NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Modeling Capabilities and Projects at NREL Related to Transmission Planning and Operation

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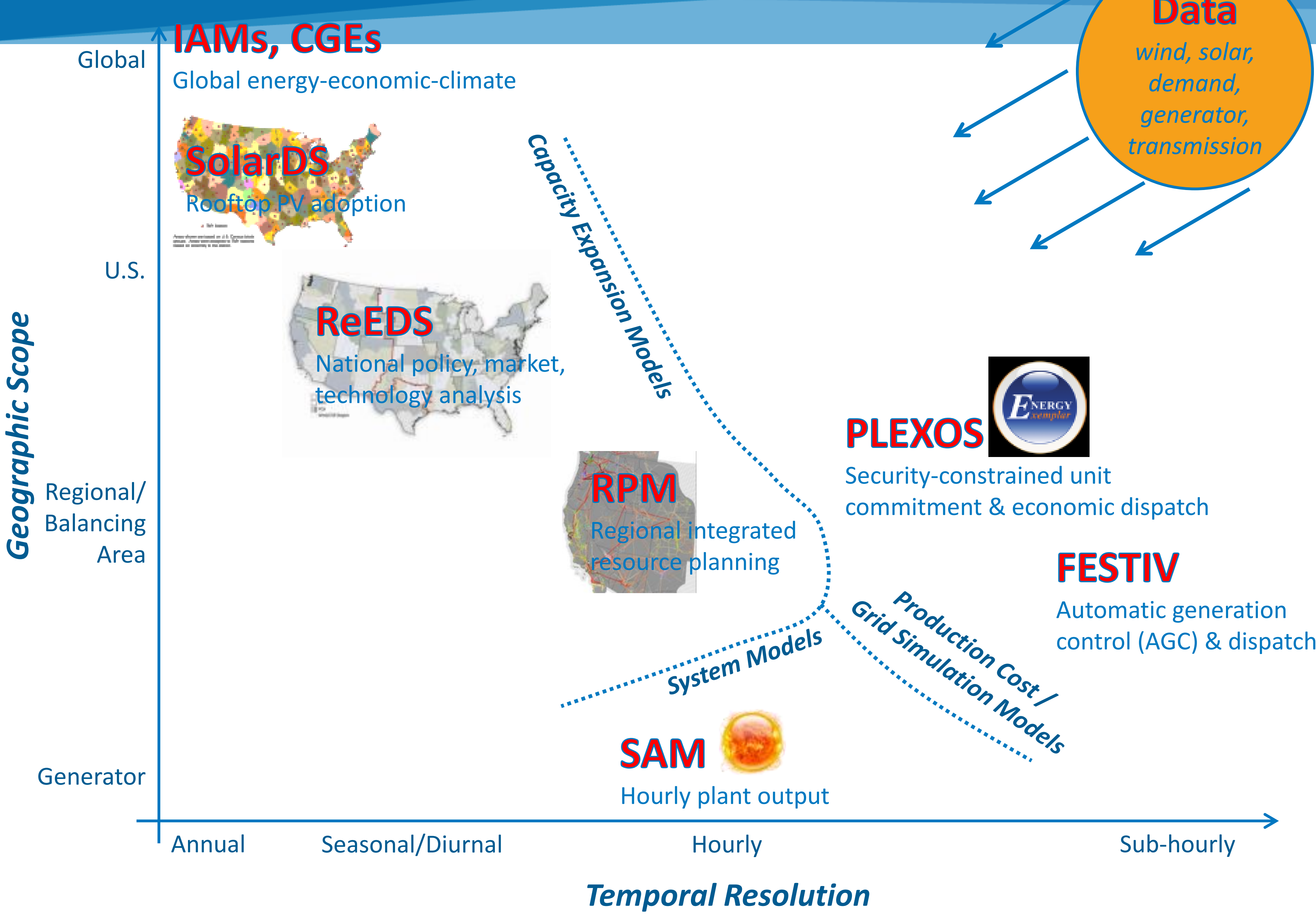
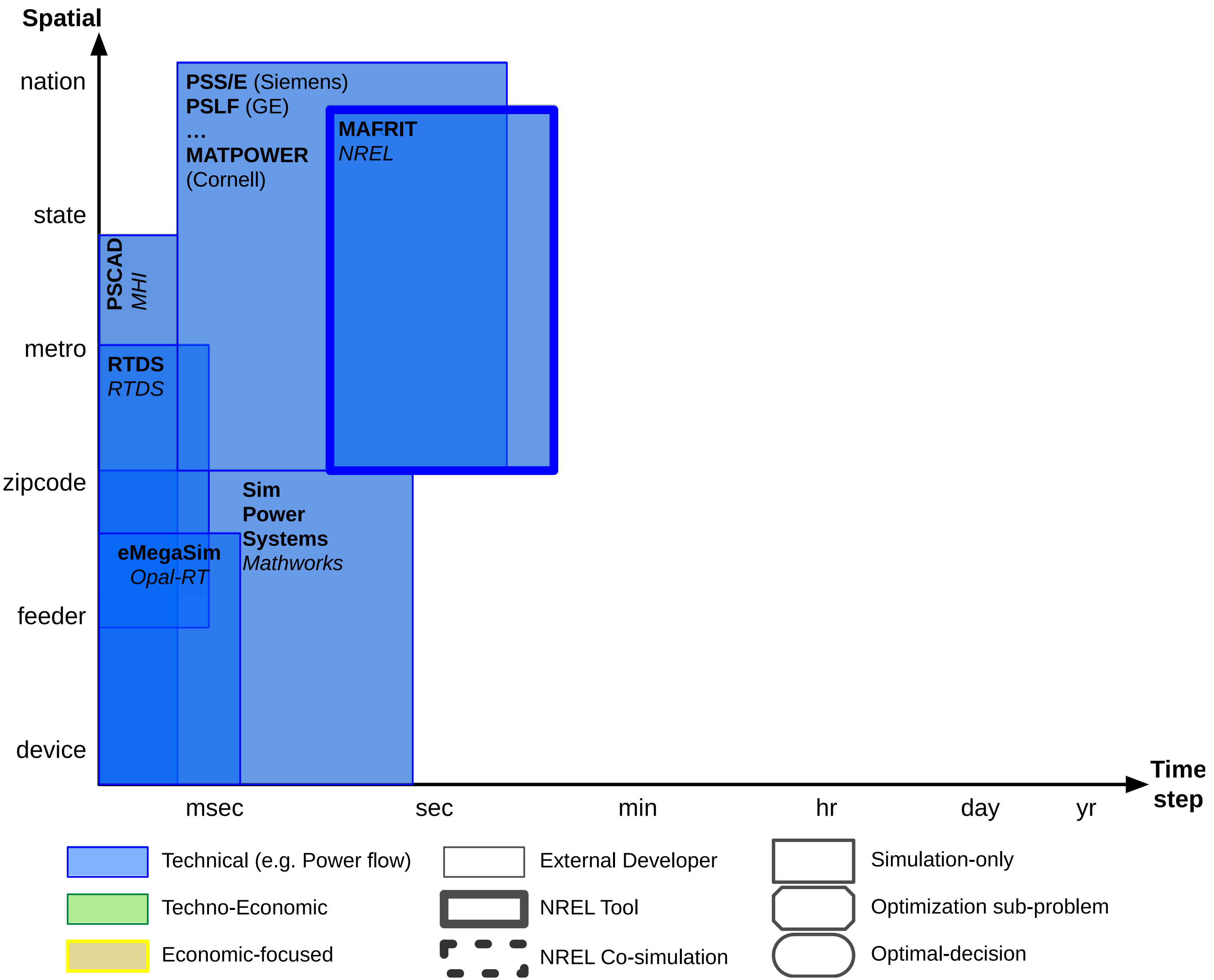
September 29, 2016

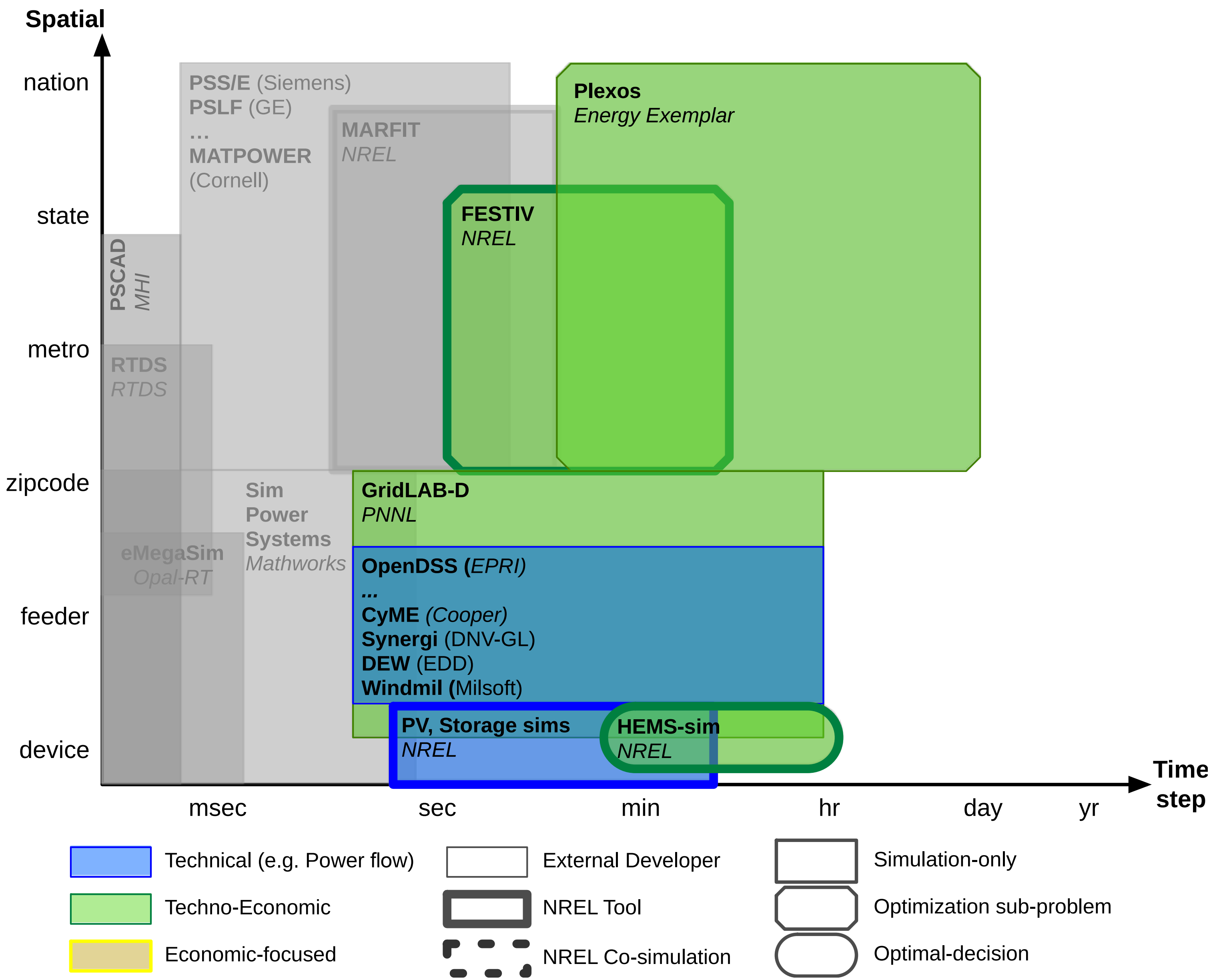
Energy Forecasting and Modeling Group



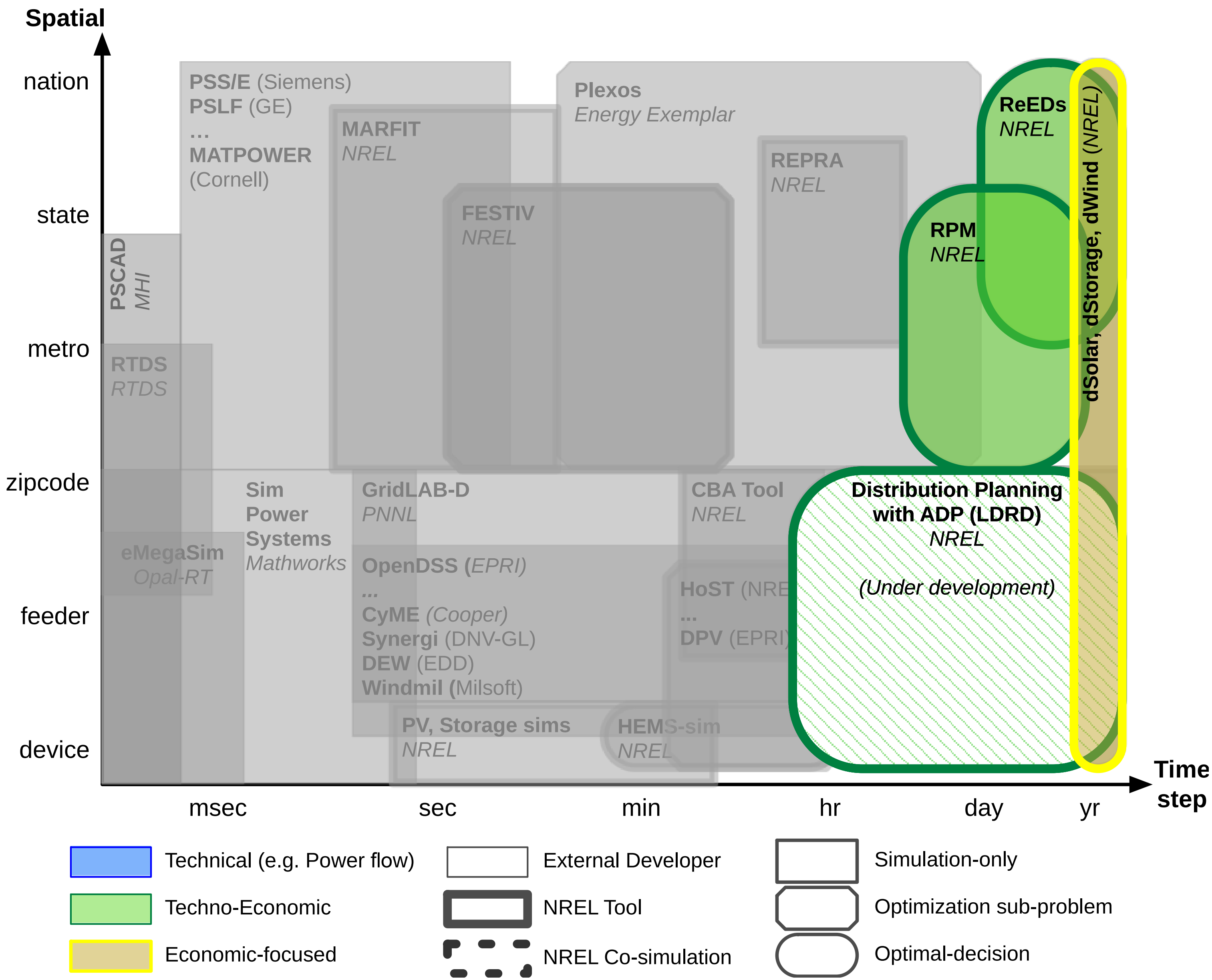
60 seconds or less



Seconds to Days



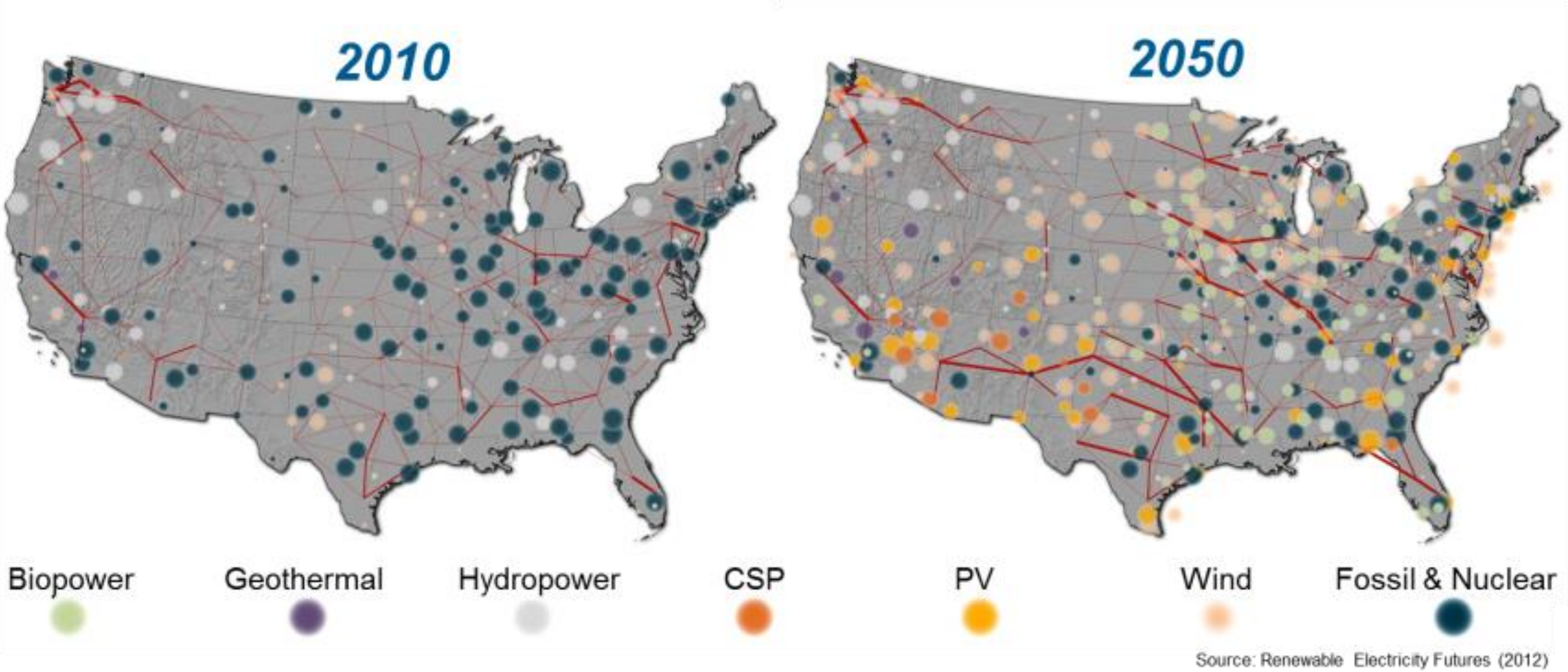
Years and decades



EFM Tools

- Capacity Expansion
  - Regional Energy Deployment System (ReEDS)
  - Resource Planning Model
  - dGen (Customer Adoption)
- Generator Dispatch & Power Flow
  - PLEXOS

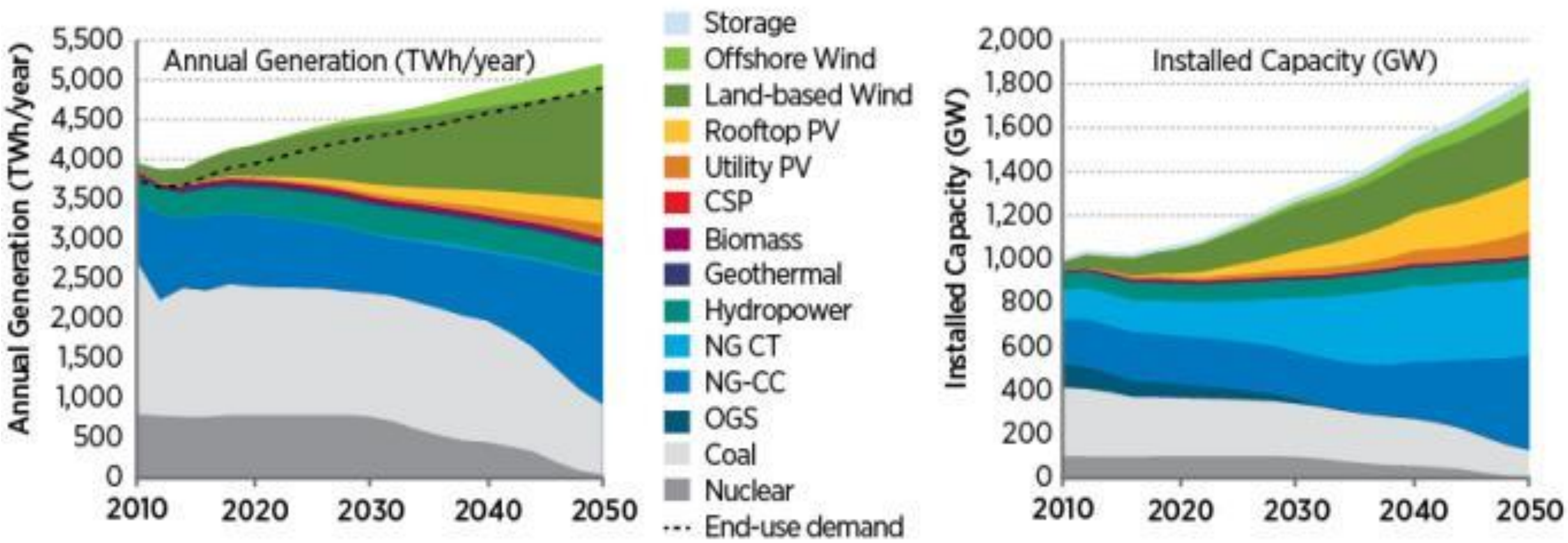
ReEDS generates scenarios of the future U.S. power system



ReEDS finds the regional mix of technologies that meet requirements of the electric sector *at least cost*.

What are the key outputs?

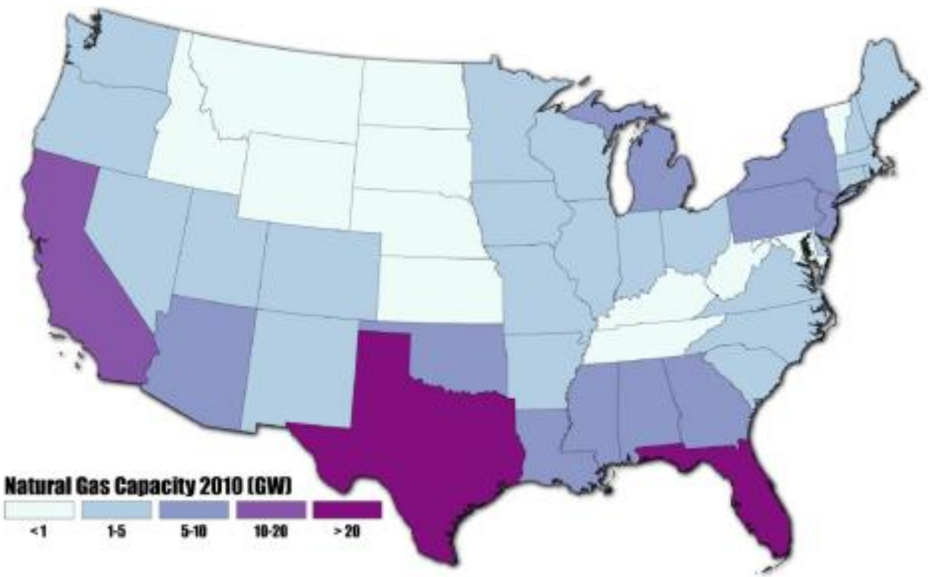
Capacity and generation evolution of all generator types

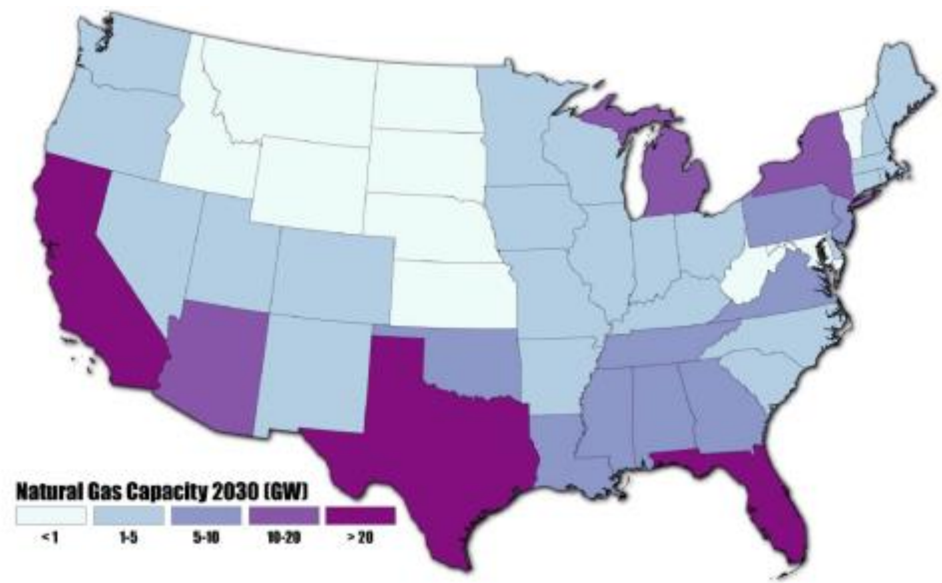


Wind Vision: A New Era for Wind Power (DOE 2015)

Capacity and generation evolution by region at high geospatial resolution

2010 → **2030**



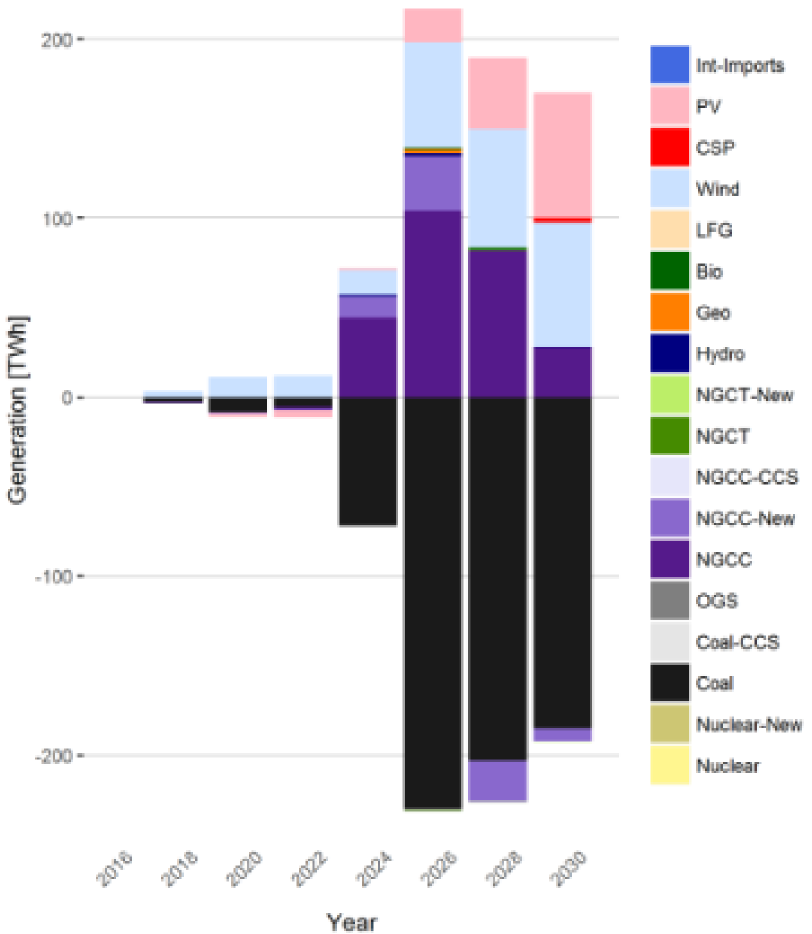


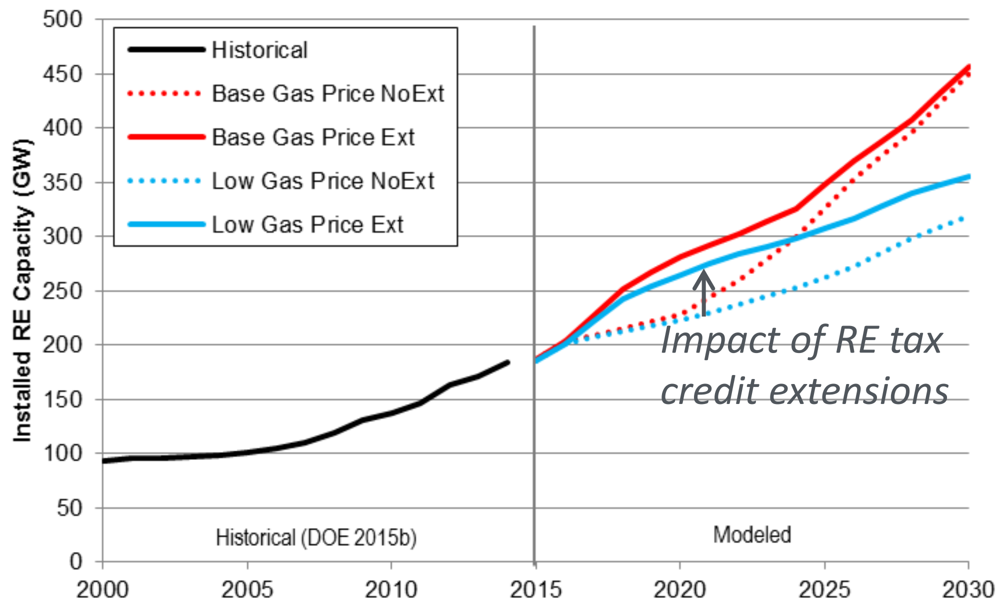
U.S. Electric Power Futures: Preliminary Results (Presentation). (Lopez et al. 2012)

What are the key outputs?

Impact of policies on clean energy deployment

Illustrative carbon regulation example

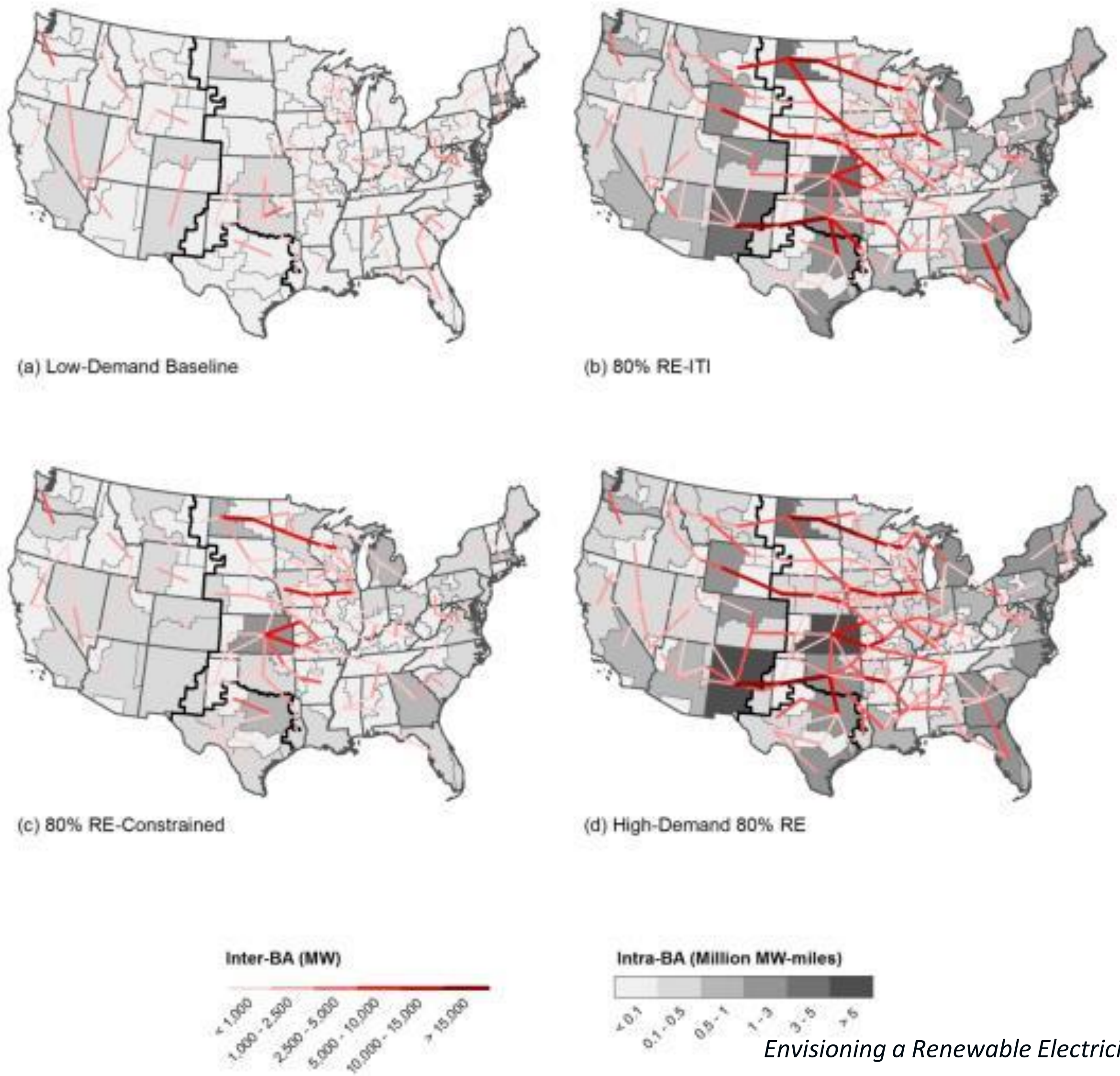




Impacts of Federal Tax Credit Extensions on Renewable Deployment and Power Sector Emissions (Mai et al. 2016)

What are the key outputs?

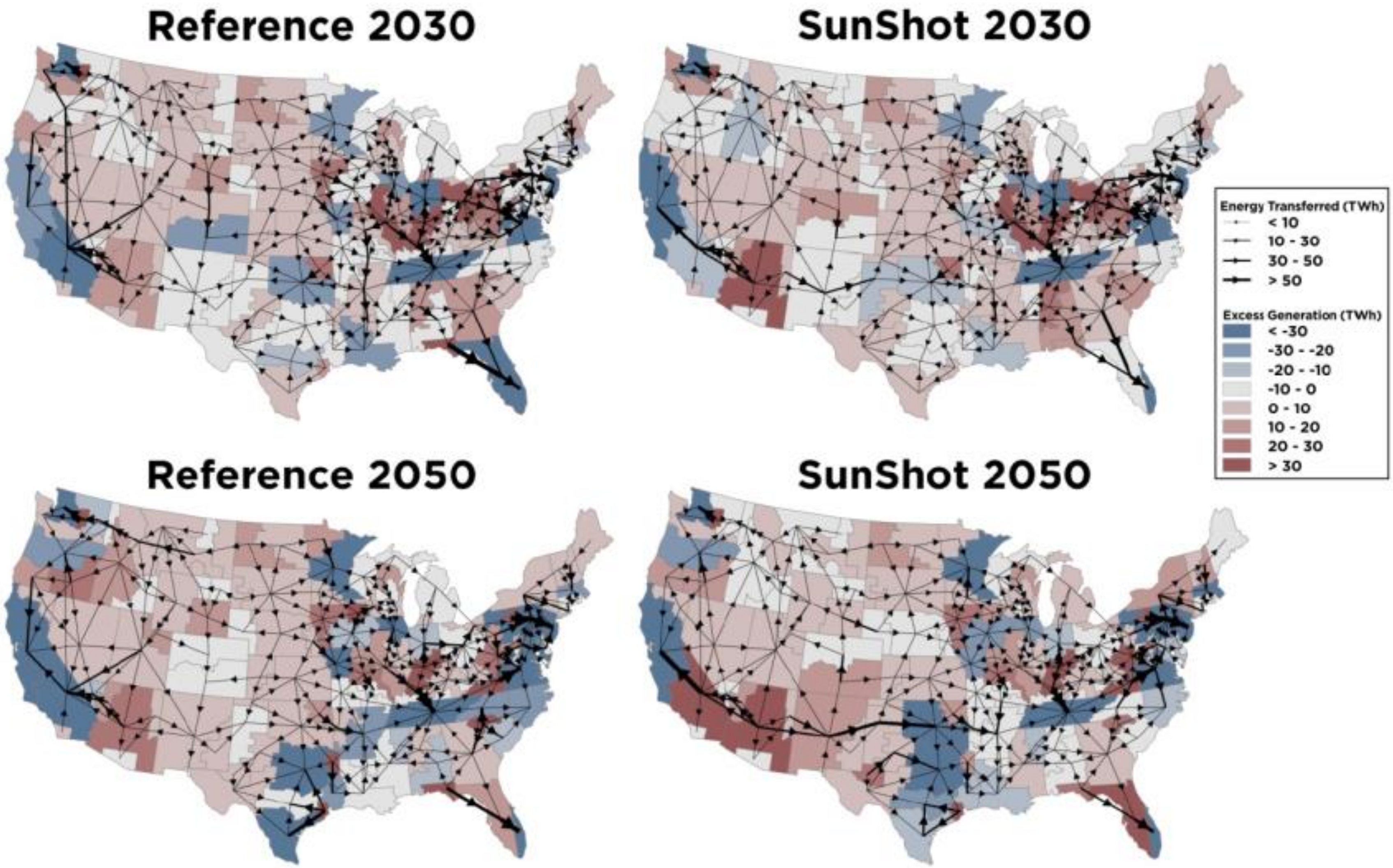
Transmission expansion



Envisioning a Renewable Electricity Future (Mai et al. 2014)

What are the key outputs?

Energy flows

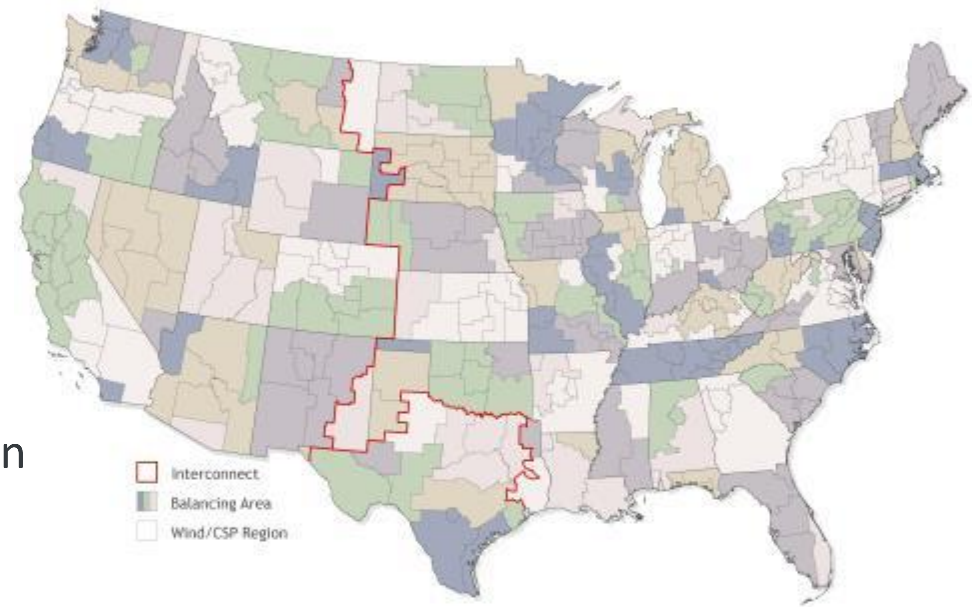


SunShot Vision Study (DOE 2012)

How does ReEDS work?

ReEDS is a spatially and temporally resolved capacity expansion model that identifies optimal scenarios for the U.S. electric sector

- High spatial resolution to represent both transmission and spatial mismatch of resource and load.
  - 134 Balancing Areas (BAs), 356 wind/CSP regions
  - 48 States, 21 “Regional Transmission Organizations” (RTOs), 13 North American Electric Reliability Corporation (NERC) regions, 3 interconnects (asynchronous networks)
- High temporal resolution to represent seasonal and diurnal variations in load and resources.
  - 17 time-slices for each year
- Statistical consideration of integration issues due to variability and uncertainty of RE supply.



Optimization details

- ReEDS is a sequential optimization, solving every two years from 2010 to 2050 (21 modeled years).
- For each year, ReEDS finds the regional mix of technologies that meet requirements of the electric sector *at least cost*. Primary requirements include:
  - Regional *load balancing* requirements
  - Regional *planning reserve* requirements
  - Regional *operating reserve* requirements
  - Policy requirements (e.g. RPS, CPP)

Ensures resource adequacy

- In addition to these *constraints*, ReEDS includes:
  - Technology-specific regional resource constraints
  - Transmission constraints
  - Other physical constraints, etc.

Technologies in ReEDS

- Conventionals (fossil & nuclear):
  - Coal (pulverized, IGCC, & IGCC-CCS)
  - Natural Gas (combustion turbine, combined cycle, & CC-CCS)
  - Oil and Gas steam (no new construction)
  - Nuclear
- Renewables:
  - Biomass (dedicated, cofired, & landfill-gas/MSW)
  - Geothermal (hydrothermal, near-field EGS, & deep EGS)
  - Hydropower (existing, upgrades, non-powered dams, new stream-reach)
  - Marine Hydrokinetic (wave)
  - Solar (CSP & PV; distributed PV separate)
  - Wind (land-based & offshore)
- Storage: pumped hydropower storage, CAES, batteries
- Demand-side techs: plug-in hybrid/electric vehicles (PHEVs), thermal energy storage in buildings, interruptible load

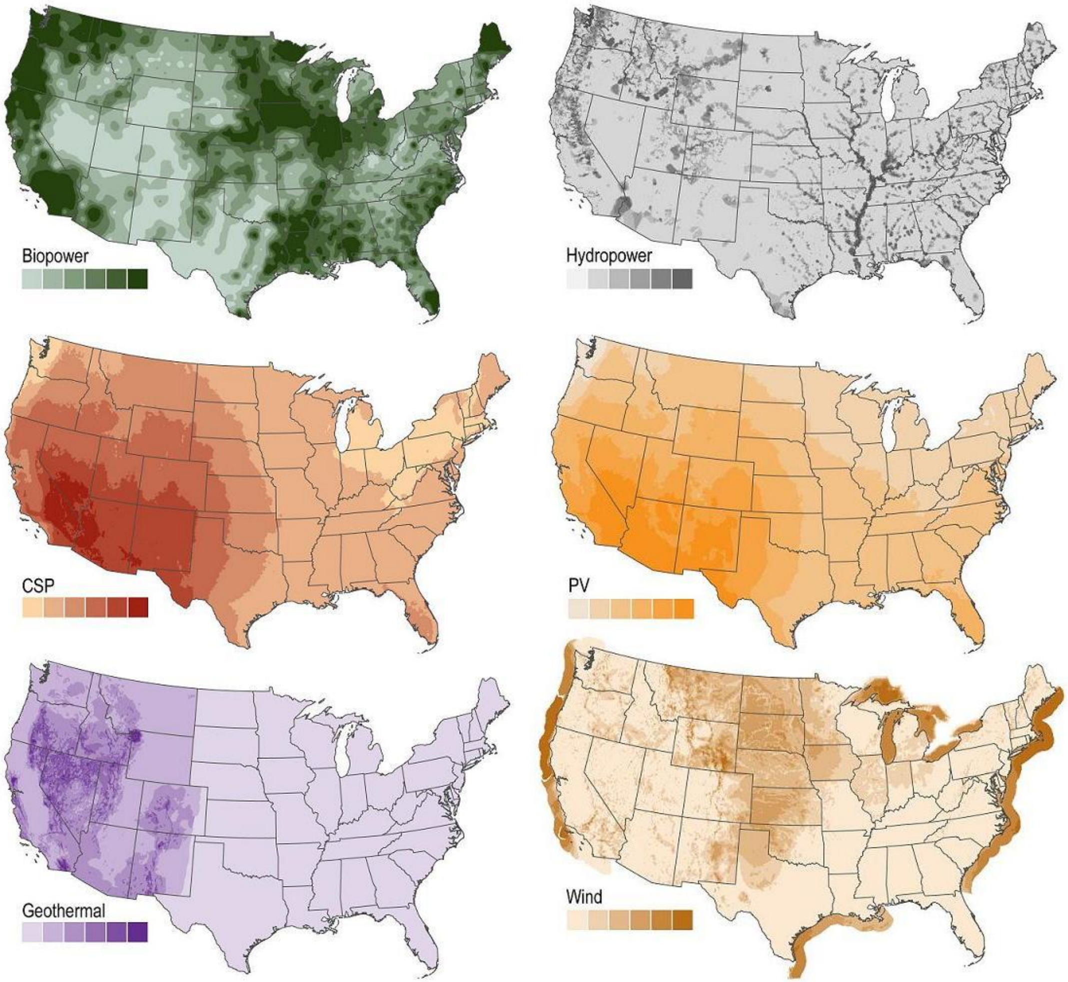
Emphasis on renewable energy

Highly resolved RE resource representations:

- Resource quality.
- Accessibility and other development costs.

Statistical representation of variable resource availability.

- Capacity value: contribution to planning reserves
- Induced operating reserves: additional reserves necessary due to forecast error
- Curtailments: unusable RE due to insufficient load



NREL RE Resource Maps

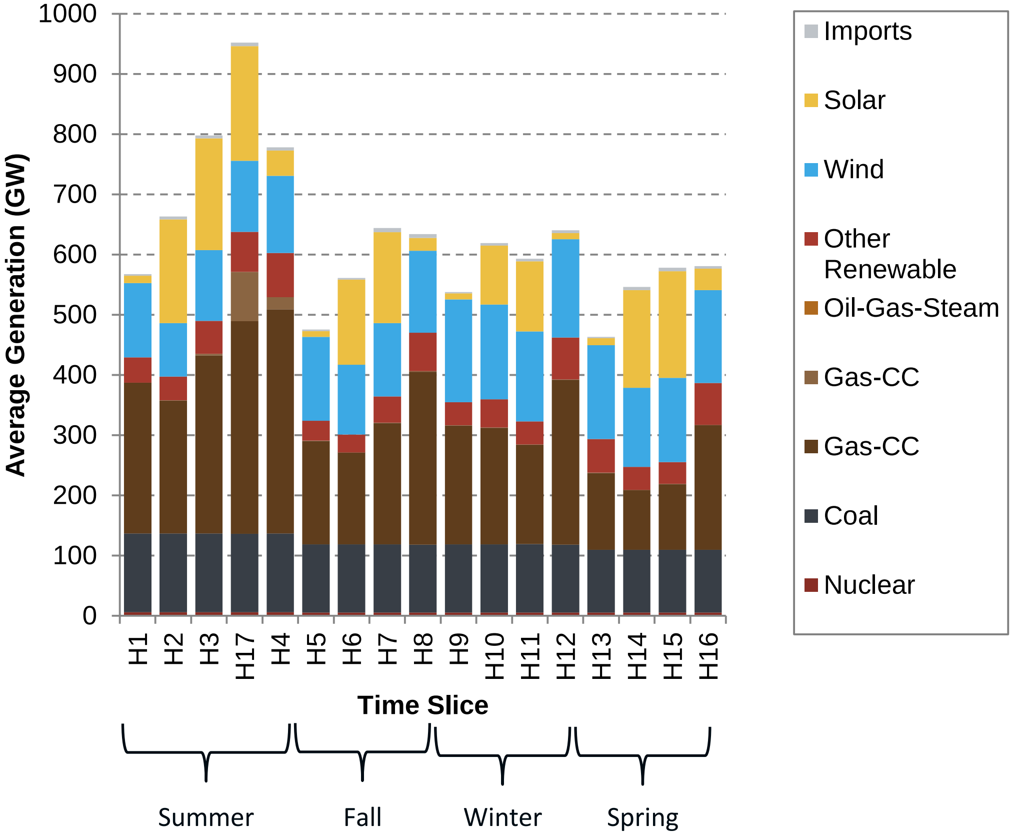
Can be applied to any location-specific resource

Reduced-form dispatch

Seventeen time-slices: four seasons x four diurnal + one superpeak representing the top 40 hours of load in a year.

Aggregated capacity by technology with stylized flexibility parameters: minimum turndown, but no startup or shutdown, flat heat rate.

Constraints guarantee adequacy requirements and ancillary services in each time slice.



Illustrative example

Transmission representation

Linear DC-power-flow representation.

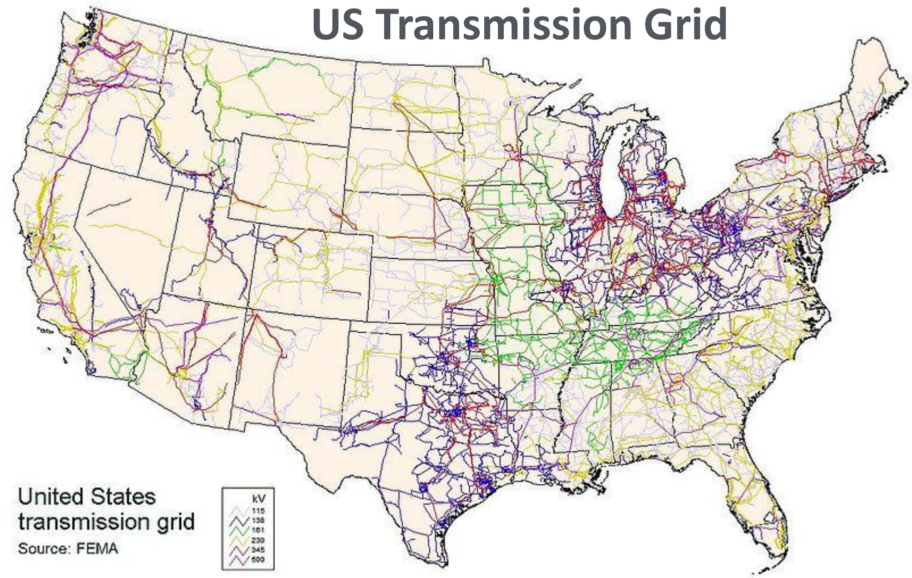
Transmission network is reduced to ~300 aggregate lines, characterized by nominal carrying capacity.

Three interconnects.

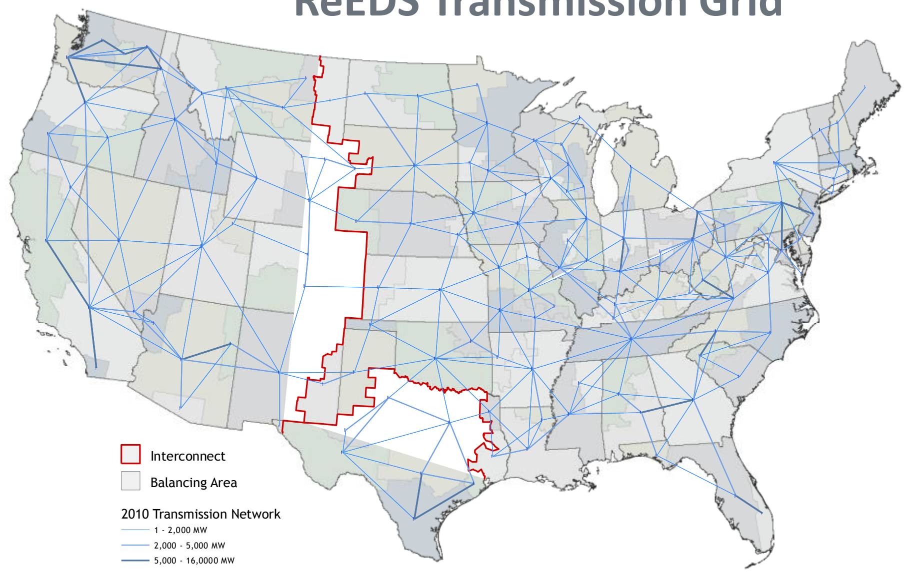
- WECC: 35 nodes, 72 AC, 2 DC lines
- East: 92 nodes, 213 AC lines
- ERCOT: 7 nodes, 12 AC lines
- 9 AC-DC-AC interconnect interties

Additional (intra-BA) spur-line transmission needs are also accounted for in ReEDS for wind, CSP, and PV. These needs affect the resource accessibility and effective project costs by region.

US Transmission Grid

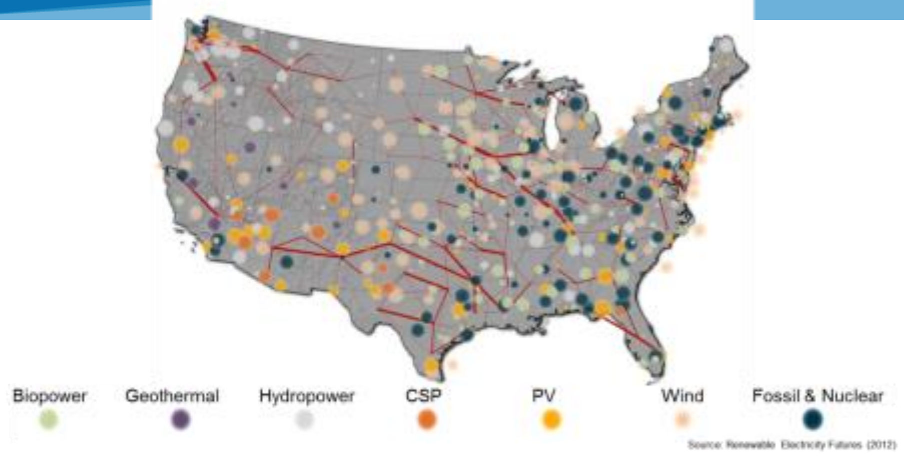


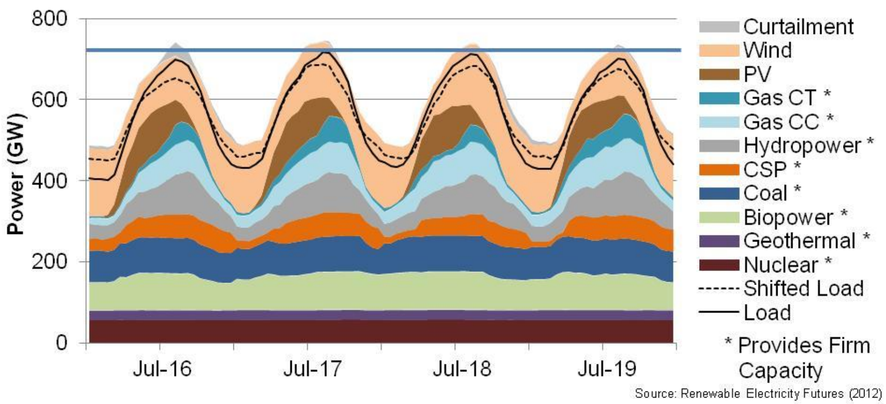
ReEDS Transmission Grid



Renewable Electricity Futures Study

Contact: Trieu.Mai@nrel.gov





National Renewable Energy Laboratory. (2012). Renewable Electricity Futures Study. Hand, M.M.; Baldwin, S.; DeMeo, E.; Reilly J.M.; Mai, T.; Arent, D.; Porro, G.; Meshek, M.; Sandor, D. eds. 4 vols. NREL/TP-6A20-52409. Golden, CO.

www.nrel.gov/analysis/re_futures

Methodology: ReEDS and SolarDS capacity expansion models used to develop high RE scenarios in the U.S. (and estimate associated cost/benefits); GridView production cost model used to evaluate hourly operability of 80%-by-2050 scenarios.

Key Findings:

- Renewable electricity generation from technologies that are commercially available today, in combination with a more flexible electric system, is more than adequate to supply 80% of total U.S. electricity generation in 2050–while meeting electricity demand on an hourly basis in every region of the country.
- Increased electric system flexibility, needed to enable electricity supply-demand balance with high levels of renewable generation, can come from a portfolio of supply- and demand-side options, including flexible conventional generation, grid storage, new transmission, more responsive loads, and changes in power system operations.
- The abundance and diversity of U.S. renewable energy resources can support multiple combinations of renewable technologies that result in deep reductions in electric sector greenhouse gas emissions and water use.
- The direct incremental cost associated with high renewable generation is comparable to published cost estimates of other clean energy scenarios. Improvement in the cost and performance of renewable technologies is the most impactful lever for reducing this incremental cost.

Resource Planning Model (RPM)

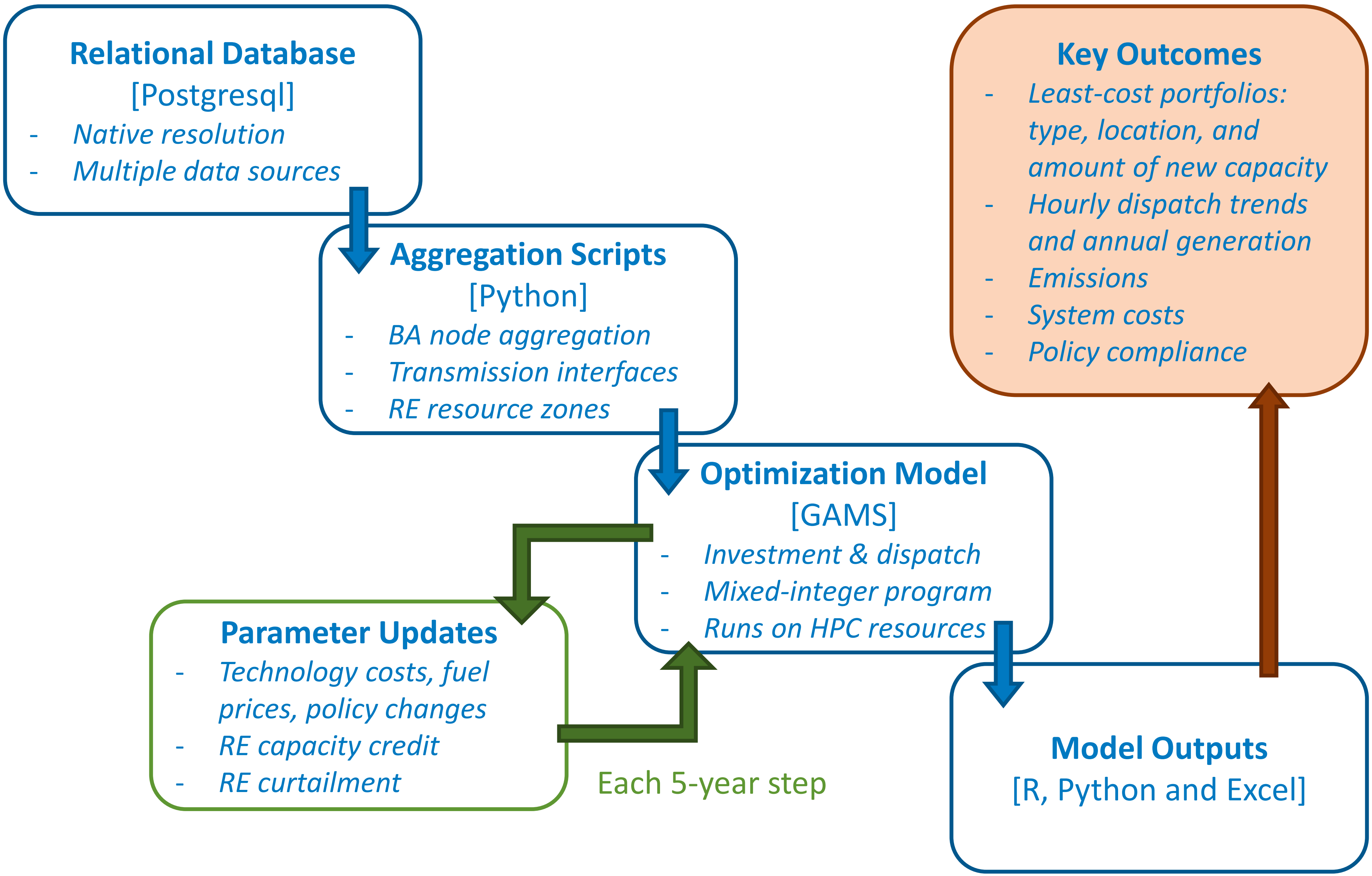
Capacity expansion model for a *regional* electric system over a utility planning horizon (through 2030).

Key features:

- Hourly chronological dispatch and detailed system operation representation
- High spatial resolution informs generator siting options, particularly for renewable resources
- Flexible data structure to develop models for customized regions
- *New*: Models the cost and value of storage and other enabling technologies

http://www.nrel.gov/analysis/models_rpm.html

RPM: model structure and flow

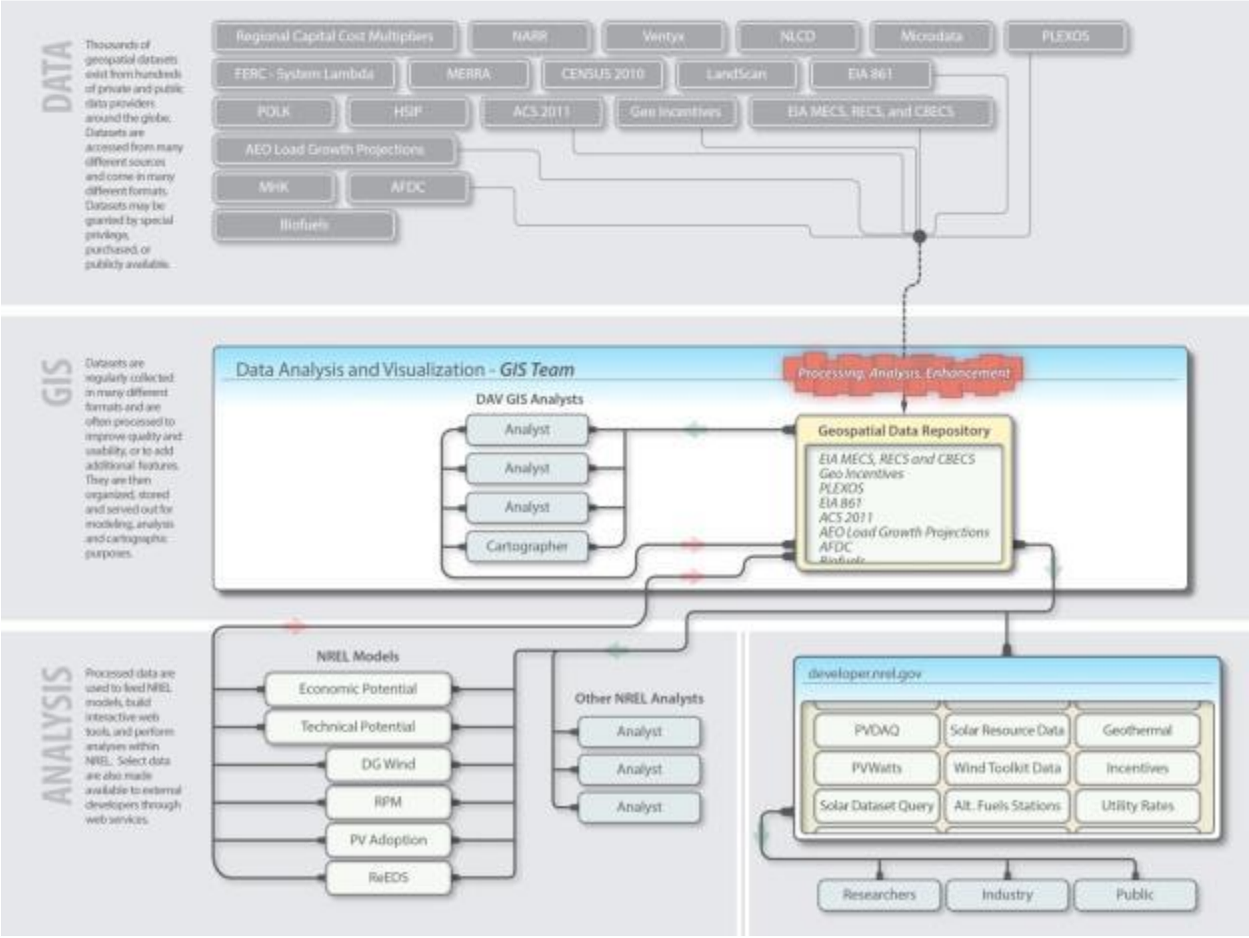


Relational database

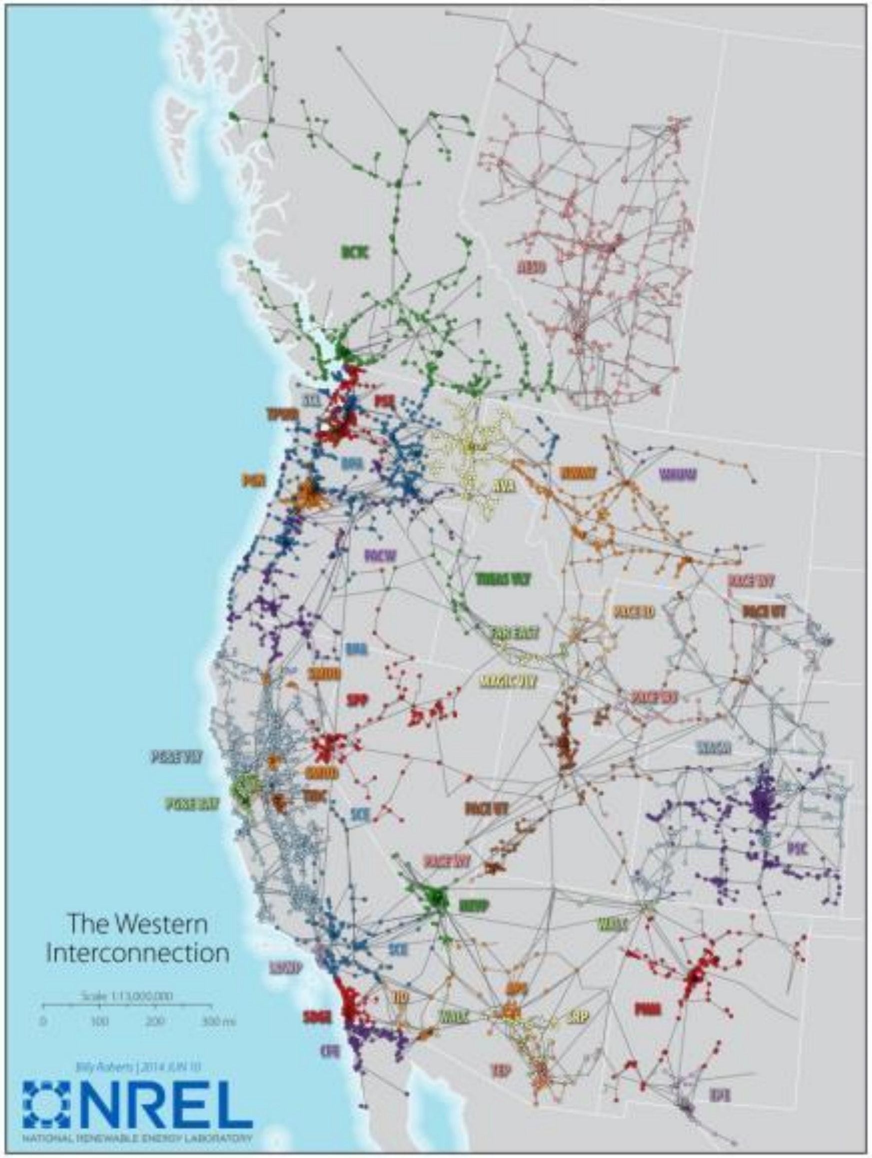
RPM pulls from many data sources within the framework:

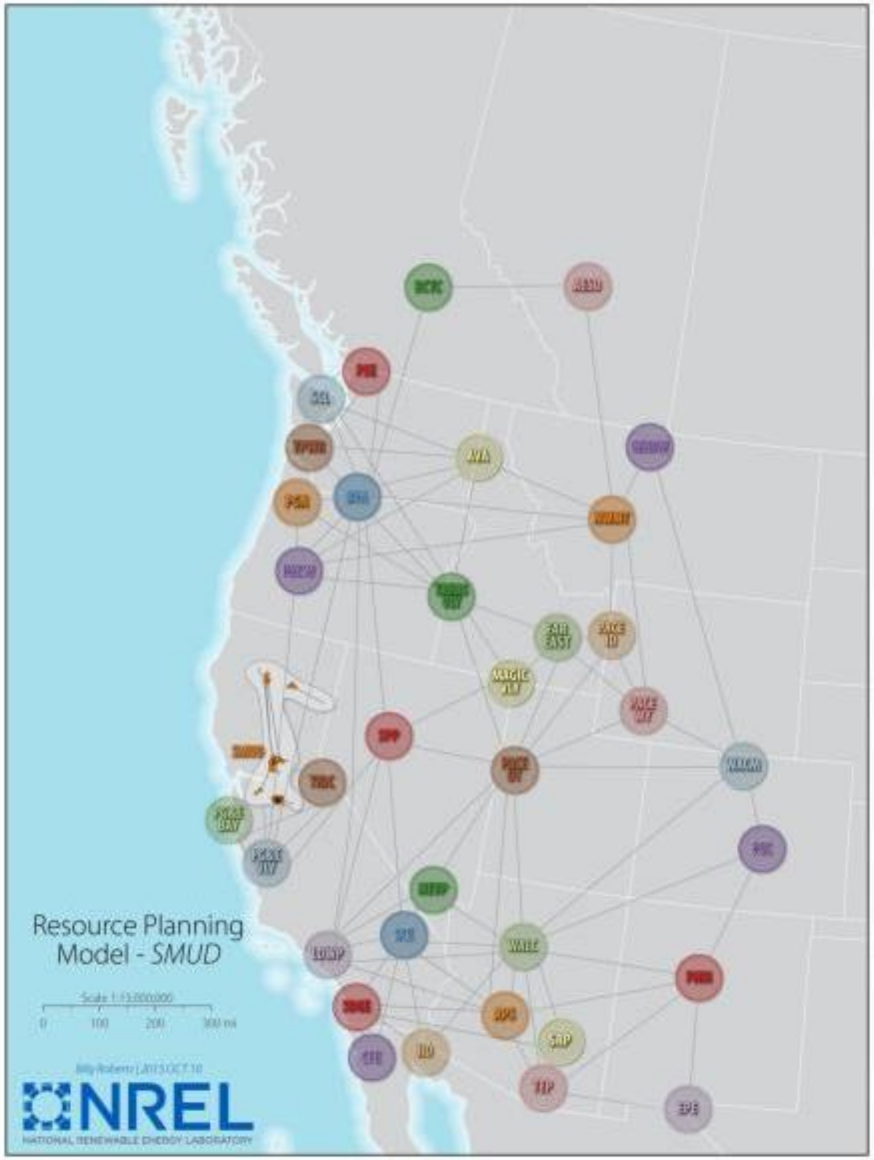
- WECC TEPPC
- NREL Technical Potential
- NSRDB (Solar)
- WWSIS (Wind)
- EIA Annual Energy Outlook
- ABB Velocity Suite
- NREL Annual Technology Baseline
- NREL Regional Energy Deployment System
- Energy Exemplar / NREL PLEXOS data

RPM exists within the larger GIS relational database framework



RPM is a mixed nodal/zonal model

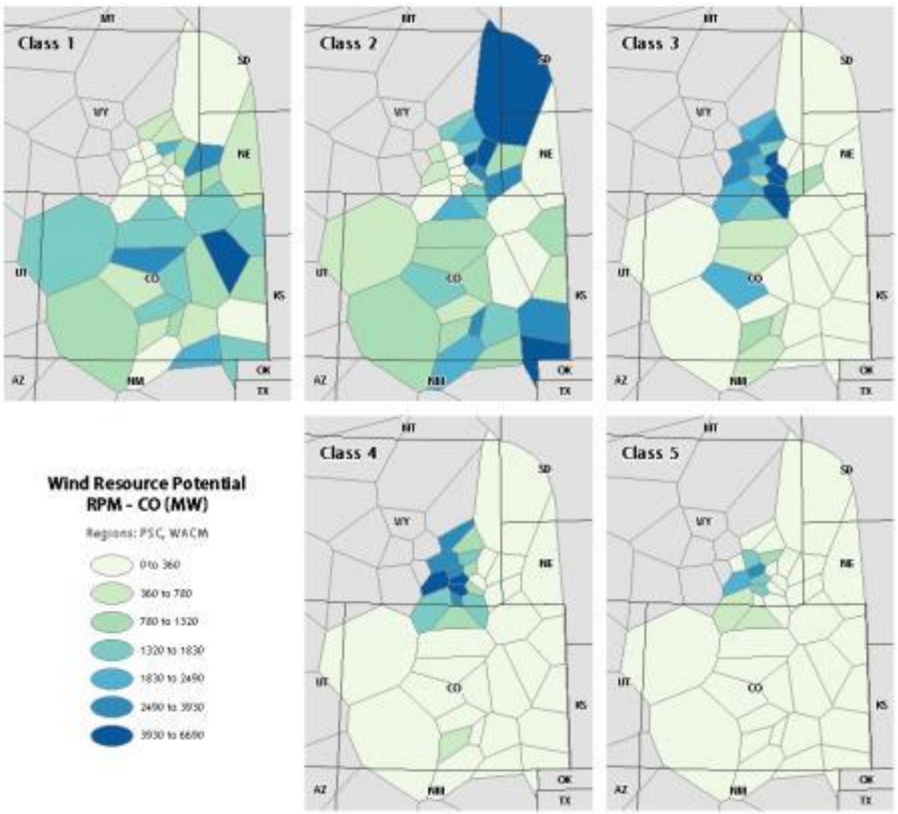




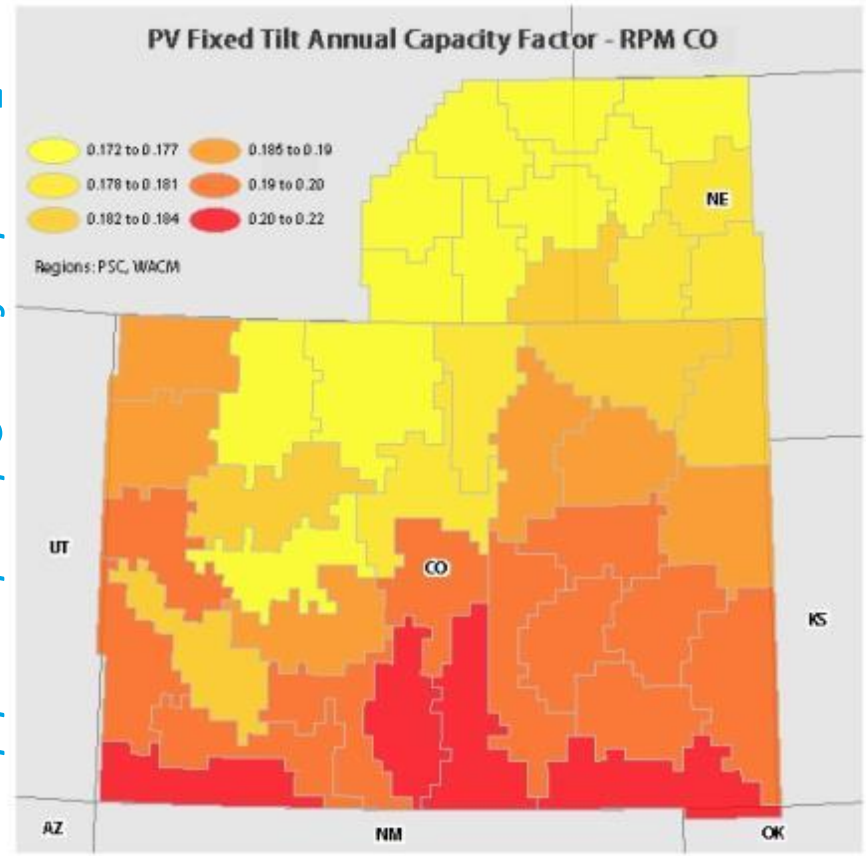
Models with different "focus regions" can be developed using the same flexible data platform

Recent and current analyses are targeted toward regions in the Western Interconnection, but a version for the East is under development

High spatial resolution modeling to accurately represent renewable resource potential and quality



Examples from Colorado model



Clustering techniques are applied to develop renewable resource zones that have similar output characteristics. Each zone is characterized by:
(1) resource potential, (2) hourly profiles, and (3) grid interconnection costs

Simultaneous investment and dispatch

Unlike traditional load duration curve-based capacity planning, RPM's optimization simultaneously models detailed economic dispatch and investment decisions

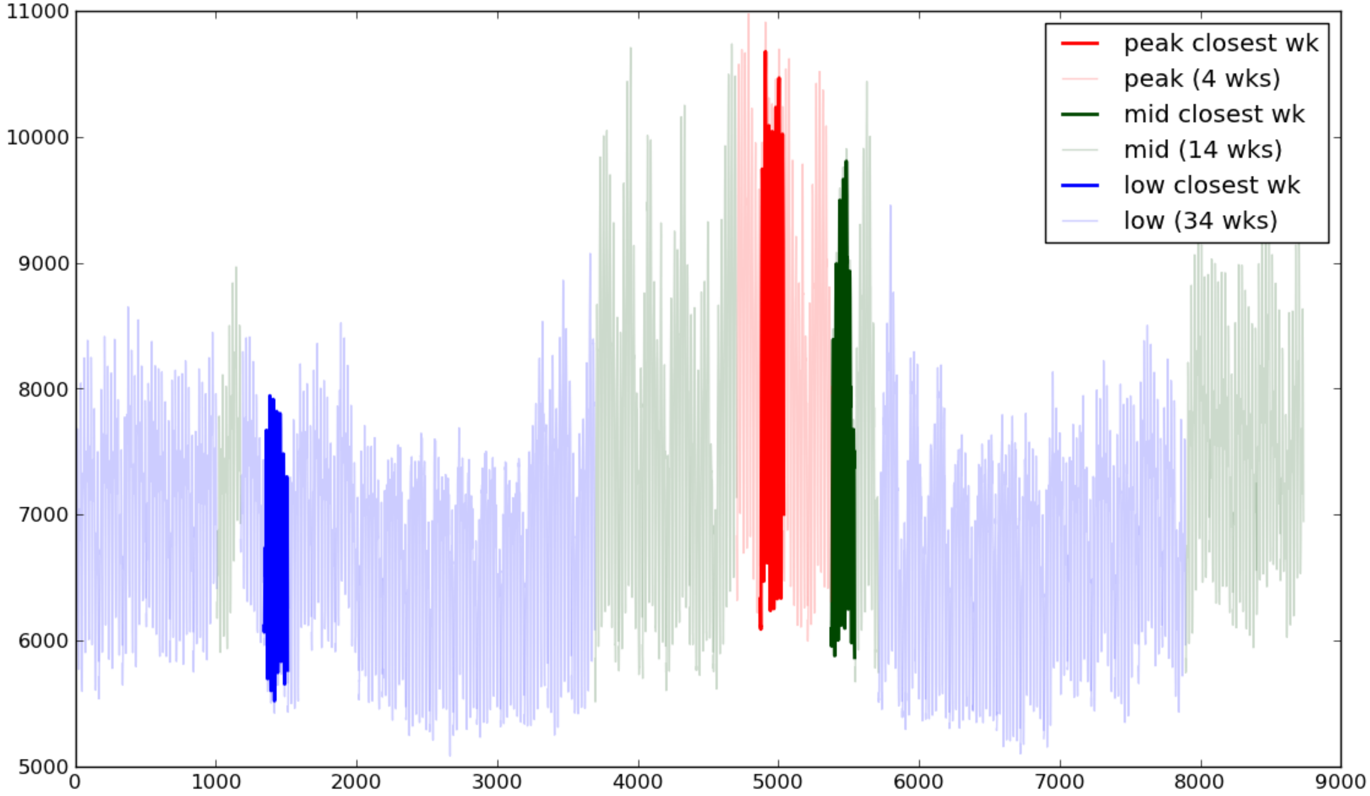
Dispatch model features / options:

- Chronological hourly dispatch for sampled dispatch periods
- Mixed integer linear programming to model unit commitment
- Security constrained dispatch: co-optimized energy and reserves (spin, regulation, flex)
- Unit-specific parameters and constraints, e.g., ramp rates, heat rates, minimum generation
- Linearized DC power flow transmission model

Models existing policies: RE tax credits, Clean Power Plan, Renewable Portfolio Standards

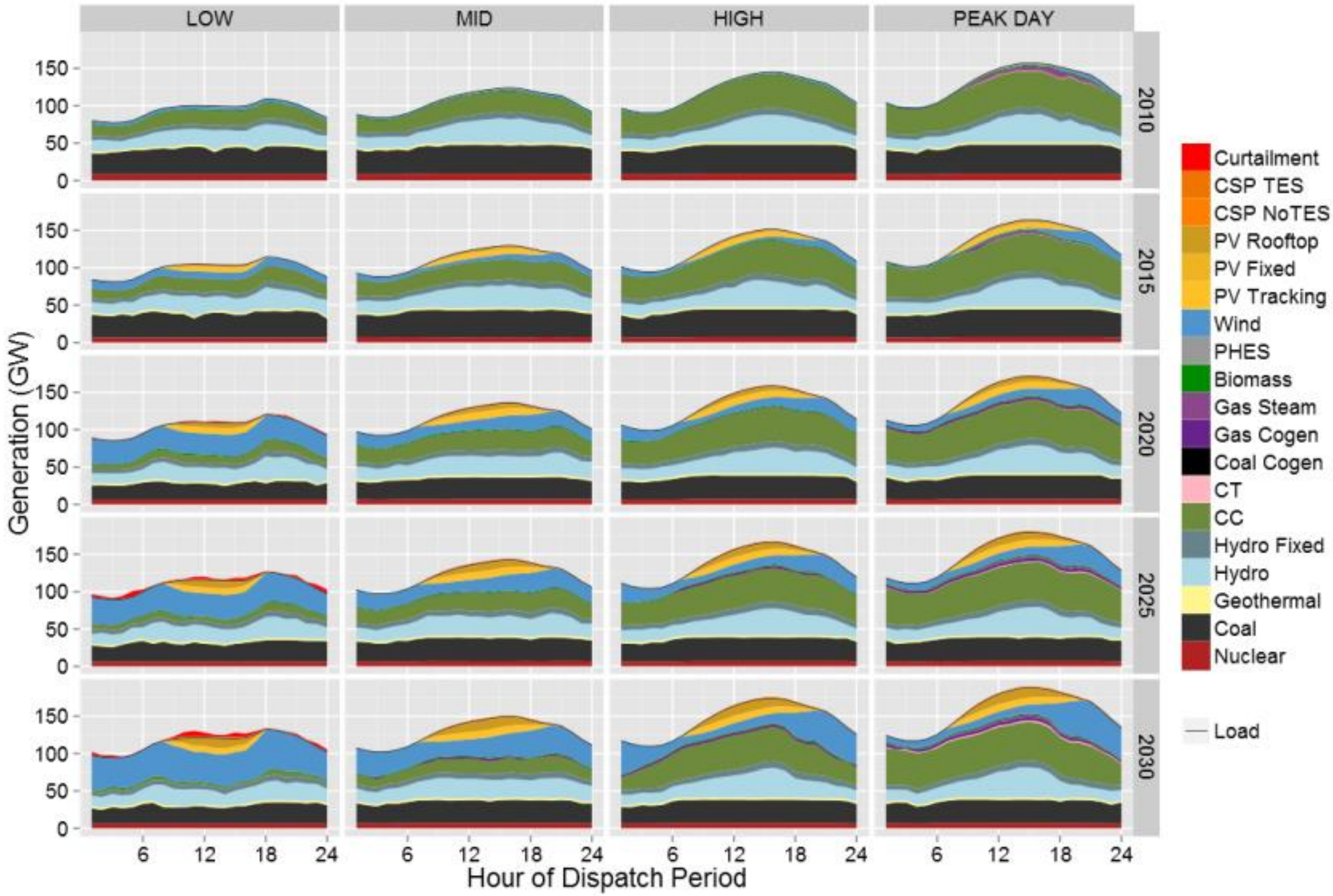
Note: computational limits often make it challenging to use all of the features

Temporal resolution and sampled dispatch



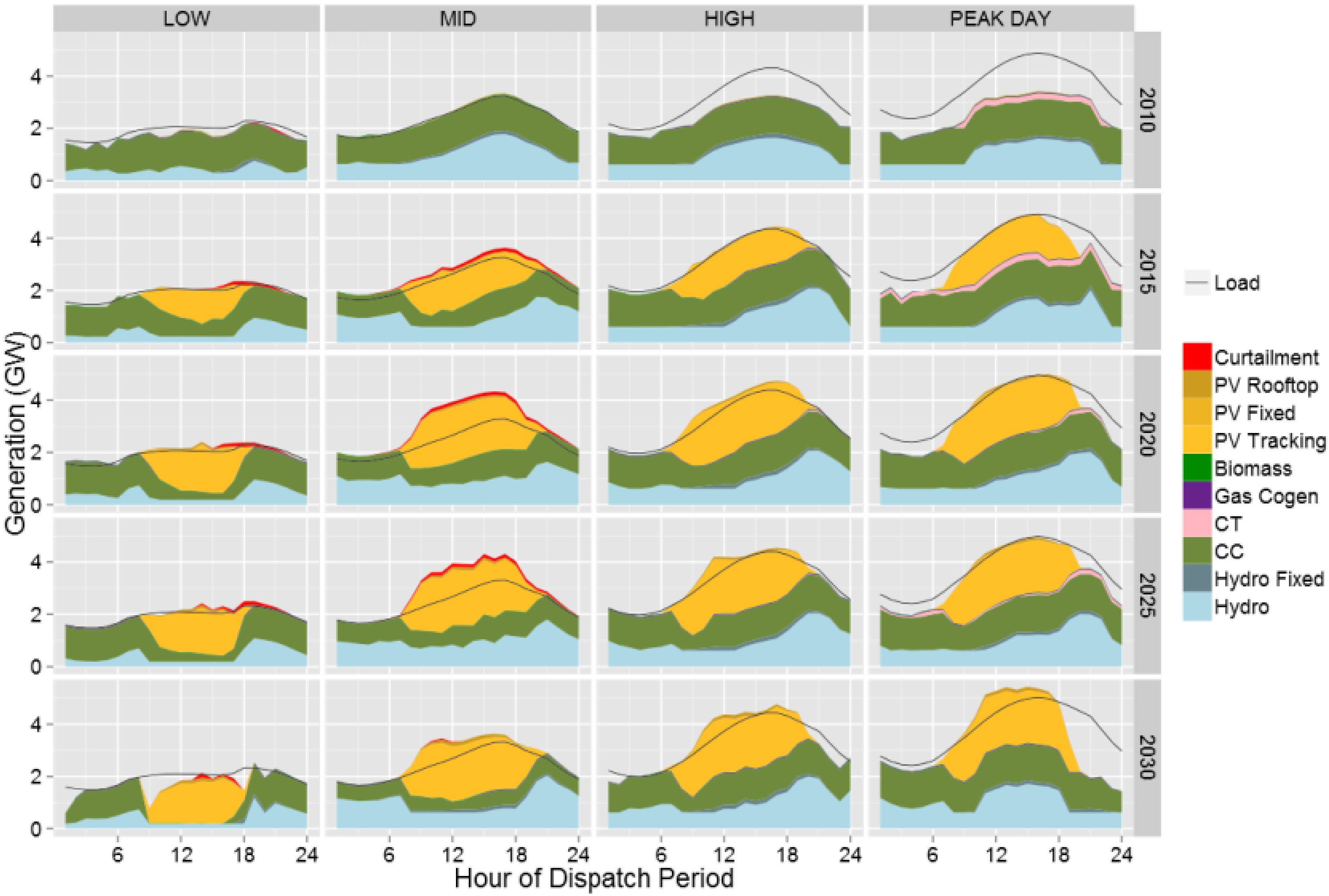
- Clustering used to select representative weeks
- Can model up to 3 weeks + peak day at hourly resolution
- Typical models include 4 separate chronological 24-hour periods, i.e. 96 hours of the year

Example 1: West-wide dispatch for 4 representative days from 2010 to 2050



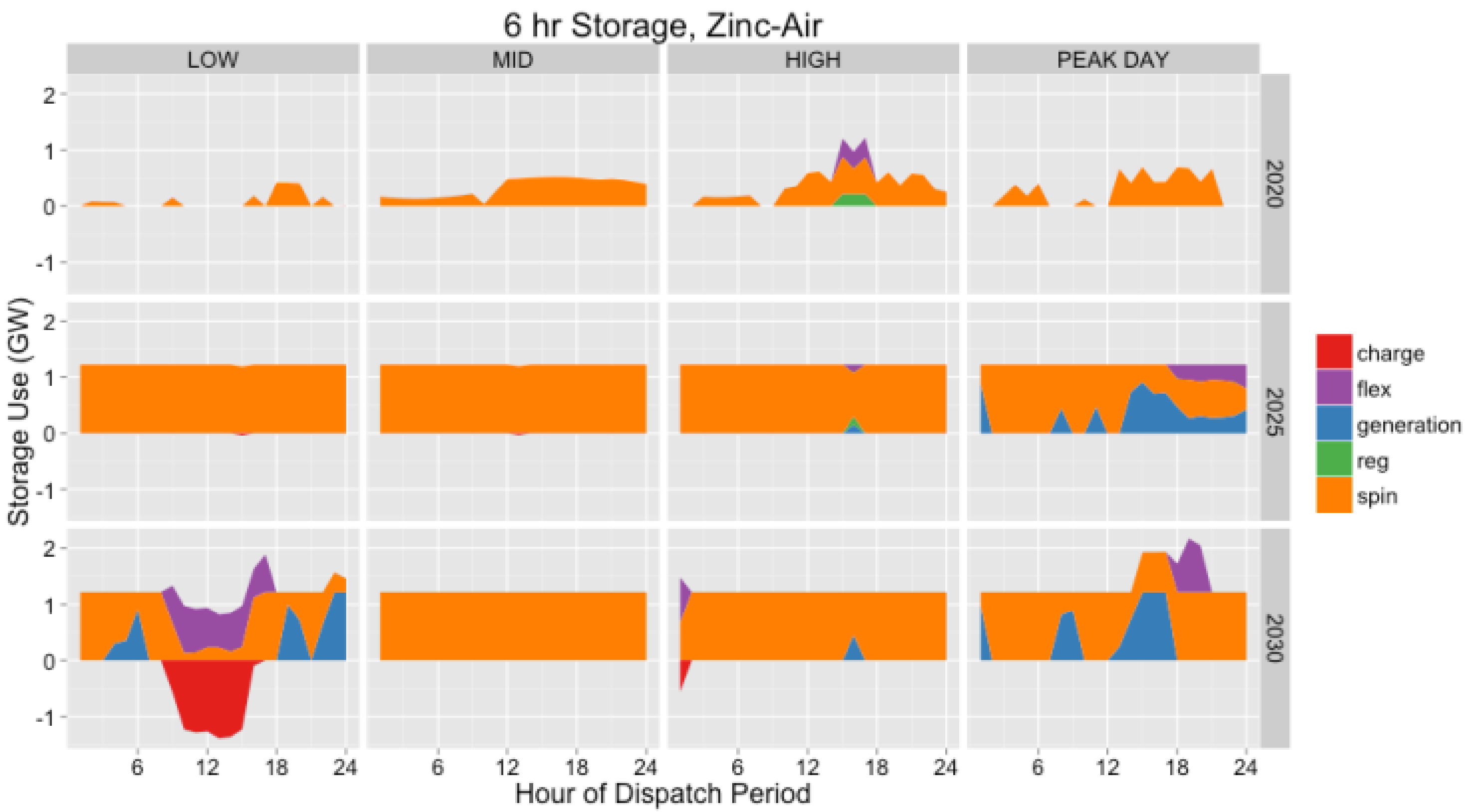
Illustrative results only (do not cite)

Example 2: Hourly dispatch for the same periods for one model Balancing Area with significant solar deployment



Illustrative results only (do not cite)

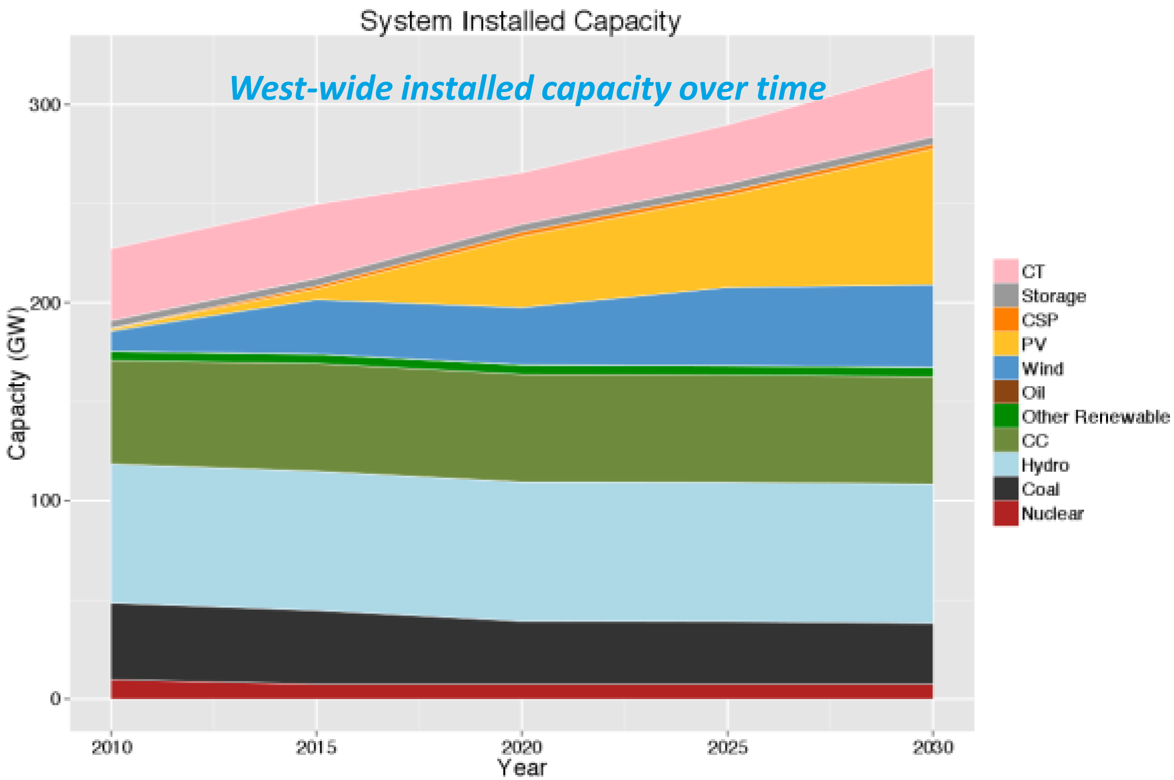
Recent developments to incorporate storage and interruptible load endogenously in RPM



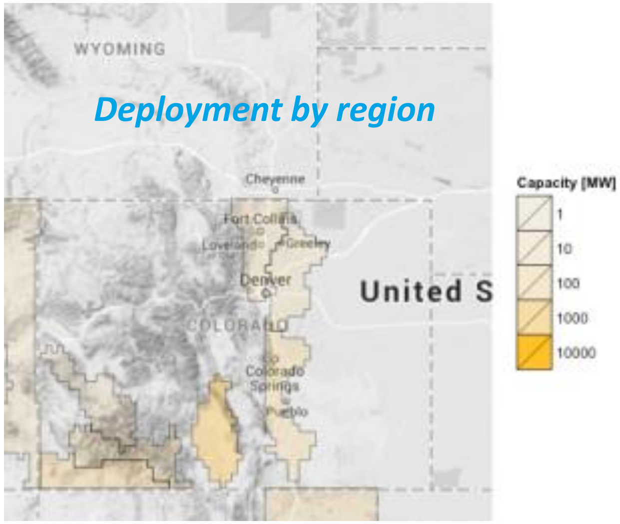
- Multiple value streams are considered, including: (1) firm capacity contributions, (2) operating reserve provision, (3) energy arbitrage, (4) RE curtailment reduction
- Costs and constraints of storage are modeled, e.g., explicit models for energy reservoirs
- *Future work*: Extend storage model to thermal energy storage

Illustrative results only (do not cite)

Detailed dispatch modeling is ultimately used to inform the core model output: *capacity expansion*



- Capacity expansion results are of course determined *primarily* by fuel price and technology assumptions
- But RPM ensures that wind and solar variability and uncertainty are properly accounted for and ensures resource adequacy for the resulting least-cost portfolio
- Other outputs: system costs, emissions, transmission upgrades

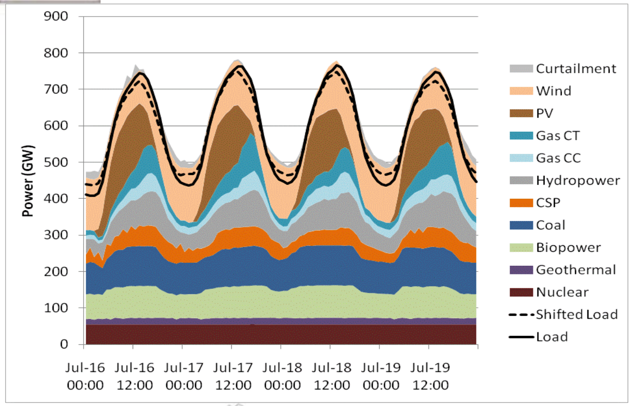


Illustrative results only (do not cite)

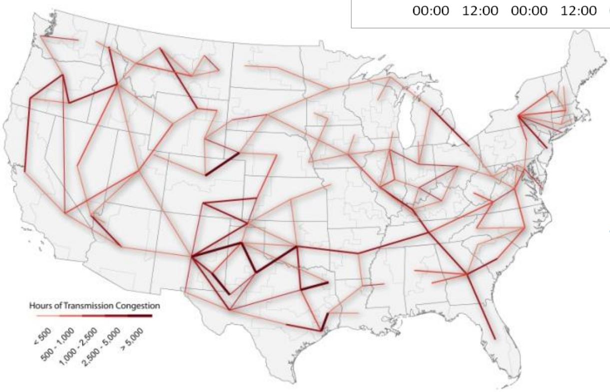
PLEXOS production cost model

- Simulate operation of electric power system
- Hourly or subhourly chronological
- Commits and dispatches generating units based on:
    - Electricity demand
    - Operating parameters of generators
    - Transmission grid parameters
- Used for system generation and transmission planning

Locational prices, production cost



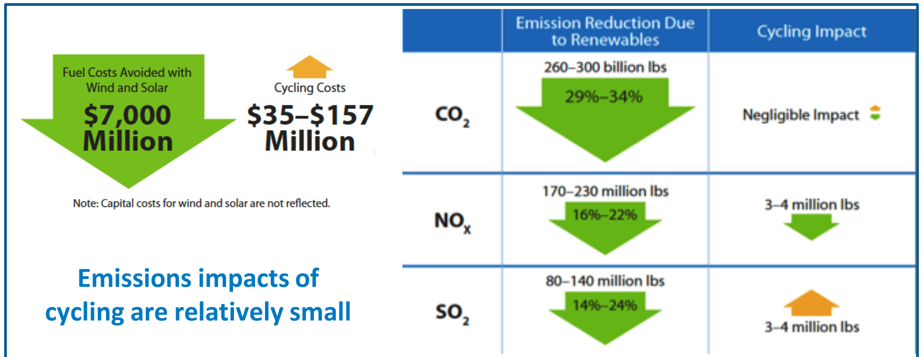
Dispatch information, fuel usage



Transmission congestion

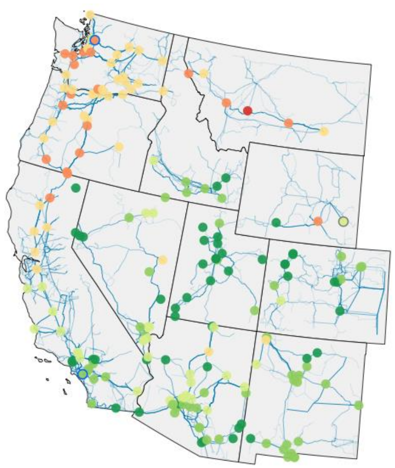
Western Wind and Solar Integration Study, Phase 1-3a

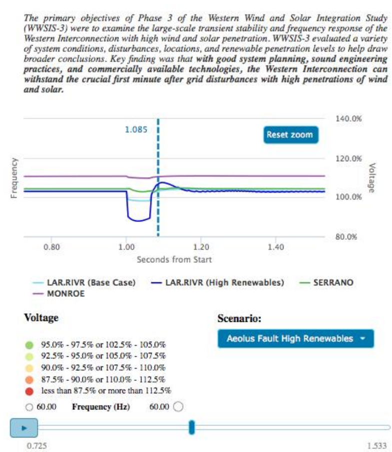
Contact: Kara.Clark@nrel.gov



Emissions impacts of cycling are relatively small

From a system perspective, cycling costs are relatively small





Lew, D., et al. (2013). *The Western Wind and Solar Integration Study Phase* 2, NREL/TP-5500-55588. Golden, CO: National Renewable Energy Laboratory.

www.nrel.gov/wwsis/

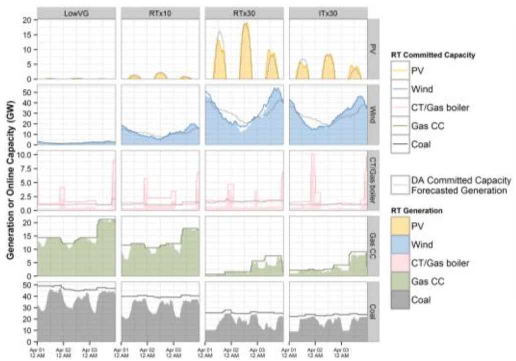
<u>Methodology</u>: Develop dataset on emissions and costs of fossil-fueled unit cycling and use PLEXOS to model the unit commitment and dispatch of the electric power system in the western United States. Analyze the costs and emissions of cycling in the presence of up to 33% wind and solar penetration.

<u>Key Findings</u>:

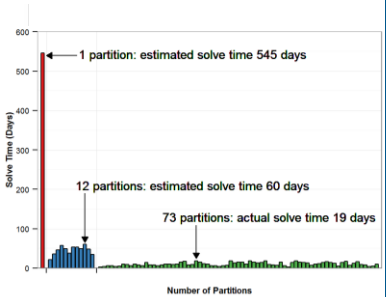
- WWSIS-2 analyzed questions raised during Phase 1 of WWSIS, which raised questions regarding the impact of cycling on wear-and-tear costs and emissions
- Emissions impacts from cycling are small compared to the emissions reductions of CO_2, NO_x, and SO_2 from wind and solar generation displacing fossil-fueled generation
- System costs of wind- and solar-induced cycling are small compared to the fuel cost reduction of wind and solar
- Operating costs per MWh at fossil-fuel generators could increase by an average of 2%-5%
- Although the number of startups at coal and gas units changes modestly when renewables are added, the number of ramps at coal units increases significantly as renewables are added.
- Adding 4 MWh of wind and solar in the west will likely displace 3 MWh of natural gas generation and 1 MWh of coal generation

Eastern Renewable Generation Integration Study (ERGIS)

Contact: aaron.bloom@nrel.gov



Commitment and Dispatch during Peak wind generation in PJM



Decrease in computation time using HPC

Bloom, A., et al. (2016). *Eastern Renewable Generation Integration Study*. Golden, CO: National Renewable Energy Laboratory.

Methodology: Create the most detailed model of the largest power system in the world to simulate power system operations at a 5-minute level under the presence of over 400 GW of wind and solar generation.

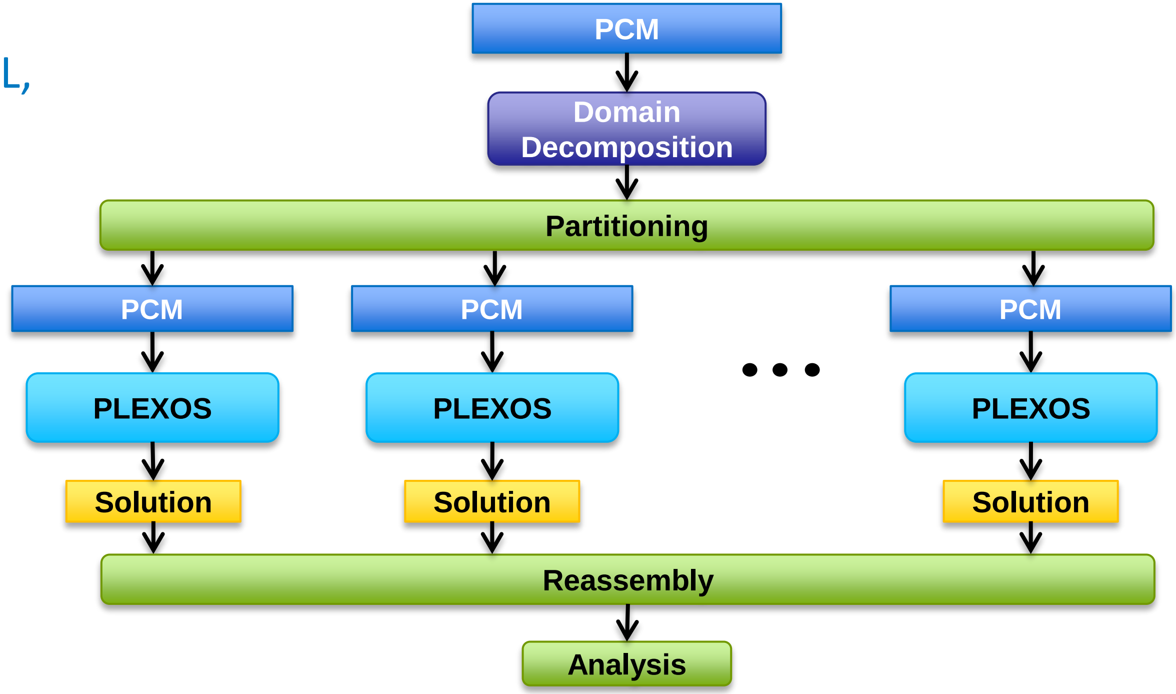
Key Findings:

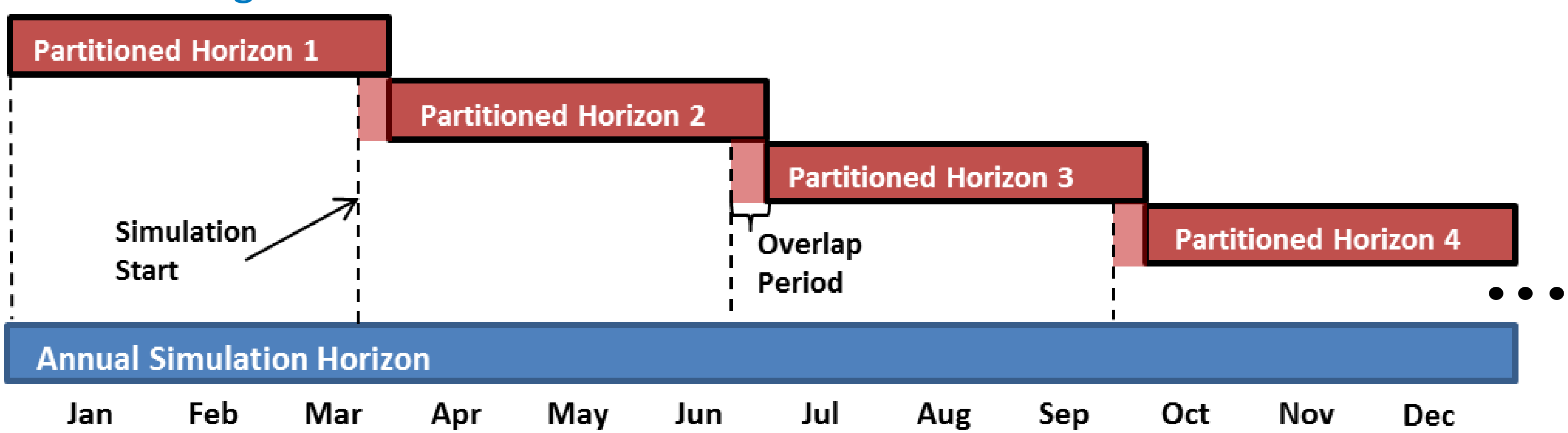
- Over 400 GW of wind and PV generation can be balanced at a 5-minute level using traditional modeling assumptions about system flexibility.
- Annual wind and PV penetrations of 30% decrease generation from fossil fuel resources and subsequently lower total system variable costs and carbon emissions by 30%.
- Model resolution matters, the nodal representation of ERGIS has significantly more curtailment than a zonal representation of the system, though solve times are dramatically different
- Conventional generation resources will likely behave very differently under high penetrations of wind and solar with increased ramping, starts, and increased time at minimum generating levels

UC on NREL's Peregrine High Performance Computer

- Partnering with Energy Exemplar and other labs (PNNL, Argonne, Sandia, LLNL)
- How can we model better fidelity with bigger systems?

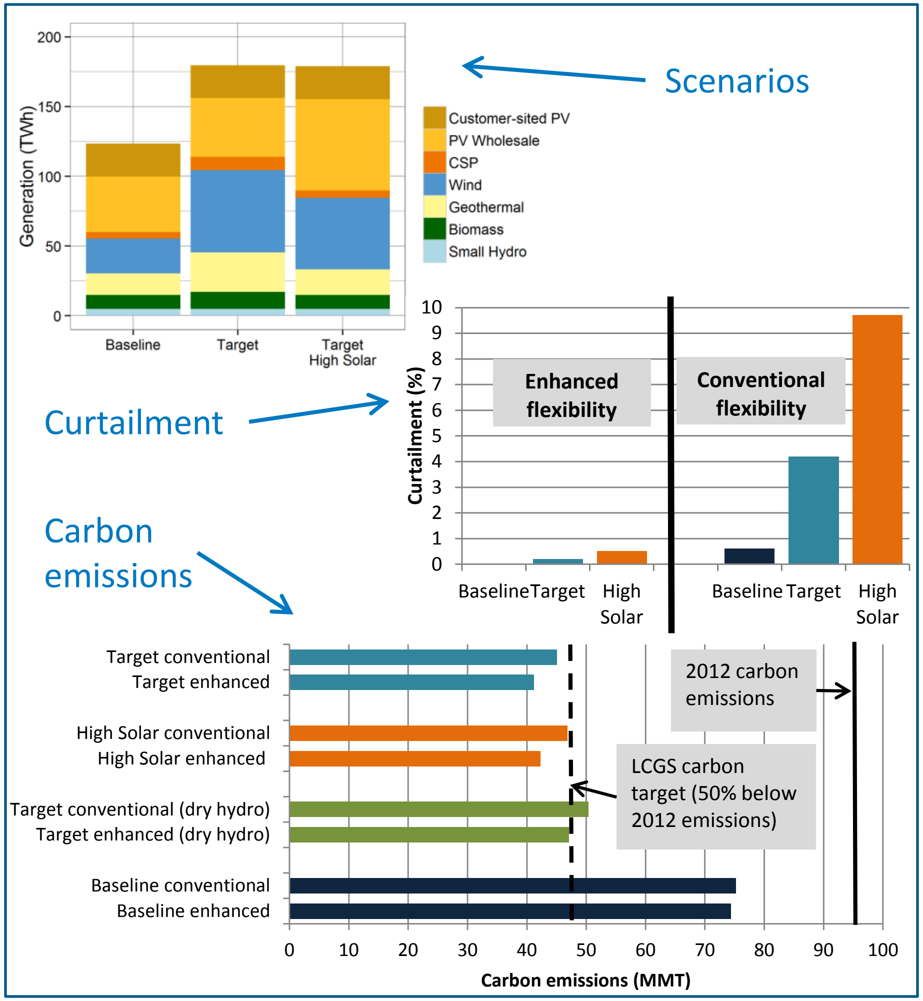
NREL Peregrine HPC





California Low Carbon Grid Study

Contact: gregory.brinkman@nrel.gov



Brinkman, G., et al. (2016). *Low Carbon Grid Study: Analysis of a 50% Emission Reduction in California*, NREL/TP-6A20-64884. Golden, CO: National Renewable Energy Laboratory.

<u>Methodology</u>: Use PLEXOS to analyze the grid impacts of scenarios that achieve a 50% carbon emissions reductions from California's electric sector by 2030, through energy efficiency, renewable energy, and grid flexibility.

<u>Key Findings</u>:

- The modeling results indicate that achieving 50% emissions reductions below 2012 levels is possible by 2030 with relatively limited curtailment (less than 1%) if institutional frameworks are flexible.
- Less flexible institutional frameworks and a less diverse generation portfolio could cause higher curtailment (up to 10%), operational costs (up to $800 million/yr higher), and carbon emissions (up to 14% higher).
  - Enhanced flexibility scenarios assume better regional coordination, more storage, and fewer restrictions on local generation and ancillary service provisions.

<u>Companion Reports</u>:

- GE Energy found that mitigation options exist to help maintain grid reliability, but more work is needed.
- JBS Energy found that the additional revenue requirement of achieving the 50% carbon reduction would be most likely be less than 1%, but could vary between -3% and +6%.

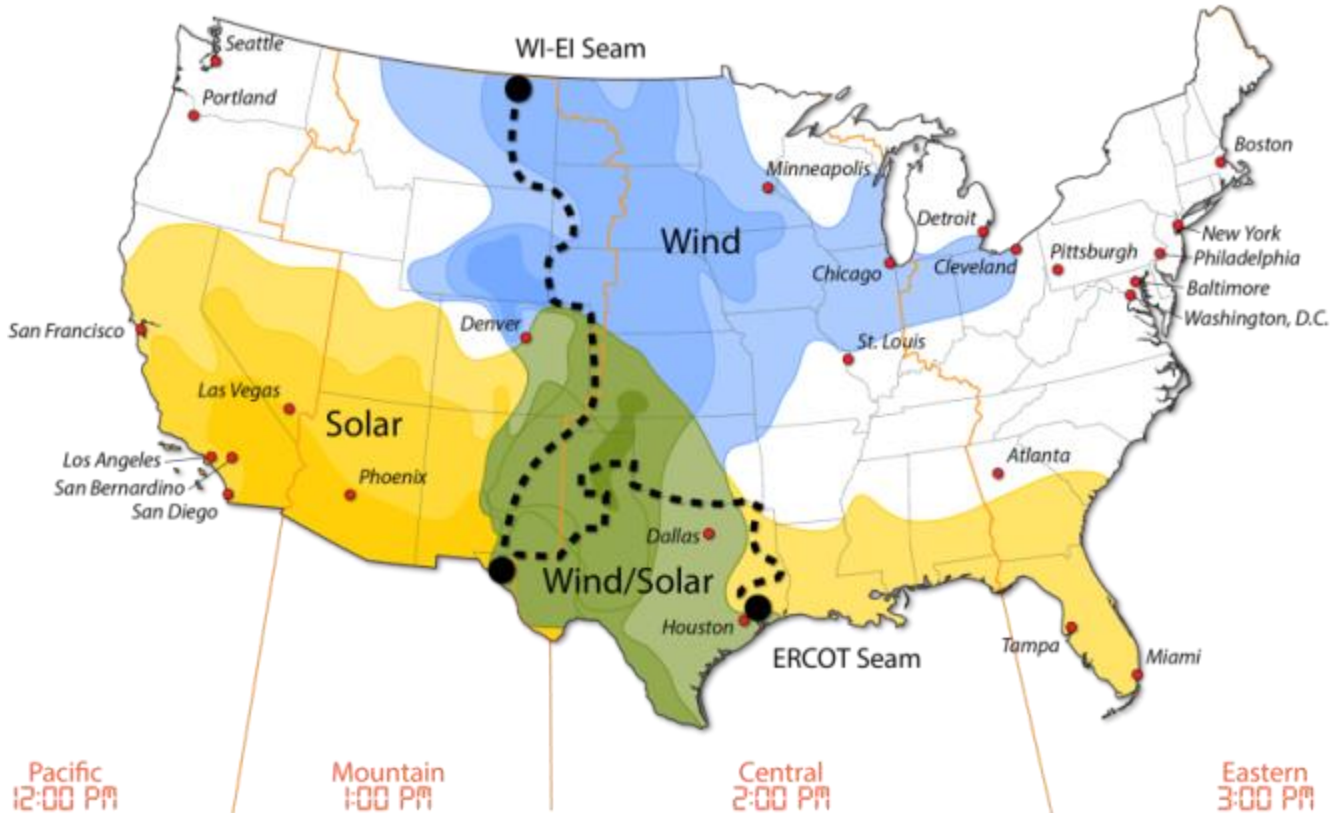
Ongoing studies

- Department of Energy’s Grid Modernization Initiative
- Highly coordinated projects at DOE and Labs
- Interconnection Seams
- Multi-scale PCM
- North American Renewable Integration Study

Interconnection Seams Study

- Department of Energy's Grid Modernization Initiative
- Goal: Understand what is necessary to ensure the US electricity system is: affordable, reliable, clean, safe, and resilient.
- In this study we will explore how tighter integration of the US interconnections could enable the development of a modernized US grid.

Interconnection Seams Study



- Great resource diversity in central U.S.
- Seams between interconnections prevent taking advantage of diversity
- How much benefit could come from better connections?

Team, Tools, and Data Overview

Team

- National Renewable Energy Laboratory
  - Aaron Bloom
- Pacific Northwest National Laboratory
  - Yuri Makarov
- Iowa State University
  - Jim McCalley
- Southwest Power Pool
  - Jay Caspary
- Midcontinent Independent System Operator
  - Dale Osborn
- Western Area Power Administration
  - Rebecca Johnson
- Oak Ridge National Laboratory
  - Fran Li
- Argonne National Laboratory
  - Jianhui Wang

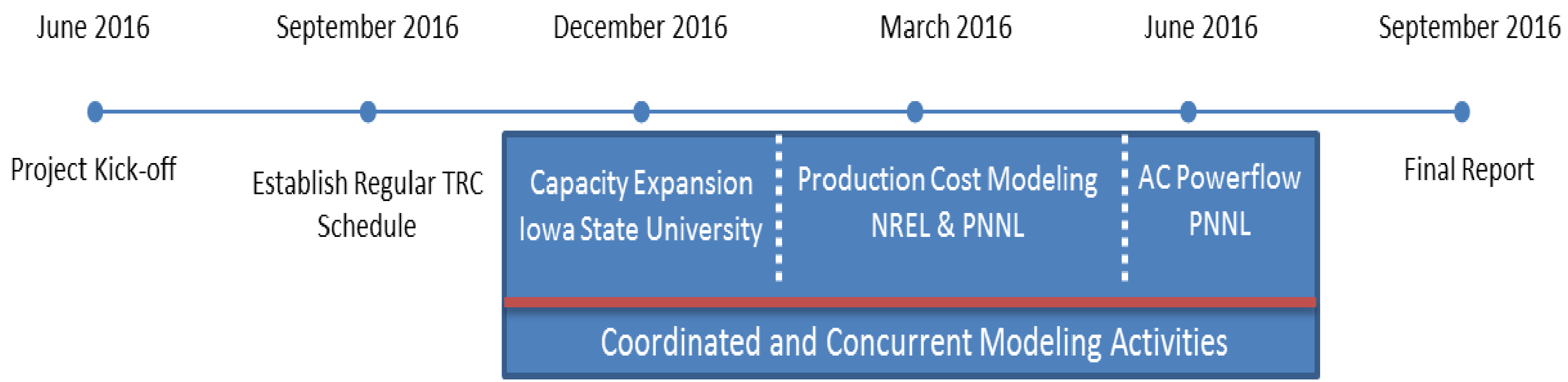
Tools

- Capacity Expansion
- Production Cost
- AC Powerflow

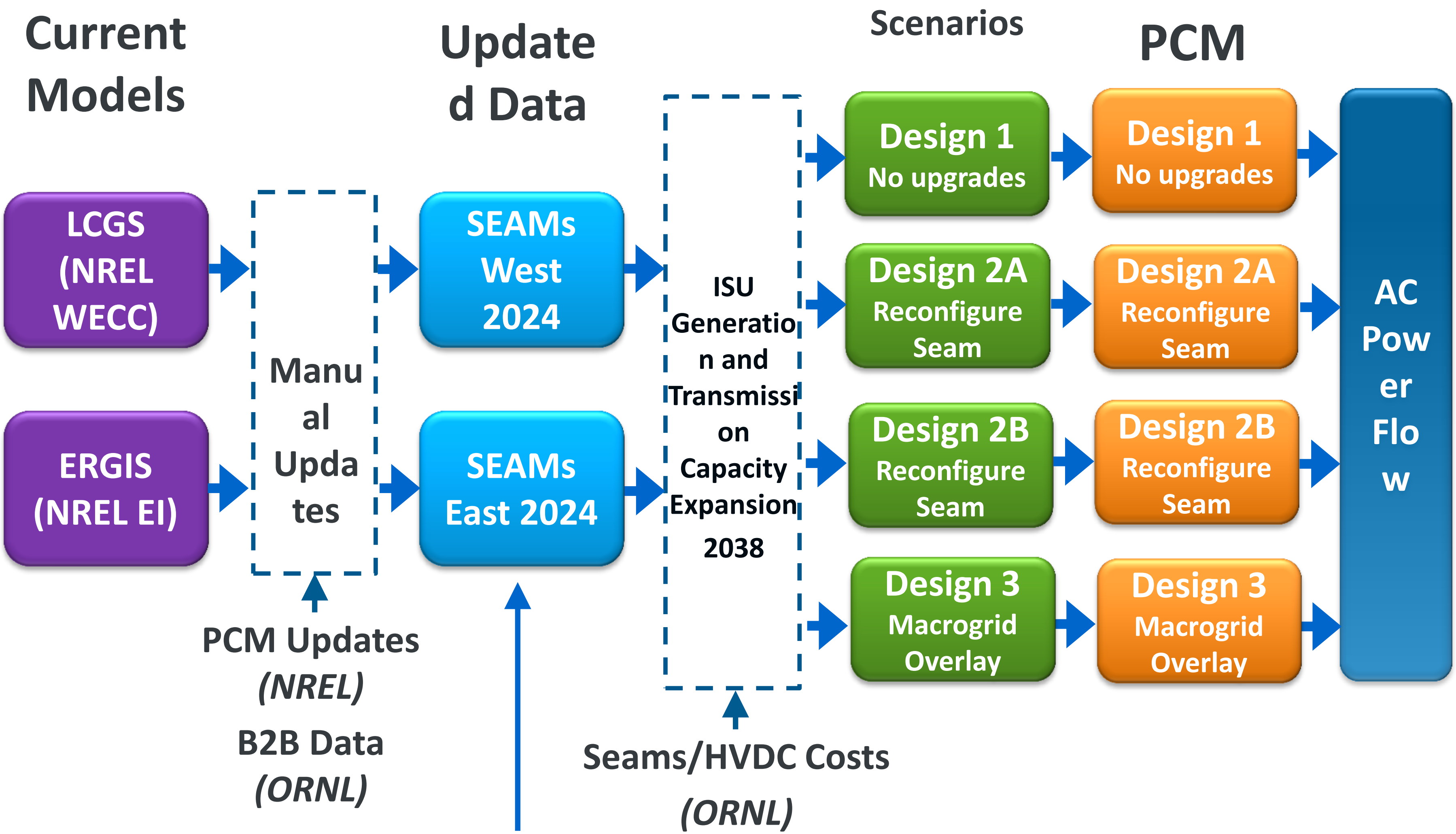
Data

- WECC TEPPC
- EIPC
- WINDToolkit
- NSRDB
- EIA

Project Timeline

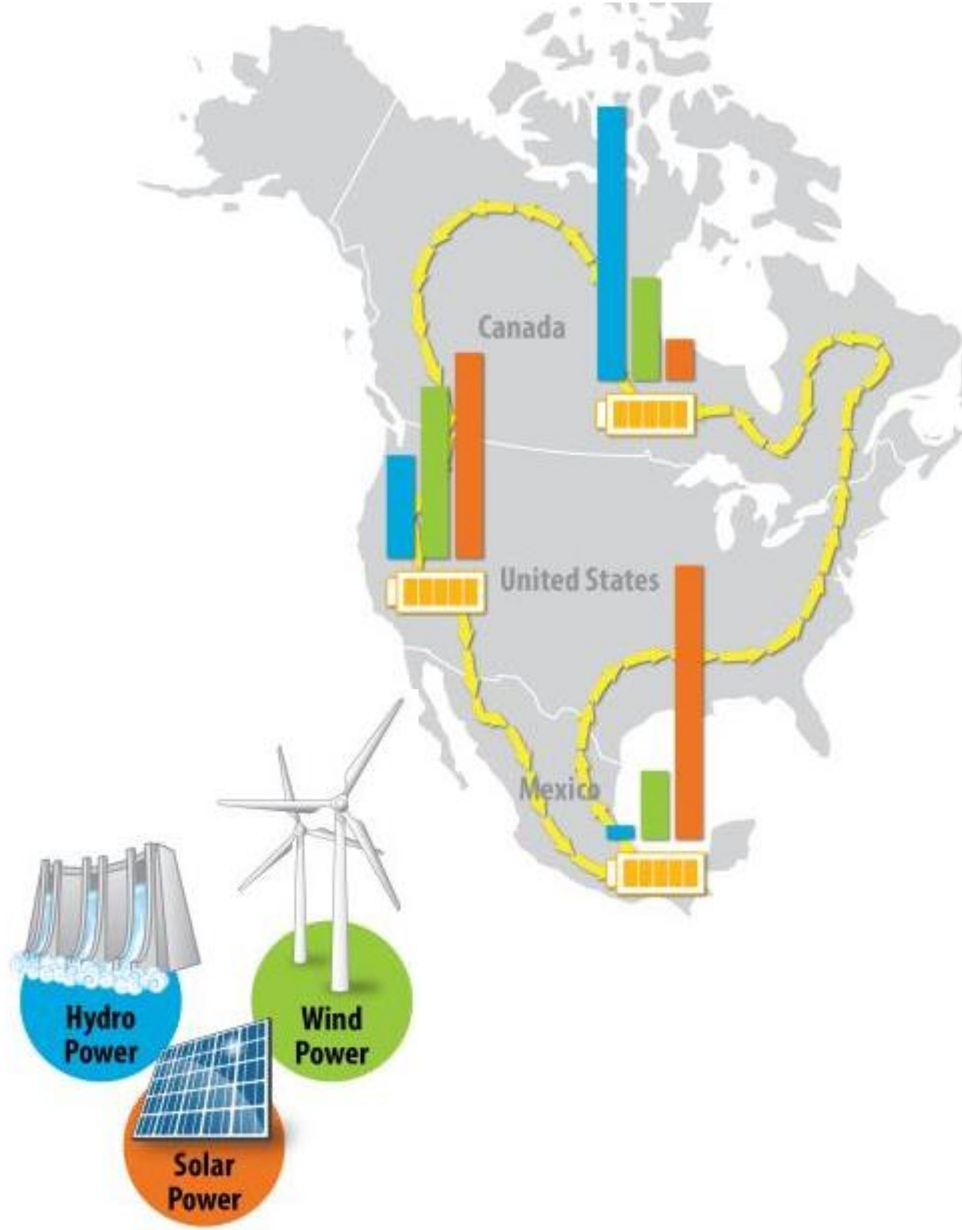


Implementing Scenarios



Initial conditions for capacity expansion & test model for PCM

North American Renewable Integration Study (NARIS)

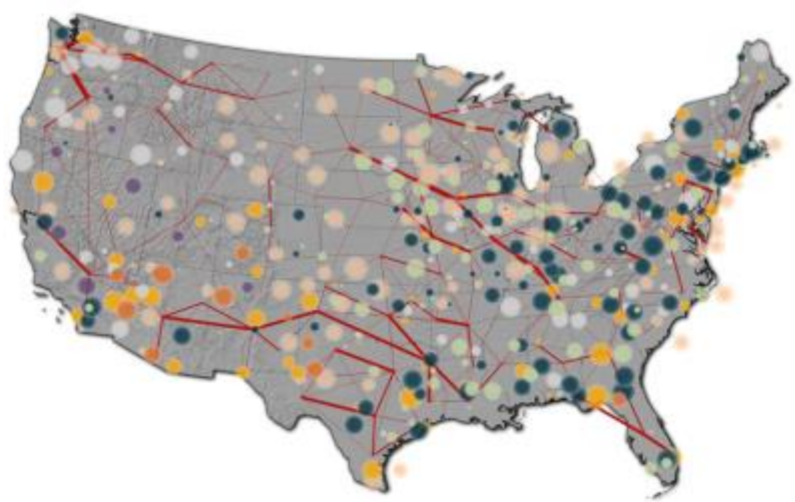


- Partner with U.S. DOE, Natural Resources Canada and Mexico's Secretaría de Energía (SENER)
- Study impacts of high penetrations of low-carbon and renewable electricity, and mitigating strategies
- Study interconnection of Canada, Mexico, and US power systems, from planning through operation and balancing at 5-minute resolution
- Understand potential benefits of cooperation
- Builds off the Interconnection Seams Study, Pan Canadian Wind Integration Study, and Mexico's Renewable Integration Study

Why is NARIS important

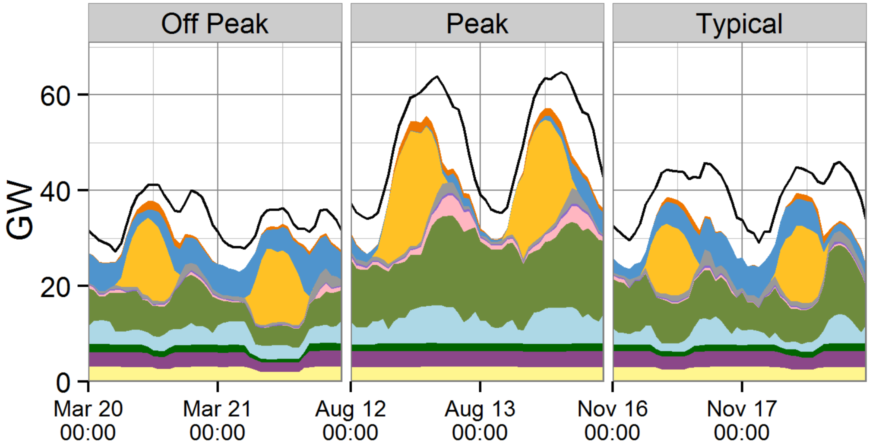
- Use state-of-the-art modeling techniques and data to understand impacts of renewables throughout North America
- Research mitigation strategies, including cross-border cooperation in planning and operation
- Apply consistent assumptions in all three countries…

Proposed Models



- ReEDS (NREL)
  - Capacity expansion

- dGen (NREL)
  - Distributed market-penetration model



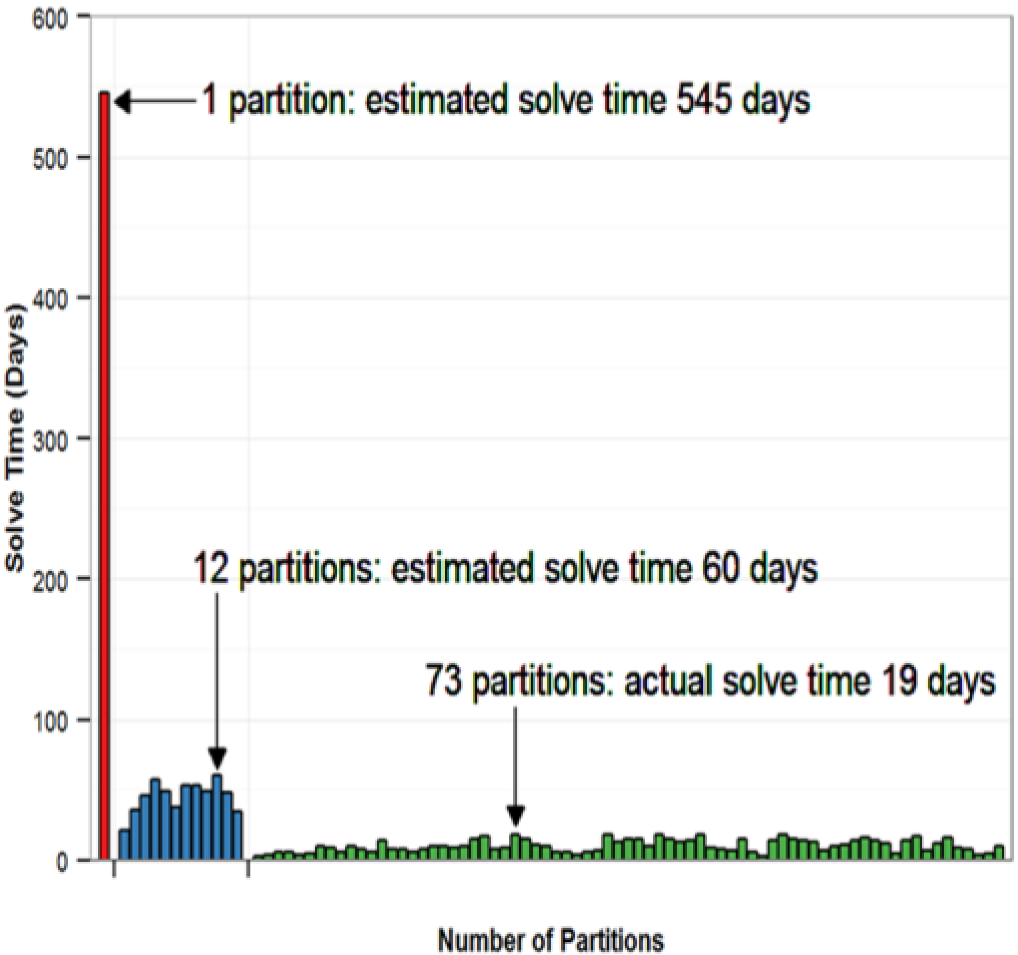
- PLEXOS (Energy Exemplar)
  - Unit Commitment, Economic Dispatch model

Multi-Scale Production Cost Modeling

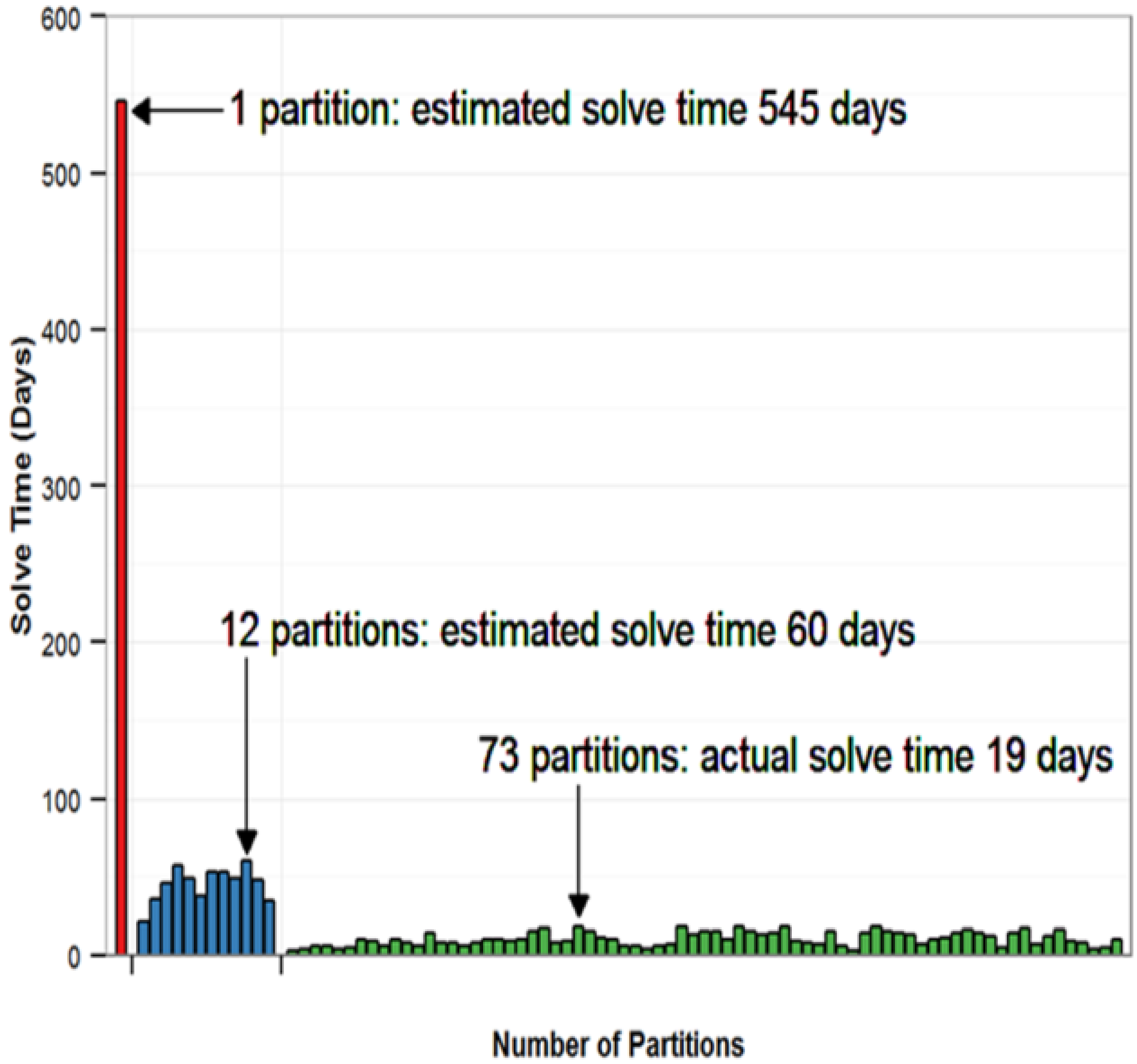
- Evaluate combinations of temporal and spatial decomposition to improve solve times and increase modeling fidelity

ERGIS – Significant improvement is in solve time, BUT

- Limited storage
- No demand response
- Did not include multiple reserve products
- Significantly aggregated transmission



The Unit Commitment Problem



Some Final Thoughts

- We all want better integration of grid modeling tools
  - Transmission + distribution
  - Capacity expansion with detailed operation
  - UC+ED + AC OPF
- But it is basically impossible to model all the parameters of electric power system operation in a single model
- For the foreseeable future, we will need multiple models

www.nrel.gov/analysis/ReEDS

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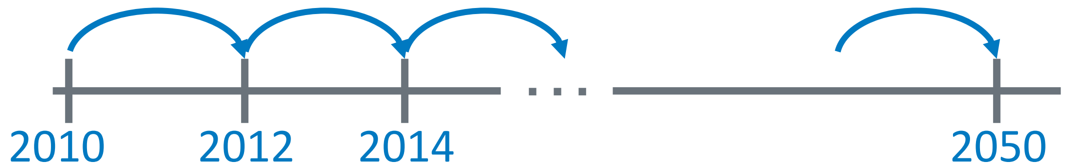
Additional Detail

Model flow

Solve Year Timeline



Define spatial and temporal resolution

Import electricity system data, e.g.
- Existing fleet
- Load
- Policies
- Resource potential
- Technology cost and performance

For each solve year (every 2 years),

Specify initial conditions using imported initial data and previous solve year results (if applicable)

ReEDS Optimization: minimize cost of system expansion and operation

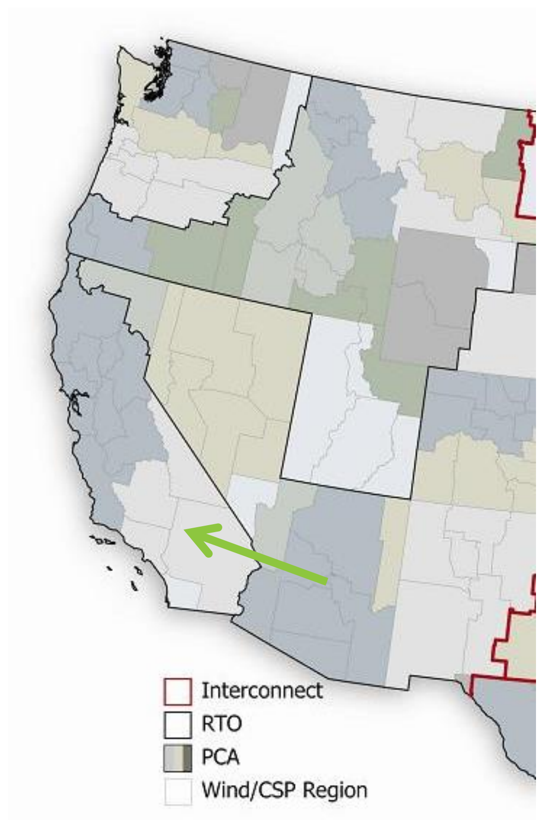
Results: e.g. new generating capacity, transmission, and dispatch

Update parameters for next solve year, e.g.
- Load
- Technology cost/performance
- Installed generation and transmission
- Variable renewable characteristics

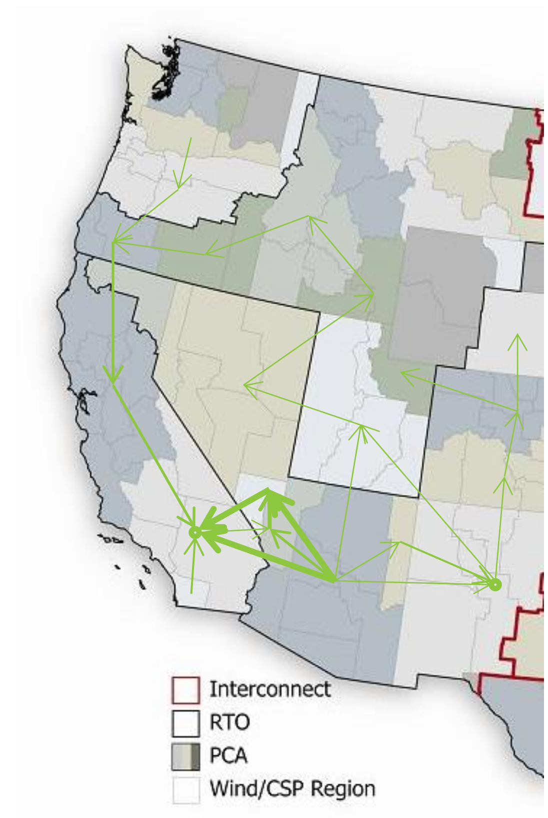
ReEDS approach: transmission power flow

Linear DC power flow representation :

- Power flow: obeys Kirchhoff's voltage law, flows are determined by generation, load, and line susceptances.
- DC: real power only; ignores reactive power.
- Linear: approximation that phase angle differences are small. Necessary for use in linear optimization.



Pipe Flow: ReEDS chooses route.



Power Flow: Route is determined by transfers and network.