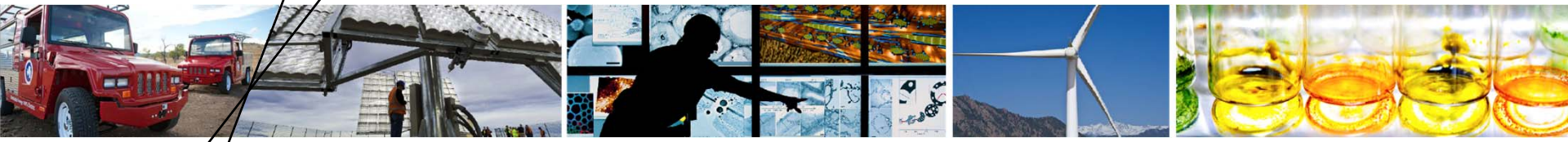
Renewable Electricity Futures: *Exploration of up to 80% renewable electricity penetration in the United States*



Maureen Hand, NREL
Ed DeMeo, RECS Inc.
Donna Hostick, PNNL
Trieu Mai, NREL
C. Adam Schlosser, MIT

World Renewable Energy Forum
Denver, Colorado
May 17, 2012

NREL/PR-6A20-54948

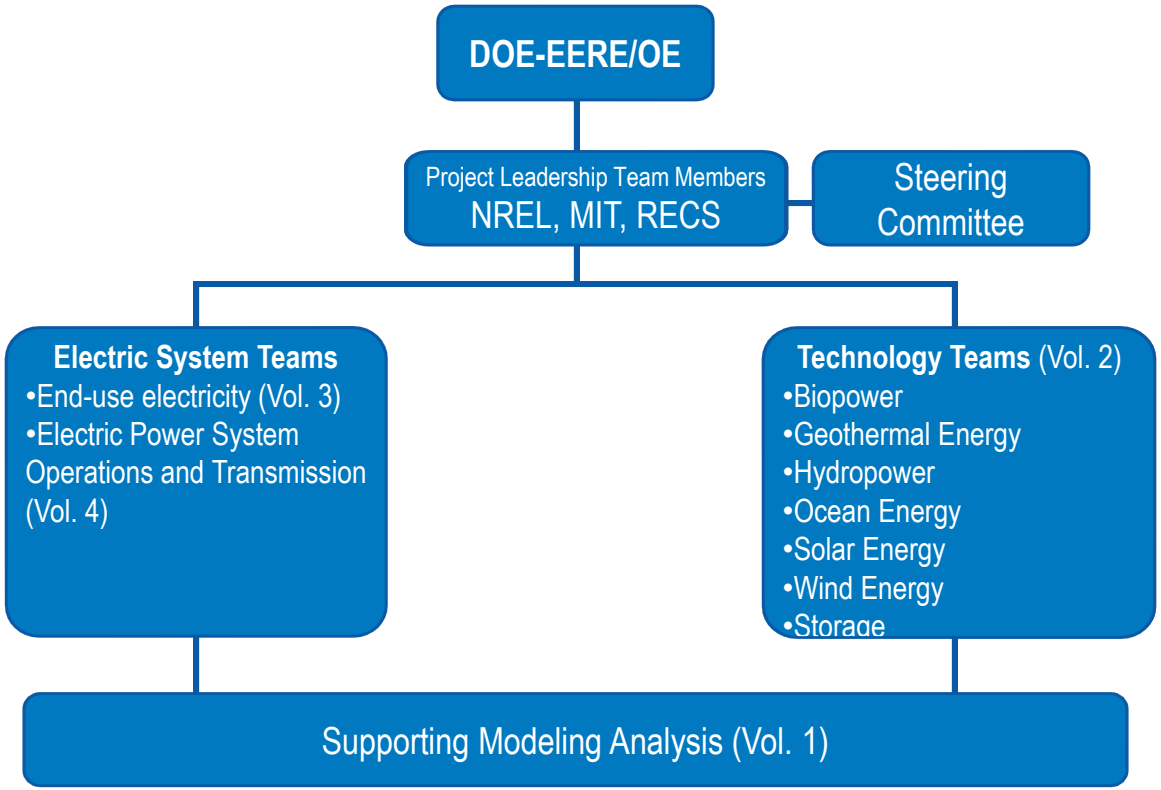
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Renewable Electricity Futures Introduction

- **Renewable electricity generation characteristics are appealing**
  - Low- or no-criteria air emissions that affect public health
  - Low-carbon emission that affect climate change
  - Low- or no-fuel costs that mitigate risk of fuel price volatility
  - Domestic, sustainable source of energy that enhances energy security
- **… which motivates analysis to explore potential characteristics of a high renewable U.S. electric sector – Renewable Electricity Futures**

- **RE Futures is a rigorous analytical study that begins to answer the question:**
  - Can the U.S. power system supply electricity to meet customer demand on an hourly basis with high levels of renewable electricity, including variable wind and solar generation?

RE Futures Study Organization



- **Over 140 Individual Contributors**
- **Over 50 Participating Organizations (Selected List)**
  - **National Laboratories:** INL, LBNL, NREL, ORNL, PNNL, SNL
  - **Industry:** Midwest Independent System Operator, Western Interstate Energy Board, Deutsche Bank, Xcel Energy, Vestas Wind Systems, RES Americas, Black &Veatch
  - **Universities:** Massachusetts Institute of Technology, University College Dublin, University of Colorado, Virginia Polytechnic Institute and University, Texas Tech
  - **NGOs:** Electric Power Research Institute, Environmental Defense Fund, American Council for an Energy-Efficient Economy, Energy Foundation

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	Fully evaluate power system reliability or explore market mechanisms to enable high RE generation
Identify electric sector characteristics associated with specific levels of RE generation	Evaluate policy efforts that yield high RE generation
Demonstrate US electric sector carbon emissions reductions	Assess optimal pathways to achieve low-carbon futures
Explore a select number of economic, environmental and social impacts	Conduct comprehensive cost-benefit analysis
Illustrate a low-carbon, domestic, sustainable, low-fossil fuel electric sector concept	Provide the final word on high RE generation, but encourages continued investigation

Forum outline

- **Renewable Electricity Technologies – Ed DeMeo (RECS Inc.)**
- **End-Use Electricity Demand – Donna Hostick (PNNL)**
- **Electric Sector Modeling – Trieu Mai (NREL)**
- **Greenhouse Gas, Water & Other Environmental Implications – C. Adam Schlosser (MIT)**
- **Summary – Maureen Hand (NREL)**

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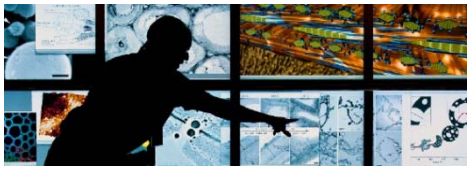
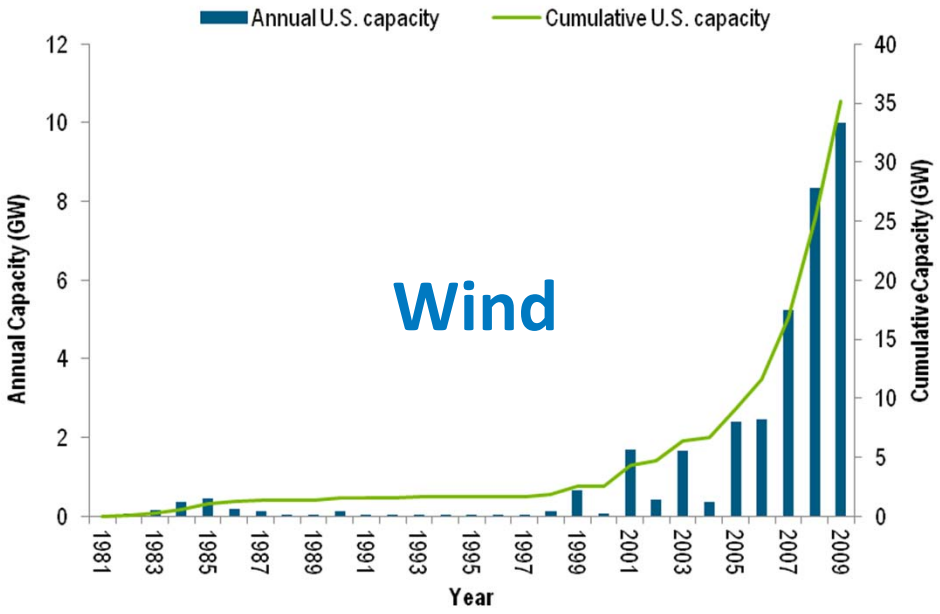
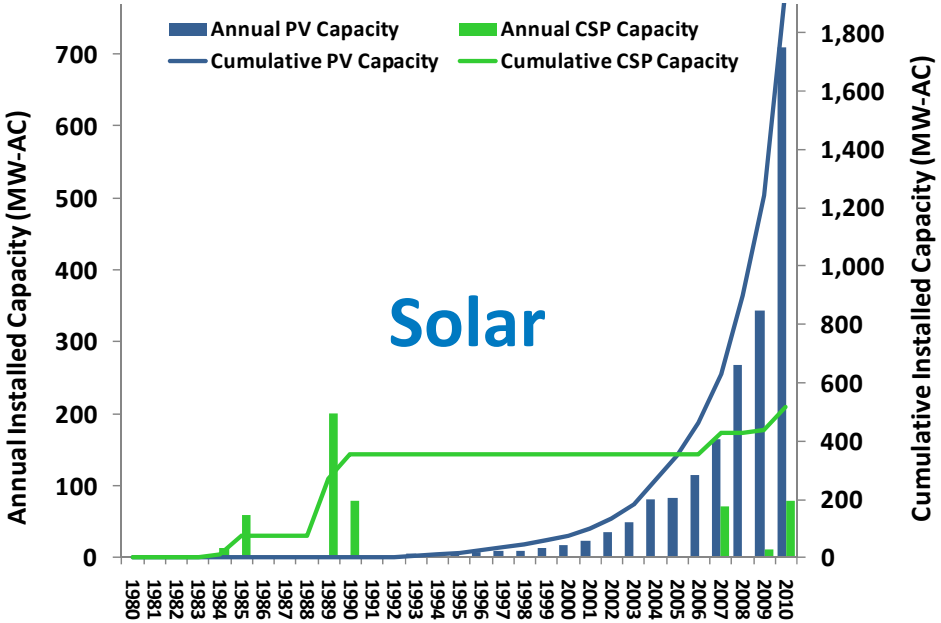


Renewable Electricity Technologies

Current State of RE Power Generation





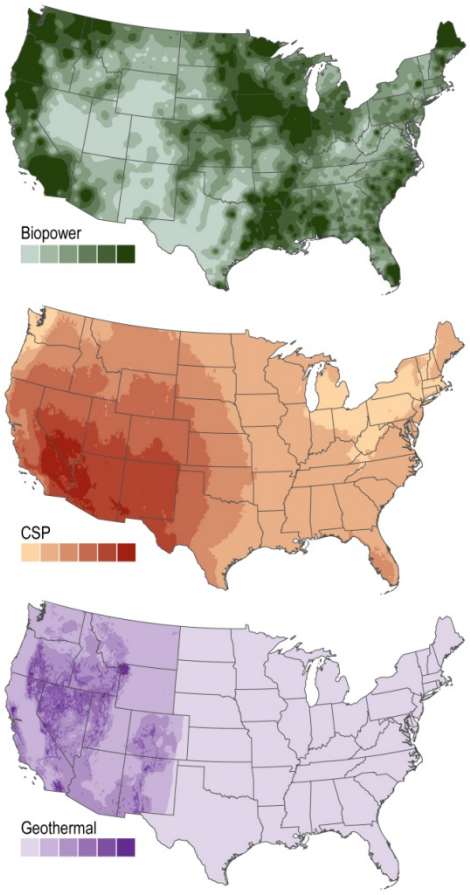
- **In 2010, 10% of U.S. electricity from renewables**
  - Hydropower = 6.4% (77 GW)
  - Wind = 2.4% (40 GW)
  - Biopower = 0.7% (6.7 GW)
  - Geothermal = 0.4% (3.4 GW)
  - Solar = 0.05% (2.6 GW)
- **RE deployment has grown rapidly in recent years, especially for wind and solar technologies**

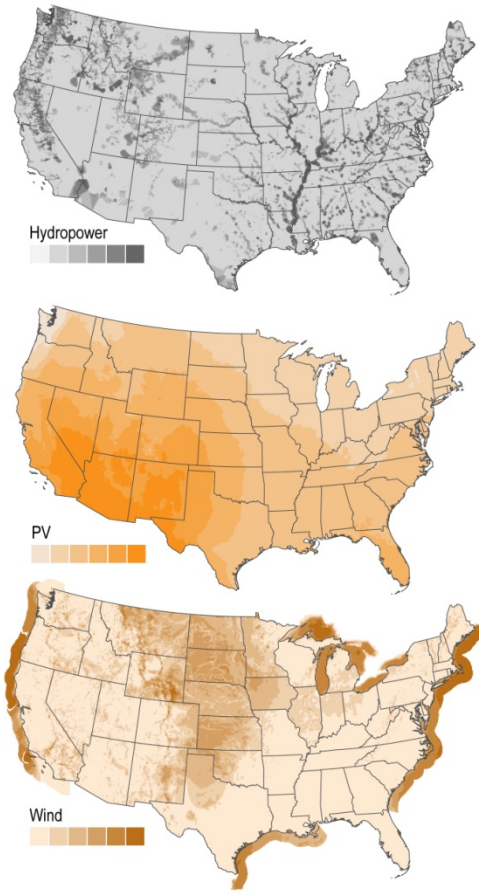
RE Resources Are Large and Widely Distributed

Bio ~100 GW

CSP ~37,000 GW

Geo ~36 GW
(Hydrothermal only)





Hydro ~200 GW

PV ~80,000 GW
(rooftop ~700 GW)

Wind ~10,000 GW

- Total U.S. installed electricity generation capacity: ~1000 GW
- Technical resource potential shown, not economic potential

RE Options Have A Wide Range of Characteristics

Technology	Variability Time Scale	Dispatch-ability	Geographic Diversity Potential	Predictability	Capacity Value Range (%)
Bioenergy	Seasons	+++	+	++	Similar to thermal
PV	Minutes to years	+	++	+	<25–75
CSP (with thermal storage)	Hours to years	++	+	++	90
Geothermal (Hydrothermal)	Years	+++	NA	++	Similar to thermal
Hydropower (run of river)	Hours to years	++	+	++	0–90
Hydropower (reservoir)	Days to years	+++	+	++	Similar to thermal
Wind	Minutes to years	+	++	+	5–40

- Some are dispatchable like conventional fossil plants (e.g., geo, bio)
- Others show variability and uncertainty (e.g., wind, PV)
- Most are widely distributed geographically (except geothermal hydrothermal)

Other Key RE Deployment Issues

- Area requirements:
  - Gross estimate for RE Futures scenarios: < 3% of US land area
  - About half used for biopower
  - Majority of remainder for wind, but only about 5% is actually disturbed

Rough Area Comparisons (000 km^2)	
Total Contiguous U.S.	7,700
REF 80% (typical)	158
Biomass	75
All Other RE	71
All Other RE (disturbed)	8
Transmission & Storage	11
2009 Corn Production*	350
Major Roads**	50
Golf Courses **	10

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

- Other siting issues:
  - Streamlined permitting processes needed
  - Wildlife and habitat disturbance concerns
  - Public acceptance for generation and transmission

- Critical materials:
  - Rare earths for permanent-magnet generators
  - Some PV materials (e.g., In, Te, Cd)

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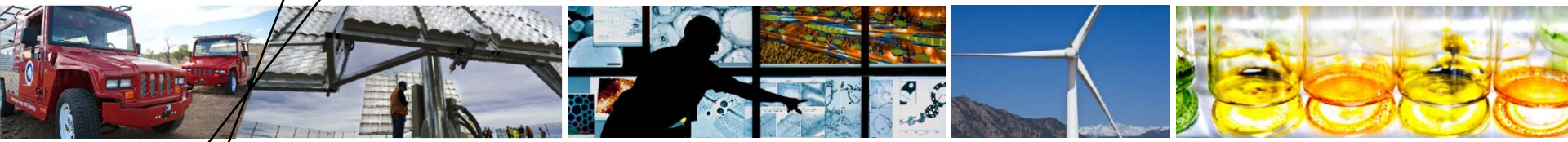
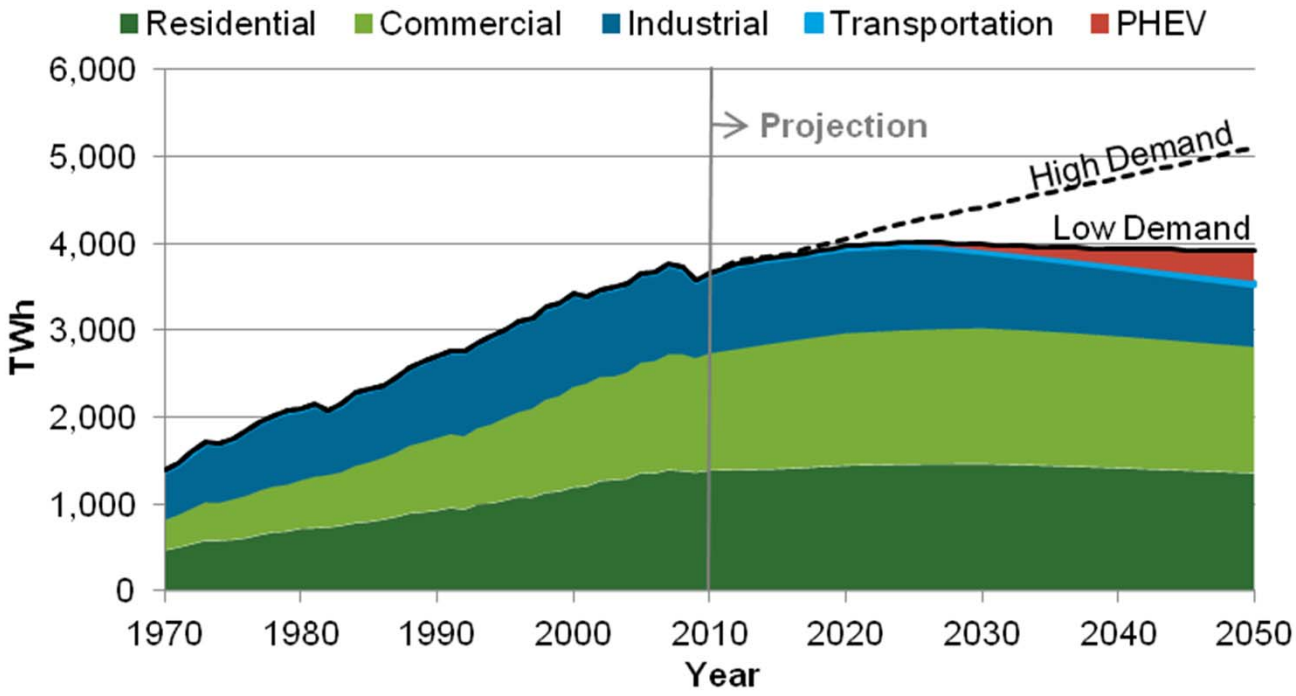


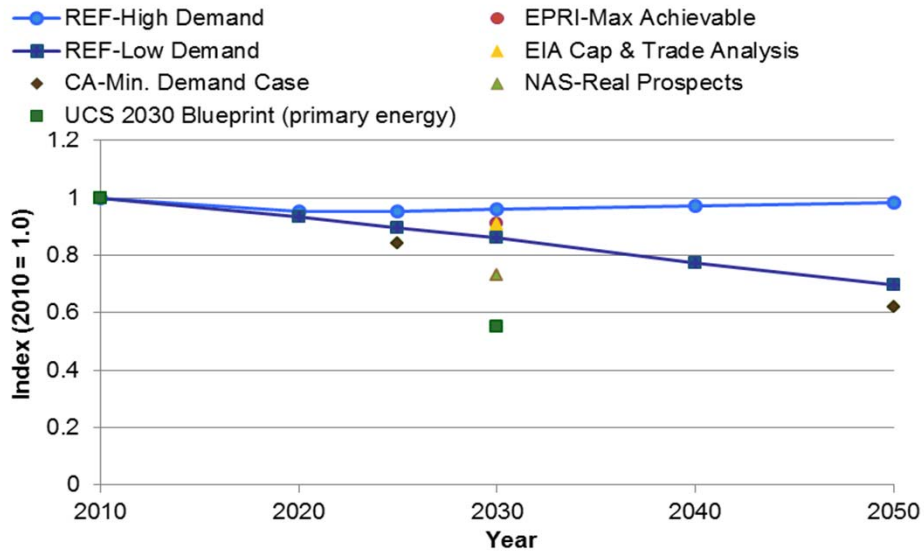
End-use Electricity Demand

Historical and Projected Demand



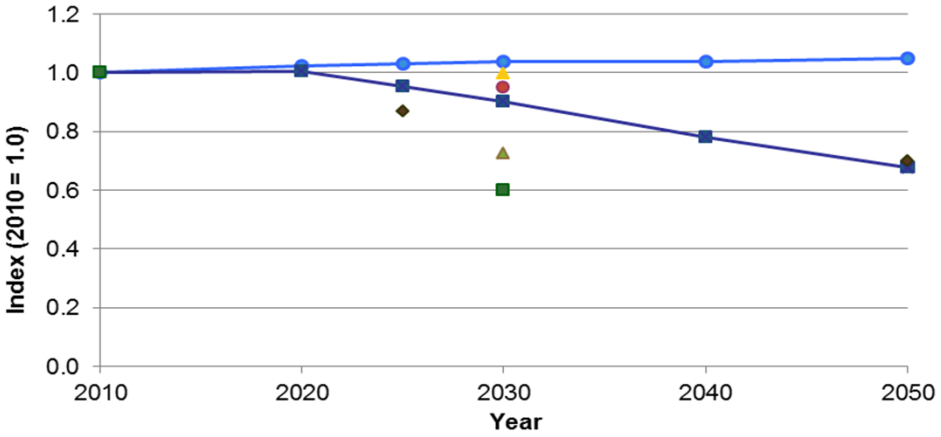
Sector	High-Demand Projection	Low-Demand Projection
Residential	2% decline in intensity over 2010 levels	30% decline in intensity over 2010 levels
Commercial	5% increase in intensity over 2010 levels	32% decline in intensity over 2010 levels
Industrial	35% decline in intensity over 2010 levels	50% decline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

Electricity Intensity Projections are Comparable to Other Studies

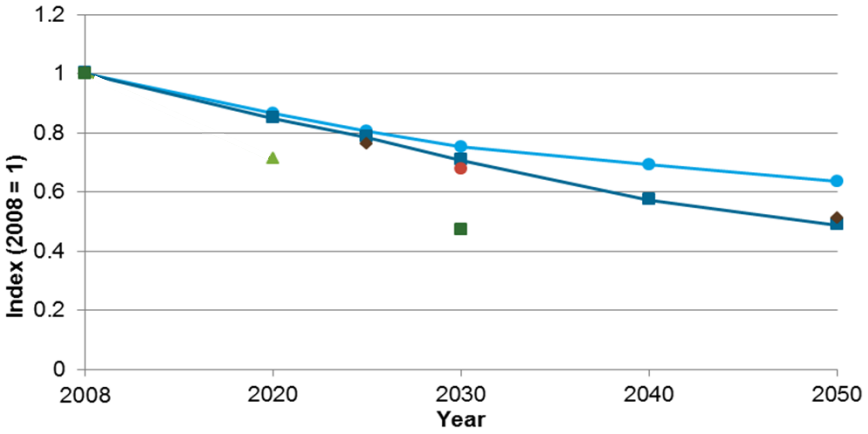


Residential (electricity use per household)

- **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 Increases the Potential for RE to Meet Electricity Requirements

- **Regional, seasonal, and diurnal variability in electricity requirements impact the potential for RE production**
  - 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 over 40% of PHEV load was under utility-controlled charging

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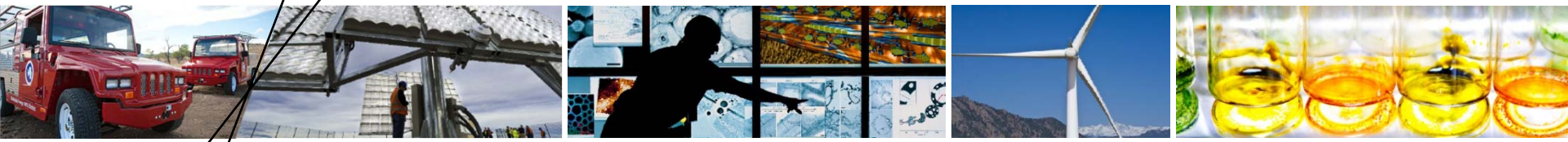
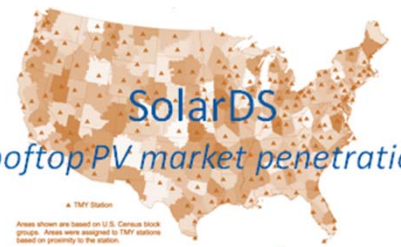


Electric Sector Modeling

RE Futures Modeling Framework

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

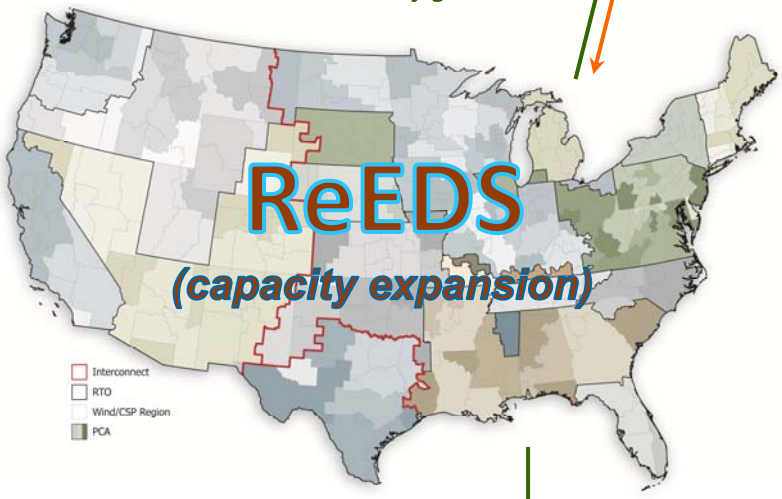


rooftop PV penetration

2050 mix of generators

does it balance hourly?

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

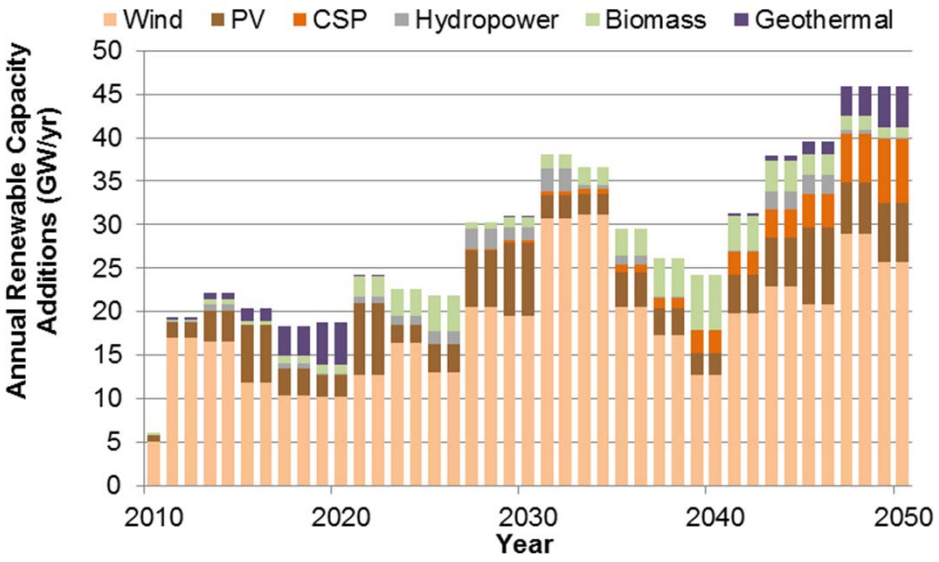


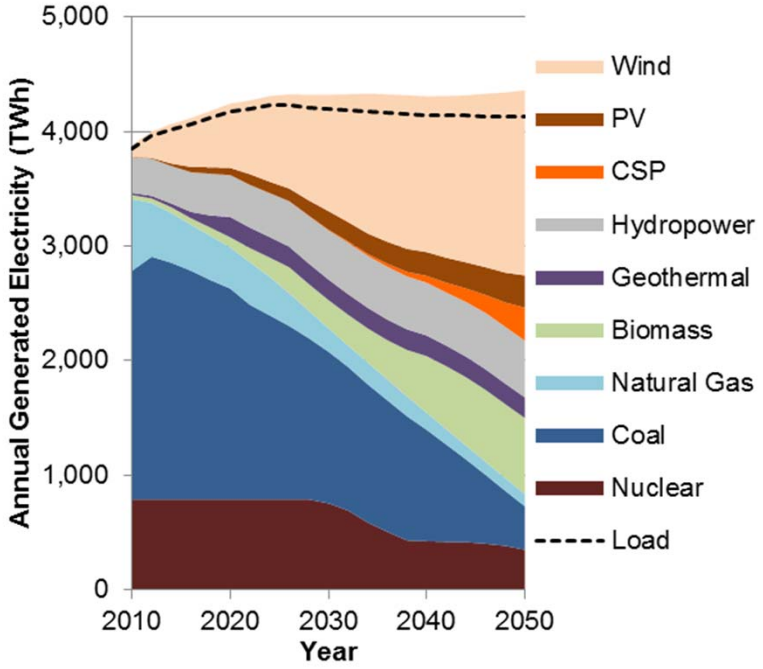
Capacity & Generation 2010-2050

Implications
GHG Emissions
Water Use
Land Use
Direct Costs

Transitioning to High Renewable Electricity

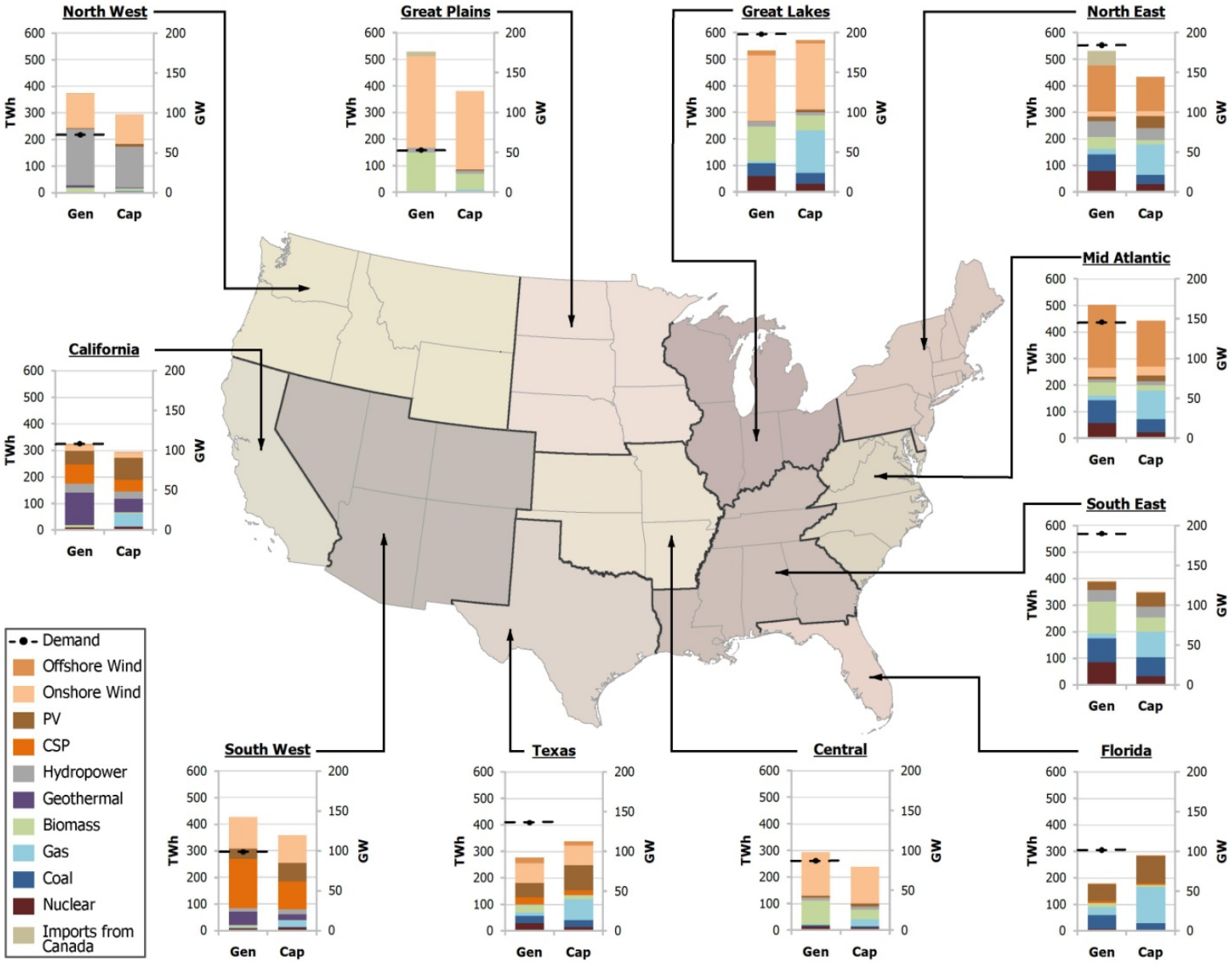
80% RE-ITI scenario



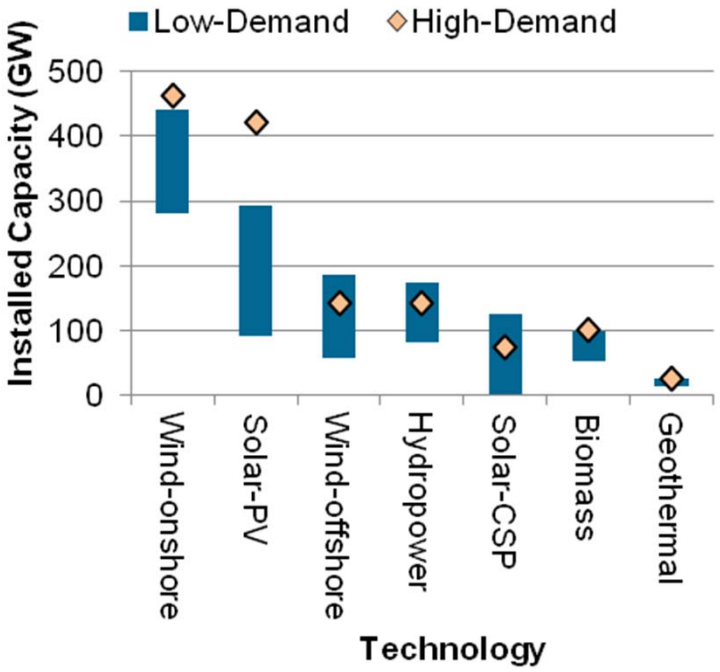


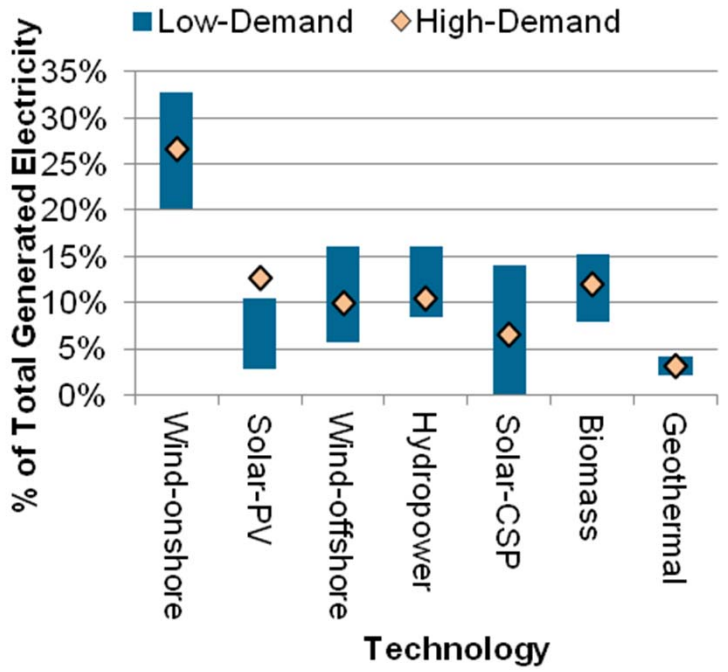
- **80% RE generation in 2050 requires ~20 GW/year between 2011-2020 and ~40 GW/year in 2041-2050 (higher under High-Demand scenario)**
- **These installation rates are higher than U.S. capacity additions in 2010 (7 GW) and 2009 (11 GW) and would place challenges on RE industries**
- **Recent growth 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**

All Regions Could Contribute to RE Supply in 2050



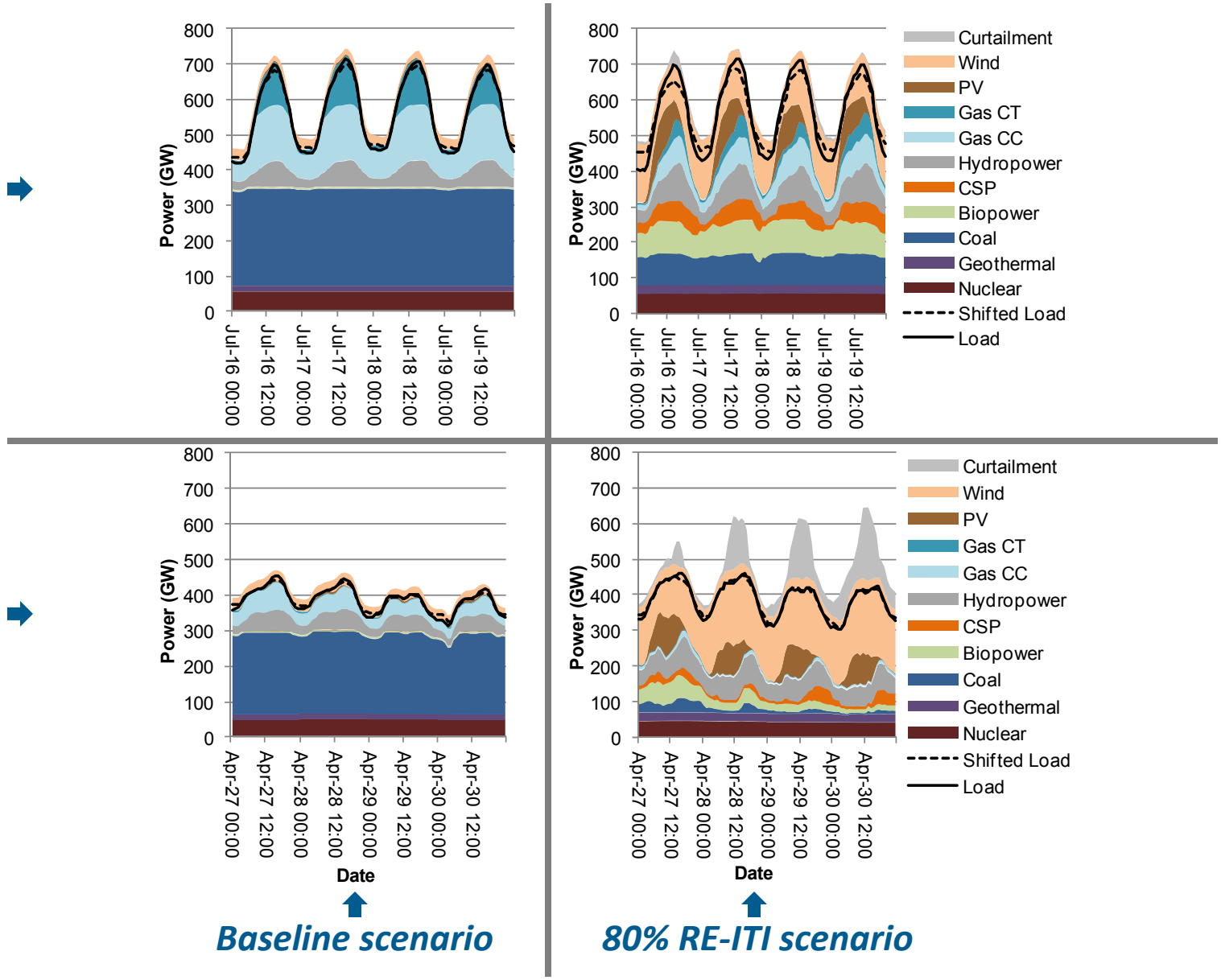
Multiple Technology Pathways Exist





- Over two dozen scenarios modeled
- Technology deployment depends on scenario assumptions, but in all cases examined, RE resources exist to compensate for variations in access to transmission, grid flexibility, resource availability, technology costs, and electricity demand
- Future RE technology cost and performance is a major deployment driver

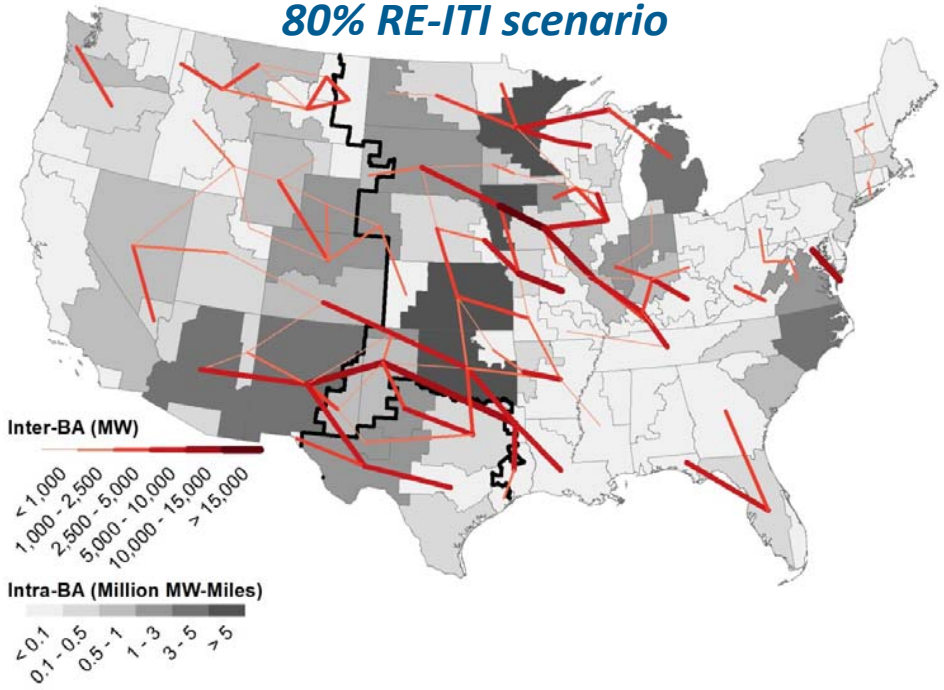
Electricity Supply & Demand Can Be Balanced at Each Hour of the Year *



*Full reliability analysis not conducted in RE Futures

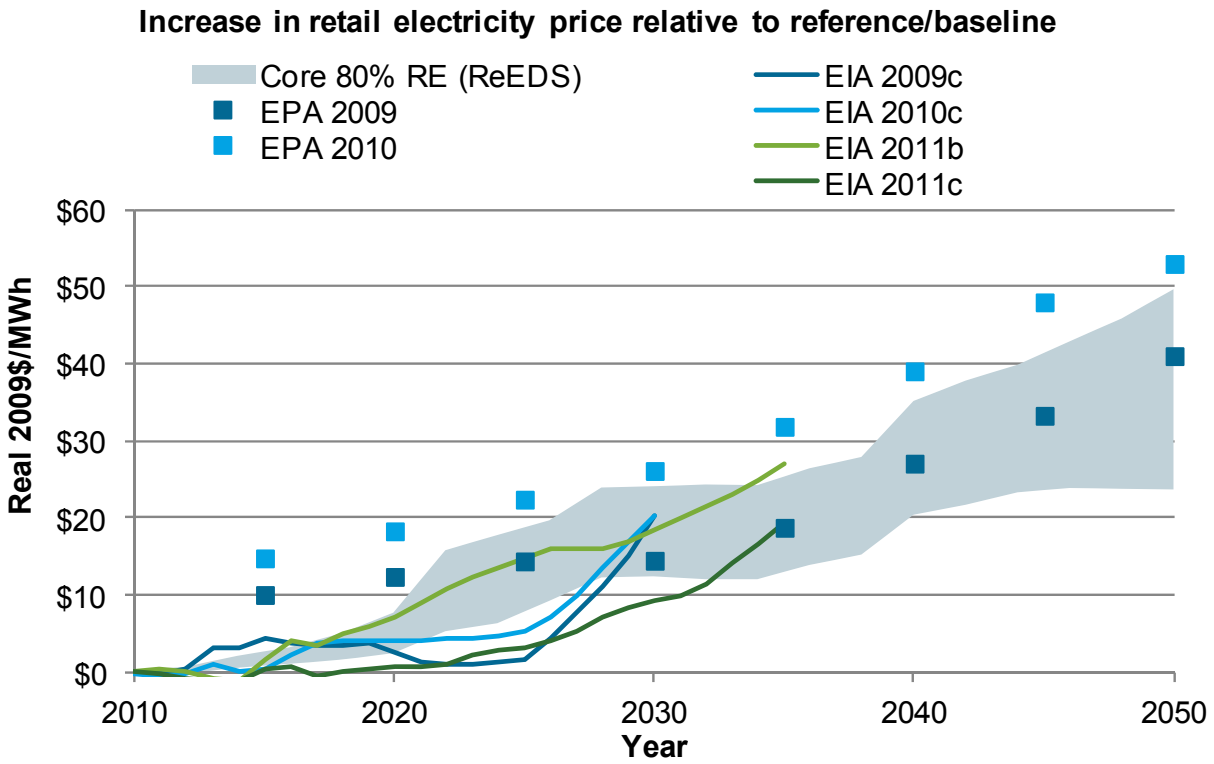
Transmission & System Flexibility Help Support Renewable Integration

80% RE-ITI scenario



- 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 variability
- Mitigating curtailment with storage and controlled charging of electric vehicles
- Relying on the dispatchability of coal, NG, and RE (e.g. biopower, hydropower, CSP with storage)
- Transmitting greater amounts of power over longer distances to smooth electricity demand profiles and aggregate variability of wind and PV

Incremental Direct Costs of Achieving High RE Penetration are Similar to Other Low Carbon Scenarios



- **The incremental costs of the RE Futures scenarios are comparable to low carbon and clean energy scenarios, evaluated by EIA and EPA, *with similar GHG reductions* (~40% reduction by 2030, ~80% reduction by 2050)**
- **Baseline scenario assumes no new policies, expiration of RE incentives, and limited coal retirements**
- **Further technological advances can reduce these incremental costs**
- **Incremental costs should be weighed with other implications of high RE deployment**

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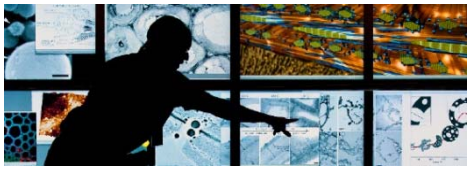
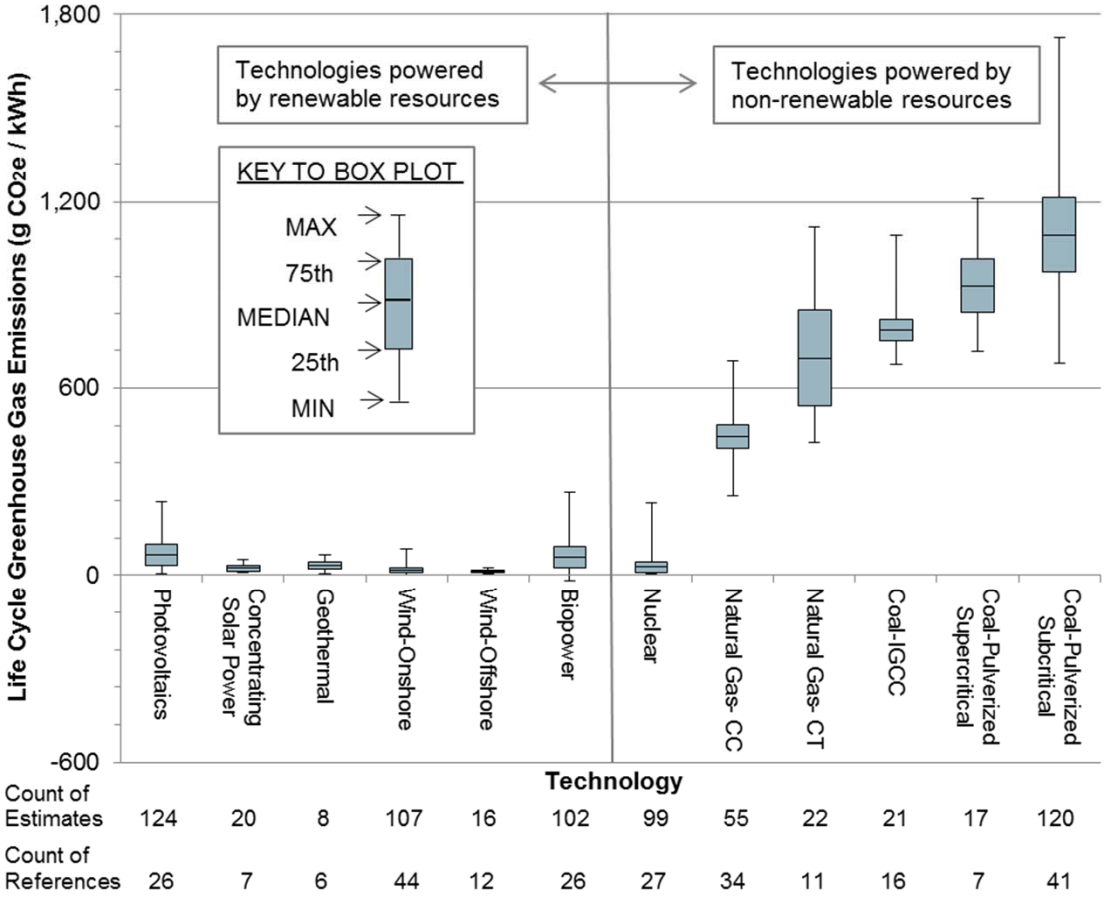
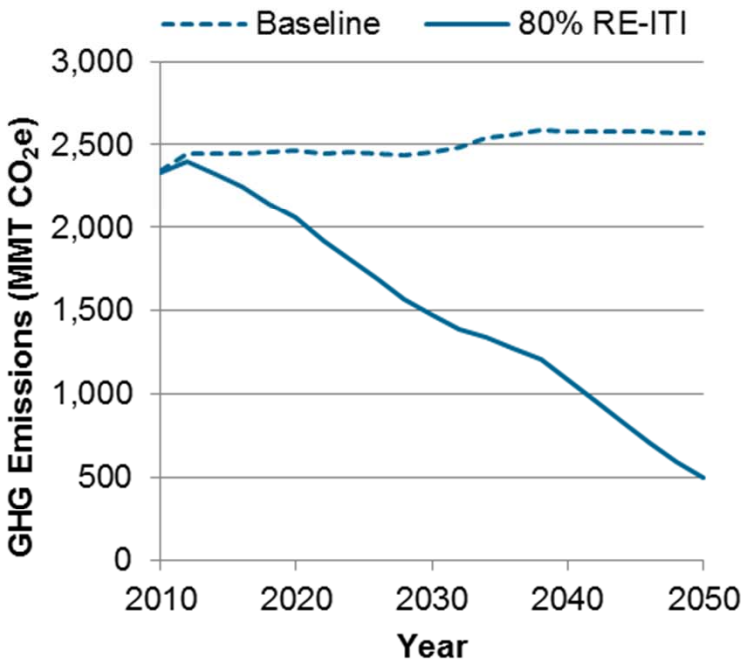


Greenhouse Gas, Water & Other Environmental Implications

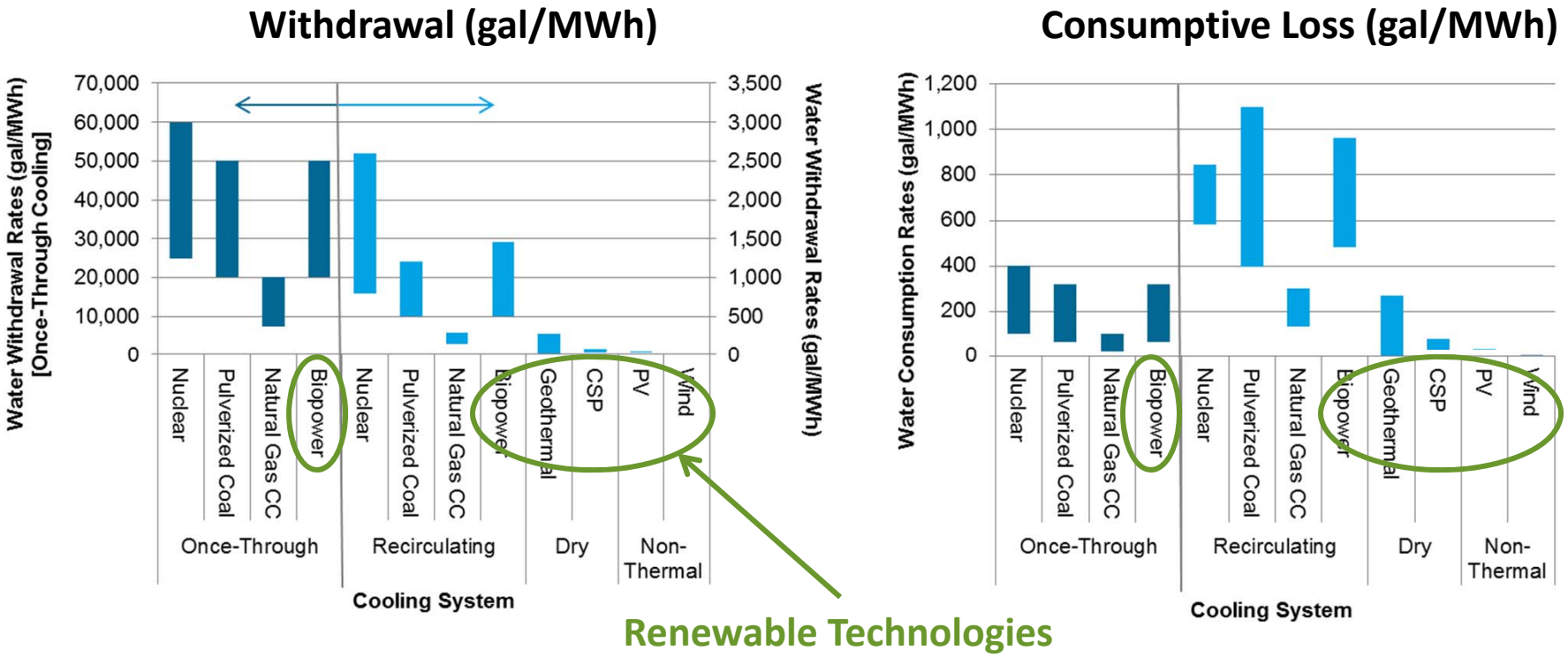
Achieving 80% RE Reduces Annual Power Sector GHG Emissions by ~80%



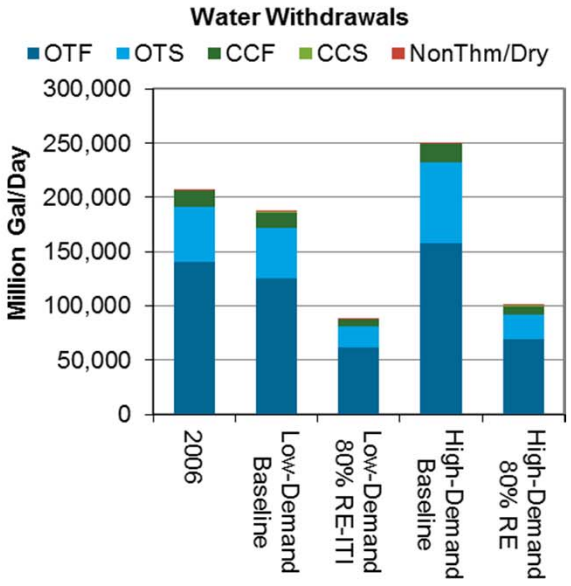


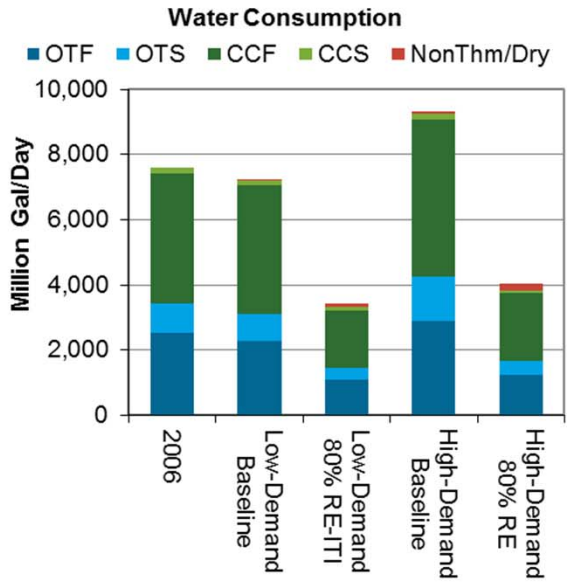
- Combustion-only and full life-cycle basis
- Other considerations include: criteria air pollutants, land use, natural gas price volatility, and power sector water use

Water Use Factors Generally Lower for RE vs Non-RE Technologies

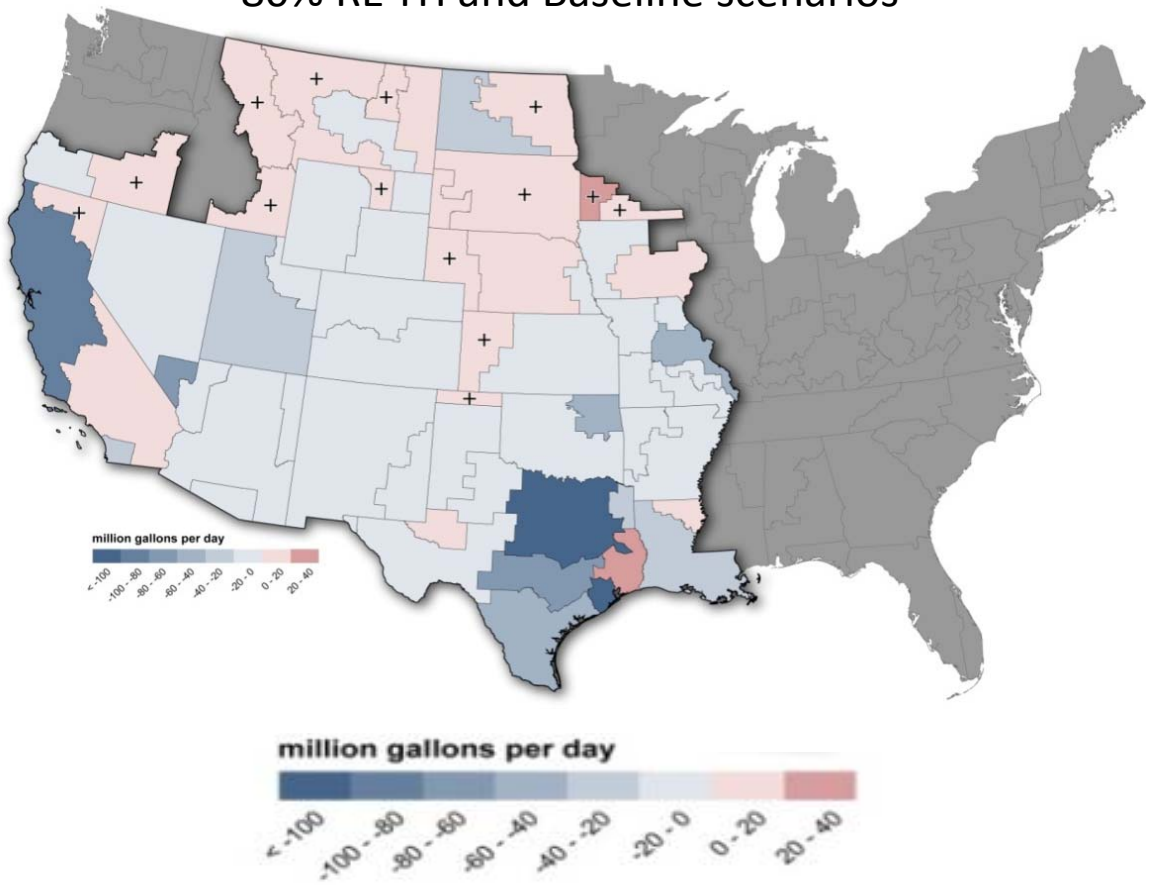


Achieving 80% RE reduces power sector water use by ~50%





Change in 2050 water consumption between 80% RE-ITI and Baseline scenarios



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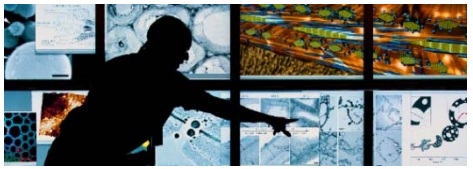

Summary

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**

Key Results: Renewable Electricity Futures

- Commercially available renewable generation technologies, are more than sufficient to supply 80% of U.S. electricity in 2050 while maintaining an operable electric power system.
- All regions of the country could contribute substantial renewable electricity supply in 2050.
- Multiple technology pathways exist to compensate for constraints limiting use of particular types of resources, power transmission infrastructure or grid flexibility.
- Annual renewable capacity additions are consistent with current global production capacities, and no insurmountable long-term constraints to manufacturing capacity, materials supply, or labor availability were identified.
- Electricity supply and demand can be balanced in every hour of the year in each region with 80% electricity from renewable resources (50% variable wind and PV).
- New challenges to power system planning and operation include management of low-demand periods and curtailment of excess electricity generation.
- A more flexible system that utilizes a broad portfolio of supply- and demand-side flexibility options is needed to accommodate increasing levels of renewable electricity generation.
- Additional transmission infrastructure is required to connect generation from cost-effective remote renewable resources to load centers, enable resource and reserve sharing over greater distances, and smooth output profiles of variable generators by enabling greater geospatial diversity.
- A direct incremental cost associated with high levels of renewable generation, relative to the continued evolution of today's conventional generation system, is reflected in higher estimated electricity prices. Direct environmental and social implications are also associated with the high renewable futures examined, including carbon emission reductions.
- With higher demand growth, high levels of renewable generation present increased resource and grid integration challenges.