High Penetration of Renewable Energy: Possible Scenarios, Implications, and Best Practices from International Experience

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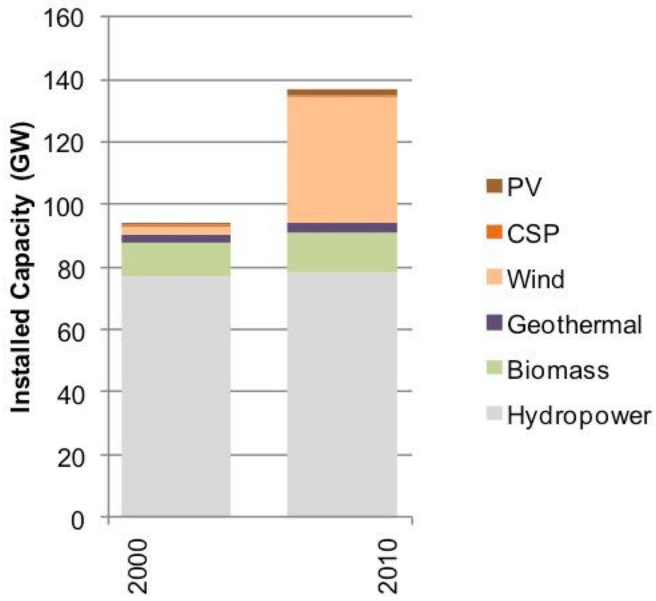
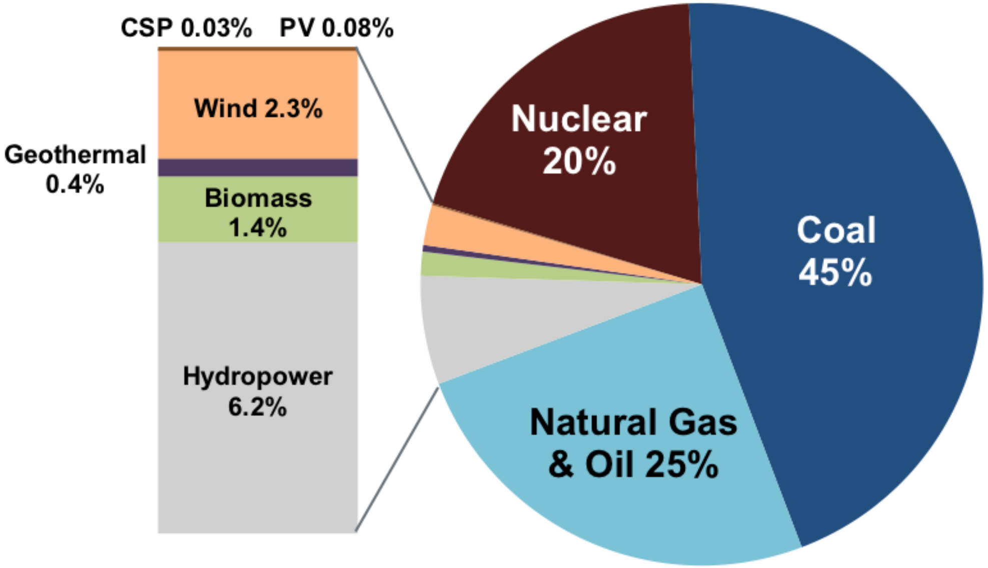
Renewable Electricity Futures Motivation

RE Capacity Growth 2000-2010



Source: RE Data Book (DOE 2011)

2010 Electricity Generation Mix



Source: Renewable Electricity Futures (2012)

- **To what extent can renewable energy technologies commercially available today meet the U.S. electricity demand over the next several decades?**

Renewable Electricity Futures Introduction

- **RE Futures is an analysis of the U.S. electric sector focused on 2050 that explores:**
  1. **Whether the U.S. power system <u>can supply electricity to meet customer demand</u> with high levels of renewable electricity, including variable wind and solar generation.**
  2. **Grid integration using models with <u>unprecedented geographic and time resolution</u> for the contiguous U.S.**
  3. **<u>Synergies, constraints, and operational issues</u> associated with a transformation of the U.S. electric sector.**

Renewable Electricity Futures Report

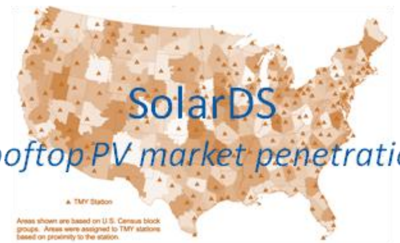
Volume 1	Exploration of High-Penetration Renewable Electricity Futures
Volume 2	Renewable Electricity Generation and Storage Technologies
Volume 3	End-Use Electricity Demand
Volume 4	Bulk Electric Power Systems: Operations and Transmission Planning

REF is a U.S. DOE-sponsored collaboration with more than 110 contributors from 35 organizations including national laboratories, industry, universities, and non-governmental organizations.

Renewable Electricity Futures Scope

RE Futures does….	RE Futures does not…
Identify commercially available RE generation technology combinations that meet up to 80% or more of projected 2050 electricity demand in every hour of the year.	Consider policies, new operating procedures, evolved business models, or market rules that could facilitate high levels of RE generation.
Identify electric sector characteristics associated with high levels of RE generation.	Fully evaluate power system reliability.
Explore a variety of high renewable electricity generation scenarios.	Forecast or predict the evolution of the electric sector.
Estimate the associated U.S. electric sector carbon emissions reductions.	Assess optimal pathways to achieve a low-carbon electricity system.
Explore a select number of economic, environmental and social impacts.	Conduct a comprehensive cost-benefit analysis.
Illustrate an RE-specific pathway to a clean electricity future to inform the development of integrated portfolio scenarios that consider all technology pathways and their implications.	Provide a definitive assessment of high RE generation, but does identify areas for deeper investigation.

Modeling Framework



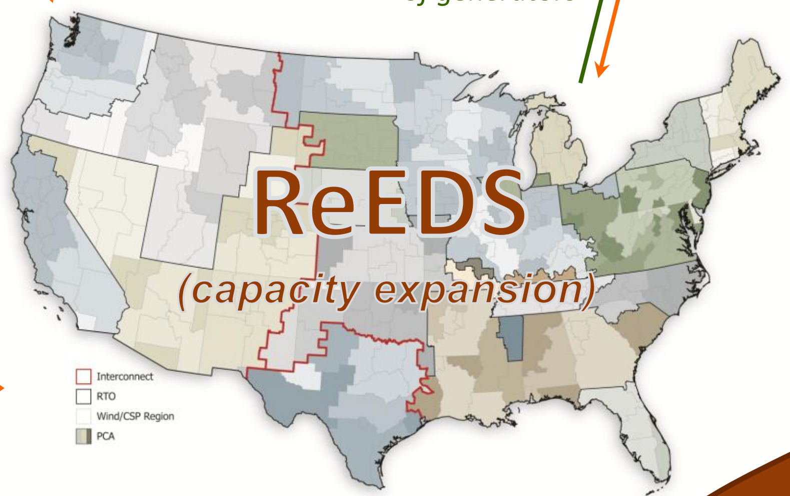
rooftop PV penetration

2050 mix of generators

does it balance hourly?

- Black & Veatch
- Technology Teams
- Flexible Resources
- End-Use Electricity
- System Operations
- Transmission

Technology cost & performance
Resource availability
Demand projection
Demand-side technologies
Grid operations
Transmission costs



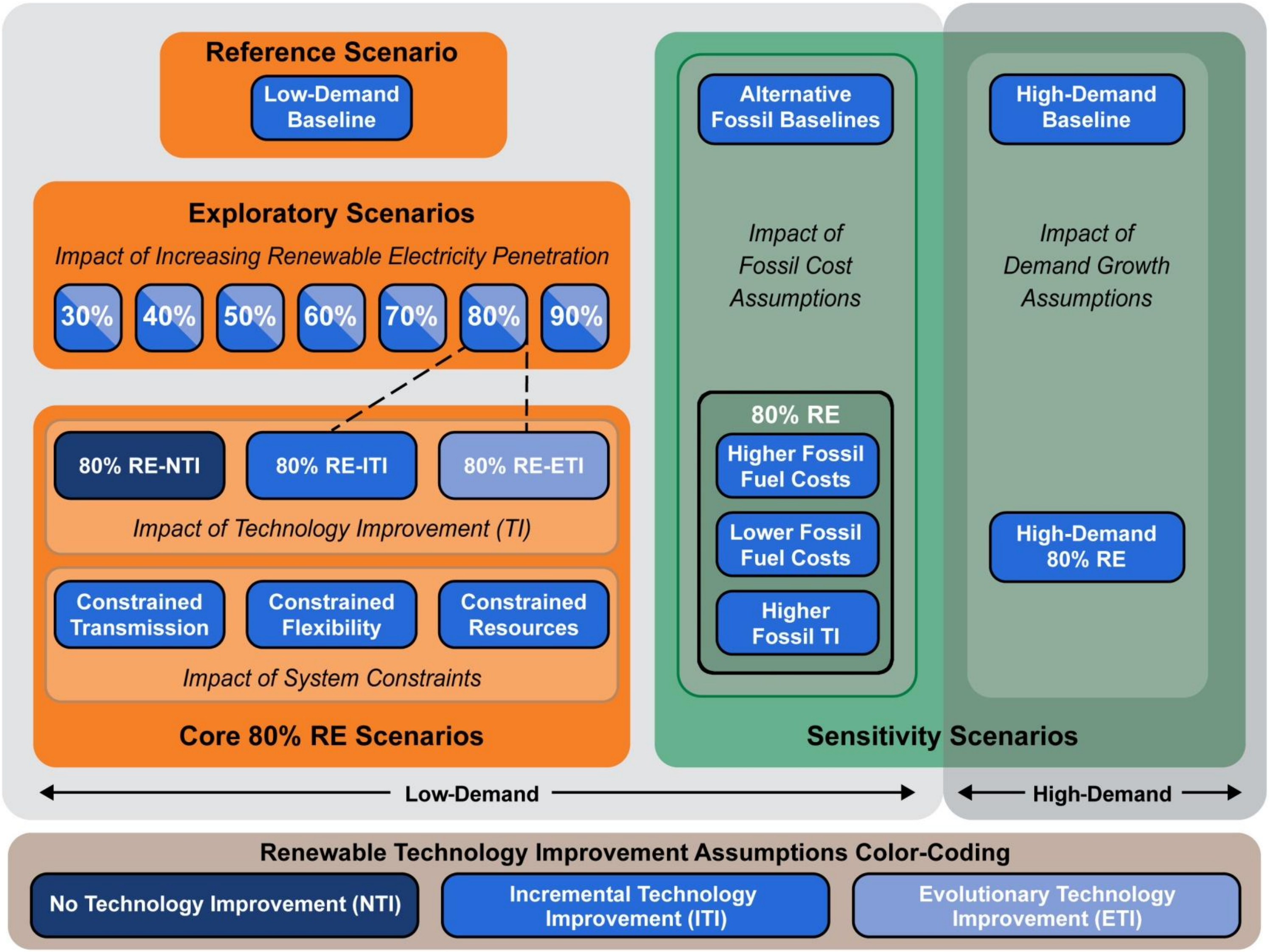
High resolution modeling using **134 nodes** & **hourly time steps**

Implications

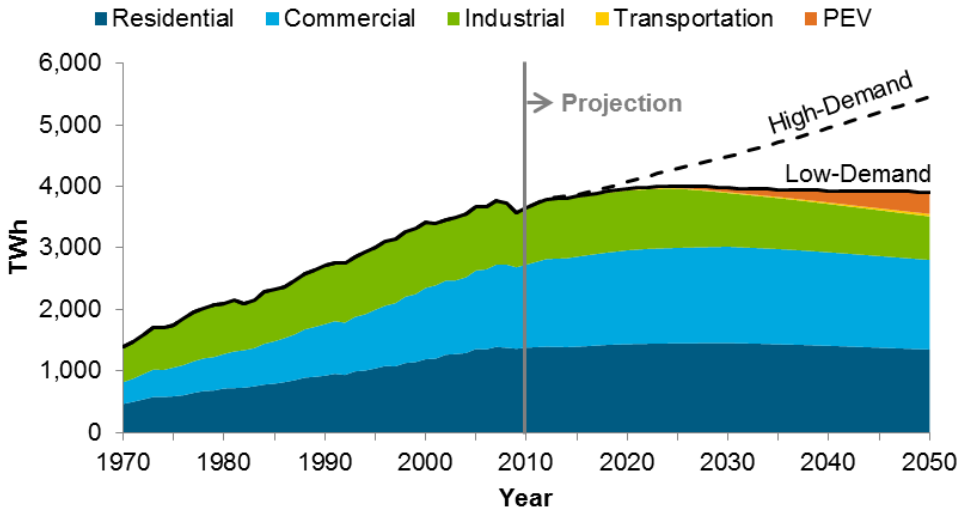
GHG Emissions
Water Use
Land Use
Direct Costs

Capacity & Generation 2010-2050

Scenario Framework



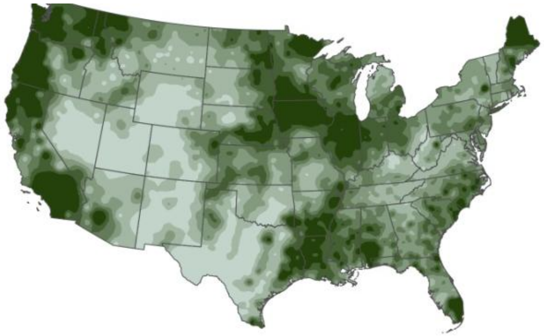
General Assumptions

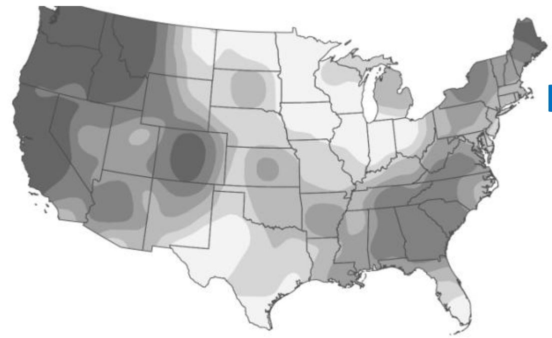


- **Energy Efficiency**: Most of the scenarios assumed significant adoption of energy efficiency (including electricity) measures in the residential, commercial, and industrial sectors.
- **Transportation**: Most of the scenarios assumed a shift of some transportation energy away from petroleum and toward electricity in the form of plug-in hybrid or electric vehicles, partially offsetting the electricity efficiency advances that were considered.
- **Grid Flexibility**: Most scenarios assumed improvements in electric system operations to enhance flexibility in both electricity generation and end-use demand, helping to enable more efficient integration of variable-output renewable electricity generation.
- **Transmission**: Most scenarios expanded the transmission infrastructure and access to existing transmission capacity to support renewable energy deployment. Distribution-level upgrades were not considered.
- **Siting and Permitting**: Most scenarios assumed project siting and permitting regimes that allow renewable electricity development and transmission expansion with standard land-use exclusions.

Renewable Resources and Technologies

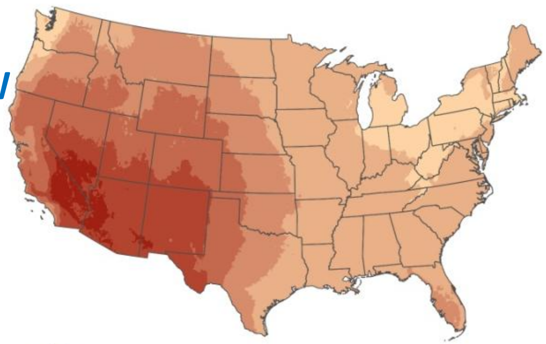
Biopower ~100 GW
- Stand-alone
- Cofired with coal

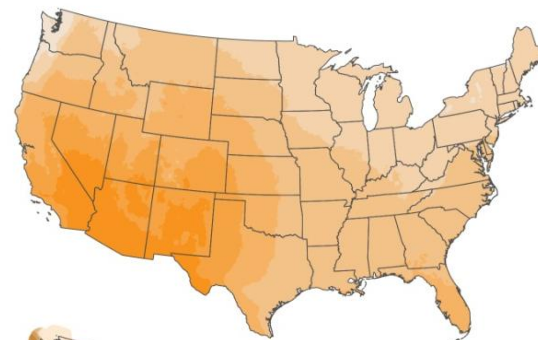




Hydropower ~200 GW
- Run-of-river

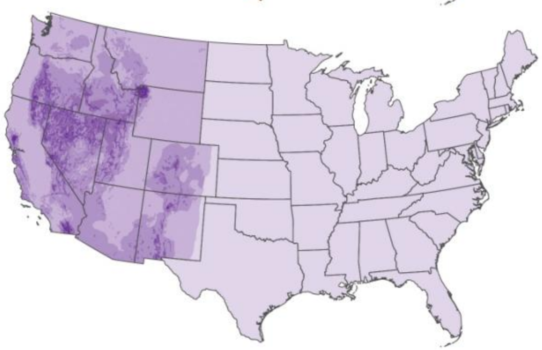
Solar CSP ~37,000 GW
- Trough ⎫ With thermal
- Tower ⎭ storage

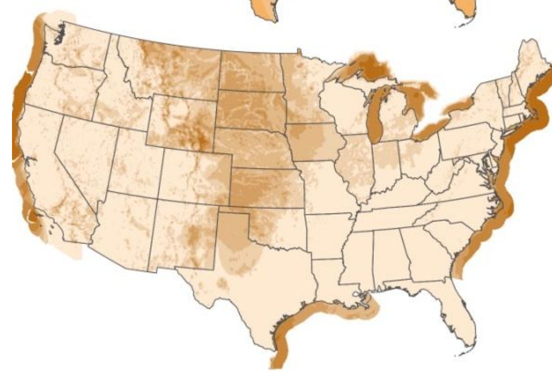




Solar PV ~80,000 GW (rooftop PV ~700 GW)
- Residential
- Commercial
- Utility-scale

Geothermal ~36 GW
- Hydrothermal





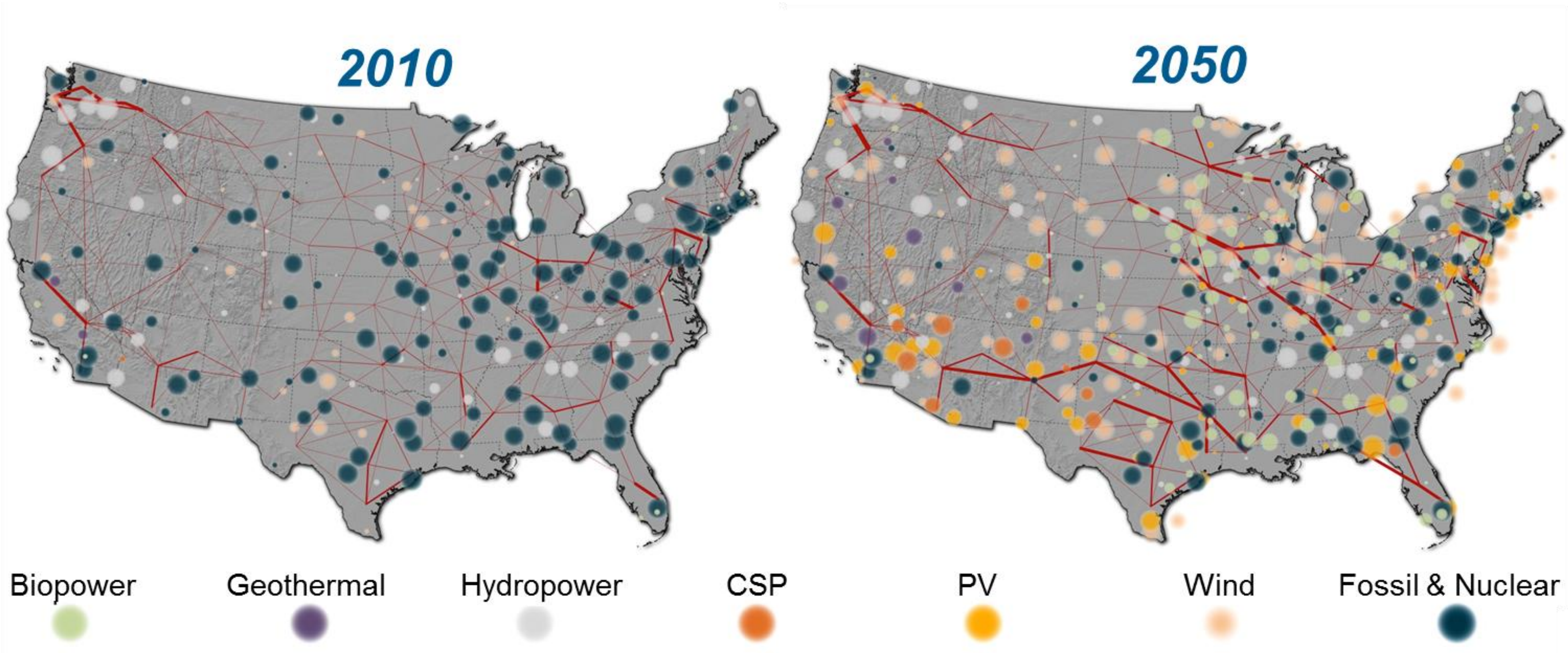
Wind ~10,000 GW
- Onshore
- Offshore fixed-bottom

- **Only currently commercial technologies were modeled (no EGS, ocean, floating wind) with incremental and evolutionary improvements.**
- **RE characteristics including location, technical resource potential, and grid output characteristics were considered.**

Key Results

Renewable Electricity Futures Study (2012). Hand, M.M.; Baldwin, S.; DeMeo, E.; Reilly, J.M.; Mai, T.; Arent, D.; Porro, G.; Meshek, M.; Sandor, D., editors. Lead authors include Mai, T.; Sandor, D.; Wiser, R.; Heath, G.; Augustine, C.; Bain, R.; Chapman, J.; Denholm, P.; Drury, E.; Hall, D.; Lantz, E.; Margolis, R.; Thresher, R.; Hostick, D.; Belzer, D.; Hadley, S.; Markel, T.; Marnay, C.; Milligan, M.; Ela, E.; Hein, J.; Schneider, T.

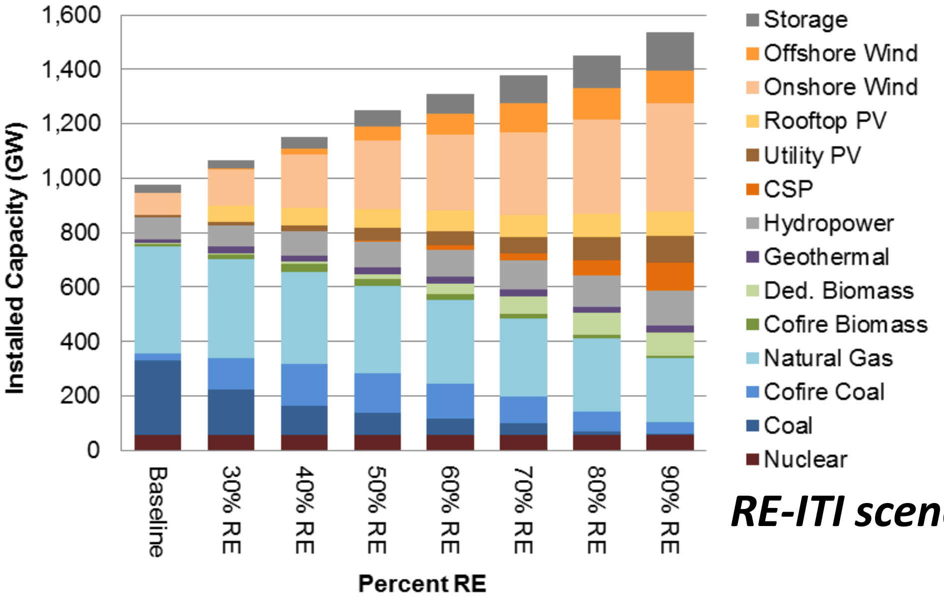
A Transformation of the U.S. Electricity System



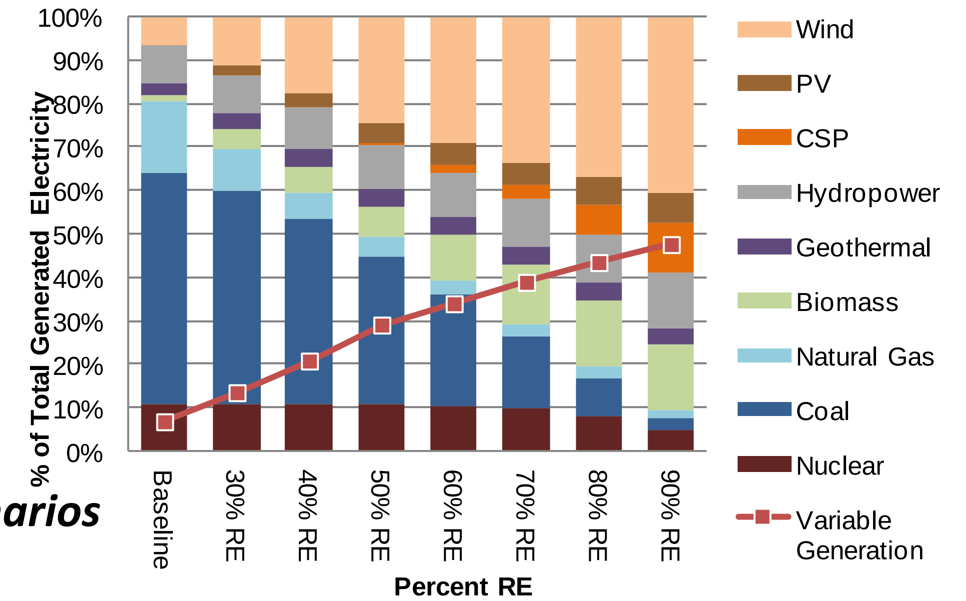
Source: Renewable Electricity Futures (2012)

RE 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.

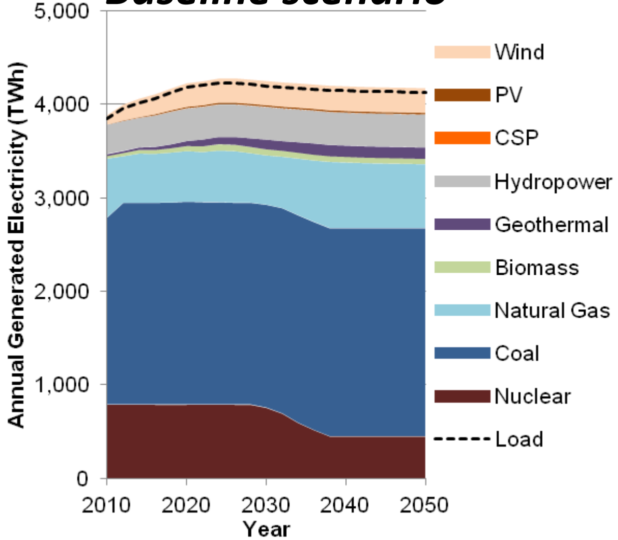
Renewable generation resources could adequately supply 80% of total U.S. electricity generation in 2050 while balancing hourly supply and demand



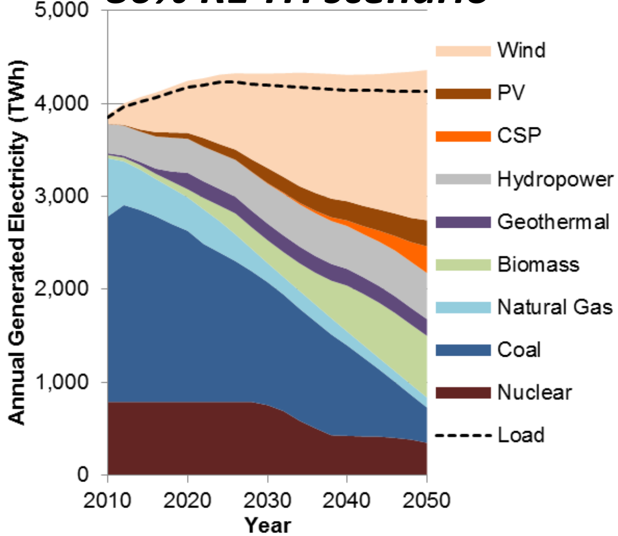
RE-ITI scenarios



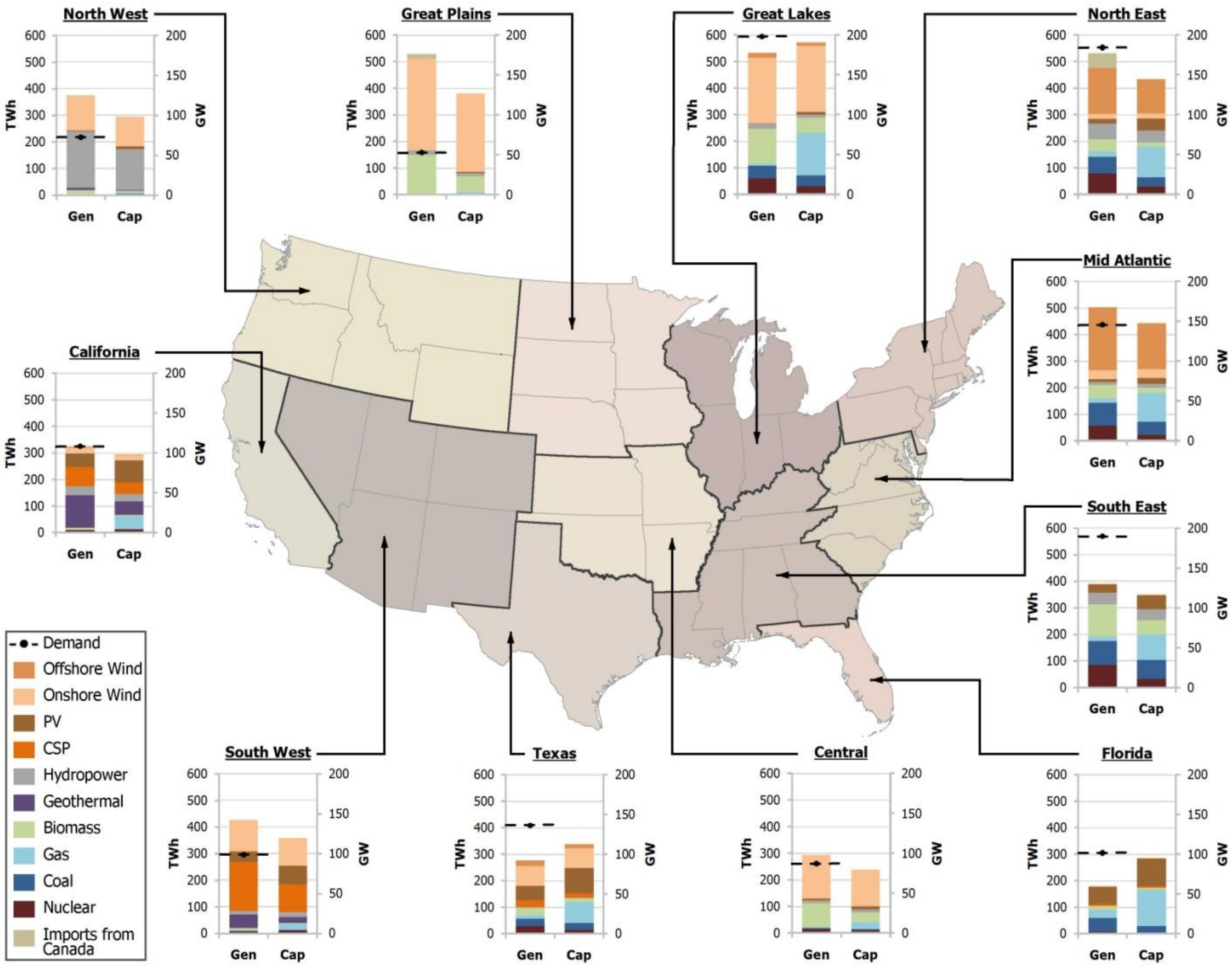
Baseline scenario



80% RE-ITI scenario



All regions of the country could contribute substantial renewable electricity supply in 2050



80% RE-ITI scenario

A more flexible electric power system is needed to enable electricity supply-demand balance with high levels of RE generation

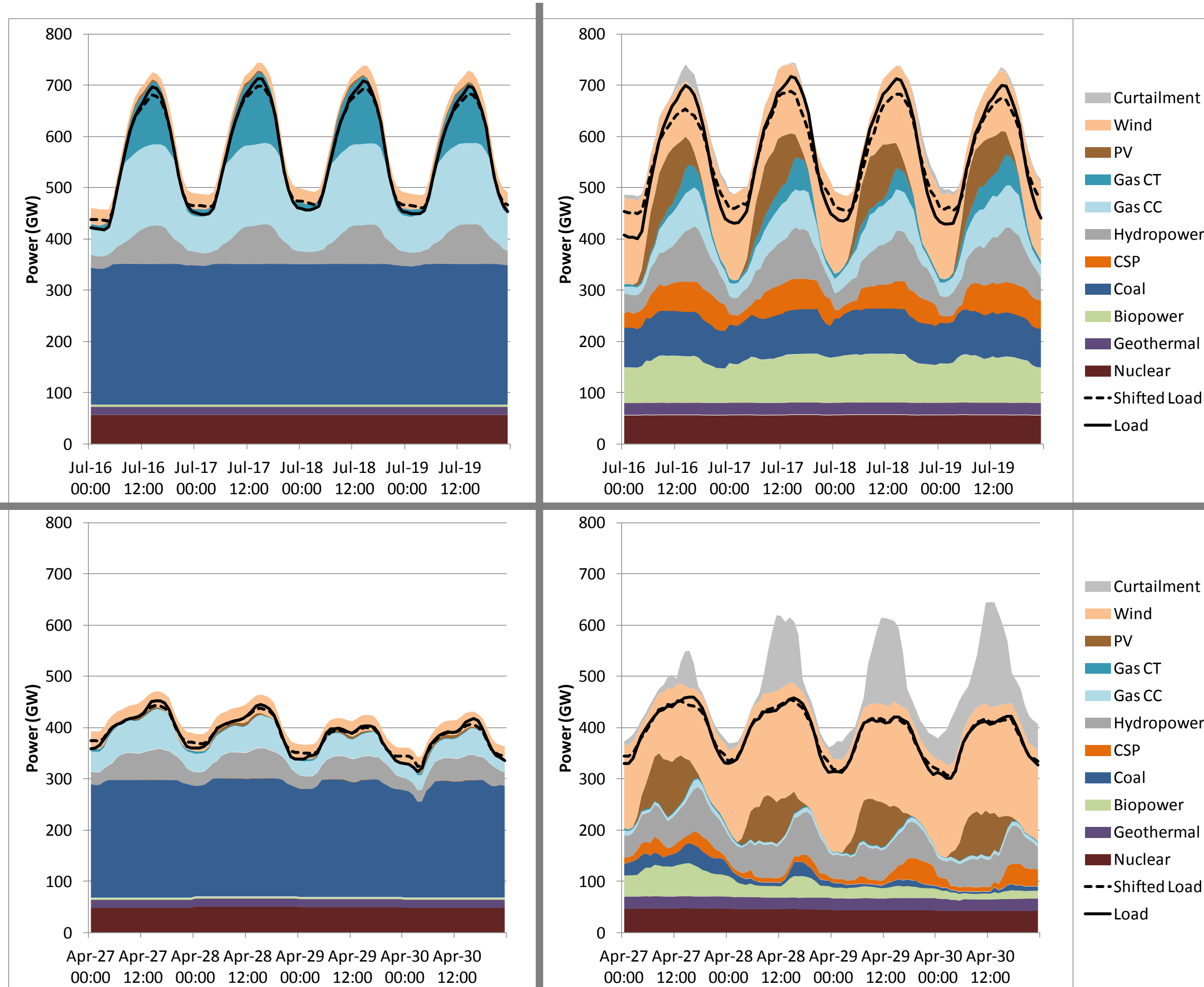
System flexibility can be increased using a broad portfolio of supply- and demand-side options, including:

- **Flexible generators (particularly natural gas)**
- **Dispatchable renewables (e.g., biopower, geothermal, CSP with storage and hydropower)**
- **Demand response (e.g., interruptible load)**
- **Controlled charging of electric vehicles**
- **Storage**
- **Curtailment**
- **Transmission**
- **Geospatial diversity of the variable resources to smooth output**
- **Coordinating bulk power system operations across wider areas**

Electricity supply and demand can be balanced in every hour of the year in each region with 80% electricity from renewable resources*

Peak →

Off-Peak →

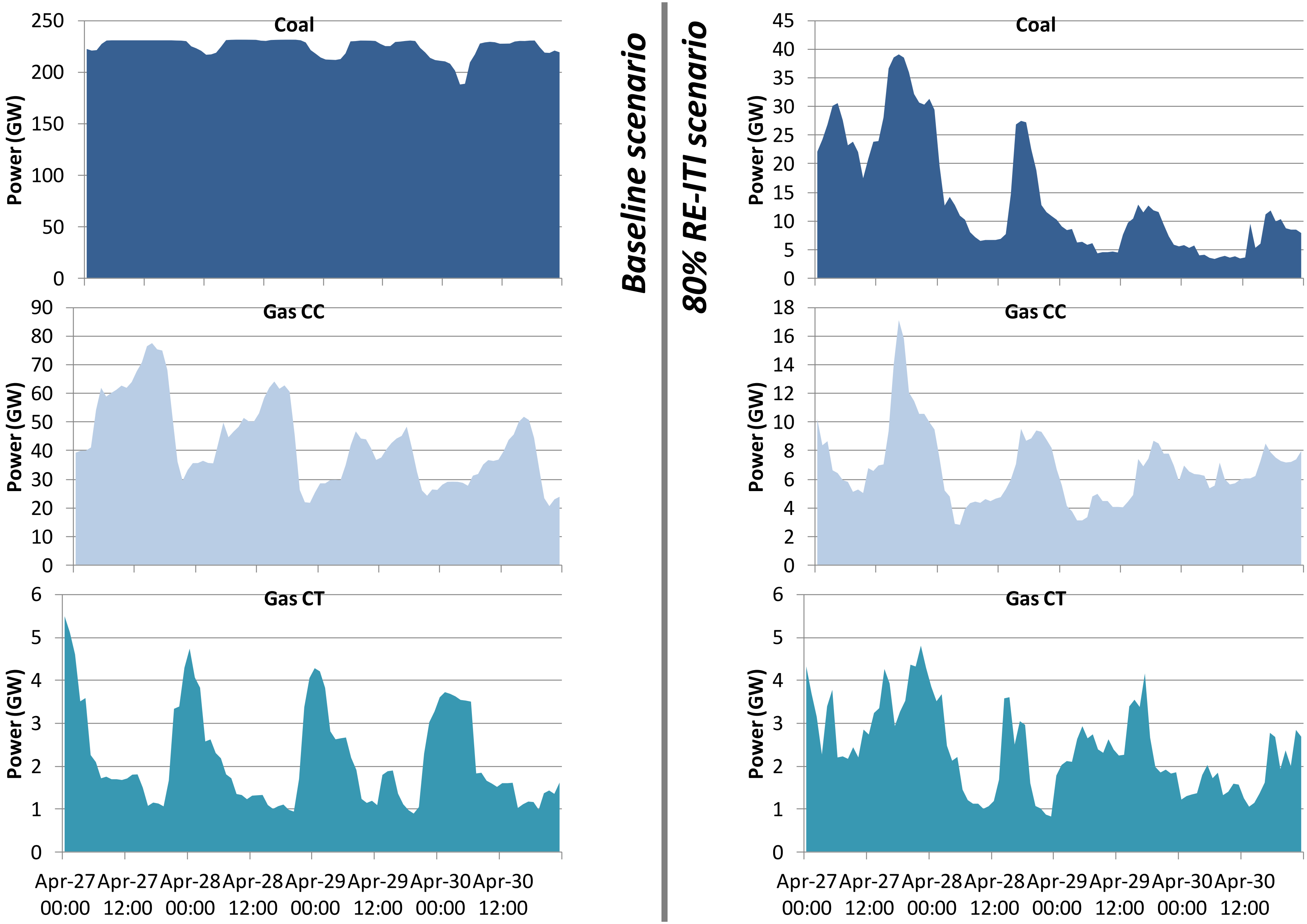


Baseline scenario

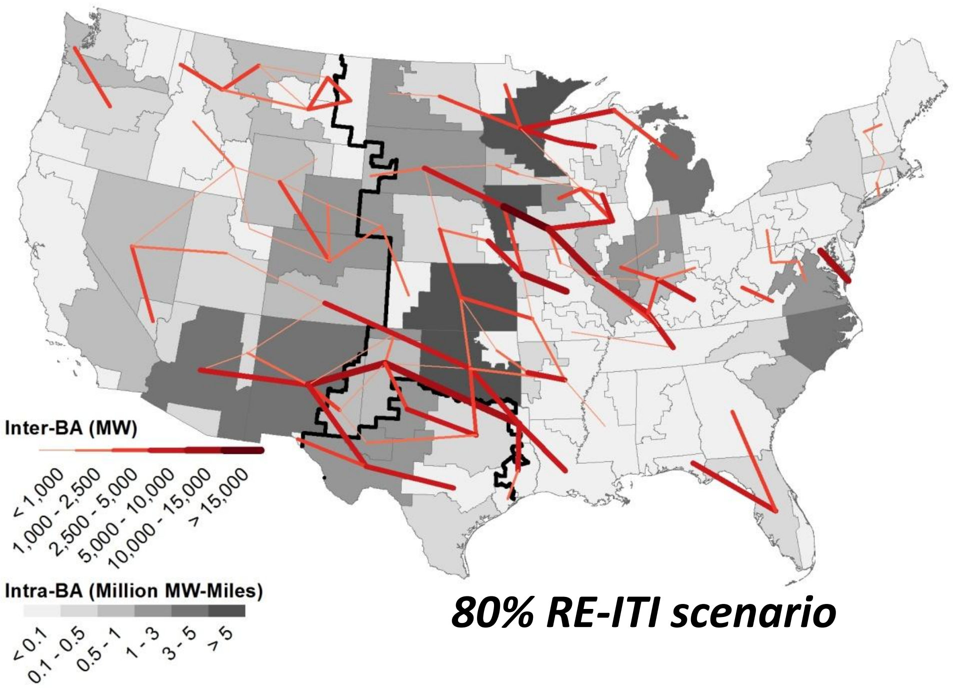
80% RE-ITI scenario / Constrained Transmission scenario

****Full reliability analysis not conducted in RE Futures***

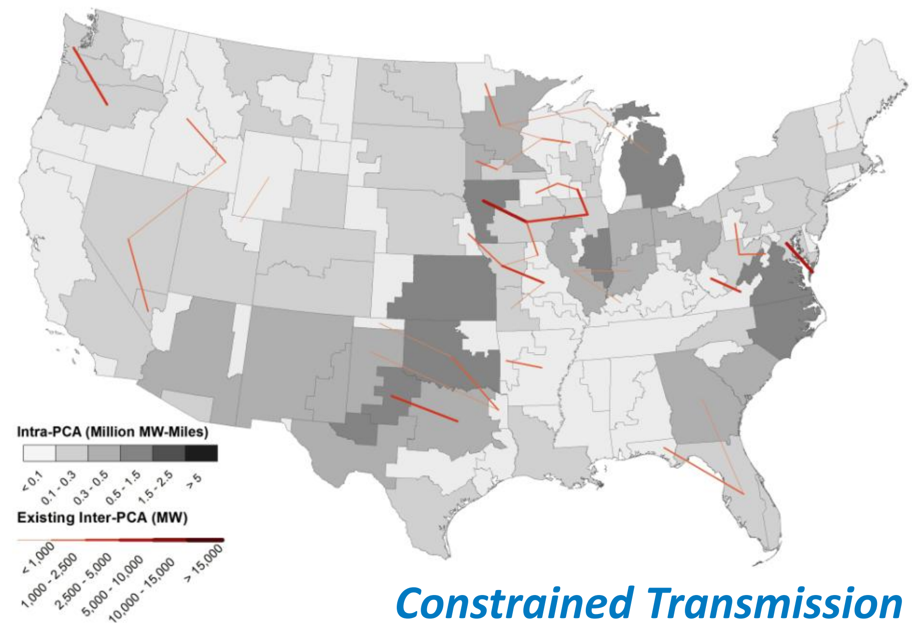
System flexibility provided through increased ramping and startup-shutdown of conventional generators, particularly in low-demand periods



80% RE is achievable with new Transmission or if new Tx is constrained.



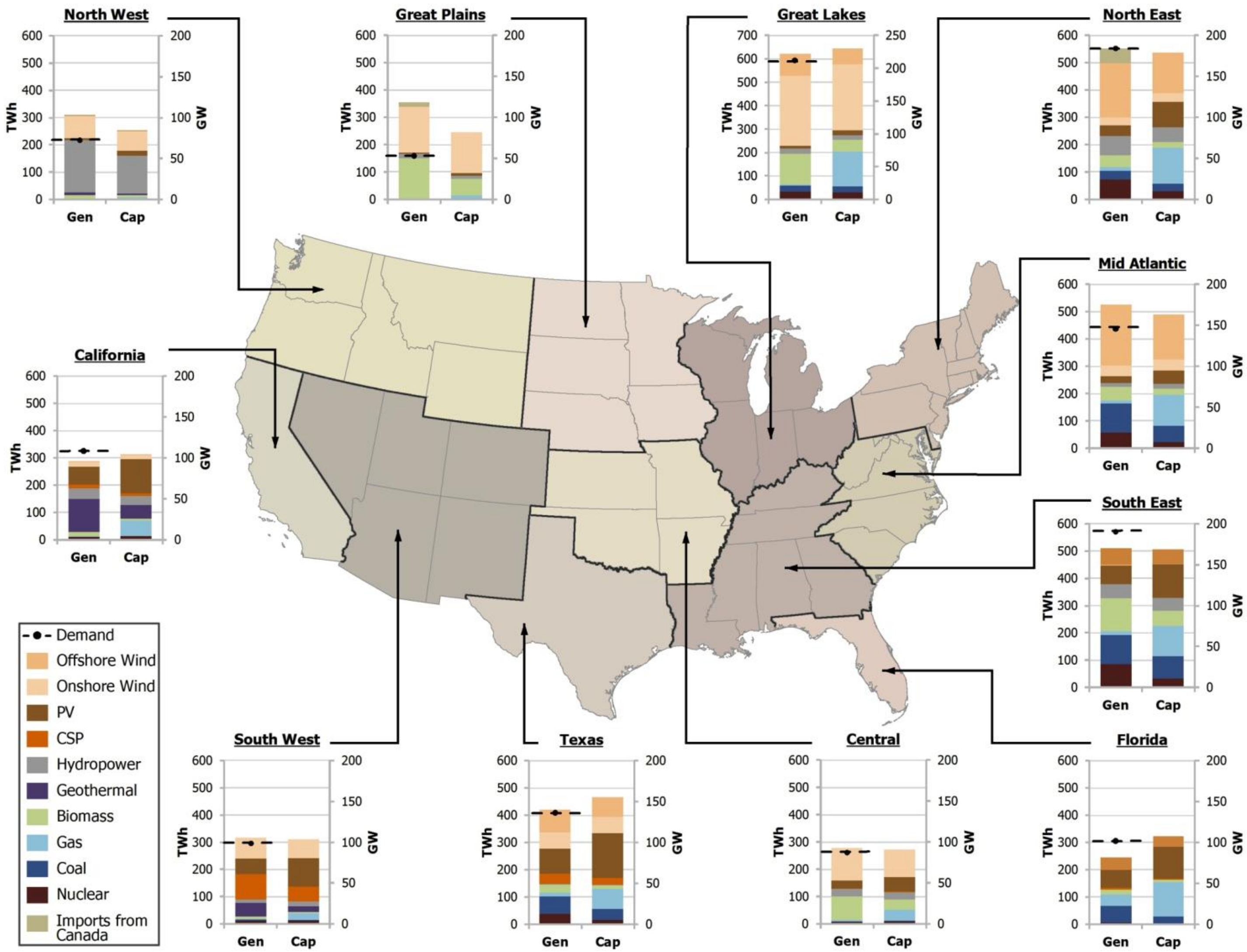
80% RE-ITI scenario



Constrained Transmission

- **In most 80%-by-2050 RE scenarios, 110-190 million MW-miles of new transmission lines are added.**
- **AC-DC-AC interties are expanded to allow greater power transfer between asynchronous interconnects.**
- **However, 80% RE is achievable even when transmission is severely constrained (30 million MW-miles)—which leads to a greater reliance on local resources (e.g. PV, offshore wind).**
- **Annual transmission and interconnection investments in the 80%-by-2050 RE scenarios range from $5.7B-8.4B/year, which is within the range of recent total investor-owned utility transmission expenditures.**
- **High RE scenarios lead to greater transmission congestion, line usage, and transmission and distribution losses.**

All regions of the country could contribute substantial renewable electricity supply in 2050 – especially when transmission is constrained



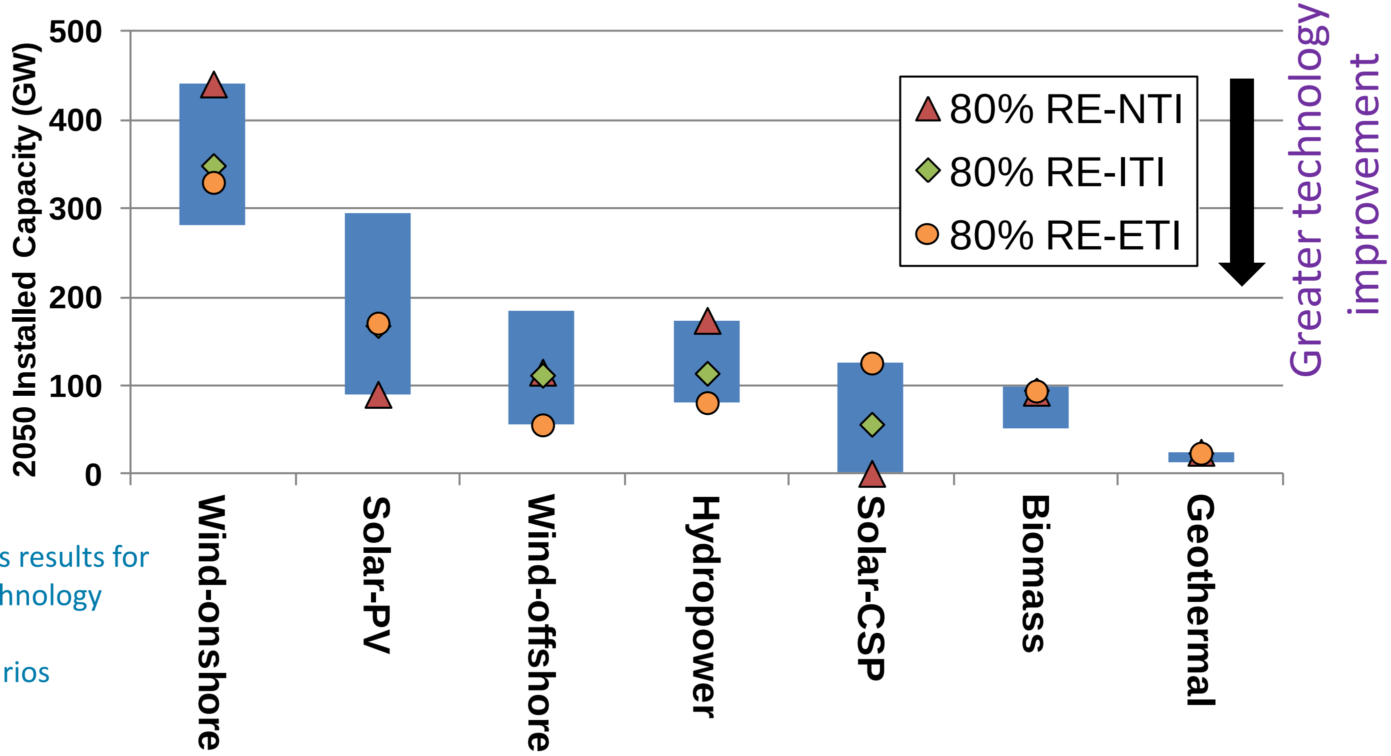
Constrained Transmission scenario

80% RE Scenario Results Comparison *(under RE-ITI technology assumption)*

	Low-Demand				
	80% RE-ITI	**Constrained Transmission**	**Constrained Flexibility**	**Constrained Resources**	**High-Demand**
% variable generation	**43%**	47% ↑	39% ↓	47% ↑	49% ↑
New Transmission	**119 million MW-miles**	28 million MW-miles ↓	132 million MW-miles ~	188 million MW-miles ↑	182 million MW-miles ↑
T&D Losses	**8.6%**	8.3% ~	9.0% ↑	9.5% ↑	8.9% ~
Operating Reserve Reqt.	**96 GW**	114 GW ↑	128 GW ↑	99 GW ~	143 GW ↑
Interruptible Load	**38 GW**	48 GW ↑	28 GW ↓	38 GW ~	64 GW ↑
Curtailment (% of var gen)	**5.6%**	8.6% ↑	7.0% ↑	6.2% ~	7.1% ↑
Storage	**122 GW**	129 GW ~	152 GW ↑	131 GW ~	136 GW ↑

Red arrows indicate magnitude and direction of change relative to the 80% RE-ITI scenario

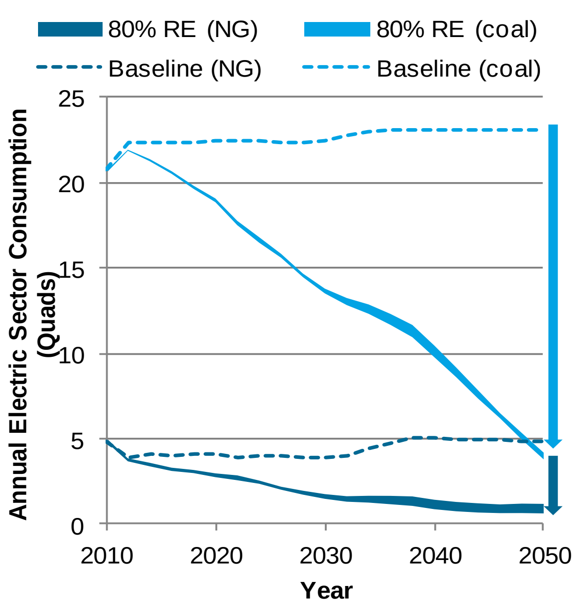
The abundance and diversity of RE resources can support multiple combinations of RE technologies to provide 80% generation by 2050

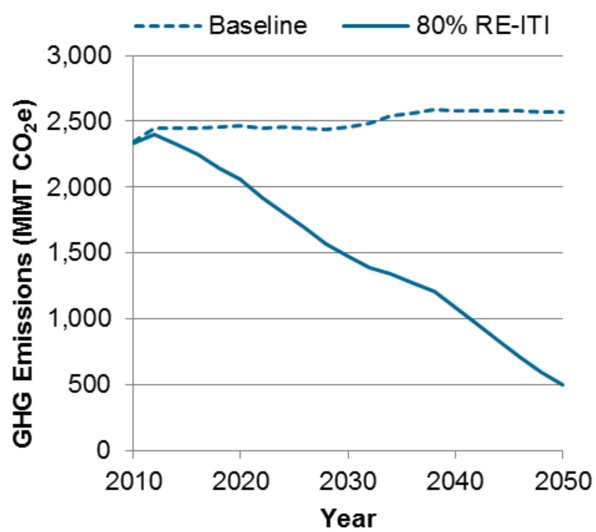


Ranges encompass results for (low-demand) Technology Improvement and Constrained scenarios

- **Future (relative) *RE technology cost and performance* drives deployment toward different mix of technologies depending on commercial and technological maturity**

High renewable electricity futures can result in deep reductions in electric sector greenhouse gas emissions and water use





80% RE scenarios (Biomass; All Other RE; All Other RE (disrupted); Transmission & Storage)

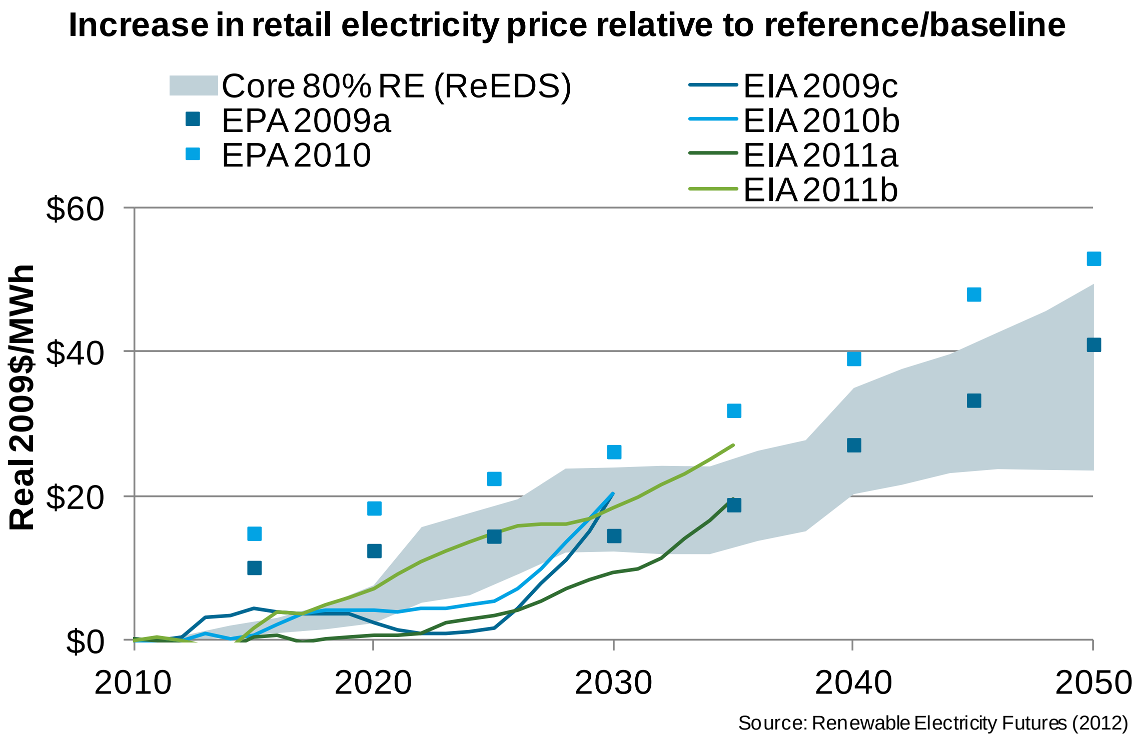
Gross Land Use Comparisons (000 km²)	
Biomass	44-88
All Other RE	52-81
All Other RE (disrupted)	4-10
Transmission & Storage	3-19
Total Contiguous U.S.	7,700
2009 Corn Production*	350
Major Roads**	50
Golf Courses **	10

** USDA 2010, **Denholm & Margolis 2008*

80% RE scenarios lead to:

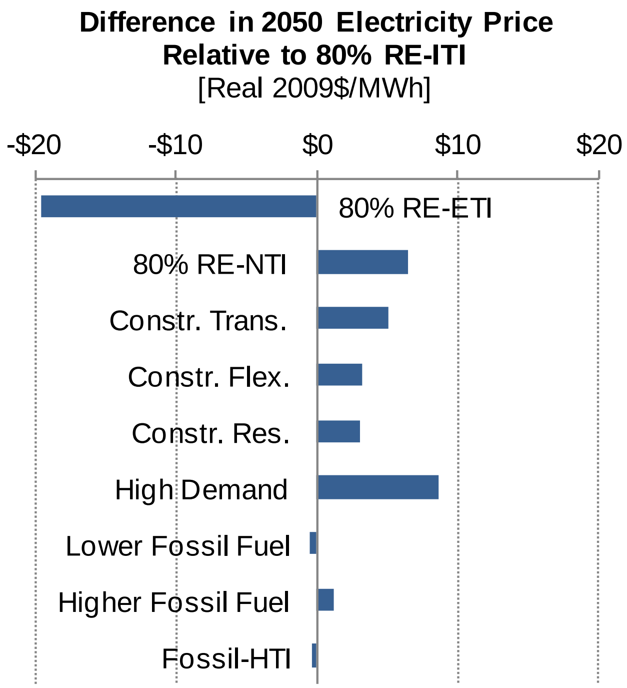
- ~80% reduction in 2050 generation from both coal-fired and natural gas-fired sources
- ~80% reduction in 2050 GHG emissions (combustion-only and life cycle)
- ~50% reduction in electric sector water use
- Gross land use totaling <3% of contiguous U.S. area; other related impacts include visual, landscape, noise, habitat, and ecosystem concerns.

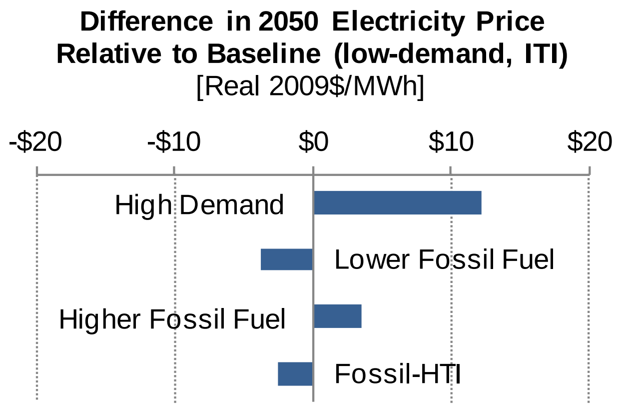
Incremental cost associated with high RE generation is comparable to published cost estimates of other clean energy scenarios



- **Comparable to incremental cost for clean energy and low carbon scenarios evaluated by EIA and EPA**
- **Reflects replacement of existing generation plants with new generators and additional balancing requirements (combustion turbines, storage, and transmission) compared to baseline scenario (continued evolution of today's conventional generation system)**
- **Assumptions reflect incremental or evolutionary improvements to currently commercial RE technologies; they do not reflect U.S. DOE activities to further lower these costs.**

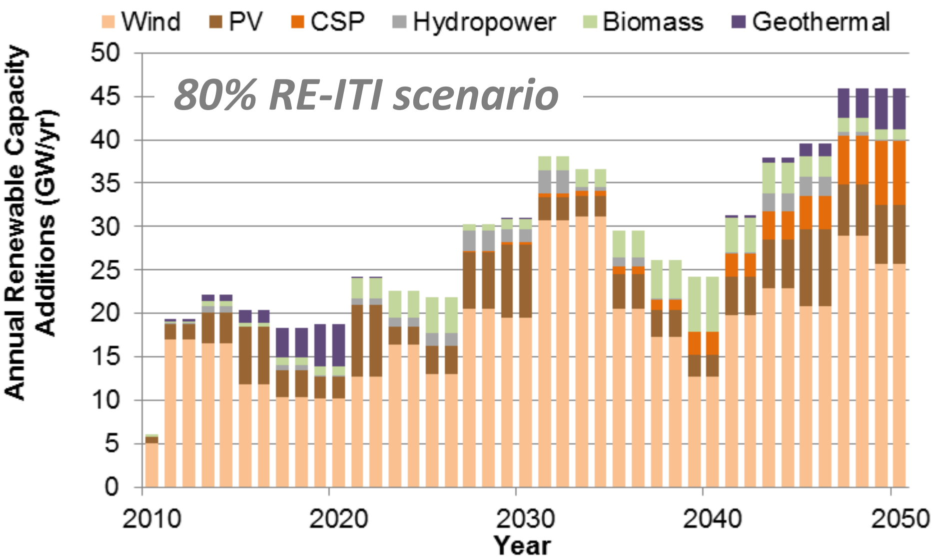
Improvement in cost and performance of RE technologies is the most impactful lever for reducing the incremental cost

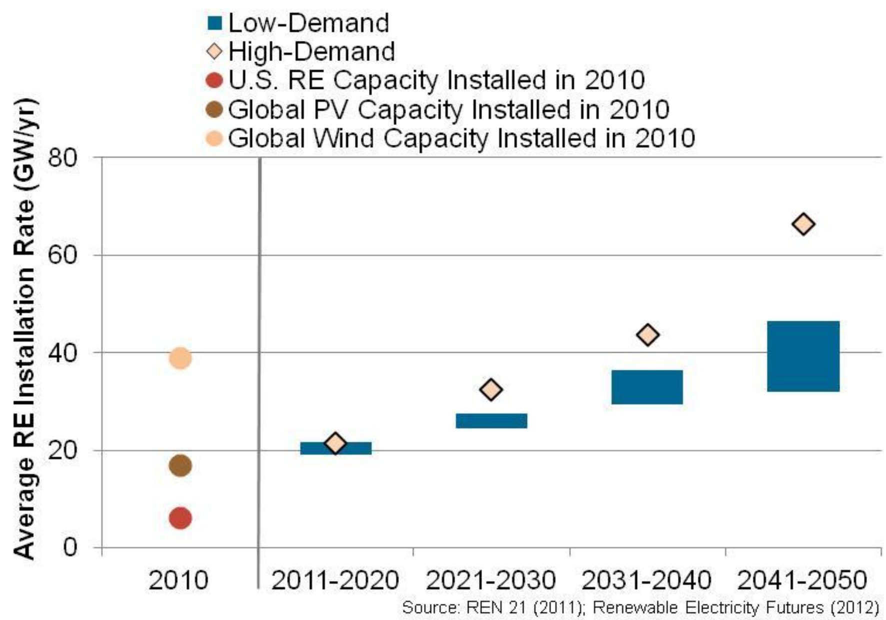




- **Cost is less sensitive to the assumed electric system constraints (transmission, flexibility, RE resource access).**
- **Electricity prices in high RE scenarios are largely insensitive to projections for fossil fuel prices and fossil technology improvements.**
- **Lower RE generation levels result in lower incremental prices (e.g., 30% RE-ETI scenario shows no incremental cost relative to the baseline scenario).**
- **Cost figures do not reflect savings or investments associated with energy efficiency assumptions in the low-demand *Baseline* and *80% RE* scenarios.**

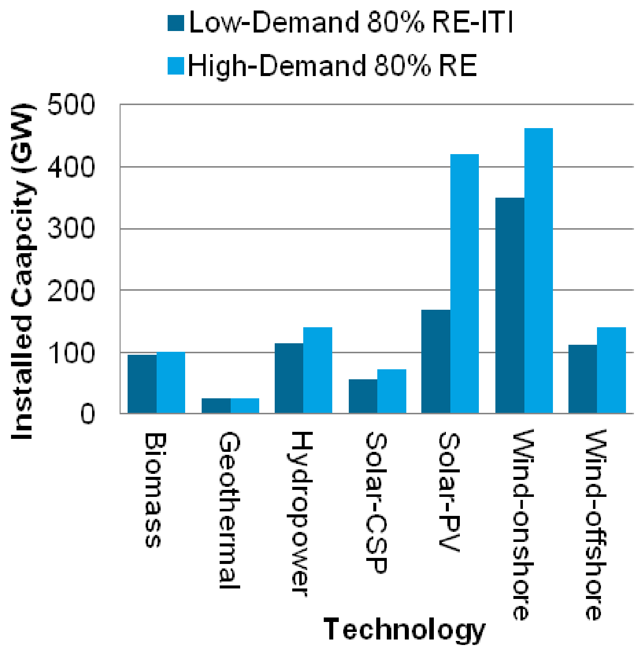
No insurmountable long-term constraints to RE technology manufacturing capacity, materials supply, or labor availability were identified



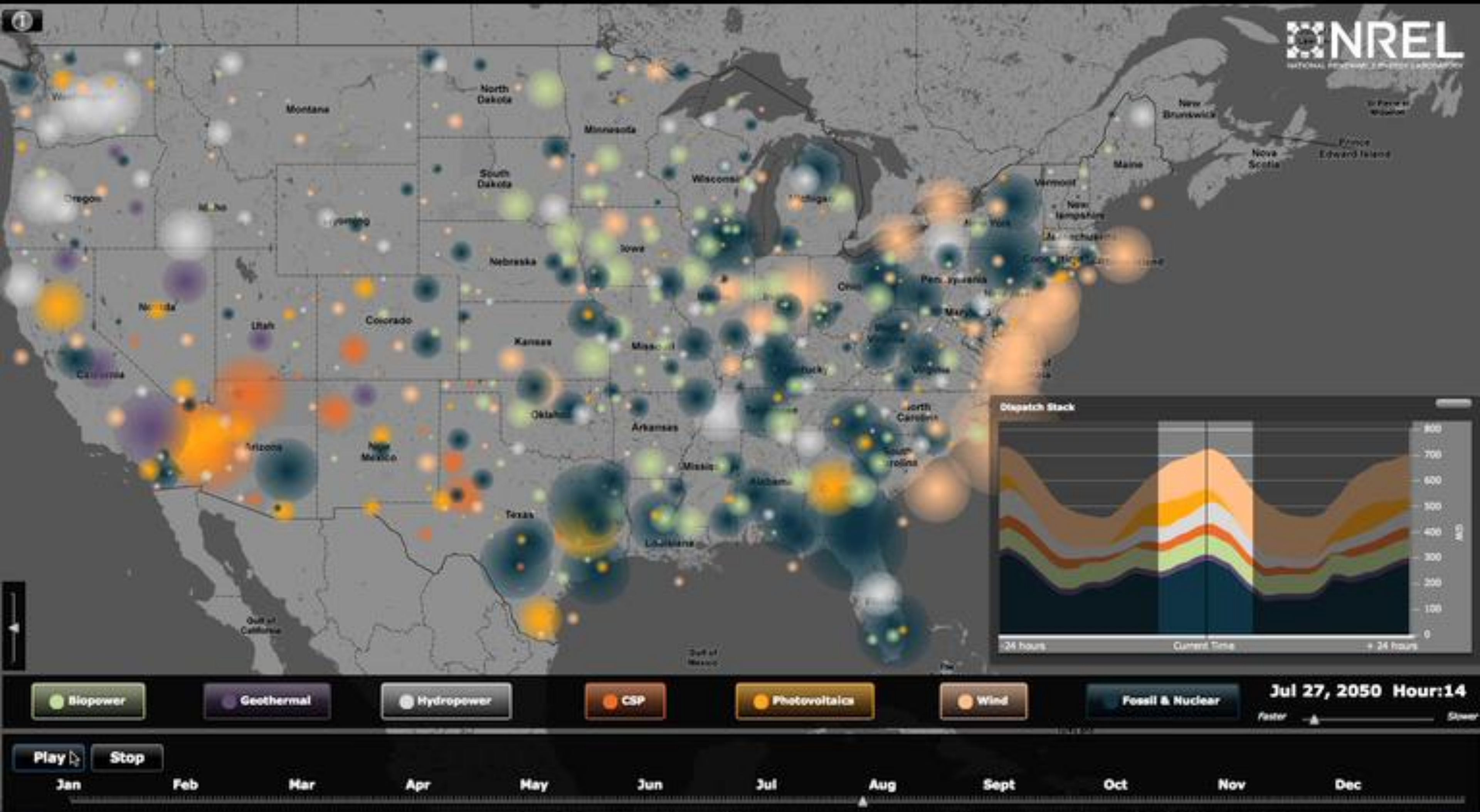


- **80% RE generation in 2050 requires additions of ~20 GW/year in 2011-2020 , ~30/GW/year in 2021-2040, and ~40 GW/year in 2041-2050 (higher under High-Demand scenario).**
- **These installation rates are higher than U.S. capacity additions in 2010 (7 GW) and 2009 (11 GW) and would place challenges on RE industries.**
- **Recent U.S. and worldwide growth demonstrate the scalability of RE industries.**
- **More informed siting practices and regulations can reduce industry scale-up challenges.**

Renewables can meet 80% of High Demand Scenario



- Higher demand growth generally implies an increased need for new generation and transmission capacity in both the baseline and 80% RE scenarios.
- More renewable generation capacity, particularly wind and PV, is needed; it will result in greater industry scale-up and resource access challenges.
- Additional flexible supply- and demand-side capacity (e.g., storage, natural gas combustion turbine power plants, and interruptible load) is also needed.
- While higher demand growth shows greater increases in electricity prices, the direct incremental cost associated with high renewable generation levels decreases (the prices in baseline also increase).
- Cost-effectiveness of energy efficiency vs. supply-side options was not evaluated.


NREL
Montana
North Dakota
Minnesota
South Dakota
Wisconsin
Nebraska
Iowa
Colorado
Kansas
Utah
Oregon
Nevada
California
Arizona
New Mexico
Oklahoma
Arkansas
Texas
Louisiana
Pennsylvania
Ohio
Vermont
Maine
New Brunswick
Nova Scotia
Prince Edward Island
Dispatch Stack
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Biopower
Geothermal
Hydropower
CSP
Photovoltaics
Wind
Fossil & Nuclear
Jul 27, 2050 Hour:14
Faster
Slower
Play
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Jan
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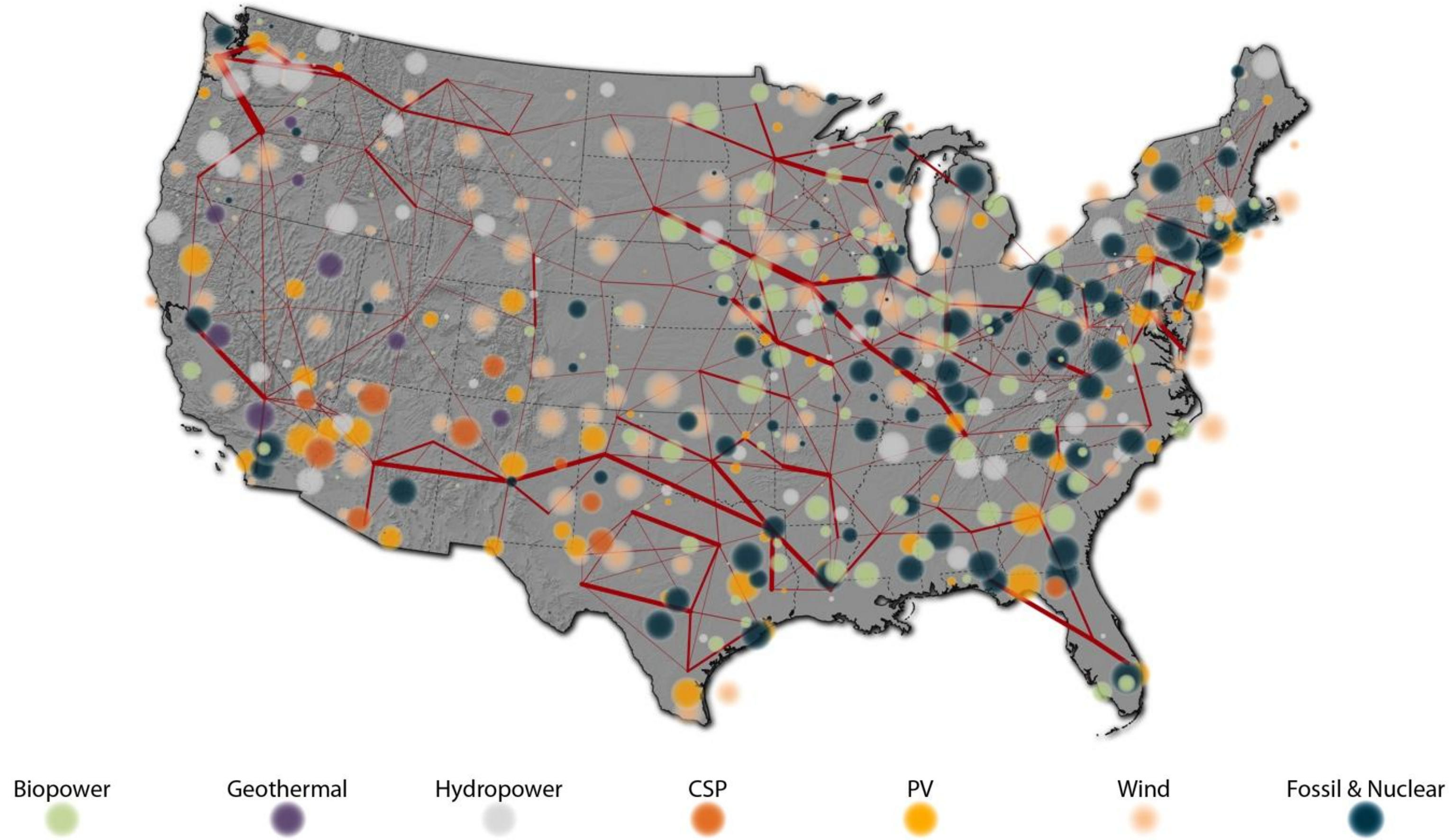
Future Work Needed

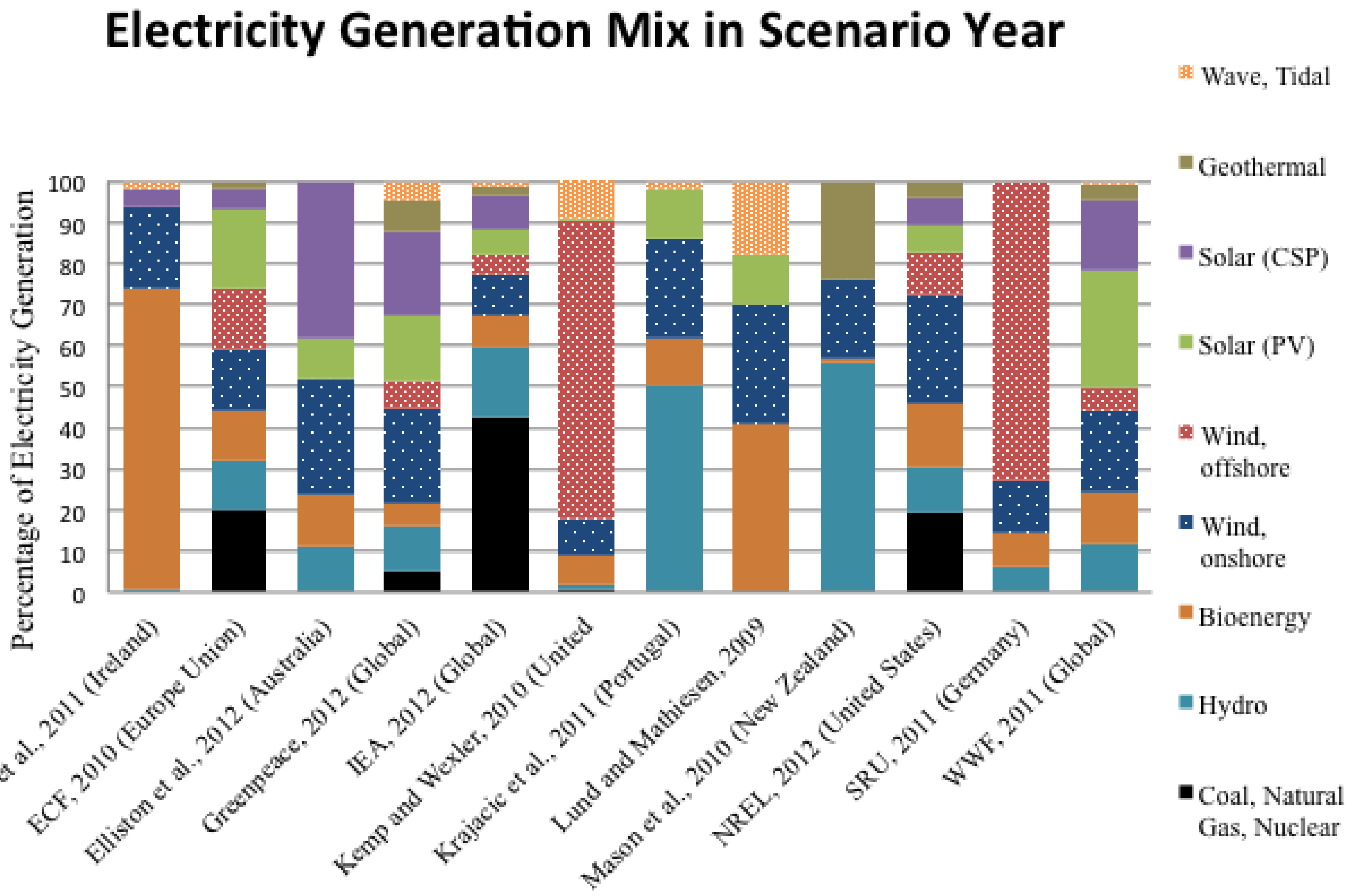
- A comprehensive cost-benefit analysis
- Comprehensive power system reliability analysis
- Market Design, Institutional, and other structural areas…
- Deeper analysis of advanced technologies, including supply and demand-side flexibility

www.nrel.gov/RE_Futures



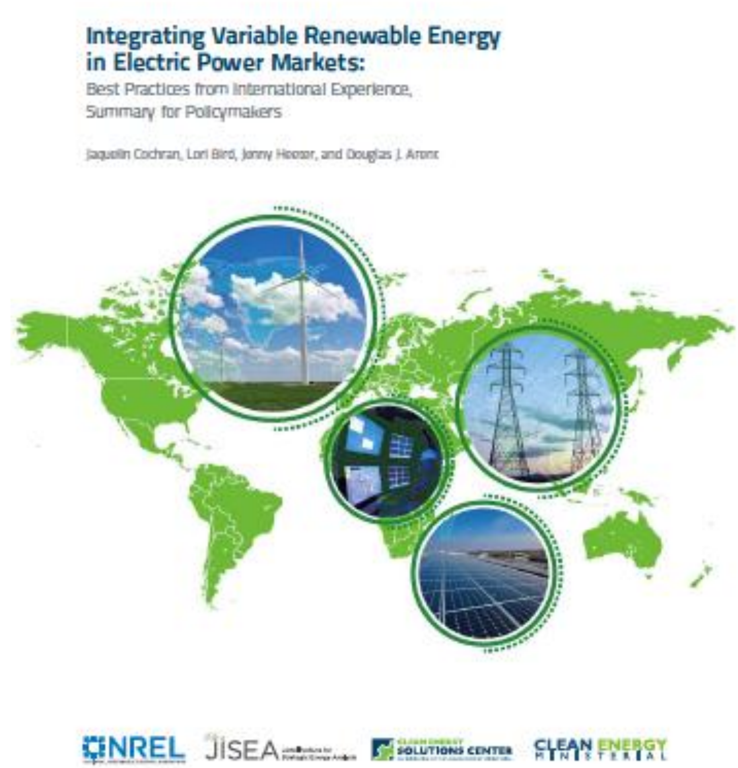
A future U.S. electricity system that is largely powered by renewable sources is possible, and further work is warranted to investigate this clean generation pathway.

International Scenarios & Best Practices



NZ, Ireland: 2007; Portugal 2020: UK 2030, rest 2050

21st Century
POWER
PARTNERSHIP
Accelerating the transformation of power systems



CLEAN ENERGY
MINISTERIAL
Accelerating the Transition to Clean Energy Technologies

21st Century Power Partnership

- **Accelerate the transition to clean, efficient, reliable and cost-effective power systems.**
  - The 21CPP is a multilateral effort of the Clean Energy Ministerial (CEM) and serves as a platform for international efforts to advance integrated policy, regulatory, financial, and technical solutions for the deployment of renewable energy in combination with large-scale energy efficiency and smart grid solutions.
  - Core Elements
    1. Global Expertise
    2. Public-private collaboration
    3. Peer-to-peer learning
    4. Integrated systems approaches

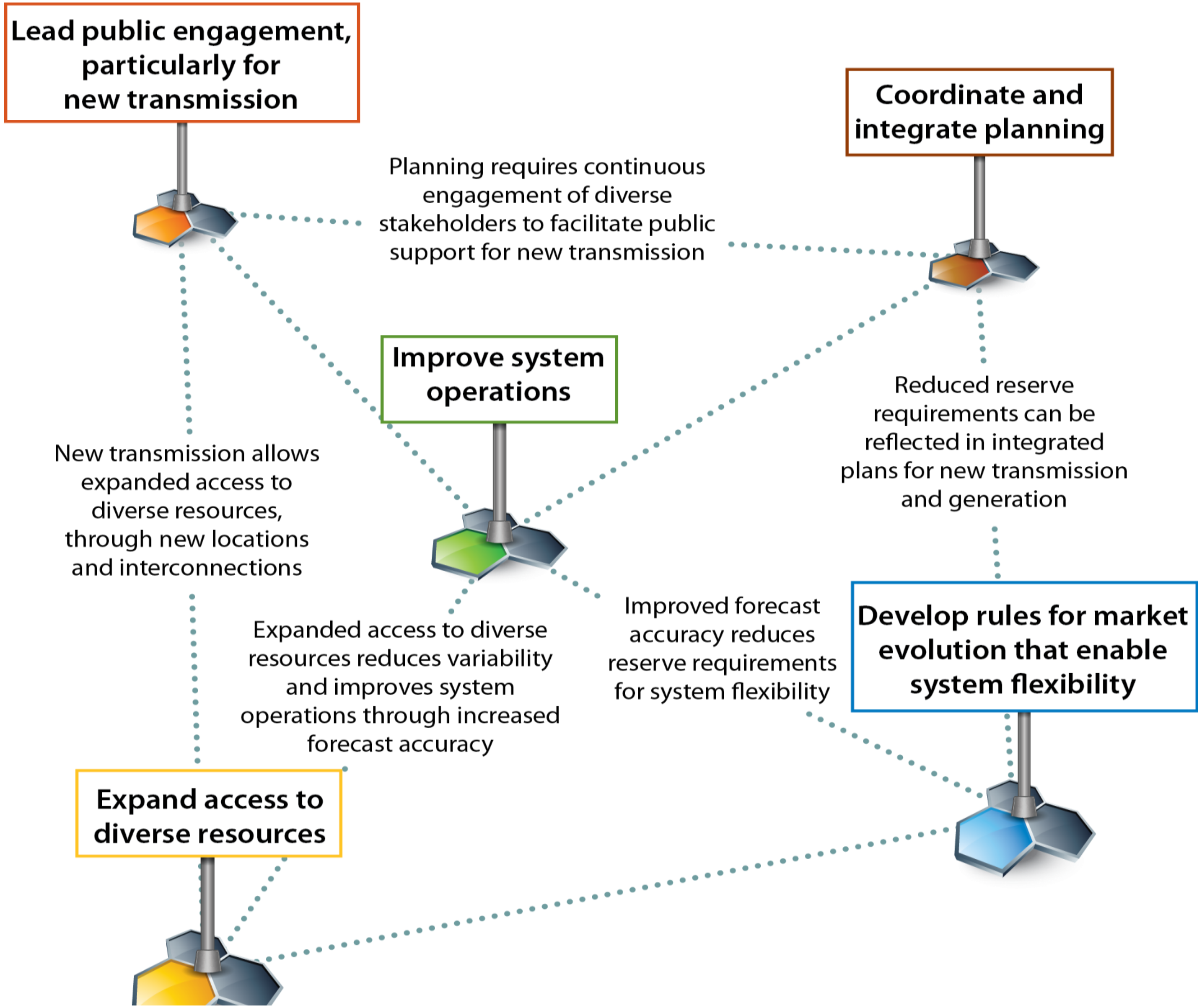
Actions to Accommodate High RE

A. Lead public engagement, particularly for new transmission
B. Coordinate and integrate planning
C. Develop rules for market evolution that enable system flexibility
D. Expand access to diverse resources and geographic footprint of operations
E. Improve system operations

Actions Reflect Market Status

	Public Outreach	Planning	Market Rules	Expanded Access	System Operations
At LOW RE Penetrations	Involve public stakeholders in planning	Evaluate system flexibility, penetration scenarios, transmission needs, and future flexibility needs	Evaluate market design and implications for higher penetrations of RE	Assess renewable energy resources and options for encouraging geographic diversity	Build capacity of grid operator staff; review regulatory changes needed to require advanced forecasting
At MEDIUM RE Penetrations	Communicate to public why new transmission is essential	Regulatory and legislative changes needed to accommodate revised scenario planning, such as laws to support renewable energy zones (REZs)	Ensure that market design and pricing environment aligns with technical needs, such as accessing flexibility, minimizing uncertainty, and managing risk	Make necessary regulatory, market, or institutional changes	Implement grid codes to accommodate high penetrations of variable RE
At HIGH RE Penetrations		Monitor and review effectiveness of actions; revise	Make additional changes to market rules to meet technical needs, such as accessing flexibility, minimizing uncertainty, and managing risk	Ensure broad systems solutions are sought, including smart grid/demand response, storage, and complementary flexible generators	

System-wide Approach More Effective



Key Findings—Actions for Ministers

1. Commission a comprehensive assessment of the technical, institutional, human capital, and market status and factors influencing renewable energy integration
2. Develop visionary goals and plans at national and regional levels, and empower appropriate leadership to bring the visions to fruition
3. Lead the public engagement to communicate goals and needed actions to attain them
4. Engage in international coordination to share best practices and strengthen technical, human and institutional capabilities to achieve higher levels of renewable energy penetration


NREL
NATIONAL RENEWABLE ENERGY LABORATORY