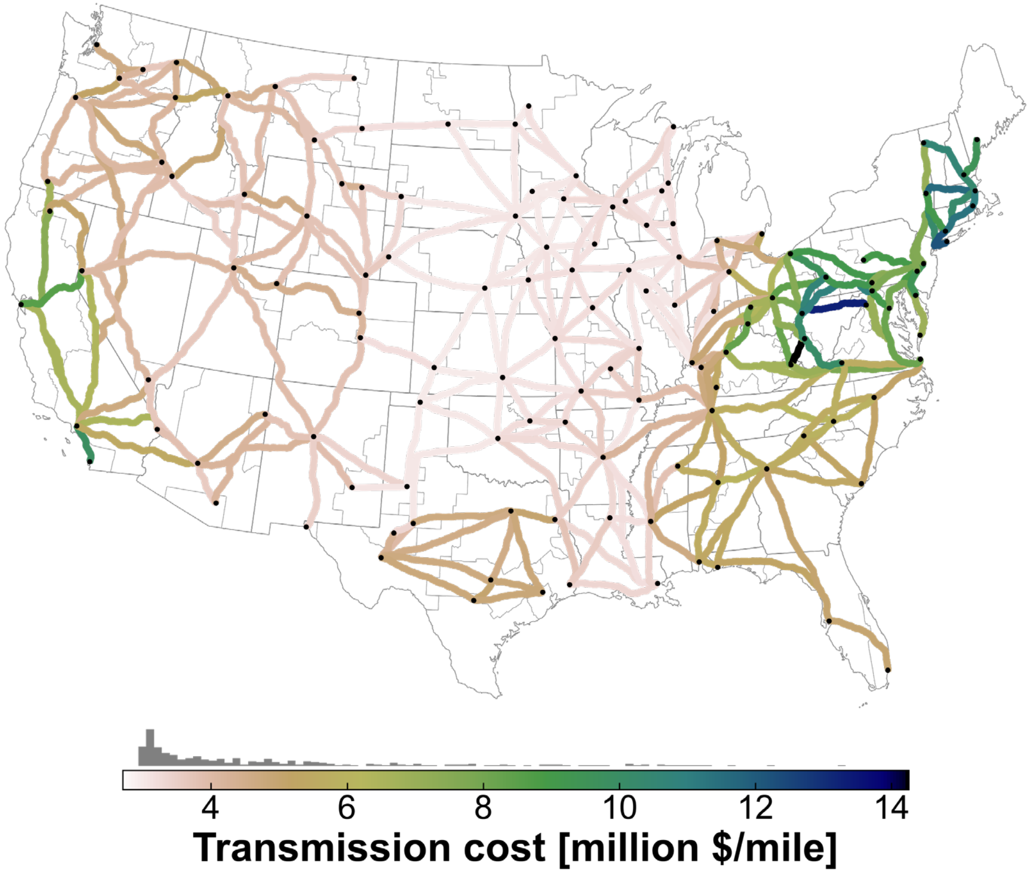
Illustrative modeling results only – do not cite



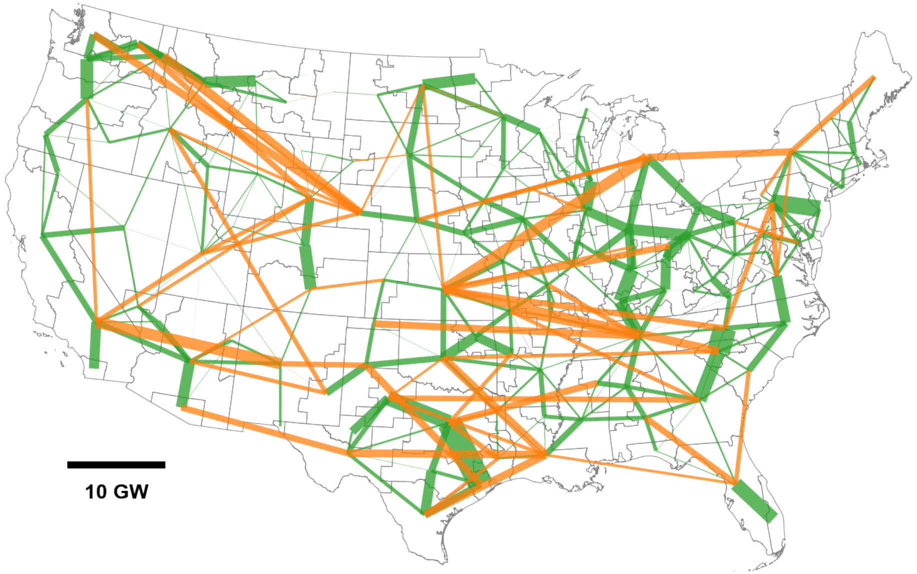
→ Repeat for every ReEDS solve year

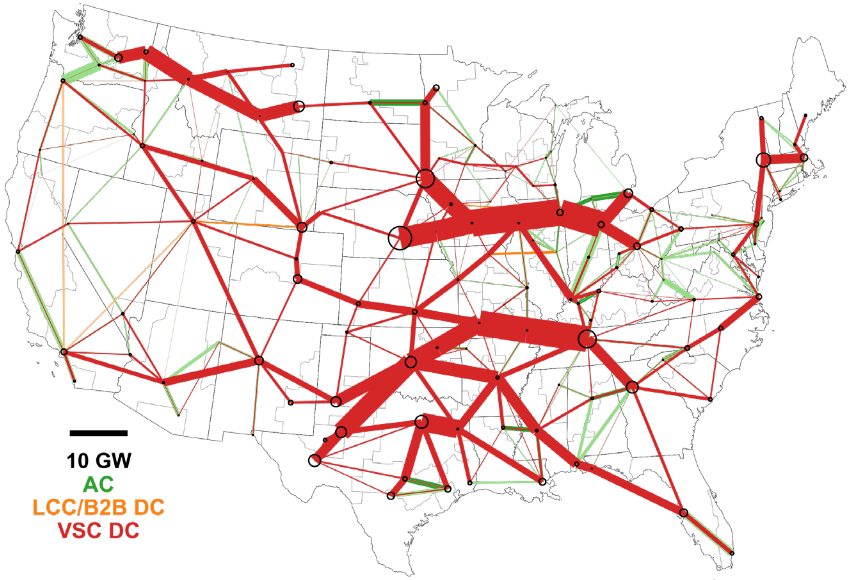
Transmission in ReEDS

1. Cost and performance



2. HVDC network design

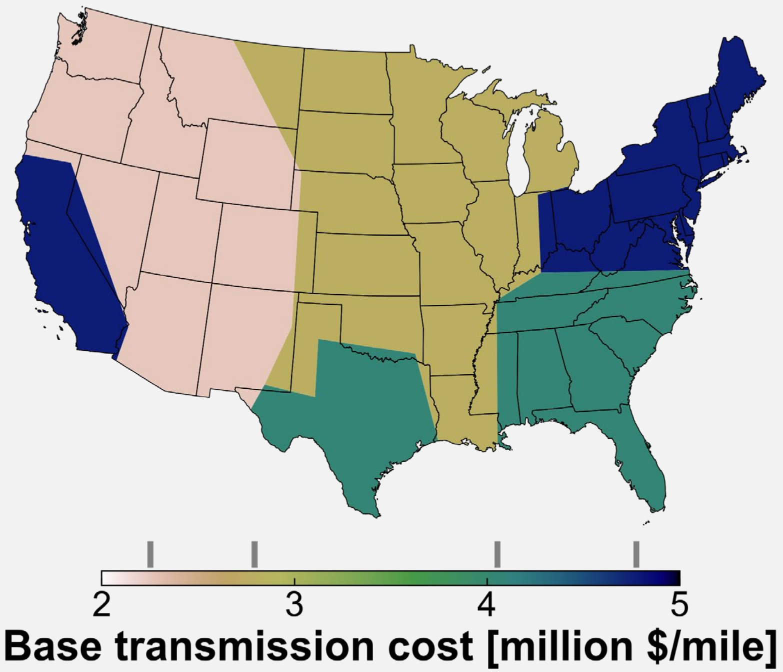




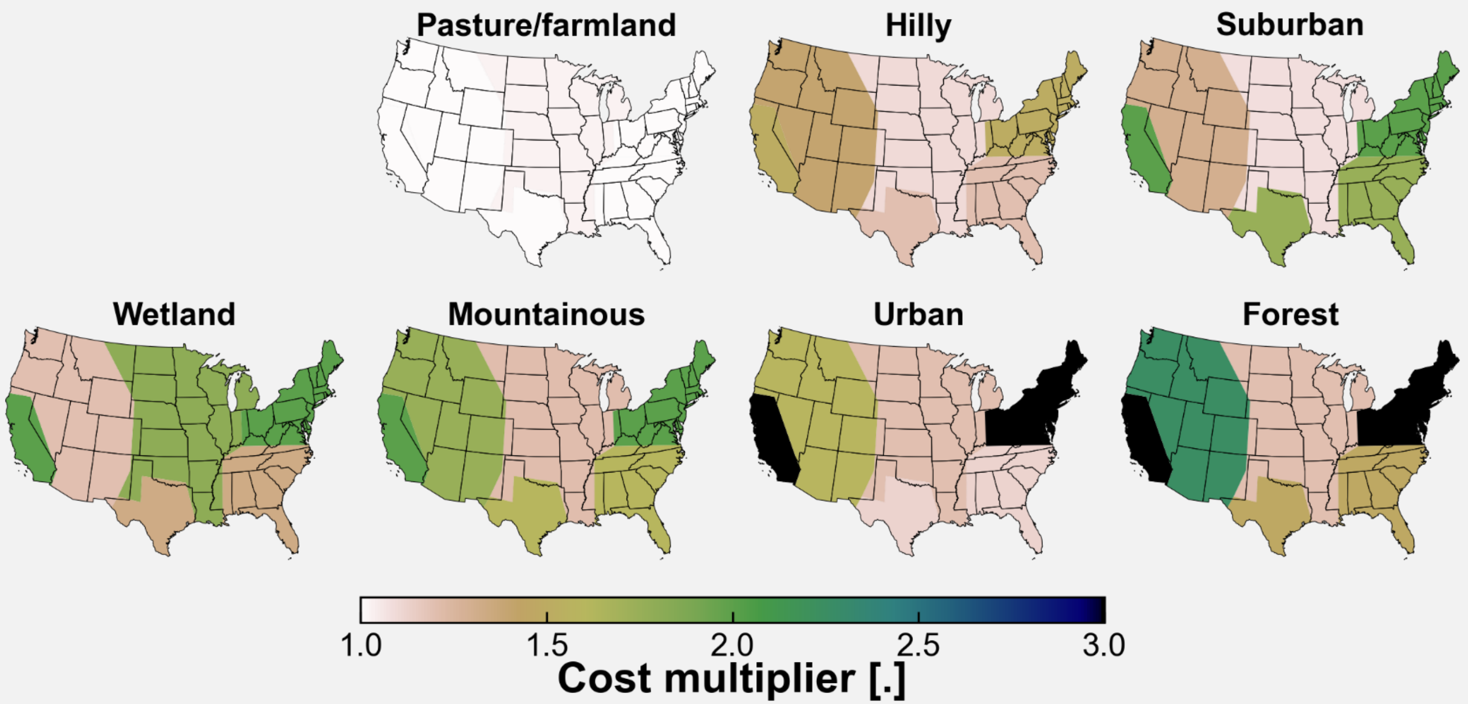
Transmission Cost Assumptions

Renewable Energy Potential (reV) model: https://github.com/NREL/reV

Base transmission cost



Siting cost multipliers (90m resolution)



500kV AC, single-circuit (for inter-zone)

- higher $/MWmile & lower voltage for interconnection spur lines
- lower $/MWmile for DC lines

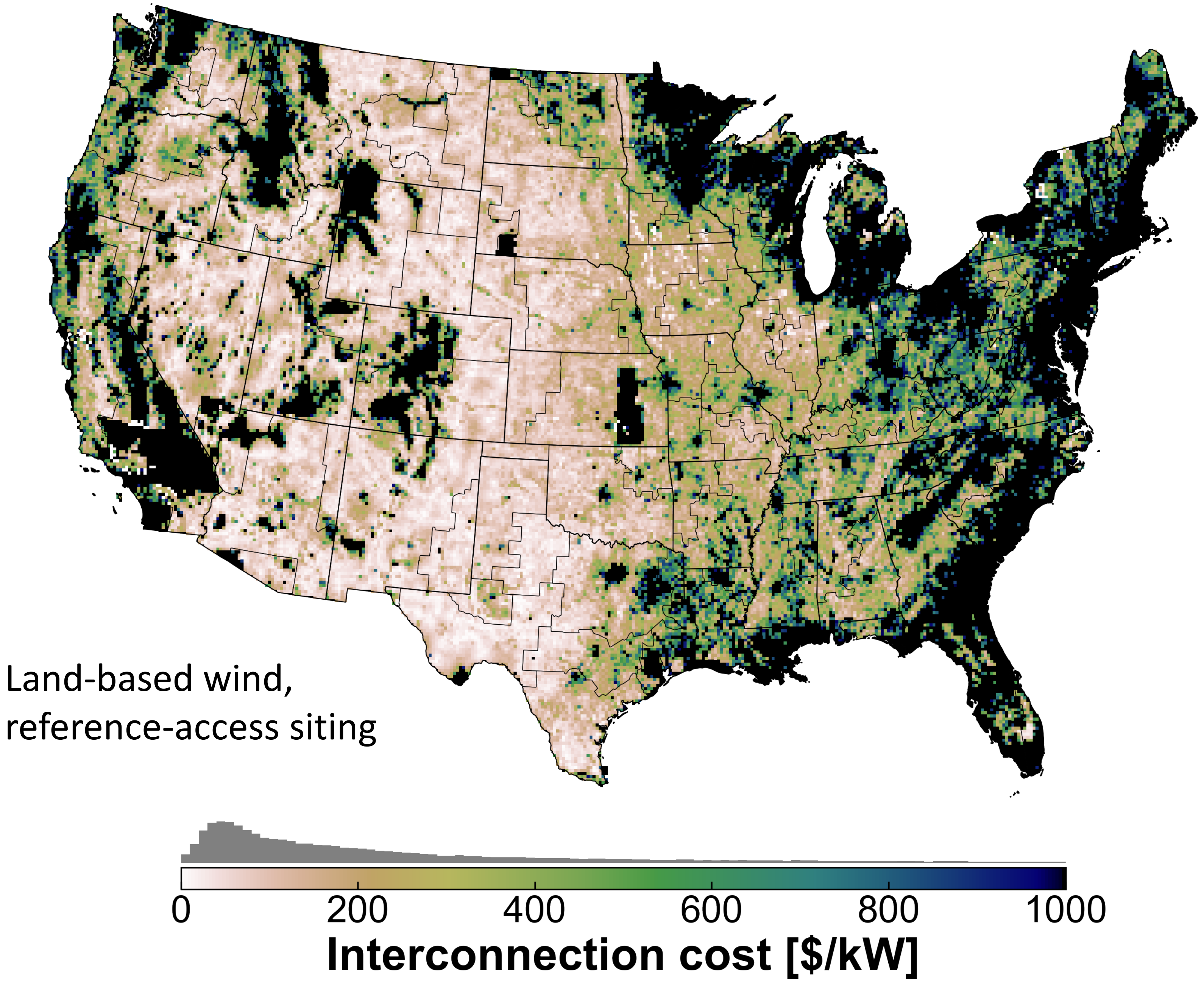
×

=

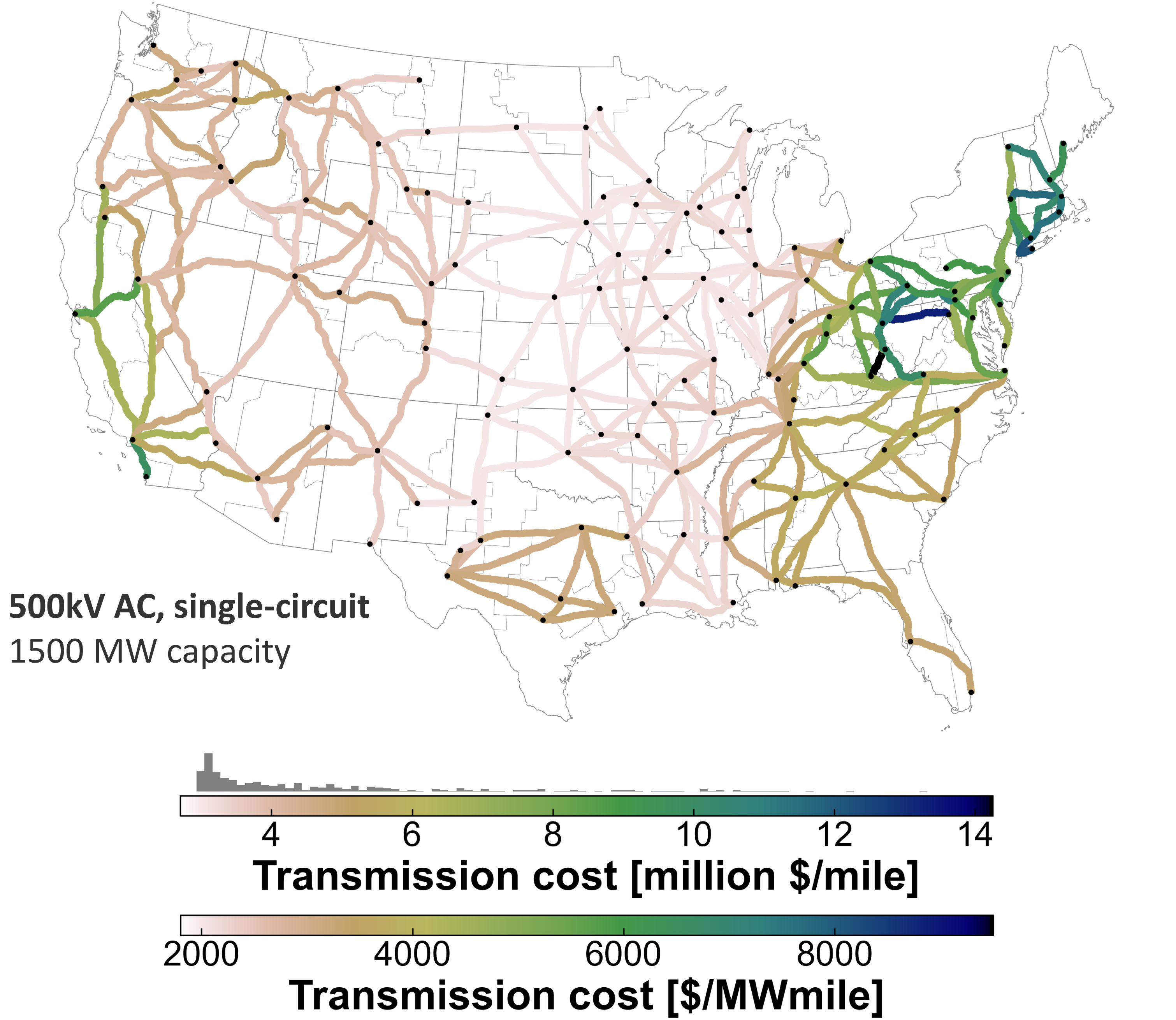
1. **Interconnection** spur-line costs for wind and solar
2. **Inter-zone** transmission costs

(next two slides)

Interconnection Spur-Line Costs



Inter-Zone Transmission Costs



TRC QUESTION: Are the assumed cost and performance characteristics appropriate? Are there other characteristics that should be considered?

Modifications for DC (from MISO cost estimation guide):

- $/MW-mile cost = ~40% of AC
- + AC/DC converter cost:
  - LCC: $140/kW
  - VSC: $180/kW

Losses:

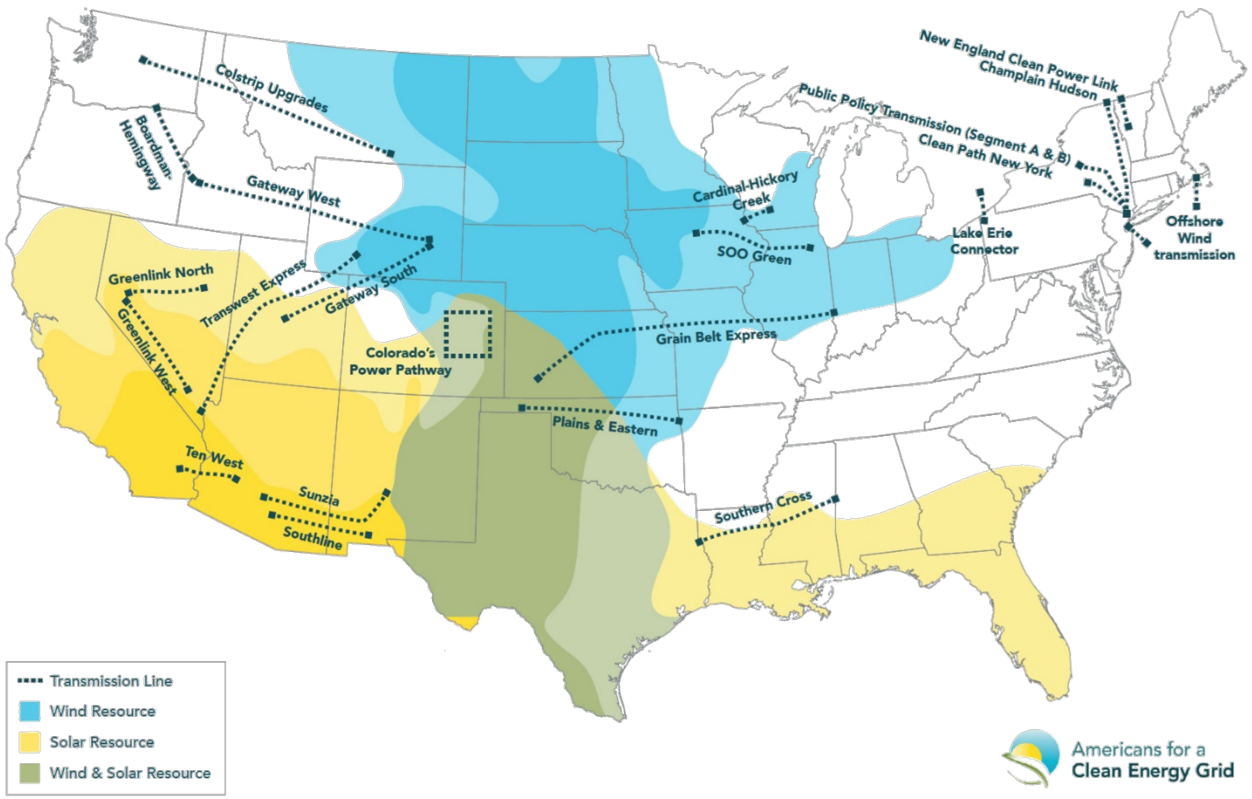
- AC: 1% / 100 miles
- DC: 0.5% / 100 miles
- AC/DC conversion:
  - LCC: 0.7%
  - VSC: 1.0%

Fixed O&M:

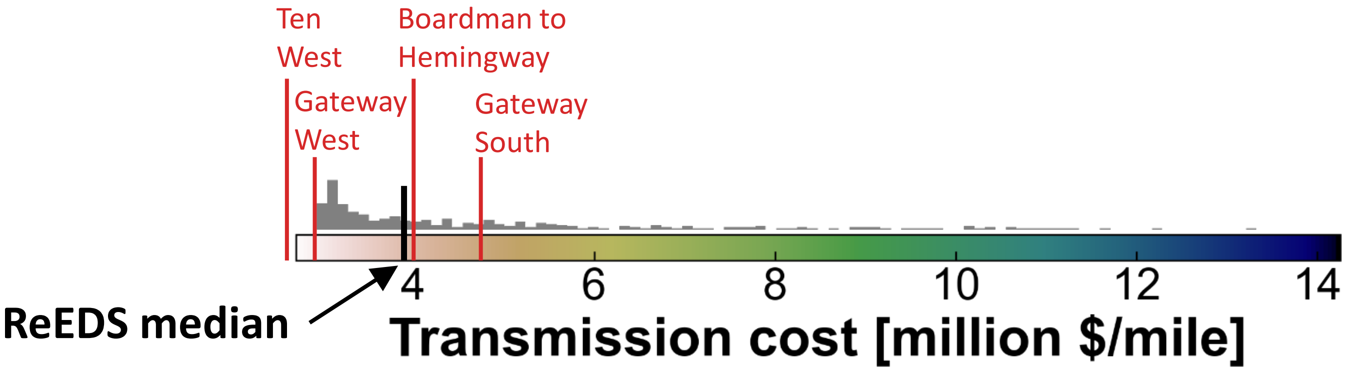
- 1.5% of upfront capex per year

How do ReEDS transmission costs compare?

Goggin, Gramlich, and Skelly 2021 – Transmission projects ready to go: Plugging into America's untapped renewable resources



Region	Project Name	Miles	kiloVolts	AC/DC	Cost $B
New England	NE Clean Power Link	150	320	DC	$1.600
New York	Clean Path New York	265	320	DC	$1.500
	Champlain Hudson	330	300	DC	$2.200
	Public Policy Transmission	100	345	AC	$1.230
Offshore	Multiple Projects	30	300	DC	$1.902
PJM	Lake Erie Connector	73	320	DC	$1.000
ERCOT- Southeast	Southern Cross	400	500	DC	$1.400
MISO	SOO Green	350	525	DC	$2.500
	Cardinal - Hickory Creek	100	345	AC	$0.520
SPP	Grain Belt Express	780	600	DC	$2.300
	Plains and Eastern Oklahoma	400	600	DC	$1.200
West	Transwest Express	730	600	DC	$3.000
	Colorado's Power Pathway	560	345	AC	$1.700
	Greenlink North Nevada	235	525	AC	$0.810
	Greenlink West Nevada	351	525	AC	$1.608
	Gateway South	400	500	AC	$1.900
	Gateway West	1000	500	AC	$2.880
	Boardman to Hemingway	300	500	AC	$1.200
	Ten West	114	500	AC	$0.300
	Sunzia	515	500	AC, DC	$1.500
	Southline	240	345	AC	$0.800
	Colstrip Upgrades	500	500	AC	$0.227

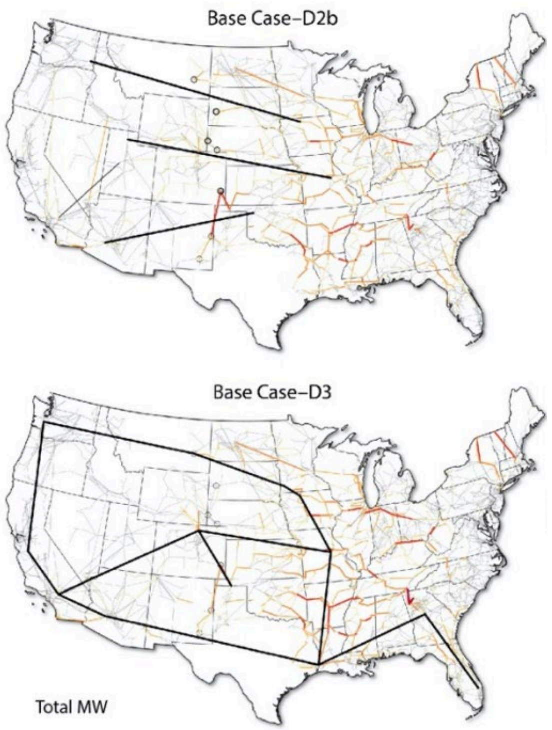


HVDC Macrogrid Design Approaches

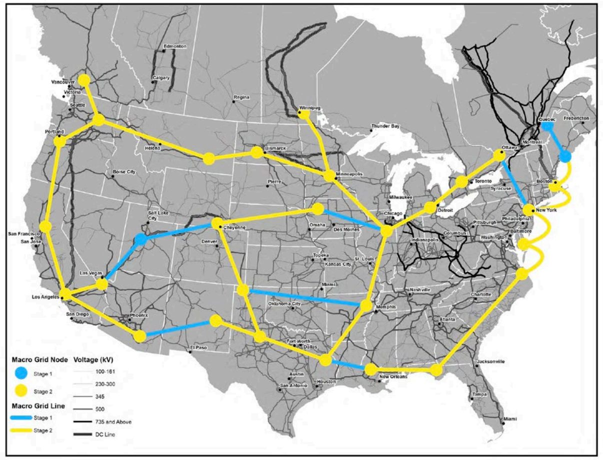
“Engineering intuition”

“Building blocks”

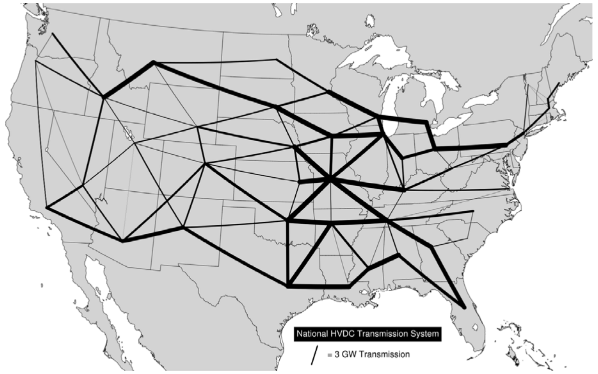
Endogenously optimized



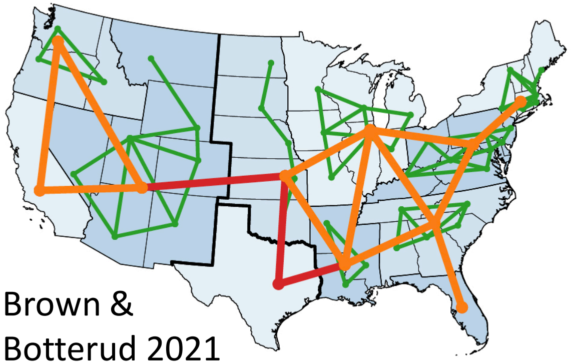
Bloom et al 2020



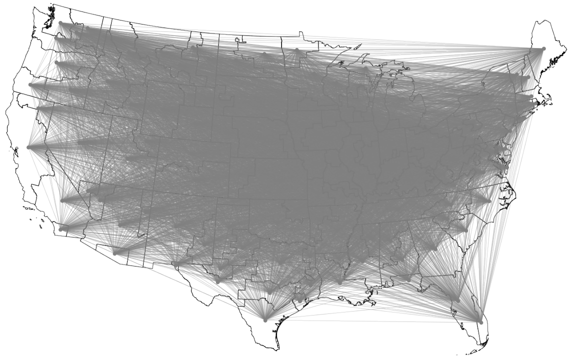
ESIG 2021



VCE 2021



Brown & Botterud 2021



1. Run ReEDS allowing investment in HVDC lines between any pair of currently-unconnected zones
2. Drop candidate HVDC lines with <3 GW of optimized investment by 2050, then re-run ReEDS

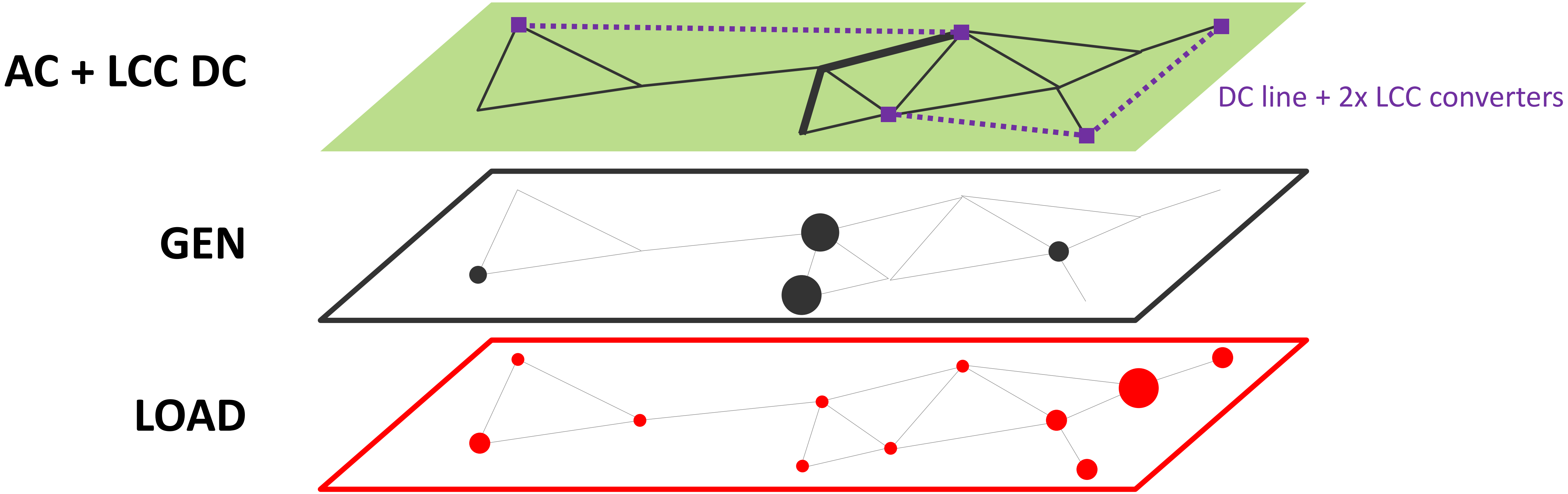
Closer to current practice

Lower total system cost

LCC vs VSC macrogrids

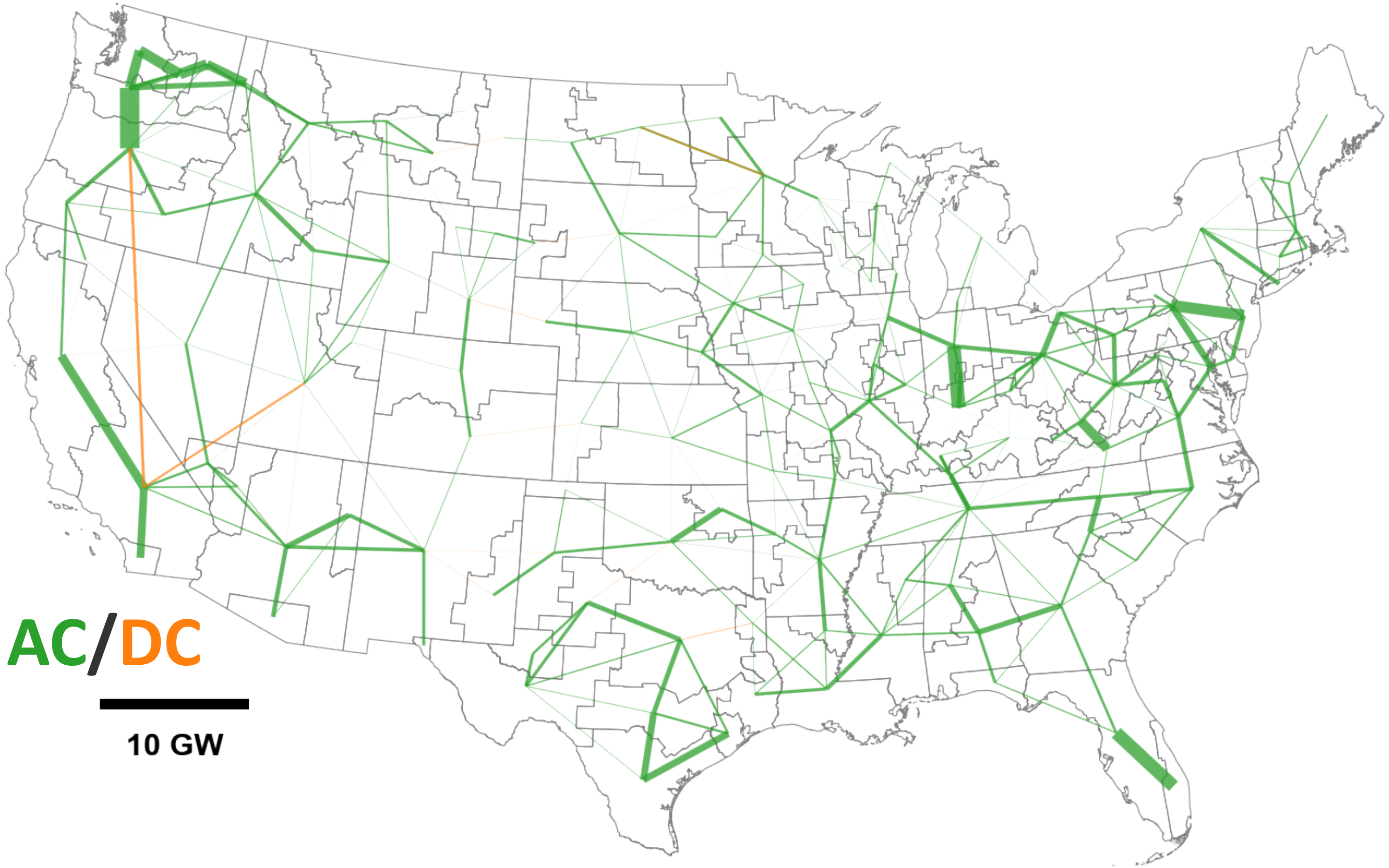
LCC (line-commutated converter):
Constant current source
Better for long individual lines

+ More proven; higher voltage; lower losses
+ Computationally simple
– Less flexible; requires reactive compensation
– Given converter losses, value is reduced if candidate links are too short



Iterative LCC System Design

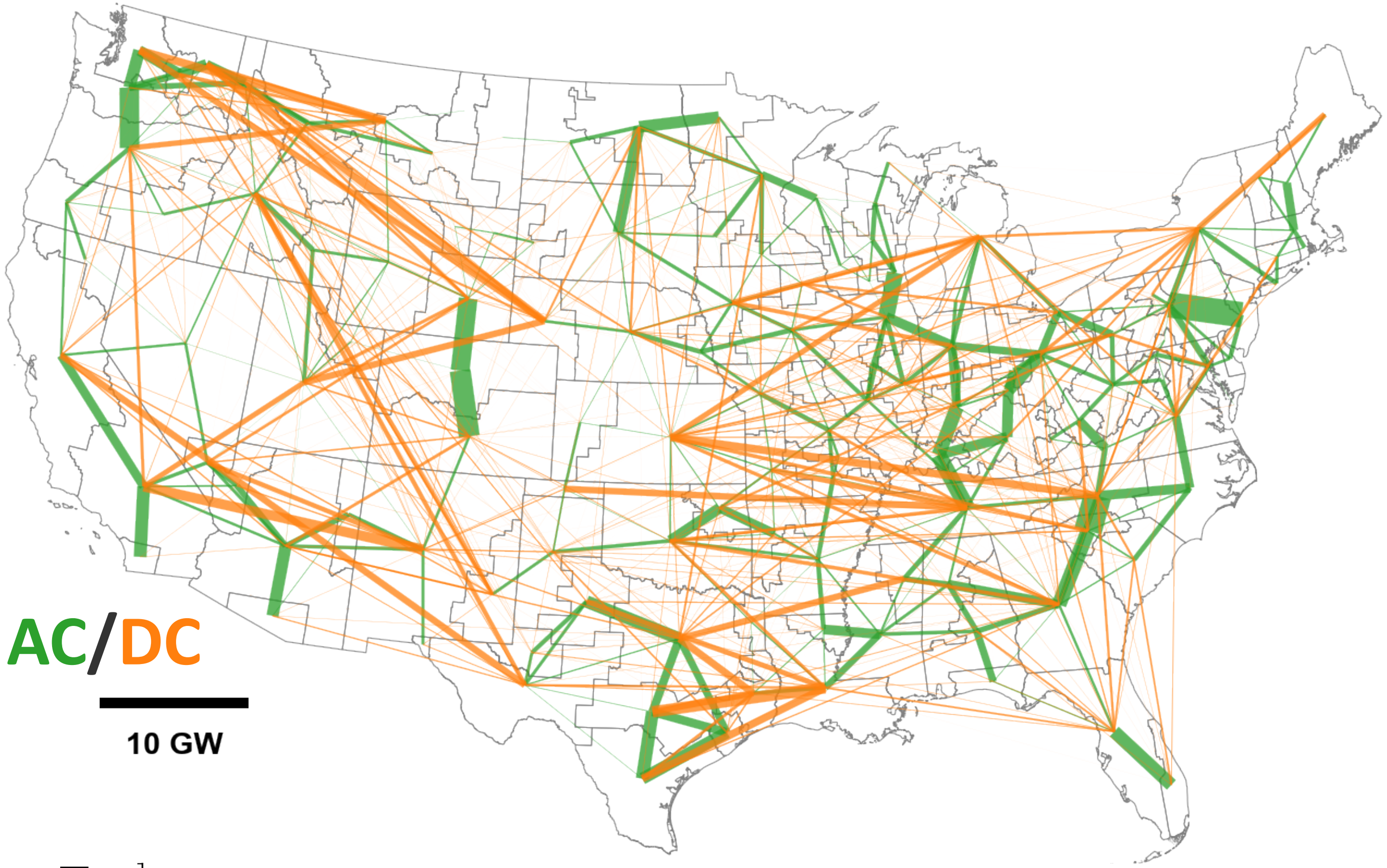
2020 transmission capacity

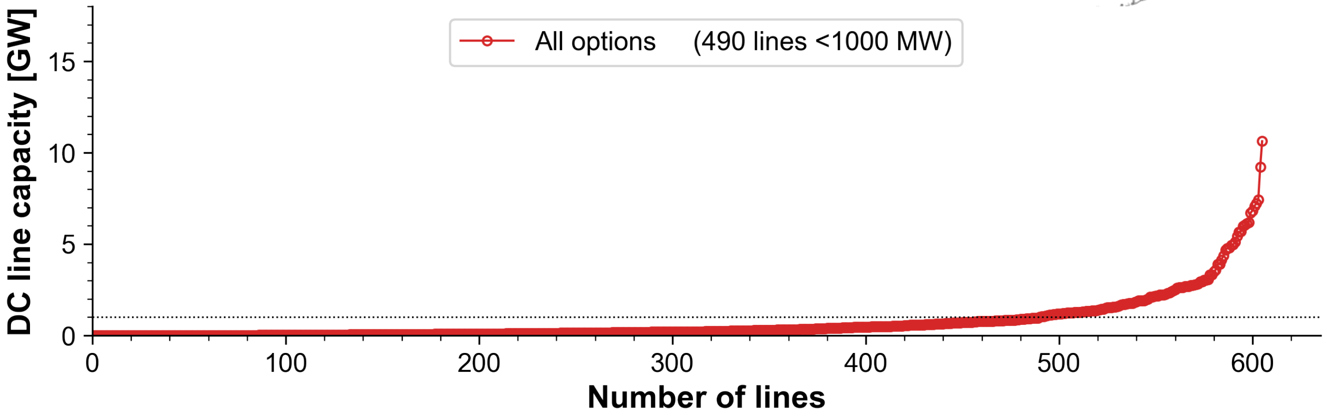


Iterative LCC System Design

2050 transmission capacity,
all HVDC options

(policy-driven decarbonization scenario)

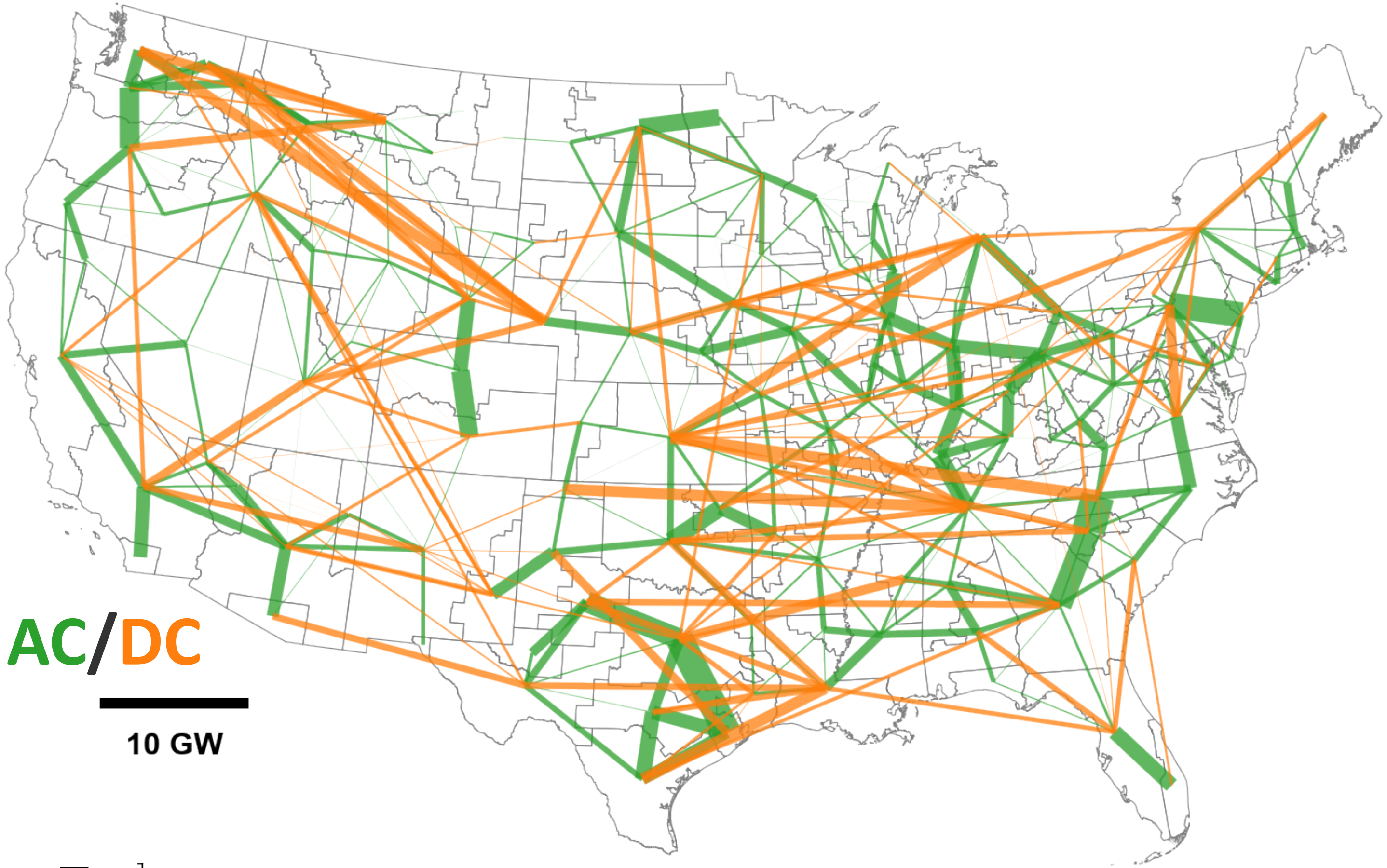


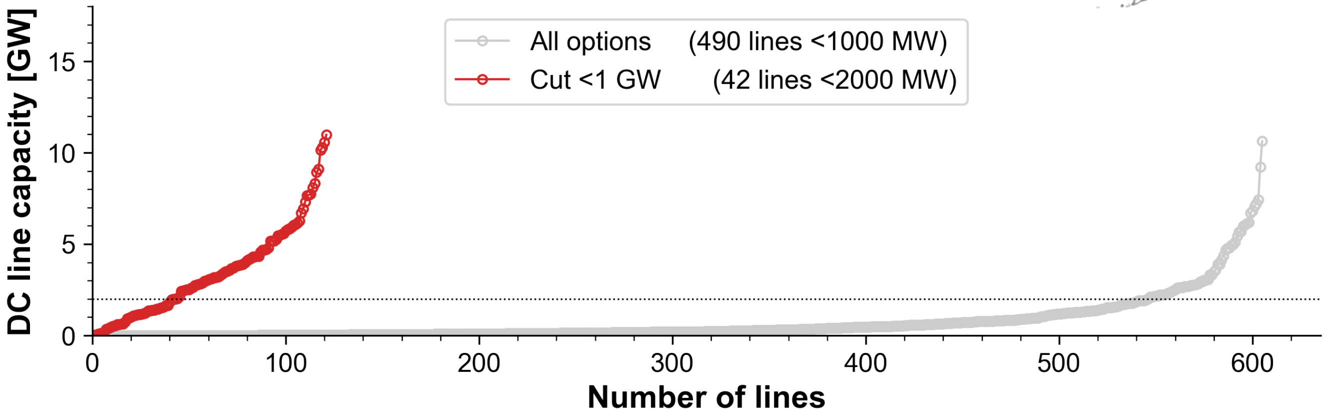


Illustrative modeling results only – do not cite

Iterative LCC System Design

2050 transmission capacity,
cut <1 GW lines





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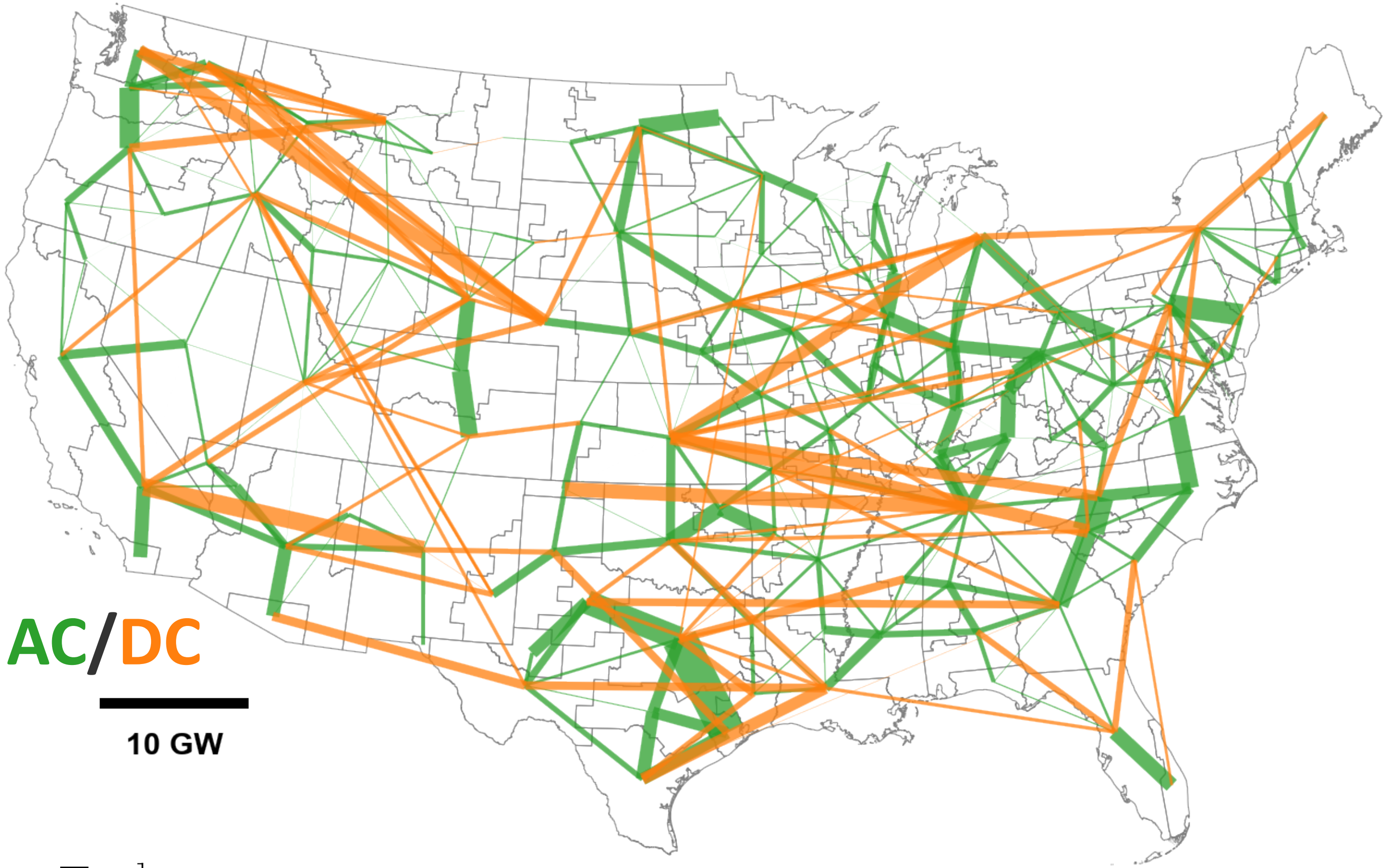
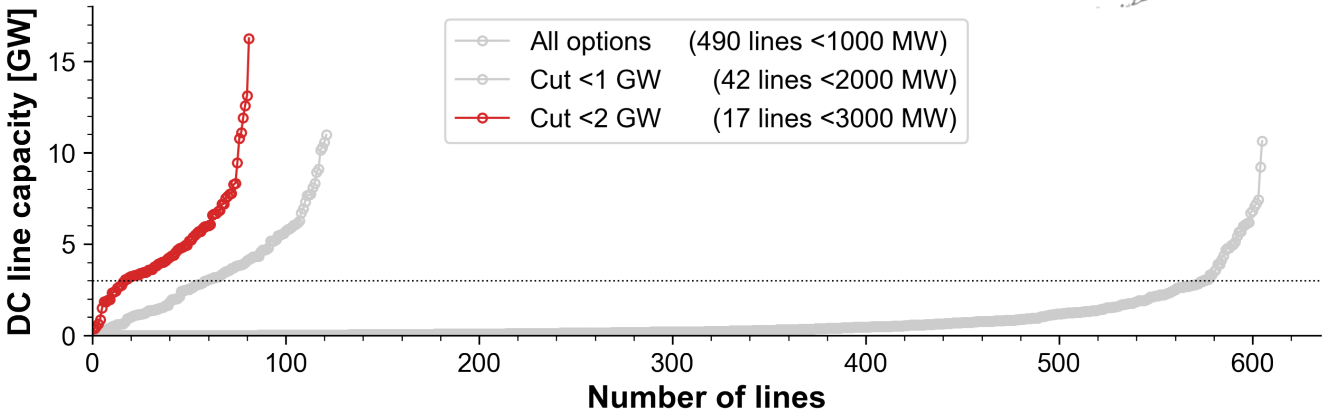
Iterative LCC System Design

2050 transmission capacity,
cut <2 GW lines

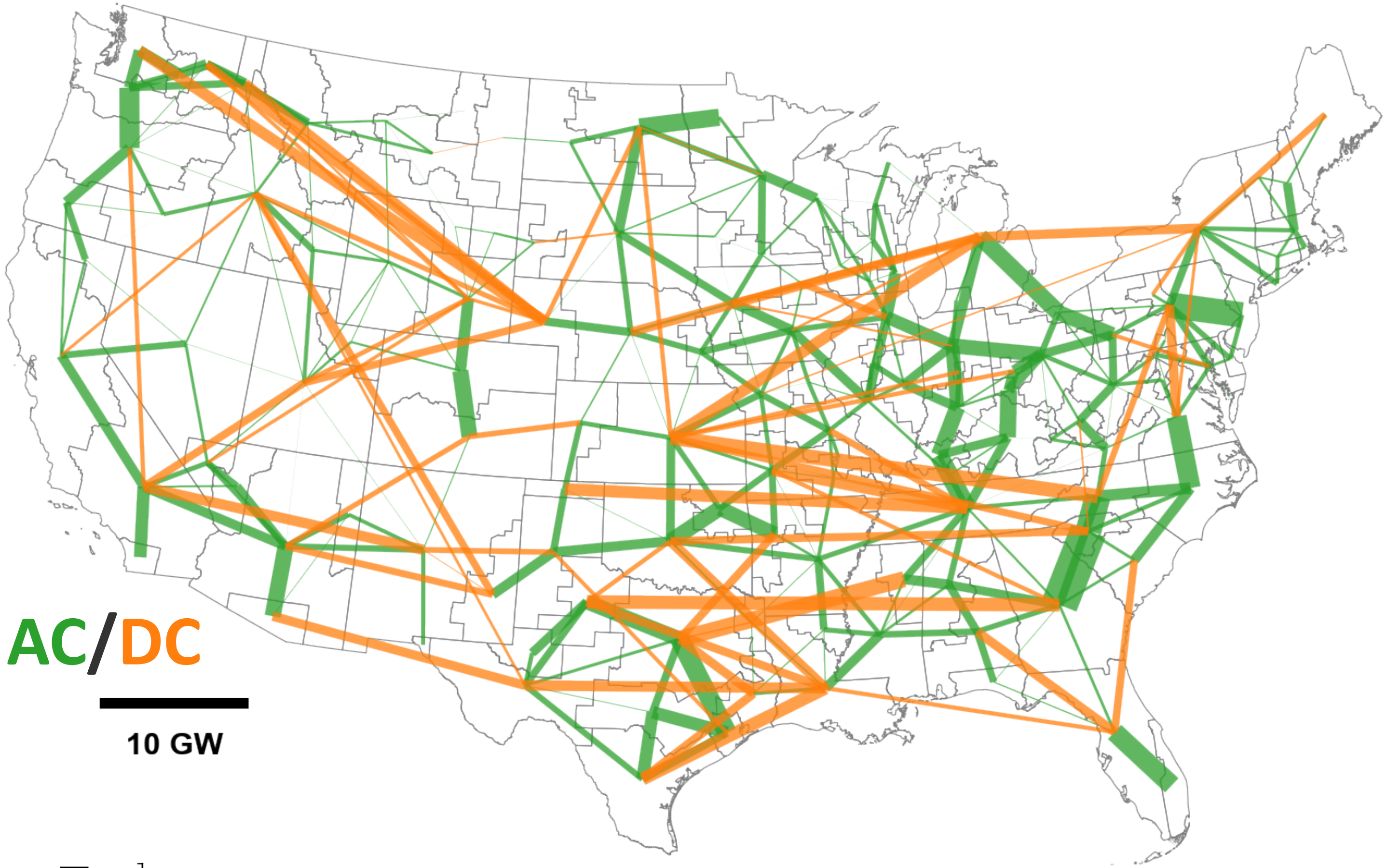


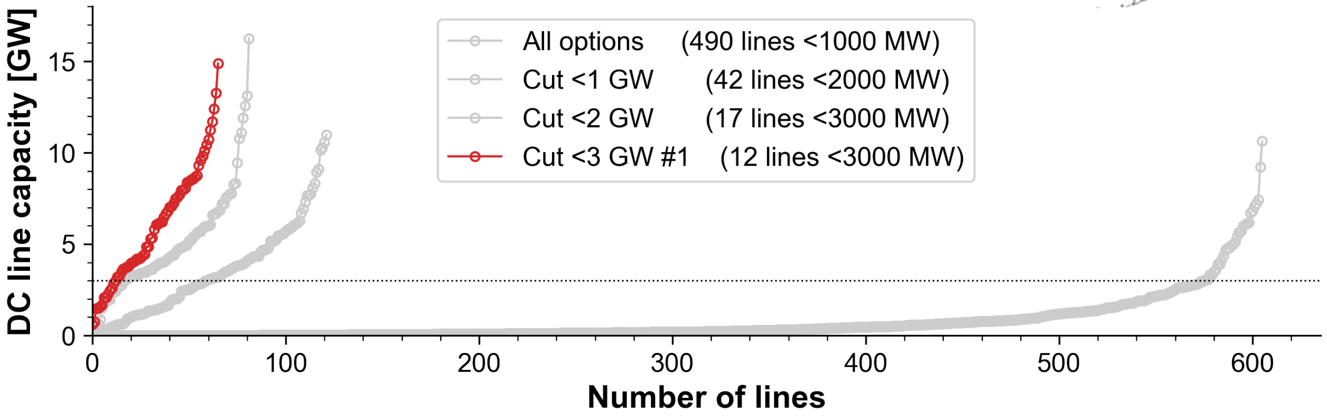


Illustrative modeling results only – do not cite

Iterative LCC System Design

2050 transmission capacity,
cut <3 GW lines #1

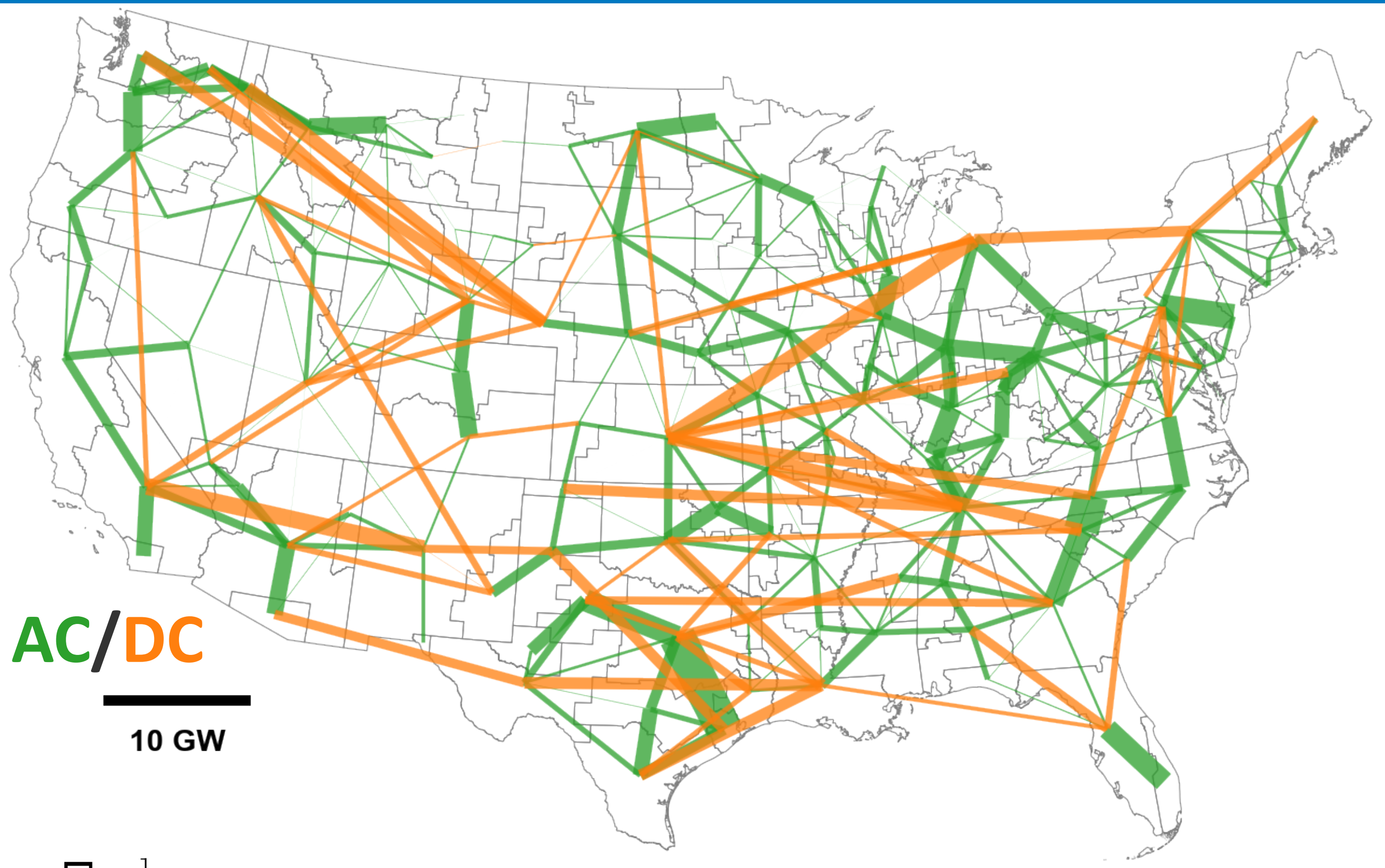


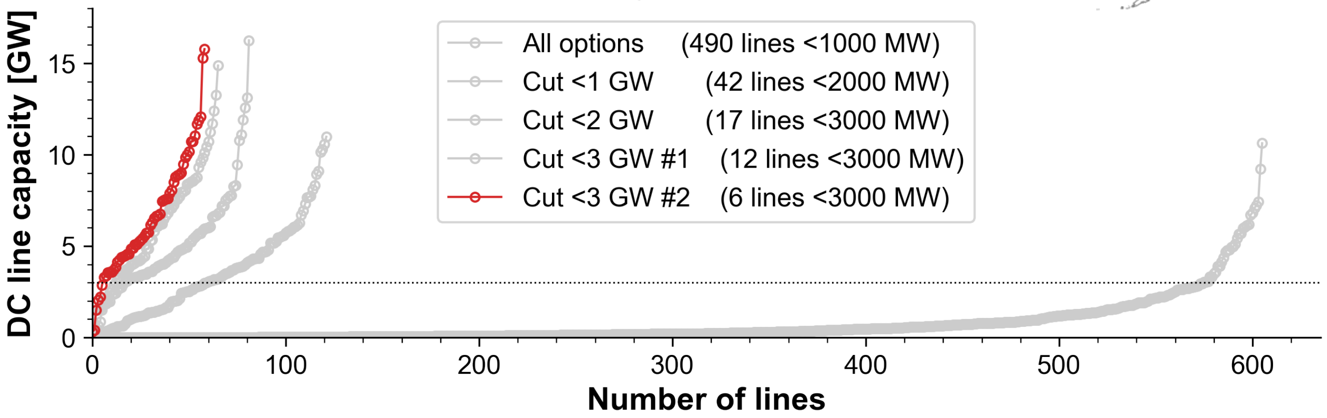


Illustrative modeling results only – do not cite

Iterative LCC System Design

2050 transmission capacity,
cut <3 GW lines #2



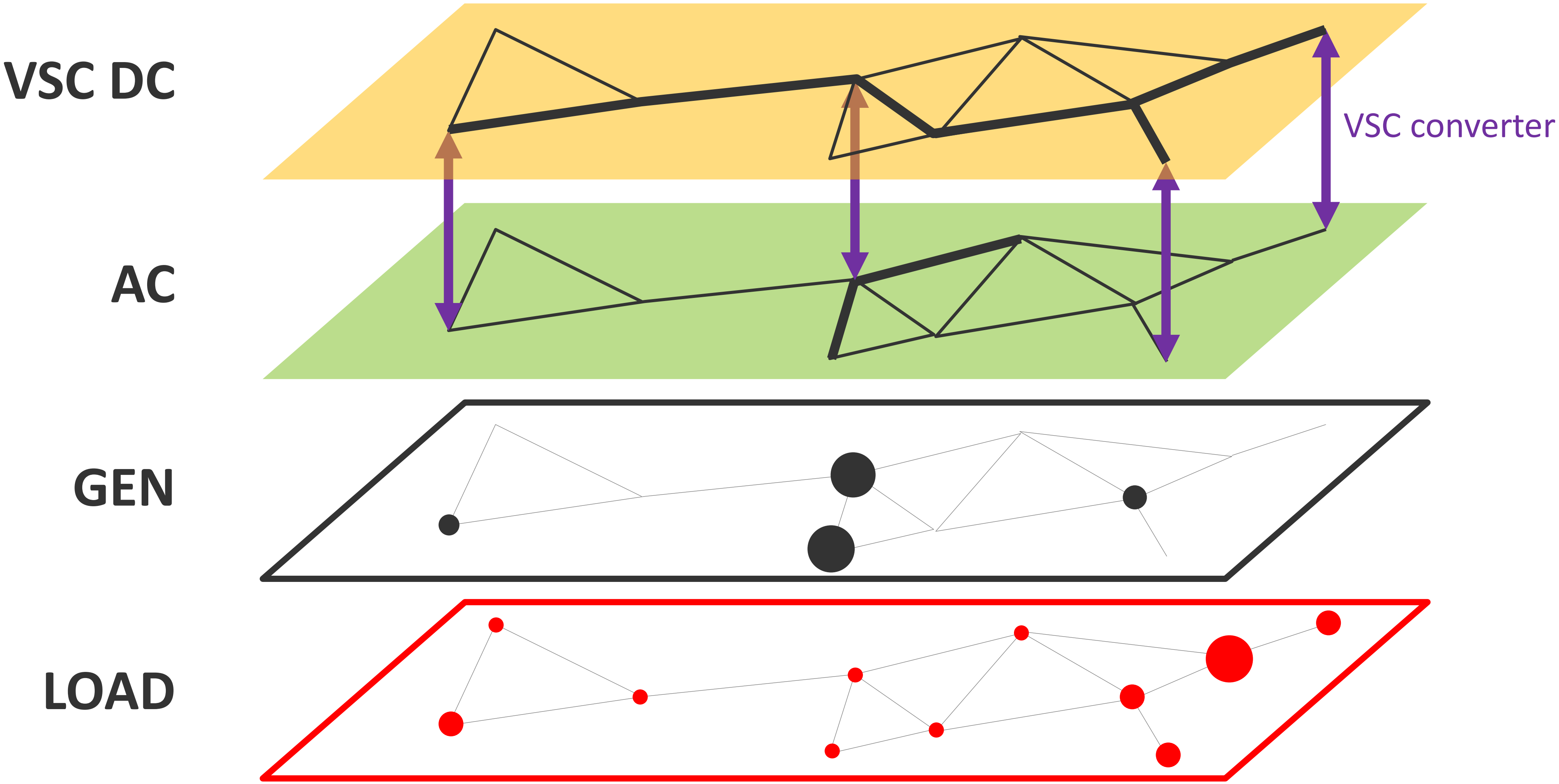


Illustrative modeling results only – do not cite

LCC vs. VSC Macrogrids

VSC (voltage-source converter):
Constant voltage source
Better for meshed network

+ Decoupled lines and converters → candidate lines can be arbitrarily short
+ Can black-start; multi-terminal compatible
– Newer technology; lower voltage; higher losses; DC breaker limitations
– More complex to model (converters = new investment variable & constraints)

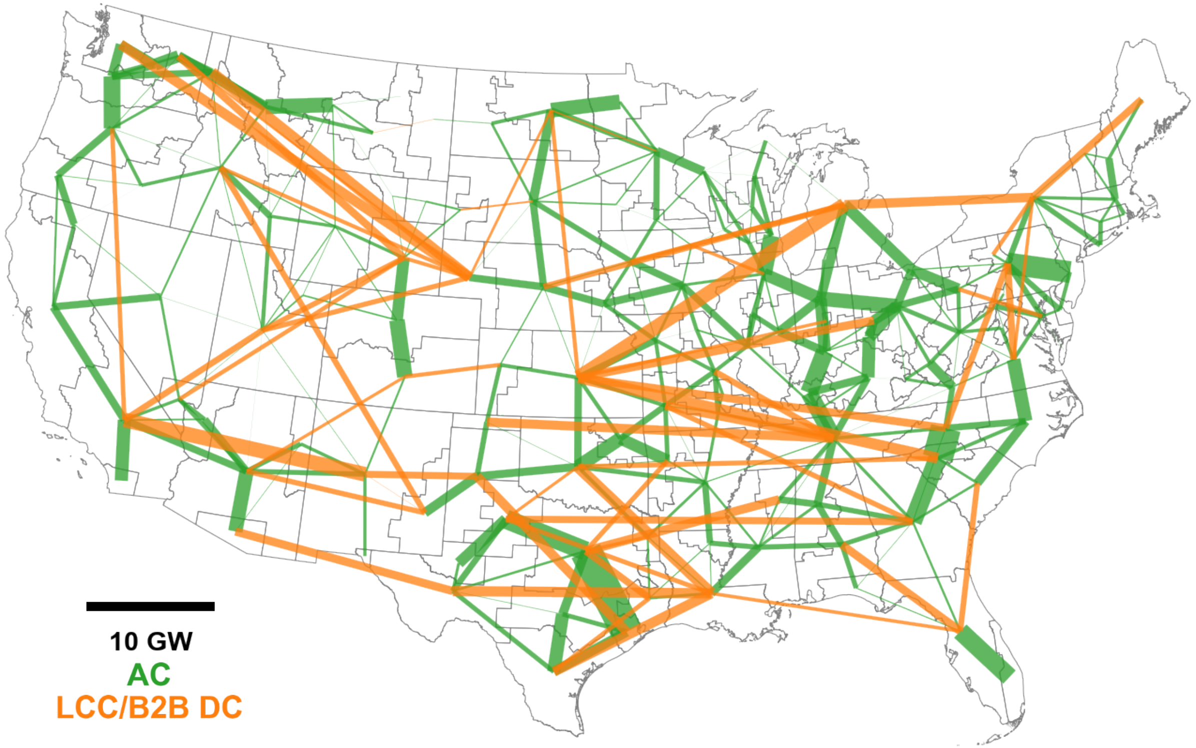


VSC Macrogrid

TRC QUESTION: Is it worthwhile to consider both LCC and VSC DC, or other high-capacity options?

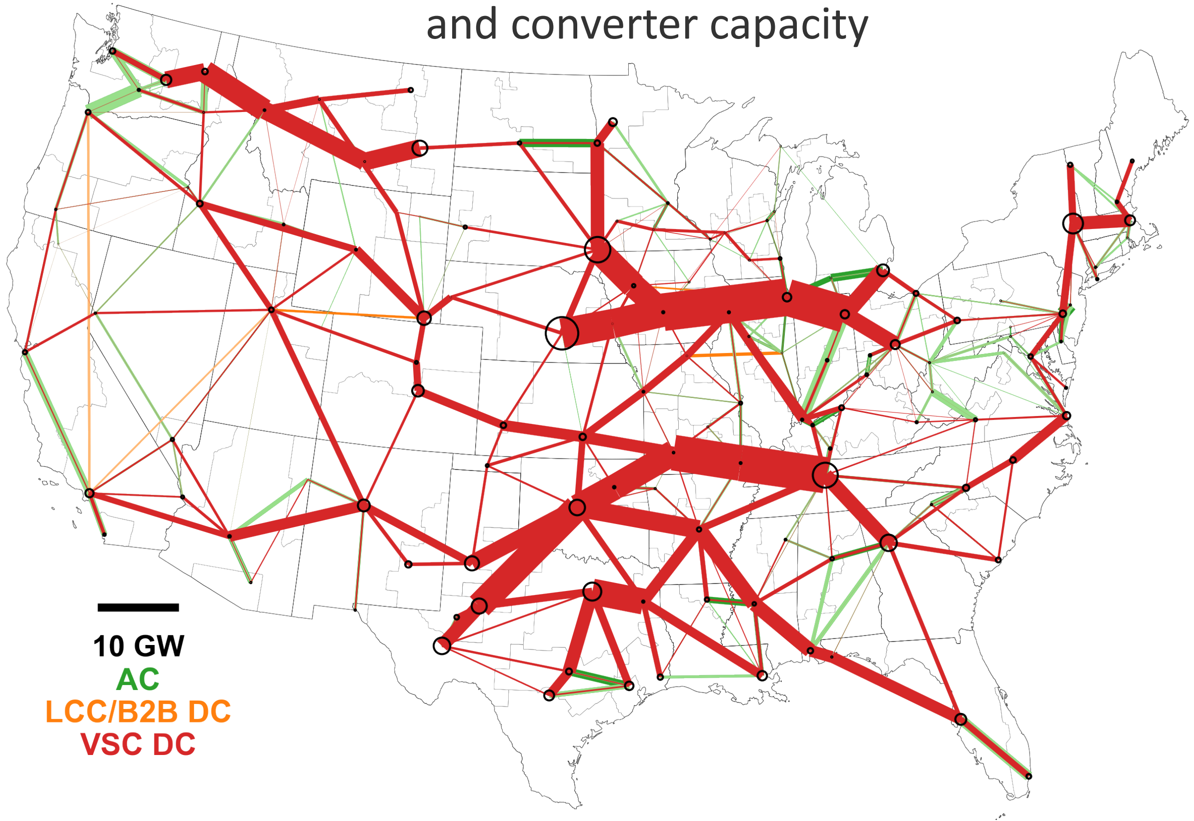
LCC

- Long, high-capacity “flyover” lines
- Iterative procedure for identifying high-value corridors in ReEDS



VSC

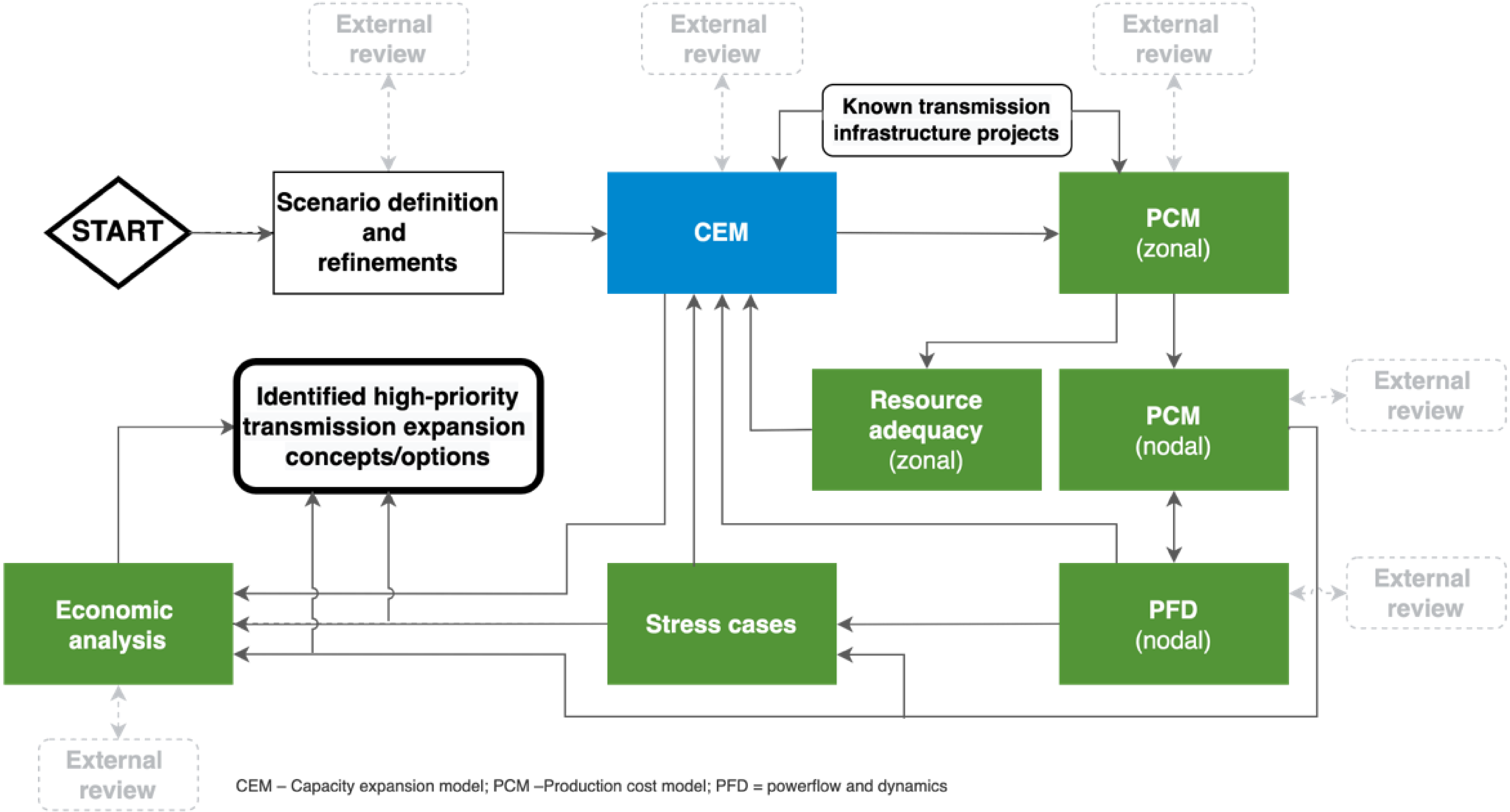
- Suitable for meshed networks; security benefits
- Independently optimize link and converter capacity



Illustrative modeling results only – do not cite

TRC QUESTION: What geographic resolution for transmission construction is needed for actionable findings? (Total TW-miles, inter-region capacities, individual lines…?)

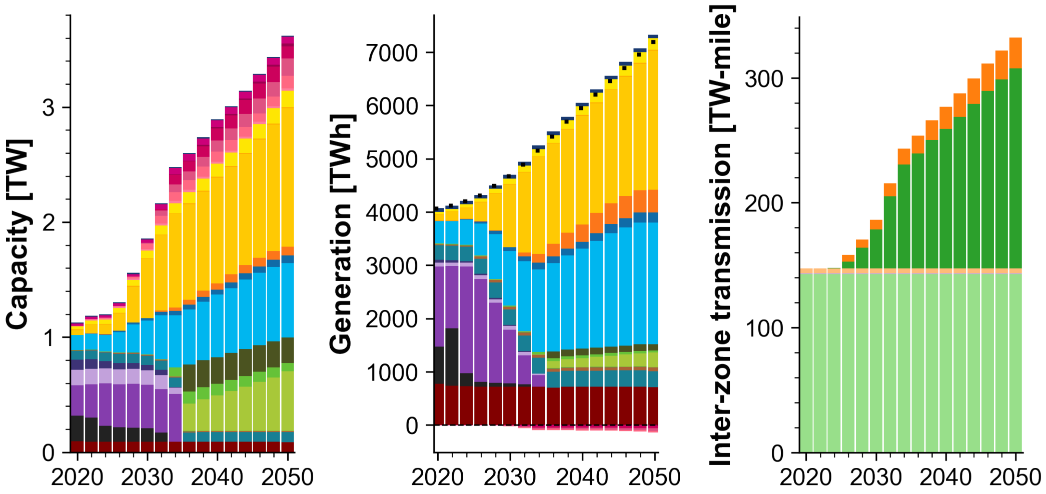
ReEDS CEM is one piece of a larger analysis framework



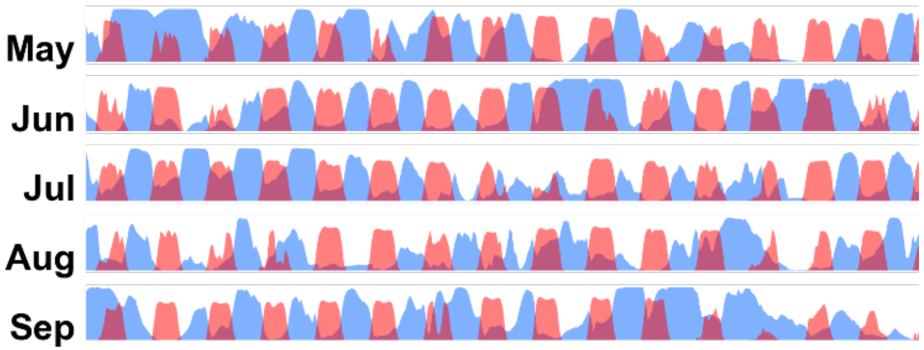
CEM – Capacity expansion model; PCM –Production cost model; PFD = powerflow and dynamics

ReEDS: Key Takeaways

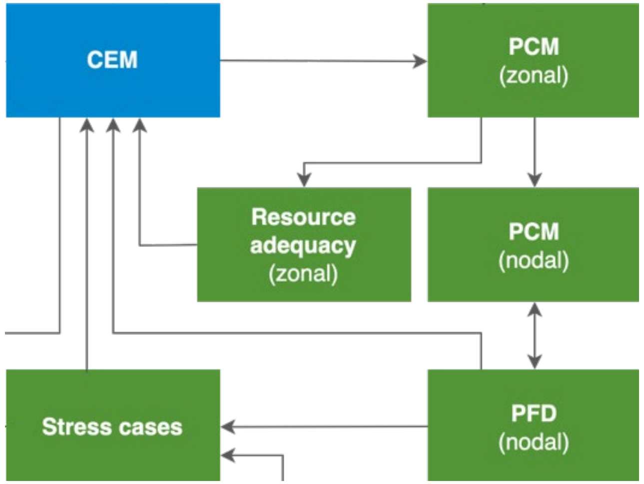
Co-optimizes generation, storage, and transmission capacity nationwide over the next 3+ decades



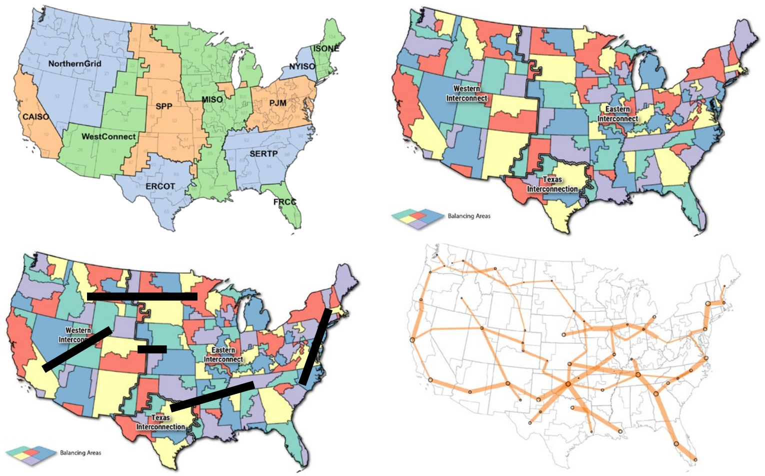
Explicit treatment of issues related to **VRE and storage**; flexible tradeoff of spatial vs. temporal resolution



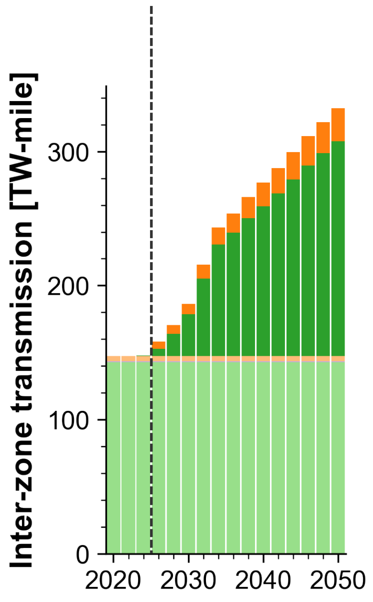
Provides **starting point** for more detailed operational models



Capable of covering a **broad range** of scenario designs & transmission topologies

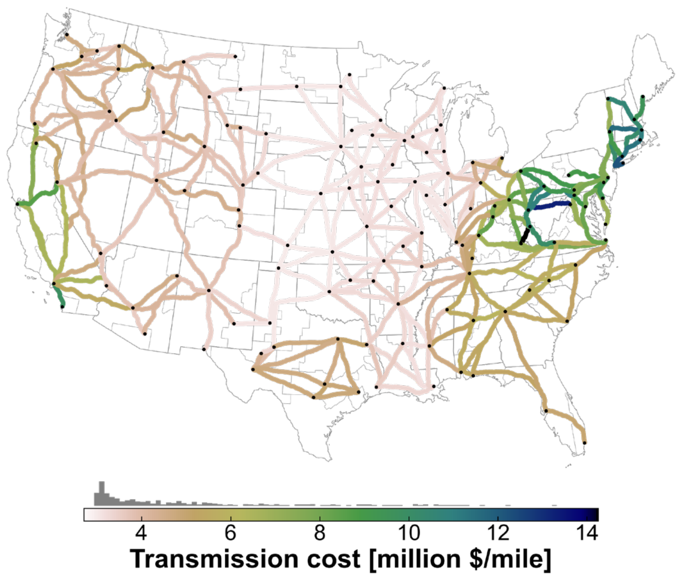


Key capacity-expansion questions for the TRC



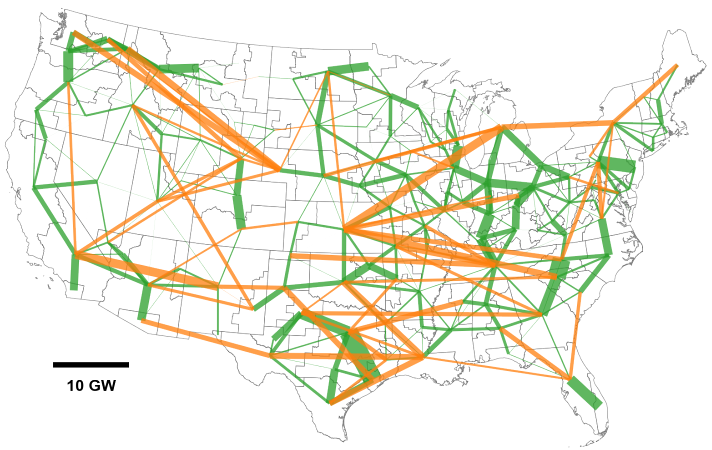
1. In what year should new, **currently unplanned** transmission capacity additions start to be allowed?

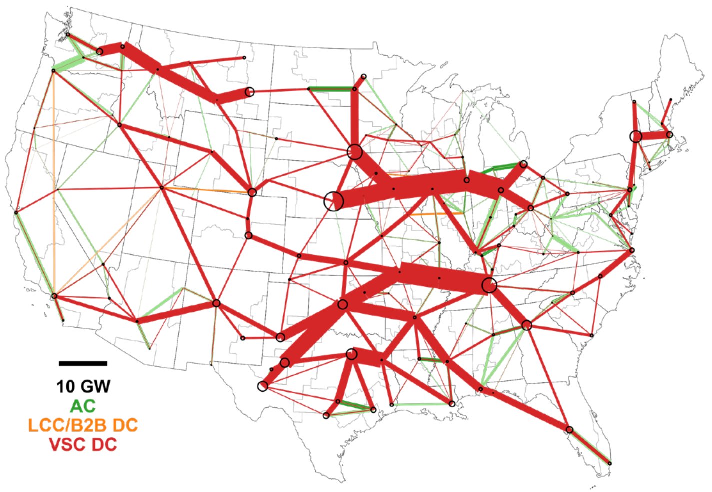
Should it depend on technology, location, or other factors?



2. Are the assumed **cost and performance** characteristics appropriate?

Are there other characteristics that should be considered?





3. Is it worthwhile to consider both **LCC** and **VSC** DC, or other high-capacity options?

4. **What geographic resolution** for transmission construction is needed for actionable findings? (Total TW-miles, inter-region capacities, individual lines…?)

Thank you

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Acronyms and Abbreviations

AC	alternating current
AEO	Annual Energy Outlook
ATB	Annual Technology Baseline
B2B	back-to-back
CC	combined cycle
CES	clean energy standard
CF	capacity factor
CSP	concentrating solar power
CT	combustion turbine
DC	direct current
DOE	U.S. Department of Energy
EASIUR	Estimating Air pollution Social Impact Using Regression model
EFS	Electrification Futures Study
EIA	Energy Information Administration
ESIG	Energy Systems Integration Group
FERC	Federal Energy Regulatory Commission
GW	gigawatts
HVDC	high-voltage direct current
InMAP	Intervention Model for Air Pollution
ITC	investment tax credit
km	kilometers
kW	kilowatts
LCC	line commutated converter
MISO	Midwest Independent System Operator
NEMS	National Energy Modeling System
NERC	North American Electric Reliability Corporation
NPV	net present value
NSRDB	National Solar Radiation Database
O-G-S	oil-gas-steam
O&M	operations and maintenance
OpRes	operating reserves
PRM	planning reserve margin
PSH	pumped storage hydro
PTC	production tax credit
PV	photovoltaics
RE	renewable energy
ReEDS	Regional Energy Deployment System model
reV	Renewable Energy Potential model
RPS	renewable portfolio standard
SAM	System Advisor Model
TRC	technical review committee
TW	terawatts
USDA	United States Department of Agriculture
VCE	Vibrant Clean Energy
VRE	variable renewable energy
VSC	voltage source converters
WTK	WIND Toolkit