Renewable Electricity Futures

Trieu Mai, Ph.D.

PSERC Webinar
September 4, 2012

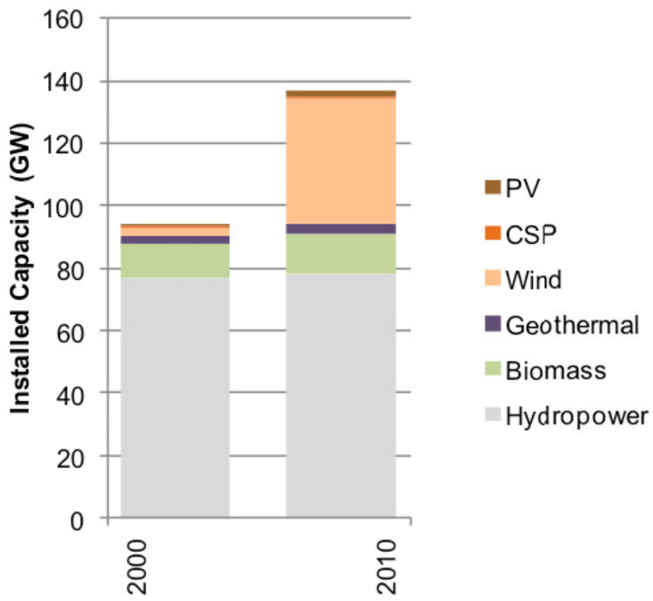
NREL/PR-6A20-56168

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 U.S. DOE-sponsored collaboration among more than 110 individuals from 35 organizations.

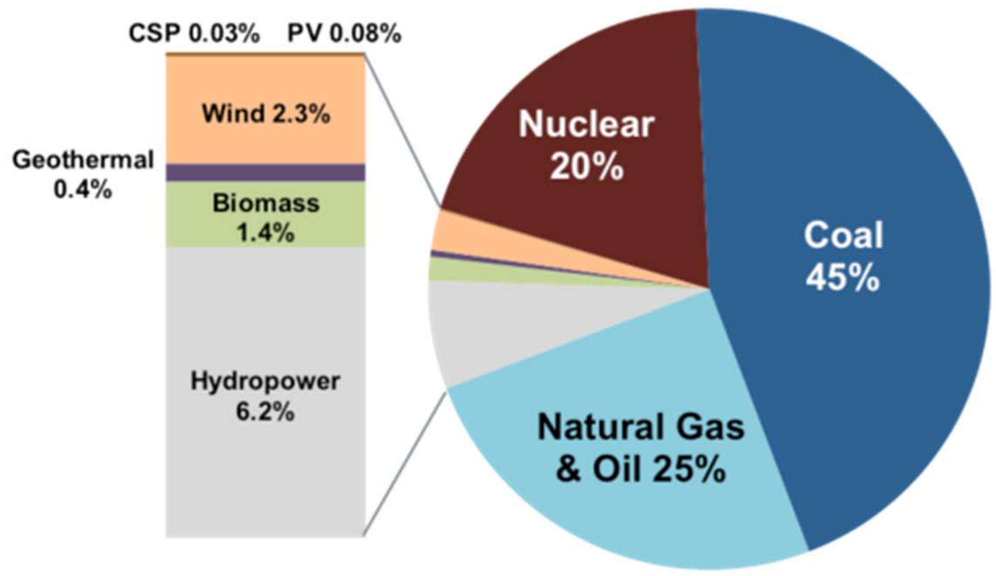
Renewable Electricity Futures Motivation

RE Capacity Growth 2000-2010



Source: RE Data Book (DOE 2011)

2010 Electricity Generation Mix



Source: RE Data Book (DOE 2011)

- **RE is a low carbon, low air pollutant, low fuel use, low water use, domestic, and sustainable electricity source.**
- **To what extent can renewable energy technologies commercially available today meet the U.S. electricity demand over the next several decades?**

Summary of Key Results

- **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.**

Renewable Electricity Futures Introduction

- RE Futures is an analysis of the U.S. electric sector focused on 2050 that explores:
  - 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.
  - Grid integration using models with <u>unprecedented geographic and time resolution</u> for the contiguous U.S.
  - <u>Synergies, constraints, and operational issues</u> associated with a transformation of the U.S. electric sector.

Renewable Electricity Futures Report

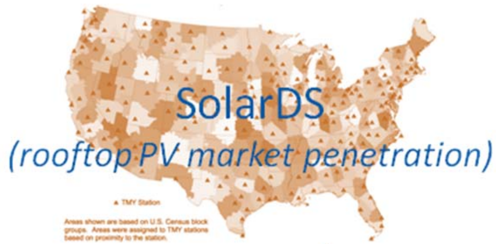
Volume 1	Exploration of High-Penetration Renewable Electricity Futures
Volume 2	Renewable Electricity Generation and Storage Technologies
Volume 3	End-Use Electricity Demand
Volume 4	Bulk Electric Power Systems: Operations and Transmission Planning

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 Introduction

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

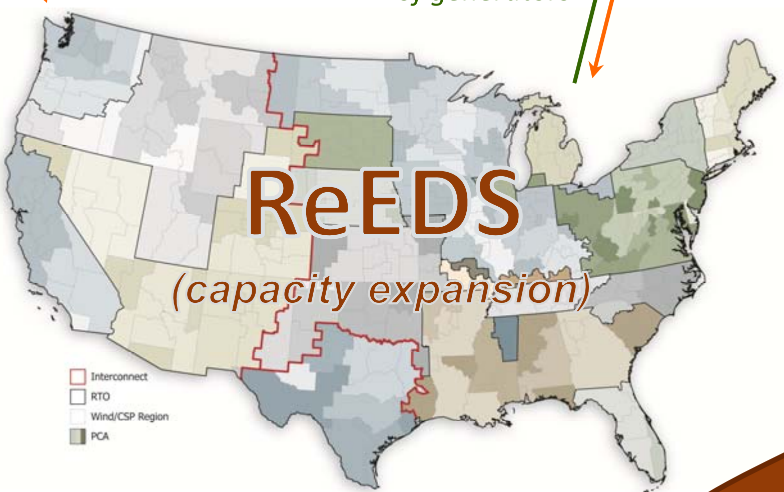
Flexible Resources

End-Use Electricity

System Operations

Transmission

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



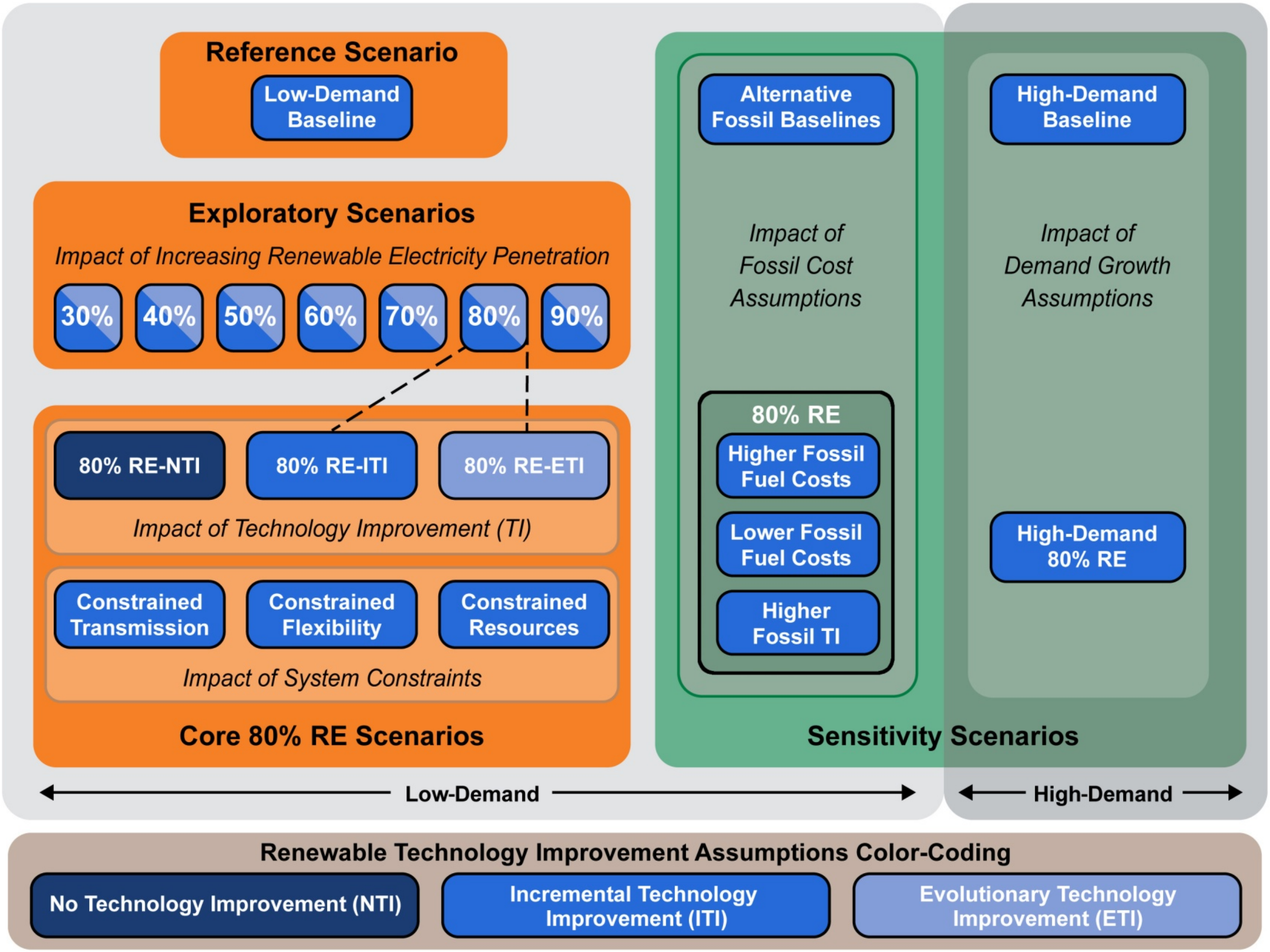
High resolution modeling using **134 nodes** & **hourly time steps**

Implications

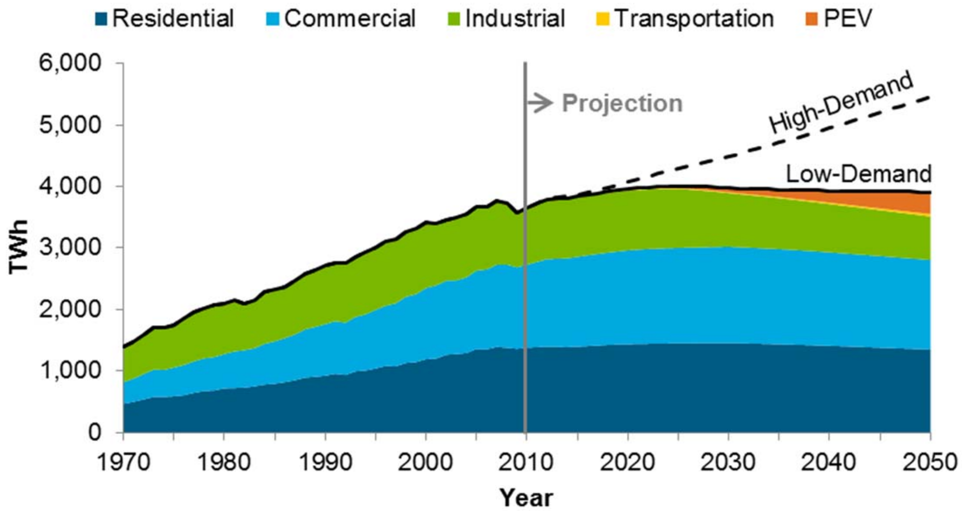
GHG Emissions
Water Use
Land Use
Direct Costs

Capacity & Generation 2010-2050

Scenario Framework



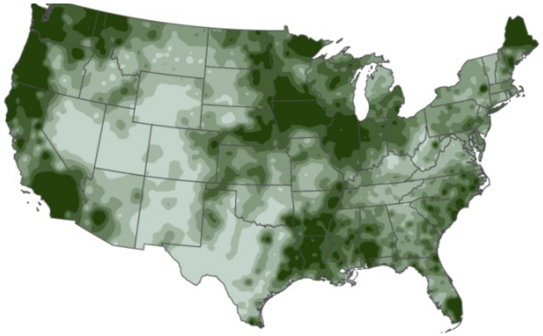
General Assumptions

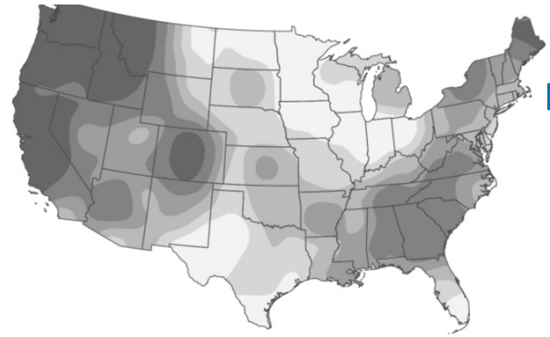


- **Energy Efficiency**: Most of the scenarios assumed significant adoption of energy efficiency (including electricity) measures in the residential, commercial, and industrial sectors.
- **Transportation**: Most of the scenarios assumed a shift of some transportation energy away from petroleum and toward 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

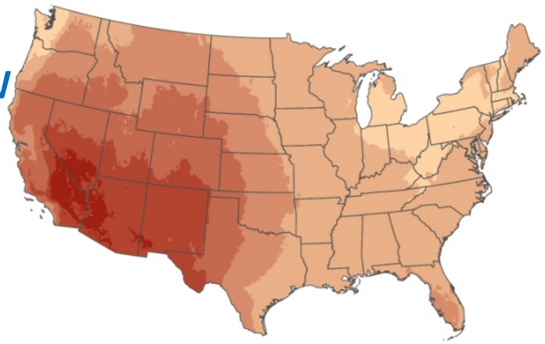


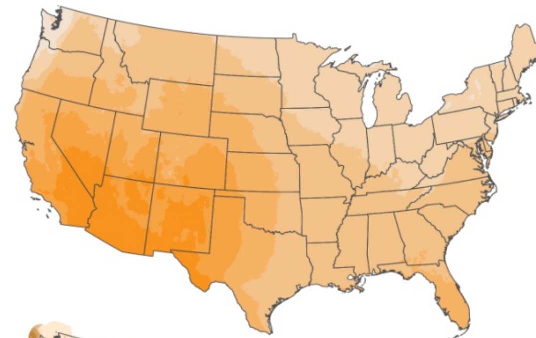


Hydropower ~200 GW
- Run-of-river

Solar CSP ~37,000 GW
- Trough
- Tower

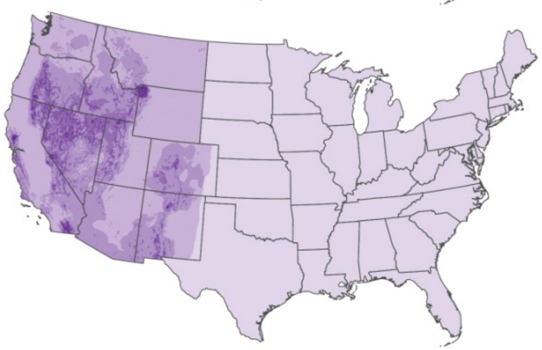
With thermal storage

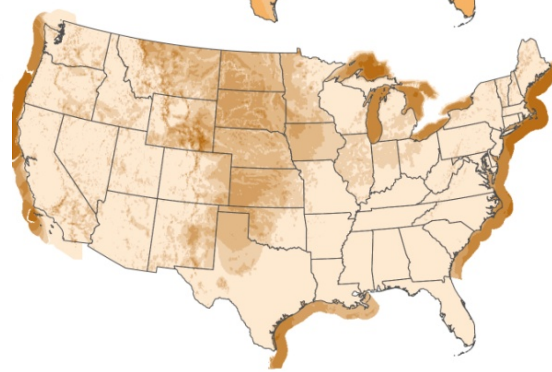




Solar PV ~80,000 GW (rooftop PV ~700 GW)
- Residential
- Commercial
- Utility-scale

Geothermal ~36 GW
- Hydrothermal



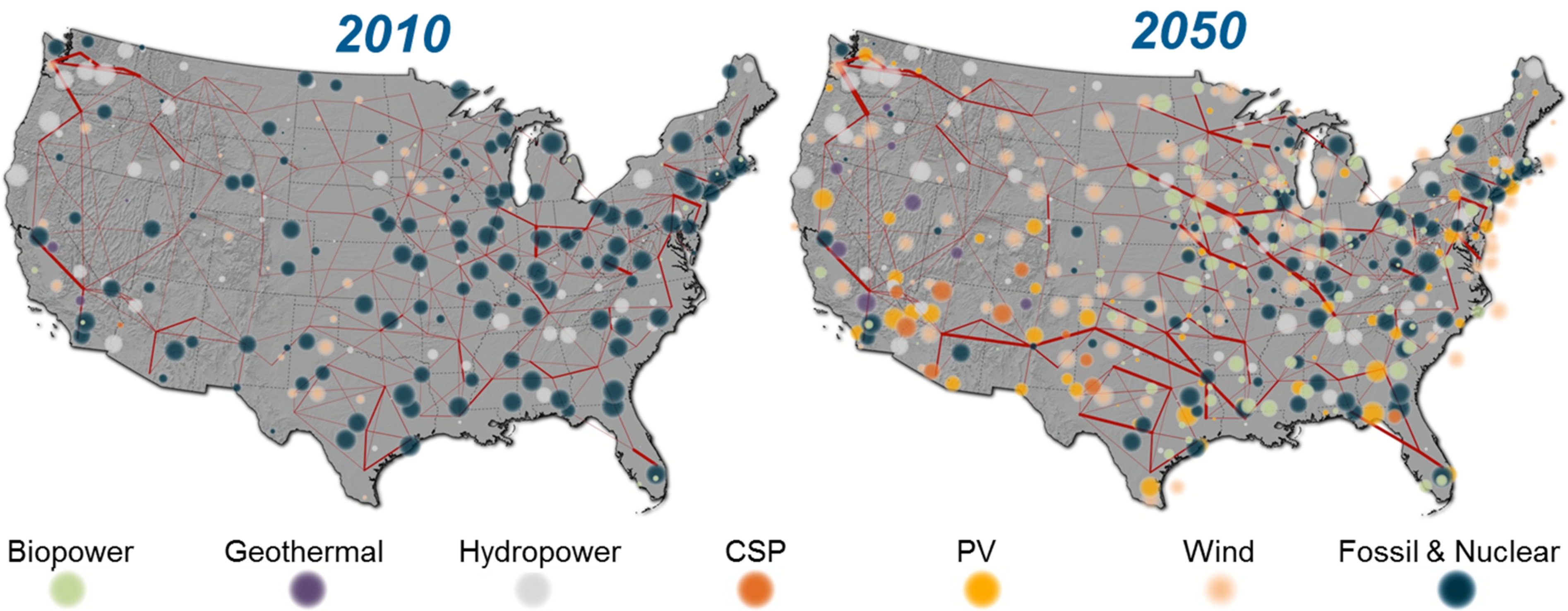


Wind ~10,000 GW
- Onshore
- Offshore fixed-bottom

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

Key Results

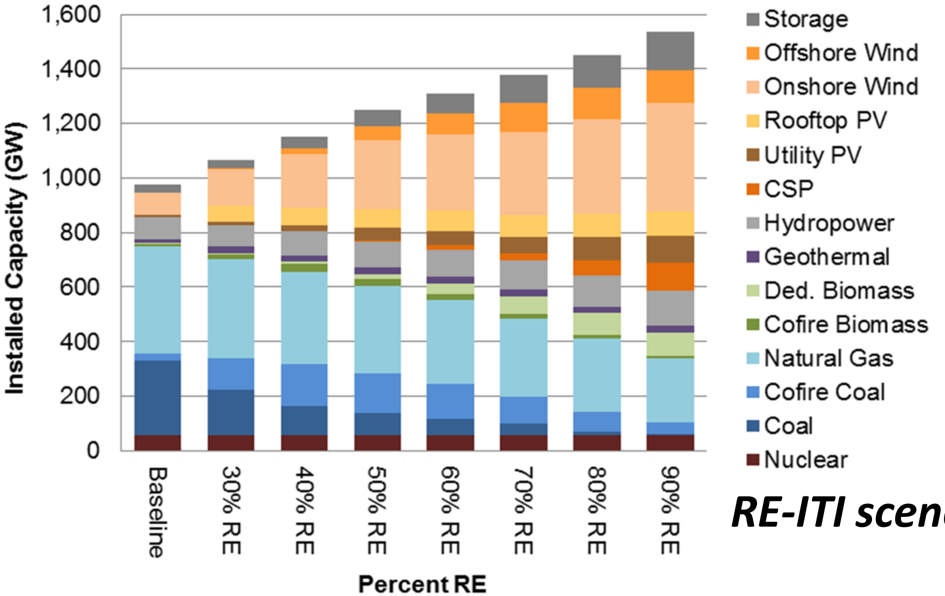
A Transformation of the U.S. Electricity System



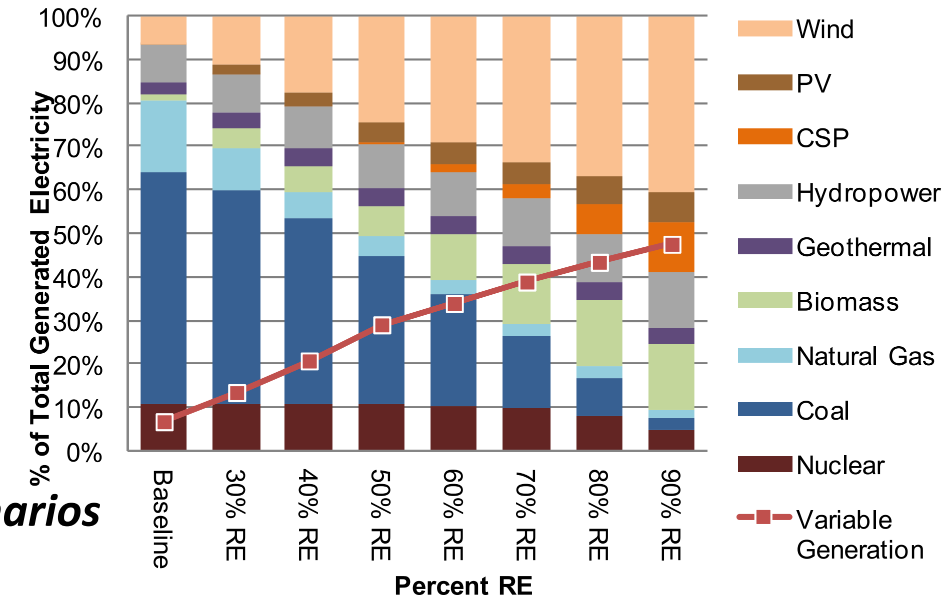
Source: Renewable Electricity Futures (2012)

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.

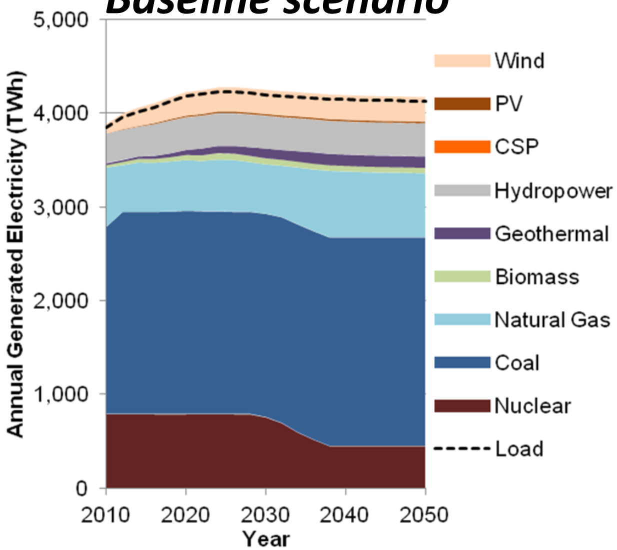
Renewable generation resources could adequately supply 80% of total U.S. electricity generation in 2050 while balancing hourly supply and demand



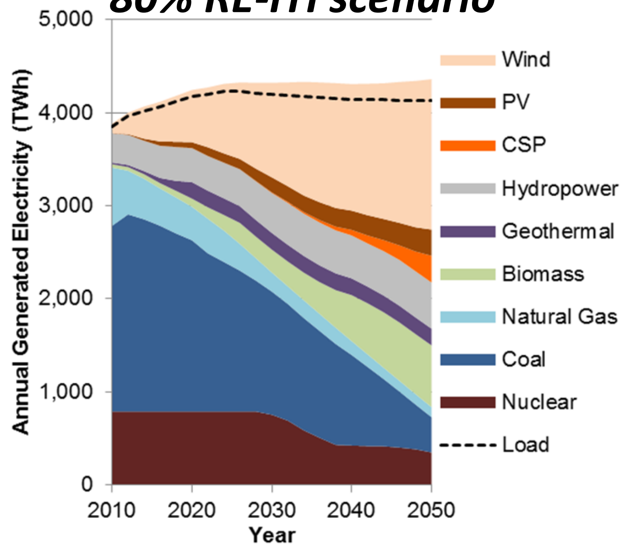
RE-ITI scenarios



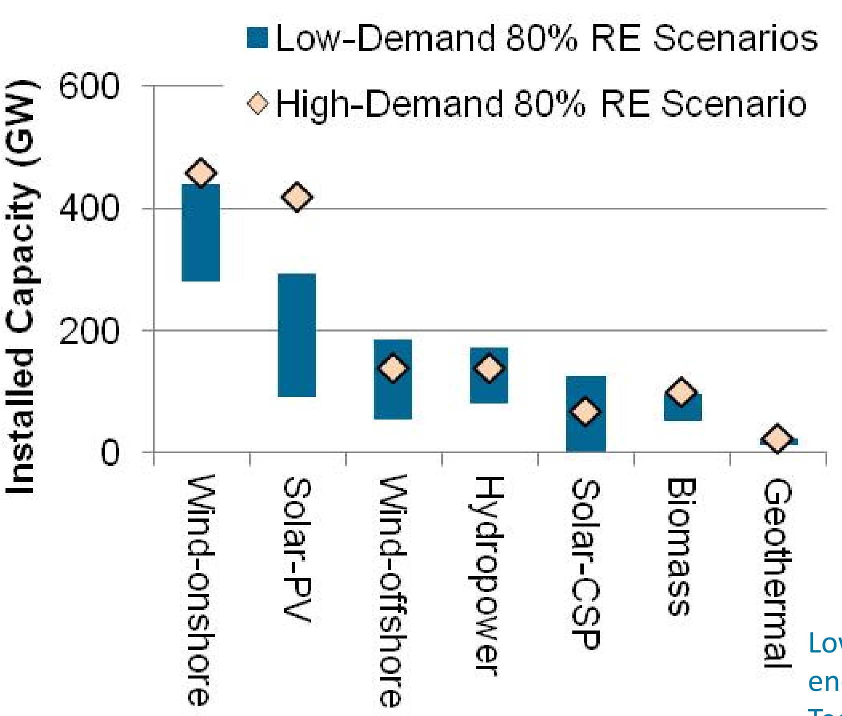
Baseline scenario

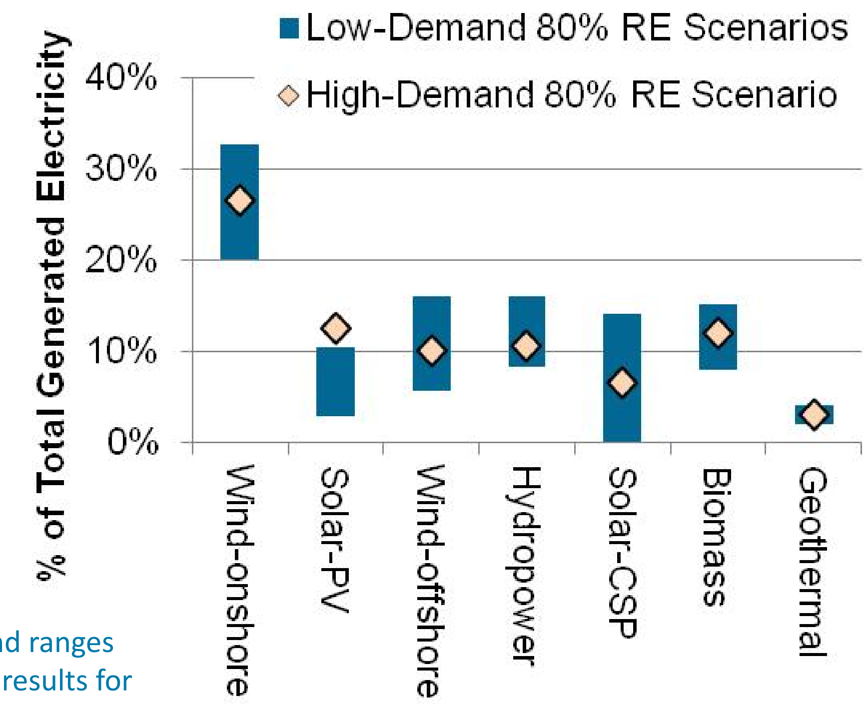


80% RE-ITI scenario



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



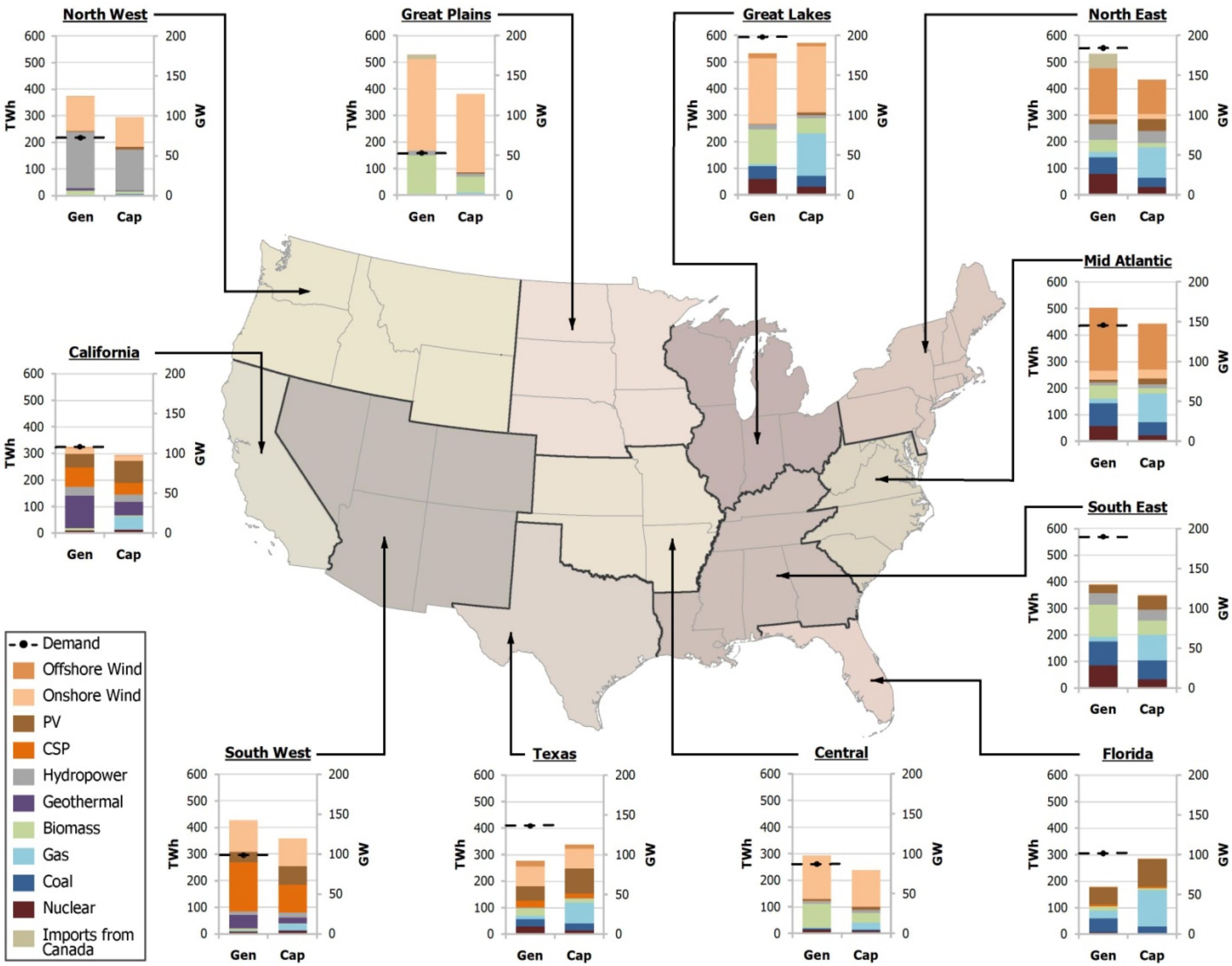


Low-Demand ranges encompass results for Technology Improvement and Constrained scenarios

Source: Renewable Electricity Futures (2012)

- **Technology deployment depends on scenario assumptions, but in all cases examined, RE resources existed to compensate for assumed variations in access to transmission, grid flexibility, resource availability, technology costs, and electricity demand.**
- **Constraints to transmission result in greater PV, offshore wind, and biopower deployment.**
- **Constraints to system flexibility result in greater dispatchable technology deployment, e.g., storage and CSP with thermal storage.**
- **Constraints to resource accessibility result in greater wind and solar deployment.**

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

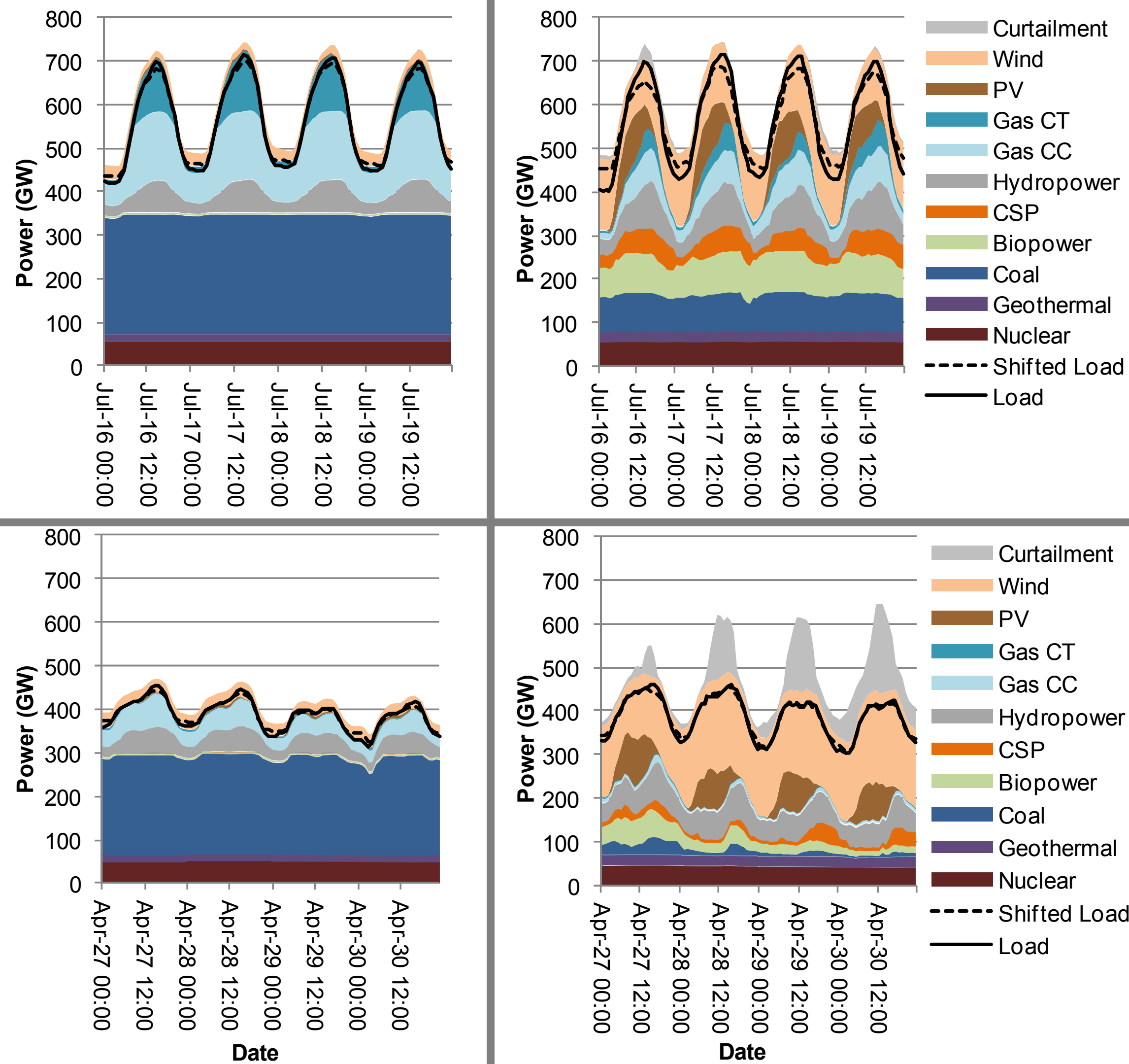


80% RE-ITI scenario

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***

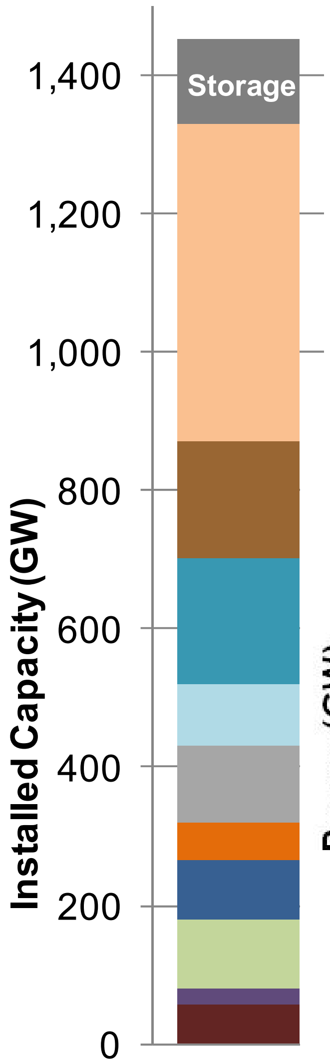
***Full reliability analysis not conducted in RE Futures**

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

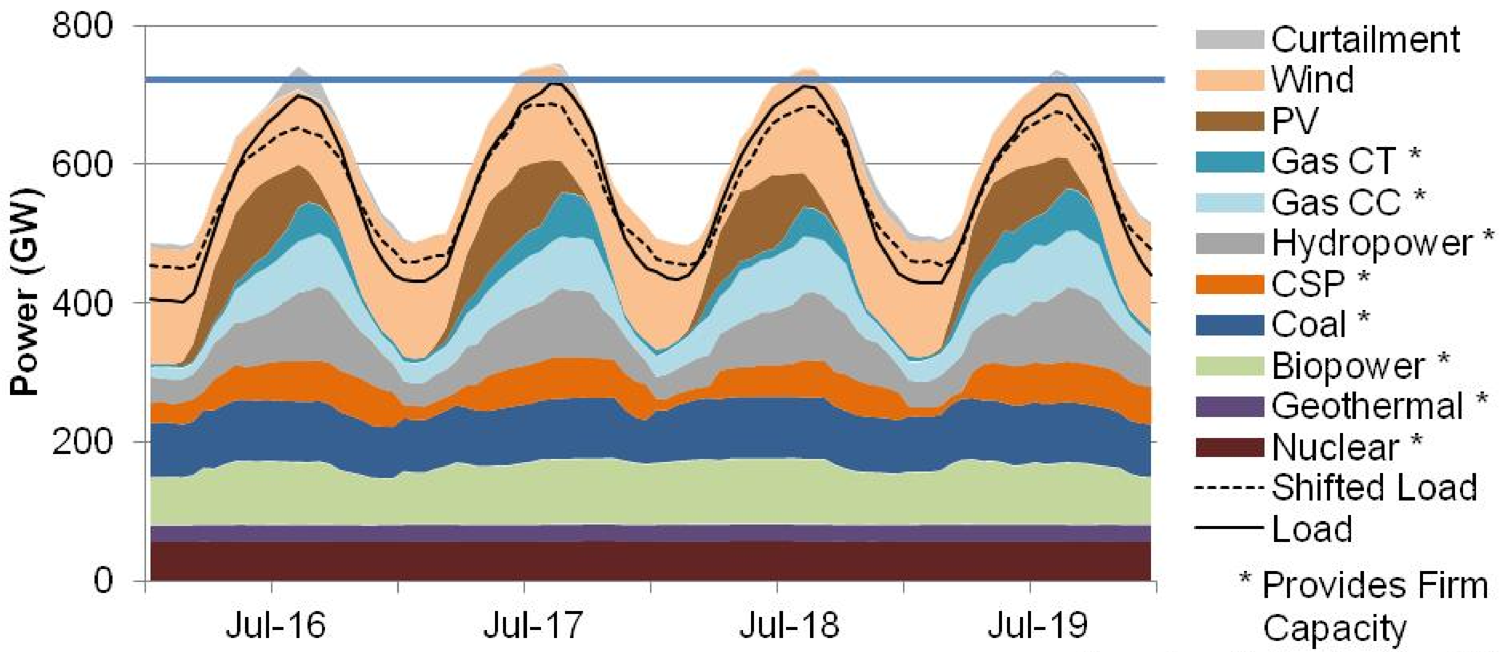
System flexibility can be increased using a broad portfolio of supply- and demand-side options, including:

- **Maintaining sufficient capacity on the system for planning reserves**
- **Relying on demand-side interruptible load, conventional generators (particularly natural gas generators), and storage to manage increased operating requirements**
- **Mitigating curtailment with storage and controlled charging of electric vehicles**
- **Operating the system with greater conventional power plant ramping**
- **Relying on the dispatchability of certain renewable technologies (e.g., biopower, geothermal, CSP with storage and hydropower)**
- **Leveraging the geospatial diversity of the variable resources to smooth output ramping**
- **Transmitting greater amounts of power over longer distances to smooth electricity demand profiles and meet load with remote generation**
- **Coordinating bulk power system operations across wider areas.**

Installed capacity is sufficient to meet summer afternoon peak demand from diverse reserves

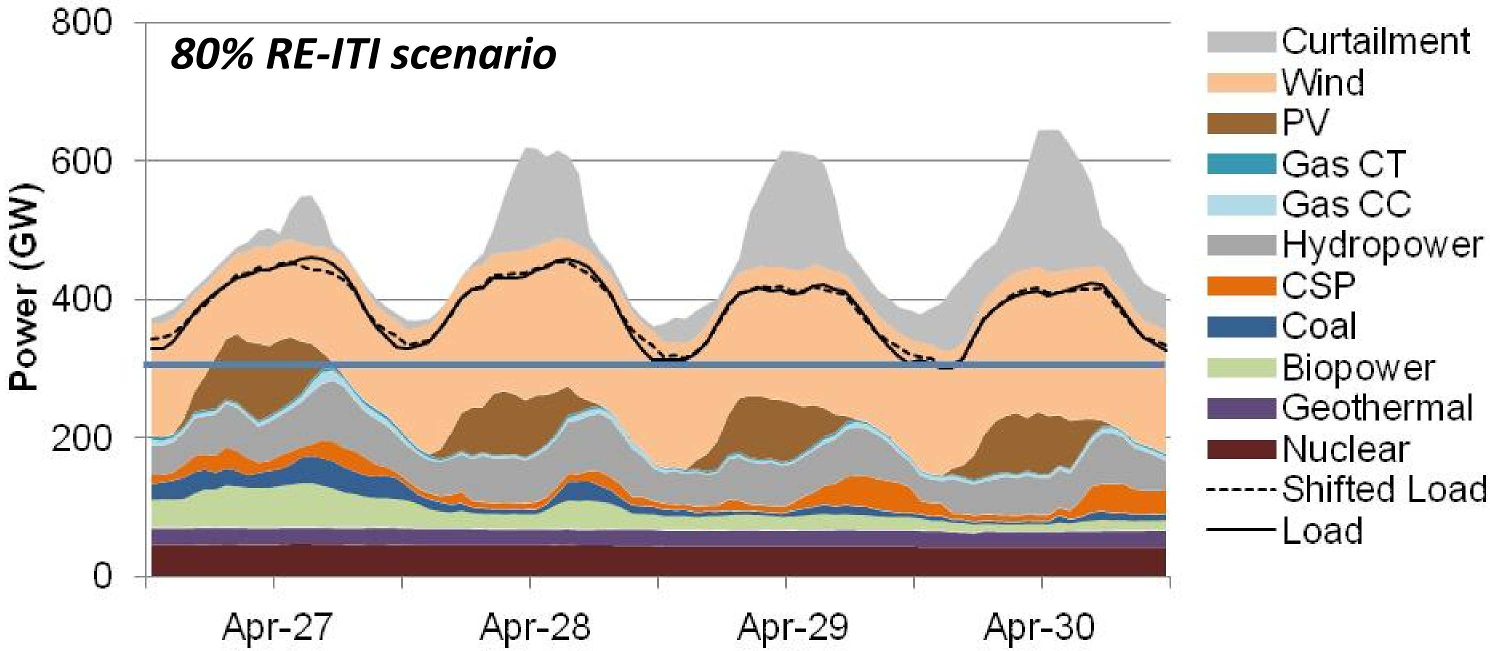


Firm capacity provided by some RE generators, conventional generators, and storage



Source: Renewable Electricity Futures (2012)

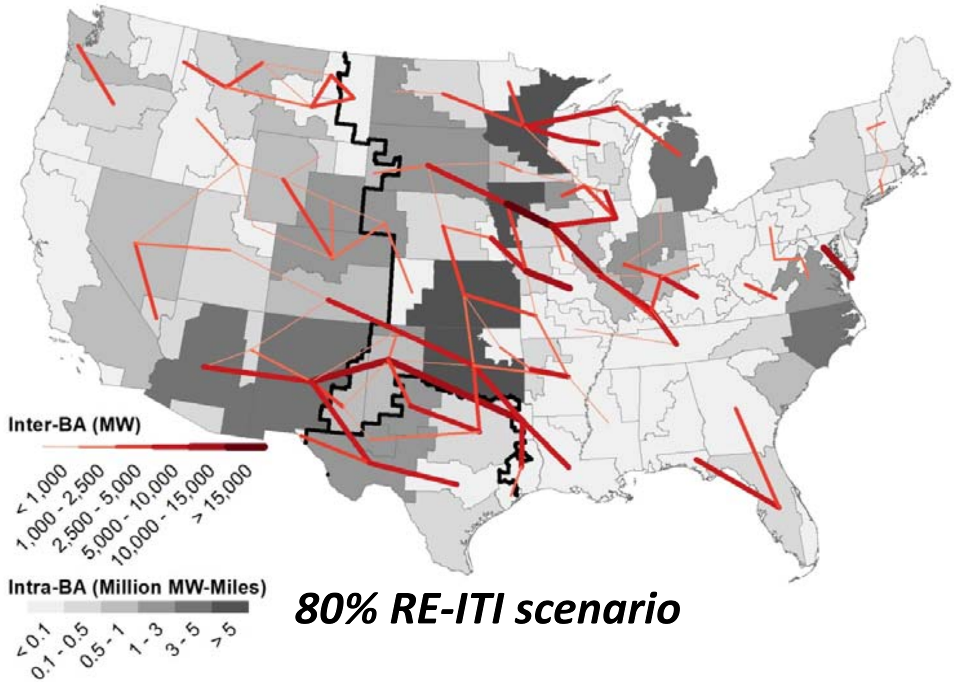
Additional planning and operational challenges include management of low-demand periods and curtailment of excess electricity



Source: Renewable Electricity Futures (2012)

- **Operational challenges for high renewable scenarios are most acute during low-demand periods (e.g., spring).**
- **There is greater thermal power plant ramping and cycling, as well as increased curtailment of excess renewable generation (8-10% of wind, solar, and hydropower curtailed in 2050).**
- **Storage and demand-side options (e.g. PHEV charging) can help shift loads to mitigate these challenges,** *e.g., 100-150 GW of storage and 28-48 GW of interruptible load deployed in 2050 for the (low demand) 80%-by-2050 RE scenarios.*

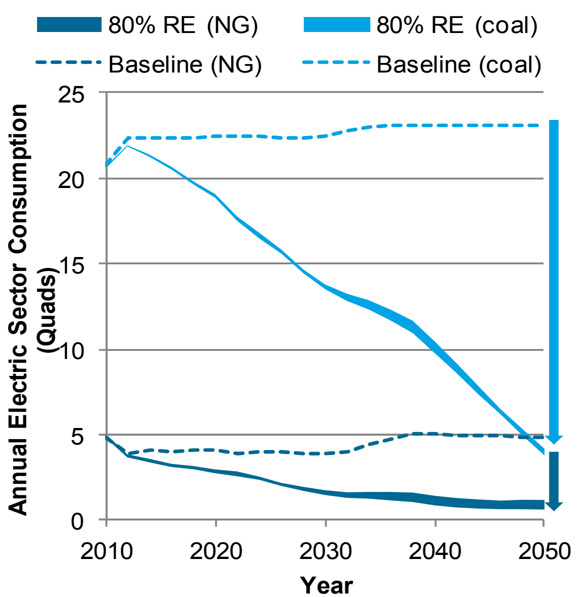
As RE deployment increases, additional transmission infrastructure is required

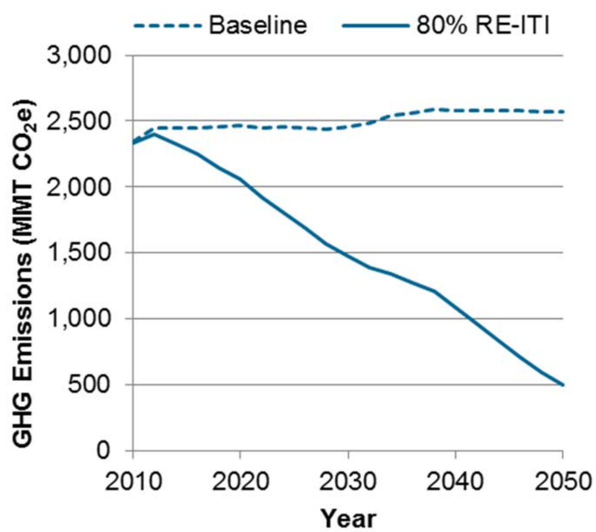


80% RE-ITI scenario

- **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 B$5.7-8.4/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.**

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





Gross Land Use Comparisons (000 km^2)	
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

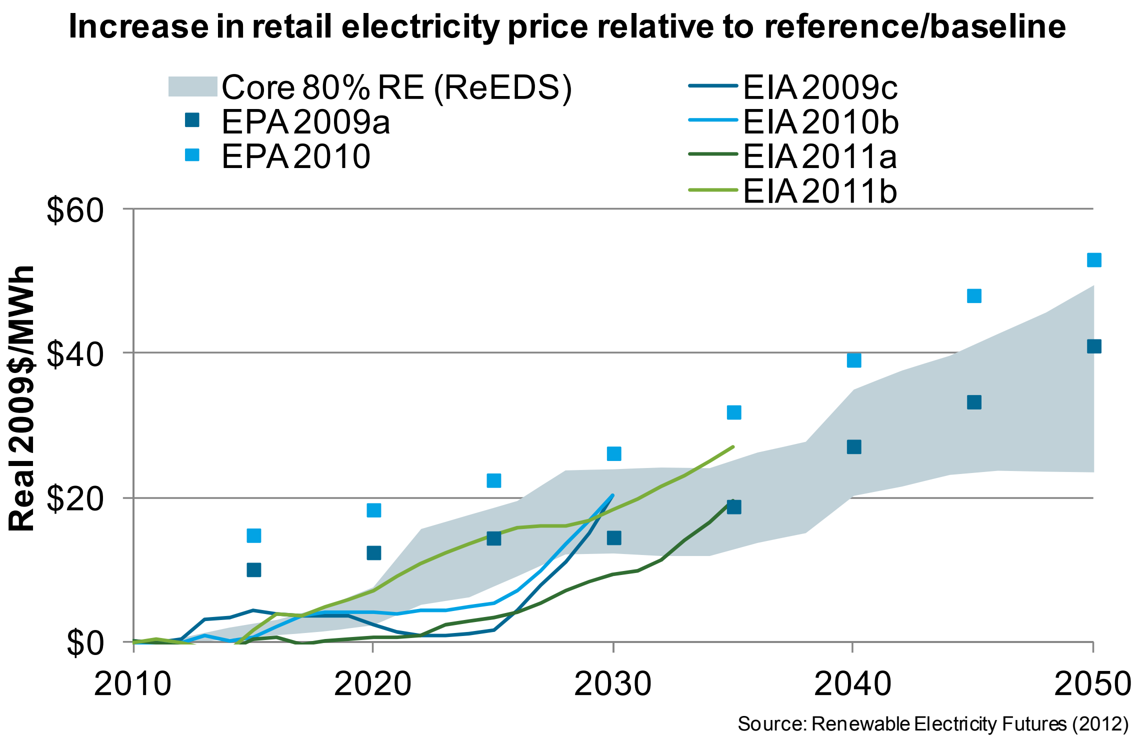
80% RE scenarios (Biomass, All Other RE, All Other RE (disrupted), Transmission & Storage)

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

80% RE scenarios lead to:

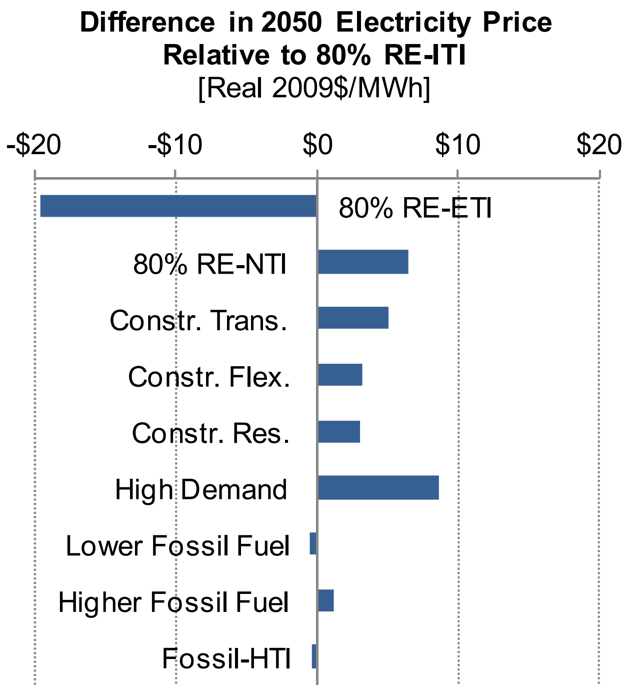
~80% reduction in 2050 generation from both coal-fired and natural gas-fired sources
~80% reduction in 2050 GHG emissions (combustion-only and life cycle)
~50% reduction in electric sector water use
Gross land use totaling <3% of contiguous U.S. area
Other related impacts include visual, landscape, noise,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

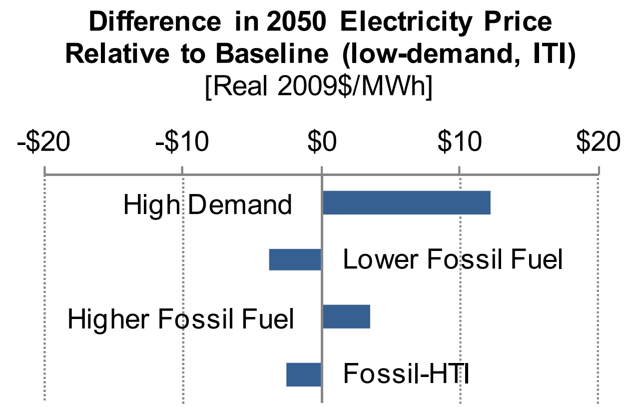
Incremental cost associated with high RE generation is comparable to published cost estimates of other clean energy scenarios



- **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.**

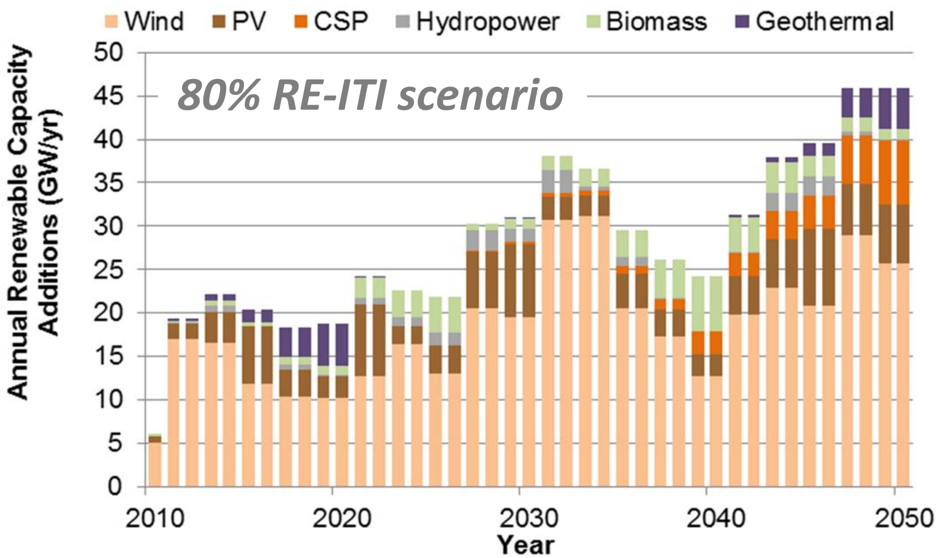
Improvement in cost and performance of RE technologies is the most impactful lever for reducing the incremental cost

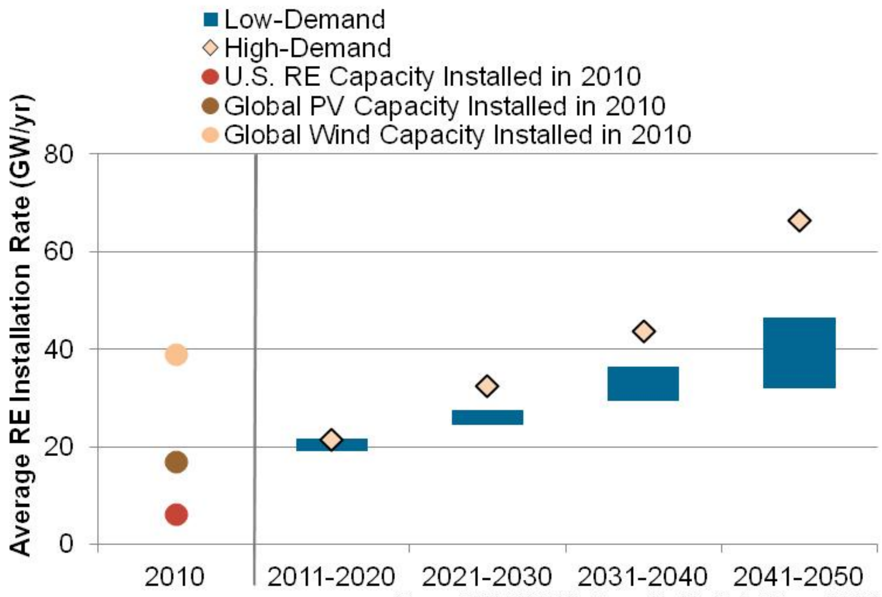




- **Cost is less sensitive to the assumed electric system constraints (transmission, flexibility, RE resource access).**
- **Electricity prices in high RE scenarios are largely insensitive to projections for fossil fuel prices and fossil technology improvements.**
- **Lower RE generation levels result 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

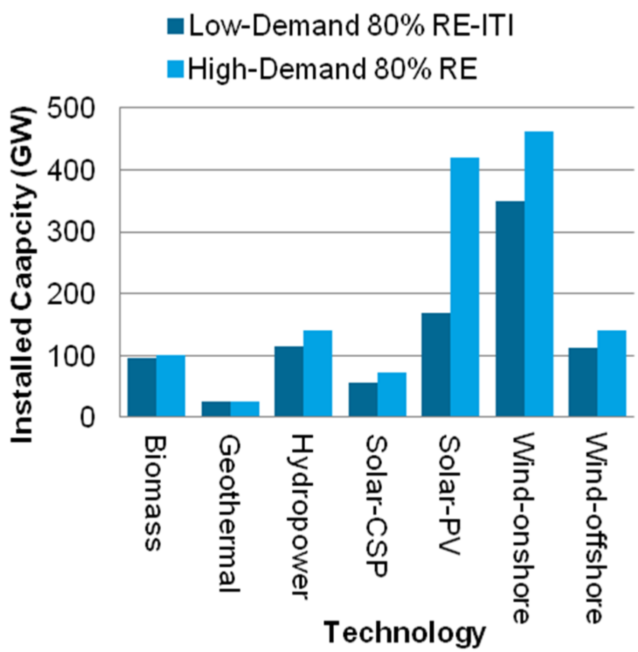




Source: REN 21 (2011); Renewable Electricity Futures (2012)

- **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.**

With higher demand growth, high levels of renewable generation present increased resource and grid integration challenges



- **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 <u>decreases</u> (the prices in baseline also increase).**
- **Cost-effectiveness of energy efficiency vs. supply-side options was not evaluated.**

Future Work Needed

- A comprehensive cost-benefit analysis is necessary in order to better understand the economic and environmental implications of high renewable electricity futures relative to today's electricity system. Today's system is largely based on conventional technologies and alternative futures in which other sources of clean energy are deployed at scale.

- Further investigation of the more complete set of issues around all aspects of power system reliability is needed because RE Futures only partially explores the implications of high penetrations of renewable energy for system reliability.

- Improved understanding of the institutional challenges associated with the integration of high levels of renewable electricity, including development of market mechanisms that enable the emergence of flexible technology solutions and mitigate market risks for a range of stakeholders, including project developers, is important.

- Analysis of the role and implications of energy research and development activities in accelerating technology advancements and in broadening the portfolio of economically viable future renewable energy supply options and supply- and demand-side flexibility tools is essential.

Summary of Key Results

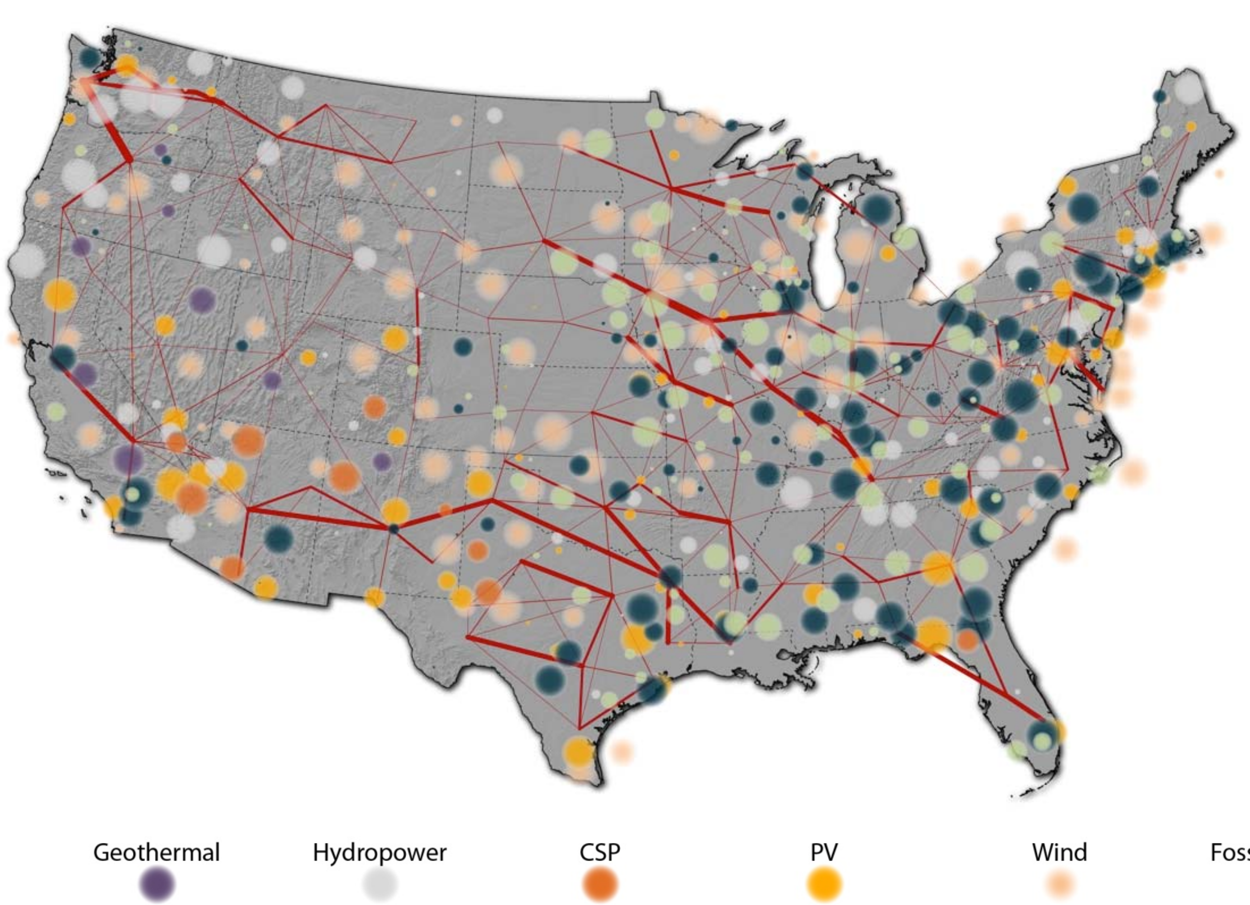
- Renewable electricity generation from technologies that are commercially available today, in combination with a more flexible electric system, is more than adequate to supply 80% of total U.S. electricity generation in 2050–while meeting electricity demand on an hourly basis in every region of the 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.

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.