Renewable Electricity Futures

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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.; Brinkman, G.; 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.; et al.
- A U.S. DOE sponsored collaboration among more than 110 individuals from 35 organizations.

Challenges

- **Economy—economic development and growth; energy imports**
- **Security—foreign energy dependence, energy availability**
- **Environment—local (particulates, water), regional (acid rain), global (GHGs)**

What role can EE & RE serve in meeting these Challenges?

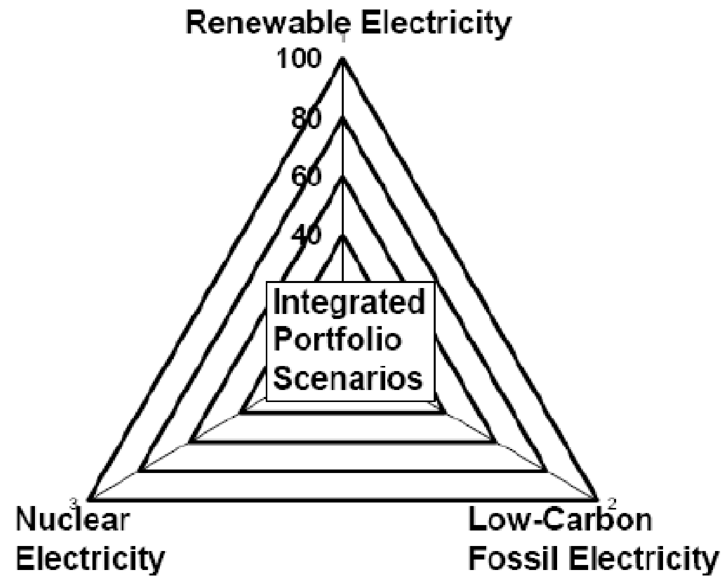
- **Efficiency: Buildings, Industry, Transport**
- **Renewable Fuels**
- **Renewable Electricity**

Speed and Scale

Context

- **Three primary pathways for providing clean electricity:**
  - Renewable energy;
  - Nuclear energy;
  - Fossil energy with carbon capture, utilization, and storage (CCUS).

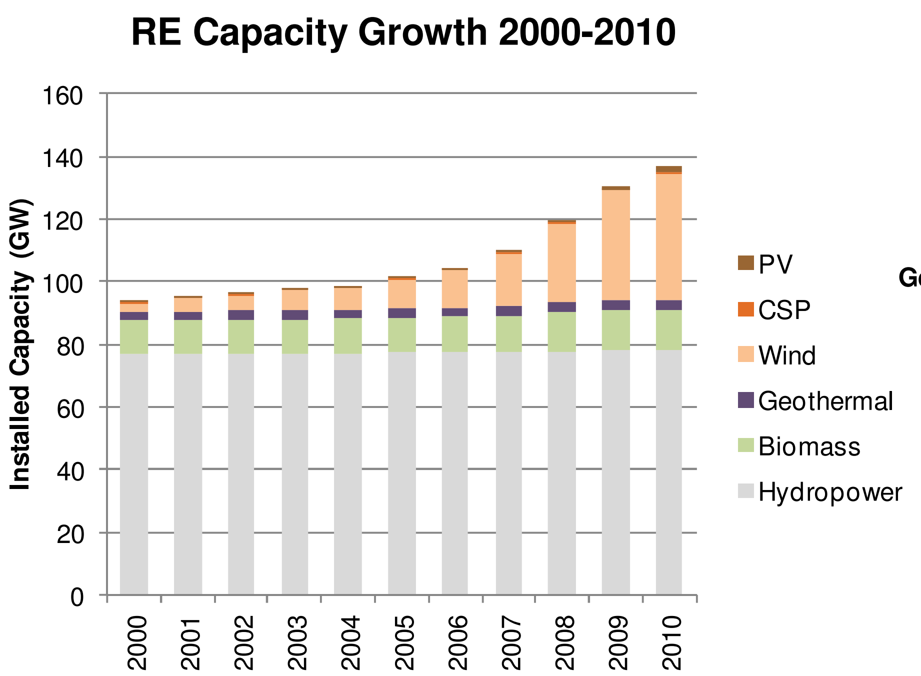
  All will likely contribute to clean electricity needs for the foreseeable future.



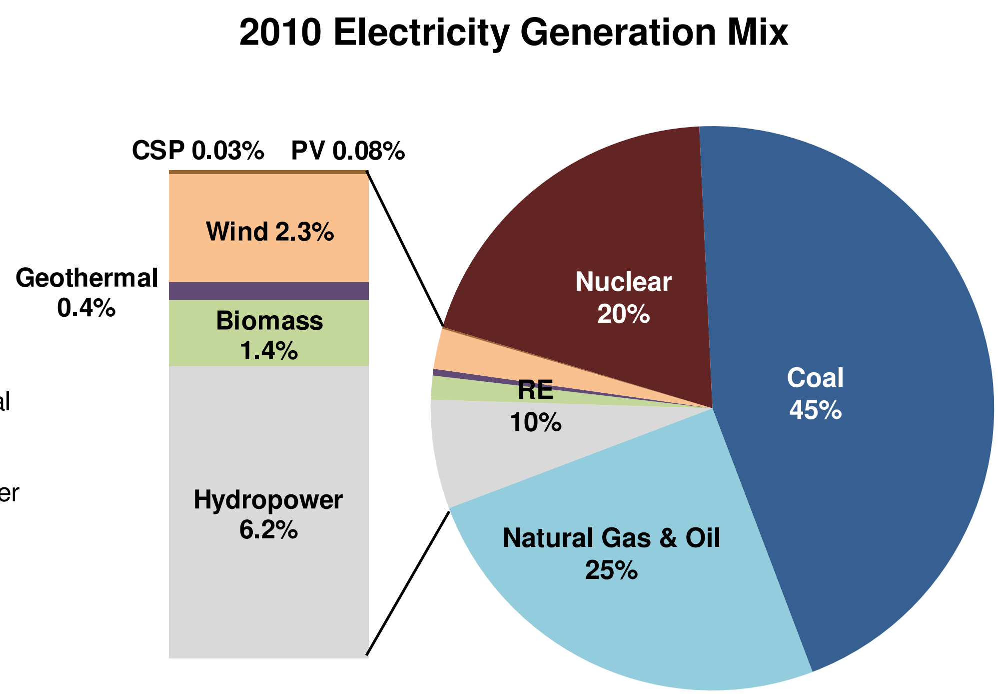
- **Energy efficiency improvements in end-use sectors are a critical contributor to all these pathways**

- **This multi-pathway approach is consistent with the Administration's all-of-the-above energy strategy.**
  - In the electricity sector, this strategy is further defined by the Administration's goal of achieving 80% of electricity generation from clean electricity sources by 2035— renewables, nuclear, efficient natural gas, clean coal.

RE Today



Source: RE Data Book (DOE 2011)



- **RE is a low carbon, low air pollutant, low fuel use, low water use, domestic, 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 Analysis 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 is needed to enable electricity supply-demand balance with high levels of renewable generation, and 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 to achieve high levels of renewable electricity use, and 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.**

Introduction

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

Boundaries

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, market rules, or regulatory frameworks 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 associated US 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 comprehensive cost-benefit analysis
Illustrate a RE-specific pathway to a clean electricity future to inform the development of integrated portfolio scenarios that include consideration of all technology pathways and their implications	Provide a definitive assessment of high RE generation, but does identify areas for deeper investigation

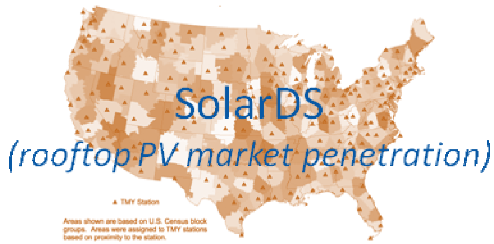
Renewable Electricity Futures Study

http://www.nrel.gov/analysis/re_futures/

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

U.S. DOE-sponsored collaboration with over 110 contributors from about 35 organizations including national laboratories, industry, universities, and NGOs

RE Futures Modeling Framework



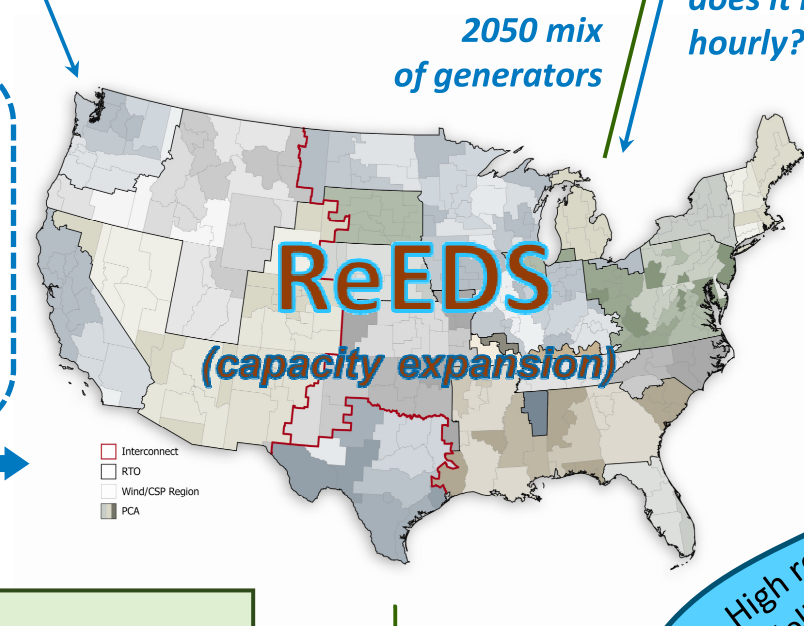
rooftop PV penetration

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

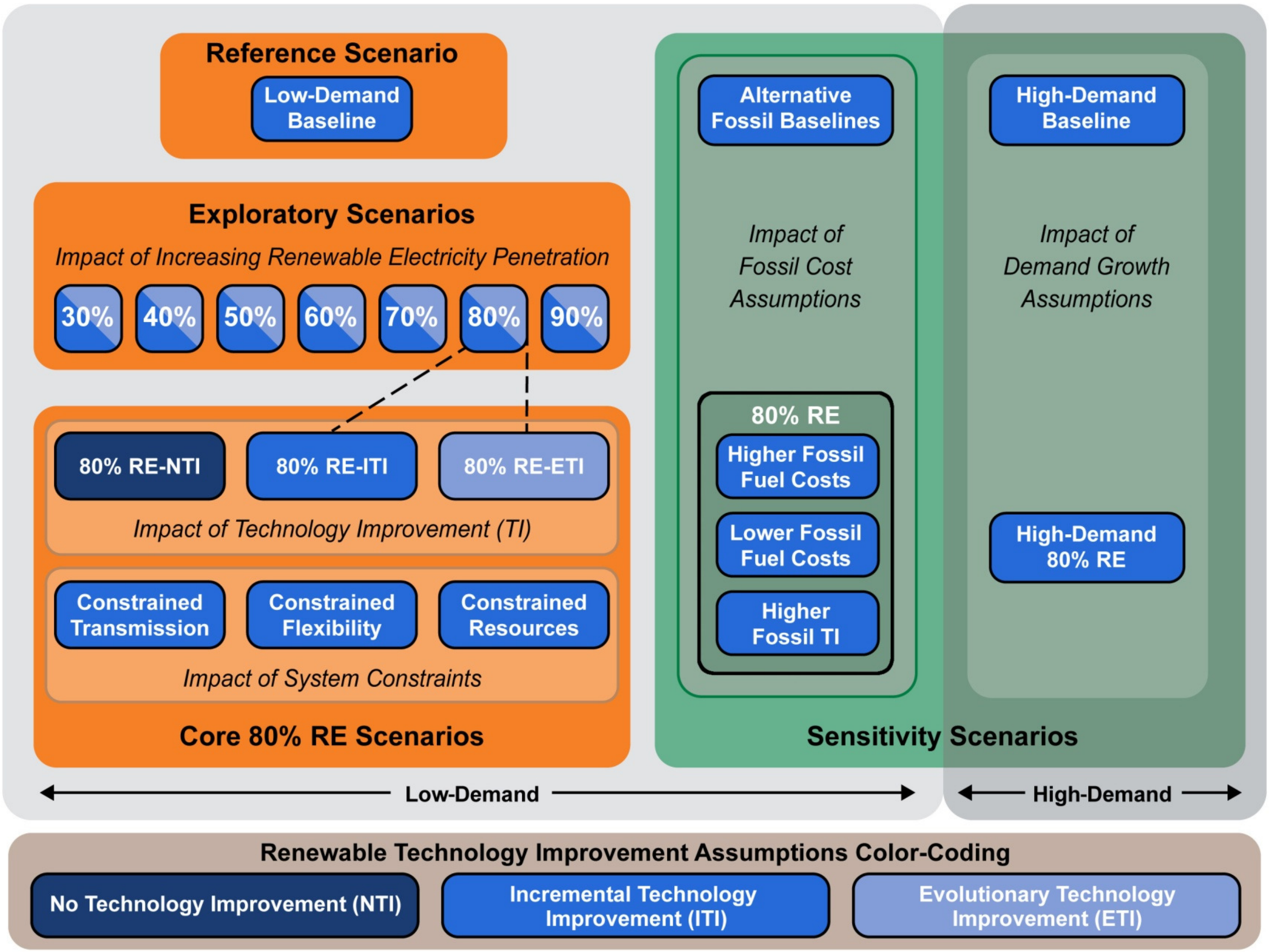


High resolution modeling using **134 nodes** & **hourly time steps**

Implications
GHG Emissions
Water Use
Land Use
Direct Costs

Capacity & Generation 2010-2050

RE Futures Scenario Framework



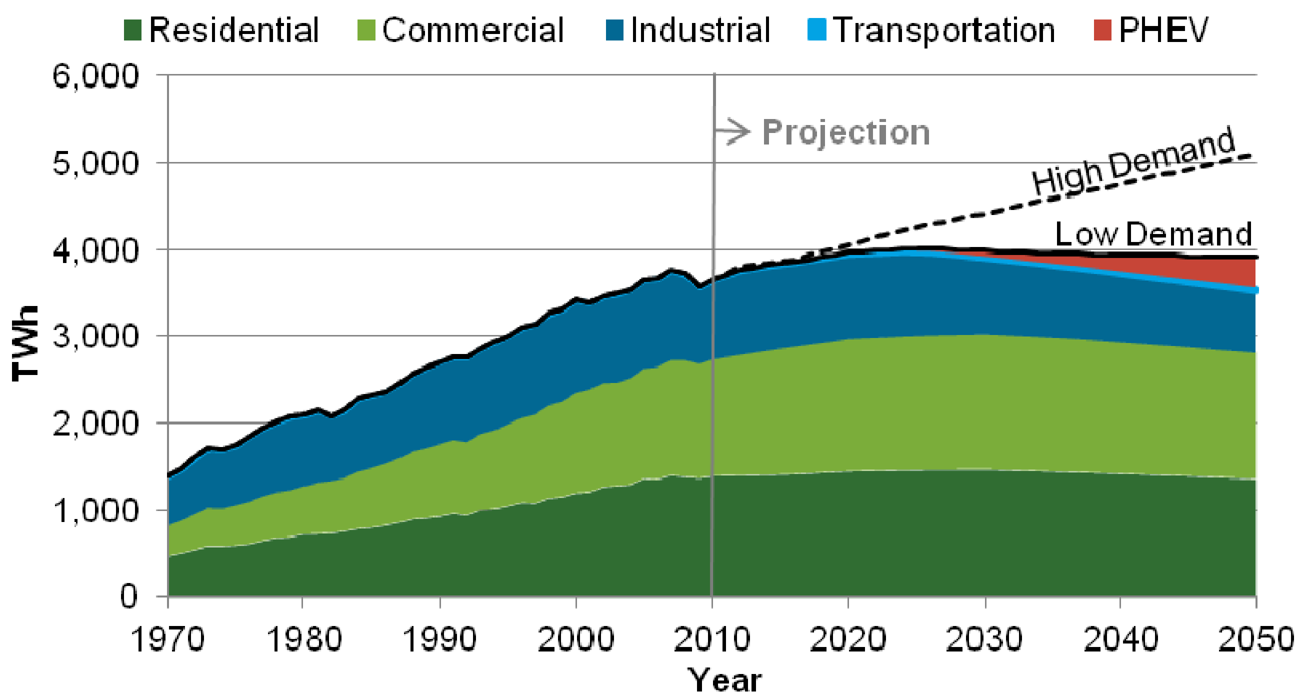
General Assumptions

- **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 towards 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 expand 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.

Scenarios and Sensitivity Cases

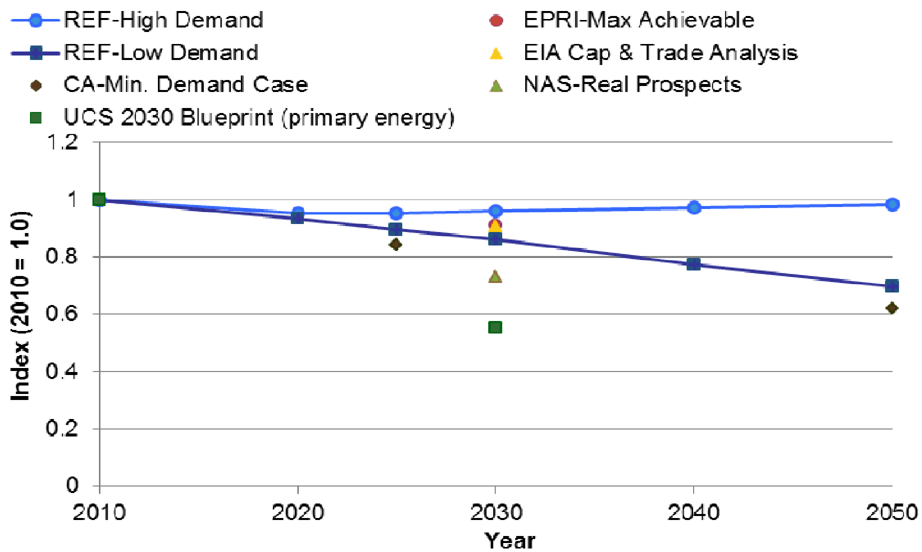
Case	Conditions
RE-ITI	• Costs at Incremental Technology Improvement; only commercial technologies considered
RE-ETI	• Costs at Evolutionary Technology Improvement; only commercial technologies considered
RE-NTI	• Costs at 2010 levels and frozen through 2050—no technology improvement
Constrained Transmission	• Costs of transmission lines increased 3X • Only allow new transmission lines along existing corridors between BAs • Disallow new intertie capacity • Double the deployment of rooftop PV • Double transmission loss factors • Limit transmission of variable RE to 1,000 miles (all other scenarios assume 2,000-mile limit)
Constrained Flexibility	• Halve the capacity value of wind and PV • Double the reserves for wind and solar forecast errors • Set required minimum load of coal & biomass plants to 70% (all other scenarios assume 40%) • Cap availability of interruptible load to 2010 levels in all years
Constrained Resources	• Halve available resource base for all RE technologies (except utility-scale and distributed PV) • For biopower, this meant halving the available biomass feedstock
High-Demand 80% RE	• "Business-as-usual" higher growth in electricity demand • 50% greater deployment of rooftop PV
FE-Cost/Tech	• Fossil fuel costs 30% higher/lower than base; Fossil Technology advances faster than base

Historical and Projected Demand



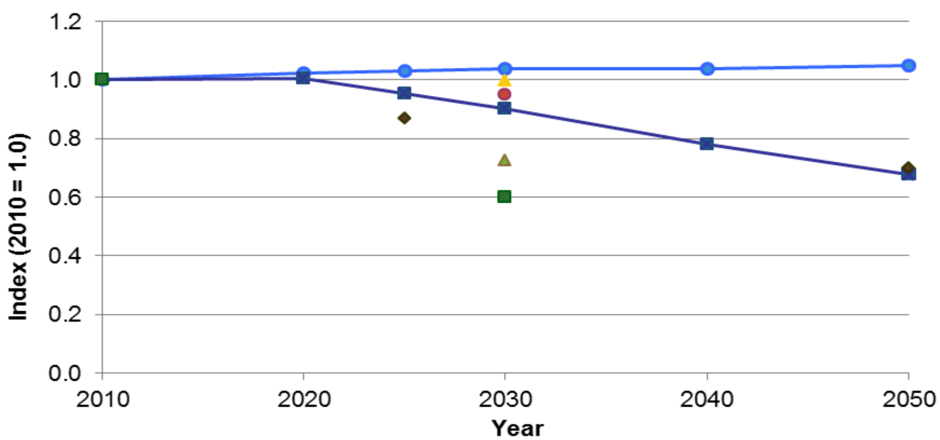
Sector	High-Demand Projection	Low-Demand Projection
Residential	2% decline in intensity over 2010 levels	30% decline in intensity over 2010 levels
Commercial	5% increase in intensity over 2010 levels	32% decline in intensity over 2010 levels
Industrial	35% decline in intensity over 2010 levels	50% decline in intensity over 2010 levels
Transportation	<3% PHEV penetration	40% of vehicle sales are PEVs

Electricity Intensity Projections In Range of Other Studies

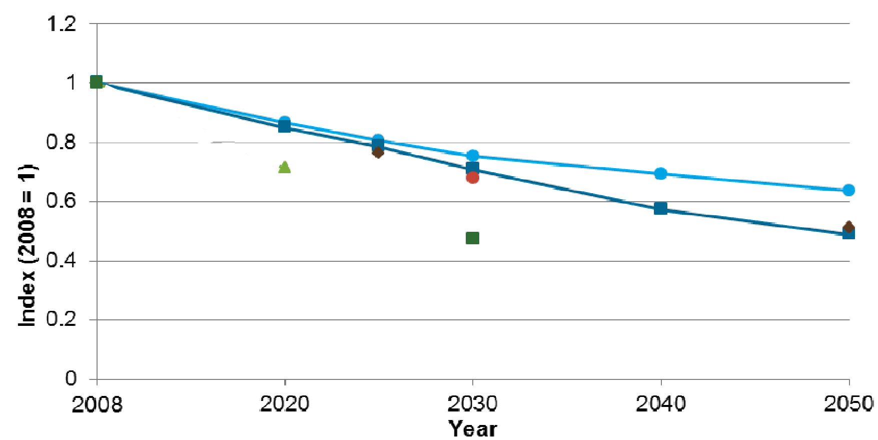


Residential (electricity use per household)

- **Building sector projections focused on whole building intensities**
- **Industrial sector projections relied on cases developed by EIA**



Commercial (electricity use per square foot)



Industrial (electricity use per dollar of shipments)

Demand-Side Flexibility

- **Demand-side flexibility increases the potential for RE to meet electricity requirements**

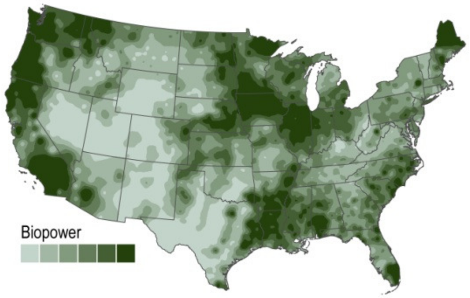
- **Regional, seasonal, and diurnal variability in electricity requirements impact the potential for RE generation**
  - Electricity use projections were converted to 13 regional hourly system load profiles

- **Demand-side options considered:**
  - Thermal (cooling) storage to shift commercial air conditioning loads based on regional cost supply curves
  - Regional demand response (interruptible load) supply curves were developed to meet operating reserves
  - Dynamic scheduling of electric vehicle charging assumed ~40% of PHEV load was under utility-controlled charging

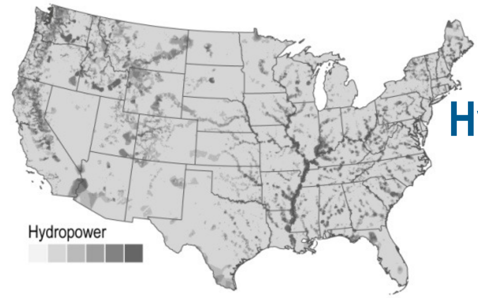
Renewable Resources

Renewable Resources and Technologies

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

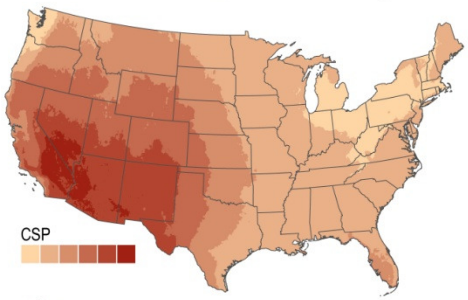


Hydropower ~200 GW
- Run-of-river

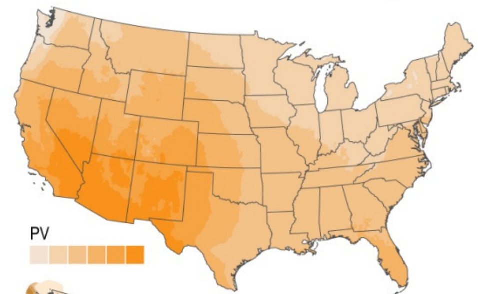


CSP ~37,000 GW
- Trough
- Tower

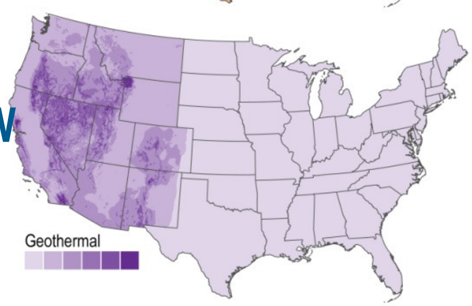
With thermal storage



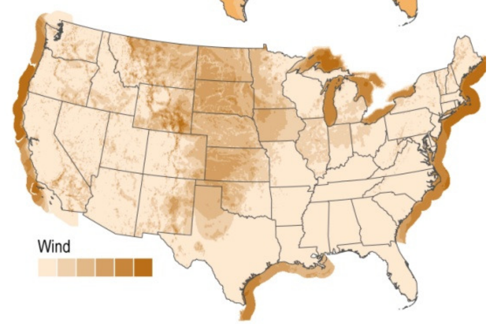
PV ~80,000 GW (rooftop ~700 GW)
- Residential
- Commercial
- Utility-scale



Geothermal ~36 GW
- Hydrothermal



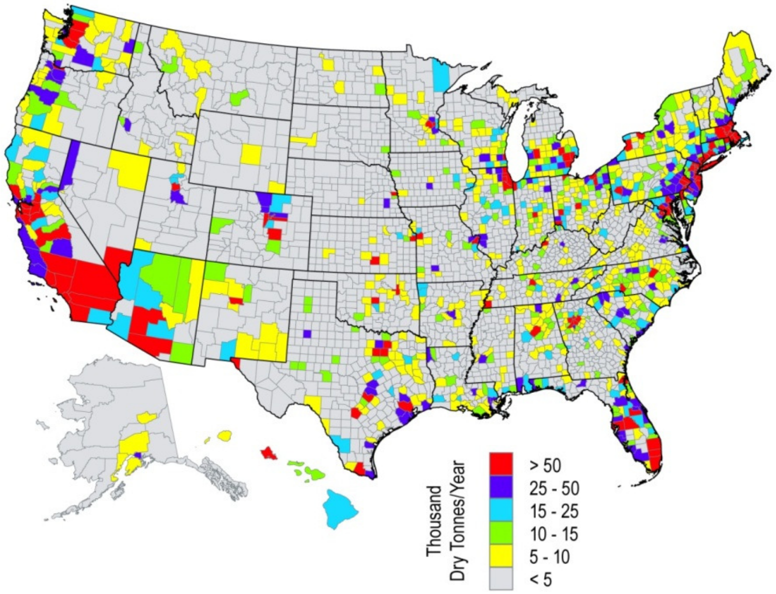
Wind ~10,000 GW
- Onshore
- Offshore fixed-bottom



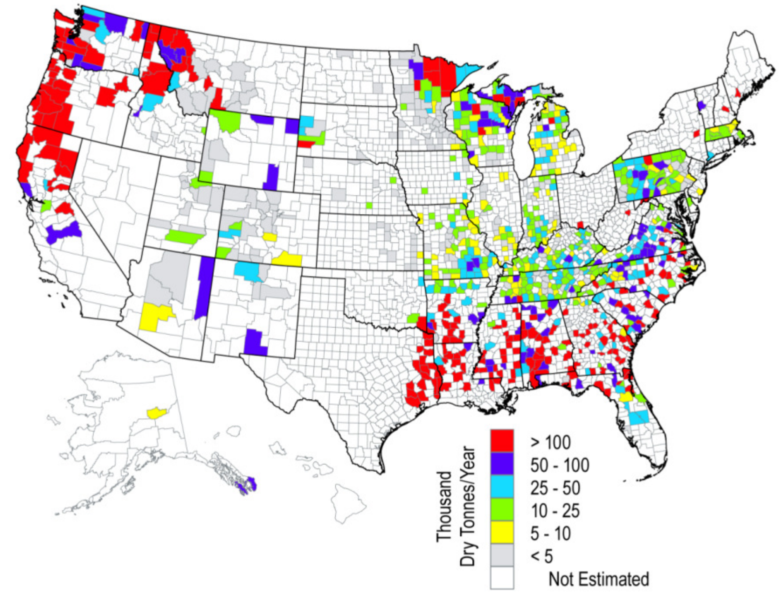
Resource
Dark = Higher
Light = Lower

- **Only currently commercial technologies were modeled (no EGS, ocean, floating wind) with incremental and evolutionary improvements.**
- **RE characteristics, including location (exclusions), technical resource potential, and grid output (dispatchability), were considered**
- **Technical resource potential shown, not economic potential**

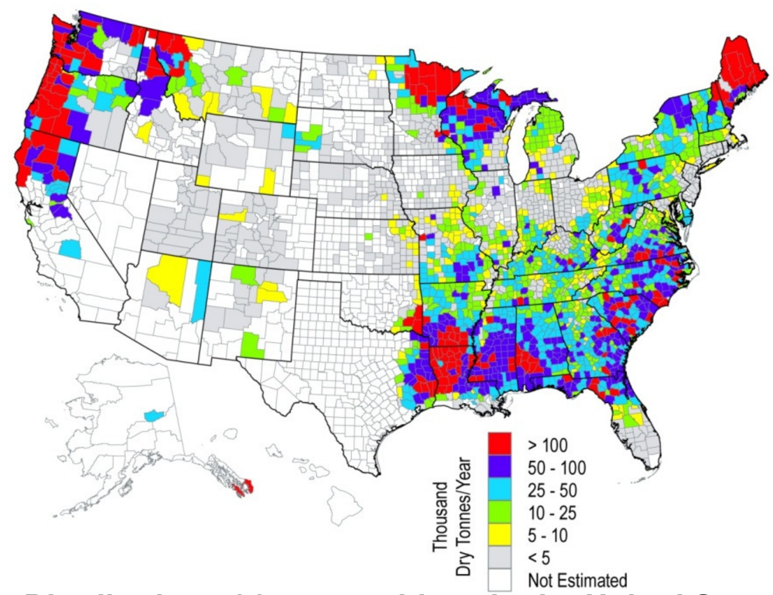
Biomass Resources



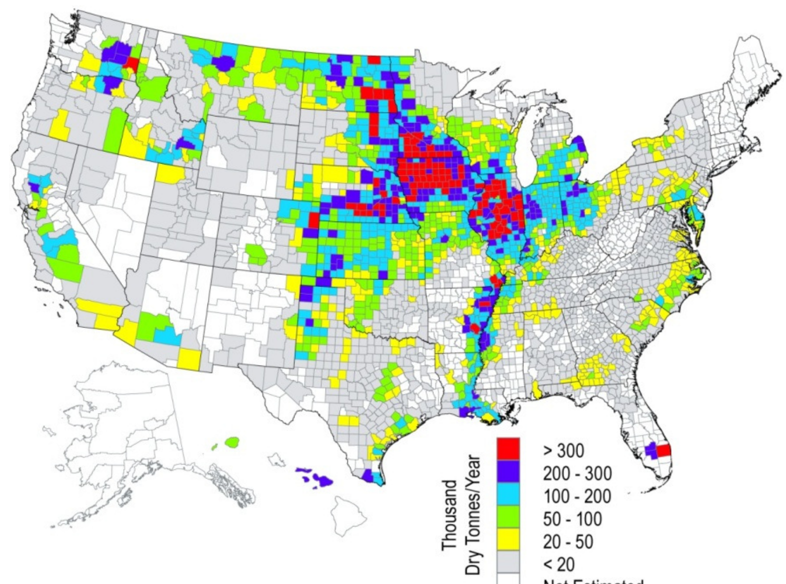
Distribution of urban wood residues in the United States



Distribution of primary wood mill residues in the United States

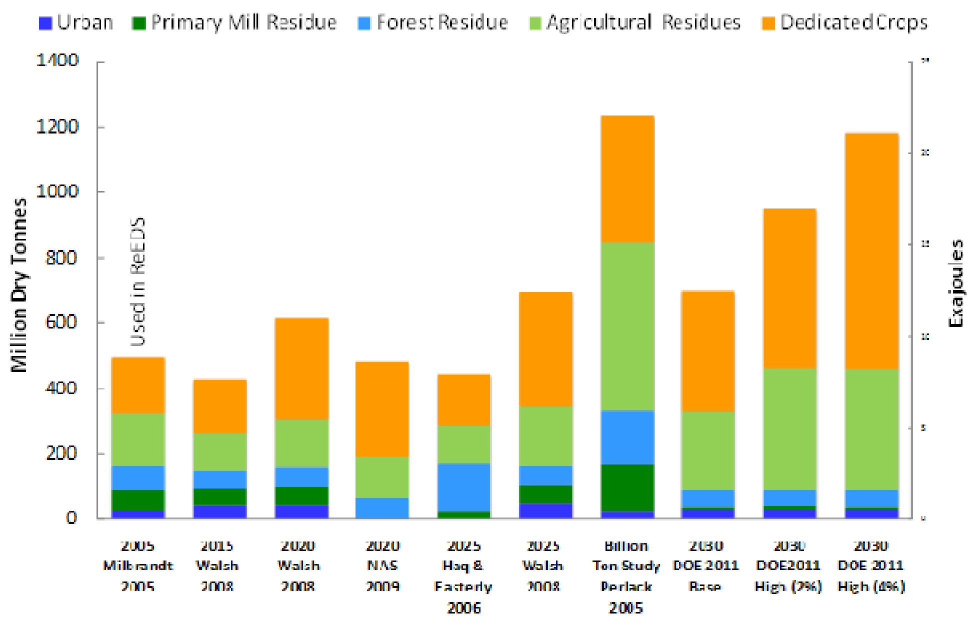


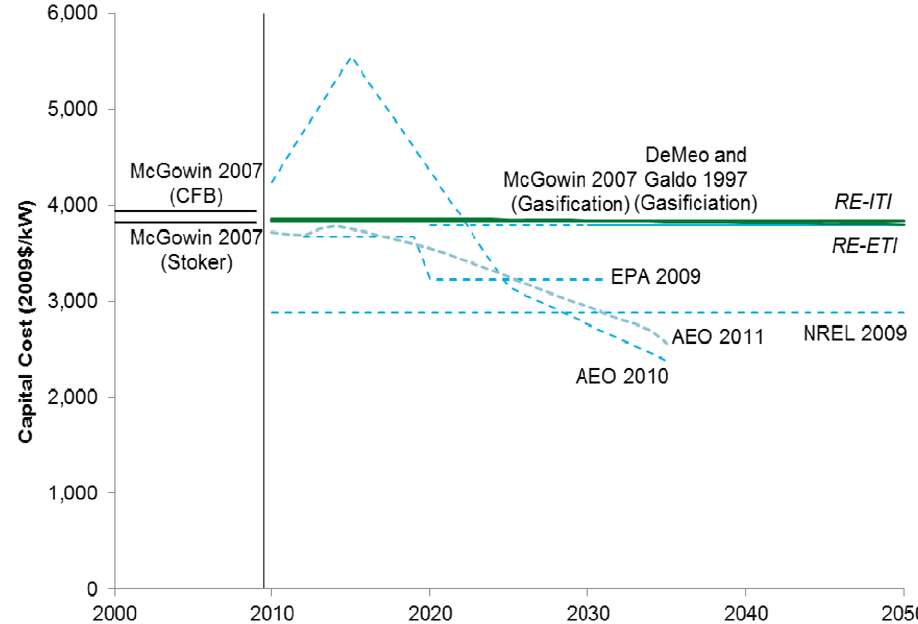
Distribution of forest residues in the United States

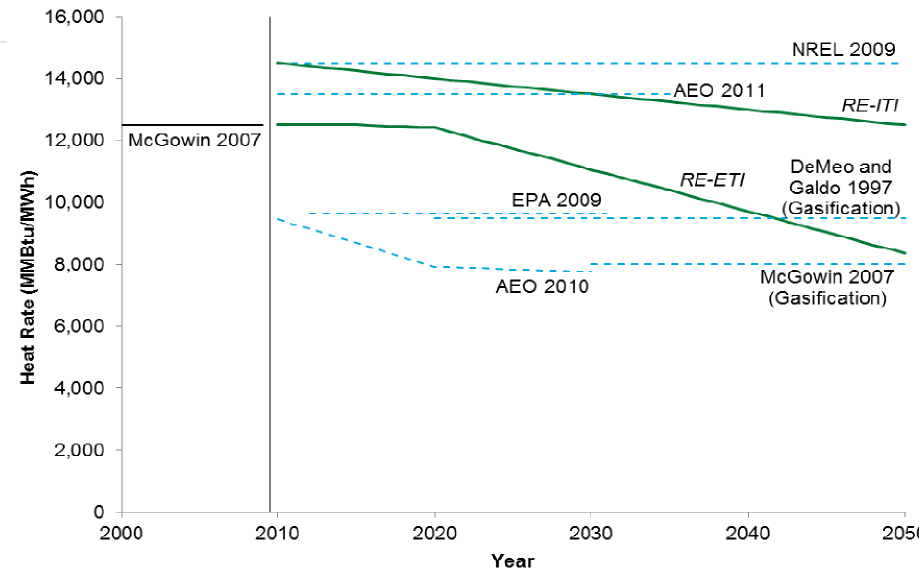


Distribution of crop residues in the United States

Biomass

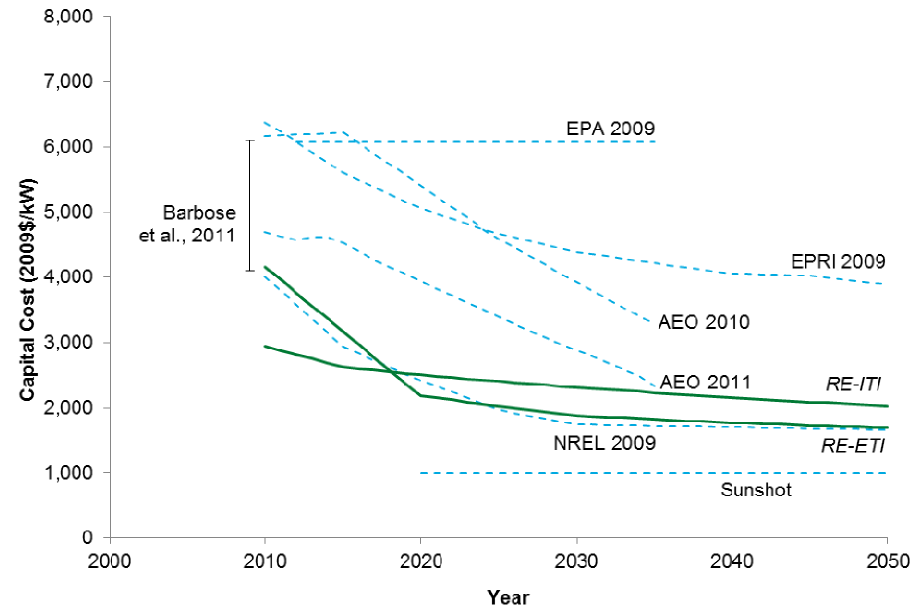


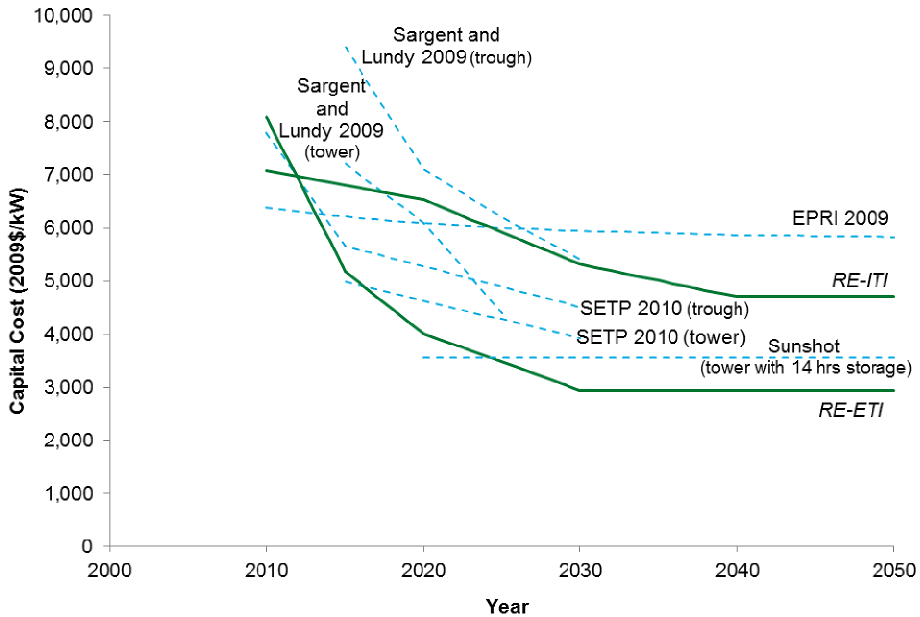




- **No growth in annual biomass feedstock availability assumed in RE Futures modeling**
- **Biofuel and other demand for biomass not considered directly in RE Futures modeling**
- **The assumed feedstock amount (first column) corresponds roughly to 100 GW of biopower capacity**
- **Biopower technologies deployed in all 80% RE scenarios with capacity expansion limited by feedstock availability**
- **Constrained resources at half the level.**

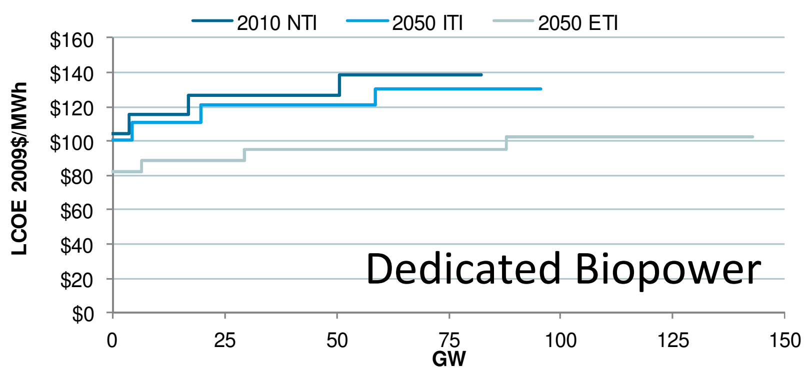
Solar Technology Cost & Performance

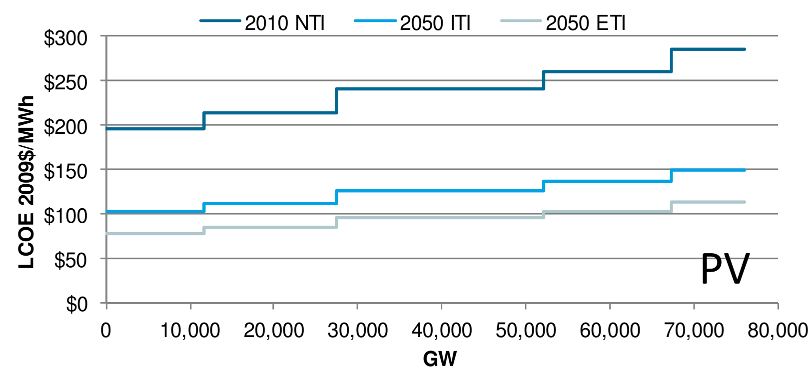


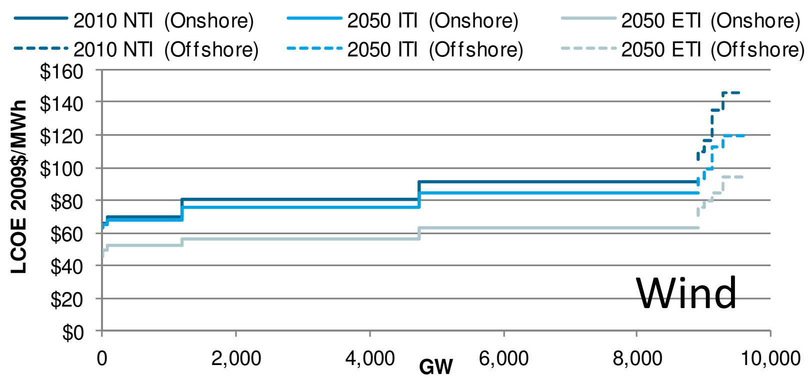


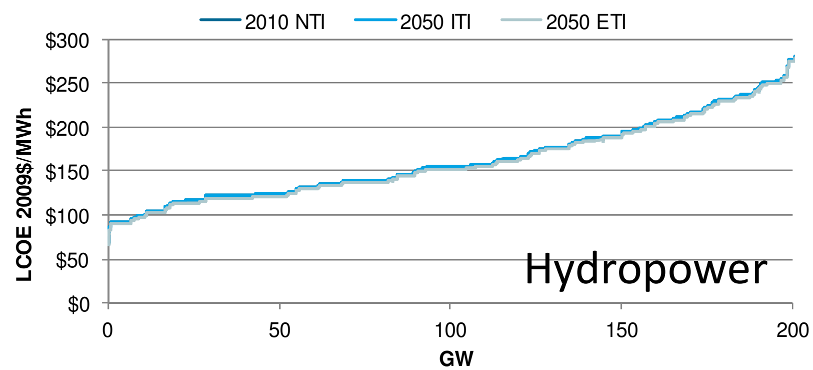
	YEAR	SunShot	RE-ITI	RE-ETI	RE-NTI
PV – Residential (2010$/$W_{DC}$)	2010	6.00	6.09	6.54	6.09
	2020	1.50	3.81	3.17	6.09
	2030	1.50	3.34	2.26	6.09
	2040	1.50	3.15	2.12	6.09
	2050	1.50	2.97	2.04	6.09
PV – Commercial (2010$/$W_{DC}$)	2010	5.00	4.86	5.18	4.86
	2020	1.25	3.39	2.31	4.86
	2030	1.25	3.00	2.01	4.86
	2040	1.25	2.81	1.89	4.86
	2050	1.25	2.66	1.81	4.86
PV – Utility (2010$/$W_{DC}$)	2010	4.00	2.98	4.22	2.98
	2020	1.00	2.55	2.21	2.98
	2030	1.00	2.34	1.91	2.98
	2040	1.00	2.19	1.80	2.98
	2050	1.00	2.06	1.72	2.98
CSP, 6/14 hour storage 2010$/$W_{AC}$)	2010	7.20	7.17	8.21	7.17
	2020	3.60	6.63	4.07	7.17
	2030	3.60	5.39	2.98	7.17
	2040	3.60	4.77	2.80	7.17
	2050	3.60	4.77	2.68	7.17

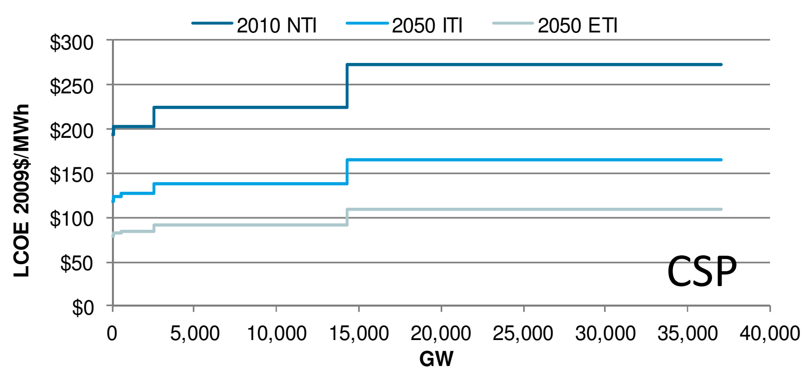
Technology Resource and Levelized Costs*

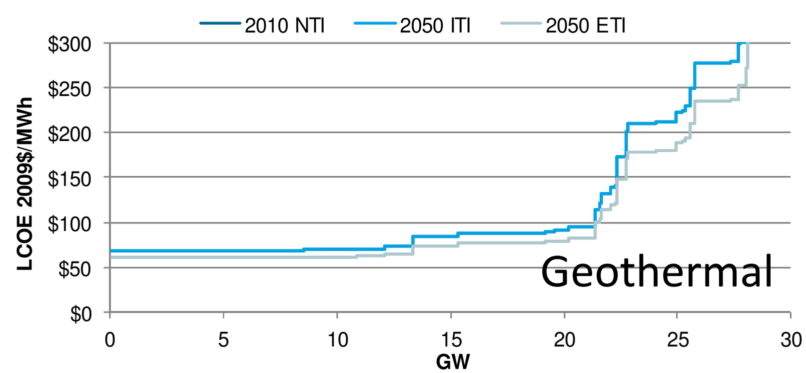








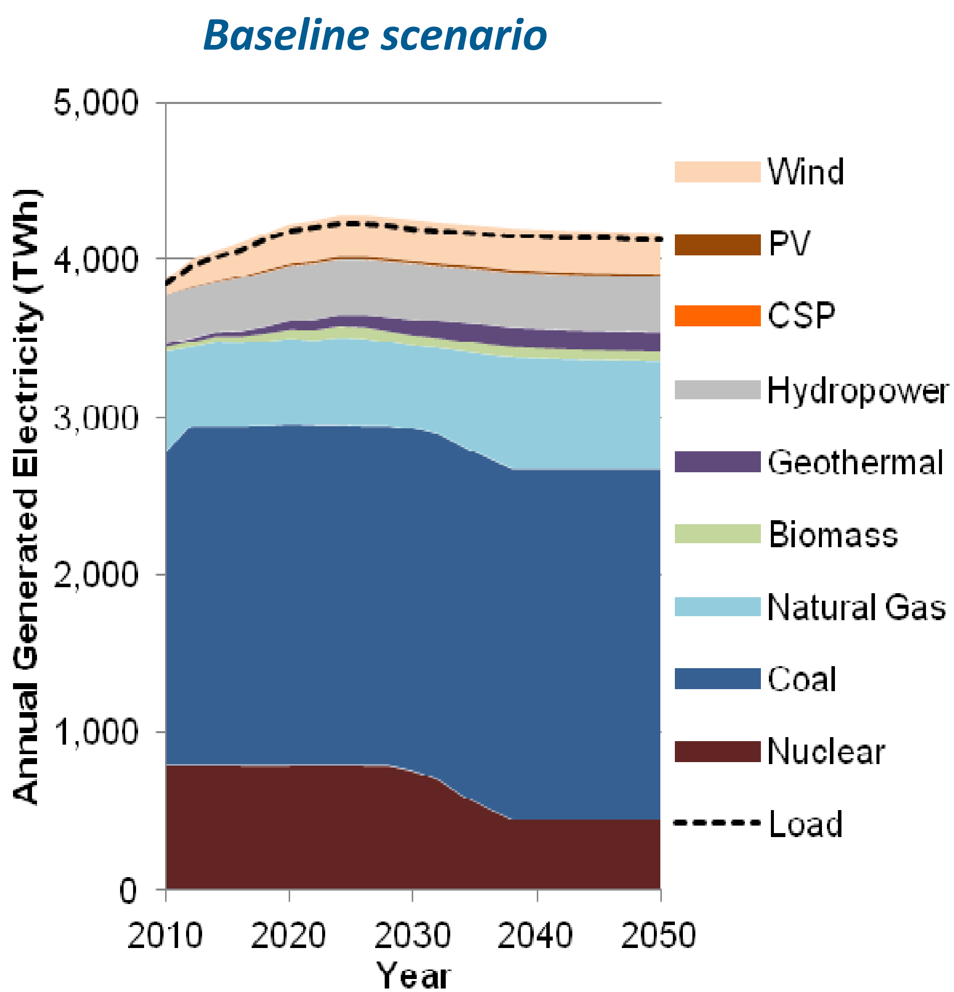


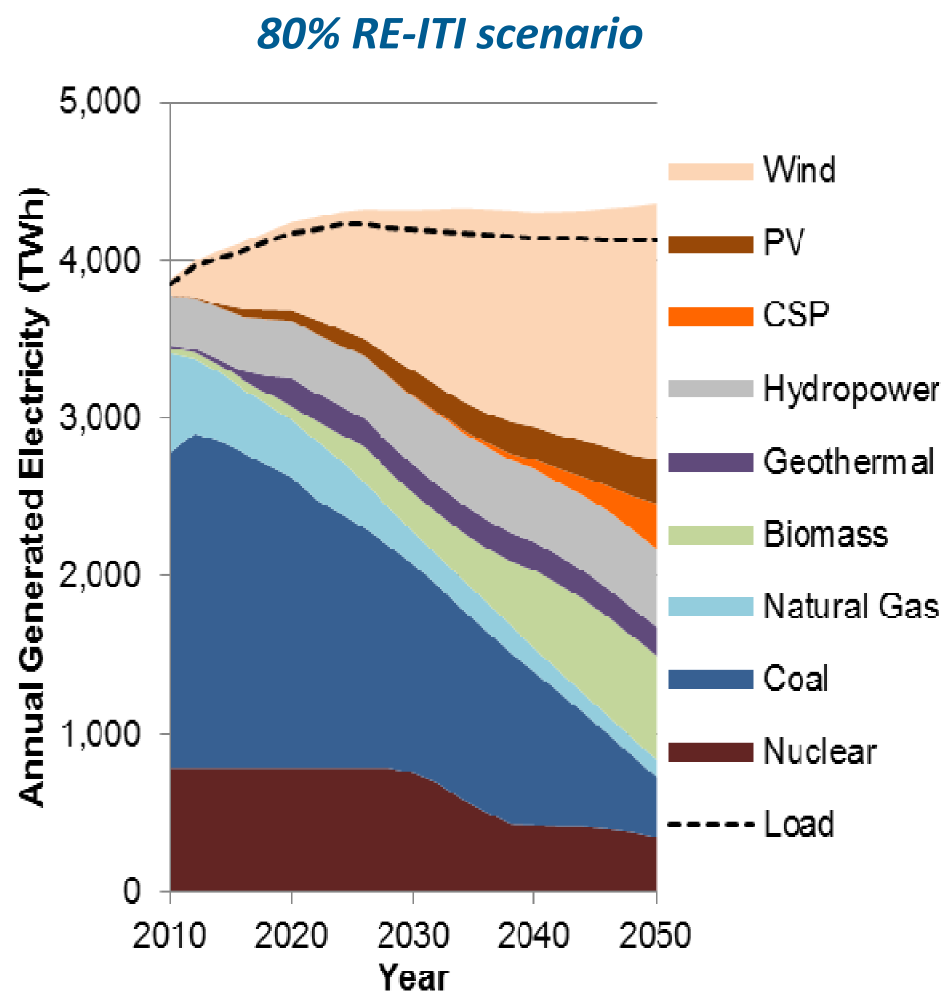


Levelized costs shown are illustrative only. ReEDS considers many other factors beyond simple levelized costs shown

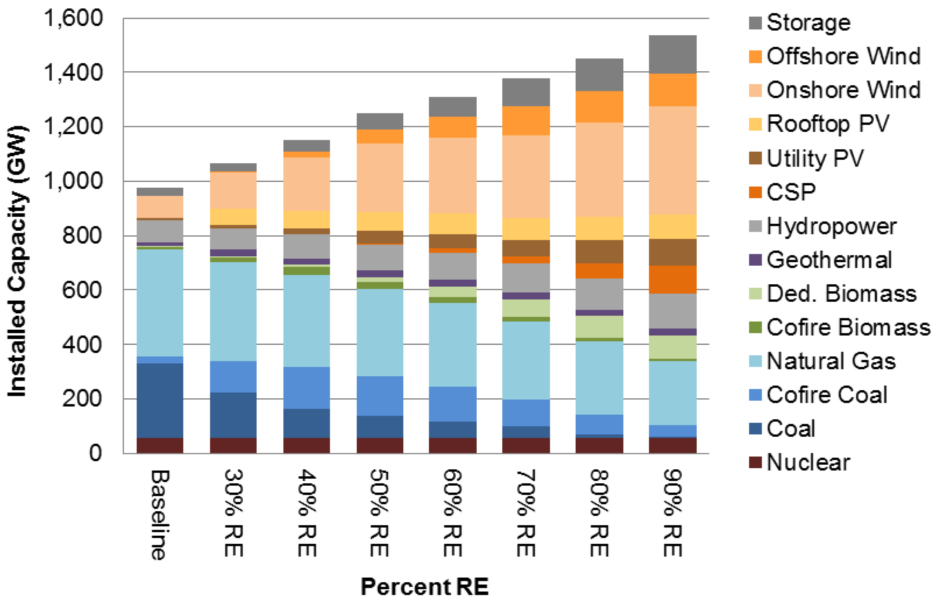
Key Results

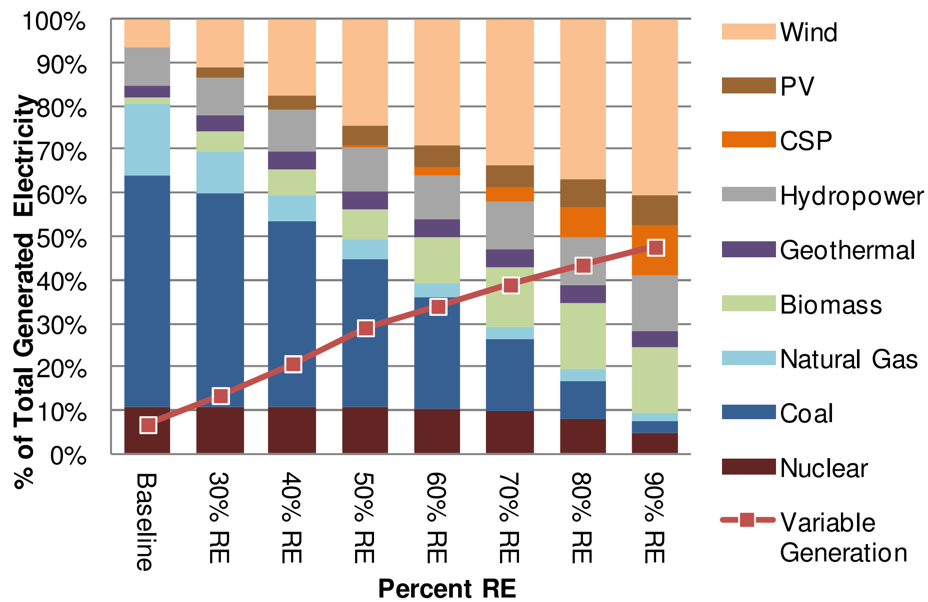
ReEDS Outputs





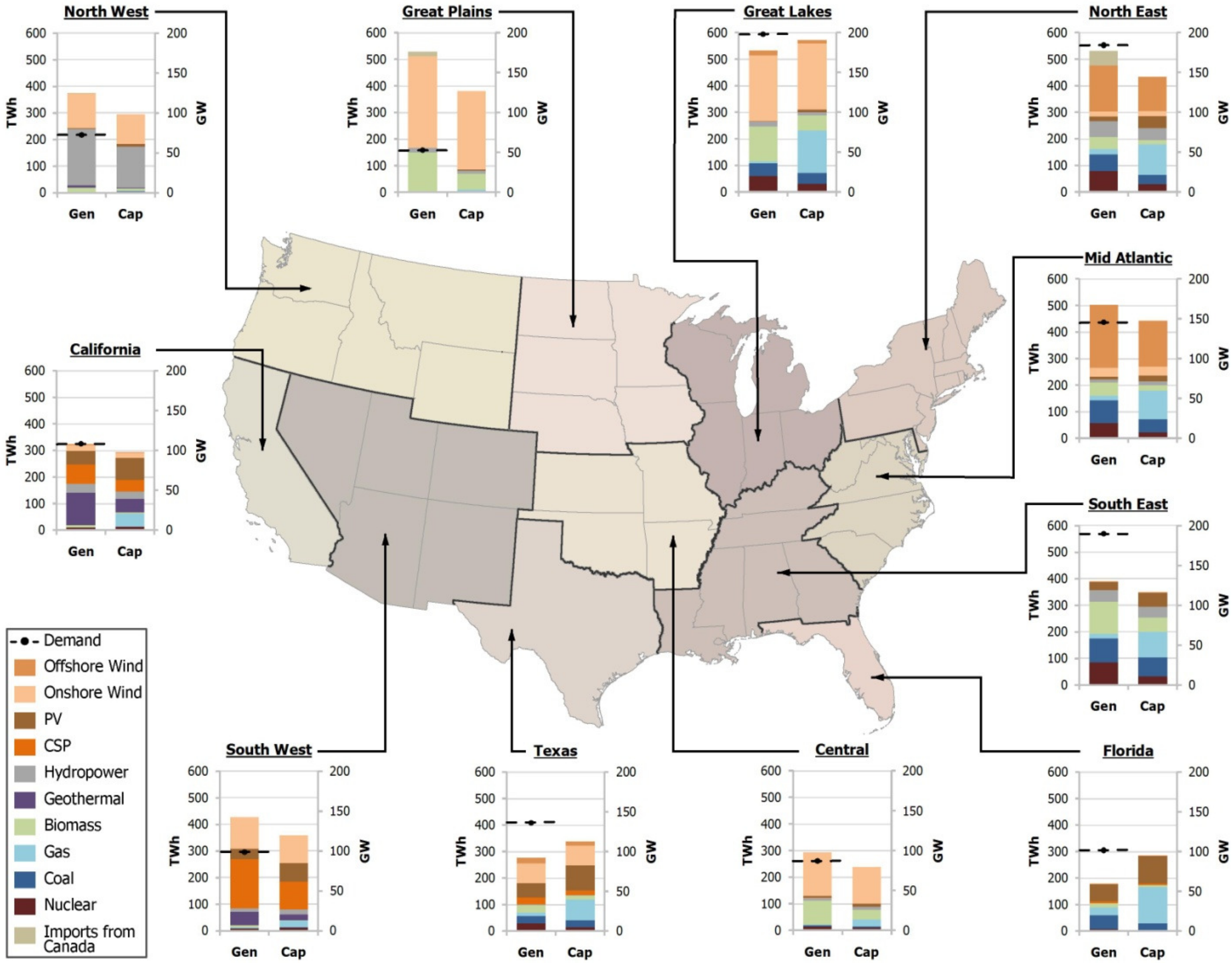
Renewable generation resources could adequately supply 80% of total U.S. electricity generation in 2050 while balancing supply and demand





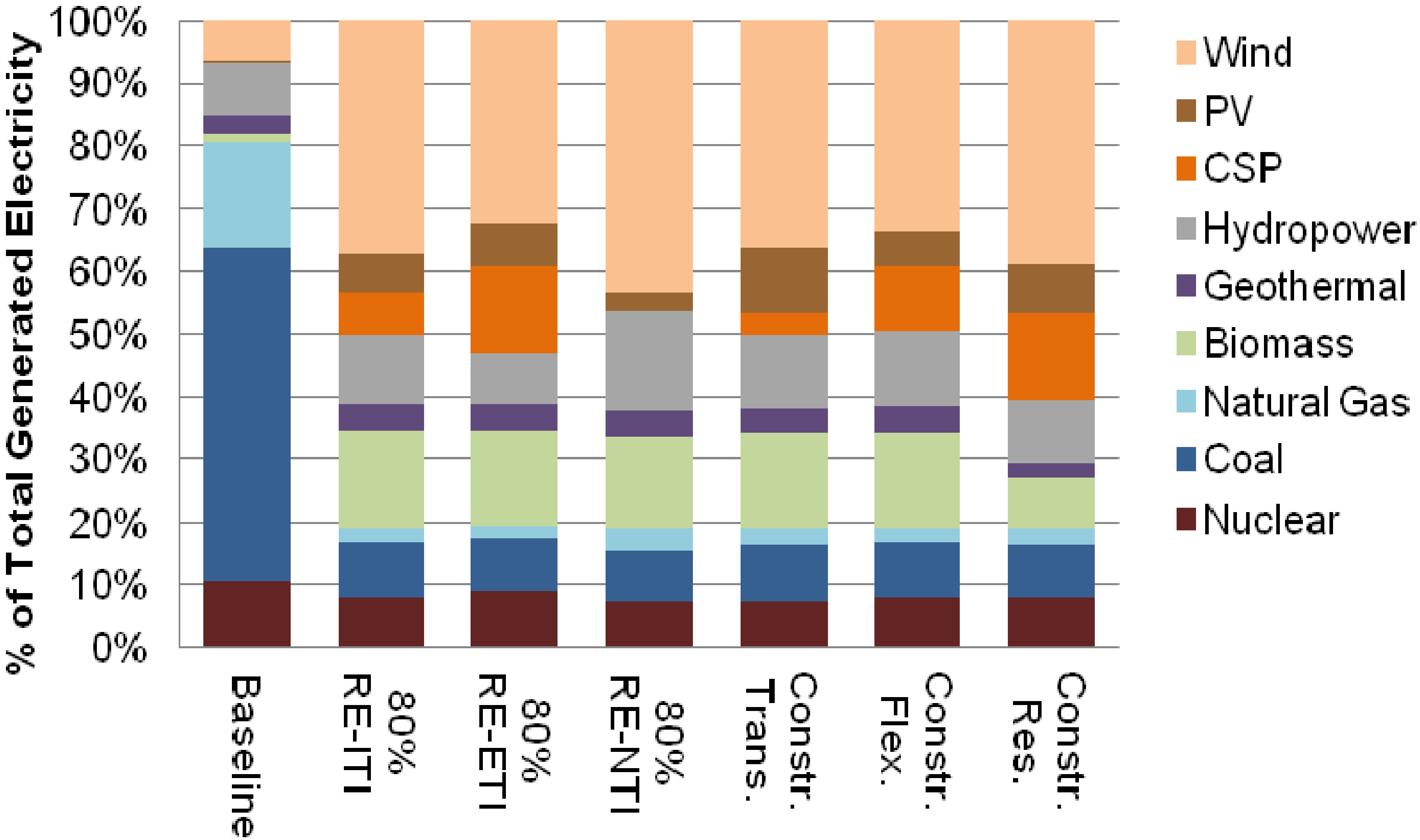
RE-ITI scenarios

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



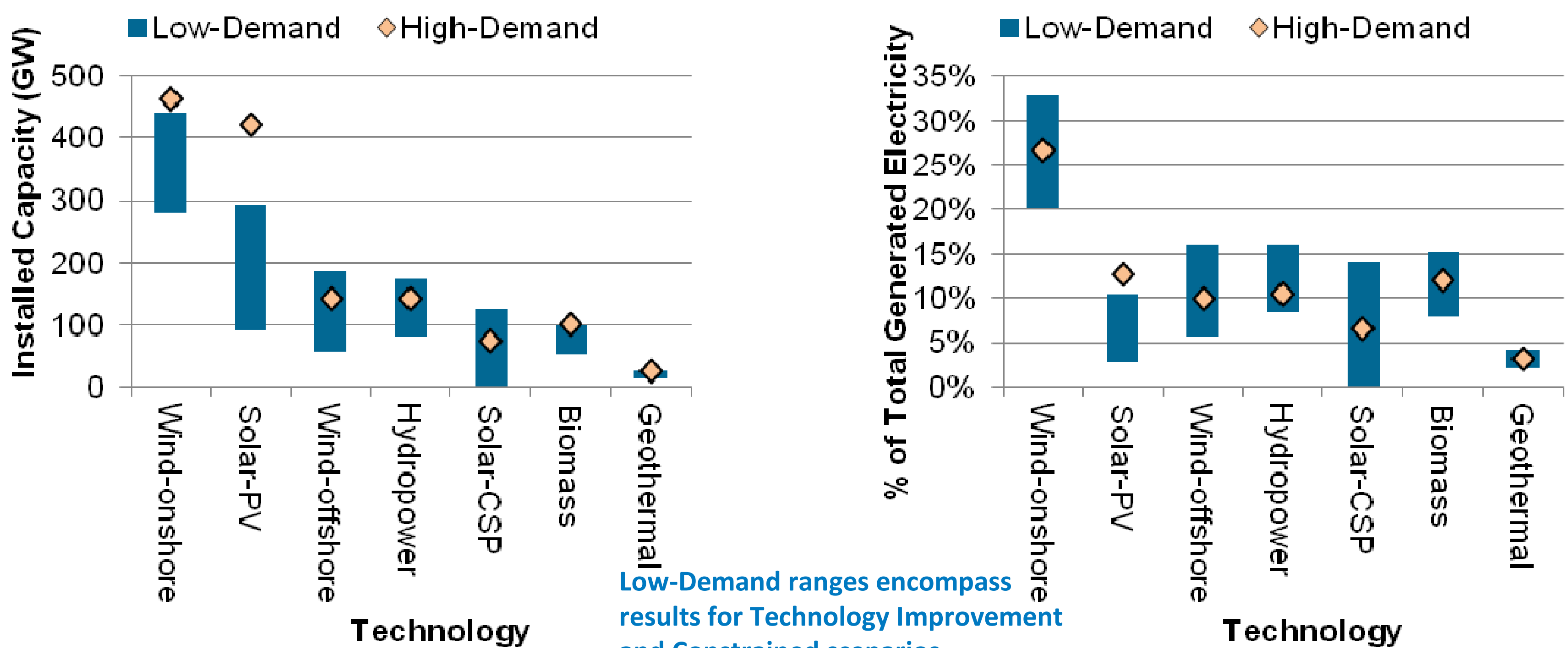
80% RE-ITI scenario

Generation Under Different Scenarios



- **Generation in 2050 for the low demand 80% cases under different constraints.**

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



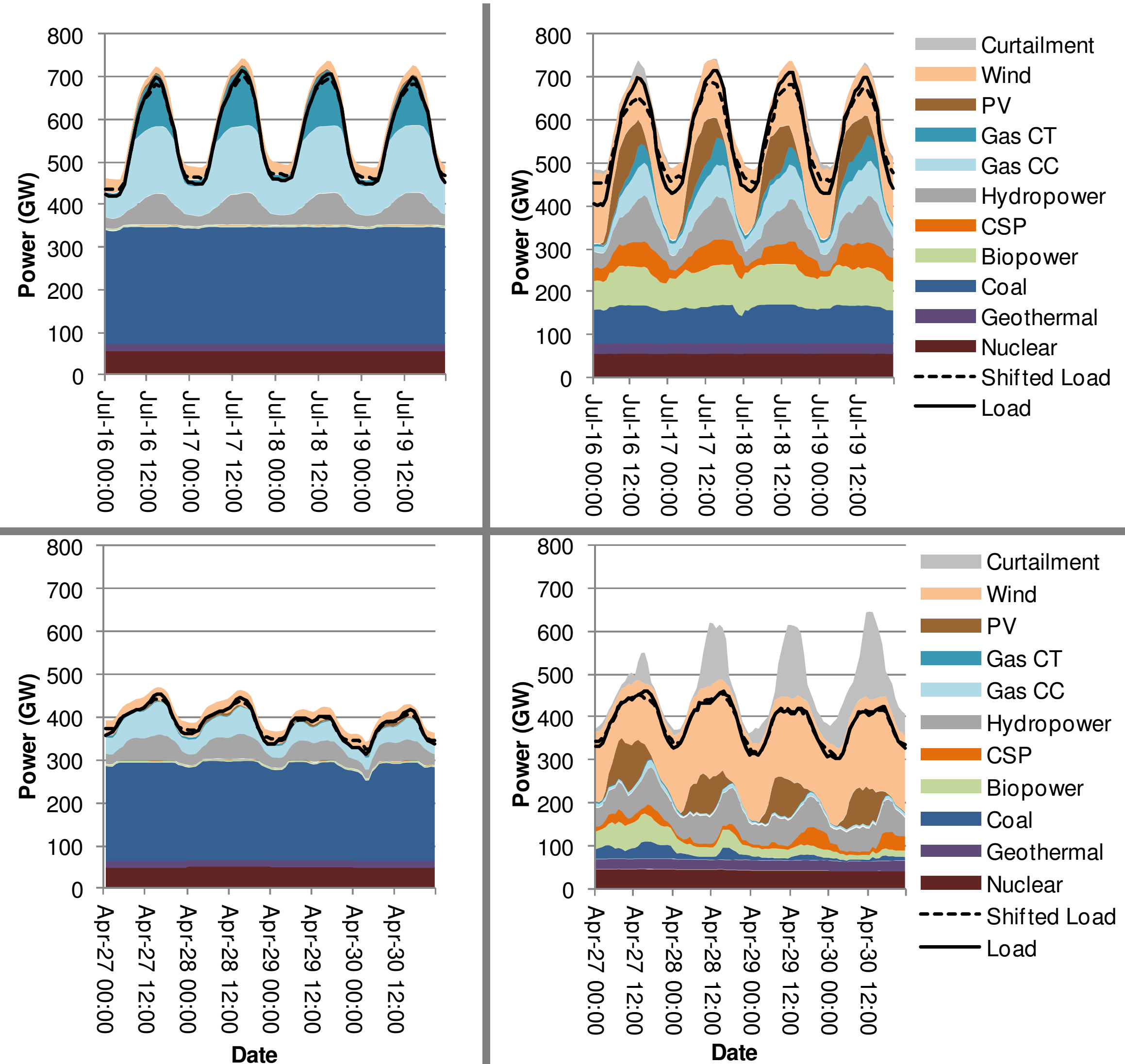
Low-Demand ranges encompass results for Technology Improvement and Constrained scenarios

- **Technology deployment depends on scenario assumptions, but in all cases examined, RE resources exist 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.**

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

Peak ➡

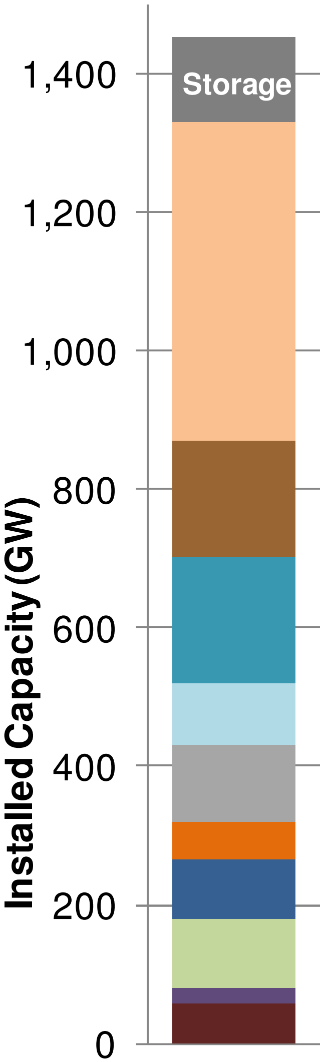
Off-Peak ➡



Baseline scenario | **80% RE-ITI scenario**

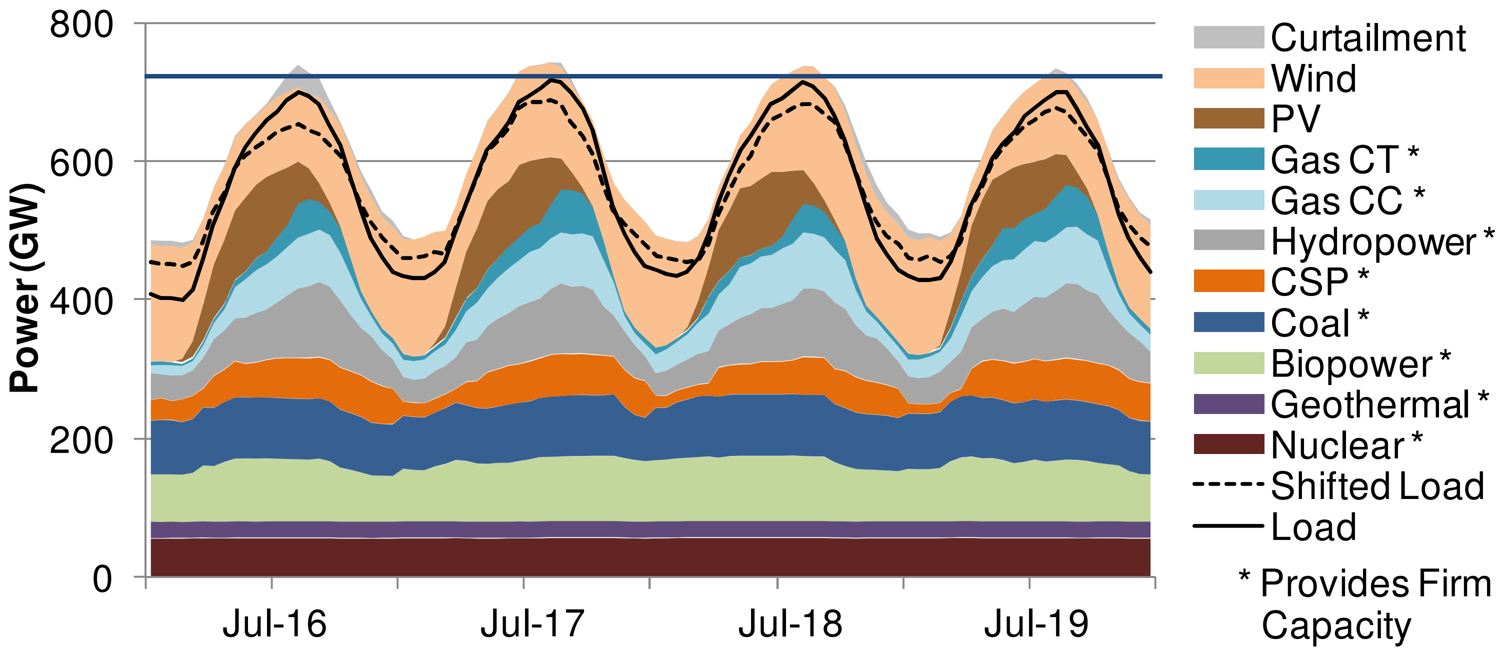
**Full reliability analysis not conducted in RE Futures*

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



Firm capacity from:

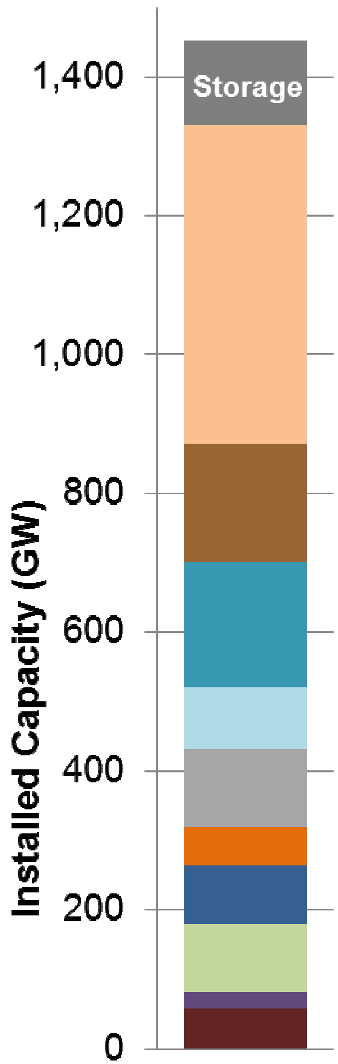
- Biopower
- Geothermal
- Hydropower
- CSP with storage
- Gas
- Coal
- Nuclear
- Utility-scale storage

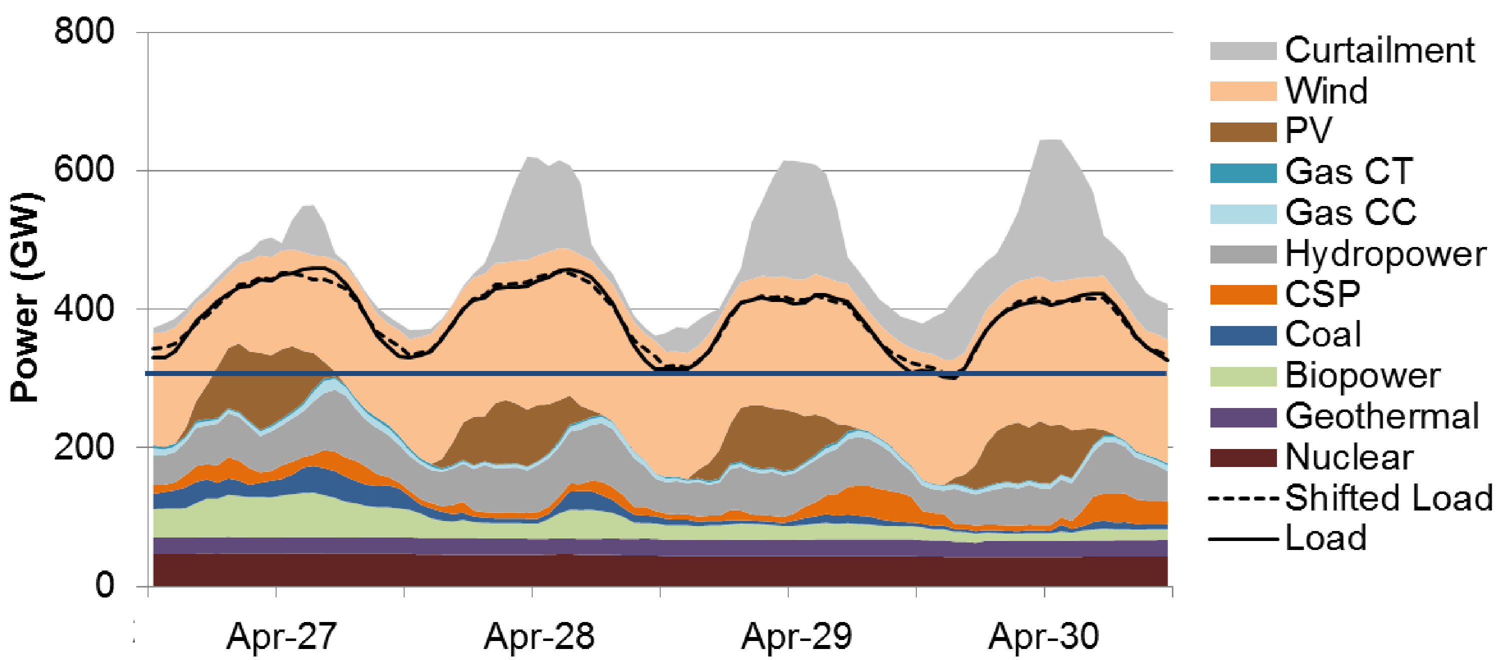


Source: Renewable Electricity Futures (2012)

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

- **Operational challenges for high renewable scenarios are most acute during low-demand periods (e.g., spring)**
- **Greater thermal power plant ramping and cycling**
- **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.*





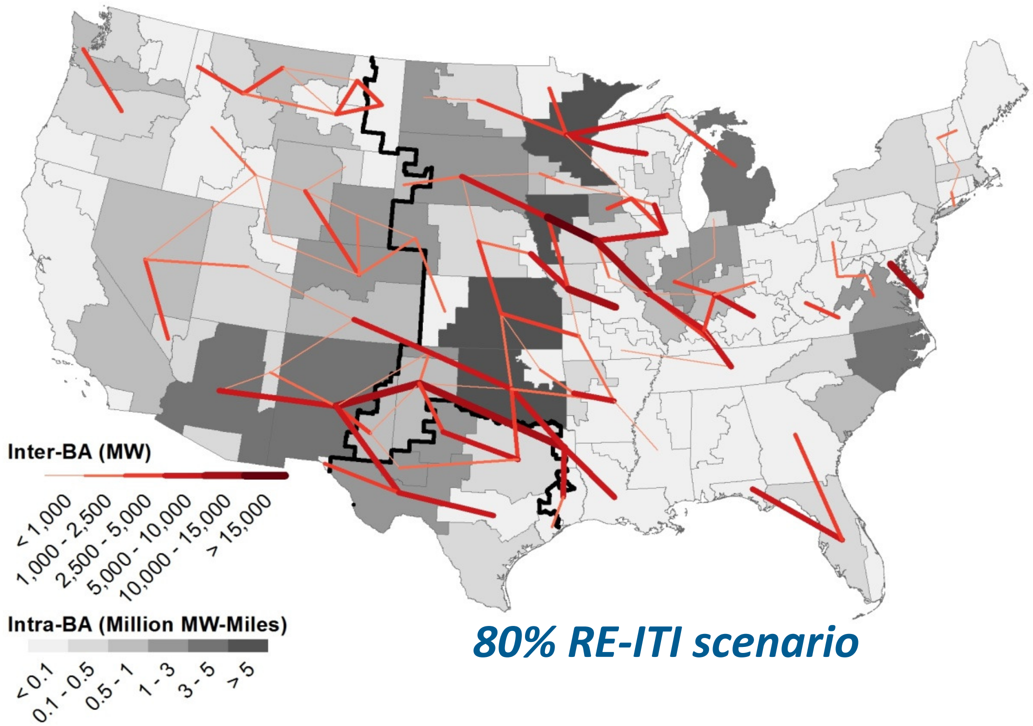
Source: Renewable Electricity Futures (2012)

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:

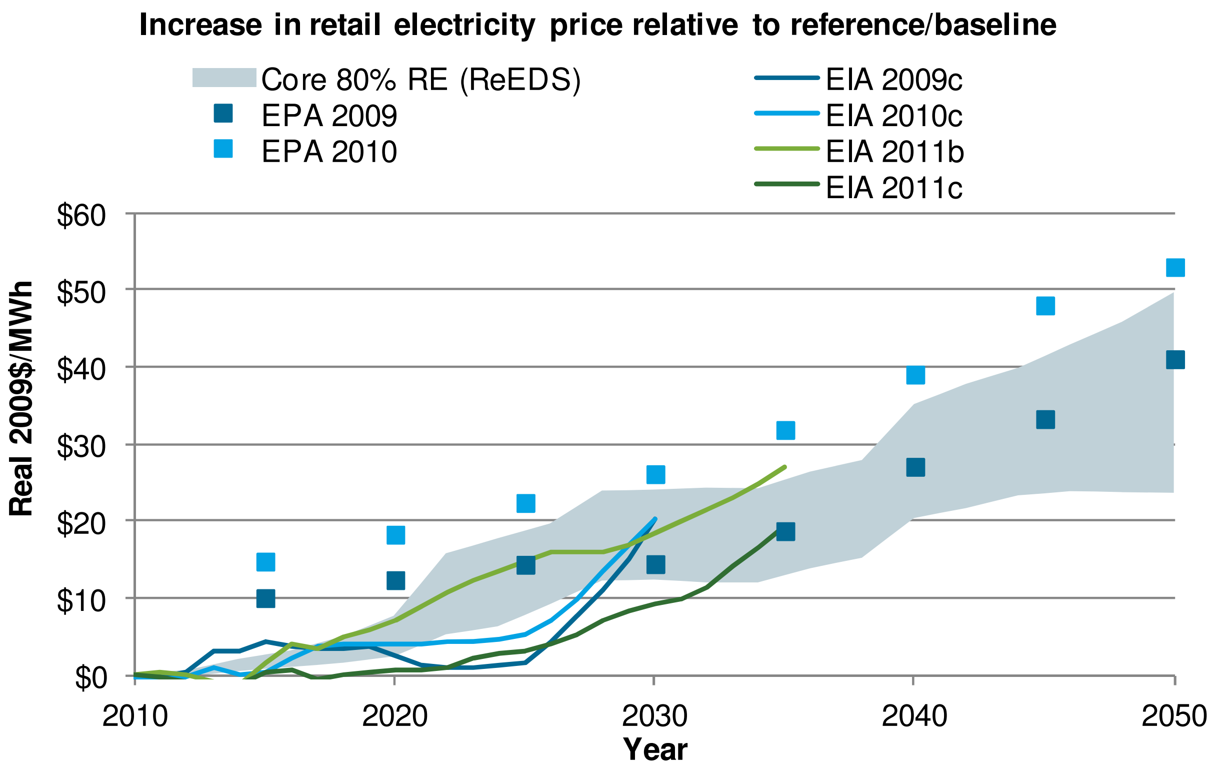
- **Maintaining sufficient capacity on the system for planning reserves**
- **Relying on demand-side interruptible load, conventional generators (particularly natural gas generators), and storage to manage increased operating requirements**
- **Mitigating curtailment with storage and controlled charging 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.**

As RE deployment increases, additional transmission infrastructure is needed



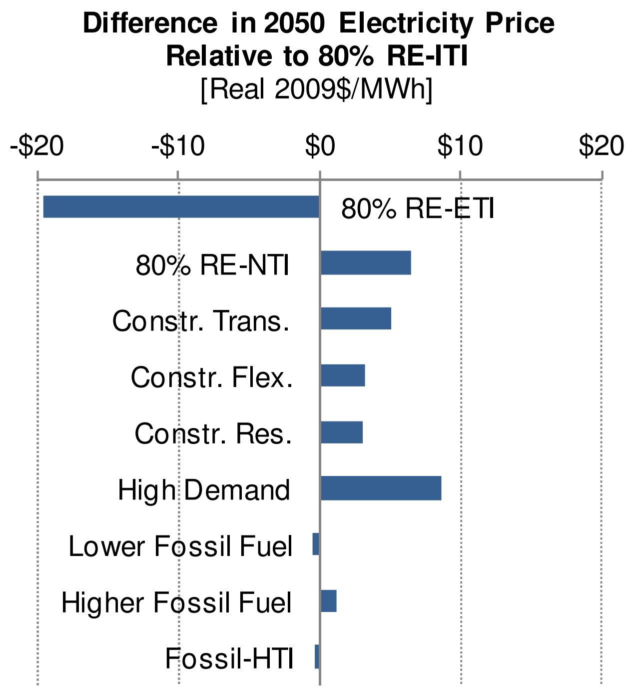
- **In most 80%-by-2050 RE scenarios, 110-190 million MW-miles of new transmission lines are added**
- **AC-DC-AC interties are expanded to allow greater power transfer between asynchronous interconnects**
- **However, 80% RE is achievable even when transmission is severely constrained (30 million MW-miles)—greater 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 & distribution losses**

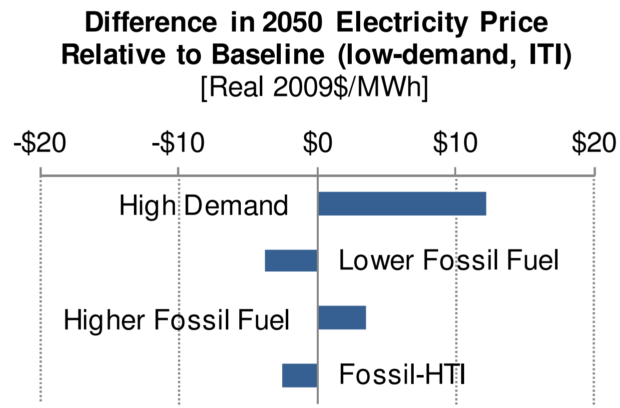
Incremental cost associated with high RE generation is comparable to published cost estimates of other Low Carbon Scenarios



- **Comparable to incremental cost for clean energy and low carbon scenarios evaluated by EIA and EPA with similar GHG reduction**
- **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 and do <u>not</u> reflect U.S. DOE activities to further lower these costs**

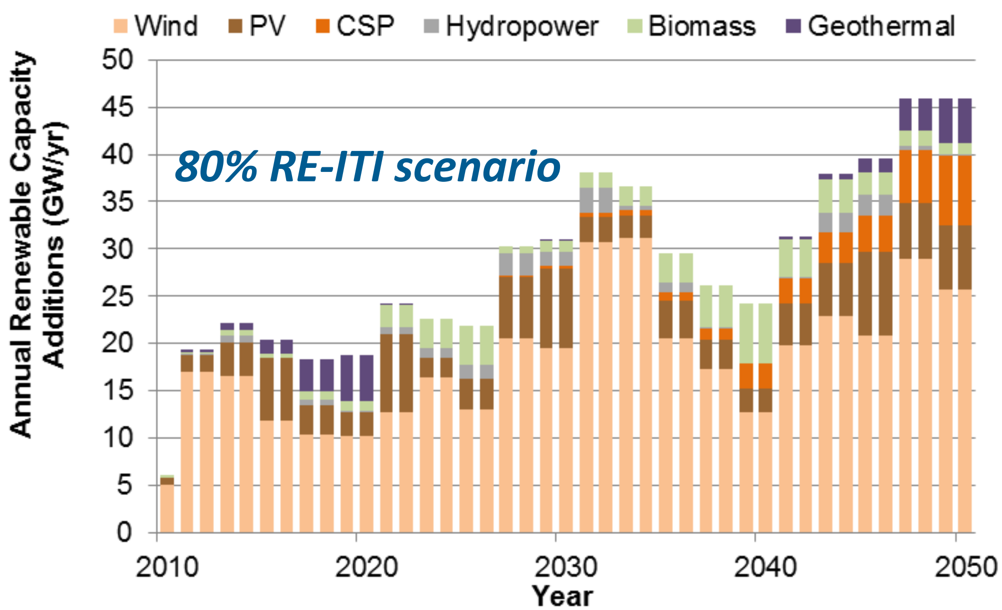
Improvement in cost and performance of RE technologies is the most impactful lever for reducing the incremental cost

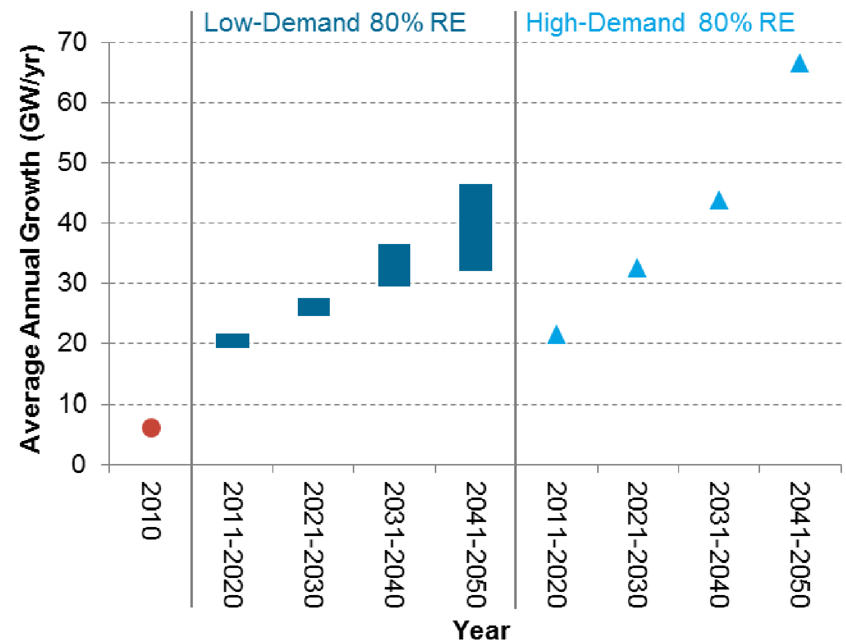




- **Cost is less sensitive to assumed electric system constraints (transmission, flexibility, RE resource access)**
- **Electricity prices in high RE scenarios are largely insensitive to projections for fossil fuel prices and fossil technology improvements**
- **Lower RE generation levels result in lower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

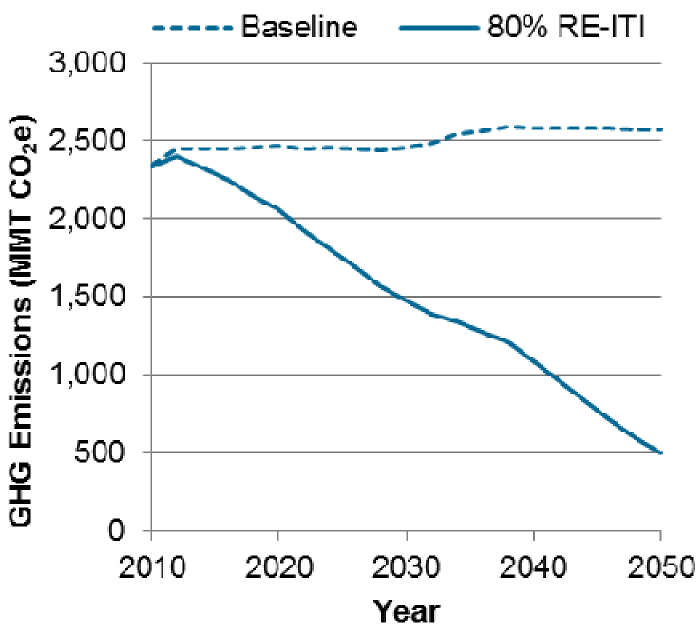
No insurmountable long-term constraints to RE technology manufacturing capacity, materials supply, or labor availability were identified

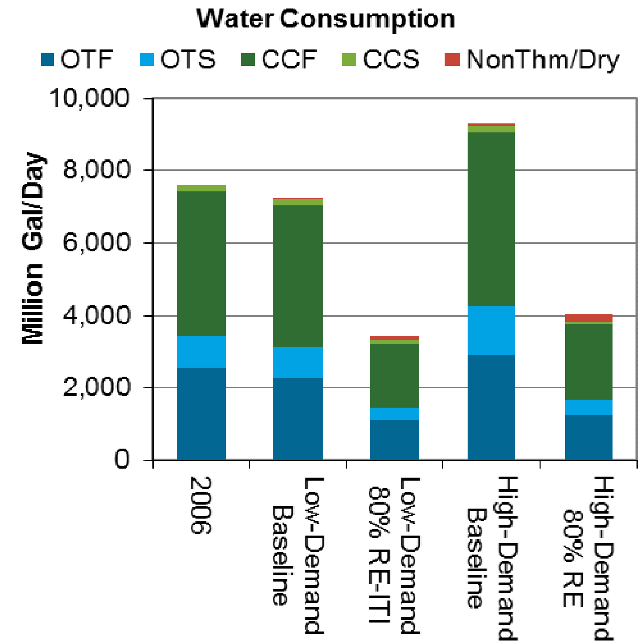




- 80% RE in 2050 requires adding ~20 GW/yr 2011-2020 , ~30 GW/yr 2021-2040, ~40 GW/yr 2041-2050 (higher under High-Demand scenario)
- These installation rates are higher than U.S. capacity additions in 2010 (7 GW) and 2009 (11 GW) and would place challenges on RE industries
- Recent growth in the U.S. and globally demonstrate the scalability of RE industries, e.g., U.S. wind industry grew rapidly during the last decade; worldwide PV production capacity comparable with scenarios
- Better informed siting practices and regulations can reduce industry scale-up challenges

High RE futures impacts on emissions and land use





80% RE scenarios lead to:

- ~80% reduction in 2050 GHG emissions (combustion-only and life cycle)
- ~50% reduction in electric sector water use
- Gross land use <3% of contiguous U.S. area
- Other related potential impacts include: visual, landscape, noise, habitat, ecosystem

80% RE scenarios

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
Major Roads**	50
Golf Courses **	10

** USDA 2010, 2012 ** Denholm & Margolis 2008*

Future work needed

- **A comprehensive cost-benefit analysis to better understand the economic and environmental implications of high renewable electricity futures relative to today's electricity system 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 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**

- **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**

Summary of Key Analysis Results

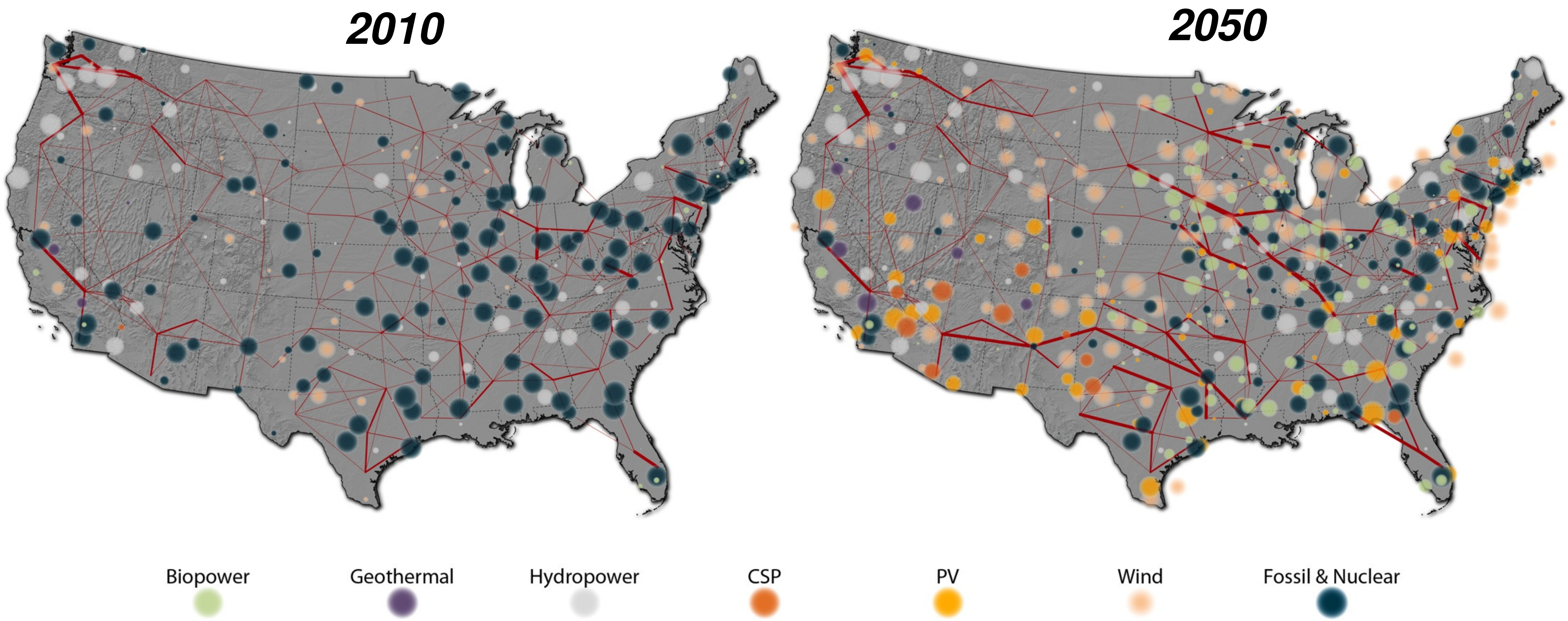
- Renewable electricity generation from technologies that are commercially available today, in combination with a more flexible electric system, is more than adequate to supply 80% of total U.S. electricity generation in 2050 while meeting electricity demand on an hourly basis in every region of the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

- Increased electric system flexibility is needed to enable electricity supply-demand balance with high levels of renewable generation, and 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 to achieve high levels of renewable electricity use, and result in deep reductions in 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.

A Transformation of the U.S. Electricity System



A future U.S. electricity system that is largely powered by renewable sources appears possible at the hourly level. Further work is warranted to investigate this clean generation pathway. http://rpm.nrel.gov/refhighre/dispatch/dispatch.html