Frontiers of Research in Renewable Energy

UC—Irvine Energy Colloquia

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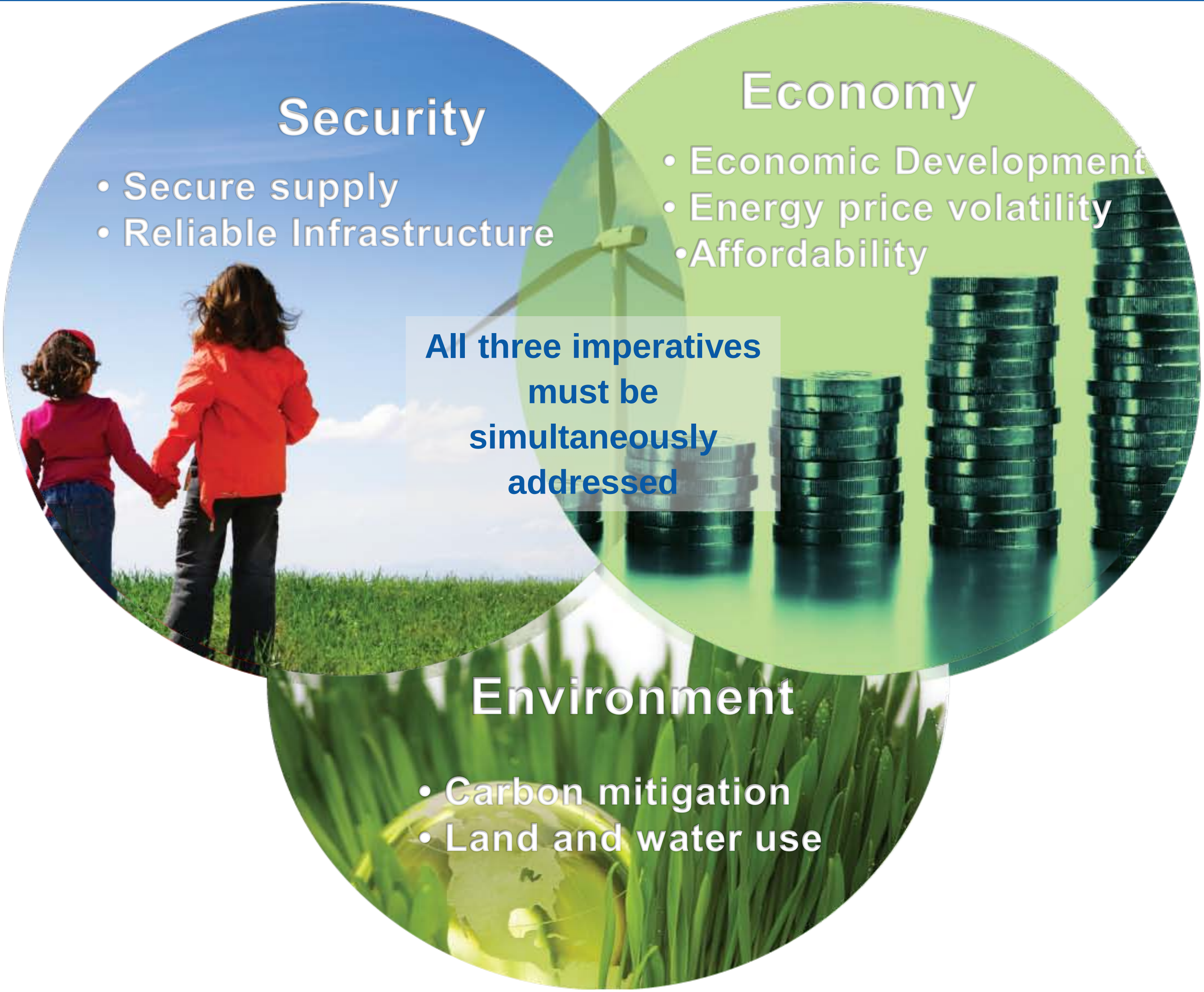
Director

National Renewable Energy Laboratory

October 8, 2009

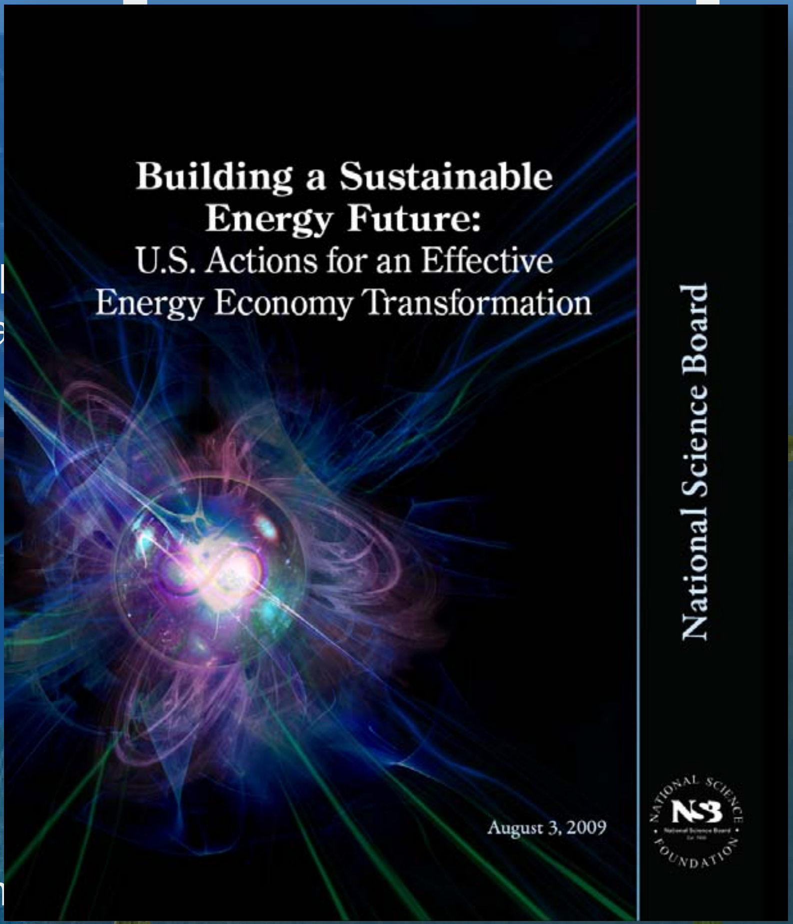
Energy Challenges



Achieving a Sustainable Energy Economy

*Requires a National Energy Grand Challenge**

Lead Coordinated RI
Strategy in Sustaina
Energy



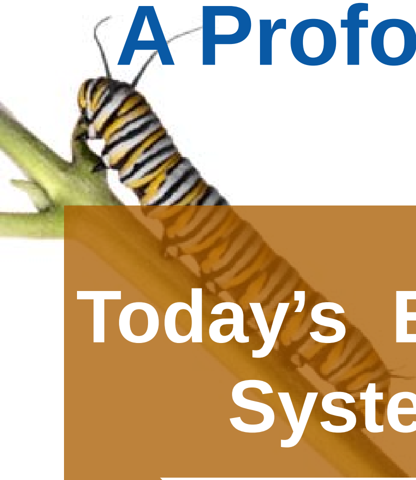
Construct Essential Policies & Market Conditions

Support Education
Workforce Developm

Promote Public Awareness & Action

* Recommendations of the National Science Board Task Force on Sustainable Energy

A Profound Transformation is Required



Today's Energy System

- Dependent on foreign sources
- Subject to price volatility
- Increasingly unreliable
- 2/3 of source energy is lost
- Produces 25% of the world's carbon emissions

Imperatives for Transformation

DEFINE THE END STATES

REDUCE NEW TECHNOLOGY RISK

ACCELERATE ADOPTION

Sustainable Energy System

- Carbon neutral
- Efficient
- Diverse supply options
- Minimal impact on resources
- Creates sustainable jobs
- Accessible, affordable and secure

Our Energy System

100 Quads

Supply & Conversion

Oil 40%

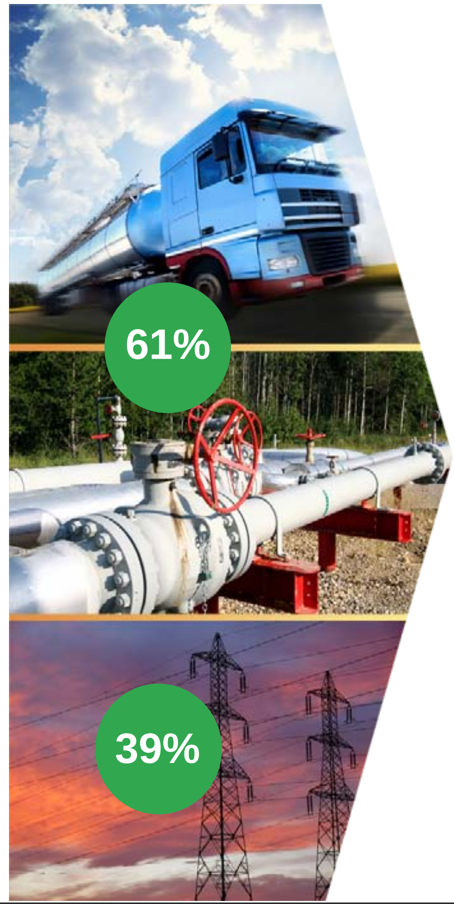
Coal 23%

Natural Gas 23%

Nuclear 8%

Hydro
Wind
Solar 6%
Biomass
Geothermal

Transmission & Distribution



Utilization

27%

40%

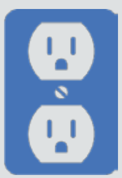
33%

Lost energy as inefficiencies – 62%

Energy is a means to an end, not an end in itself

Heat and power for where we live and work





Sustainable Electricity System

Fuel and power for mobility and access



Sustainable Transportation System

Energy System Vision for 2050

Sustainable Electricity System

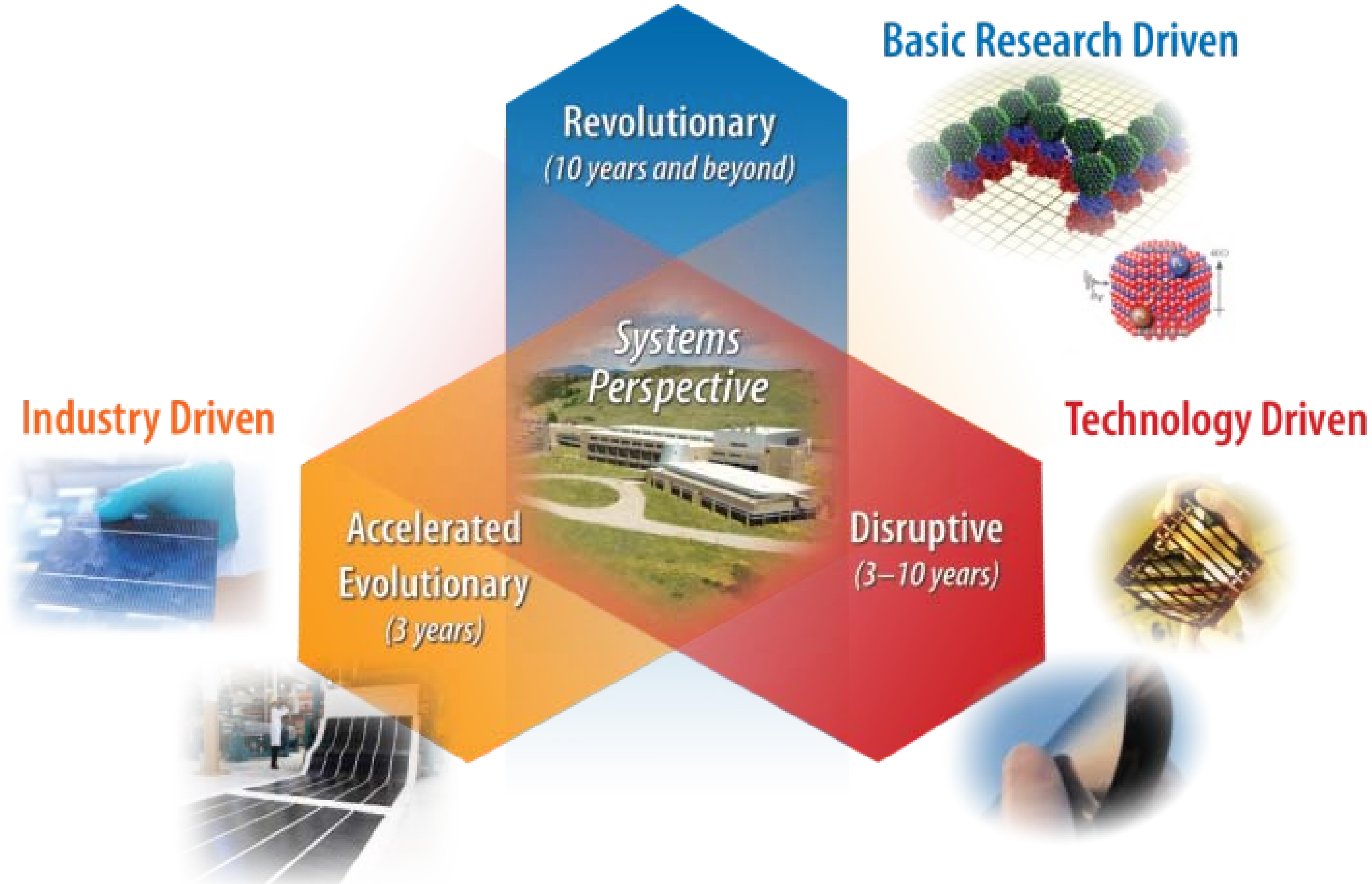
- CO_2 emissions reduced 80% from 1990 levels and impact on scarce resources is minimized
- The average capacity factor of the system approaches 80% and overall system efficiency is at least doubled
- Each region uses an optimal mix of coal, nuclear, and integrated renewable systems
- A smart, resilient, adaptive electric grid places no limitations on accessing energy resources
- Electrification of transportation does not add peak load

Sustainable Transportation System

- U.S. oil usage reduced to 15% of current levels
- CO_2 emissions reduced 80% from 1990 levels and impact on other scarce resources minimized
- Conventional and alternative fuels optimally match transportation modes
- The system places no more limits to economic growth than it does today
- Mobility continues to be enhanced
- Alternative fuel and propulsion technologies are cost-competitive or cheaper than oil

Renewable Energy and **Energy Efficiency** are essential parts of a sustainable energy future

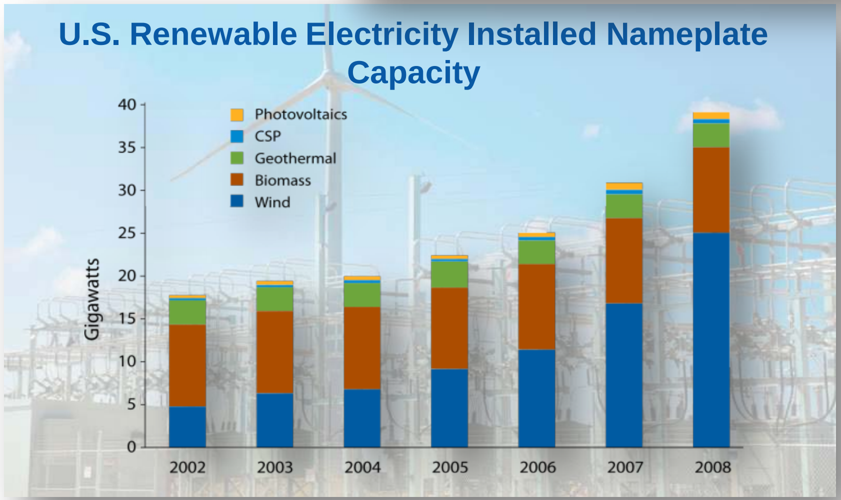
Achieving the Potential Requires A Balanced Portfolio



Near-Term Impact: Harvest Past R&D Energy Investments

Remove Barriers to Broad Deployment

- Fuels Economic Recovery
- Creates Jobs



Source: EIA Annual Energy Outlook 2009 Early Release

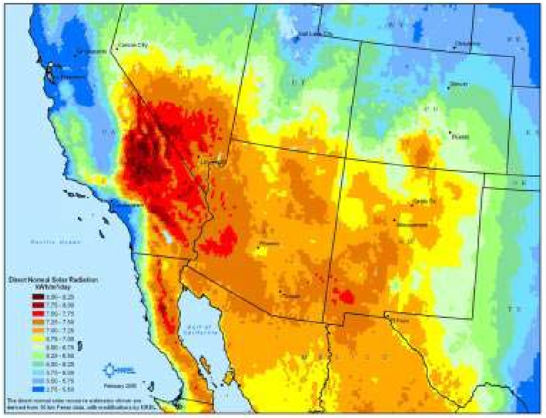
NREL Provides Data, Tools and Technical Assistance to:

Educate and inform

Develop codes and standards

Inform policy options, program design, and investment choices

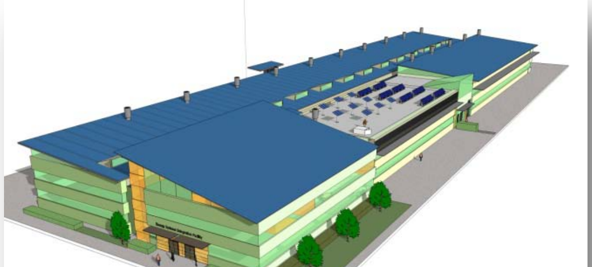
- Resource Assessment
- Technology Analysis
- Policy Analysis



Mid-Term Impact: Accelerate Next-Generation Technology to Market

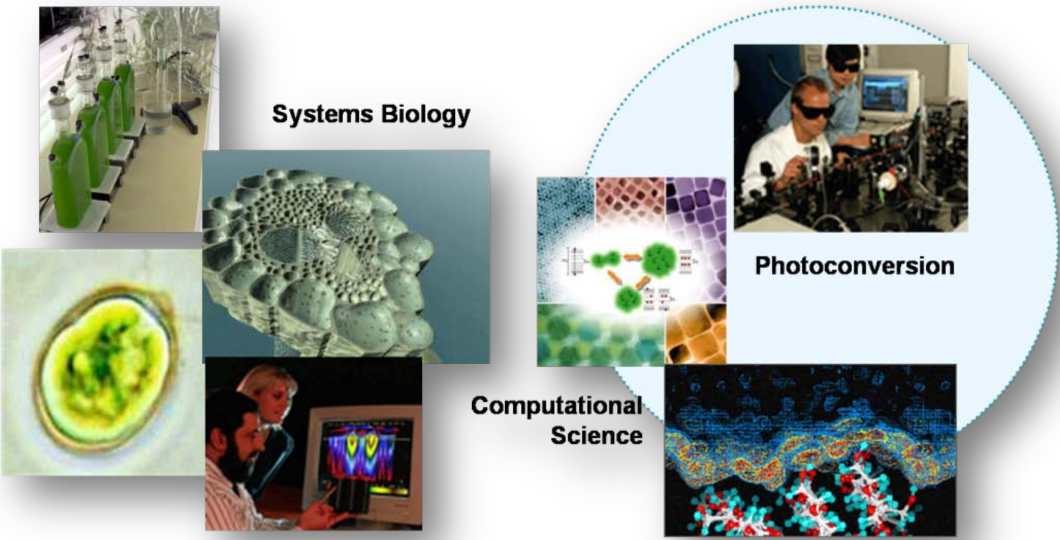
- NREL Focus on Technology and Systems Development
- Unique Partnering Facilities
- Testing and Validation Capabilities

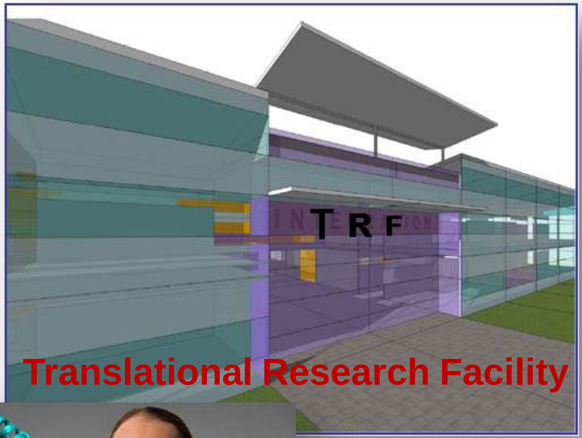
Integrated Biorefinery Research Facility

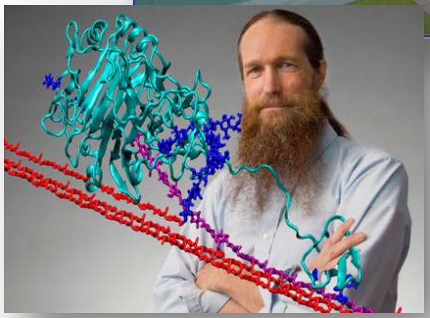


Energy Systems Integration Facility

Long-Term Impact: Requires Breakthrough/Translational Science



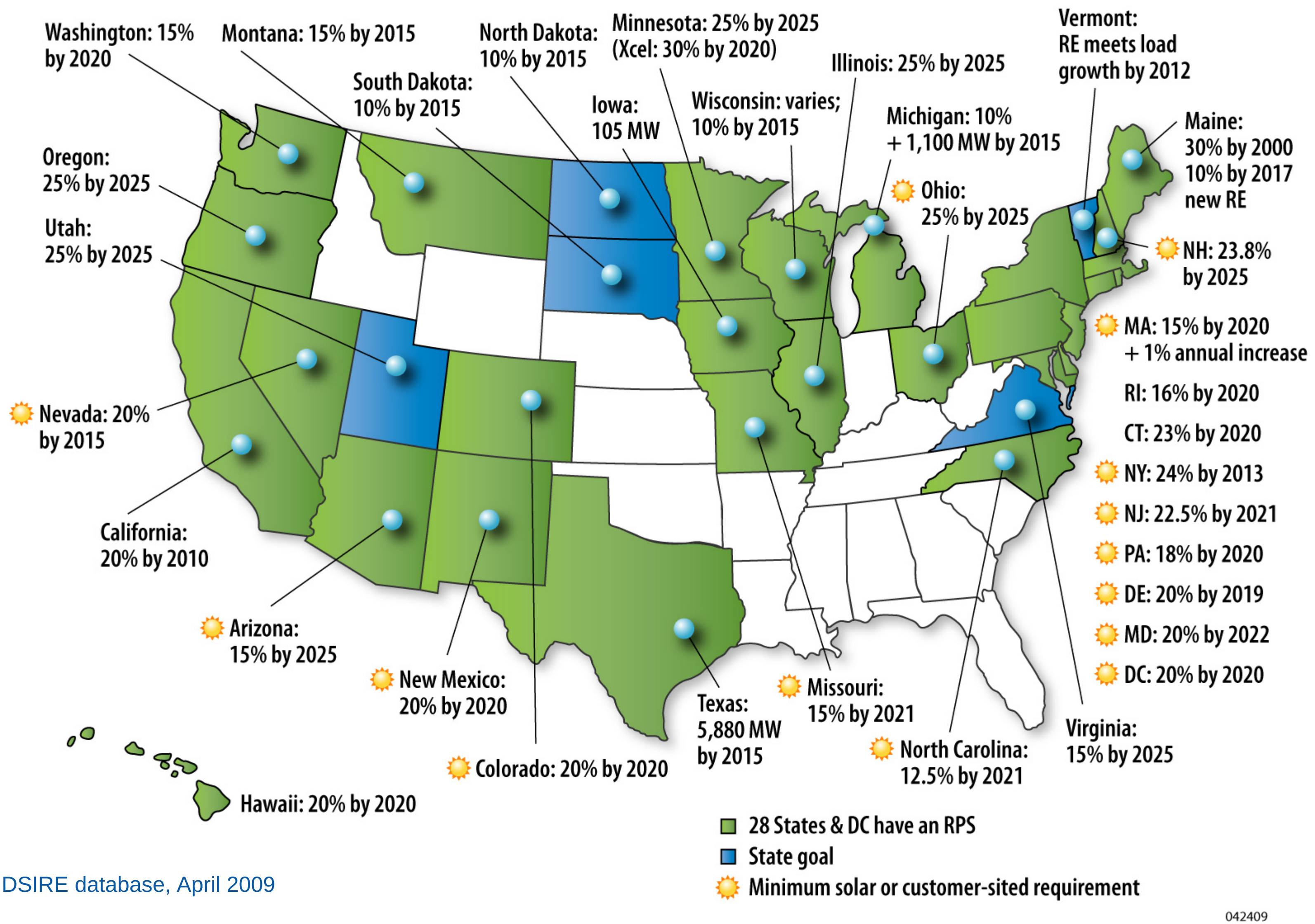




Managing the science-to-technology interface

State Policy Framework

Renewable Portfolio Standards



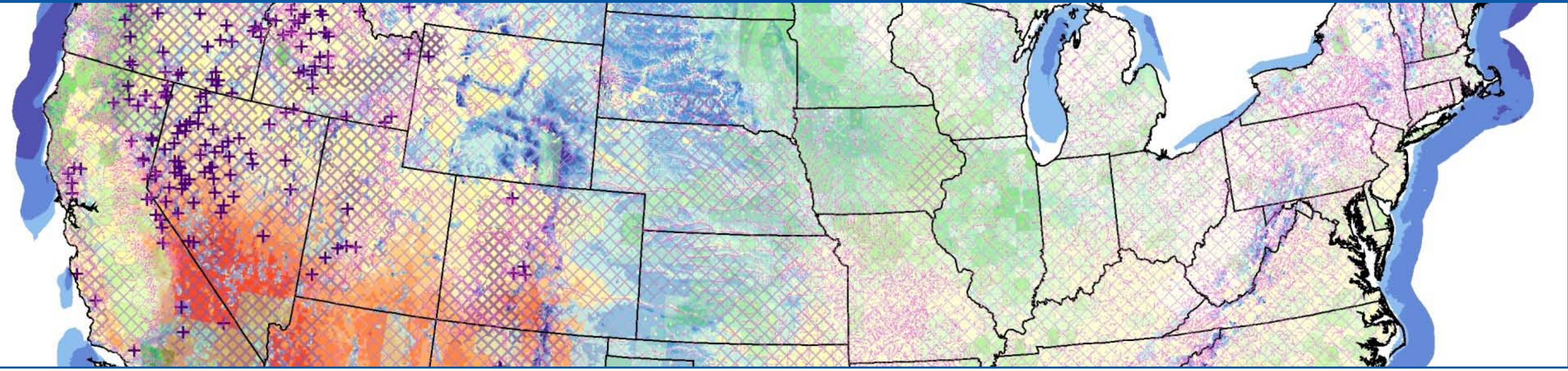
Source: DSIRE database, April 2009

Looking Ahead with Optimism—New National Priorities

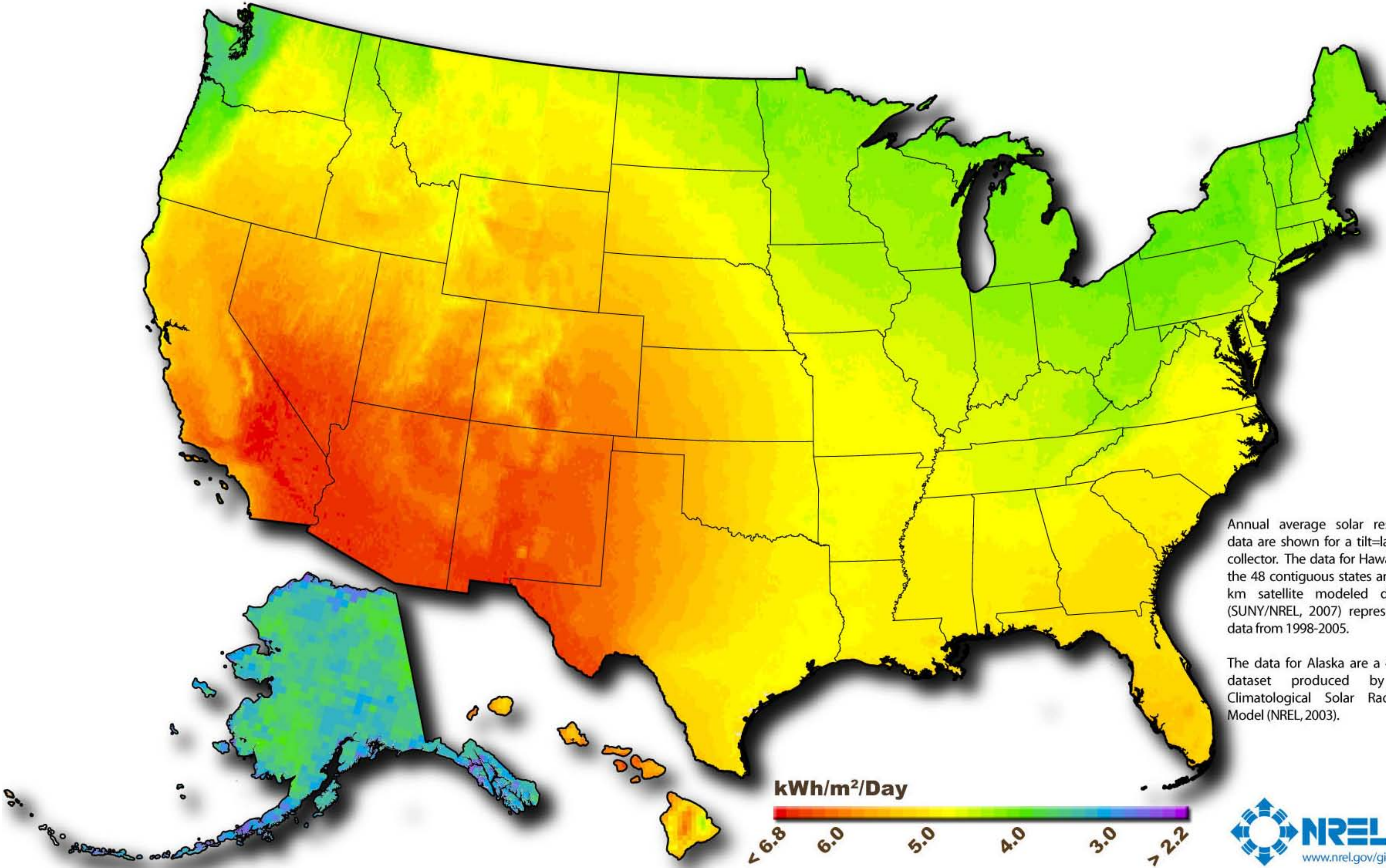
- Invest $150B in alternative energy over 10 years
- Create green jobs with clean, efficient American energy
- Double production of alternative energy in three years – enough to power 6 million homes
- Upgrade the efficiency of more than 75% of federal buildings and two million private homes
- Put one million PHEVs on U.S. roads by 2015
- Reduce CO_2 emissions by 80% below 1990 levels by 2050
- Transform our economy with science and technology

G8Website/ANSA Photo: Alessandro Di Meo

Resource Potential



U.S. Photovoltaic Solar Resource



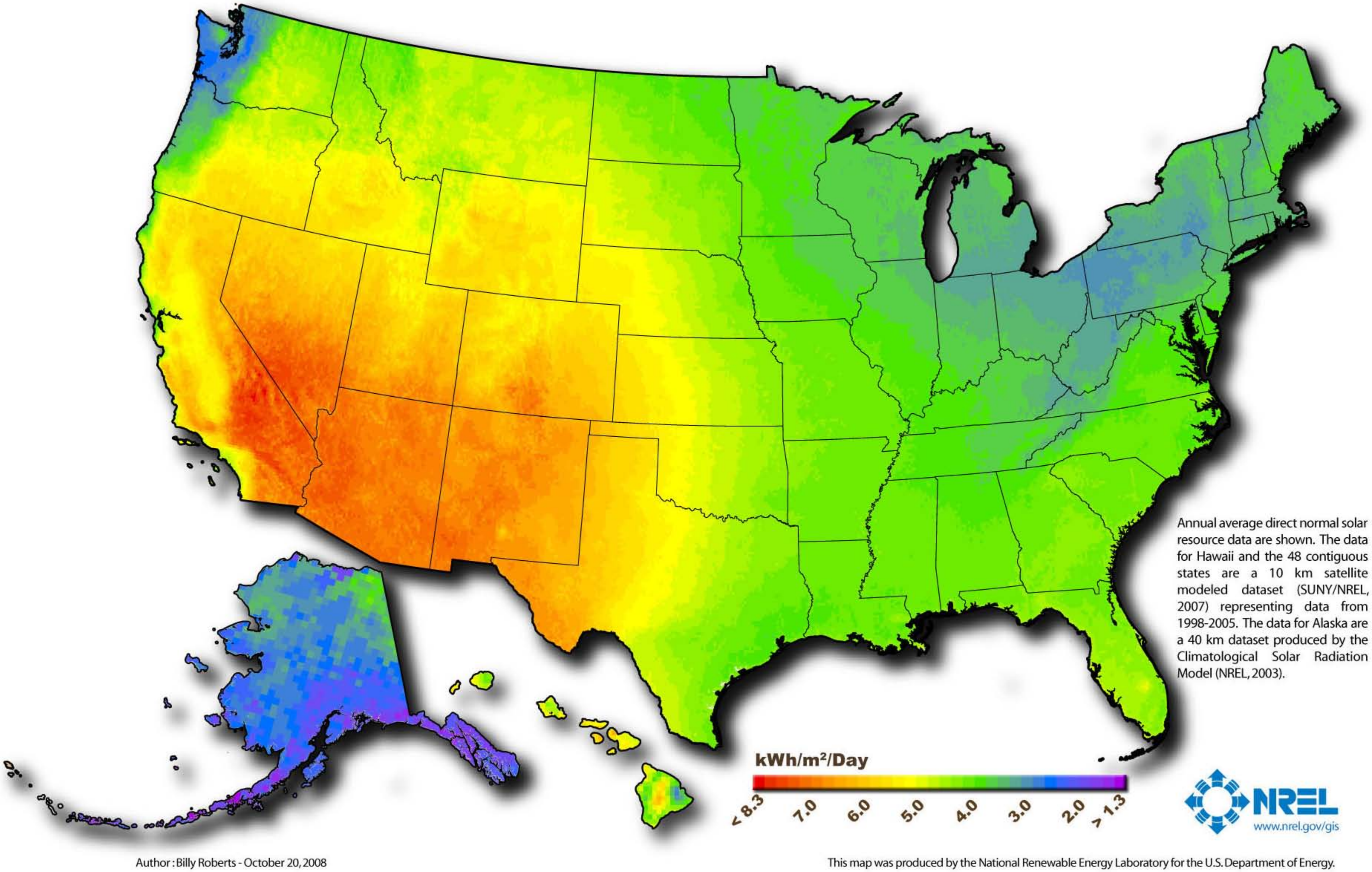
Annual average solar resource data are shown for a tilt=latitude collector. The data for Hawaii and the 48 contiguous states are a 10 km satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.

The data for Alaska are a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).

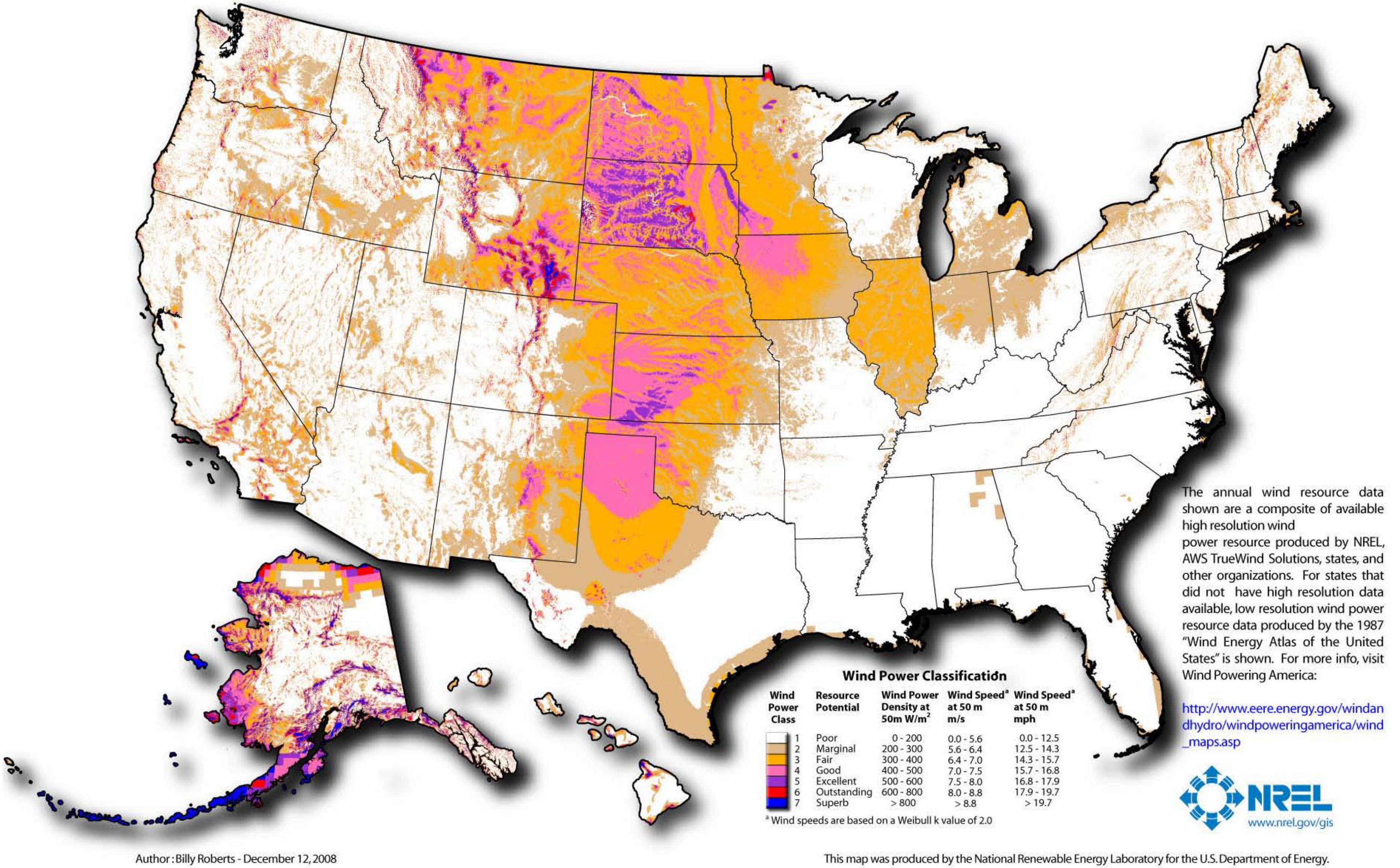
Author : Billy Roberts - October 20, 2008

This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy.

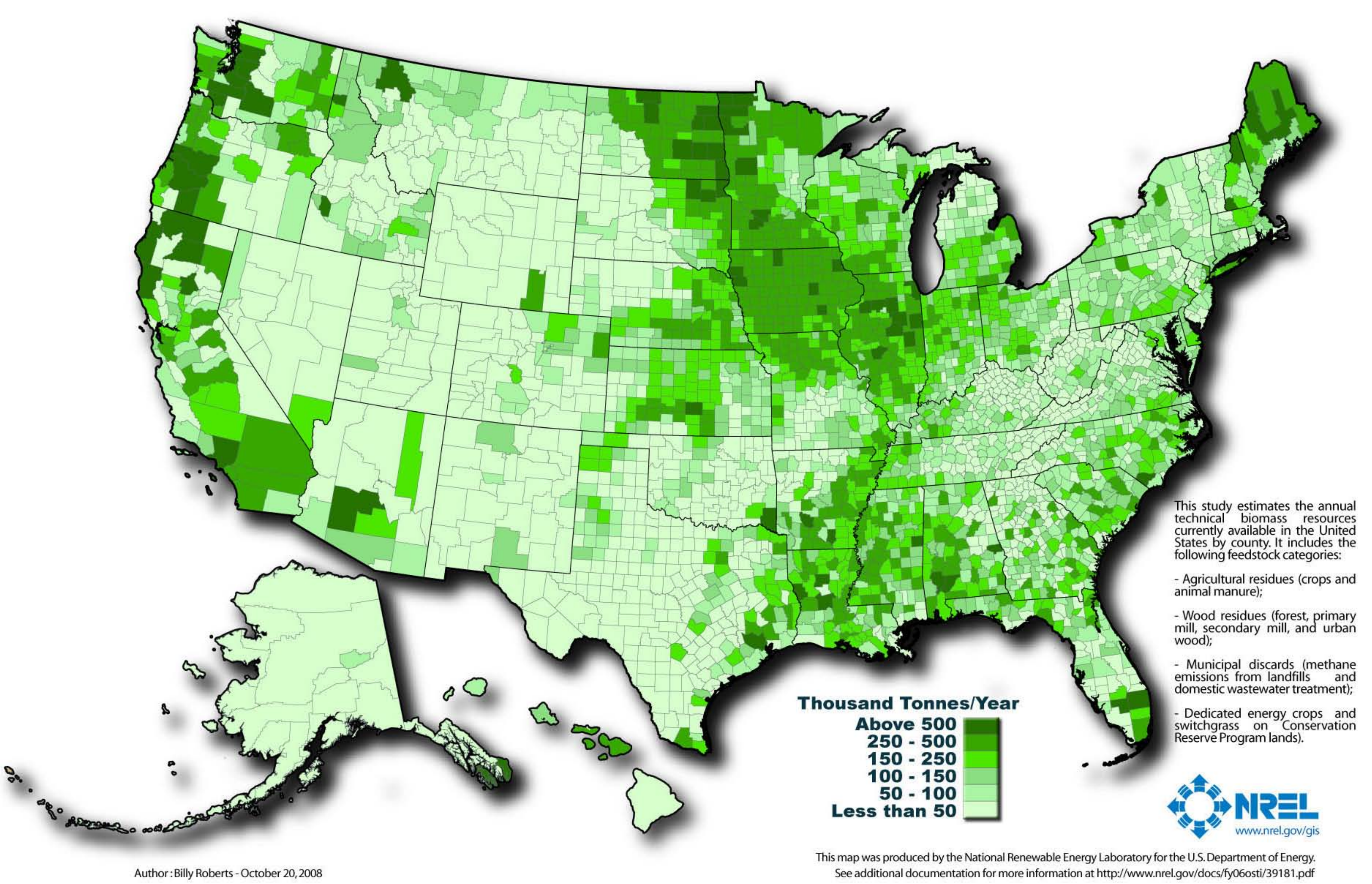
U.S. Concentrating Solar Resource



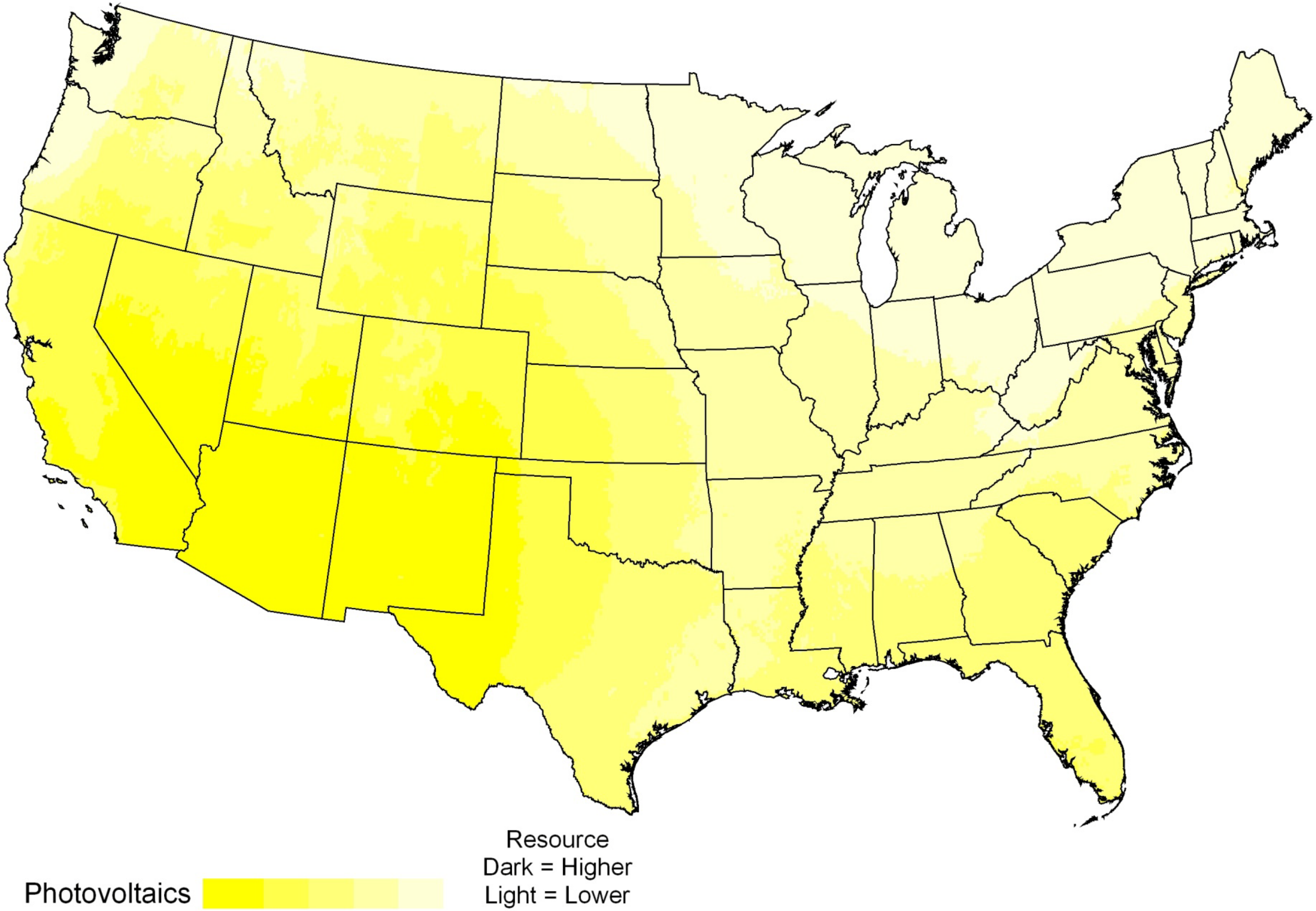
U.S. Wind Resource (50m)



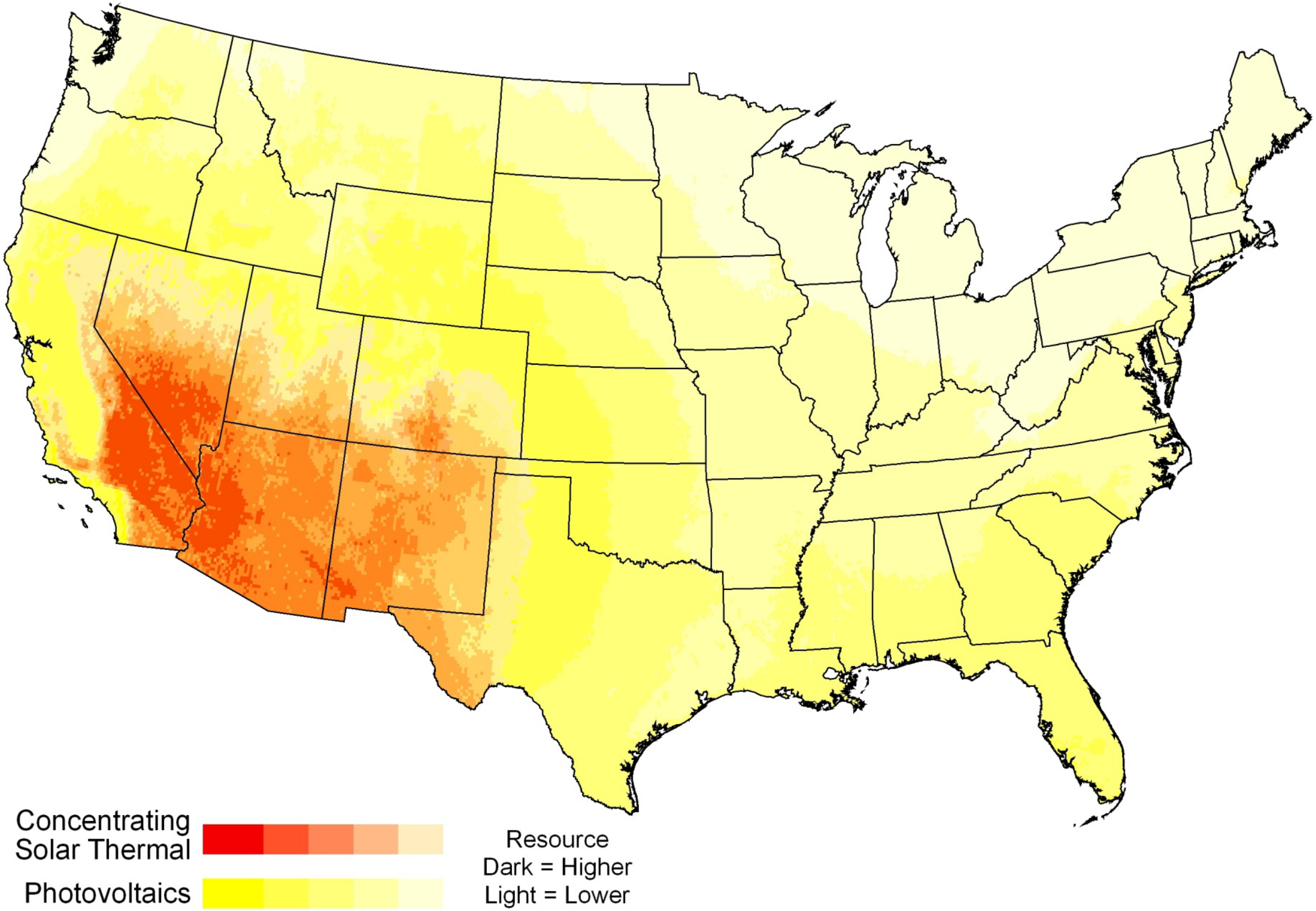
U.S. Biomass Resource



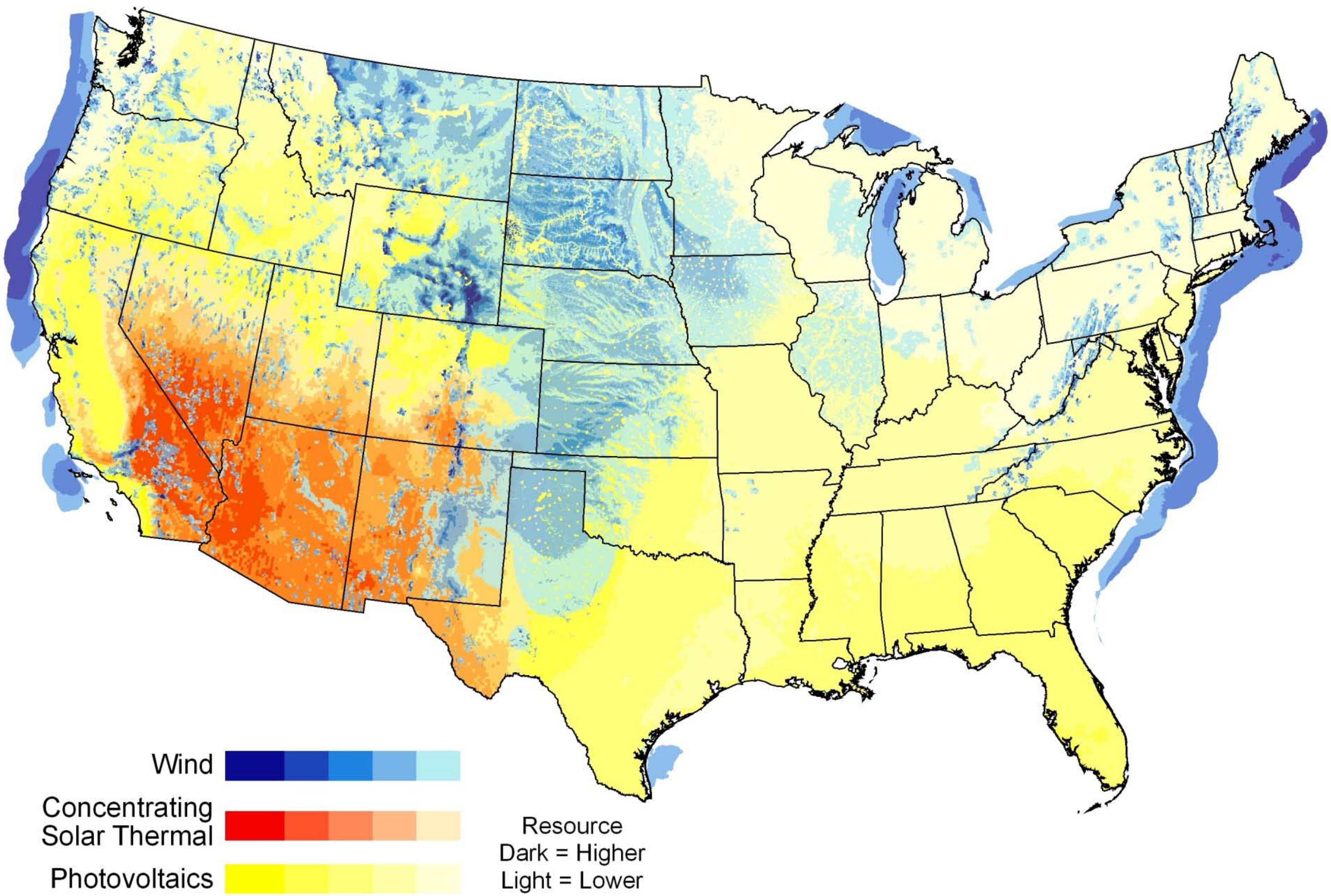
U.S. Renewable Resources



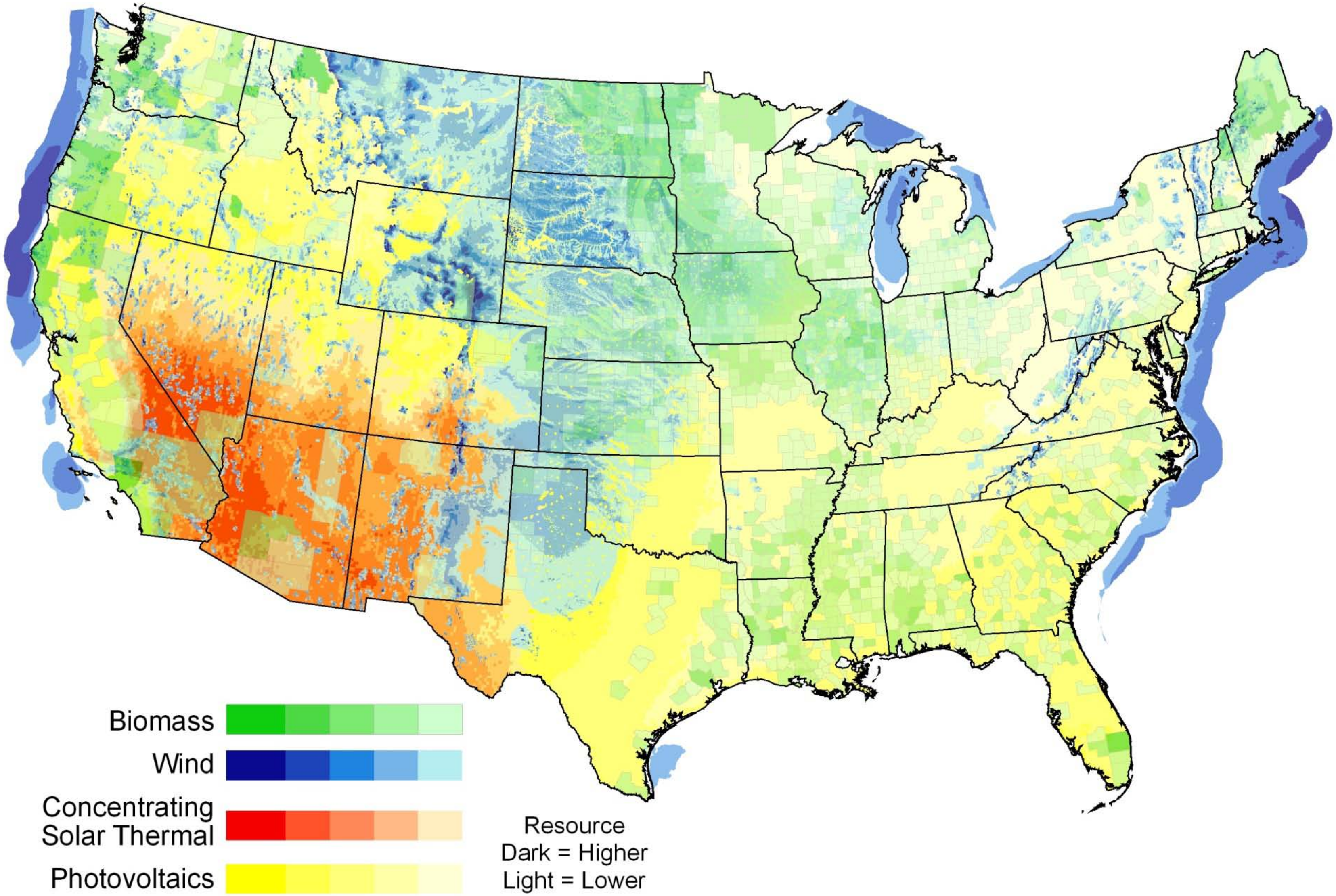
U.S. Renewable Resources



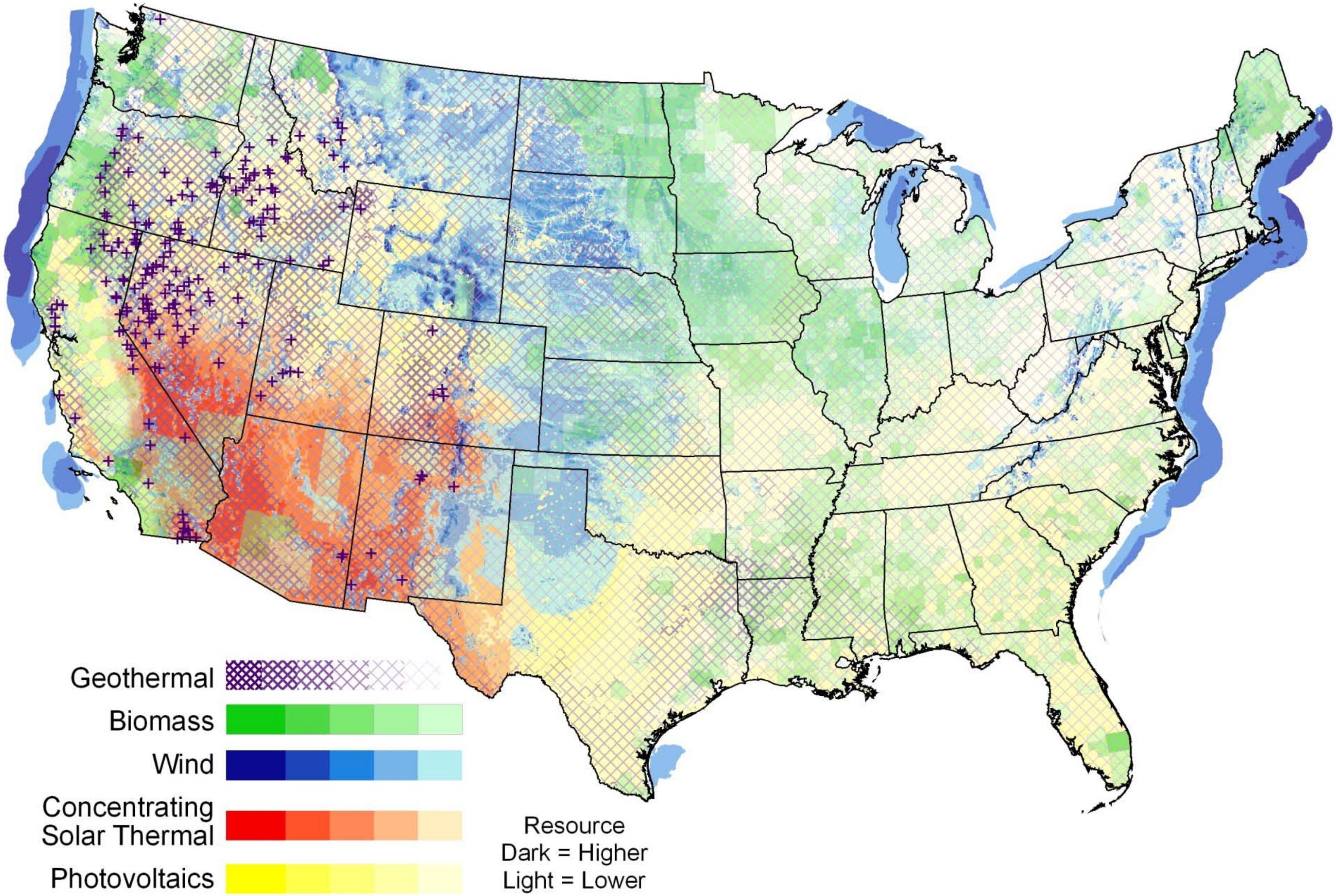
U.S. Renewable Resources



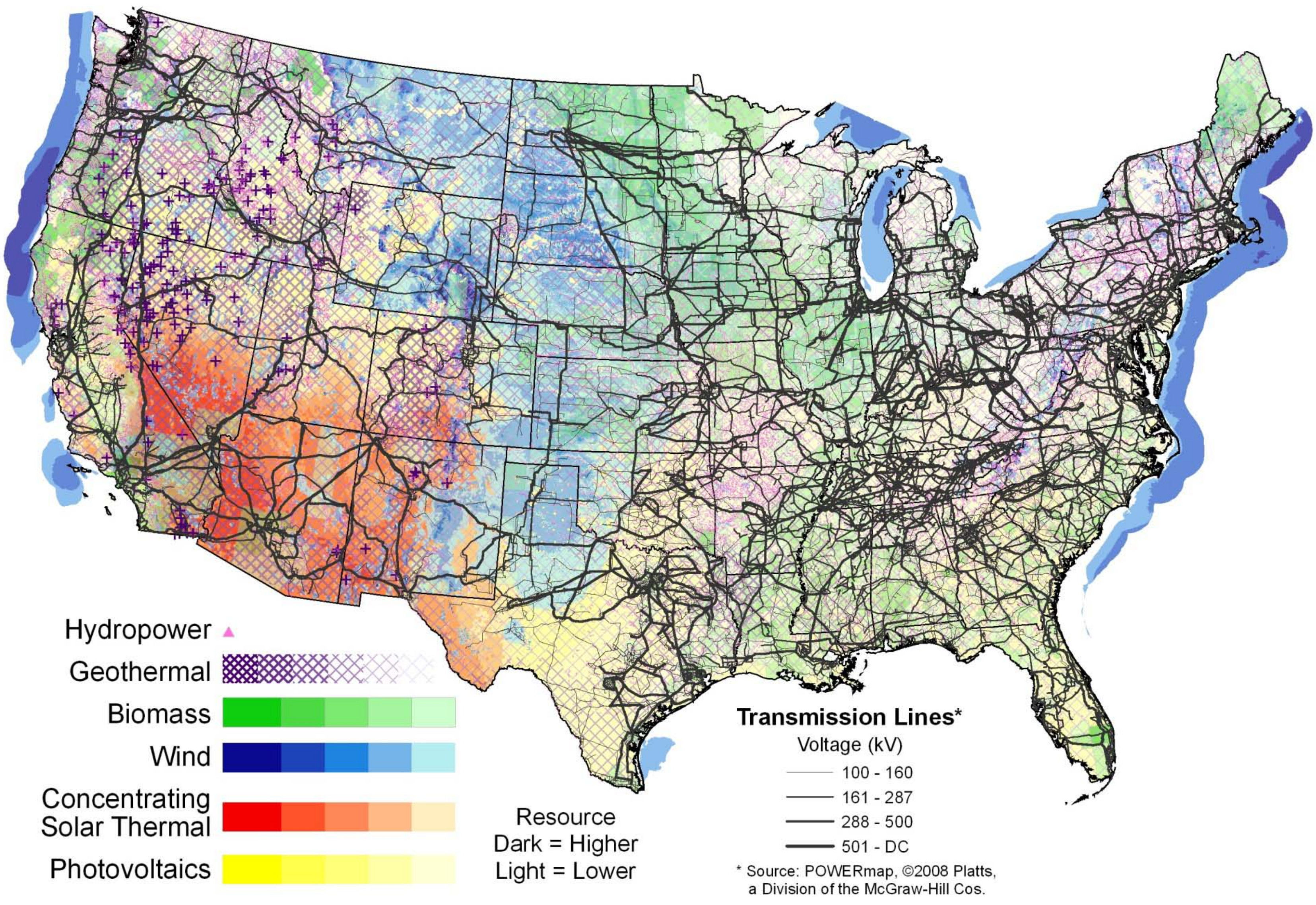
U.S. Renewable Resources



U.S. Renewable Resources

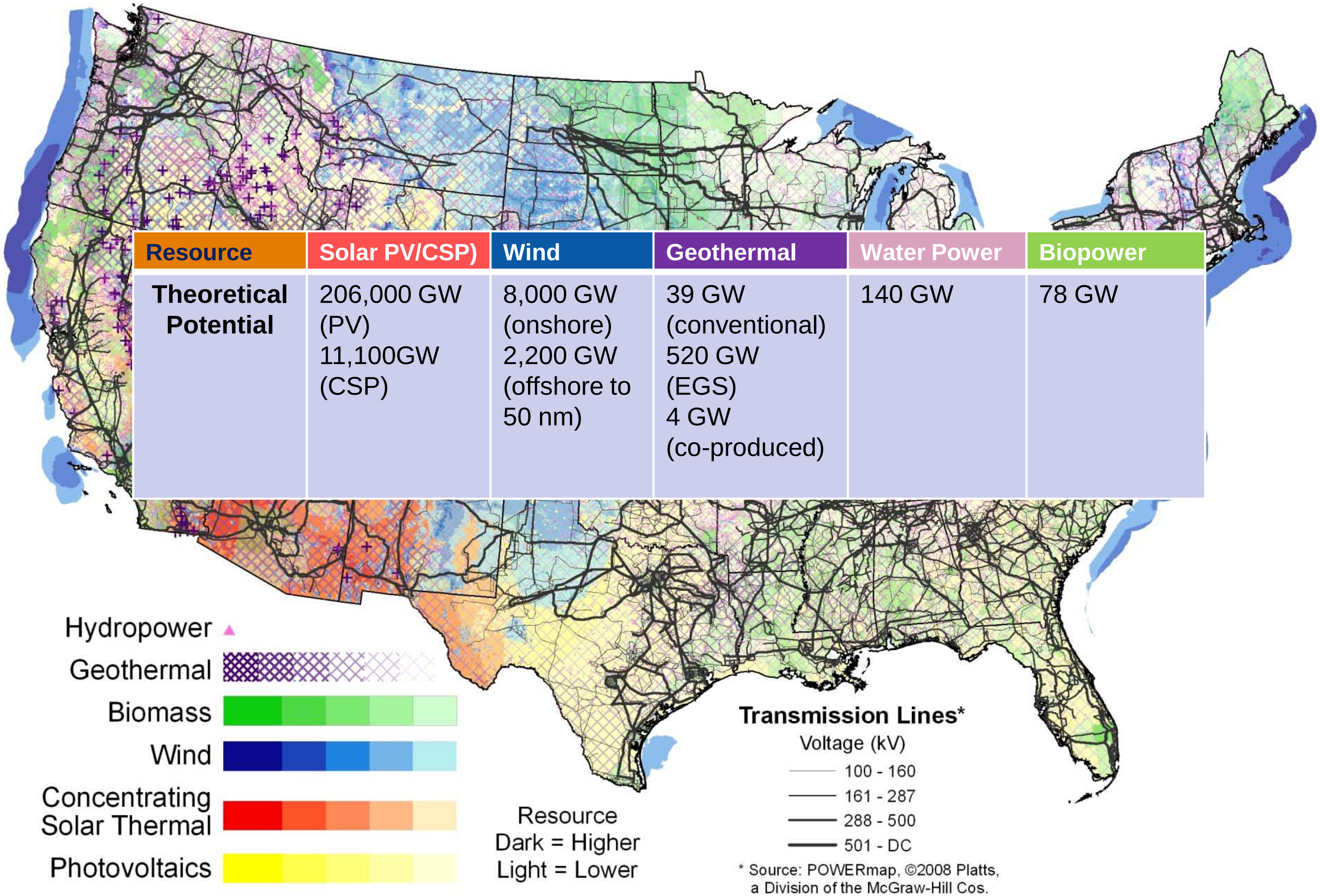


U.S. Renewable Resources



U.S. Renewable Resources

Resource	Solar PV/CSP)	Wind	Geothermal	Water Power	Biopower
Theoretical Potential	206,000 GW (PV) 11,100GW (CSP)	8,000 GW (onshore) 2,200 GW (offshore to 50 nm)	39 GW (conventional) 520 GW (EGS) 4 GW (co-produced)	140 GW	78 GW



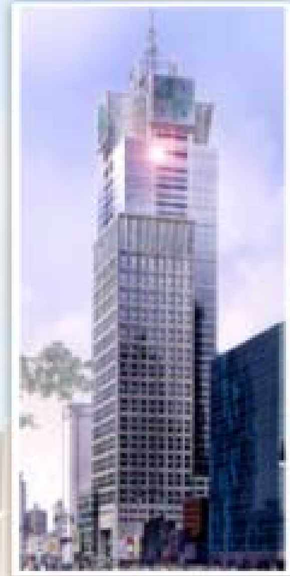
Energy Efficiency

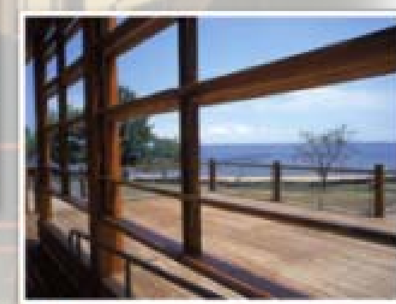
Buildings

Status U.S. Buildings:
- 39% of primary energy
- 71% of electricity
- 38% of carbon emissions

DOE Goal:
- Cost effective, marketable zero energy buildings by 2025
- Value of energy savings exceeds cost of energy features on a cash flow basis

NREL Research Thrusts
- Whole building systems integration of efficiency and renewable features
- Computerized building energy optimization tools
- Building integrated PV

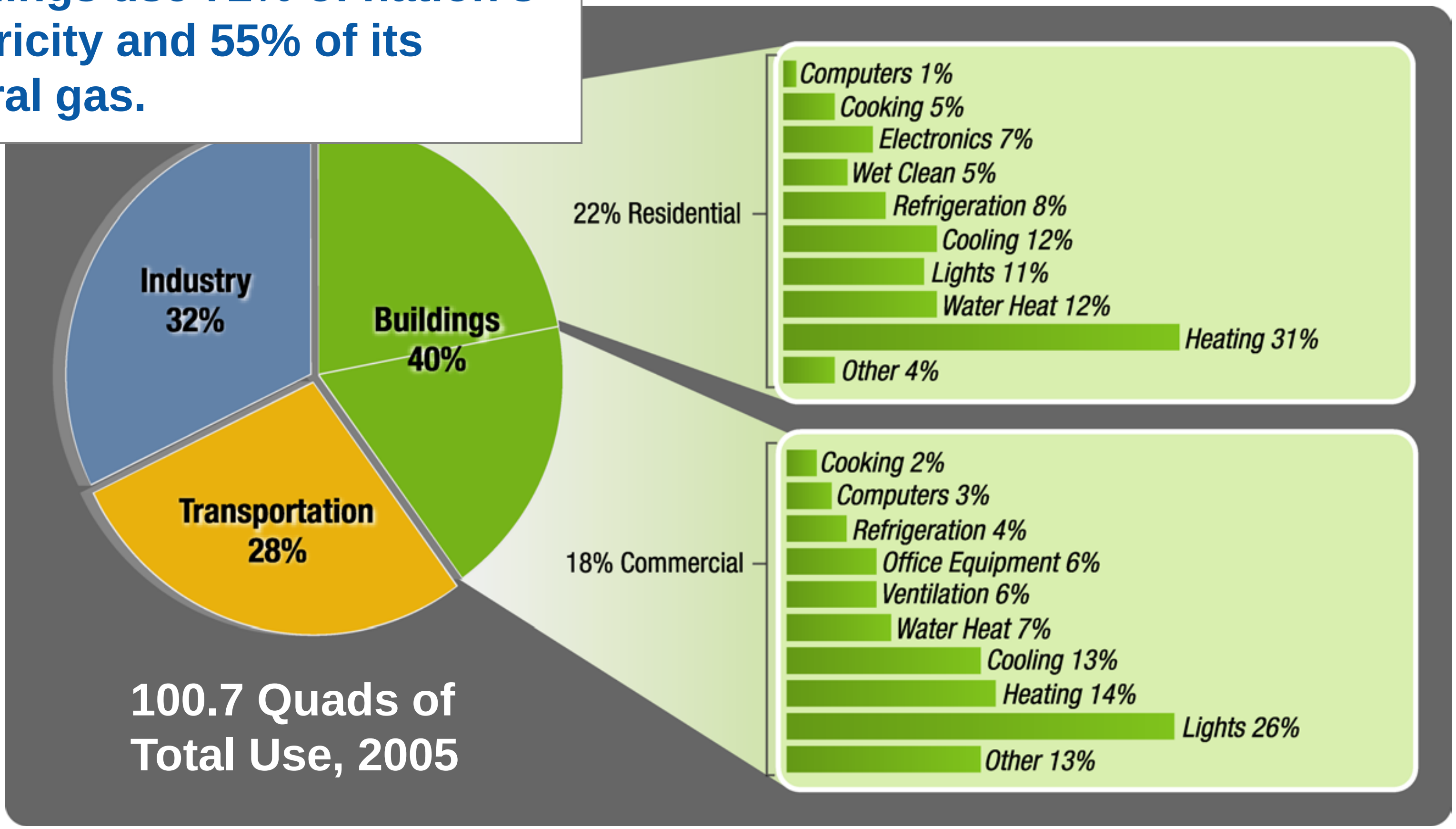




April 10, 2008

Energy Used in Buildings

Buildings use 72% of nation's electricity and 55% of its natural gas.



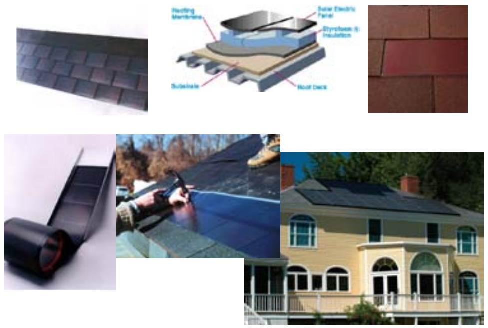
Buildings use 72% of the nation's electricity and 55% of its natural gas.

Source: *Buildings Energy Data Book 2007*

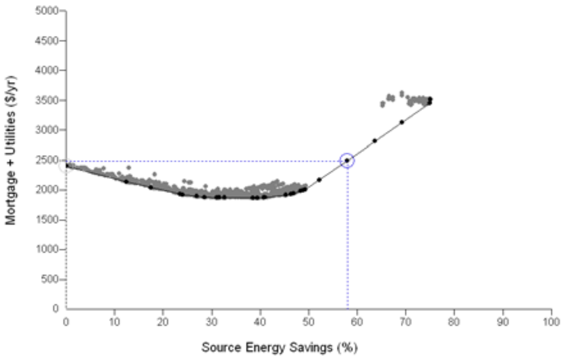
Technology for Cost Effective Zero Energy Buildings

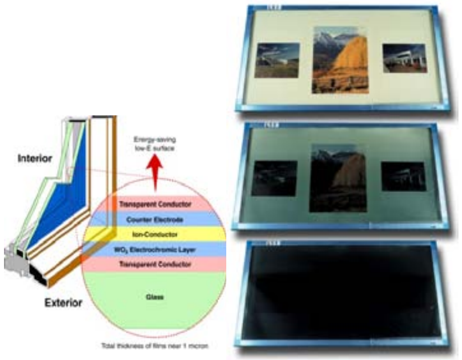
Compressorless Cooling

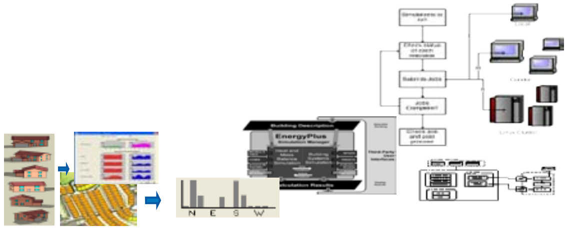
NREL Zero Energy Habitat House



BIPV Products & PV-T Array







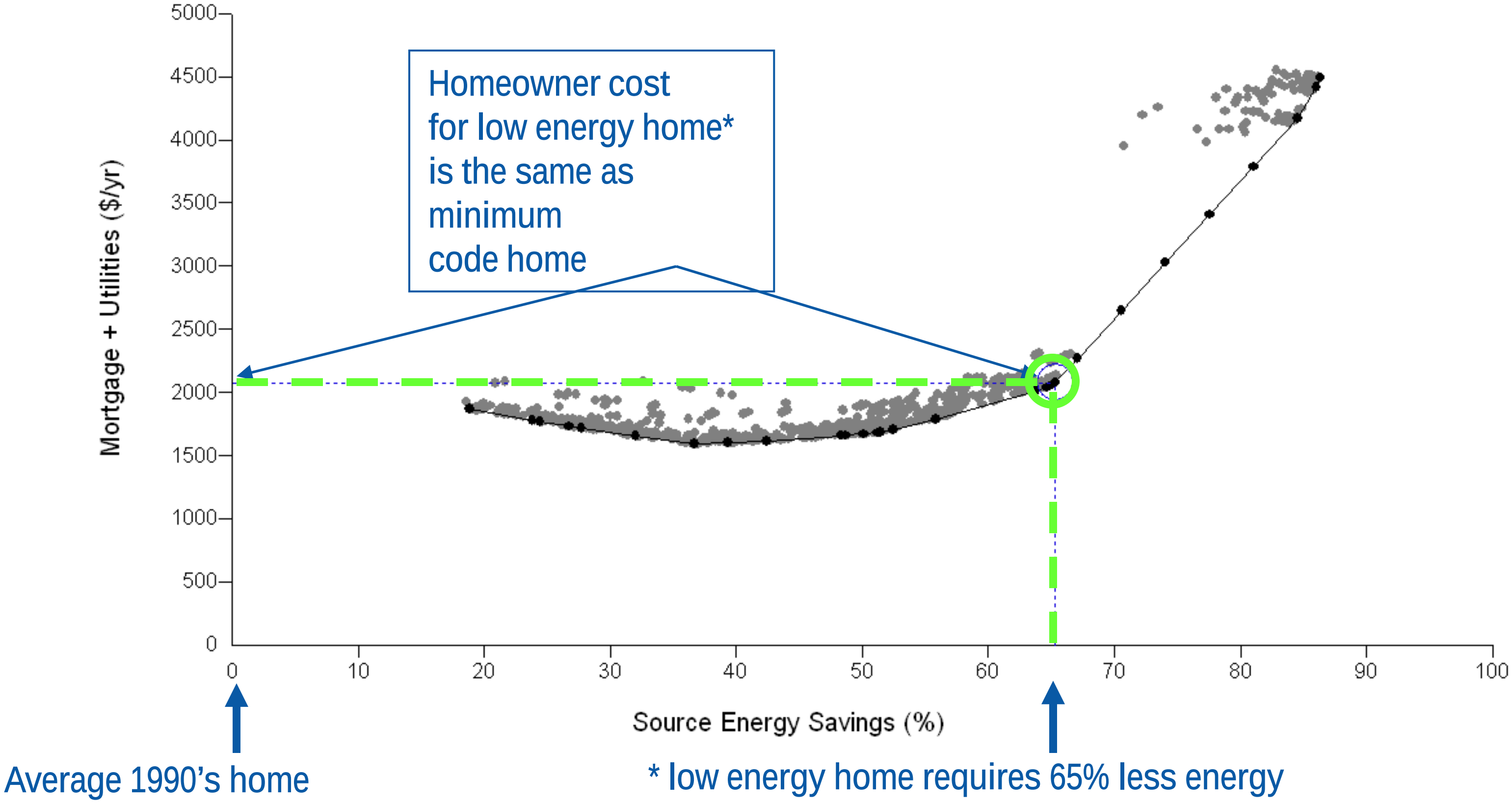
Electrochromic Windows

Polymer Solar Water Heaters

Computerized optimization & simulation Tools

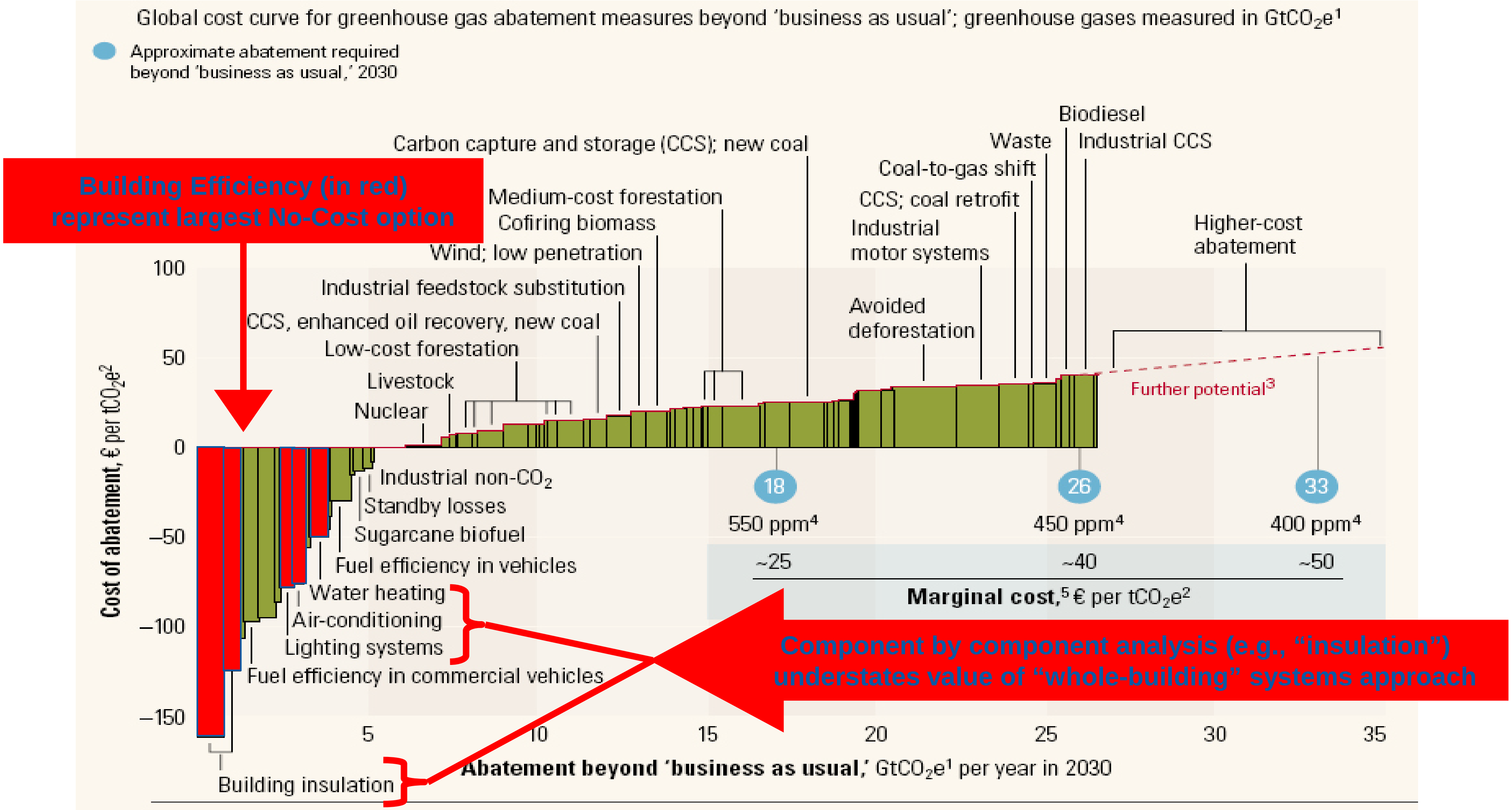
Net-Zero Energy Homes That Are Cashflow Neutral

• NREL Analysis using BEOpt software for Boulder,CO climate



Example taken from the "GEOS" Neighborhood. Courtesy of Wonderland Hills Development, Boulder Colorado

Energy Efficiency Offers Low or No-Cost Carbon Reduction Options



[1] $GtCO_2e$ = gigaton of carbon dioxide equivalent; "business as usual" based on emissions growth driven mainly by increasing demand for energy and transport around the world and by tropical deforestation.
[2] tCO_2e = ton of carbon dioxide equivalent.
[3] Measures costing more than €40 a ton were not the focus of this study.
[4] Atmospheric concentration of all greenhouse gases recalculated into CO_2 equivalents; ppm = parts per million.
[5] Marginal cost of avoiding emissions of 1 ton of CO_2 equivalents in each abatement demand scenario.

Source: McKinsey Global Institute, 2007

Renewable Electricity Supply

Wind

Today's Status in U.S.

- 25,300 MW installed capacity
- Cost 6-9¢/kWh at good wind sites*

DOE Cost Goals

- 3.6¢/kWh, onshore at low wind sites by 2012
- 7¢/kWh, offshore in shallow water by 2014

Long Term Potential

20% of the nation's electricity supply

* With no Production Tax Credit
Updated May 8, 2009
Source: U.S. Department of Energy, American Wind Energy Association

The "20% Wind Report" Informs Our RD&D

The 20% Wind Energy by 2030 Scenario

How it began:

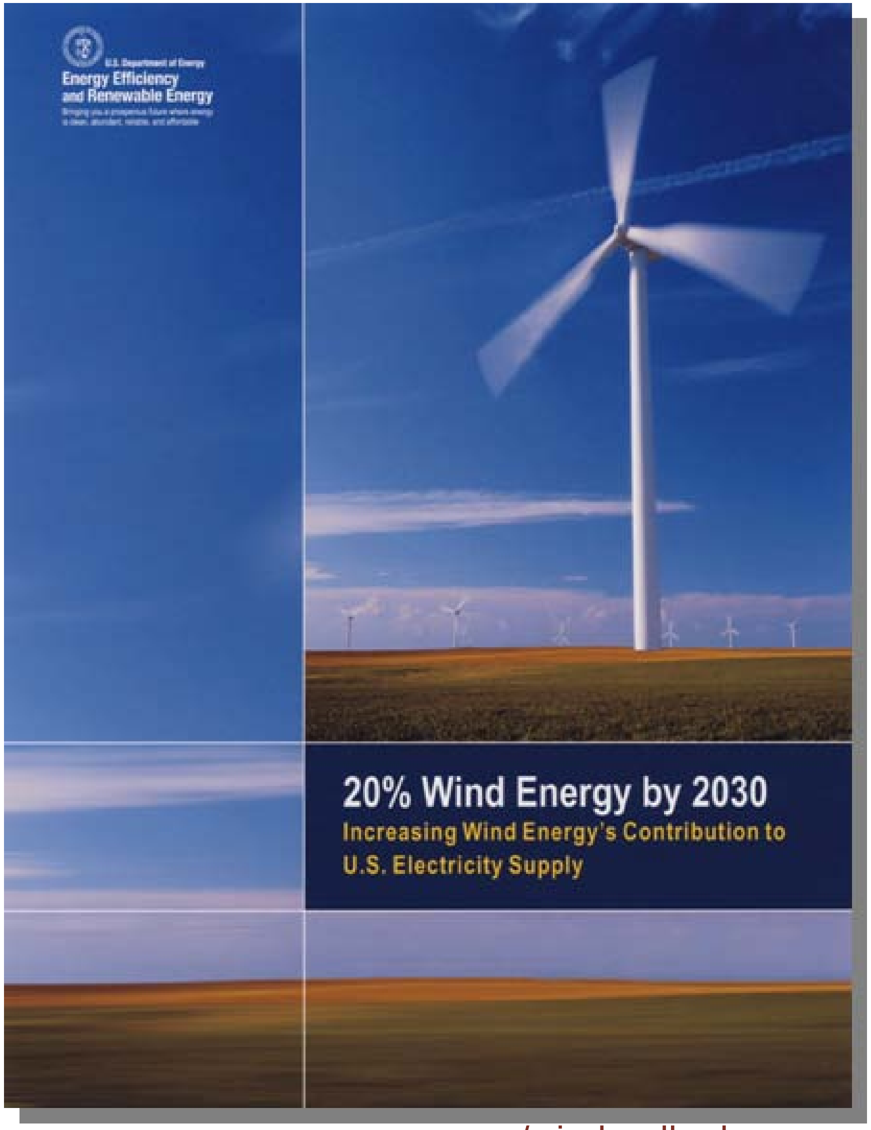
- 2006 State of the Union and Advanced Energy Initiative
- Collaborative effort of government and industry (DOE, NREL, and AWEA) to explore a modeled energy scenario in which wind provides 20% of U.S. electricity by 2030

Primary Assumptions:

- U.S. electricity consumption grows 39% from 2005 to 2030—to 5.8 billion MWh (Source: EIA)
- Wind turbine energy production (capacity factor) increases about 15% by 2030
- Wind turbine costs decrease about 10% by 2030
- No major breakthroughs in wind technology

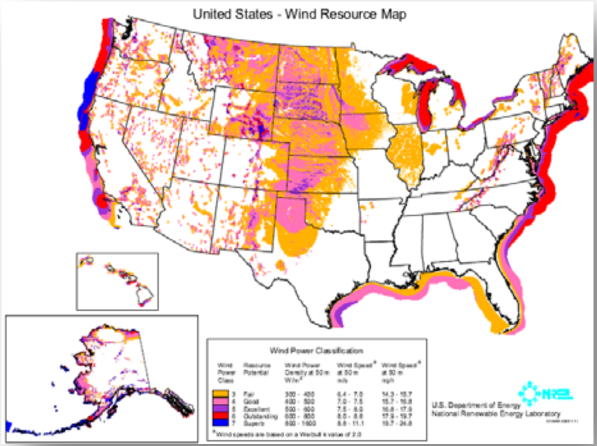
Primary Findings:

- 20% wind electricity would require about 300 GW (300,000 MW) of wind generation
- Affordable, accessible wind resources available across the nation
- Cost to integrate wind modest
- Emissions reductions and water savings
- Transmission a challenge



www.eere.energy.gov/windandhydro

Wind Energy Technology



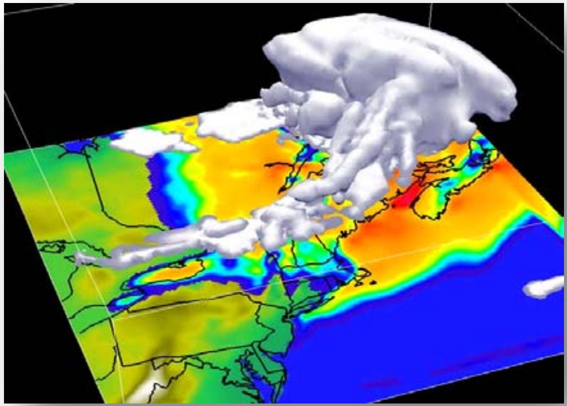
US Wind Resource Exceeds Total Electrical Demand

Offshore Wind

Advanced Blades

Innovative Tall Towers

Giant Multi-megawatt Turbines



Courtesy:WindLogics, Inc. St. Paul, MN

Wind Forecasting

NREL Research Thrusts

- Improved performance and reliability
- Advanced rotor development
- Utility grid integration

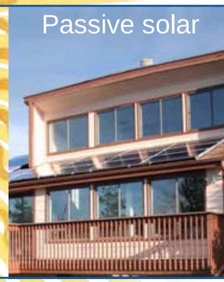
Photo credit: Megavind

Horns Rev Offshore Wind Farm
North Sea, Denmark

Photo used by permission of Uni-Fly A/S

Applications of Solar Heat and Electricity

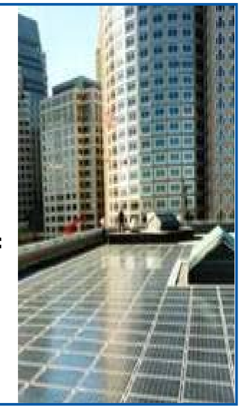
Solar Thermal



Photovoltaics (PV)

Concentrating Solar Power (CSP)

Distributed Generation, on-site or near point of use



Centralized Generation, large users or utilities

Transportation

Residential & Commercial Buildings

Industrial

Solar – Photovoltaics and CSP

Status in U.S.

PV
- 1,000 MW installed capacity
- Cost 18-23¢/kWh

CSP
- 419 MW installed capacity
- Cost 12¢/kWh

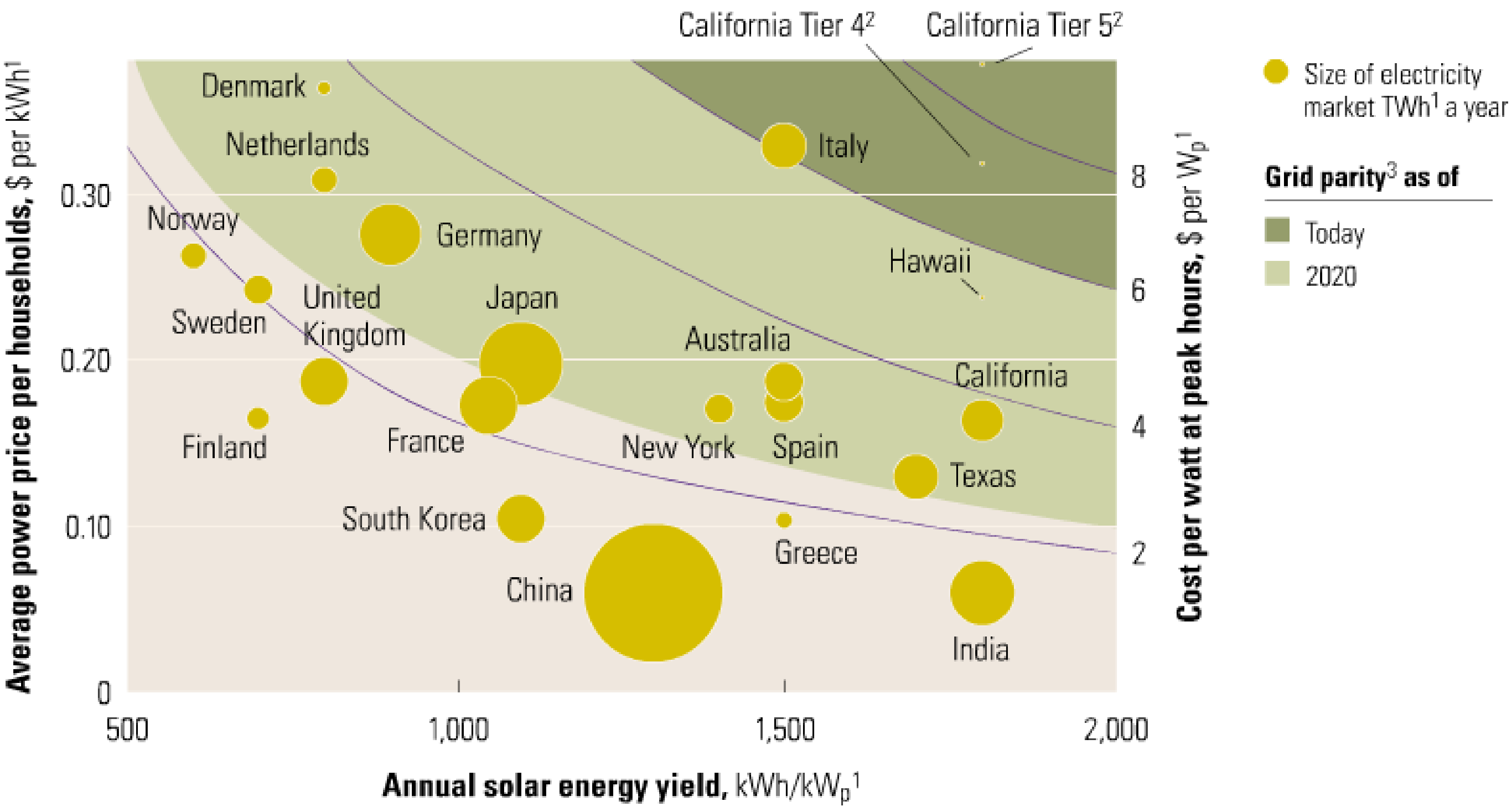
Potential:

PV
- 11-18¢/kWh by 2010
- 5-10 ¢/kWh by 2015

CSP
8.5 ¢/kWh by 2010
6 ¢/kWh by 2015

Source: U.S. Department of Energy, IEA
Updated January 1, 2009

Growing Competiveness of Solar



Source: McKinsey Quarterly, June 2008

Solar Research Thrusts

Photovoltaics

Higher performance cells/modules

New nanomaterials applications

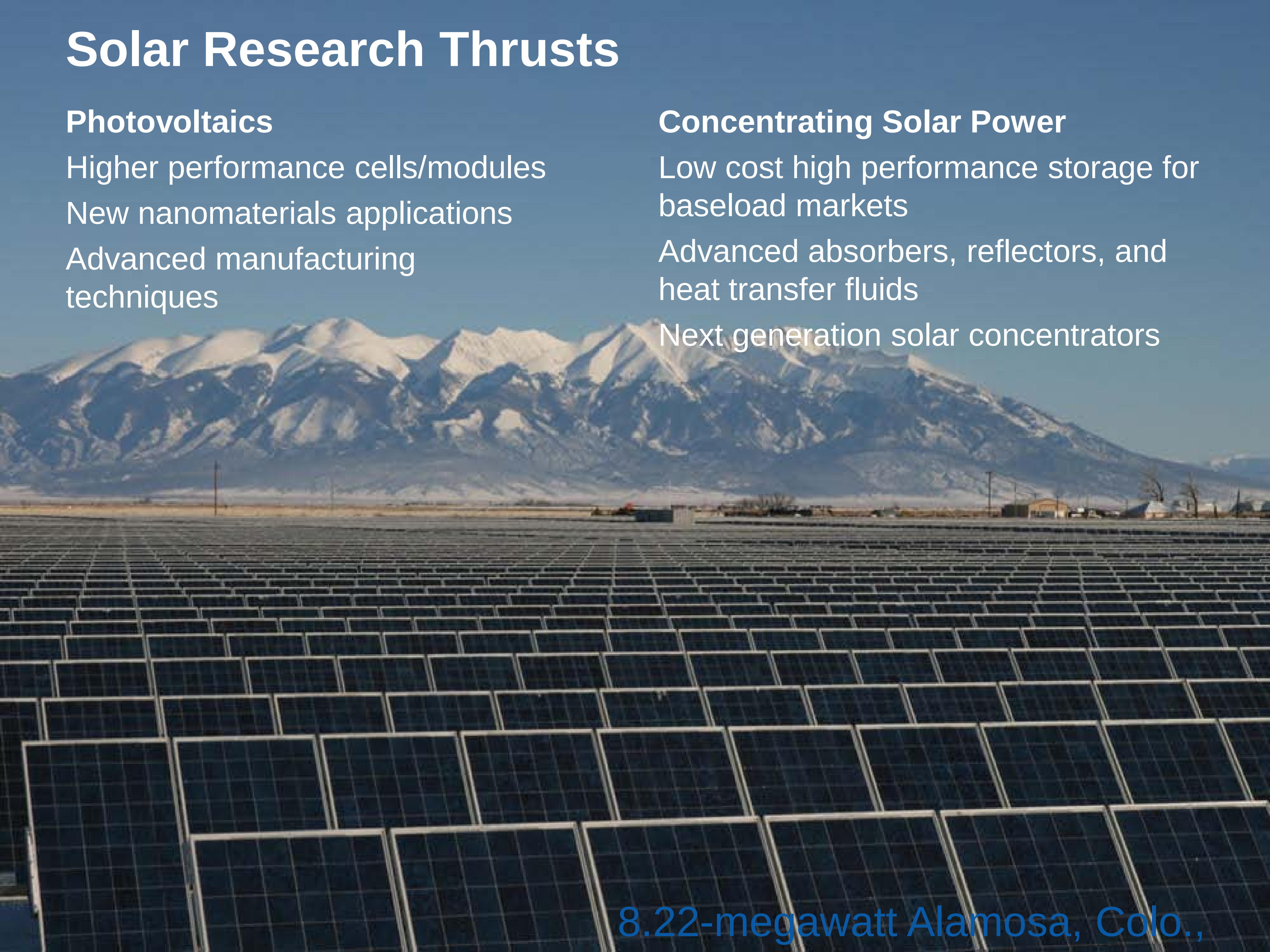
Advanced manufacturing techniques

Concentrating Solar Power

Low cost high performance storage for baseload markets

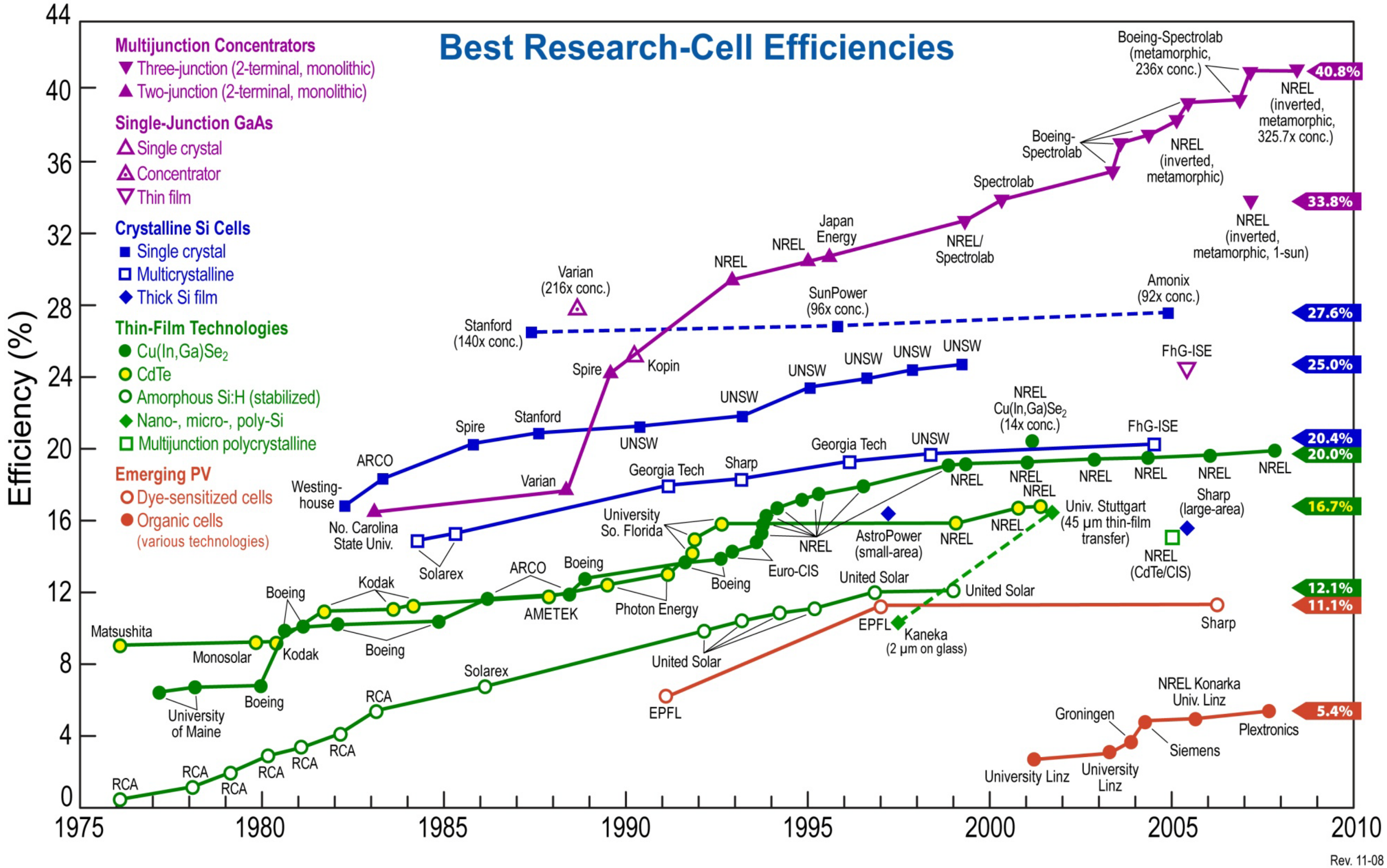
Advanced absorbers, reflectors, and heat transfer fluids

Next generation solar concentrators



8.22-megawatt Alamosa, Colo.,

PV Conversion Technologies—Decades of NREL Leadership



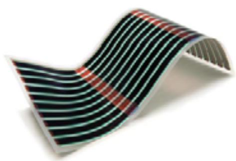
PV Conversion Technology Portfolio

Market-Competitive Targets

Market Sector	Current U.S. Market Price Range (¢/kWh)	Cost (¢/kWh) Benchmark 2005	Cost (¢/kWh) Target 2010	Cost (¢/kWh) Target 2015
Residential	5.8-16.7	23-32	13-18	8-10
Commercial	5.4-15.0	16-22	9-12	6-8
Utility	4.0-7.6	13-22	10-15	5-7

Thin Films (aSi)

Advancing amorphous and wafer replacement crystal silicon film solar cells on low-cost substrates



Organic PV

Customizing molecules, substrates, and deposition techniques to yield ultra low-cost modules

Next Generation

Investigating advanced concepts [redacted]

[redacted]

Crosscut

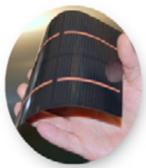
Synergistic technologies, evaluation approaches, and process engineering approaches applicable across multiple absorber materials and processes

Concentrating PV

Combining new, lower cost multijunction cells and innovative optical packages

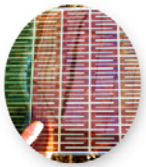
Thin Films (CIGS)

Supporting the manufacture of non-vacuum processes and transferring record efficiency device performance into large area commercial modules



Dye-Sensitized Cells

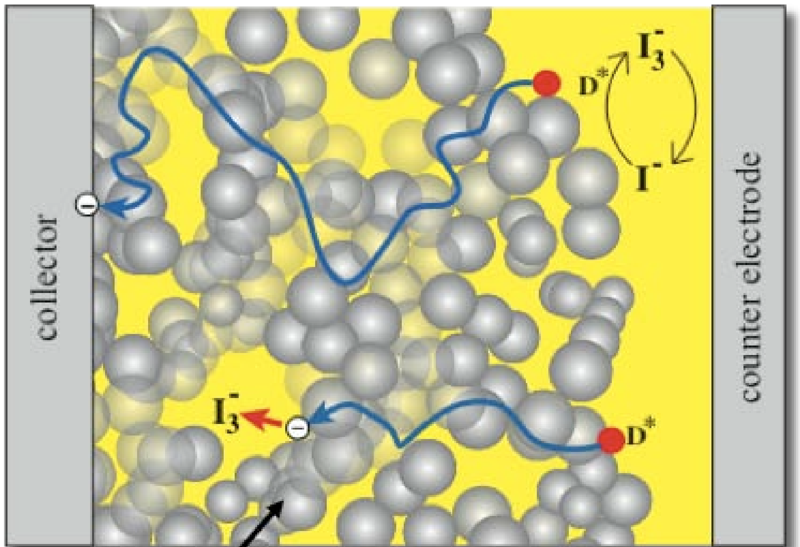
Advancing the efficiency and stability of inexpensive dye-based solar cells with novel nanostructures



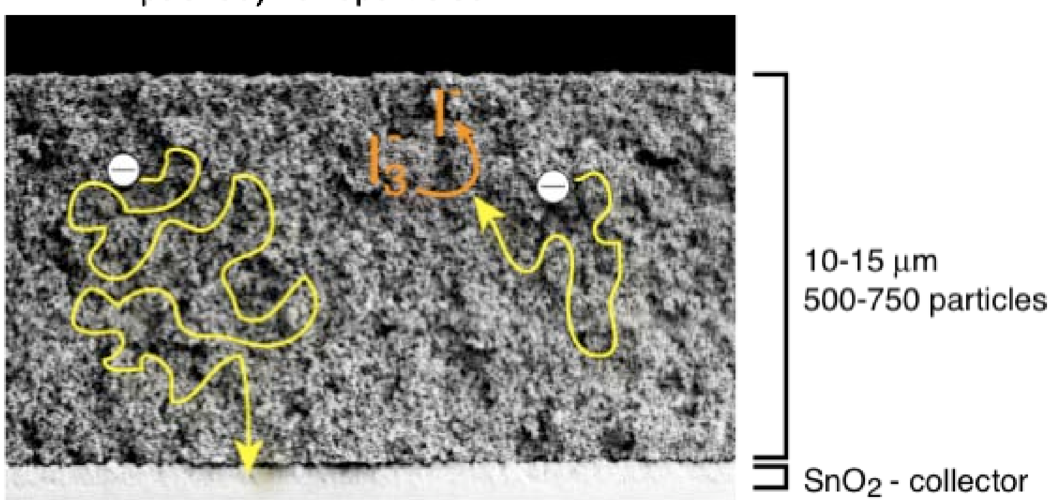
Building Integrated PV

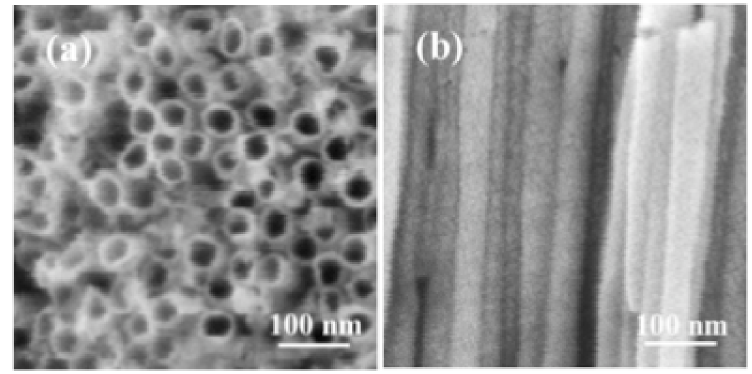
Creating module form factors [redacted]

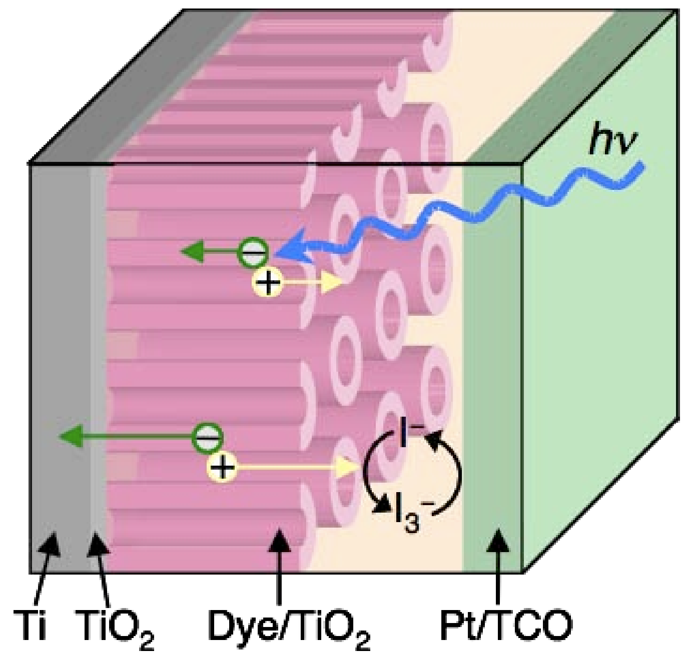
Current Research Moves from Nanoparticles to Nanotubes to Improve Electron Transport



Disordered (randomly packed) nanoparticles

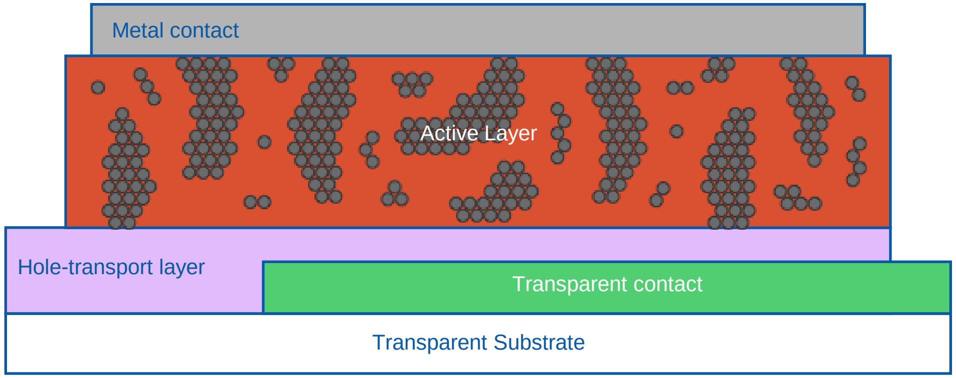






Credits: Art Frank

Typical Bulk Heterojunction Solar Cells Use C-60

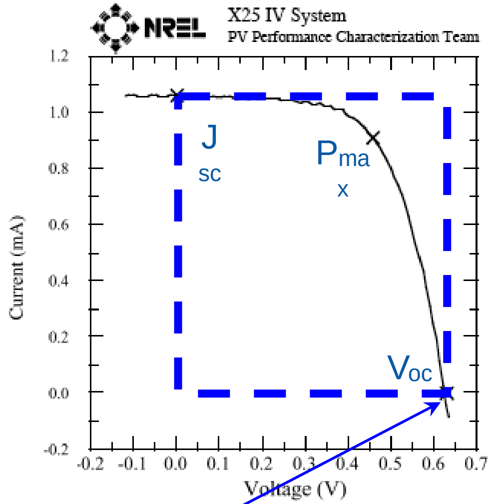


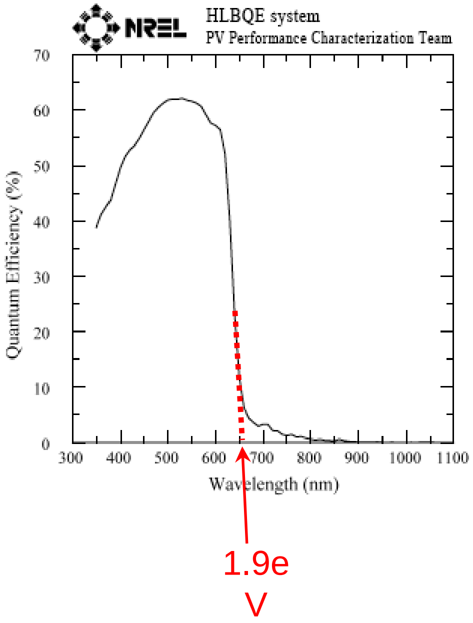
Device ID: 070407mor_A
Jul 05, 2007 11:01
Spectrum: AM1.5 Global

Device Temperature: 25.0 ± 1.0 °C
Device Area: 0.112 cm^2
Irradiance: 1000.0 W/m^2

Sample: 041107mor2-BaA13 #6
Apr 11, 2007 12:45

Temperature = 25.0 ± 2°C
Device Area = 0.1160 cm^2



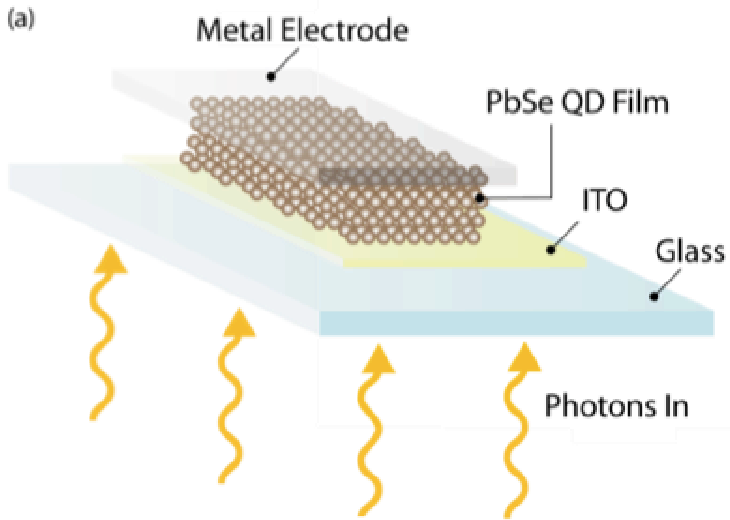


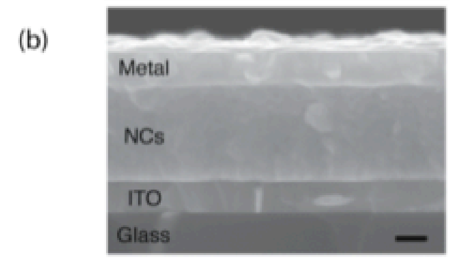
V_{oc} = 0.6268 V
I_{sc} = 1.0578 mA
J_{sc} = 9.411 mA/cm^2
Fill Factor = 62.50 %

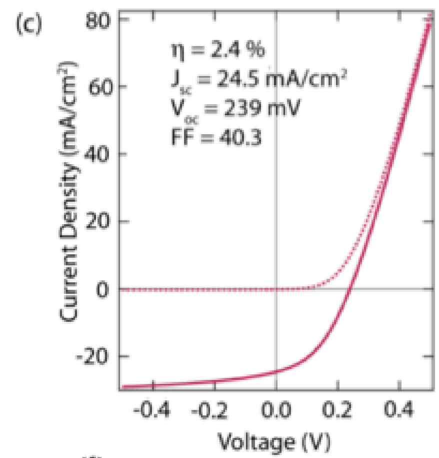
I_{max} = 0.90810 mA
V_{max} = 0.4563 V
P_{max} = 0.41438 mW
Efficiency = 3.69 %

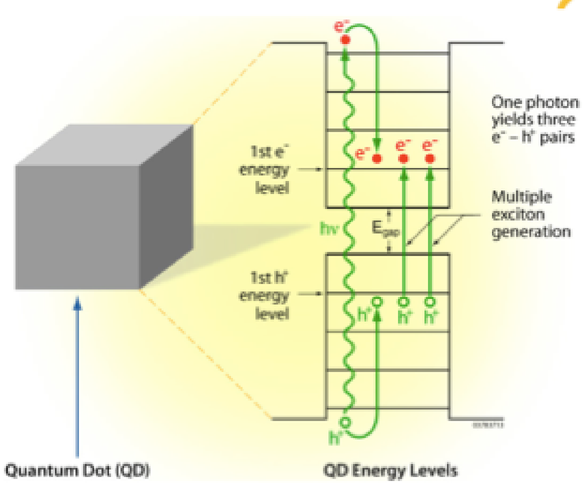
Credits: Matt Reese

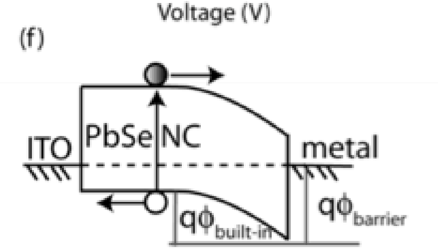
Connecting the Dots: Moving to the 3rd Generation











Credits: Art Nozik, Matt Beard – NREL

Geothermal

Today's Status in U.S.

- 2,800 MWe installed, 500 MWe new contracts, 3000 MWe under development
- Cost 5-8¢/kWh with no PTC
- Capacity factor typically > 90%, base load power

DOE Cost Goals:

- <5¢/kWh, for typical hydrothermal sites
- 5¢/kWh, for enhanced geothermal systems with mature technology

Long Term Potential:

- Recent MIT Analysis shows potential for 100,000 MW installed Enhanced Geothermal Power systems by 2050, cost-competitive with coal-powered generation

NREL Research Thrusts:

- Analysis to define pathways to commercialization of enhanced geothermal systems (EGS)
  Systems engineering/integration to enable fast track development of EGS and other Program goals
  Geothermal energy conversion RD&D
  Low temperature geothermal, direct use, and ground source heat pump RD&D

Biomass Power

Biopower status in U.S.

- 2007 capacity – 10.5 GWe
  - 5 GW Pulp and Paper
  - 2 GW Dedicated Biomass
  - 3 GW MSW and Landfill Gas
  - 0.5 GW Cofiring
- 2004 Generation – 68.5 TWh
- Cost – 8-10¢/kWh

Potential

- Cost – 4-6¢/kWh (integrated gasification combined cycle)
- 2030 – 160 TWh (net electricity exported to grid from integrated 60 billion gal/yr biorefinery industry)

Biofuels

Biofuels

Current Biofuels Status in U.S.

Biodiesel – 171 companies; 2.2 billion gallons/yr capacity[1]

Corn ethanol

- 174 commercial plants[2]
- 10.8 billion gal/yr. capacity[2]
- Additional 2.4 billion gal/yr planned or under construction

Cellulosic ethanol (current technology)

- Projected commercial cost ~$3.50/gge

Key DOE Goals

- 2012 goal: cellulosic ethanol $1.33/ETOH gallon or ~$1.99/gge
- 2022 goal: 36B gal Renewable Fuel; 21B gal “Advanced Renewable Fuel”– 2007 Energy Independence and Security Act
- 2030 goal: 60 billion gal ethanol (30% of 2004 gasoline)

NREL Research Thrusts

- The biorefinery and cellulosic ethanol
- Solutions to under-utilized waste residues
- Energy crops
- New biofuels

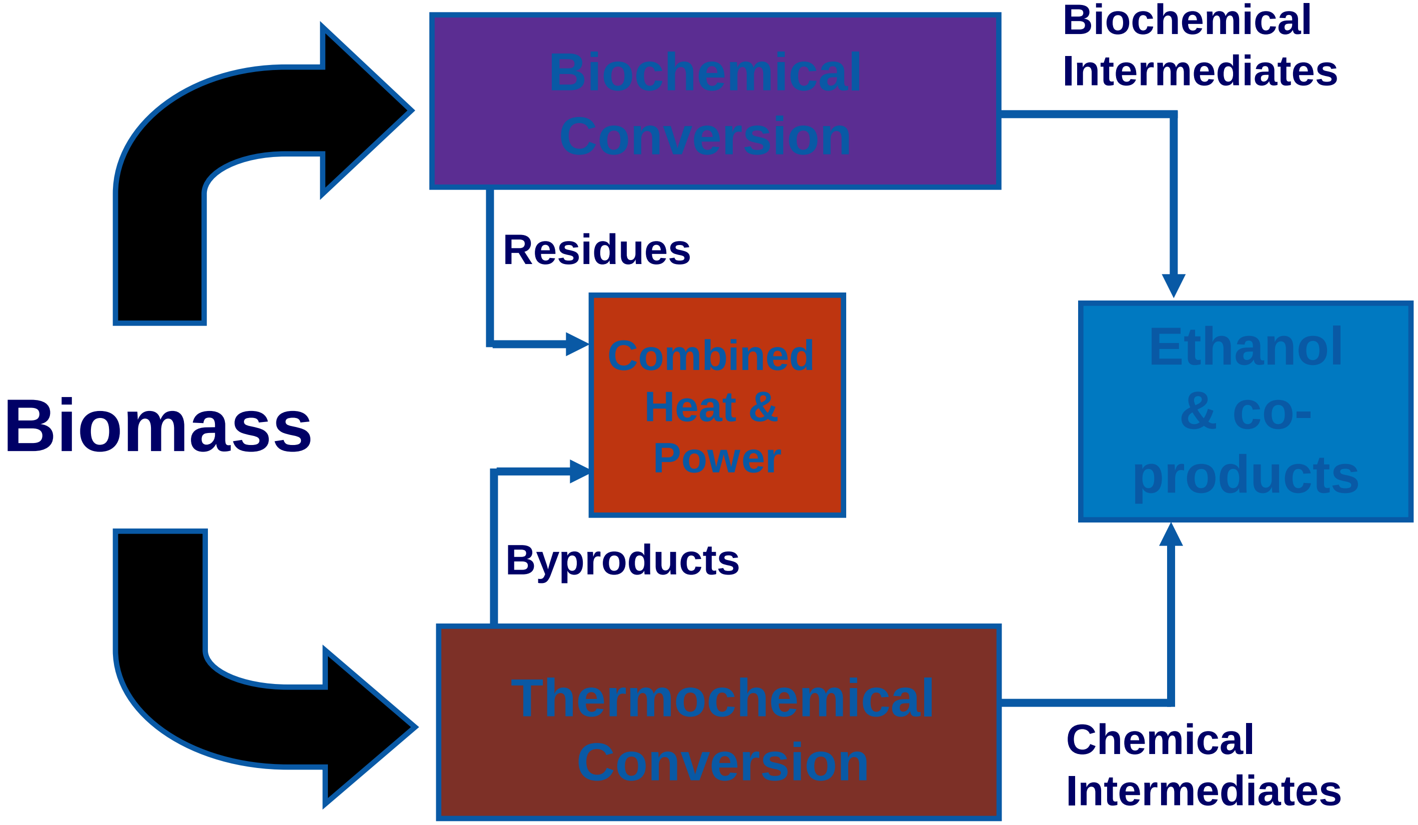
Updated February 2009

Sources: 1- National Biodiesel Board

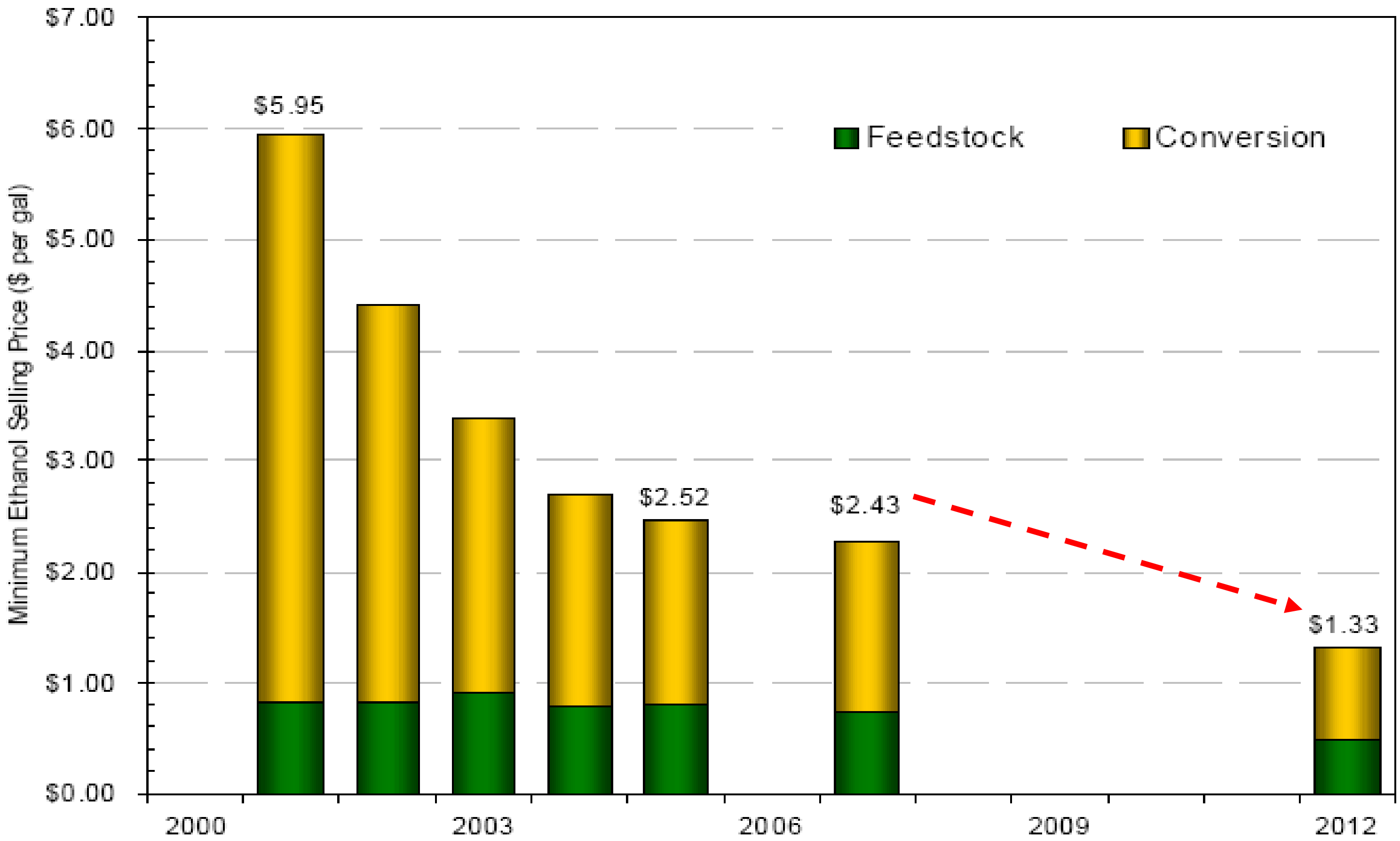
2 - Renewable Fuels Association, all other information based on DOE and USDA sources

Generation 2 (Cellulosic Ethanol)

- **2nd generation—**from lignocellulosic biomass materials, primarily producing ethanol via biochemical or thermochemical conversion

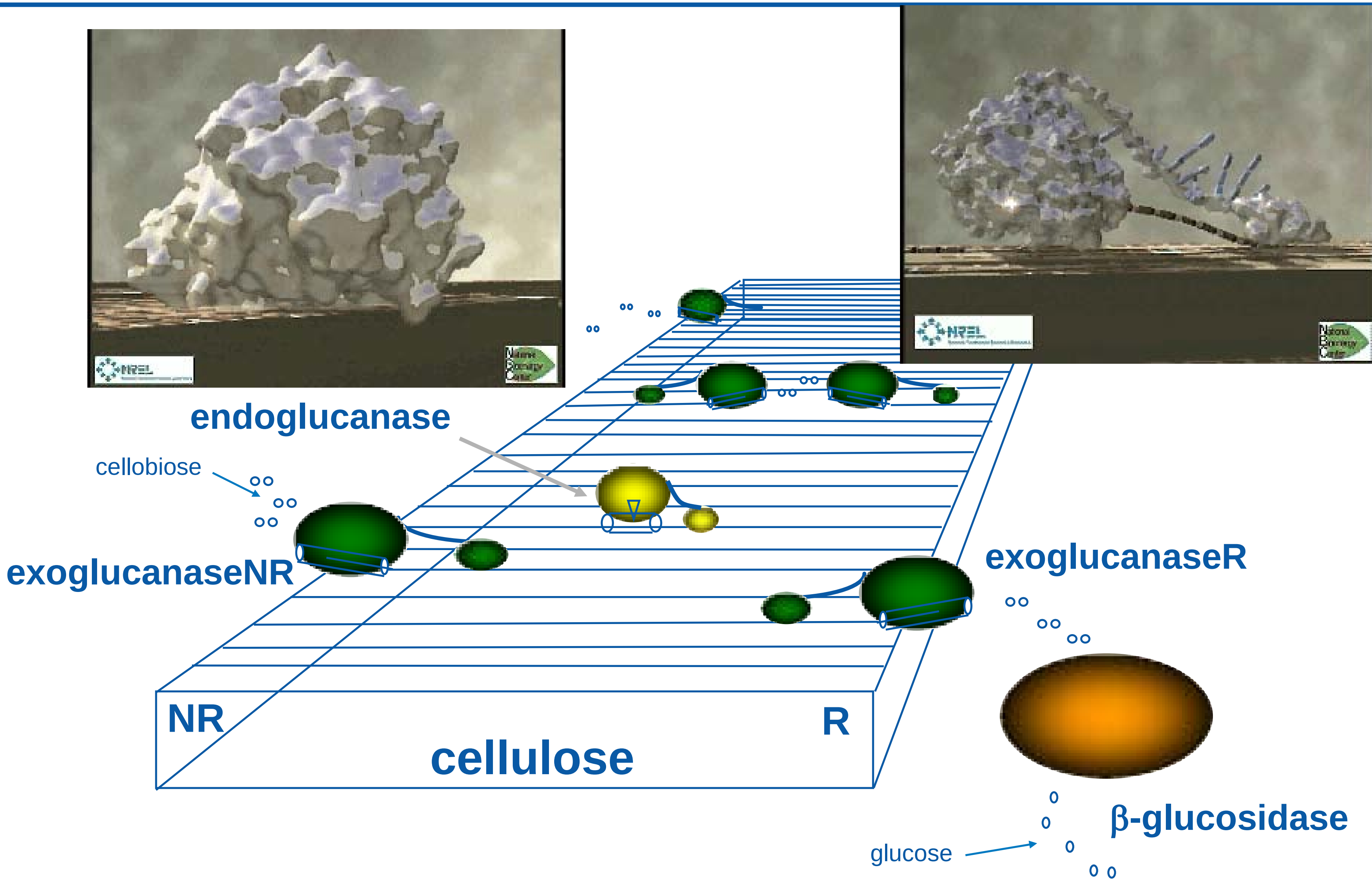


State of Technology—Biochemical Conversion



STATE OF TECHNOLOGY PROGRESS TOWARD THE 2012 GOAL (ESTIMATED 2007 DOLLARS)

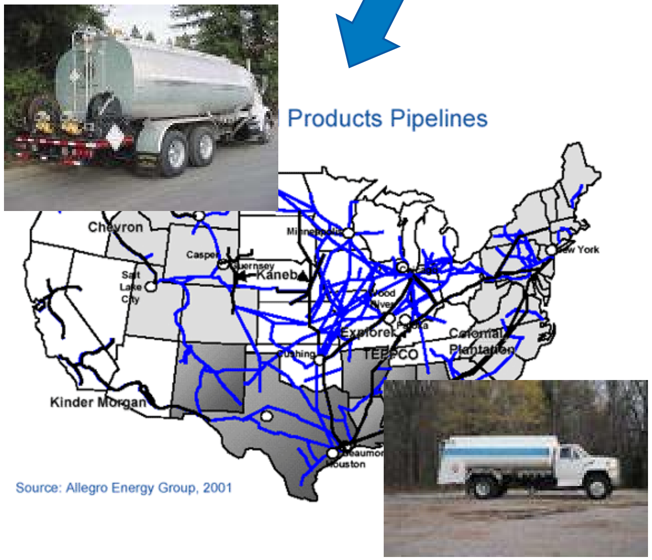
Action of Fungal Cellulases

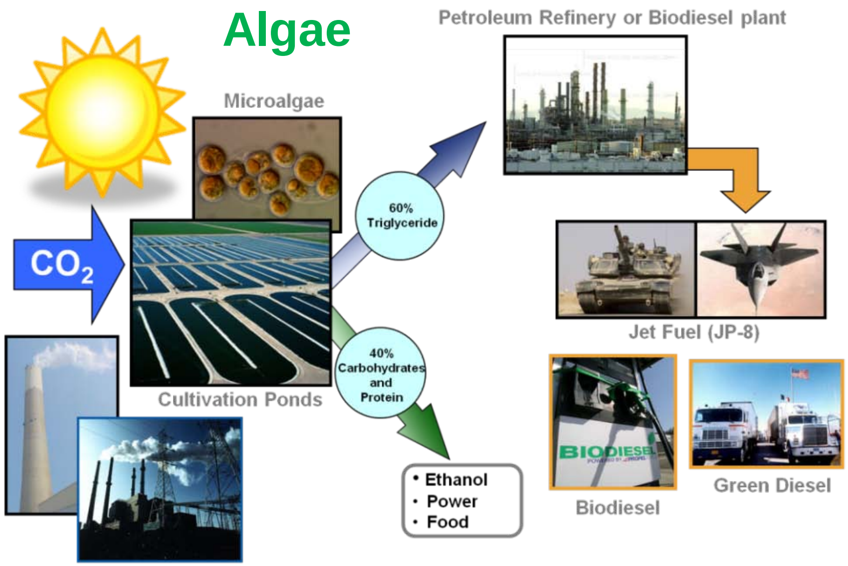


Why Follow-On Generations?

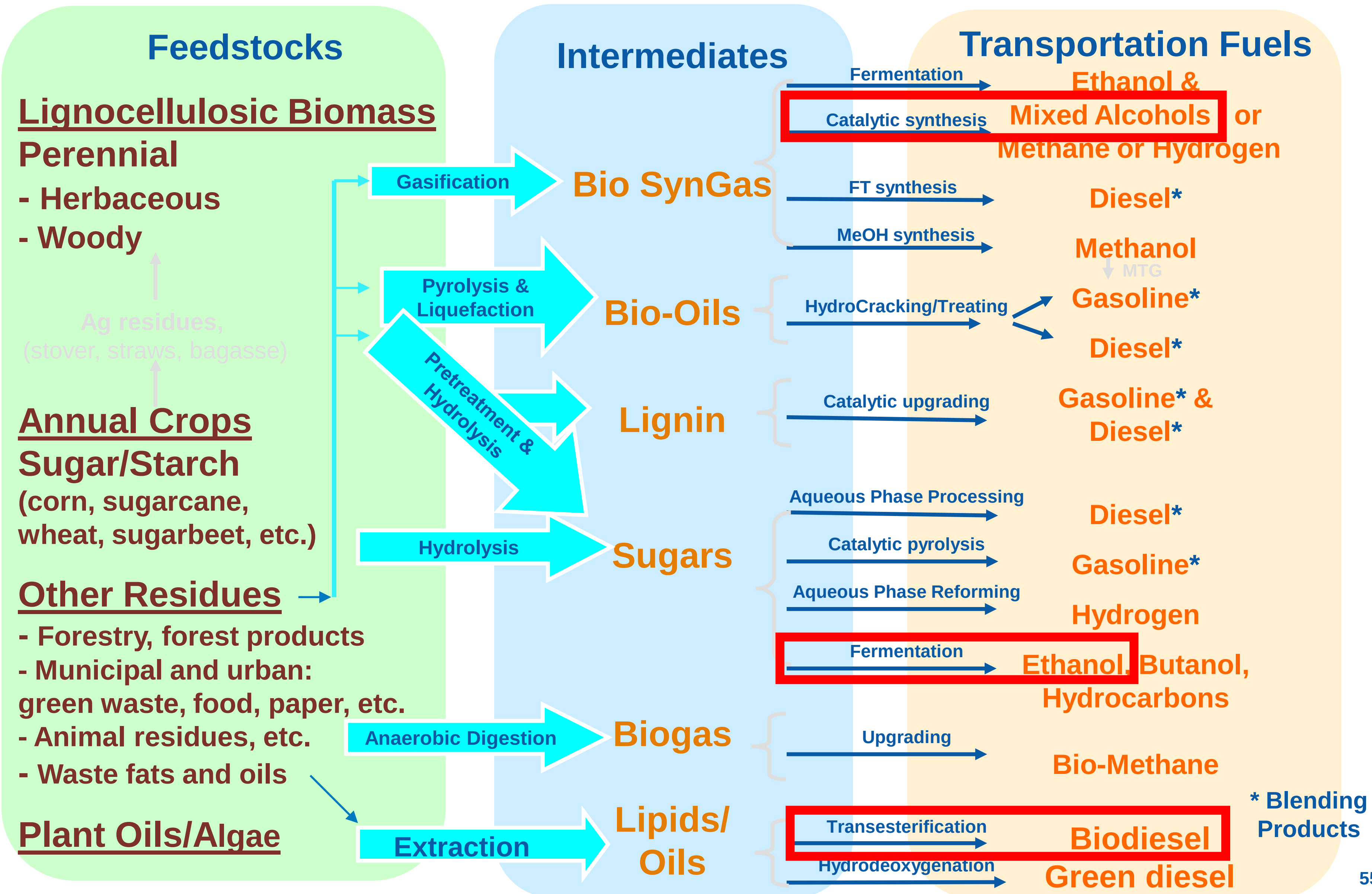
3rd & 4th Generations – “beyond ethanol”

- Higher energy density/suitability
- Better temp and cold start ability
- Energy and tailored feedstocks
- Infrastructure compatibility

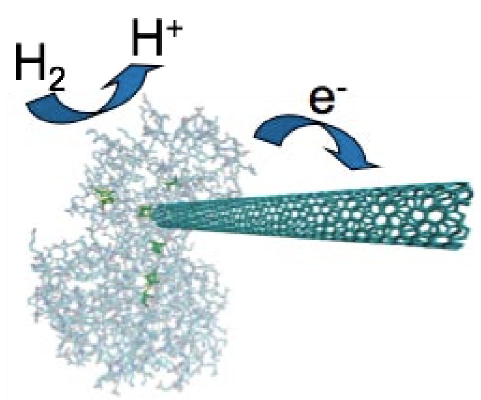




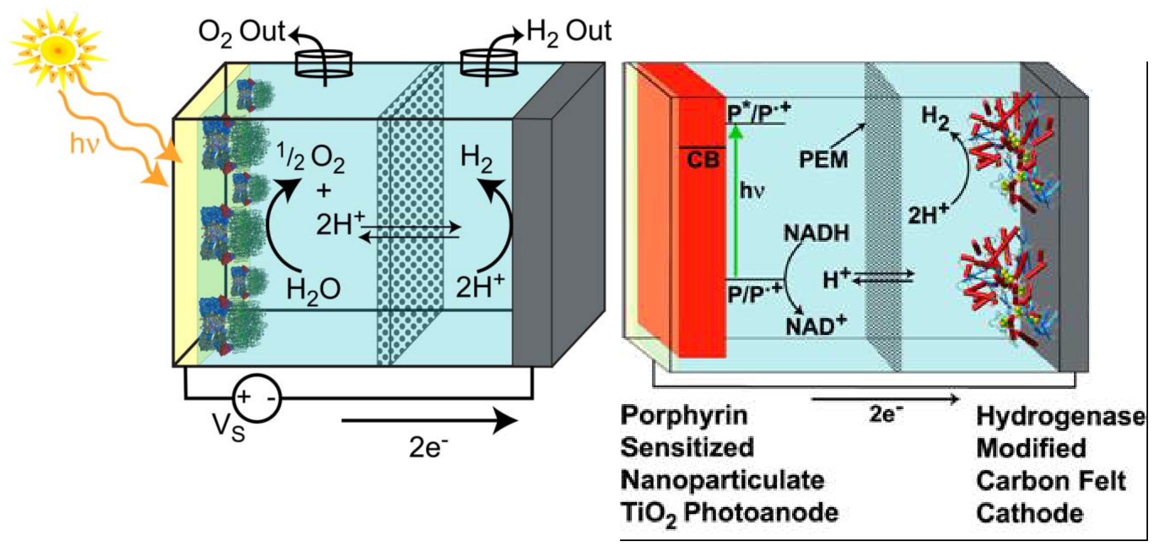
Wide Range of Biofuel Technologies



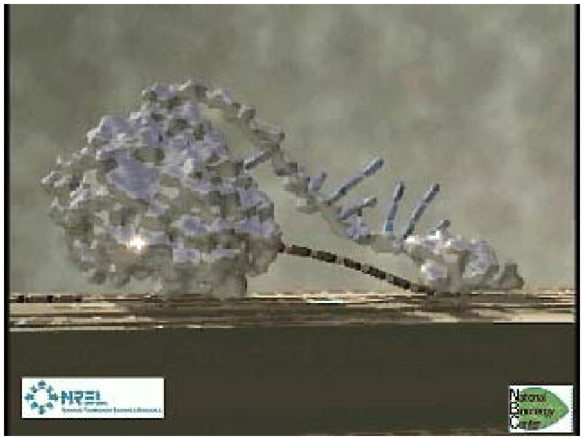
Nanoparticles Can Also Be Used to Make Fuels (and Energy Carriers)



Wiring up hydrogenase



Photobiohybrid H2-Production Processes



Fungal Cellulases

Credits: Paul King, Maria Ghirardi, Mike Himmel – NREL

Sustainable Transportation

Plug-In Hybrid Electric Vehicles (PHEV)

Status:

- PHEV-only conversion vehicles available
- OEMS building prototypes
- NREL PHEV Test Bed

NREL Research Thrusts

- Energy storage
- Advanced power electronics
- Vehicle ancillary loads reduction
- Vehicle thermal management
- Utility interconnection
- Vehicle-to-grid

Key Challenges

- Energy storage – life and cost
- Utility impacts
- Vehicle cost
- Recharging locations
- Tailpipe emissions/cold starts
- Cabin heating/cooling
- ~33% put cars in garage

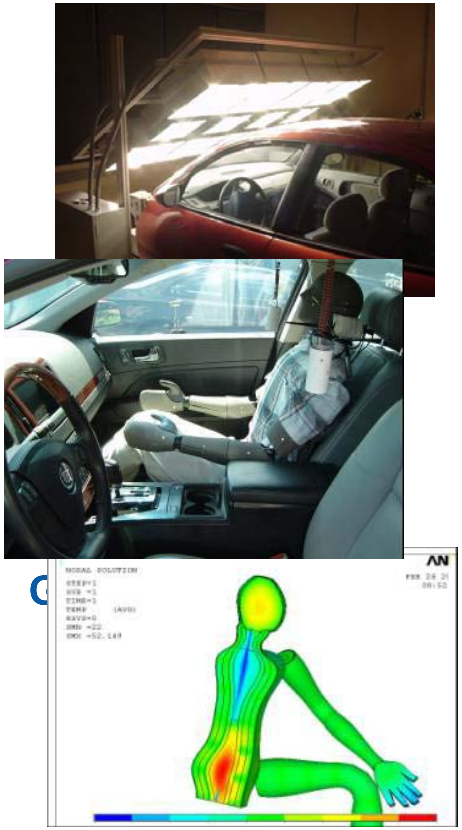
Advanced Vehicle Technologies

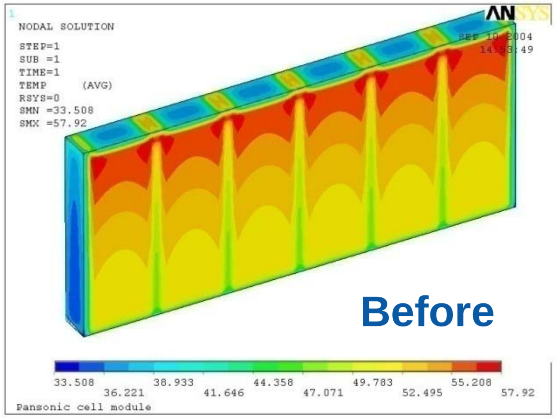
Energy Storage

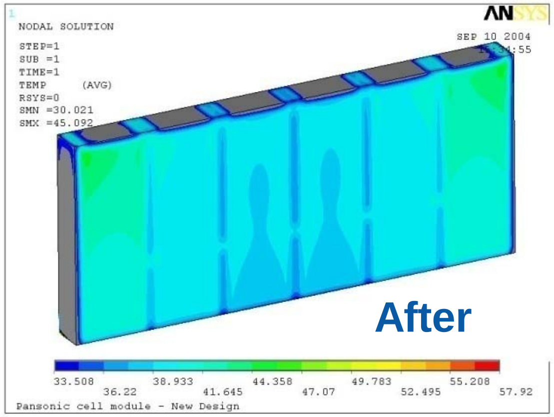
UltraCaps

Advanced Power Electronics

Vehicle Ancillary Loads Reduction







Fuels Performance

Coordinating Research Council
- FACE
- Biodiesel Stability
- E10/E20/E85

Fuels Chemistry Lab
- Test Methods
- Impurities
- Chemical analysis

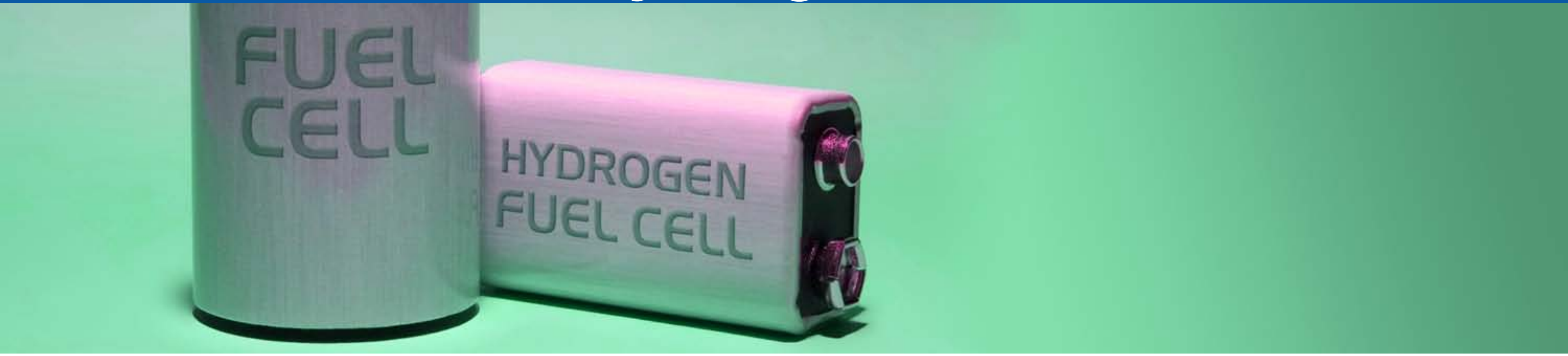
Fuel Surveys
- Biodiesel
- E85

ASTM
- Specs & Test Method Development
- Biodiesel
- E85

NBB CRADA - Biodiesel
- Quality/Stability
- Compatibility with Emission Controls
- Real-World Evaluation

IQT Projects
- Fundamental Ignition Studies
- Pollutant formation
- FACE Fuels Testing

Hydrogen and Fuel Cells



Hydrogen and Fuel Cells

U.S. Status

- 400+ fuel cell vehicles on the road
- 58 hydrogen fueling stations

Goals

Hydrogen Production

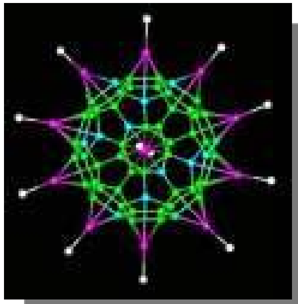
- $2-3/Kg for all pathways
- Renewables in $5-10/Kg range

Fuel Cells

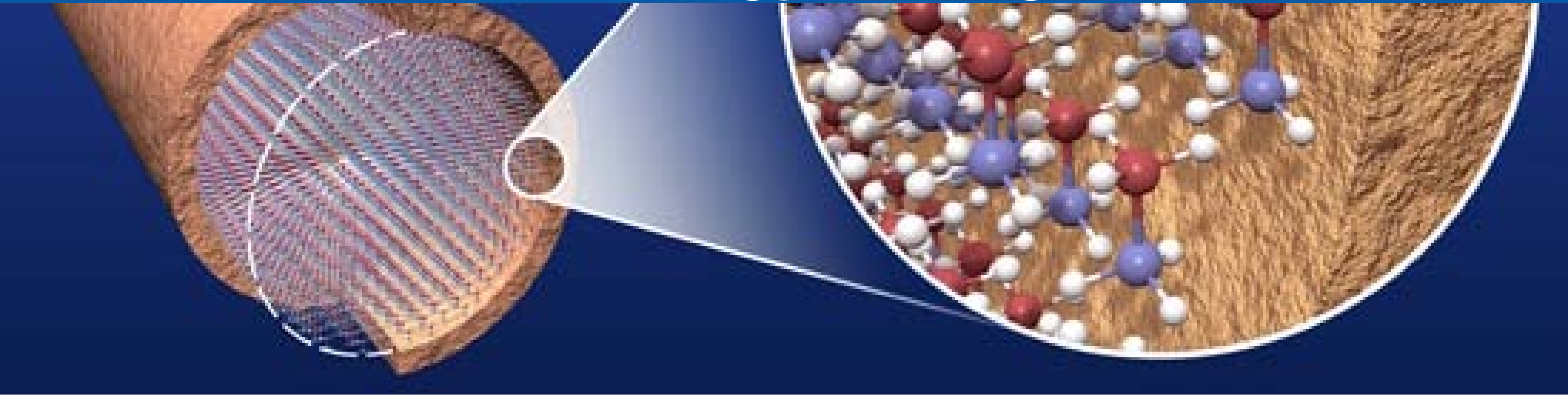
- $30/kW by 2015
- 5,000 hour stack life

NREL Research Thrusts

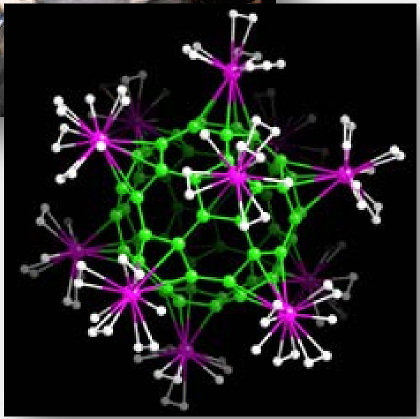
- Renewable H2 production
- Safety/codes/standards
- Early market introduction



Energy Storage



Designer Nanostructured Materials are Critical to Enabling Energy Storage Systems for Renewables



Organometallic Buckyballs for Hydrogen Storage

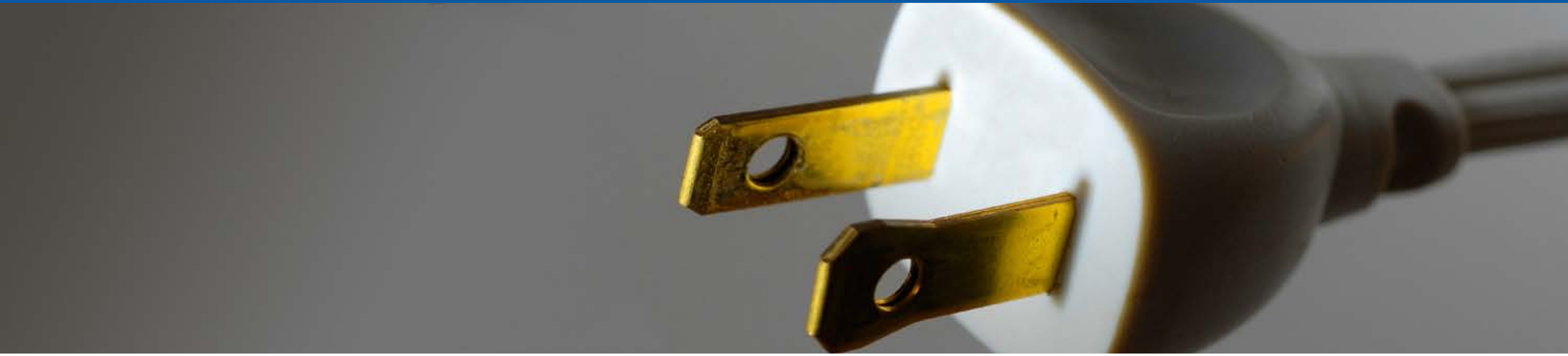
State-of-the-art processing to create novel nanomaterials for energy storage:

- Hydrogen storage: porous carbons, boro-carbons, metcars, macromolecules
- Batteries: novel electrolytes and metal oxides for cathodes and anodes
- Ultracapacitors: nanotubes and high dielectric materials
- Dynamic smart windows

NREL leads DOEs hydrogen sorption Center of Excellence

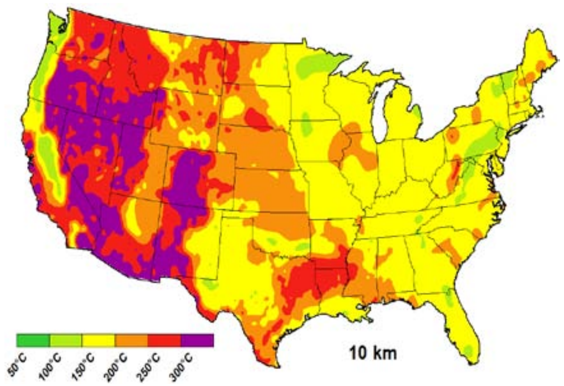
- Develops high surface area, low-weight and low-cst materials
- 15 projects: 4 national labs, 10 universities, and on industrial parnter

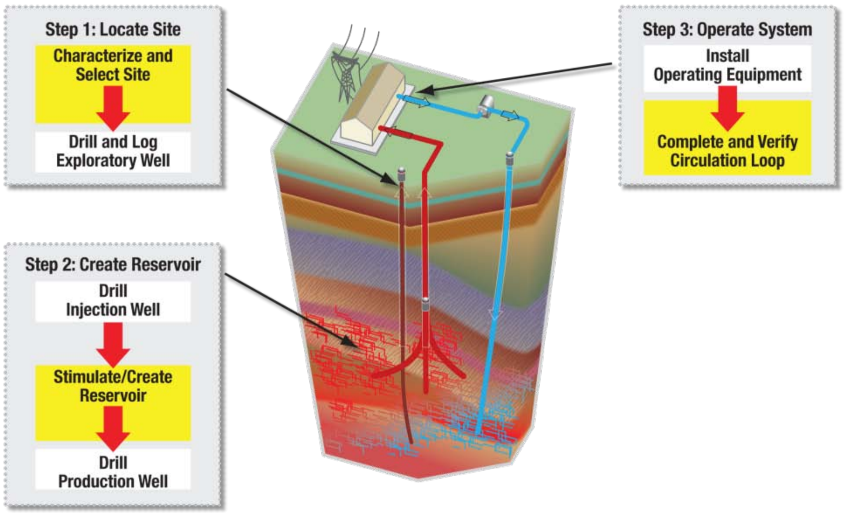
New Directions



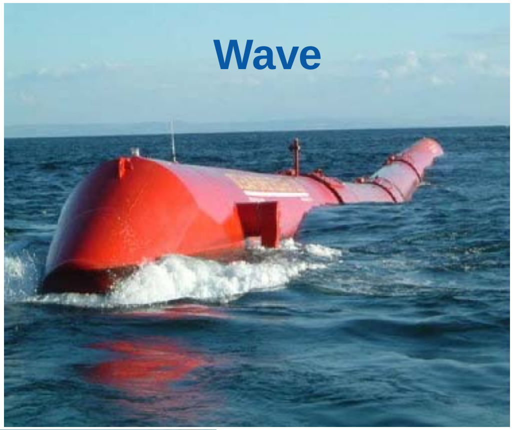
Evaluating Potential New Directions

Enhanced Geothermal Systems





Ocean Kinetic Energy



Pelamis—Ocean Power Delivery

Tidal

Verdant—Power RITE Turbine

Enhanced Geothermal Systems Challenges

Technical

Site selection - exploration techniques for EGS

– EGS paradigm shift from hydrothermal

Creating EGS in variety of geologic environments

– Create a subsurface fracture system to enable extraction of heat
  - Sufficient flow rates (80 kg/sec)
  - Heat exchange volume (recoverable energy) and surface area (recovery rate)
  - Minimal loss of injected fluid

Few EGS field experiments yet conducted worldwide

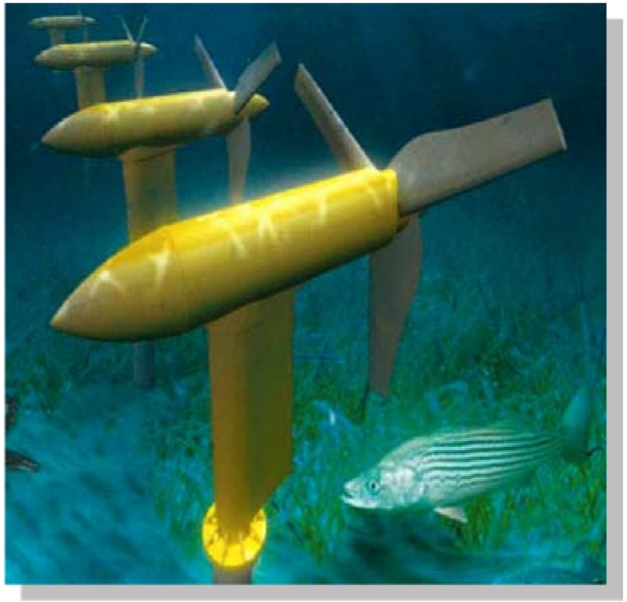
– Experimental evidence of EGS well productivity, heat exchange volume, and longevity is lacking

Geologic variability and uncertainty create technical challenges

FY09 NREL Water Program

Market Development and Transformation

- International Collaborations and Standards
- Technical Support
- Industry Technology Support



Industry Status

- New industry extracting power from natural Ocean and River Currents, Tidal, Wave, and Thermal energy

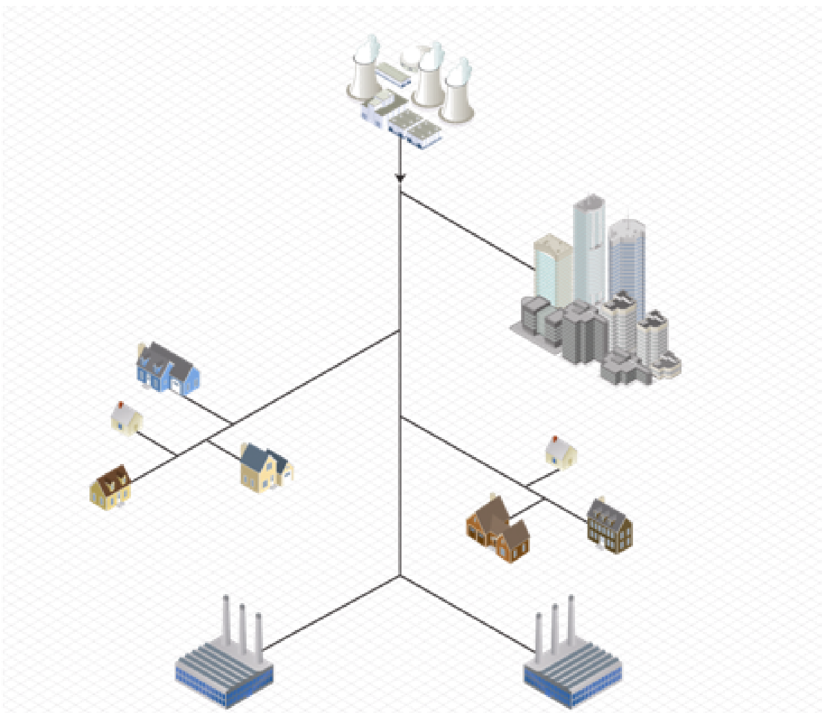
Water Power Mission

Assess the potential of extractable energy from water resources and facilitate the development and deployment of renewable, environmentally-friendly, and cost-effective energy systems from domestic rivers, estuaries and coastal waters

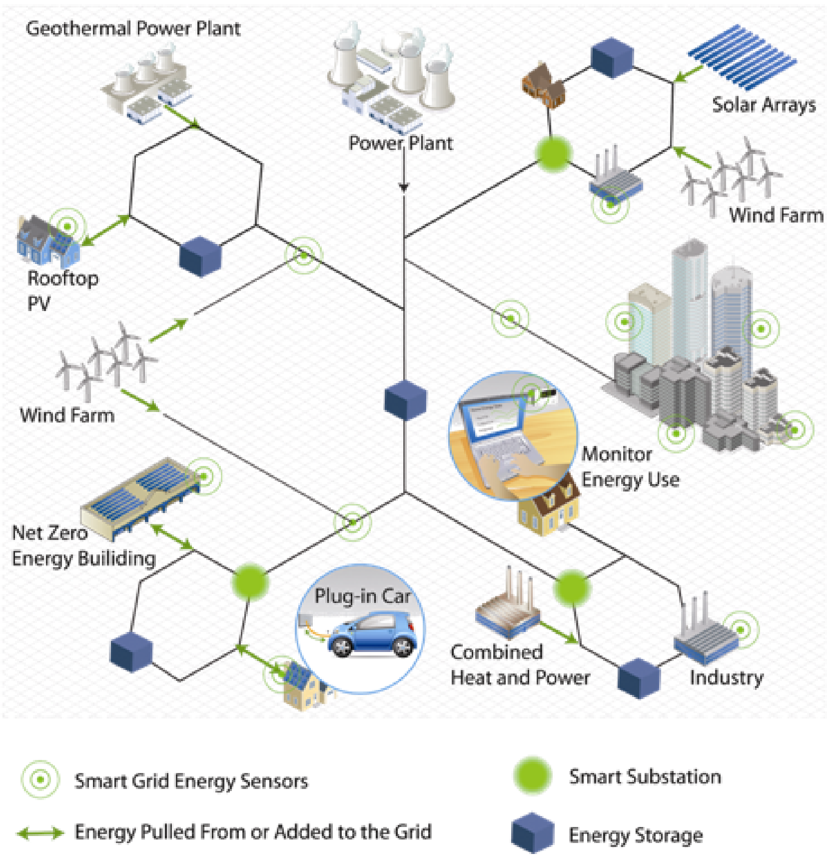
Include R&D for economic and environmental improvements to existing hydroelectric facilities and dams

Smart Grid – Renewable Energy Integration in Systems at All Scales

Today



Future



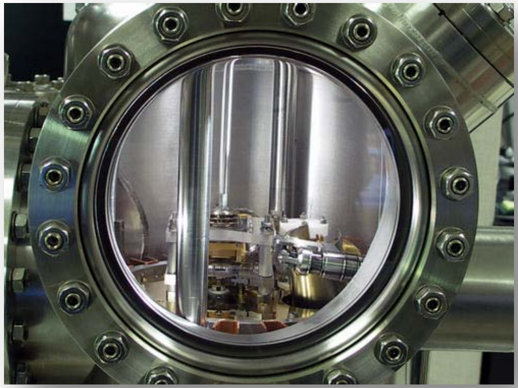
Energy Solutions Require a New Approach

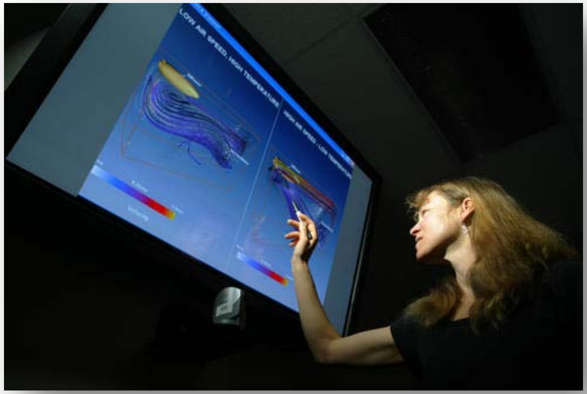
Multi-disciplinary/multi-institutional collaboration

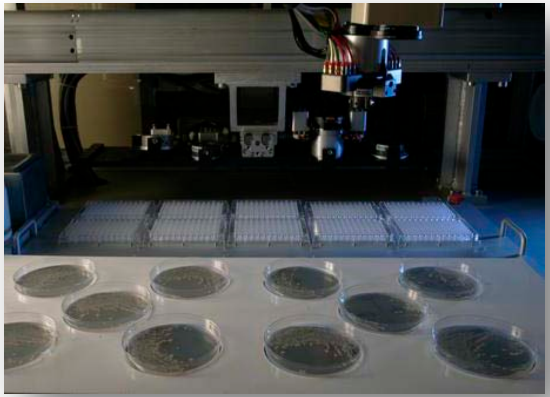
- Chemistry, materials science
- Computational modeling
- Biology

Translational science—bridge basic to applied

Revolutionary opportunities at the nano-scale







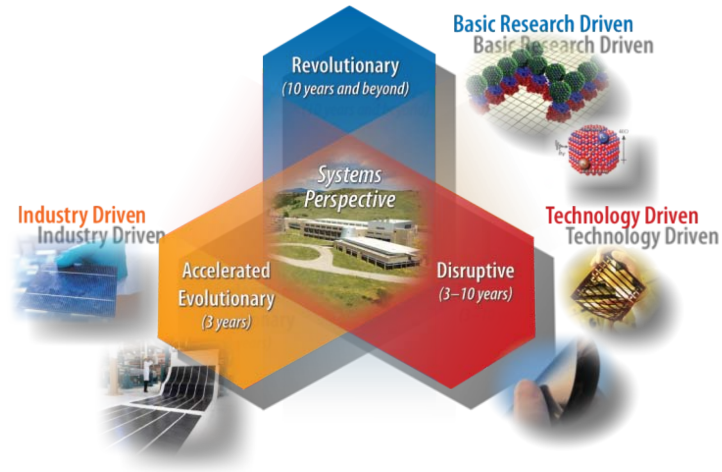
Breakthough/Translational Science

Bioscience Centers

Energy Frontiers

Energy Innovation Hubs

ARPA-E



An Integrated Approach is Required

Making Transformational Change

The opportunity for making renewable energy transformational change is now before us as a solution to a global crisis.

We must seize the moment.

NREL National Renewable Energy Laboratory

Innovation for Our Energy Future

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