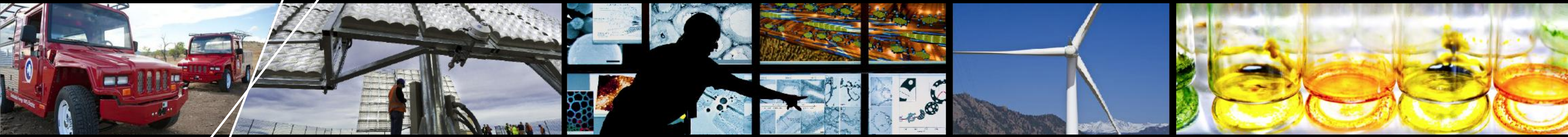
NATIONAL RENEWABLE ENERGY LABORATORY

Realizing a Clean Energy Future

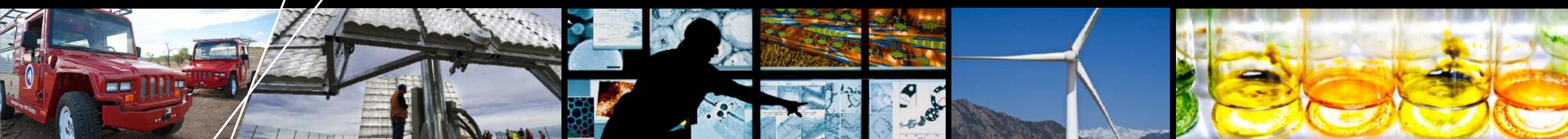


Energy@Stanford & SLAC

Stanford Graduate Summer Institute

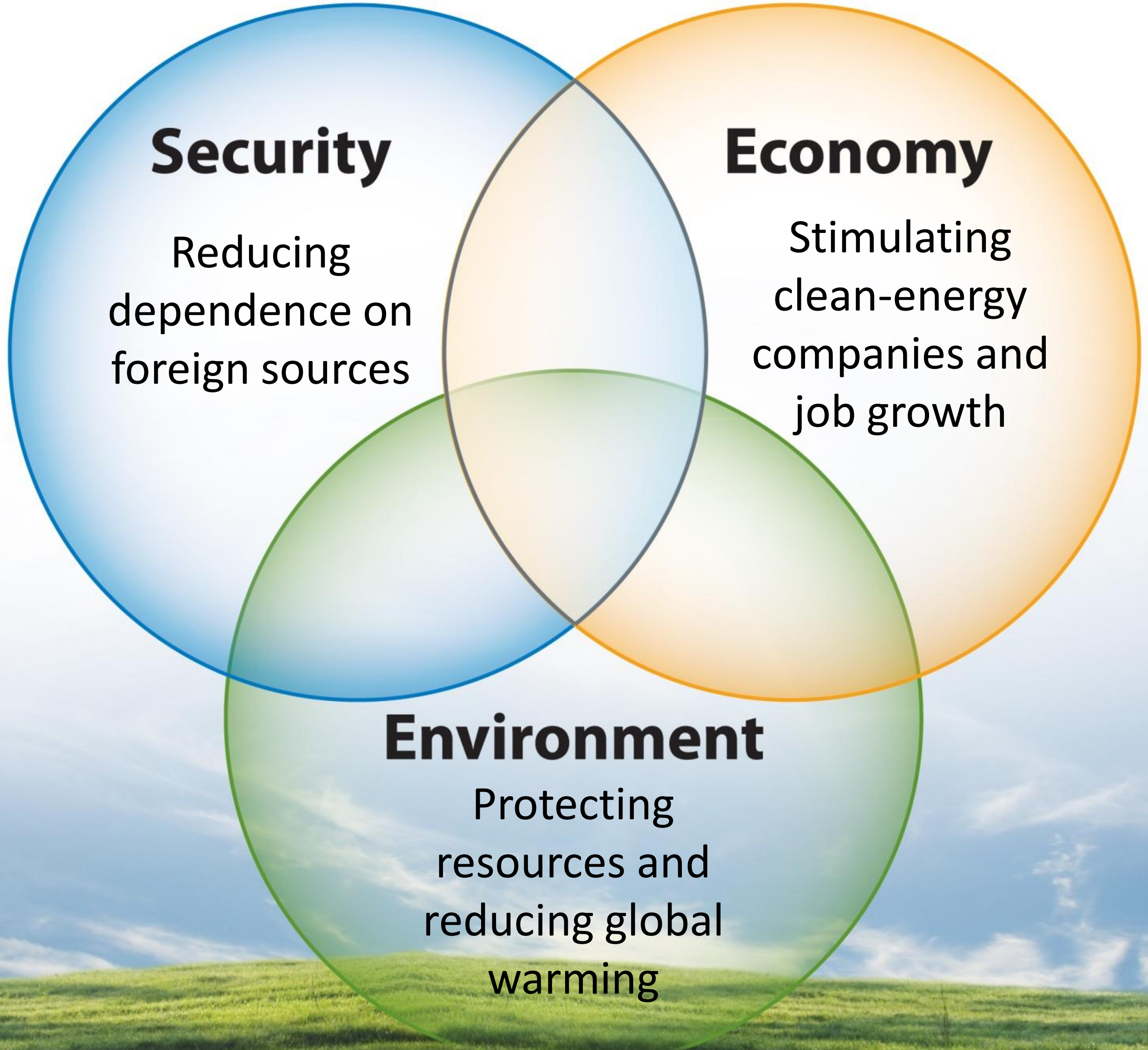
Dr. Dan E. Arvizu

Laboratory Director



Energy Context

National Energy Imperatives



A Profound Transformation is Required

Today's Energy System

TRANSFORMATION

Sustainable Energy System

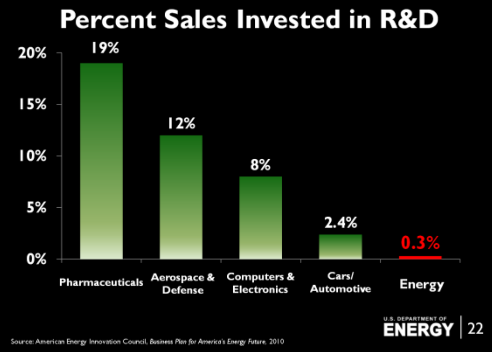
Today's Energy System

- Dependent on non-domestic sources
- Subject to price volatility
- Increasingly vulnerable energy delivery systems
- 2/3 of source energy is wasted
- Significant carbon emissions
- Role of electricity increasing

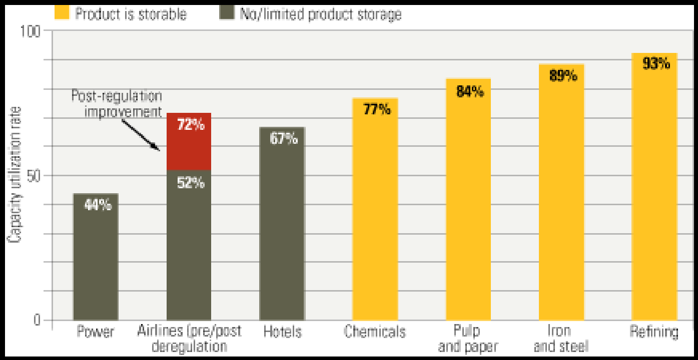
Sustainable Energy System

- Carbon neutral
- Efficient
- Diverse supply options
- Sustainable use of natural resources
- Creates economic development
- Accessible, affordable and secure

Energy Sector Challenges



R&D Investment Drives Innovation



Asset Utilization

Capital Intensive with Long Life Cycles

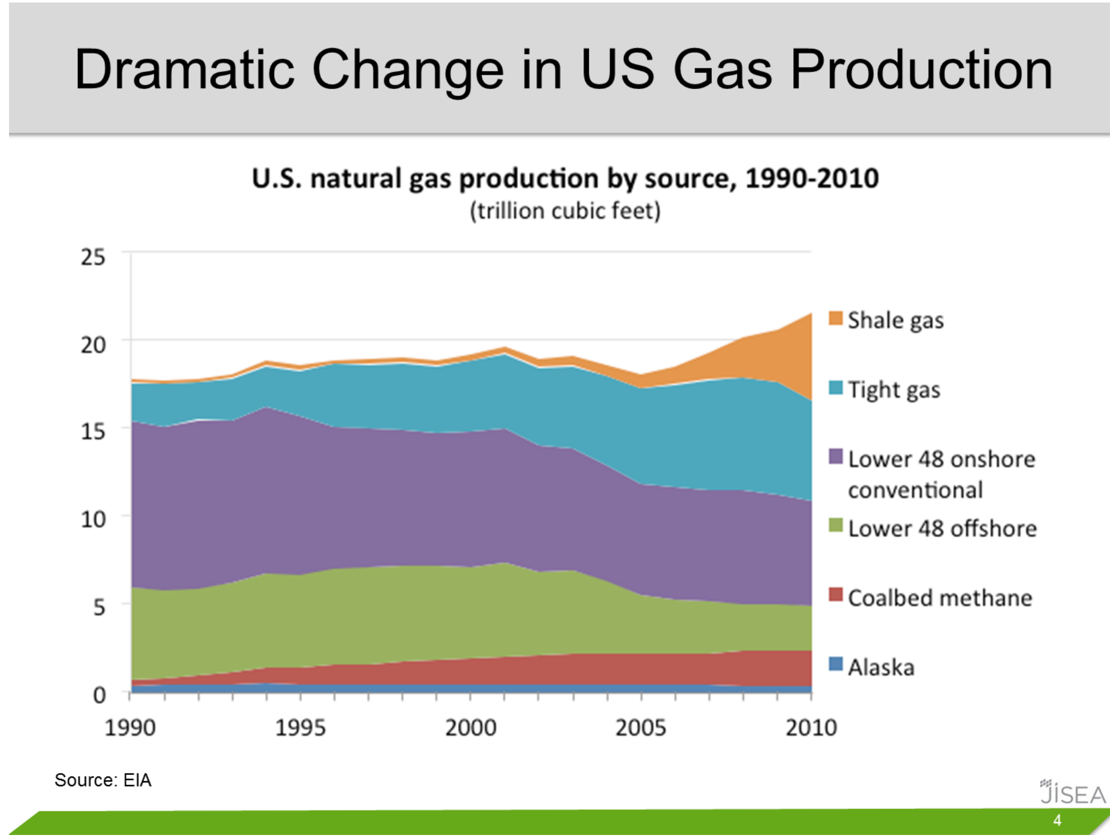
National Strategies Driving Energy Market

The Role of Natural Gas?

"We are in the midst of a natural gas revolution in America that is a potential game changer for the economy, environment and our national security—if we do it right."

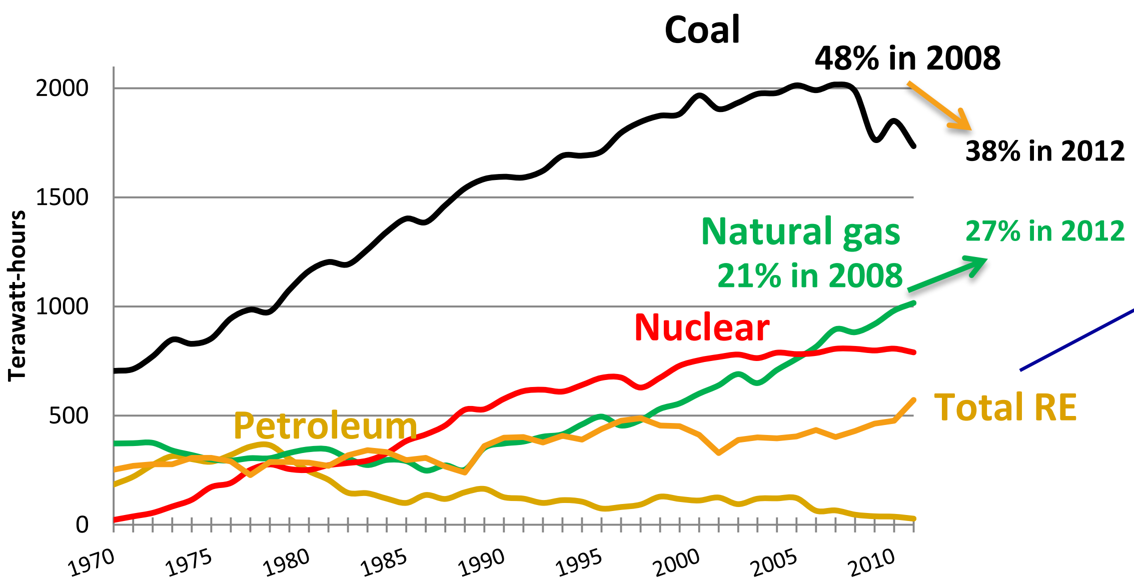
—Tom Friedman

New York Times, August 4, 2012

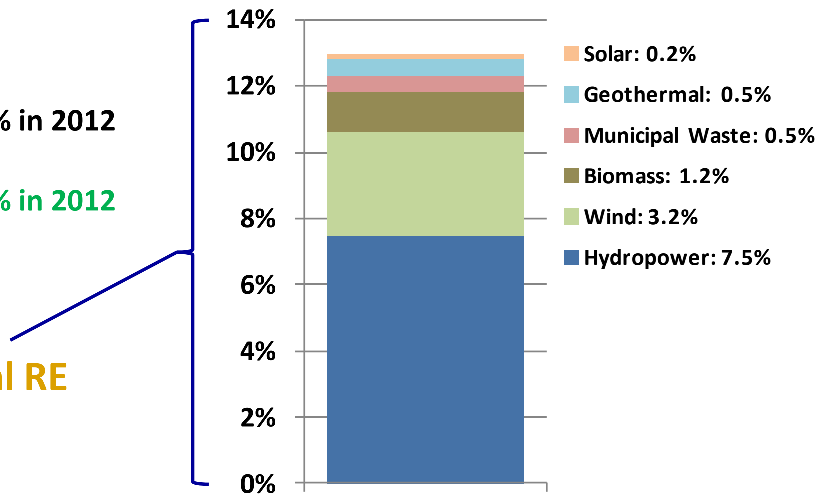


U.S. Electric Sector Trends

U.S. Electric Sector Net Generation



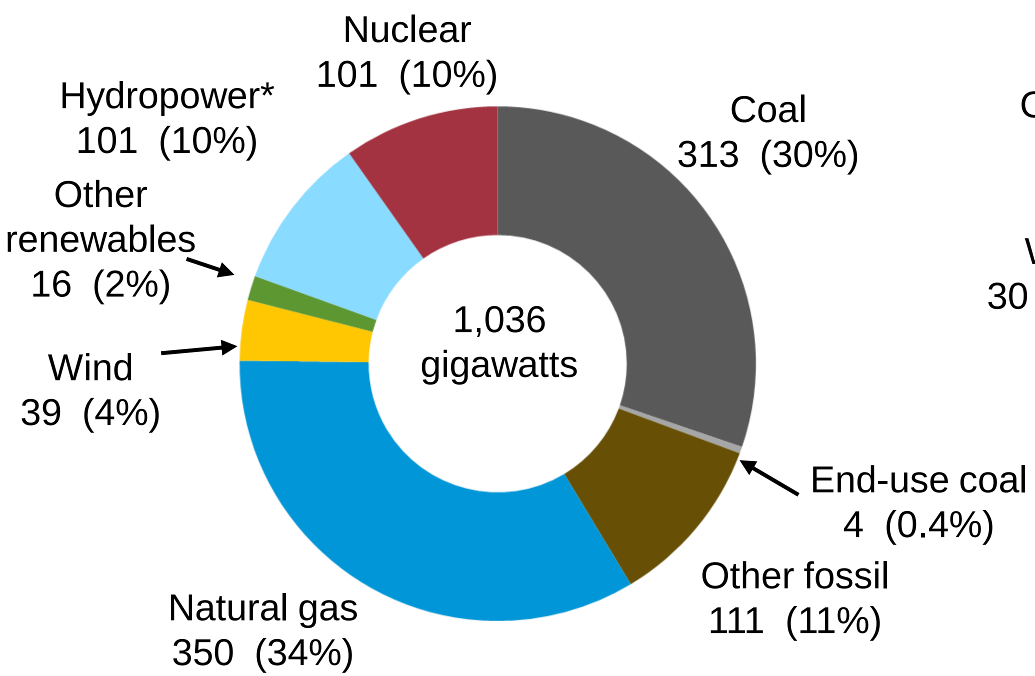
U.S. Renewable Generation



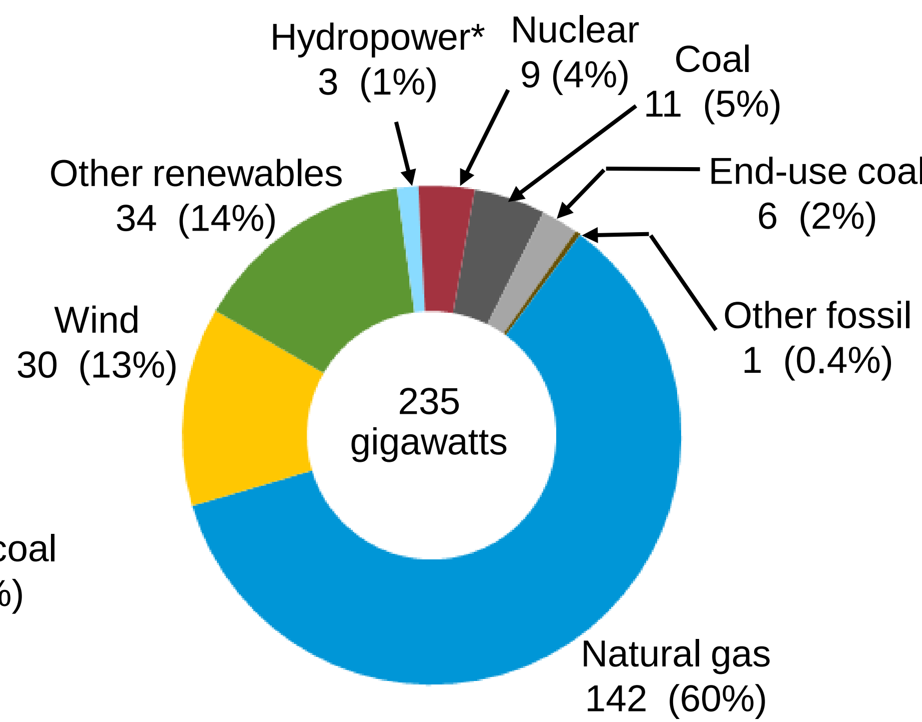
Source: EIA, Annual Energy Outlook 2012

Natural gas, wind and other renewables account for the vast majority of capacity additions from 2010 to 2035

2010 capacity



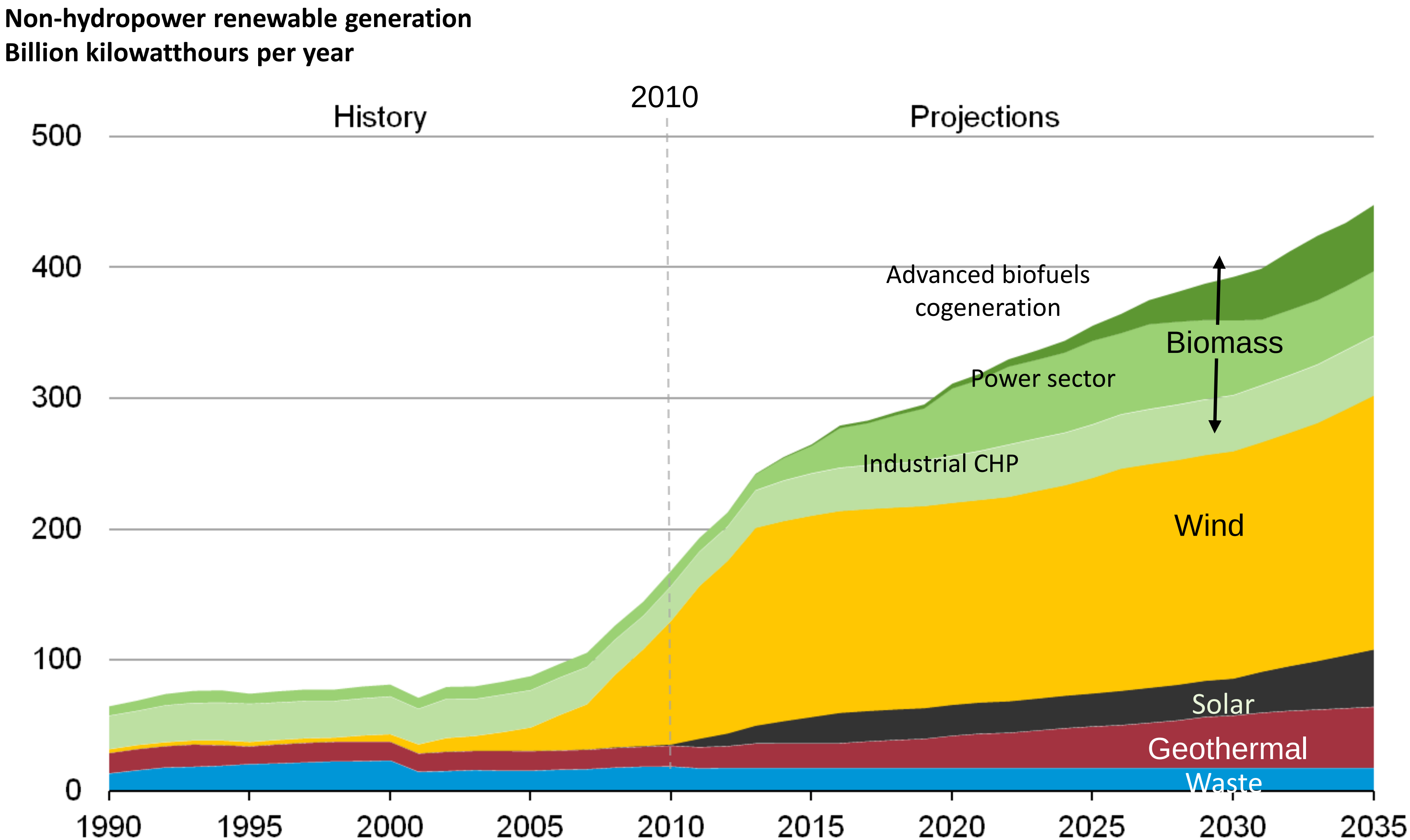
Capacity additions 2010 to 2035



* Includes pumped storage

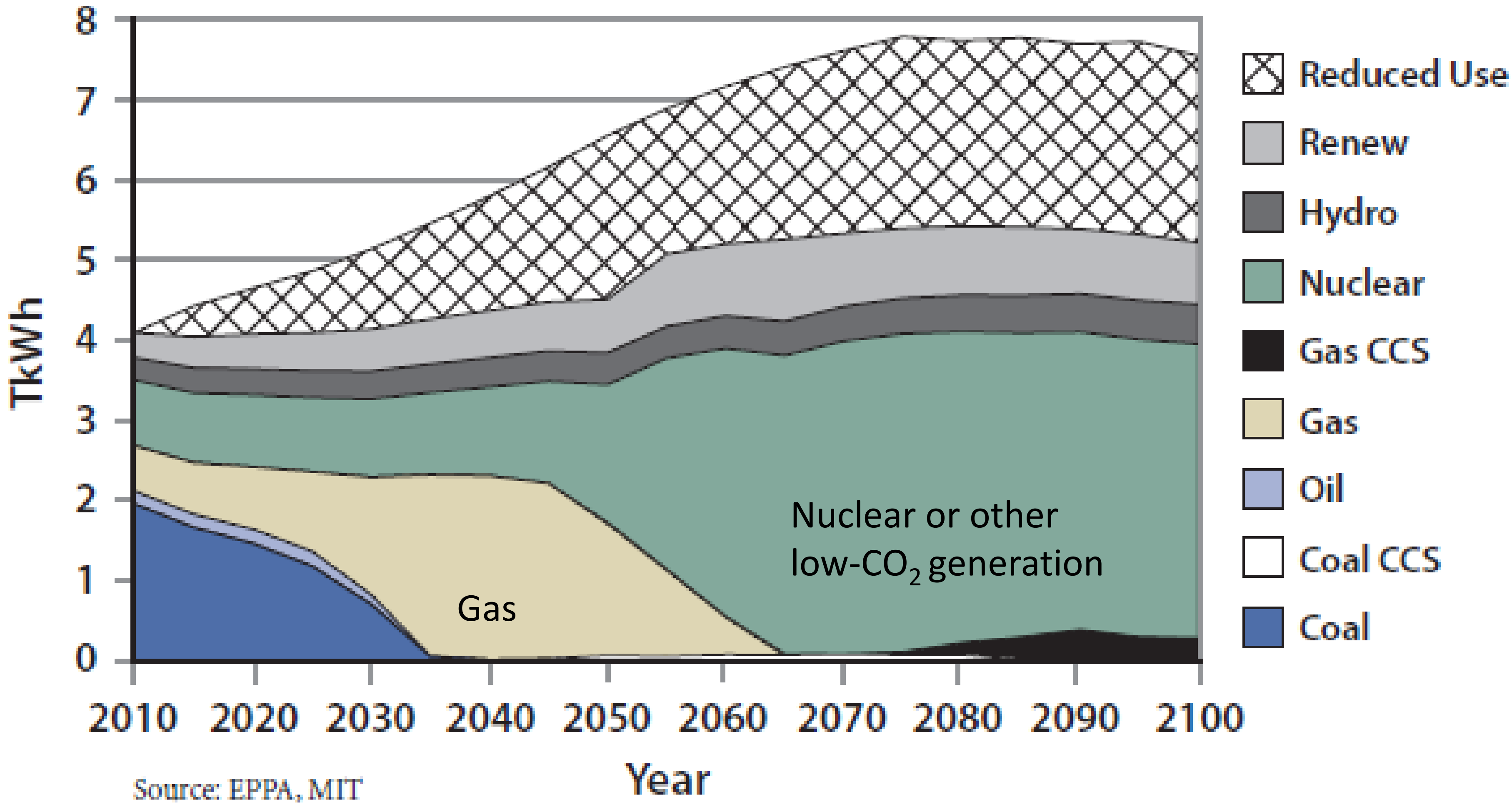
Source: EIA, Annual Energy Outlook 2012

Non-hydro renewable sources more than double between 2010 and 2035



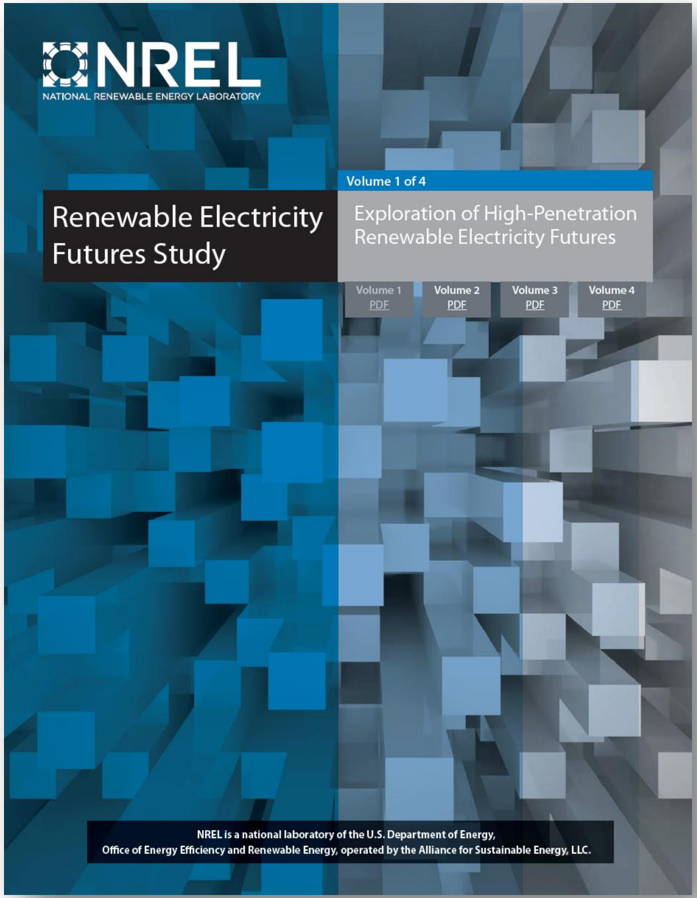
Source: EIA, Annual Energy Outlook 2012

MIT Future of Natural Gas Study*



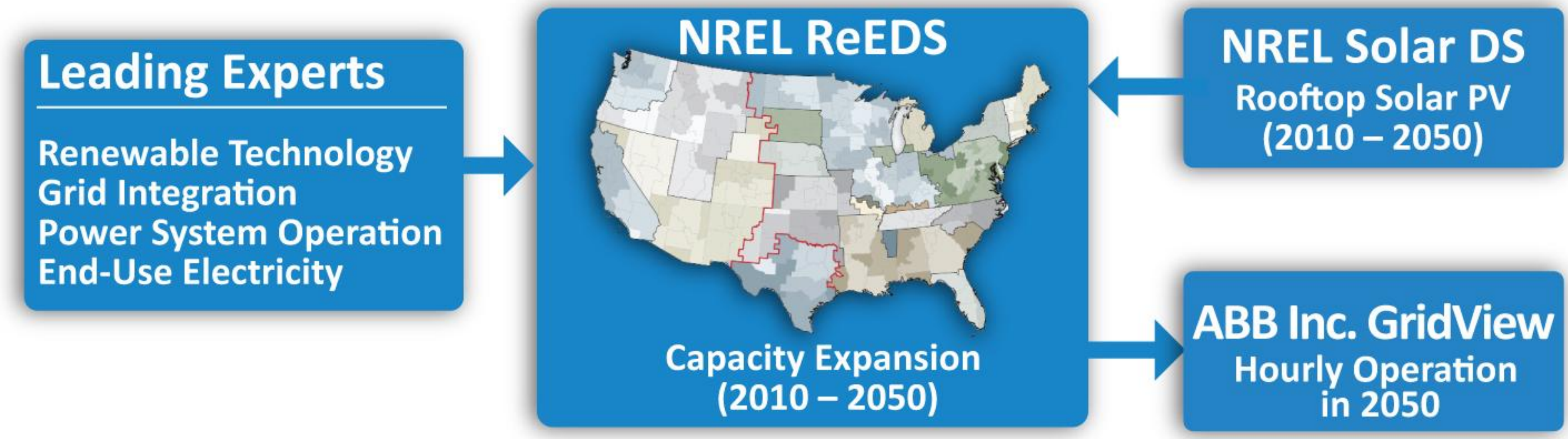
* Fig. 3.12 Energy Mix in Electric Generation under a Price-Based Climate Policy, Mean Natural Gas Resources and Regional Natural Gas Markets (TkWh) [reduced GHG 80% below 2005]

Renewable Electricity Futures Study



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

State of the Art Electric System Models

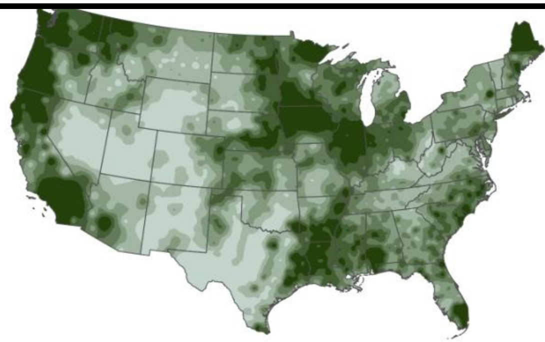


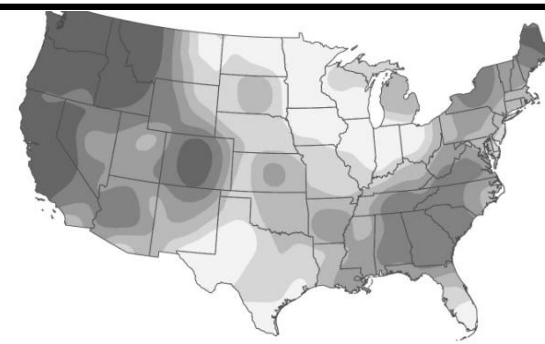
- **Unprecedented geographic and time resolution for the contiguous United States**
- **Over two dozen scenarios of RE generation focused on 2050**

Abundant Renewable Energy Resources

Biopower ~100 GW

- Stand-alone
- Cofired with coal





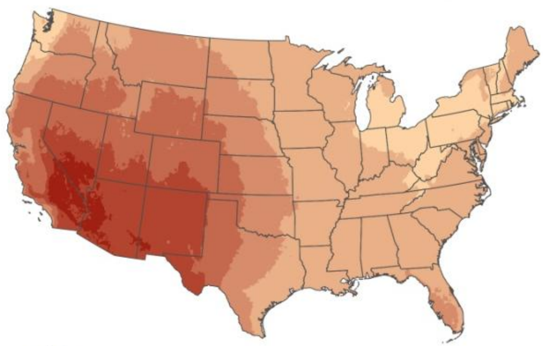
Hydropower ~200 GW

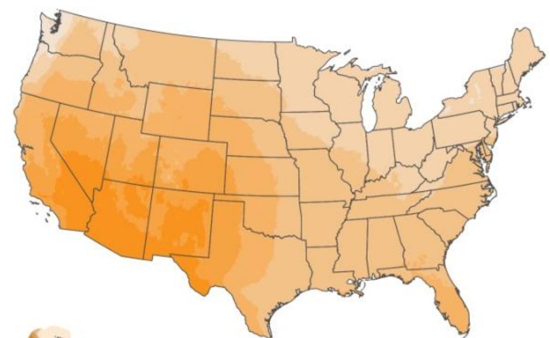
- Run-of-river

Solar CSP ~37,000 GW

- Trough
- Tower

With thermal storage



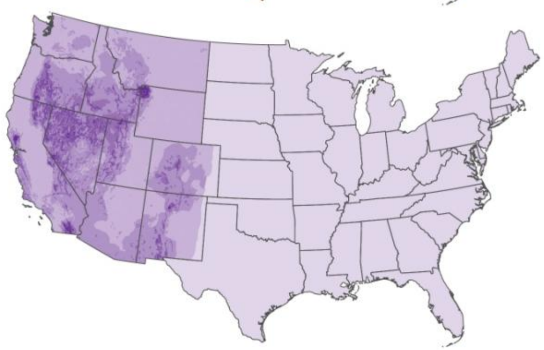


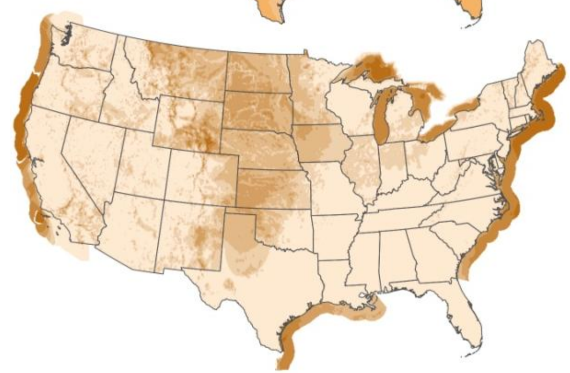
Solar PV ~80,000 GW (rooftop PV ~700 GW)

- Residential
- Commercial
- Utility-scale

Geothermal ~36 GW

- Hydrothermal





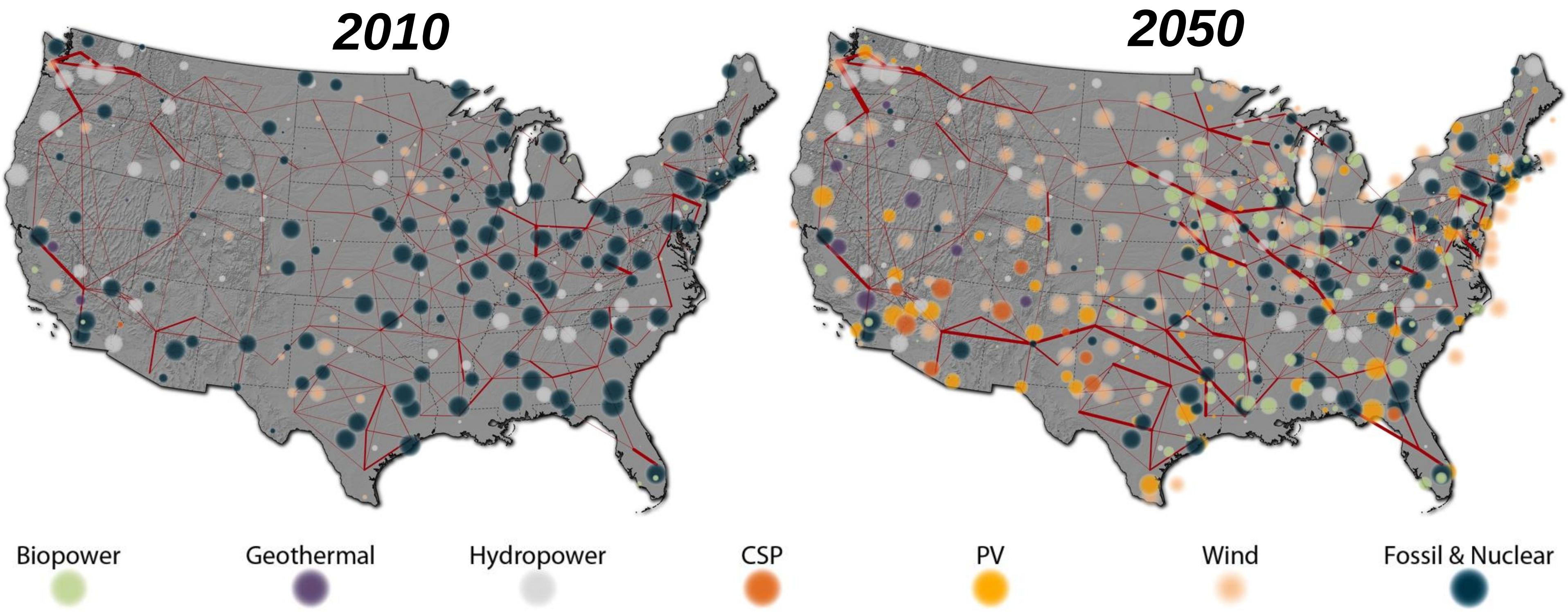
Wind ~10,000 GW

- Onshore
- Offshore fixed-bottom

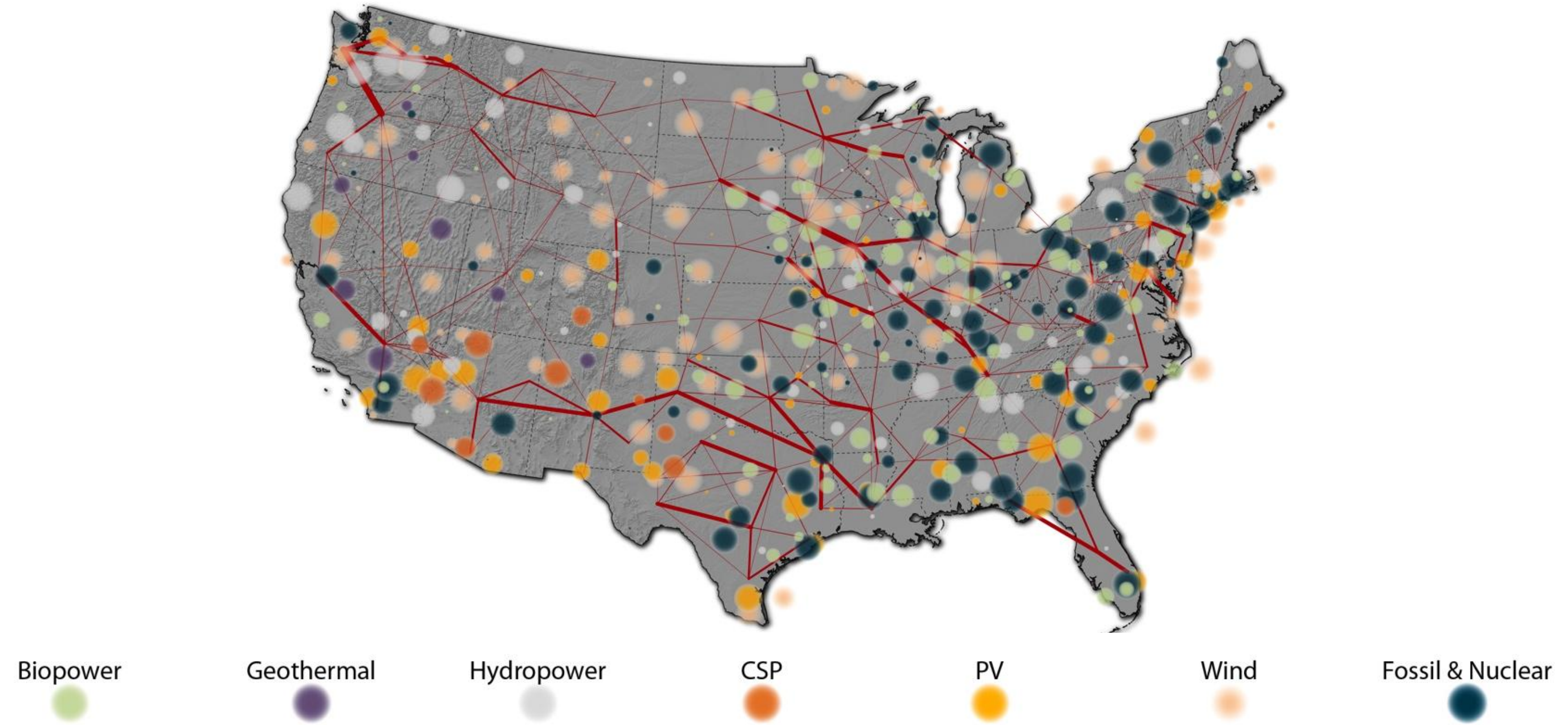
Darker Colors = Higher Resource

Geographic location, technical resource potential, and output characteristics are unique to each RE generation technology.

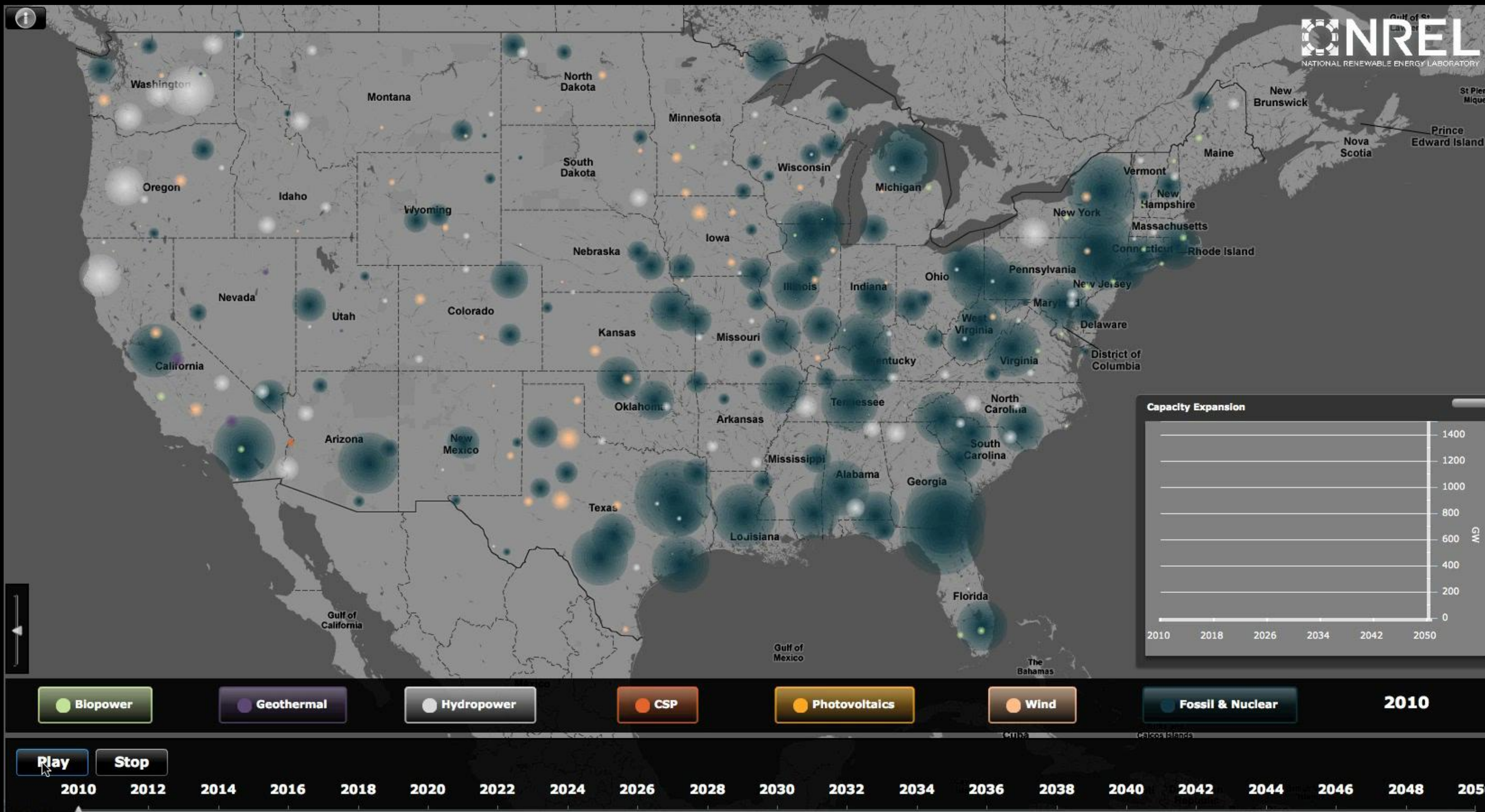
A Transformation of the U.S. Electricity System



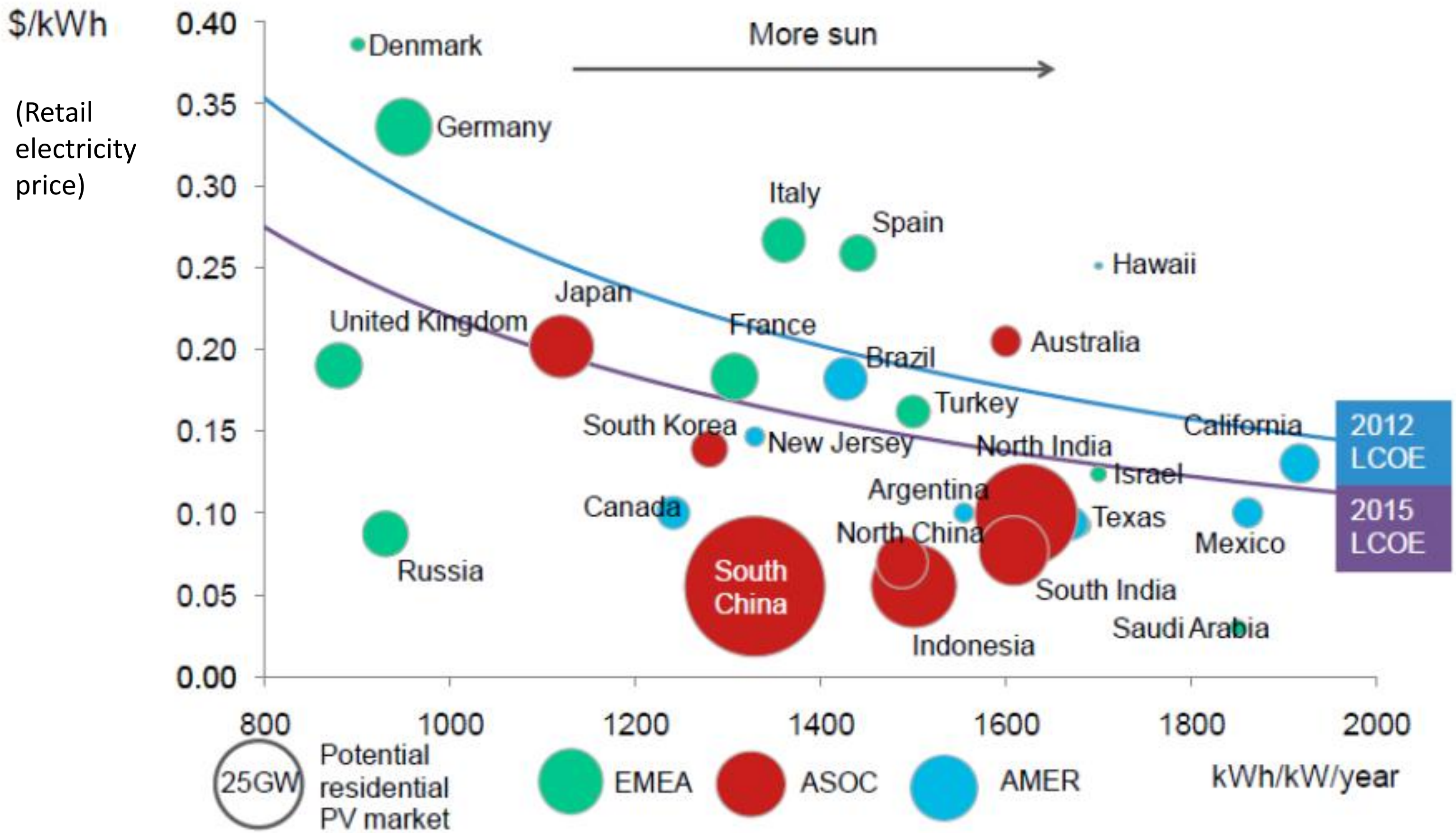
RE generation from technologies that are commercially available today, in combination with a more flexible electric system, is more than adequate to supply 80% of total U.S. electricity generation in 2050 while meeting electricity demand on an hourly basis in every region of the country



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.


NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Washington
Montana
North Dakota
Minnesota
Oregon
Idaho
Wyoming
South Dakota
Wisconsin
Michigan
New York
Vermont
New Hampshire
Maine
New Brunswick
Nova Scotia
Prince Edward Island
Massachusetts
Connecticut
Rhode Island
Nebraska
Iowa
Nevada
Utah
Colorado
Illinois
Indiana
Ohio
Pennsylvania
New Jersey
Delaware
District of Columbia
California
Kansas
Missouri
Virginia
Oklahoma
Arkansas
Tennessee
North Carolina
South Carolina
Arizona
New Mexico
Mississippi
Alabama
Georgia
Texas
Louisiana
Florida
Gulf of California
Gulf of Mexico
The Bahamas
Capacity Expansion
1400
1200
1000
800
600
400
200
0
GW
2010
2018
2026
2034
2042
2050
Biopower
Geothermal
Hydropower
CSP
Photovoltaics
Wind
Fossil & Nuclear
2010
Play
Stop
2010 2012 2014 2016 2018 2020 2022 2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050

Globally, PV Retail Competiveness is Spreading Fast



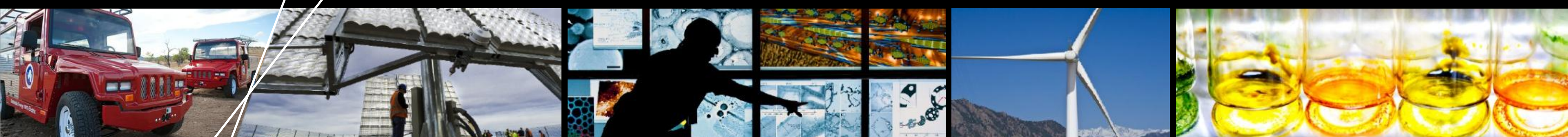
Countries above the 2012 line have already achieved grid parity.

Source: BNEF, 2012. Size of bubbles refers to market size. Assumptions: Parity defined as the installed price at which a household can make 5% or more return on investment in a PV system just by using the energy generated to replace household energy consumption. LCOE based on 6% weighted average cost of capital, 0.7%/year module degradation, 1% capex as O&M annually, $3.01/W capex assumed for 2012, $2.00/W for 2015.

Innovation, Integration, & Adoption

Reducing Investment Risk

- Enable basic and applied clean energy technology innovation
- Accelerate technology market introduction and adoption
- Integrate technology at scale
- Encourage collaboration in unique research and testing “partnering” facilities
- Provide analysis and expertise to inform decisions



Status of the Technologies

Solar Electricity: *State of the Technology*




Photovoltaics (PV)

- Market: Residential; Commercial, Utility
- Geographically diverse
- kWs to MWs to GWs
- U.S. Capacity: 4.0 GW
- U.S. Forecast: 22+ GWs in pipeline
- Costs. \$3 to \$7/W: *LCOE 7 to 16¢/kWr
- Technologies: Conversion; thin-films, crystalline silicon. Storage; battery

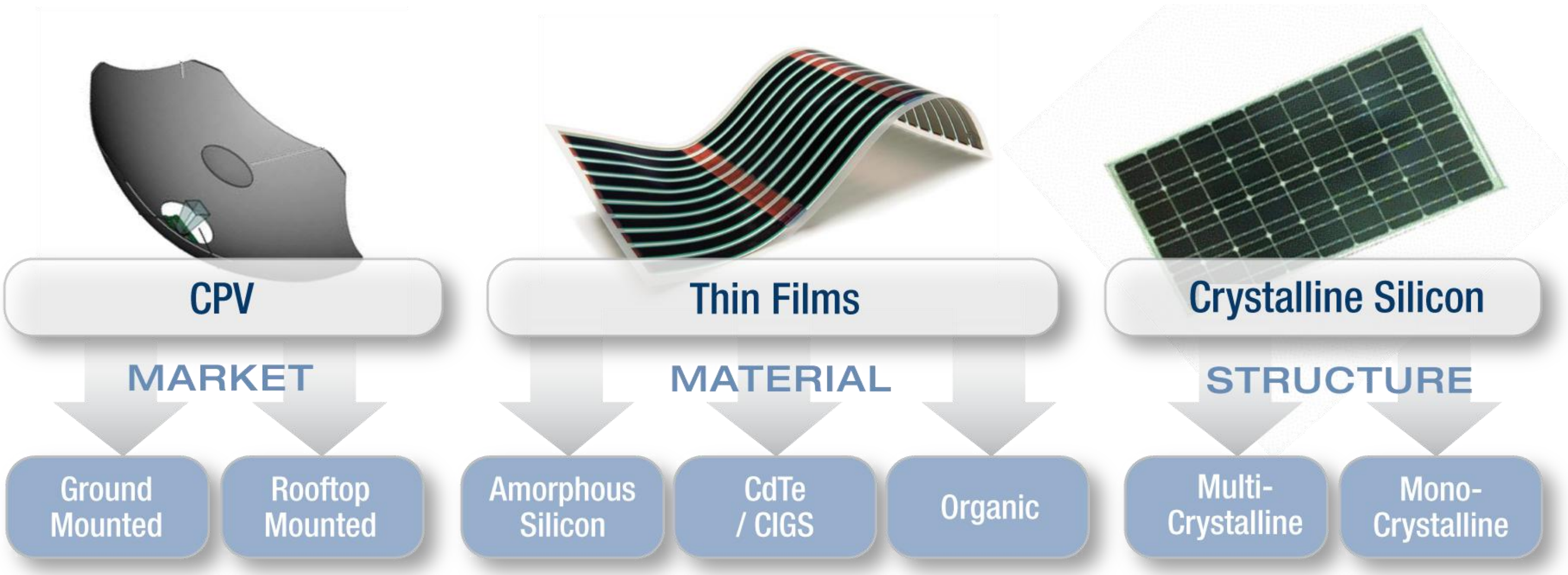
Solar Thermal Electric (CSP)

- Market: Commercial; Utility
- Geographically confined to “sun bowls”
- MWs to GWs
- U.S Capacity: 0.5 GW
- U.S. Forecast: ~6 GWs in pipeline
- Costs. \$4 to \$8/W: *LCOE 12 to 20 ¢/kWr
- Technologies: Conversion; parabolic troughs, central receivers, dish. Storage; thermal, up to 15 hours.

*With federal incentives; e.g. the FTC.

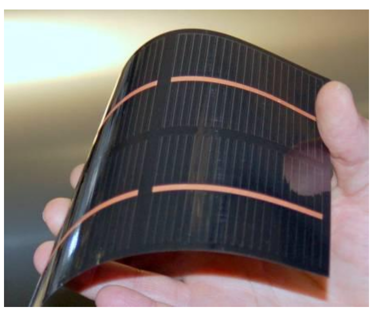
Updated: April 2012
Source: GTM/SEIA : U.S. Solar Market Insight Q4 2011 & 2011 Year-in-Review

Multiple Promising PV Technologies

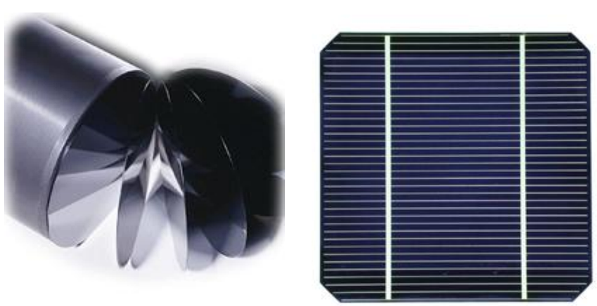


20x-100x

500x



$Cu(In,Ga)Se_2$ ~ 1-2 um

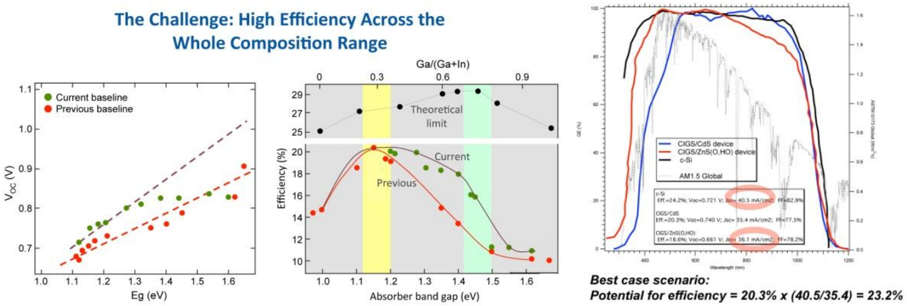


c-Si ~ 180 um

Sunshot R&D Agenda

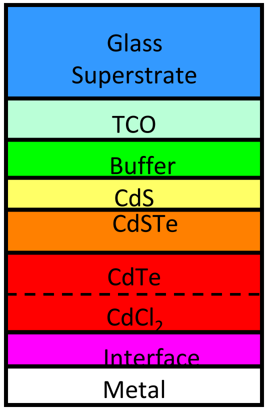
CIGS/CZTS

- Higher photovoltage
- Higher photocurrent
- Rapid growth rate
- Minimize electrical defects in PV quality

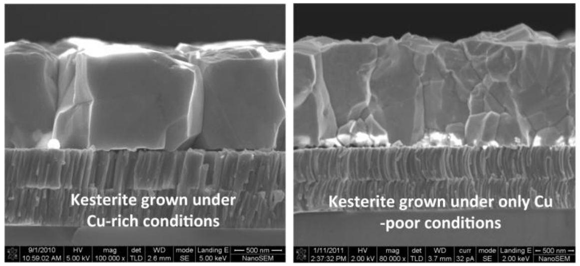


CdTe

- Minority carrier lifetime
- Grain boundary structure and charge transport
- Correlation between TRPL lifetime and device performance
- Synthesize an effective set of samples

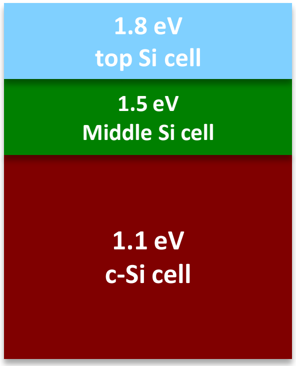


Efficiency = 9.2%



Wafer-Si

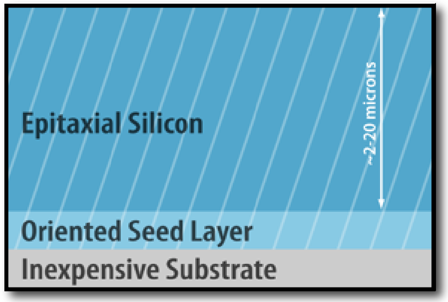
- Multijunction device modeling
- Engineered (tailored material) for middle and top cell
- High quality middle Si cell around 1.5 eV
- High performance and understand the tunneling junction
- Surface and bulk passivation of c-Si
- Improved light management for component cell



Sunshot R&D Agenda

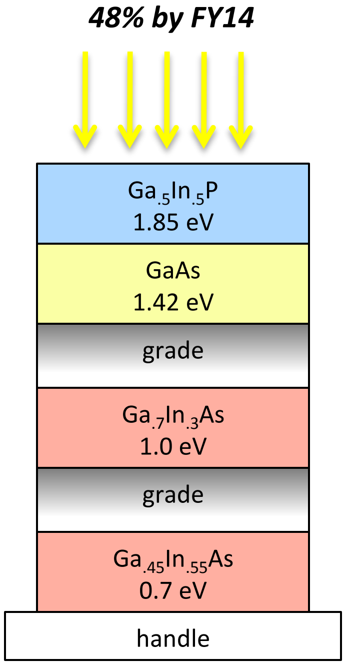
Film-Si

- Improved thin-film silicon cells at high growth rate
- Develop low-cost oriented crystal seeds for film c-Si
- Improve epitaxy quality and rates at low T
- Develop light-trapping for thin c-Si



III-V

- Next-generation cells to increase power/lower LCOE
- Deeper reliability heritage for cells and systems
- Design cells for operation in real-time systems

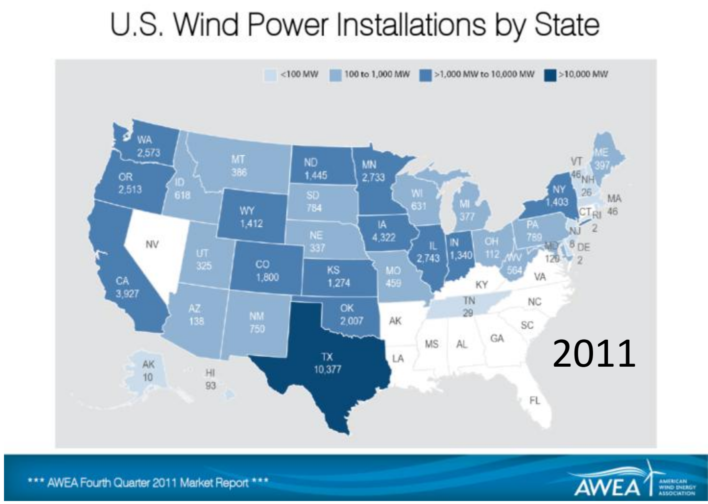


OPV

- Lower band gap absorbers with appropriate HOMO/LUMO
- Stability >30,000 hours (intrinsic and extrinsic)
- Scalability of lab scale efficiencies to >100 cm^2 modules
- International coordination and standardization

Konarka

Wind energy: *State of the Technology*



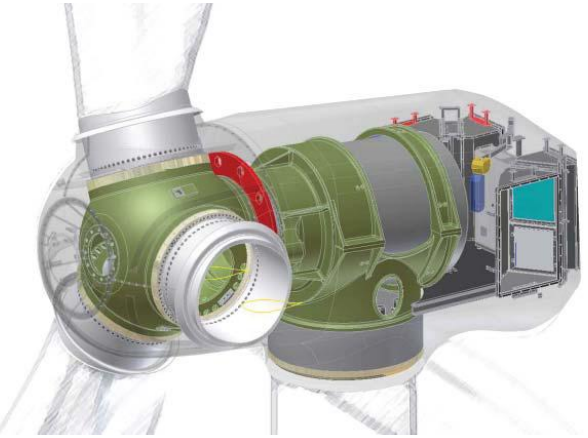
- Costs: 7-10 cents/kWh LCOE*
- Installed wind project cost = $2,155/kW
- 1.5-3.0 MW commercial turbines are typical
- 10 MW prototype machines in development
- Direct drive generators more common
- Variable speed and grid-friendly operation
- Technologies targeting offshore wind markets

- U.S. installed capacity = 46.9 GW (12/2011)
- 38 of 50 states have utility-scale wind with 14 states > 1,000 MW installed
- Over 8.3 GW currently under construction
- U.S. wind capacity represents more than 20% of the world's installed wind power
- U.S. wind percentage of electricity is over 2.3%
- Over 400 manufacturing facilities across the U.S. make components for wind turbines

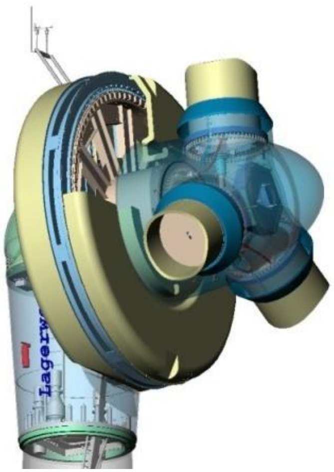
Updated: April 2012

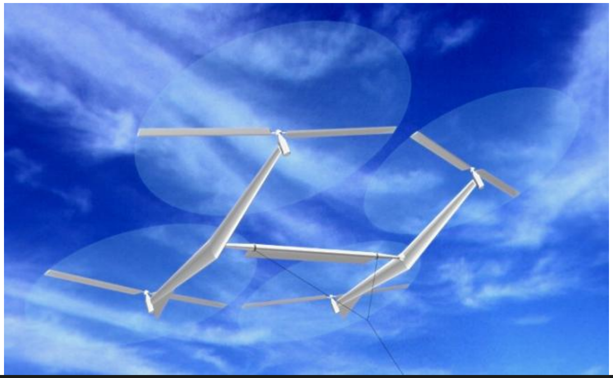
* Estimate for utility-scale wind, class 4 wind sites, no subsidies

Wind Technology Innovation



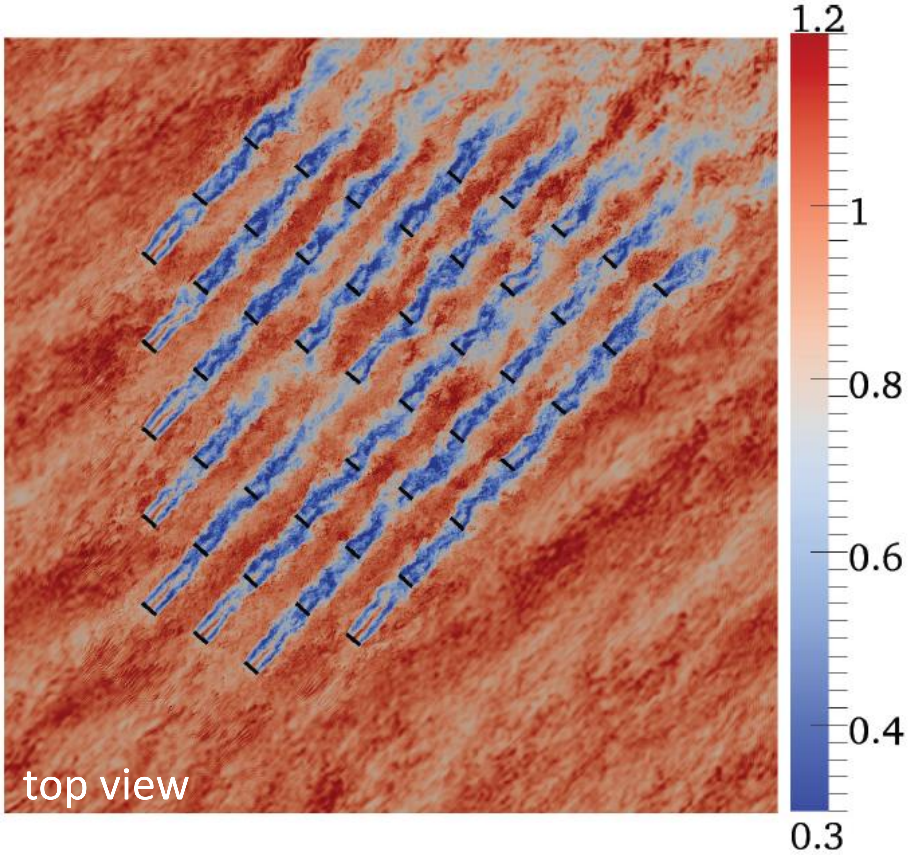
- Modular large components – blades, drivetrains, and tall towers
- Advanced drivetrain power conversion systems – superconducting direct drive generators
- Flexible, ultra-large rotors and systems
- Active controls for structural load reduction, improved wind plant performance, and grid-friendly operation
- Floating offshore wind turbines
- Airborne wind power systems



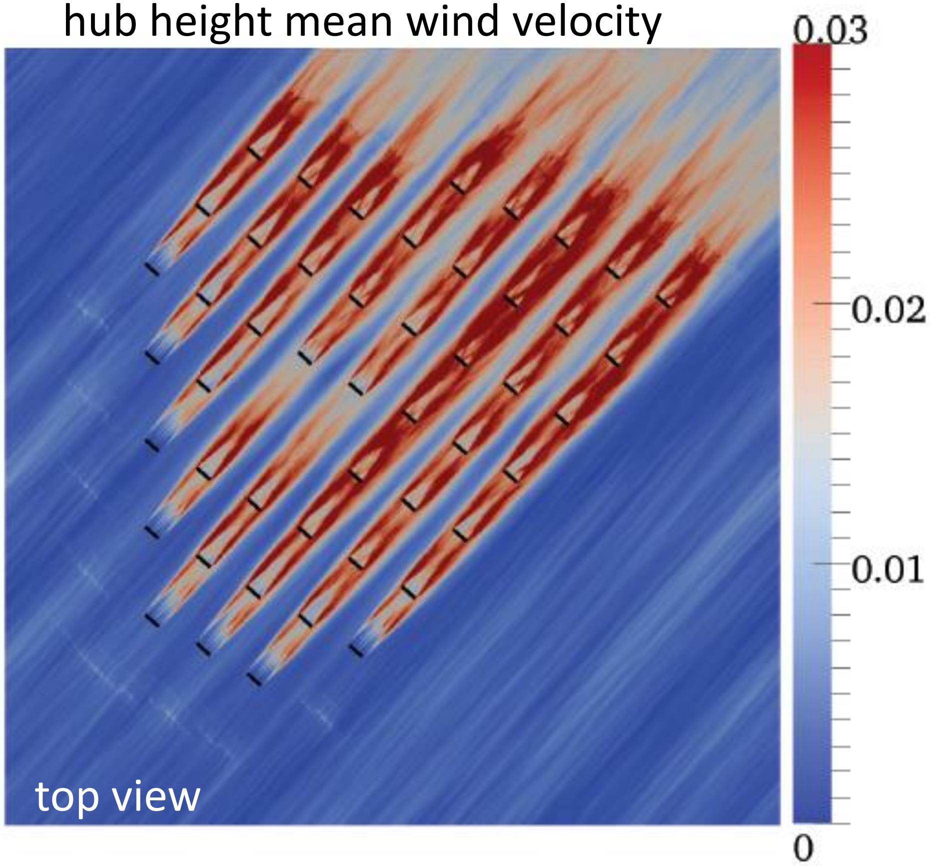


Wind Plant Simulation

Instantaneous velocity normalized by hub height mean wind velocity

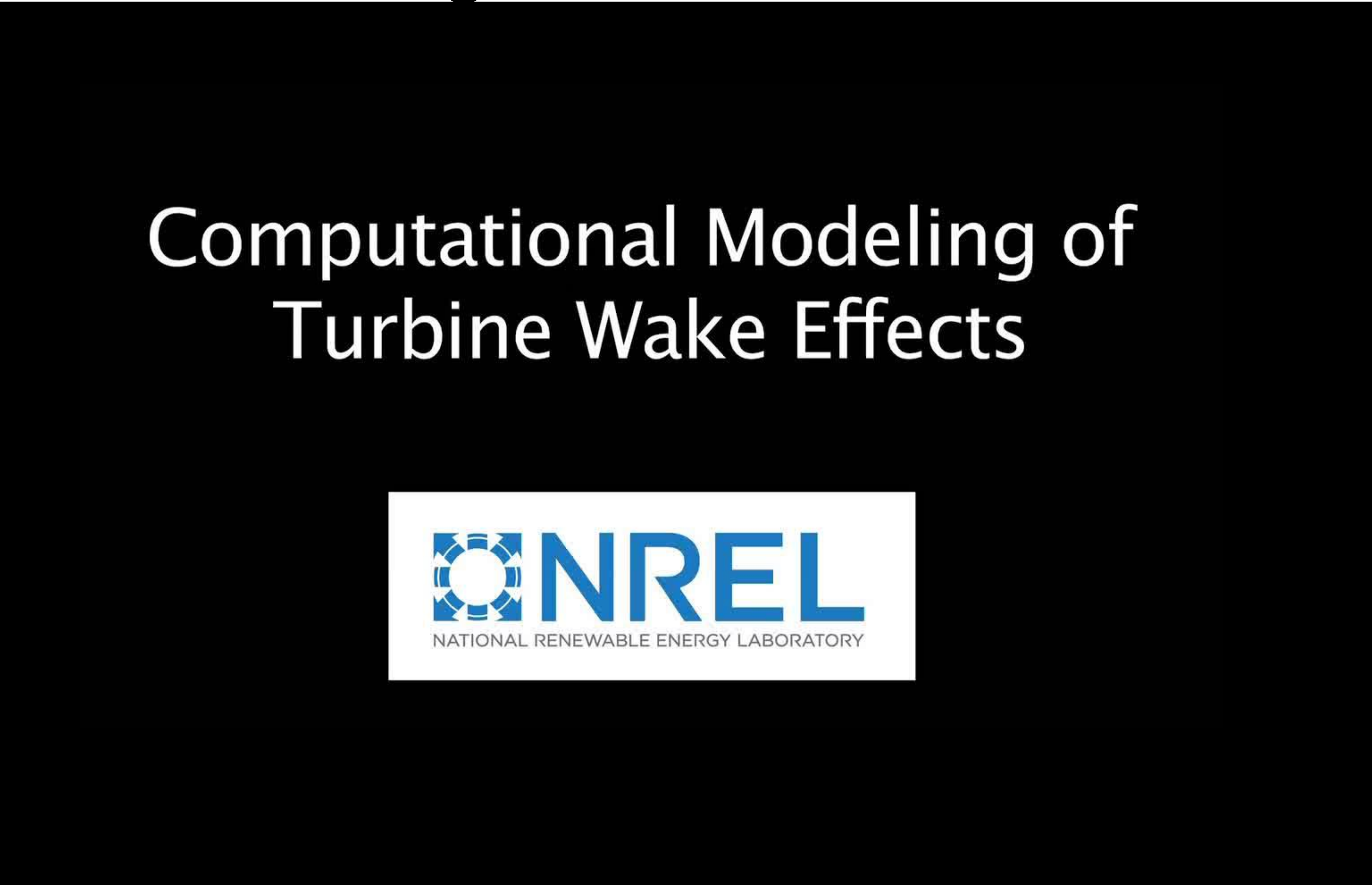


Resolved-scale turbulent kinetic energy normalized by square of hub height mean wind velocity



Meandering shows up in resolved turbulent kinetic energy

Forward Progress: Wind at Half the Cost



Biofuels: *State of the Technology*

Current Status:

U.S. produced 13.5 billion gallons of ethanol and 1.1 billion gallons of biodiesel (2011)

Biorefineries:

- 219 commercial corn ethanol plants
- 180 biodiesel refineries
- 28 cellulosic ethan

Cost goal:

Cellulosic ethanol—cost parity with gasoline by 2012

Major Technology Directions:

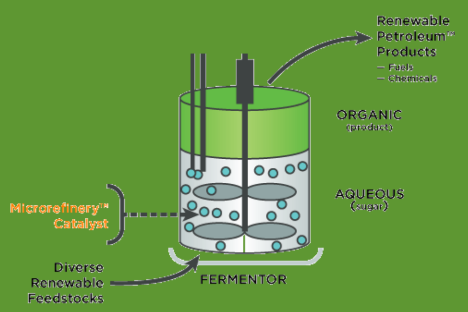
- Foundational Science: Enzymes, fermentation, understanding biomass and cell composition
- Feedstocks: Sustainable feedstock production systems
- Pretreatment & Conversion R&D: Biochemical and thermochemical conversion processes
- Advanced Biofuels and Algae: Broadening RD&D beyond cellulosic ethanol to address “drop in’ and high-energy content fuels from algae and other biomass resources

Updated: 4/2012

Biofuels Innovation

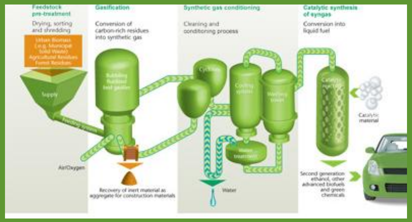
New conversion technologies are being developed, offering the possibility of revolutionary, high volume methods for producing biofuel hydrocarbon fuels for our trucks, trains, ships, and aircraft . . .

Biological Conversion



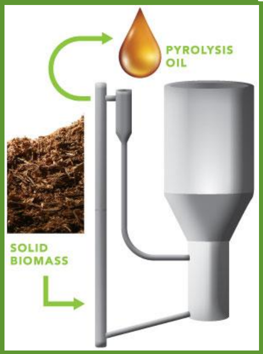
LS9 AMYRIS

Chemical Catalytic Conversion



VIRENT IT'S ABOUT TIME RENTECH® ClearFuels® TECHNOLOGY, INC. Enerkem

Pyrolysis/Bio-Oil Pathways

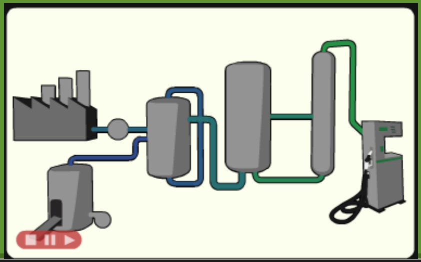


Envergent TECHNOLOGIES A Honeywell Company

Heterotrophic Algae Conversion

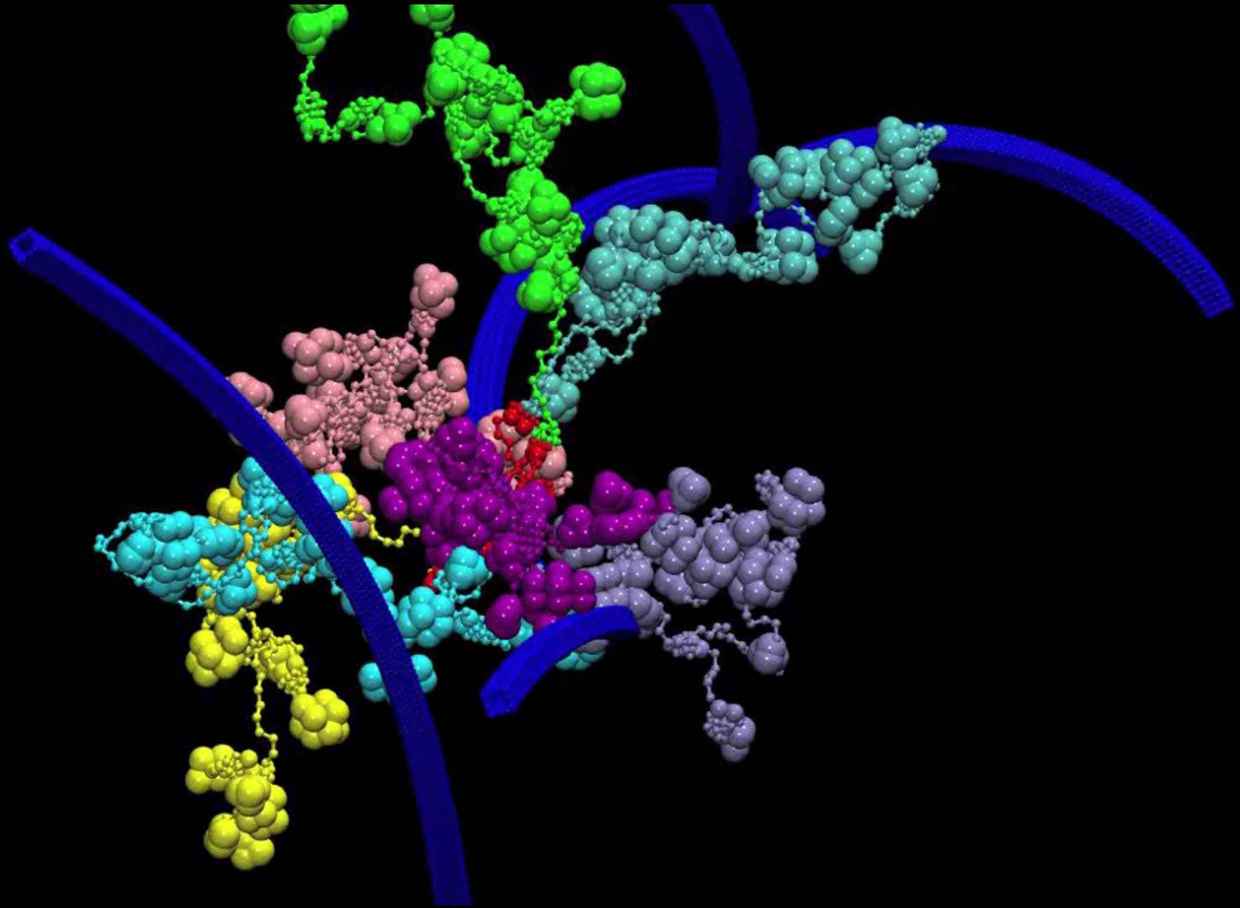
solazyme® MARTEK life enriched.™

Hybrid Conversion Technologies



LanzaTech coskata

Forward Progress: Infrastructure-Compatible Biofuels



A computer simulation of the process used by some very efficient cellulose degrading bacteria to deconstruct plant cell walls.

Transportation Innovation

Portfolio of technologies leading to 54.5 mpg


Degree of electrification (power electronics & energy storage)


Start/stop


Regenerative braking


Low rolling resistance tires


Electric infrastructure


Electric powered steering


Light weighting

8 speed transmissions

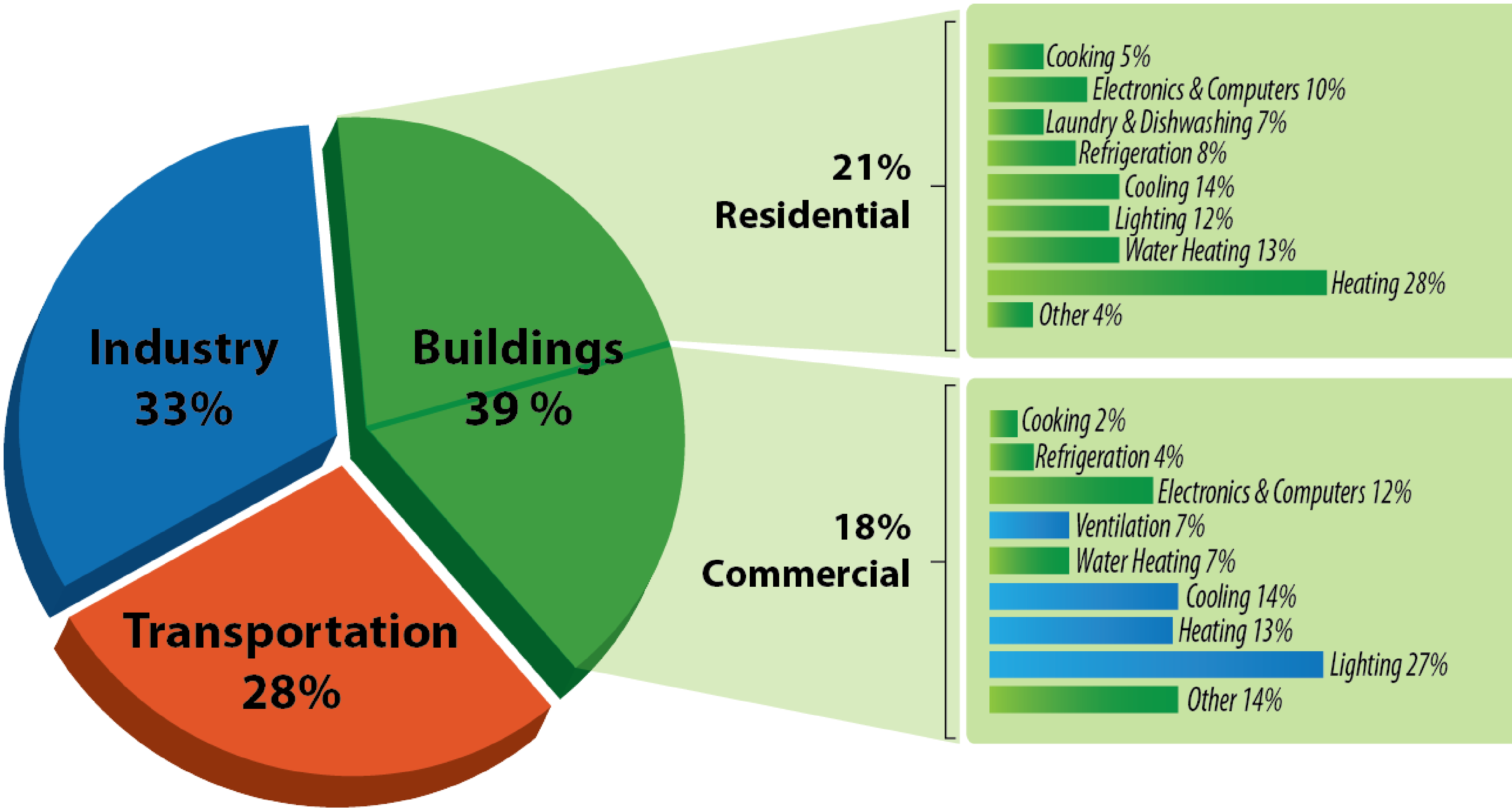

Turbocharging, direct fuel injection, advanced combustion


Variable cylinder mgmt


Improved aerodynamics


Diesel powered & or Alternative Fuels, H2

Energy Consumption in the U.S.



Source: Buildings Energy Data Book, 2006

Buildings Innovation

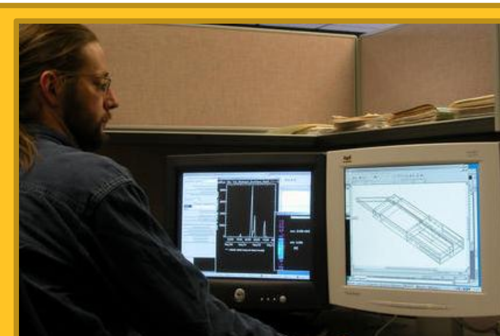
High Performance Buildings

BIPV Products & PV-T Array

Compressorless Cooling

Electrochromic Windows

Polymer Solar Water Heaters



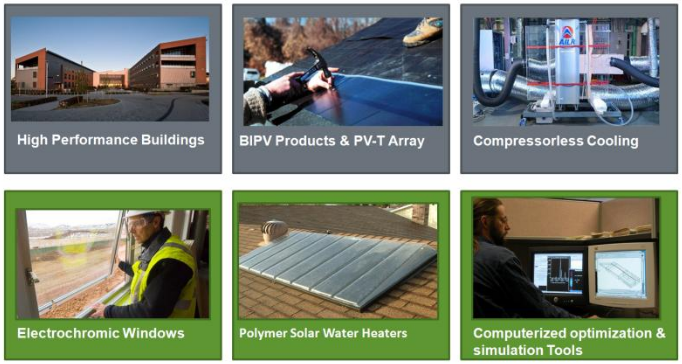
Computerized optimization & simulation Tools

NREL Research Support Facility

Efficiency/Integration Innovation

Buildings

- **Whole building systems integration**
- Computerized building energy optimization tools
- Advanced HVAC (Heating Ventilating and air conditioning)
- Cost effective ultra energy efficient retrofits



Grid Integration

Interconnection Standards

- IEEE Standards Development
- Standards Testing and Validation

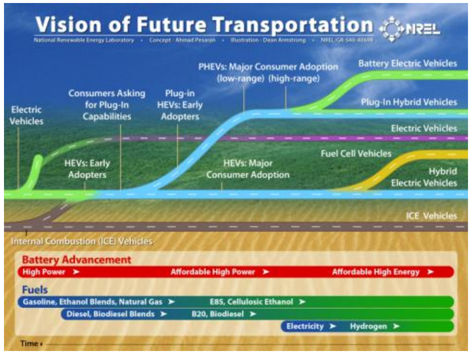
Smart-Grid Data Hub

RE Grid Integration

- Power Electronics for Interconnection monitoring and control
- Grid-to-vehicle interface

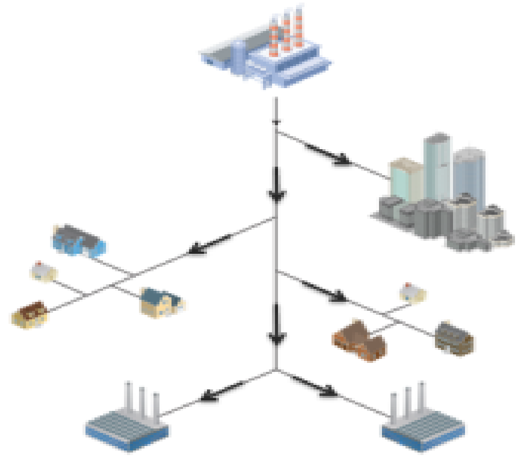
Advanced Vehicles

- Fuels utilization
- Component technologies
- Electric vehicle-to-grid interface

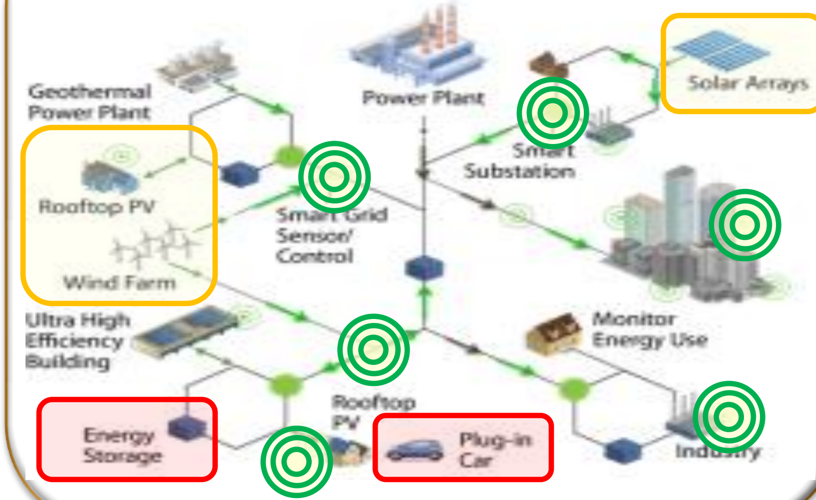


Why Energy Systems Integration?

Current Energy Systems



Future Energy Systems



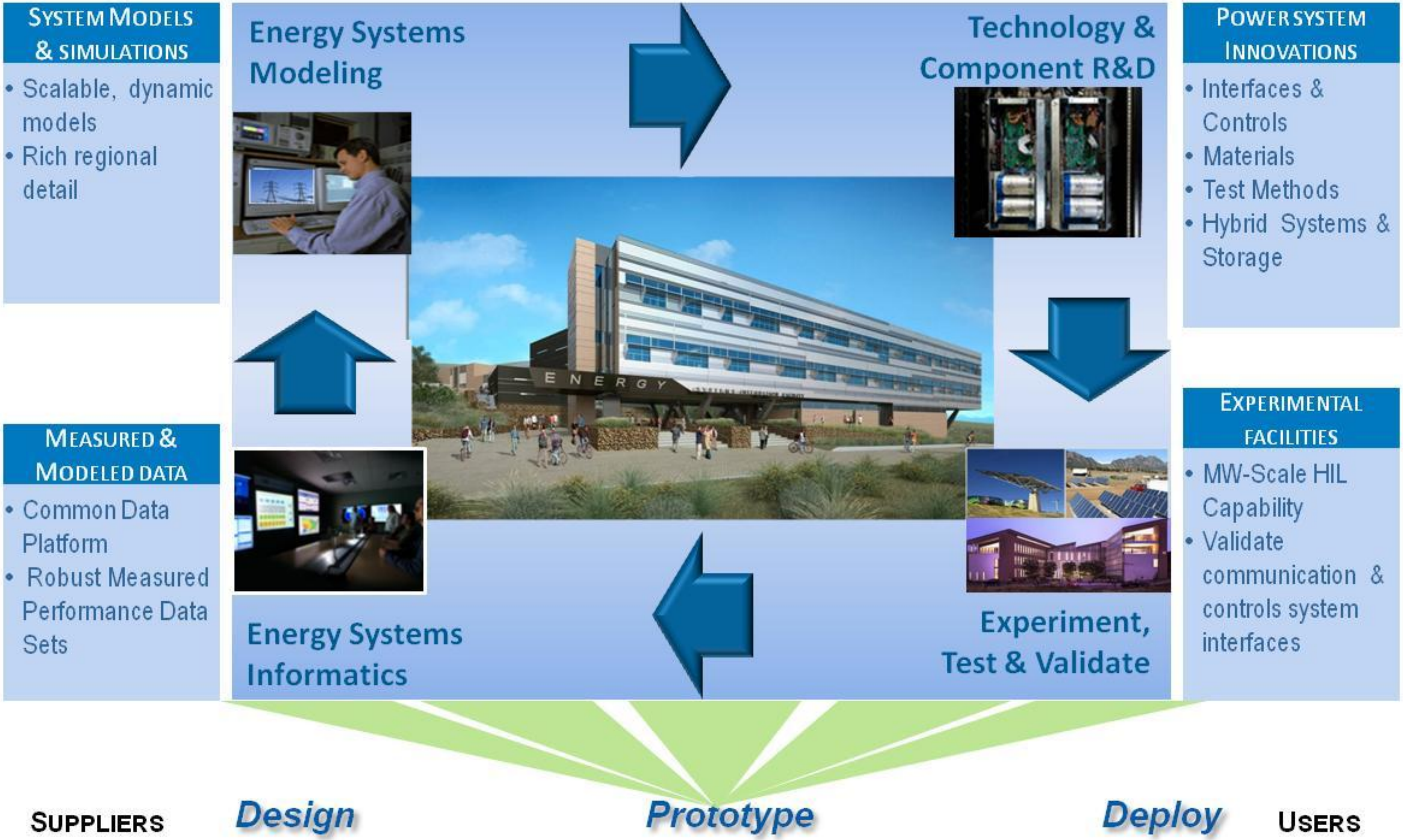
New Challenges – Need to tackle difficult problems

- Increasing penetration of variable RE in grid
- New communications and control models
- Electrification of transportation
- New energy technologies and services integrating energy storage
- Increasing system flexibility
- Understanding interactions between electricity/thermal/fuels

Systems Integration Capabilities

- **RE Grid Integration**
  - Power Electronics for Interconnection monitoring and control
  - Grid-to-vehicle interface
- **DG Interconnection Standards**
  - IEEE Standards Development
  - Standards Testing and Validation
- **Smart-Grid Data Hub**

Energy Systems Integration Concept



Business Sensitive

NREL PV Grid Integration Activities

NREL is working with Utilities, System Integrators, Universities and other National Laboratories to help integrate higher levels of PV into the electric power grid

- **Distribution Integration**
  - Monitoring real-world high penetration cases
  - Developing and validating models and simulations
  - Updating integration approaches and standards
- **Transmission Integration**
  - Collecting and validating field data
  - Conducting operational analysis and optimization
  - Developing models for new technologies
  - Integrating into transmission expansion planning

Utility Partners

- **Southern California Edison (SCE)**
- **Sacramento Municipal Utility District (SMUD)**
- **Xcel Energy (Colorado)**
- **CPS Energy (San Antonio)**
- **Arizona Public Service (APS)**
- **Kauai Island Electric Cooperative (KIUC)**
- **Maui Electric Company (MECO)**
- **FPL/NextEra**
- **Sempra Energy**

Forward Progress: Energy Systems Integration at All Scales

NREL is working with the Sacramento Municipal Utility District on visualizing impact of DG deployments.

To achieve a clean energy vision, we must…

Invest in innovation

Invent the future we desire

Improve access to capital

Partner on a global scale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