PV: Global Perspective for a Sustainable Future

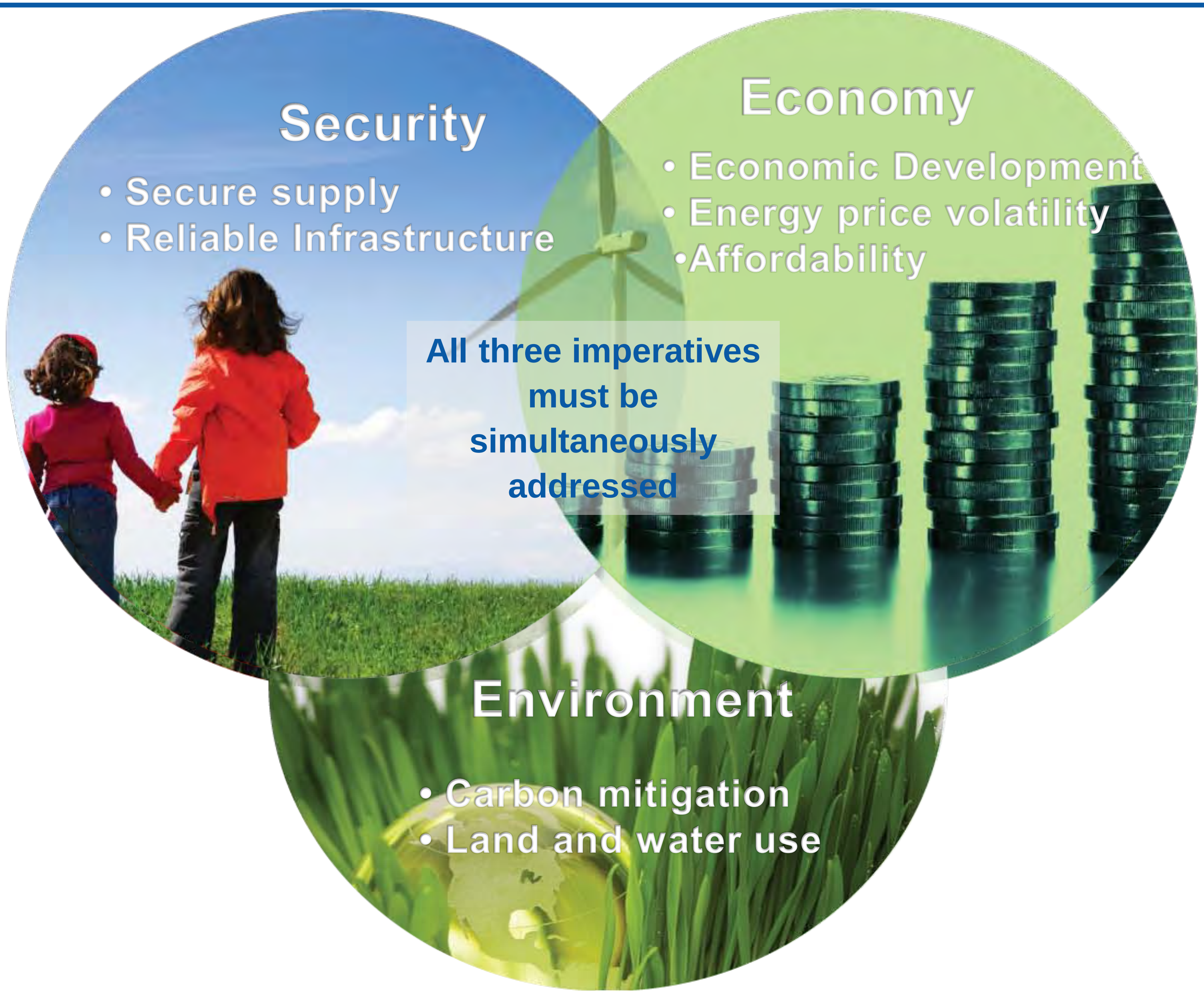
October 14, 2011

Scialog 2011

Dr. Dan E. Arvizu

Laboratory Director

Energy Challenges

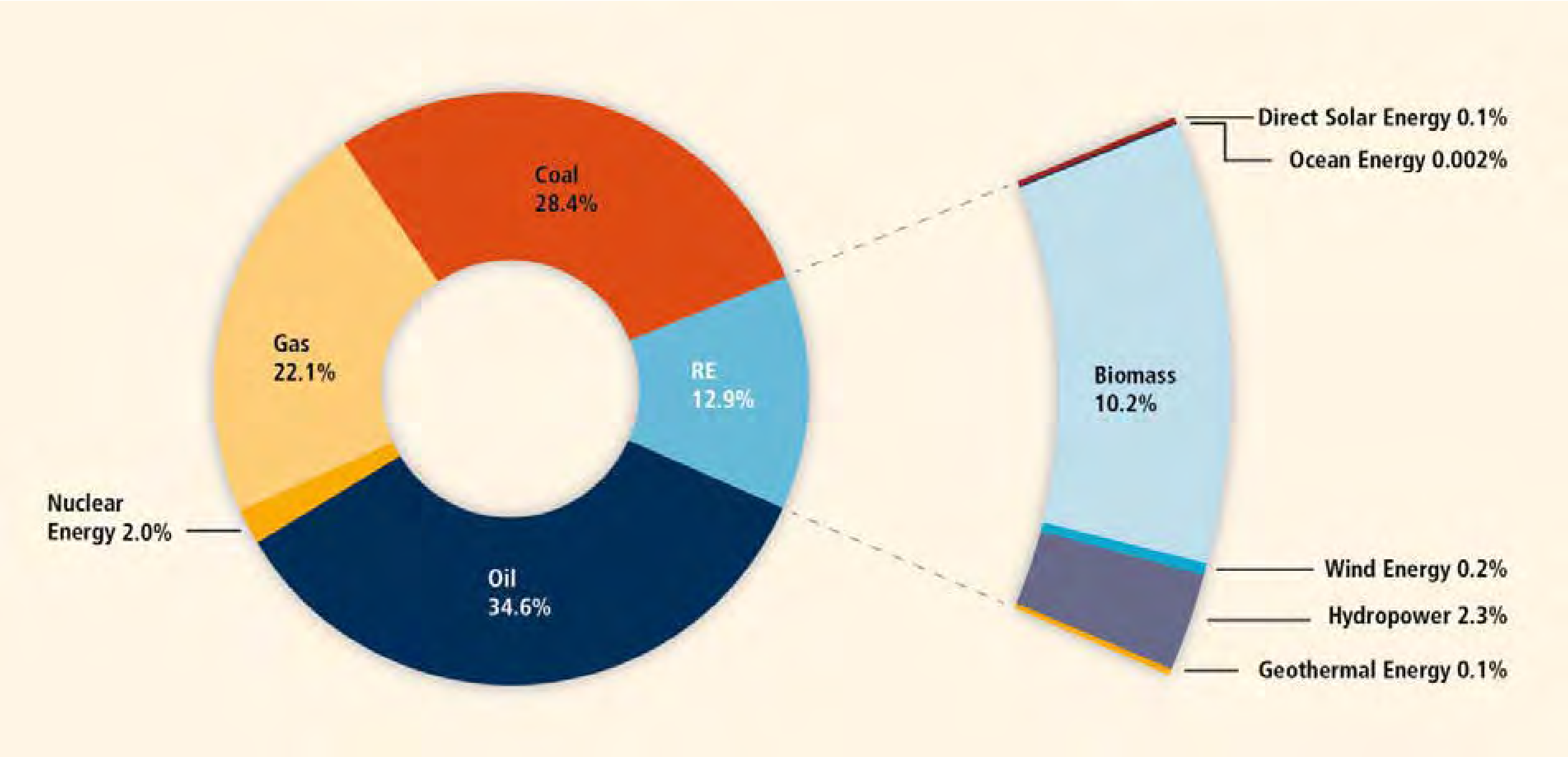


"When we put a priority on renewable energy we address job creation, we address climate change, women's empowerment and food security. Sustainable energy cuts across nearly every major challenge we face today and will face in the future."

—U.N. Secretary General Ban Ki-moon at NREL, August 25, 2011

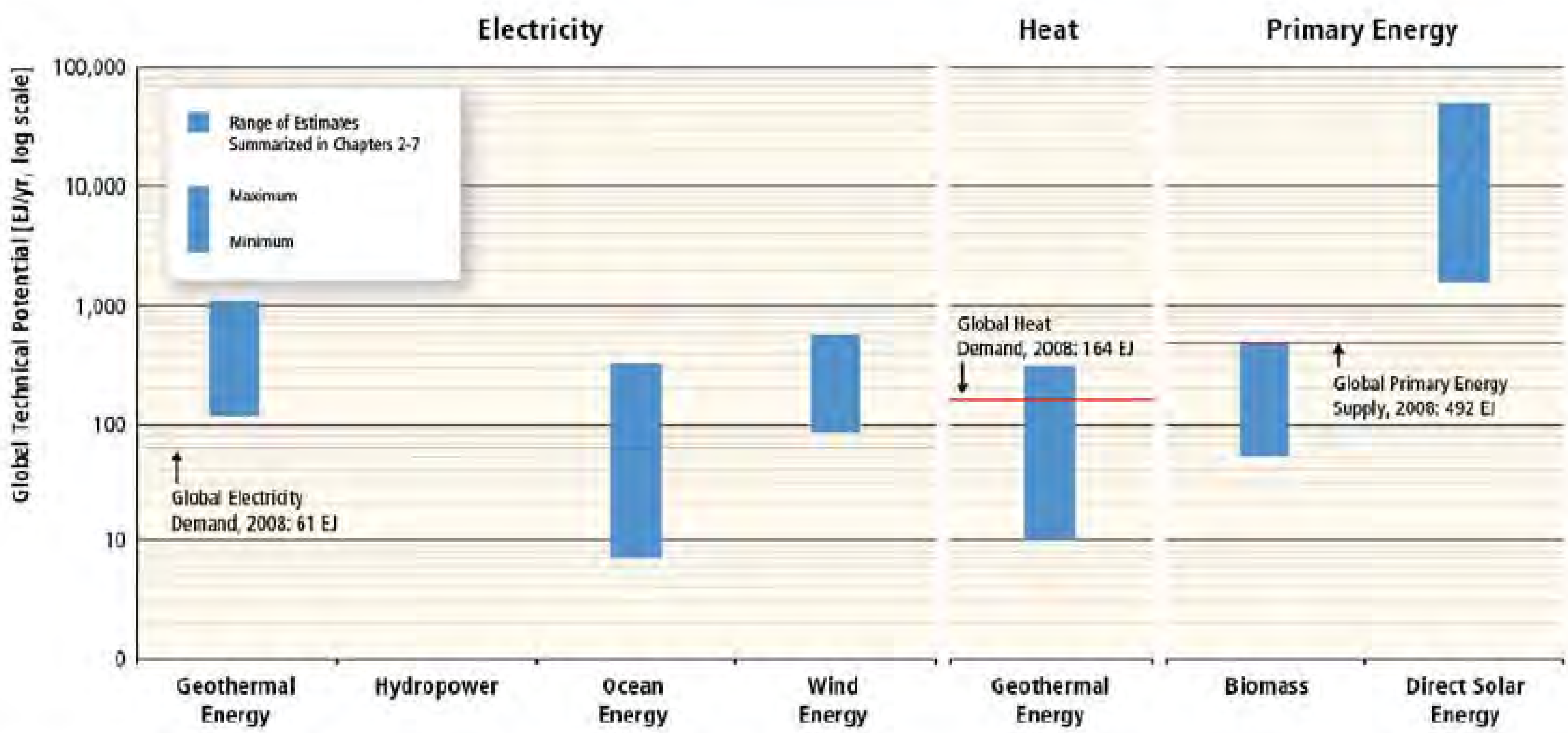
The global context

Shares of energy sources in total global primary energy supply in 2008



Source: IPCC Special Report Renewable Energy Sources (SRREN)

Ranges of global technical potentials of RE sources

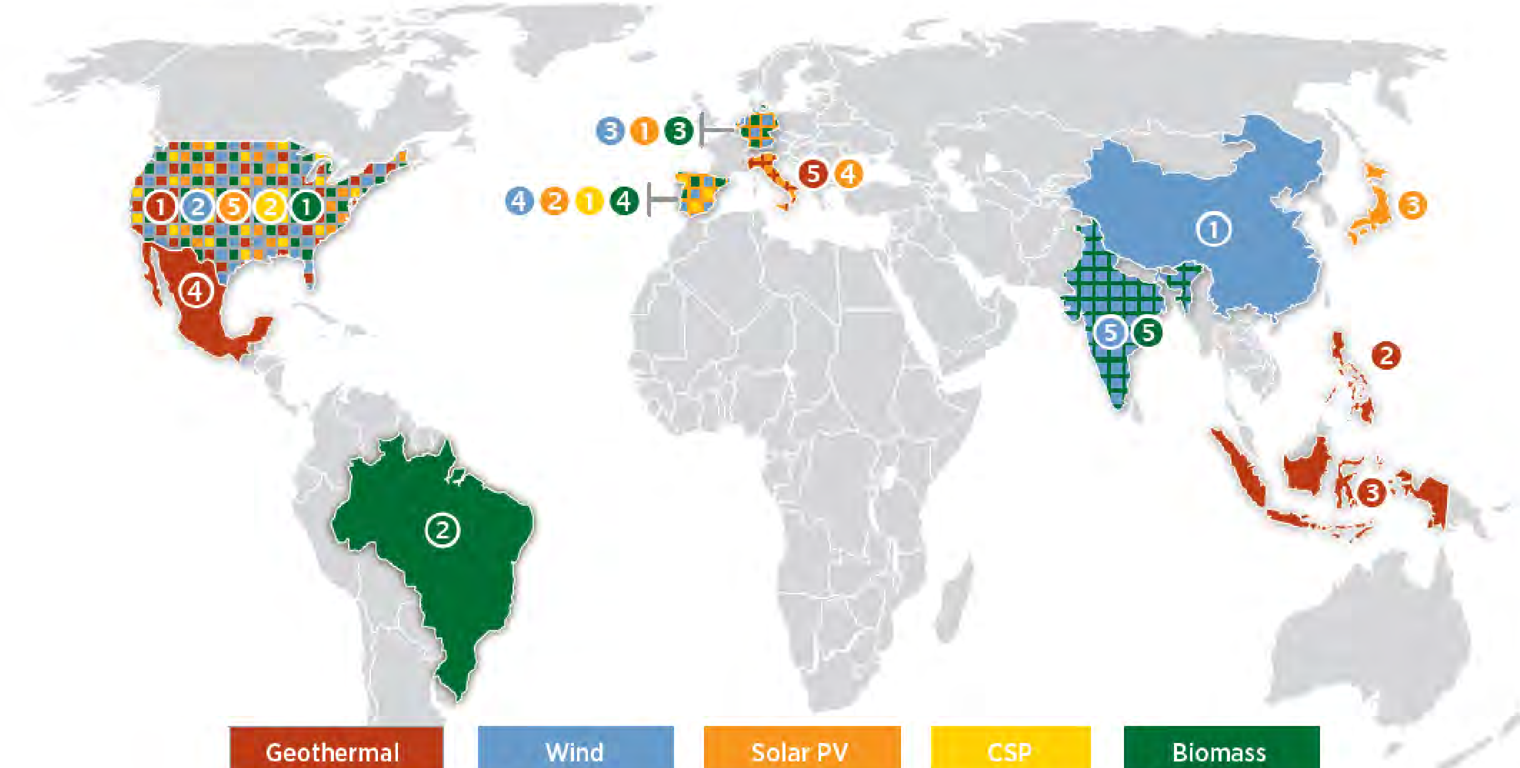


Range of Estimates of Global Technical Potentials

	Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Geothermal Energy	Biomass	Direct Solar Energy
Max (in EJ/yr)	1109	52	331	580	312	500	49837
Min (in EJ/yr)	118	50	7	85	10	50	1575

Source: IPCC Special Report Renewable Energy Sources (SRREN)

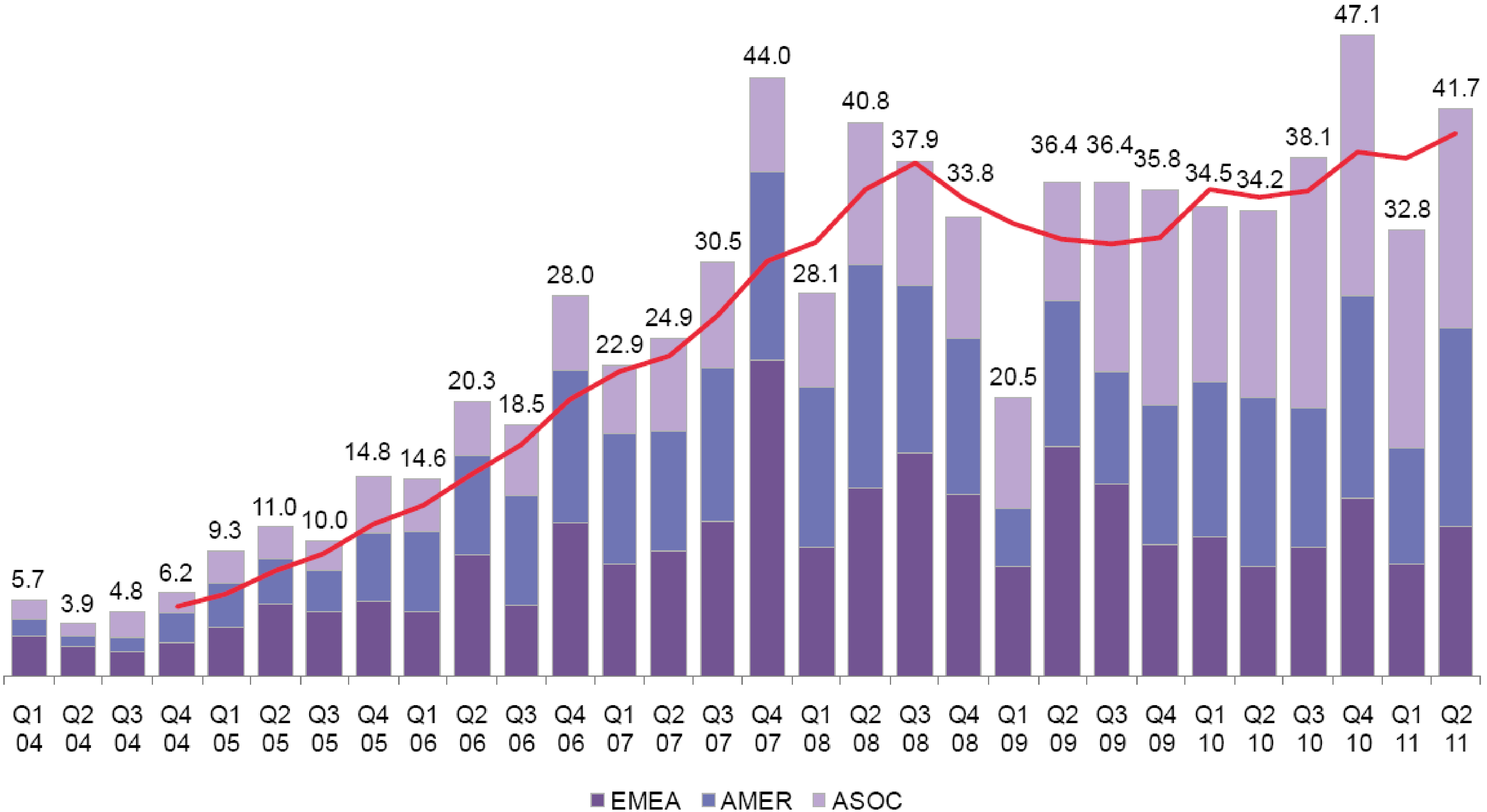
Top Countries with Installed Renewable Electricity by Technology (2010)



Geothermal	Wind	Solar PV	CSP	Biomass
1 U.S.	1 China	1 Germany	1 Spain	1 U.S.
2 Philippines	2 U.S.	2 Spain	2 U.S.	2 Brazil
3 Indonesia	3 Germany	3 Japan		3 Germany
4 Mexico	4 Spain	4 Italy		4 Spain
5 Italy	5 India	5 U.S.		5 India

Sources: REN21, GWEC, SEIA/GTM

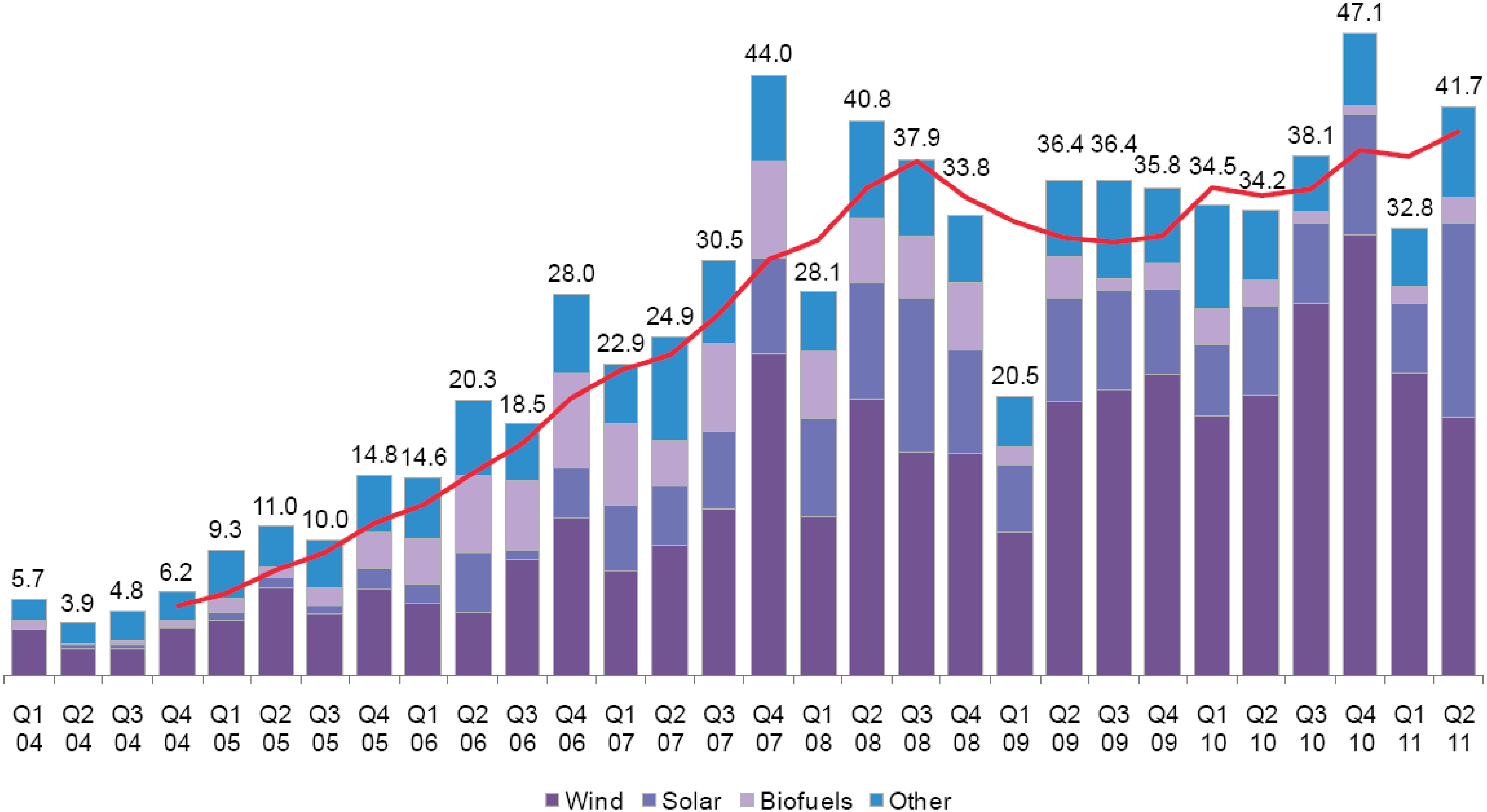
New Financial Investment in Clean Energy by Region Q1 2004-Q2 2011 ($Bn)



Note: Excludes corporate and government R&D, and small distributed capacity. Not adjusted for re-invested equity

Source: Bloomberg New Energy Finance

New Financial Investment in Clean Energy by Sector Q1 2004-Q2 2011 ($Bn)



Note: Excludes corporate and government R&D, and small distributed capacity. Not adjusted for re-invested equity

Source: Bloomberg New Energy Finance

The Role for Clean Energy—A Decade of Real Progress

Wind power capacity increased by more than **a factor of 10 to more than 200 GW.**

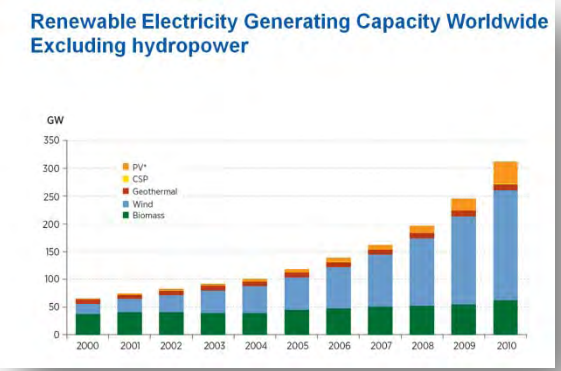
Solar PV global installed capacity **grew by factor of almost 30** to about 35 GW in 2010.

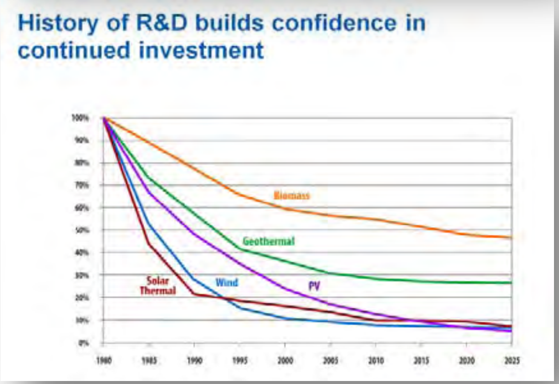
Biofuels emerged as a **major global industry** (~28 billion gallons/year)

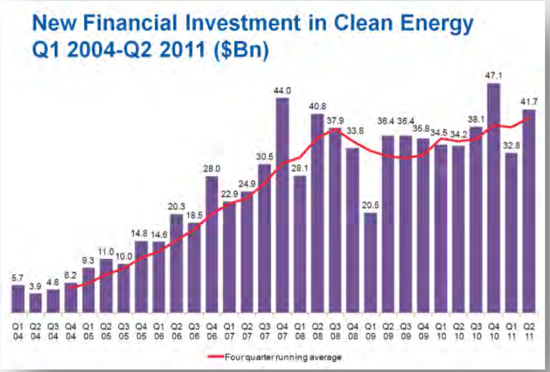
LEED-certified commercial buildings grew to more than 10,000

Costs have been significantly reduced and are **approaching grid parity**

Clean energy grew from $1B/year to a **$211B/year market**

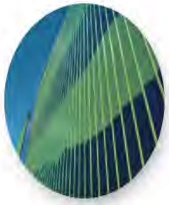






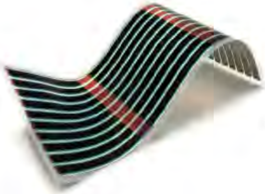
The promise of the technology: A look at solar PV

PV Conversion Technology Portfolio



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 aimed at delivering revolutionary performance improvements

Crystalline Silicon

Developing higher efficiency devices and lower cost processing methods for traditional silicon cells

Concentrating PV

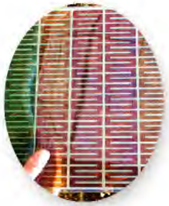
Combining new, lower cost multijunction cells and innovative optical packages

Thin Films (CIGS)

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

Dye-Sensitized Cells

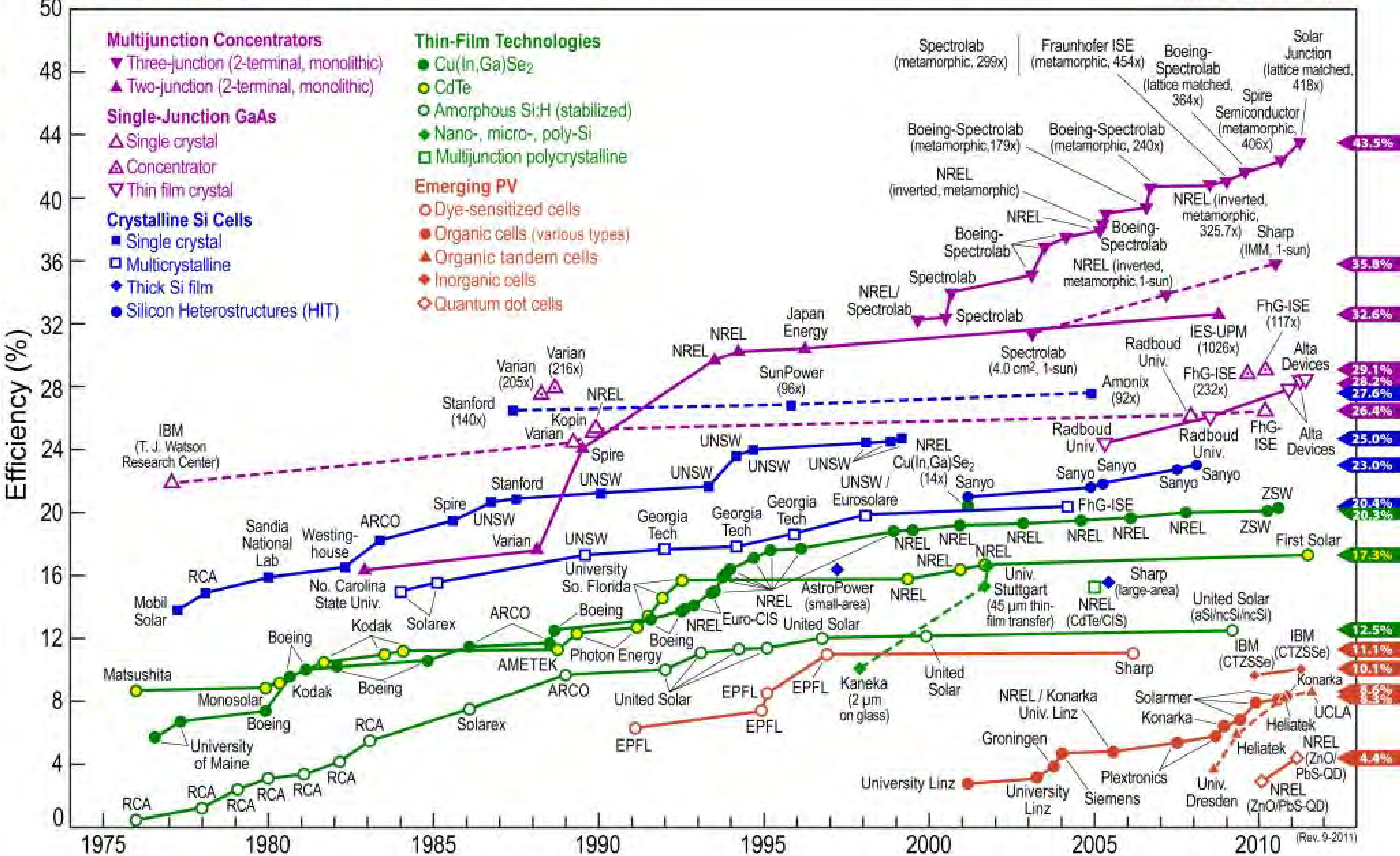
Advancing the efficiency and stability of inexpensive dye-based solar cells with novel nanostructures



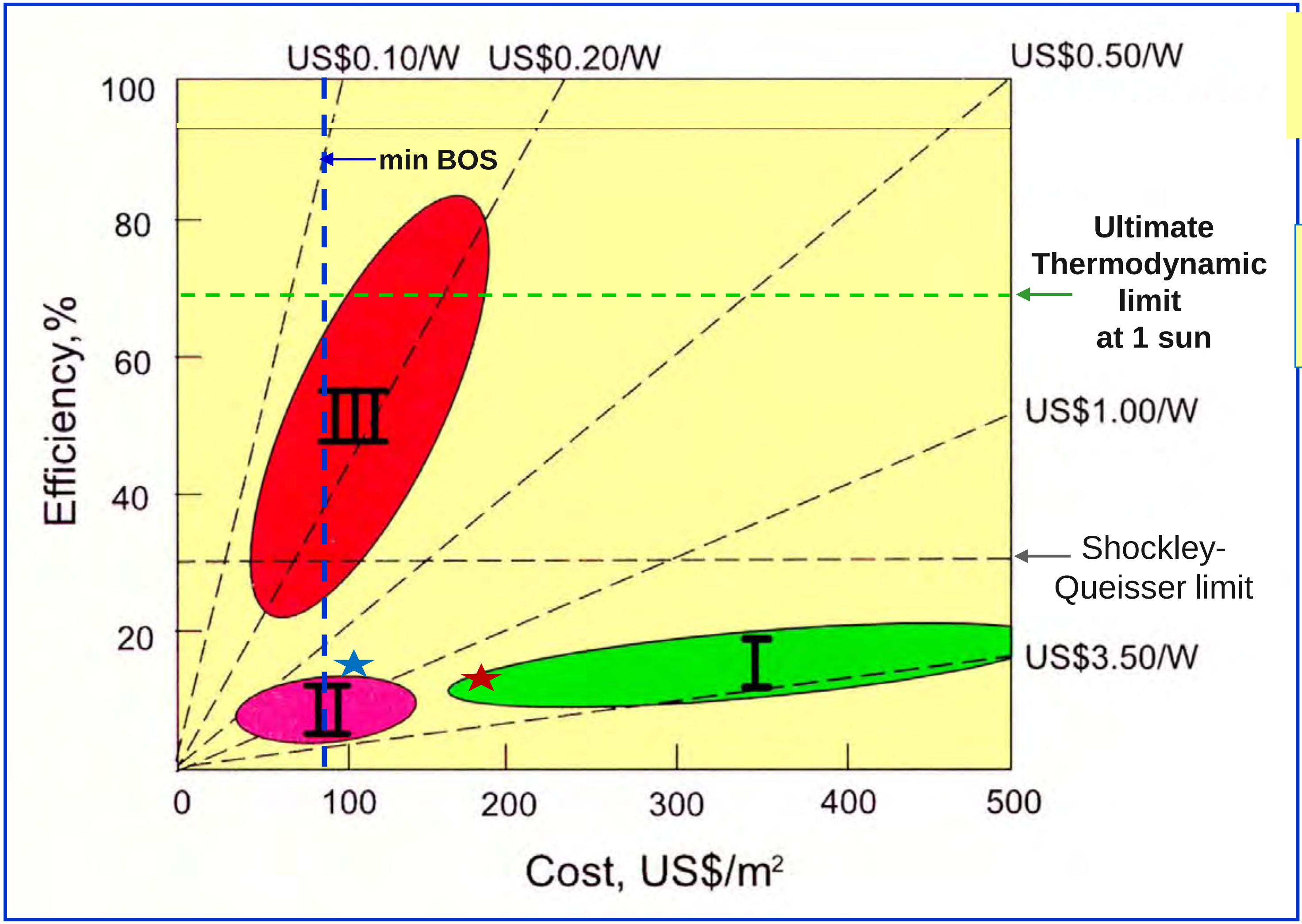
Building Integrated PV

Creating module form factors aimed at dramatically reducing or eliminating solar installation costs

Best Research-Cell Efficiencies



PV Power Costs as Function of Module Efficiency and Areal Cost
3rd Generation PV: Beyond 1$/watt



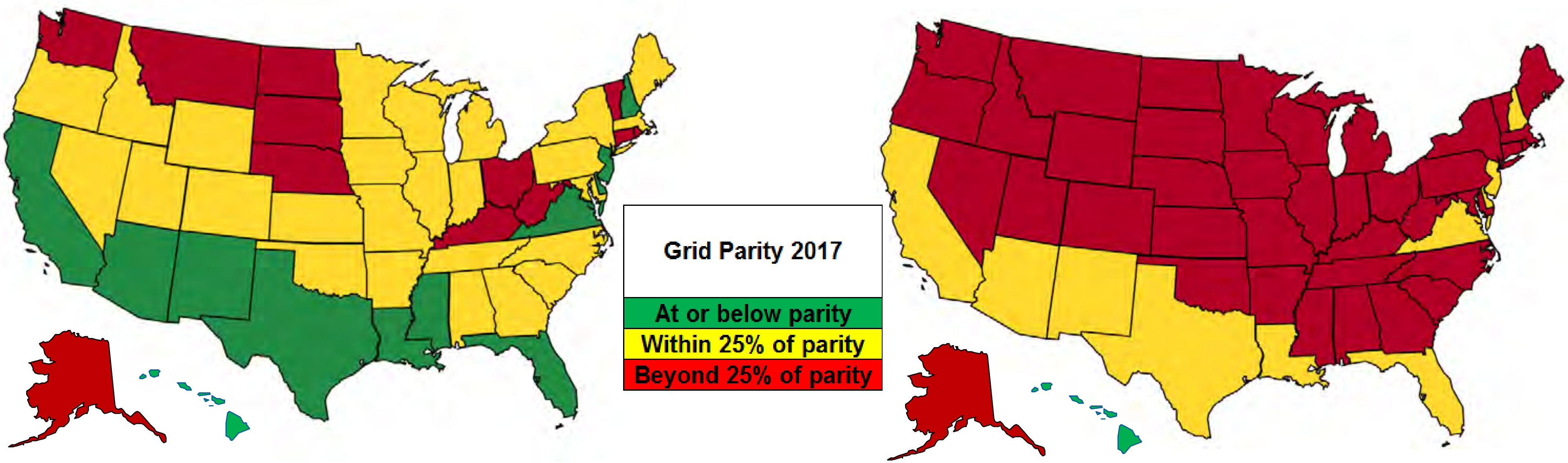
$/W_p = ($/m^2)/(W/m^2)$

$/kWh ≈ 0.05 x $/W_p

★ 2011-Thin Si
★ 2011-CdTe

For PV or PEC to provide a major fraction of C-free energy required for electricity and fuel, power cost needs to be equivalent to coal (2-3 cents/kWh—module cost of $0.20-0.30/W)

Grid Parity with $1 / Watt



$1 / Watt Scenario

Current Projection

- Assumes no Federal, State, Local, and Utility incentives
- Assumed an installed system size of 20 MW, and an 86% conversion factor between DC and AC module capacity.
- Utilized weighted average wholesale electricity prices from the 2008 EIA-861 Data. The data were escalated to 2017 prices based on an annual electricity escalation rate of 1%.
- Current projection for utility scale PV is assumed to be $2/Watt by 2017.

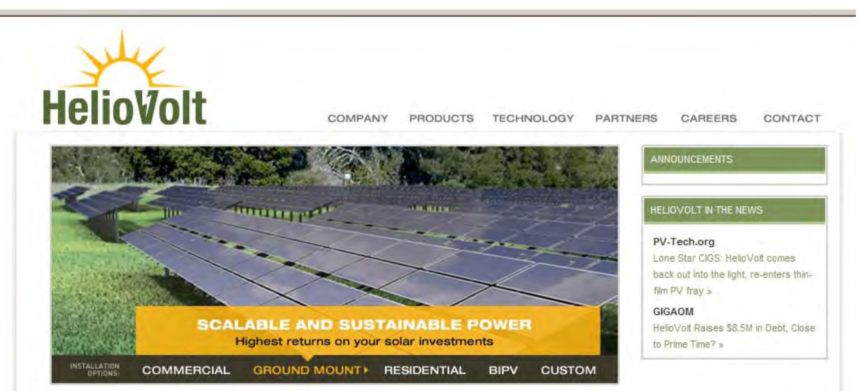
Market Relevant Process Innovation

"Black Silicon" Nanocatalytic Wet-Chemical Etch

2010 R&D 100

Flash Quantum Efficiency System

2011 R&D 100



Revolutionary CIGS thin-film manufacturing process using inkjet printing

HelioVolt

R&D 100

2008

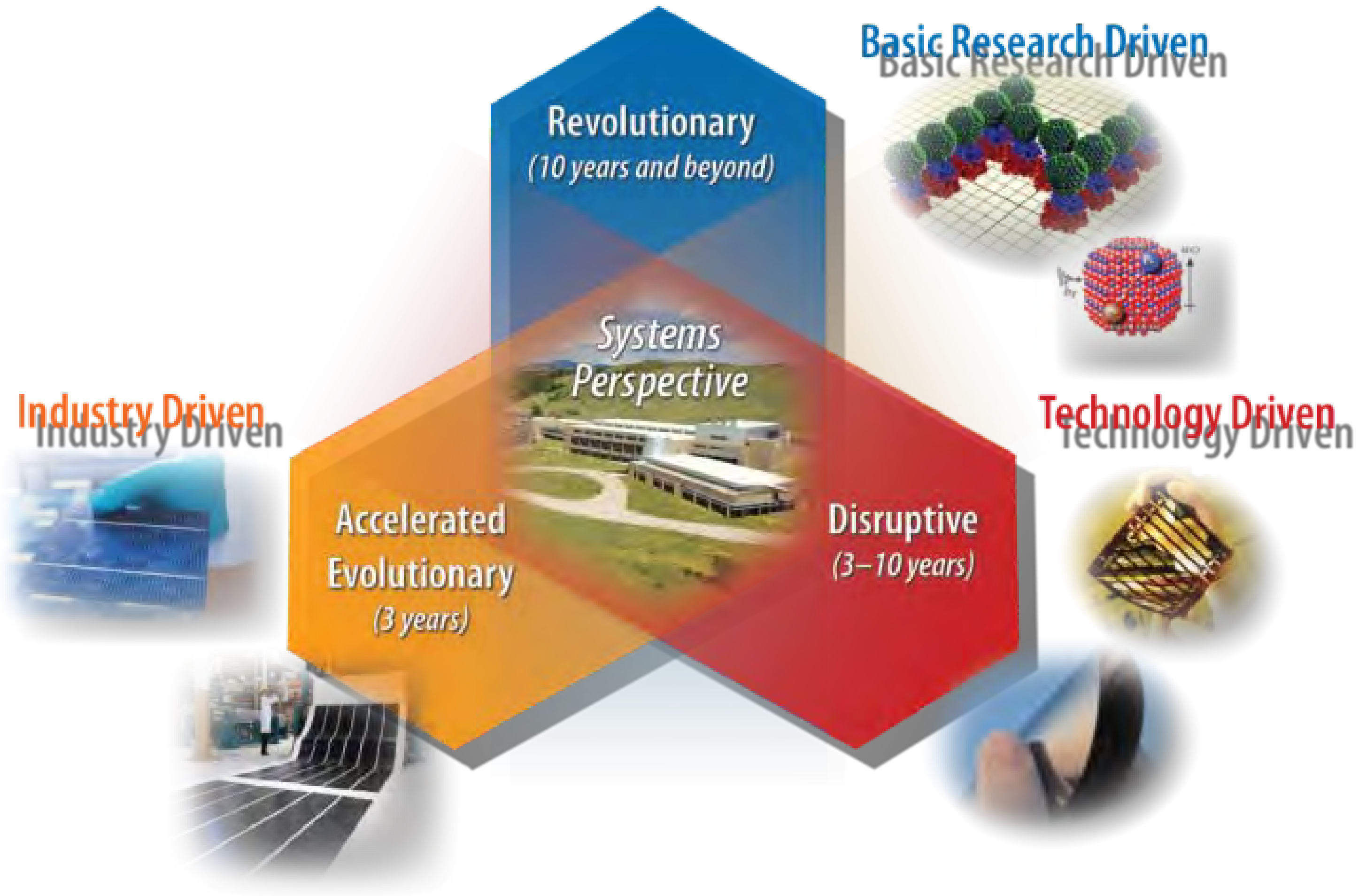
Silicon Ink
NREL Incubator Project

2011 R&D 100

innovation Impact: Partnering is Key

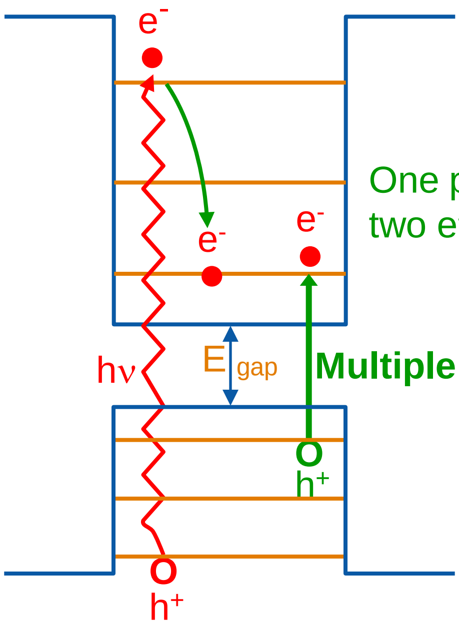
GE
Bank of America
ABENGOA SOLAR
ALSTOM
RF MICRO·DEVICES
JM JOHNSON MATTHEY
AMPULSE
PHOTON SOLAR POWER *The Art of The Sun*
HelioVolt
FedEx
JCPenney
1366 TECHNOLOGIES
SIEMENS
Walmart Save money. Live better.
GLOBAL SOLAR
SkyFuel
bp
OPTONY Solar for Life™
novozymes®
Ascent SOLAR
BERGEY WINDPOWER
SPECTROLAB A BOEING COMPANY
LOCKHEED MARTIN
DOW
labsphere®
Eskom
Xcel Energy℠
KONARKA®
DELPHI
Clipper®
IBERDROLA
JOHN DEERE
Coolerado®
orion
OPTIMA BATTERIES THE ULTIMATE POWER SOURCE™
regency centers www.regencycenters.com
CALPINE®
RAYOVAC®
PLANAR™
QUANTUM SPHERE™
Ford
GENENCOR® A Danisco Division
DAIMLERCHRYSLER
BEST BUY
CATERPILLAR®
MiaSolé Thin-film solar
PardeeHomes Where smart solutions live.
AWS Truewind

Breakthrough/Translational Science



Quantum Dot Solar Cells

Enhanced Photovoltaic Efficiency in Quantum Dot Solar Cells by Inverse Auger Effect (MEG)

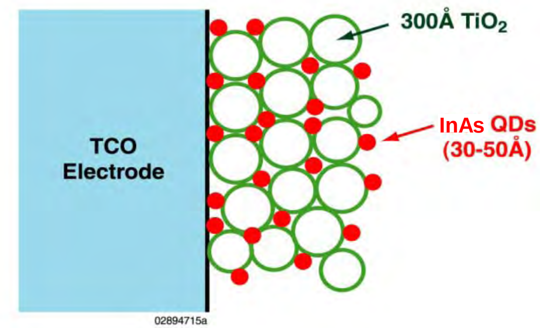


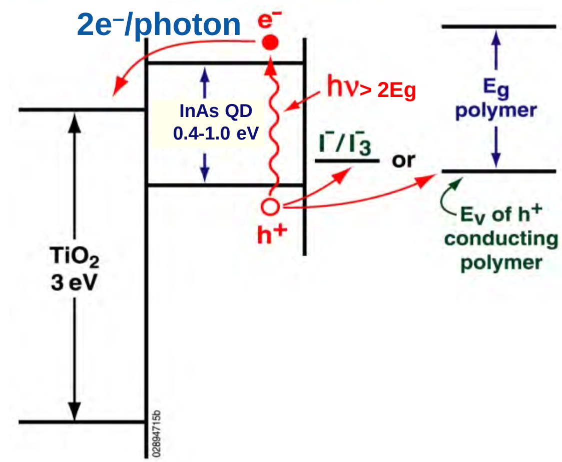
One photon yields two e-–h+ pairs

Multiple Exciton Generation (MEG)

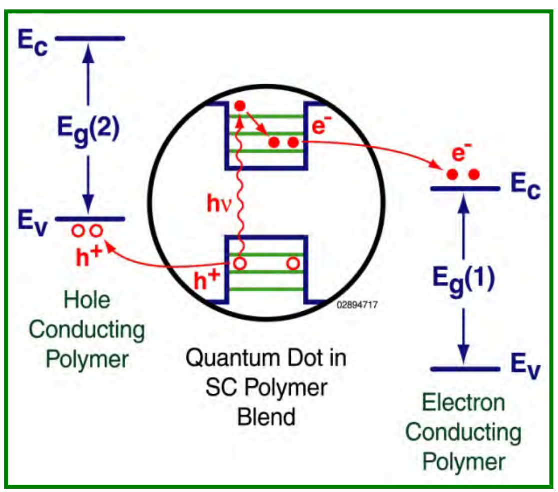
A.J. Nozik, *Physica E* **14**, 115 (2002);

QD-Sensitized Nanocrystalline TiO_2 Solar Cell

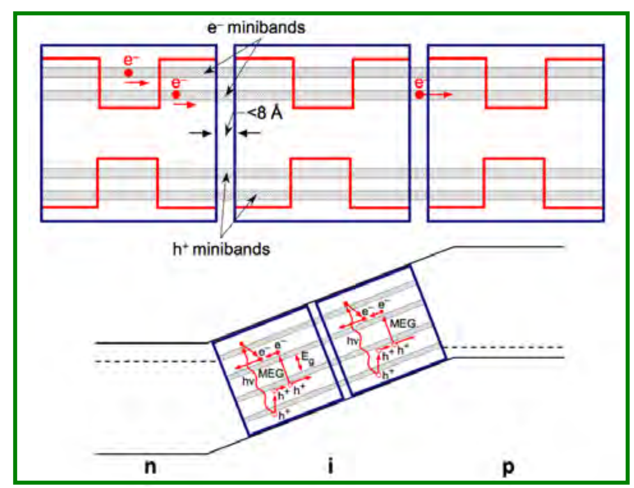




QD-Conducting Polymer Blend Solar Cell



p-i-n QD Array Solar Cell



High Level Visibility in Prestigious Publications

Science

Comparing Photosynthetic and Photovoltaic Efficiencies and Recognizing the Potential for Improvement

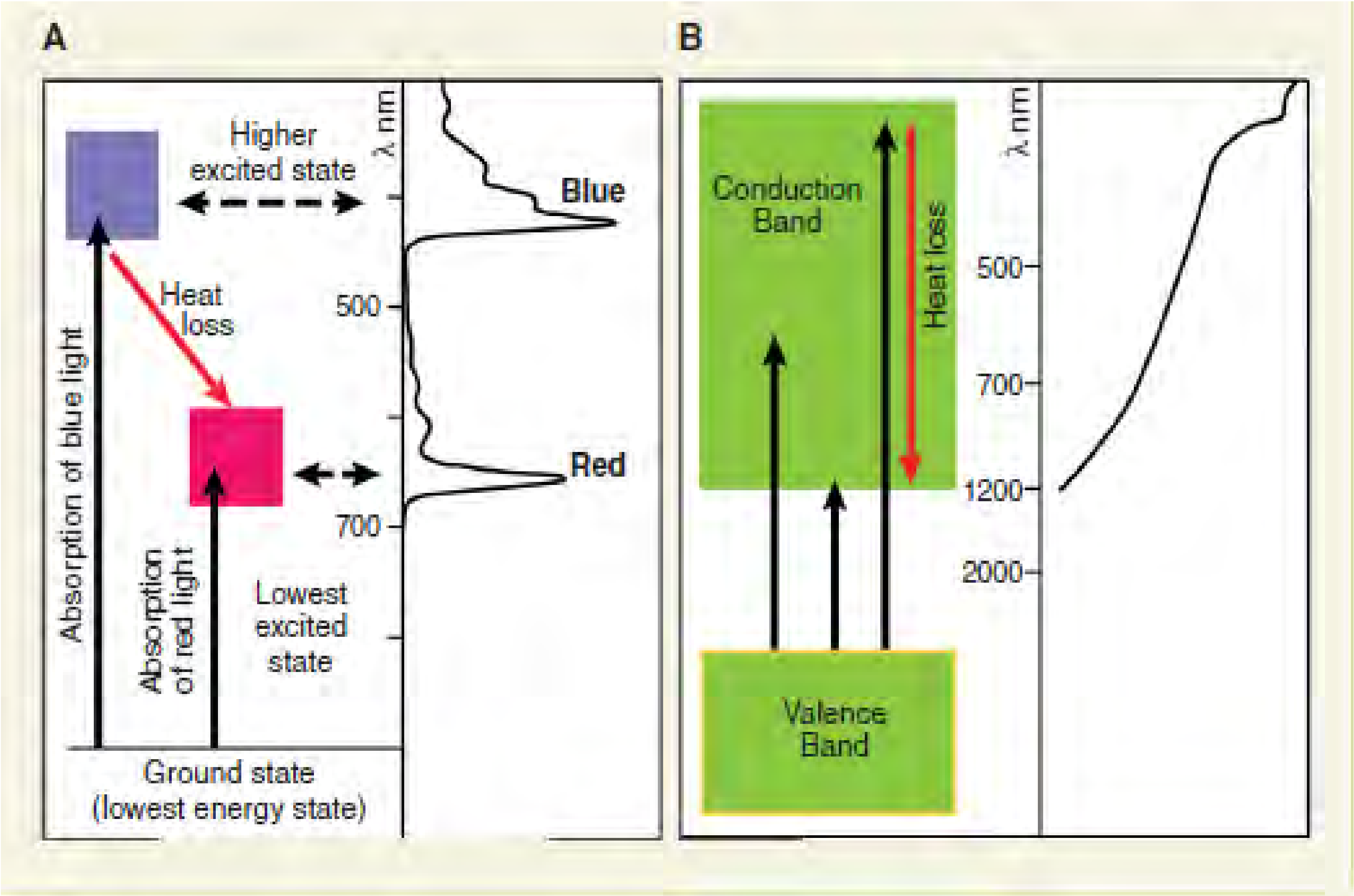
Robert E. Blankenship,[1*] David M. Tiede,[2*] James Barber,[3] Gary W. Brudvig,[4] Graham Fleming,[5] Maria Ghirardi,[6] M. R. Gunner,[7] Wolfgang Junge,[8] David M. Kramer,[9] Anastasios Melis,[10] Thomas A. Moore,[11] Christopher C. Moser,[12] Daniel G. Nocera,[13] Arthur J. Nozik,[14] Donald R. Ort,[15] William W. Parson,[16] Roger C. Prince,[17] Richard T. Sayre[18]

Comparing photosynthetic and photovoltaic efficiencies is not a simple issue. Although both processes harvest the energy in sunlight, they operate in distinctly different ways and produce different types of products: biomass or chemical fuels in the case of natural photosynthesis and nonstored electrical current in the case of photovoltaics. In order to find common ground for evaluating energy-conversion efficiency, we compare natural photosynthesis with present technologies for photovoltaic-driven electrolysis of water to produce hydrogen. Photovoltaic-driven electrolysis is the more efficient process when measured on an annual basis, yet short-term yields for photosynthetic conversion under optimal conditions come within a factor of 2 or 3 of the photovoltaic benchmark. We consider opportunities in which the frontiers of synthetic biology might be used to enhance natural photosynthesis for improved solar energy conversion efficiency.

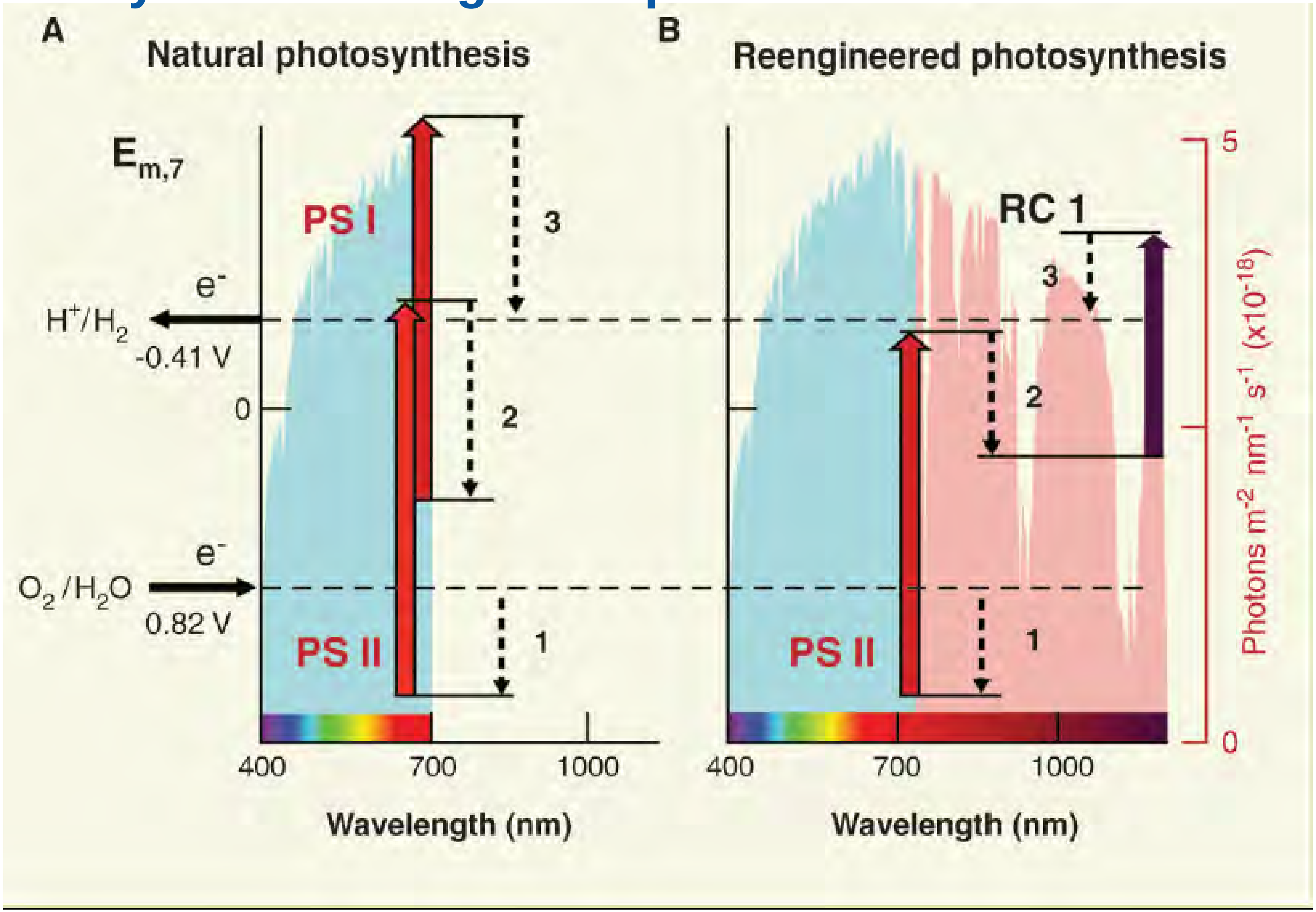
www.sciencemag.org SCIENCE VOL 332 13 MAY 2011 805

Absorption Properties

Chlorophyll | Silicon



How to Enhance Efficiency of Biological Photosynthesis using Principles of Multi-Junction PV



Science *332*, 805 (2011) (18 authors)

The vision: Optimizing the role of solar energy

Applications of Solar Heat and Electricity

Solar Thermal

Photovoltaics (PV)

Concentrating Solar Power (CSP)

Distributed Generation, on-site or near point of use

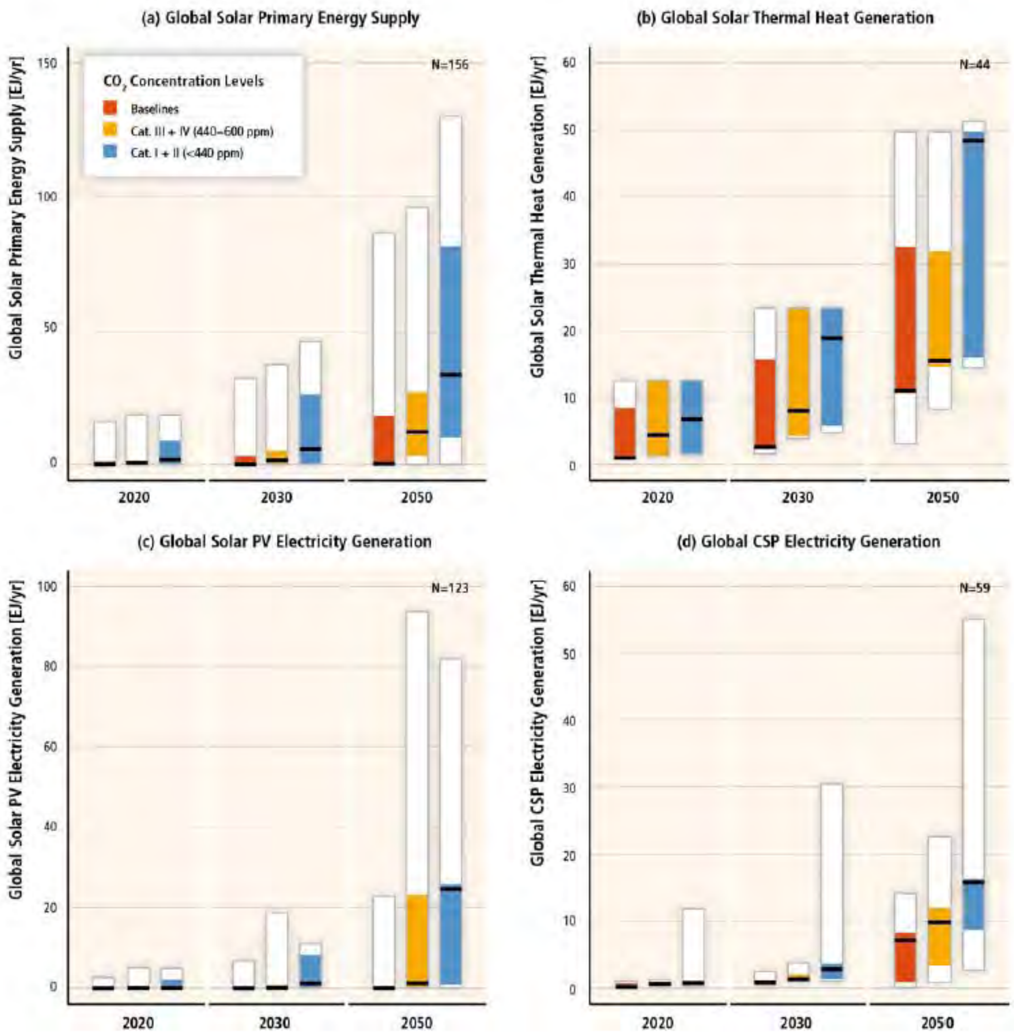
Centralized Generation, large users or utilities

Transportation

Residential & Commercial Buildings

Industrial

Global solar supply and generation in long-term scenarios

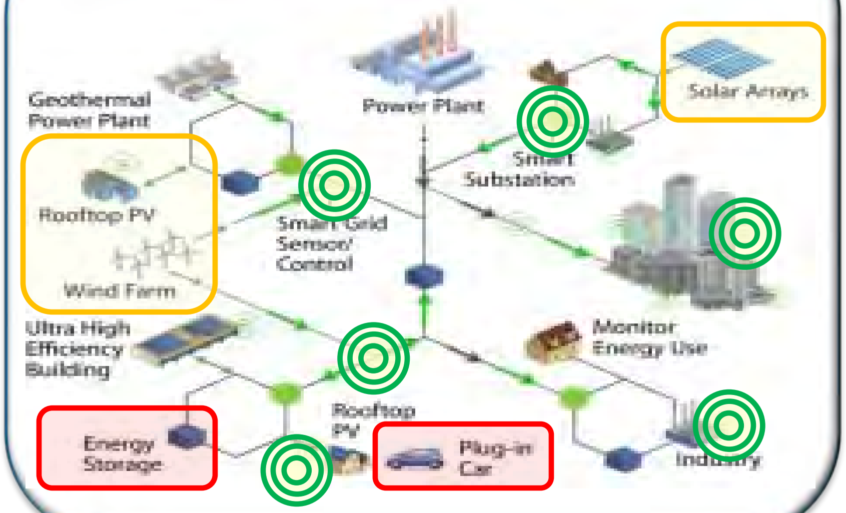


Source: IPCC Special Report Renewable Energy Sources (SRREN)

Why Energy Systems Integration?

Current Energy Systems

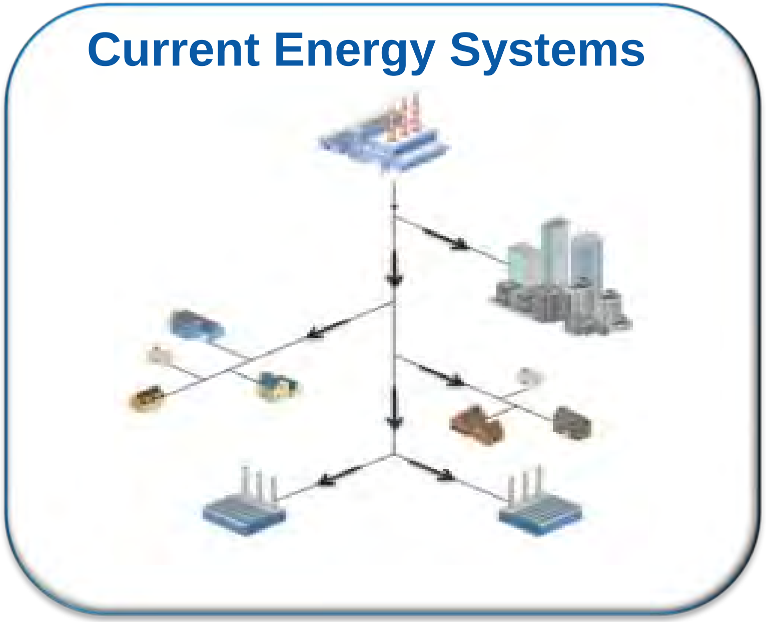
Future Energy Systems

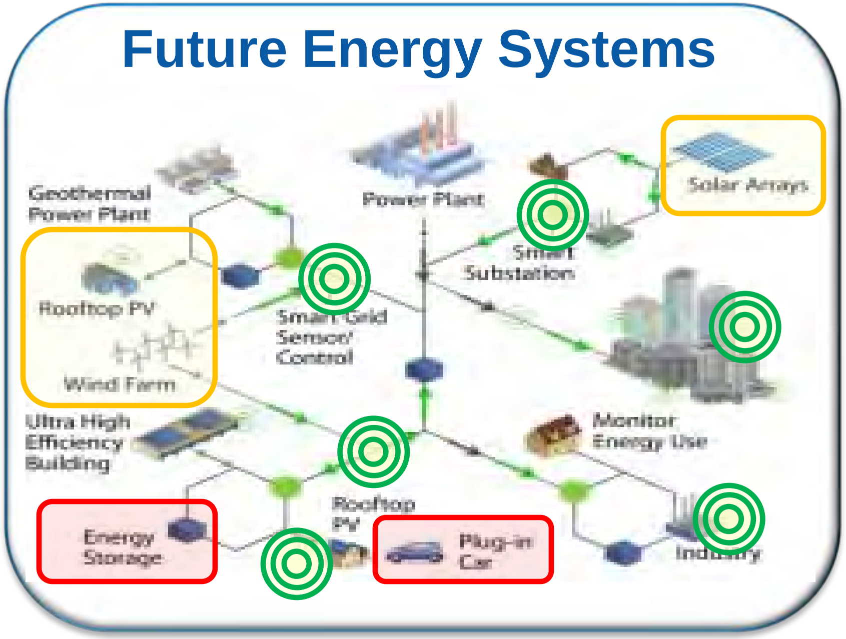


New Challenges – Need to tackle difficult problems

- 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

Why Energy Systems Integration?





New Challenges – Need to tackle difficult problems

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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

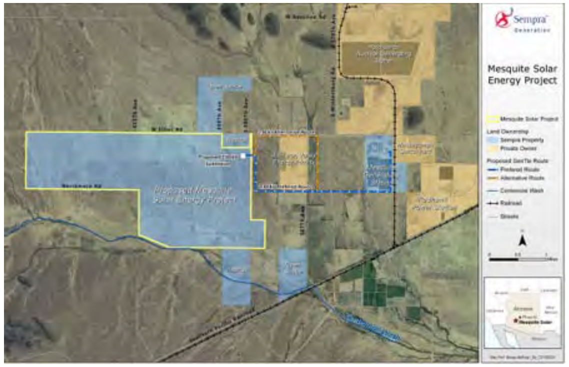
Sempra Energy

Sempra Energy has recently completed the U.S.'s largest photovoltaic power plant, the 48-megawatt Copper Mountain Solar facility near Boulder City, Nevada.

NREL is working with Sempra to understand large-scale system variability and transmission connected PV systems.

As PV plants in the US reach towards the 1GW level, the bulk-system impacts become extremely important in system operations.

Copper Mountain 48MW PV plant



Plans for Mesquite 600MW PV site

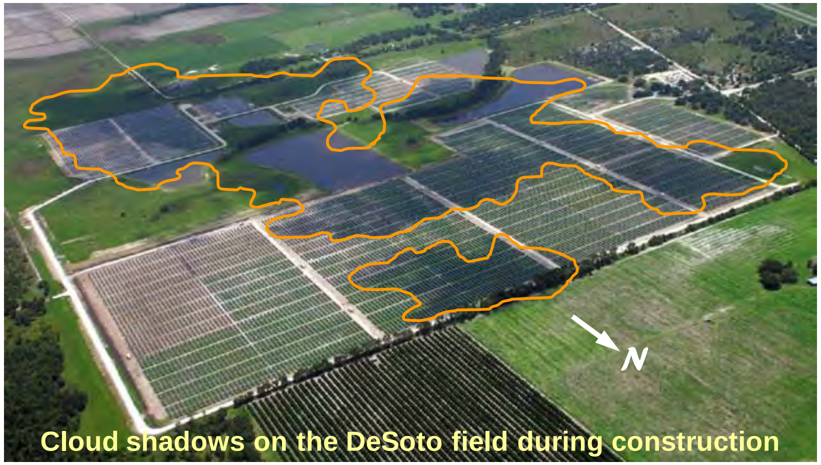
FPL/NextEra

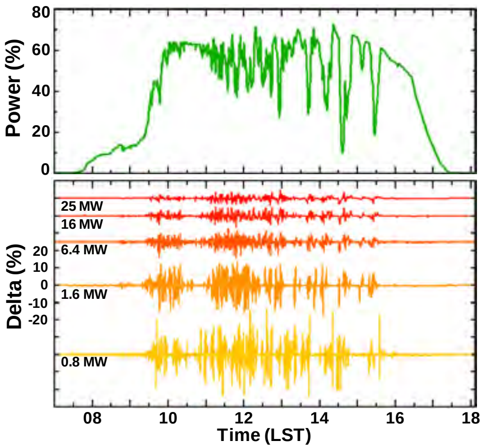
NREL is working with FPL/NextEra and WindLogics on understand the variability of very large-scale PV deployments.

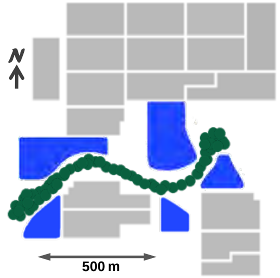
The pictures show the 25MW PV plant in Desoto, Florida.

The graph shows the impacts of clouds over time for various MW sections of the system.

The ramps dampen as the MW increases because of spatial diversity.





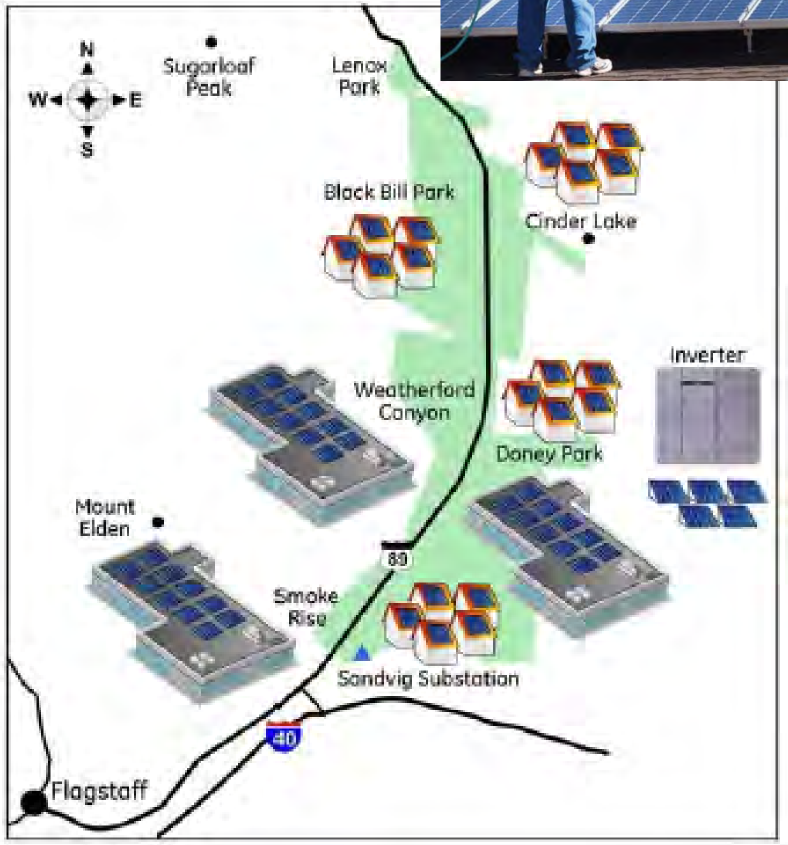


Ten second ramp rates dampen out as MW increase

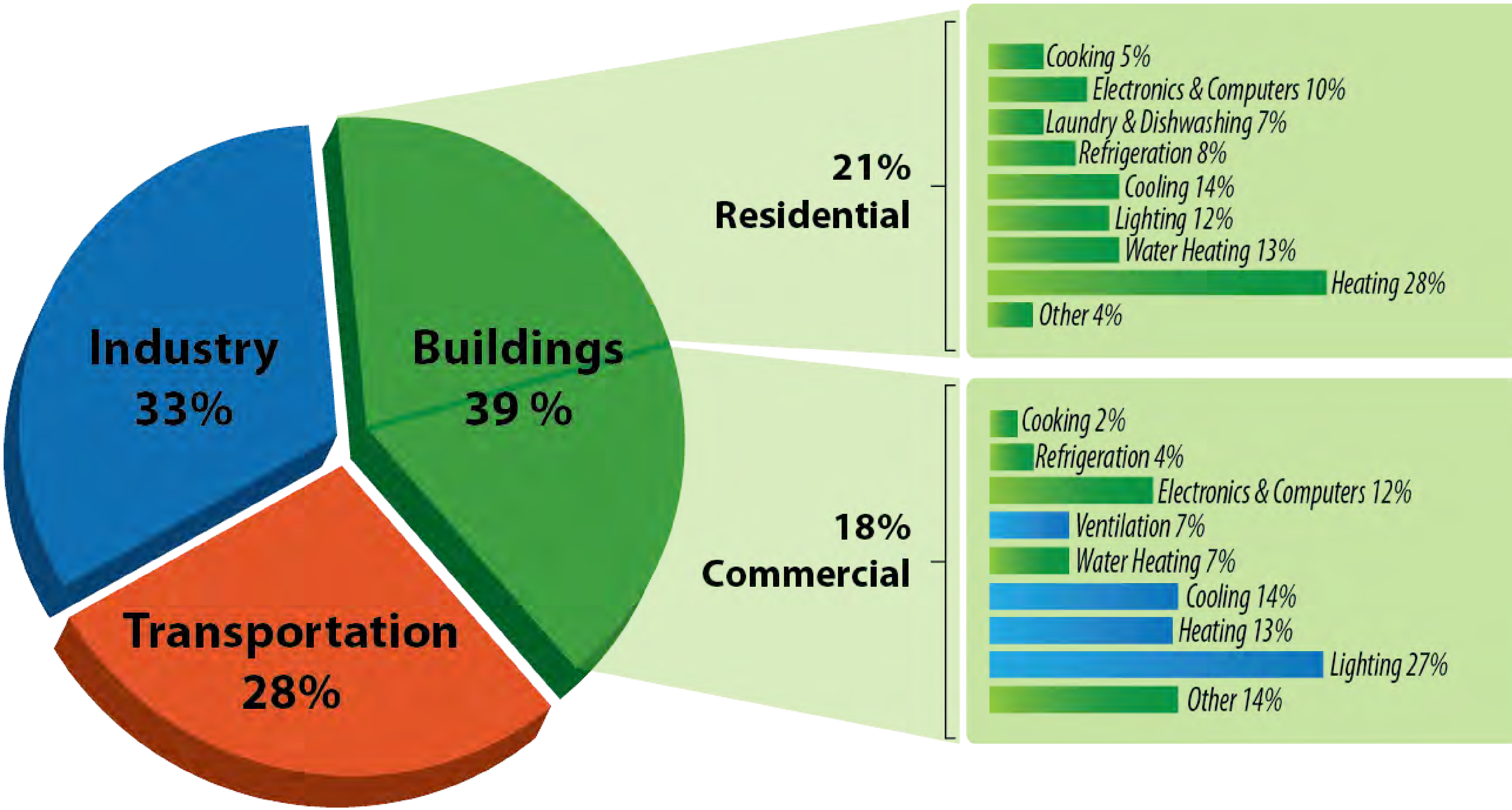
Observed Impacts of Transient Clouds on Utility-Scale PV Fields, A. Kankiewicz, D. Moon and M. Sengupta, SOLAR 2010 , May 2010

Arizona Public Service

- APS is conducting a unique pilot project in Flagstaff, AZ designed to increase the deployment of renewable energy, especially distributed energy from solar panels.
- Study the effects of large amounts of distributed PV on a utility feeder and it's associated customers
- Create and validate models to describe the interactions between weather/PV/feeder equipment and operations
- Identify technical and operational modifications that could be deployed in future feeder designs.



Energy Consumption in the U.S.

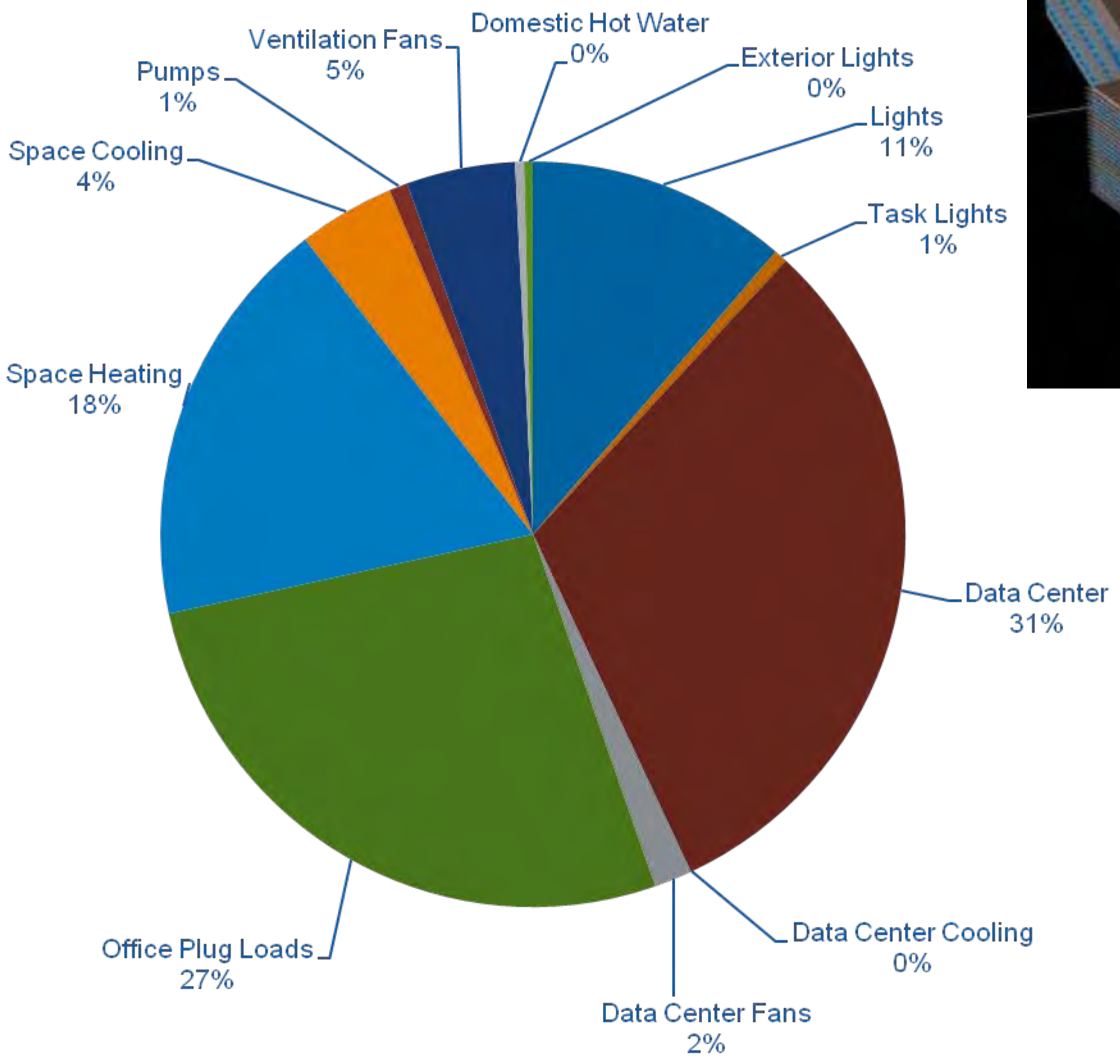


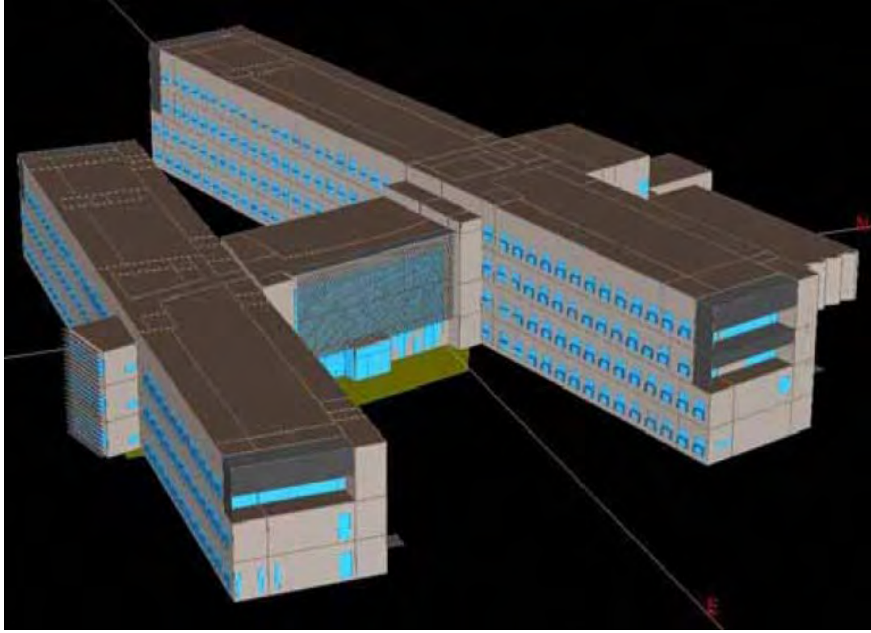
Source: Buildings Energy Data Book, 2006

NREL Research Support Facility

Energy Modeling

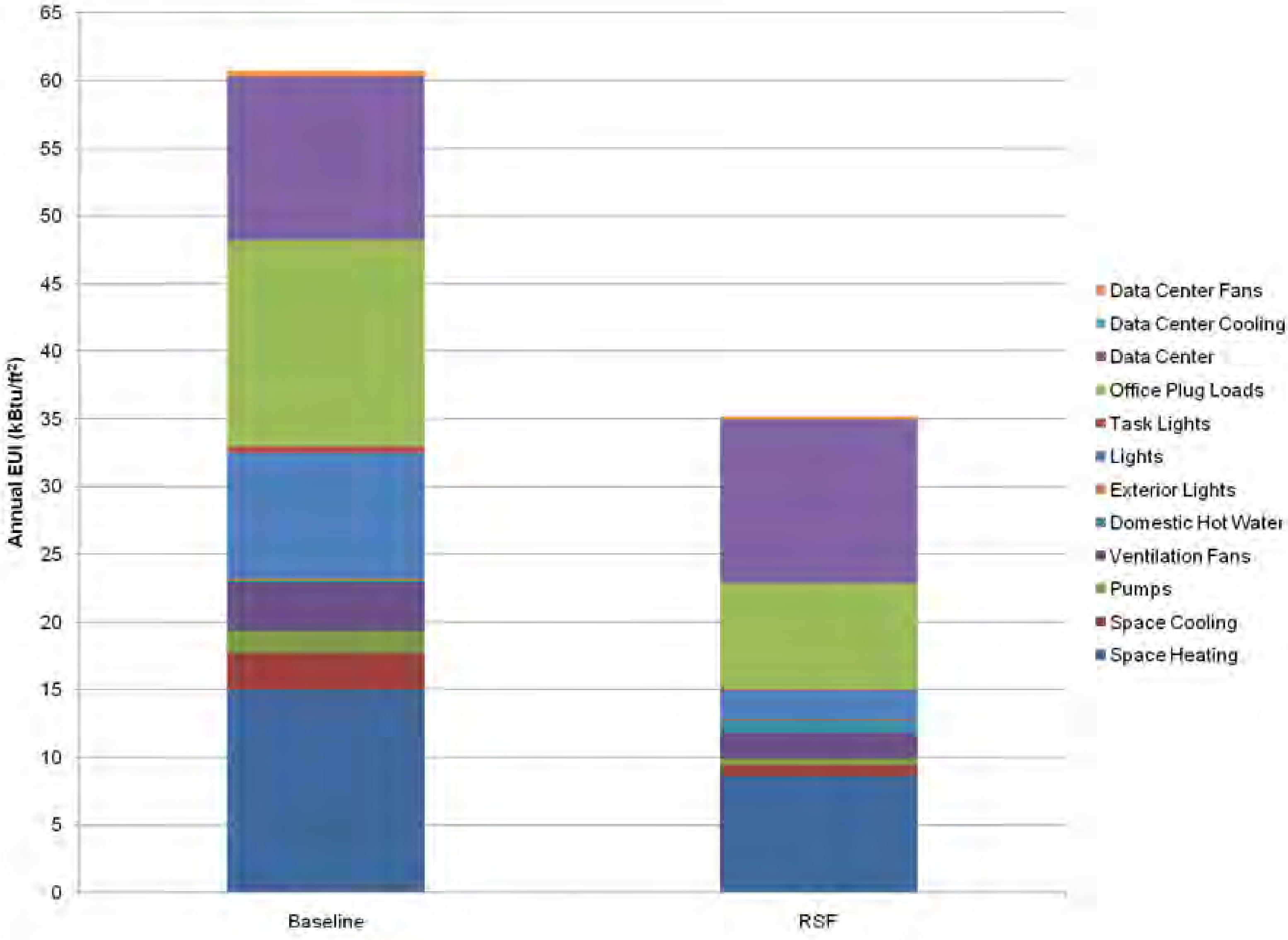
NREL RSF Energy Use Breakdown





End Use	kBtu/ft²
Lights	3.85
Task lights	0.19
Data center	10.60
Data center cooling	0.01
Data center fans	0.55
Office plug loads	9.16
Space heating	6.11
Space cooling	1.42
Pumps	0.27
Ventilation fans	1.61
Domestic hot water	0.13
Exterior lights	0.12

NREL RSF Annual Energy Consumption Comparison



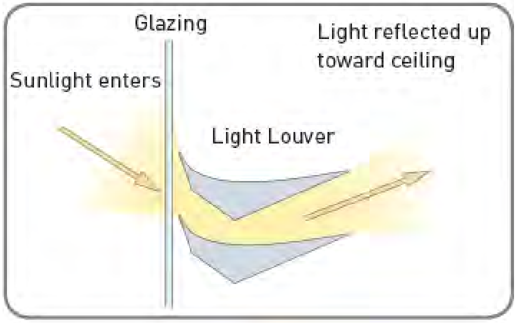
Daylighting

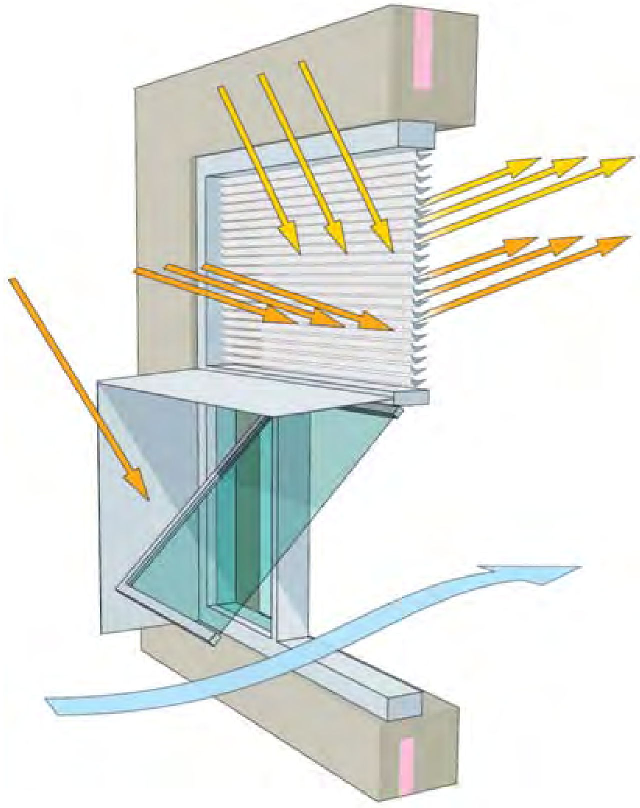
- Two long 60-foot wide wings with east-west orientation
- Design reduces electrical lighting

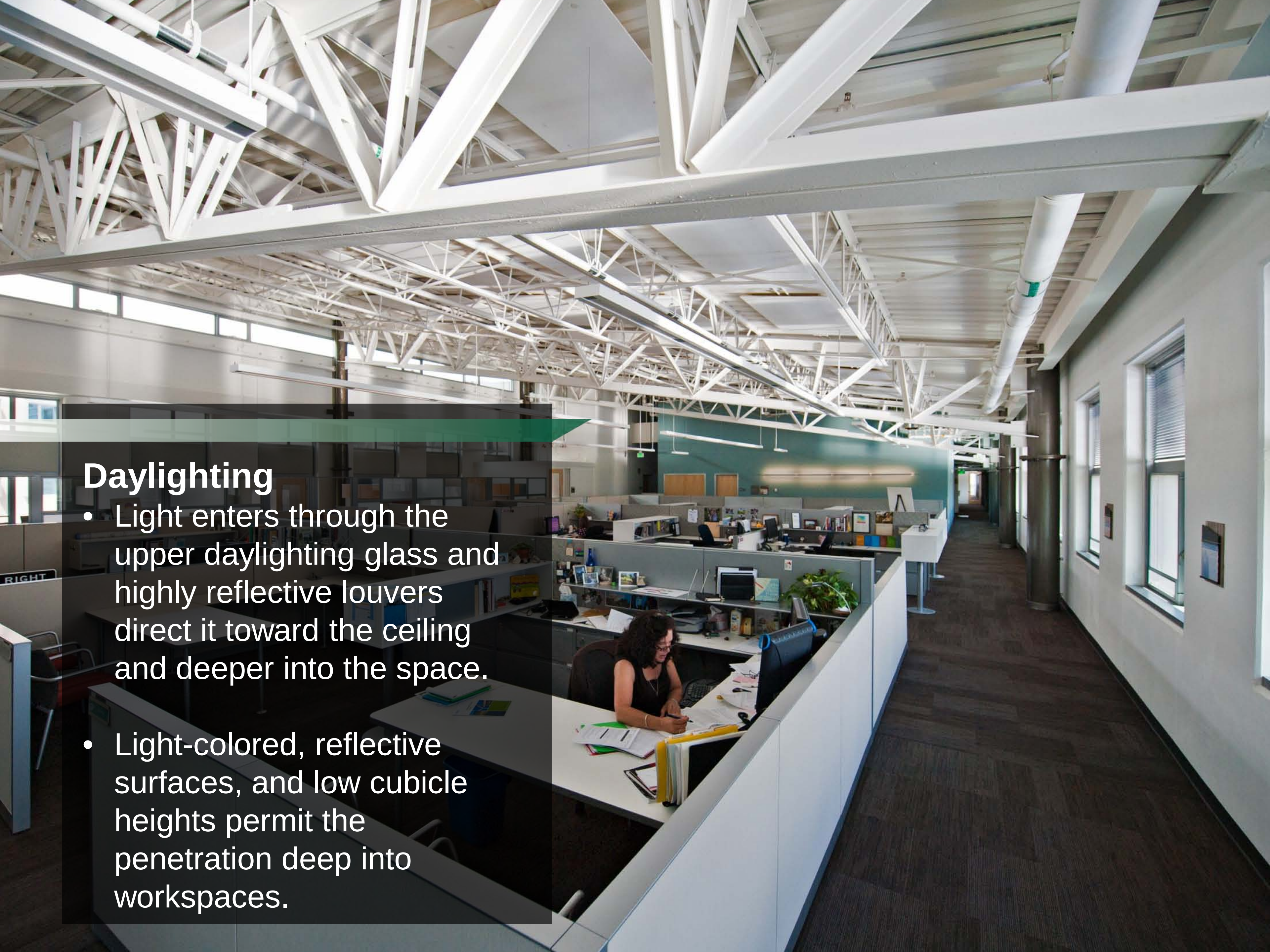
Daylighting: Light Louvers

A light louver daylighting system reflects sunlight to the ceiling, creating an indirect lighting effect.

Fixed sunshades limit excess light and glare.







Daylighting

- Light enters through the upper daylighting glass and highly reflective louvers direct it toward the ceiling and deeper into the space.

- Light-colored, reflective surfaces, and low cubicle heights permit the penetration deep into workspaces.

Thermal Mass

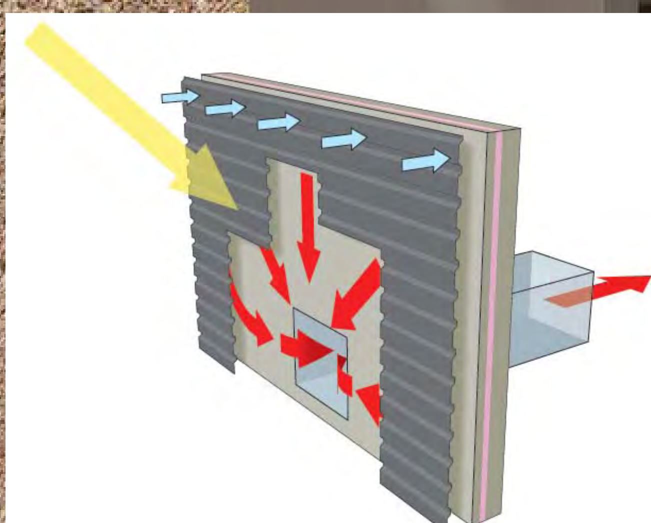
- Incorporates many passive heating and cooling techniques.

- Pre-cast thermal mass wall – 3” concrete, 2” rigid insulation, 6” concrete – helps moderate internal temperatures year round.

- Nighttime purges in summer months trap cool air inside, keeping temperatures comfortable for the warm summer days.

NREL-developed transpired solar collector

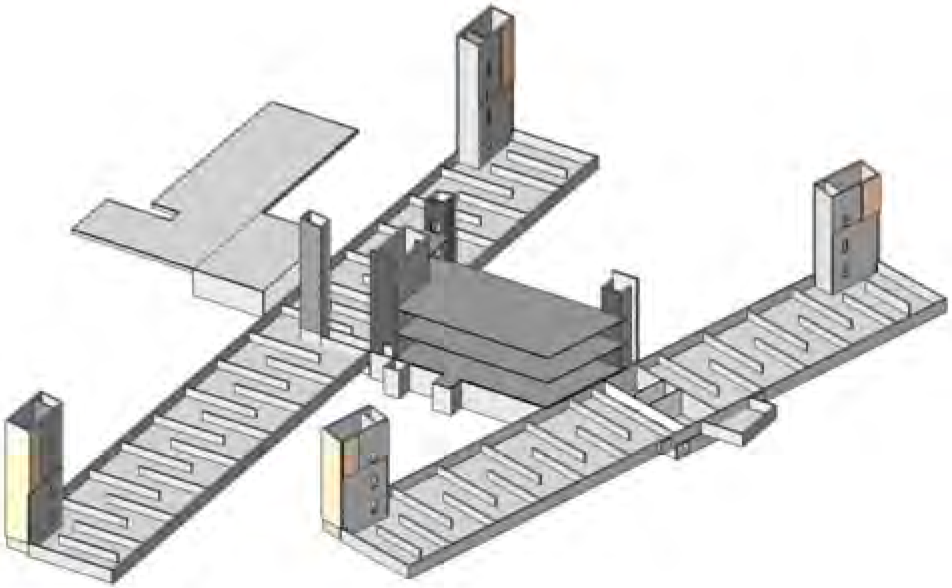
- Metal sheet perforated with small holes
- Fans pull air through the holes on sunny winter days to preheat building air
- During colder weather, air heated by the transpired solar collectors is stored in the labyrinth



Labyrinth

Labyrinth Thermal Storage

- Massive, staggered concrete structures in the basement crawl space stores thermal energy to provide passive heating and cooling of the building.



Natural Ventilation

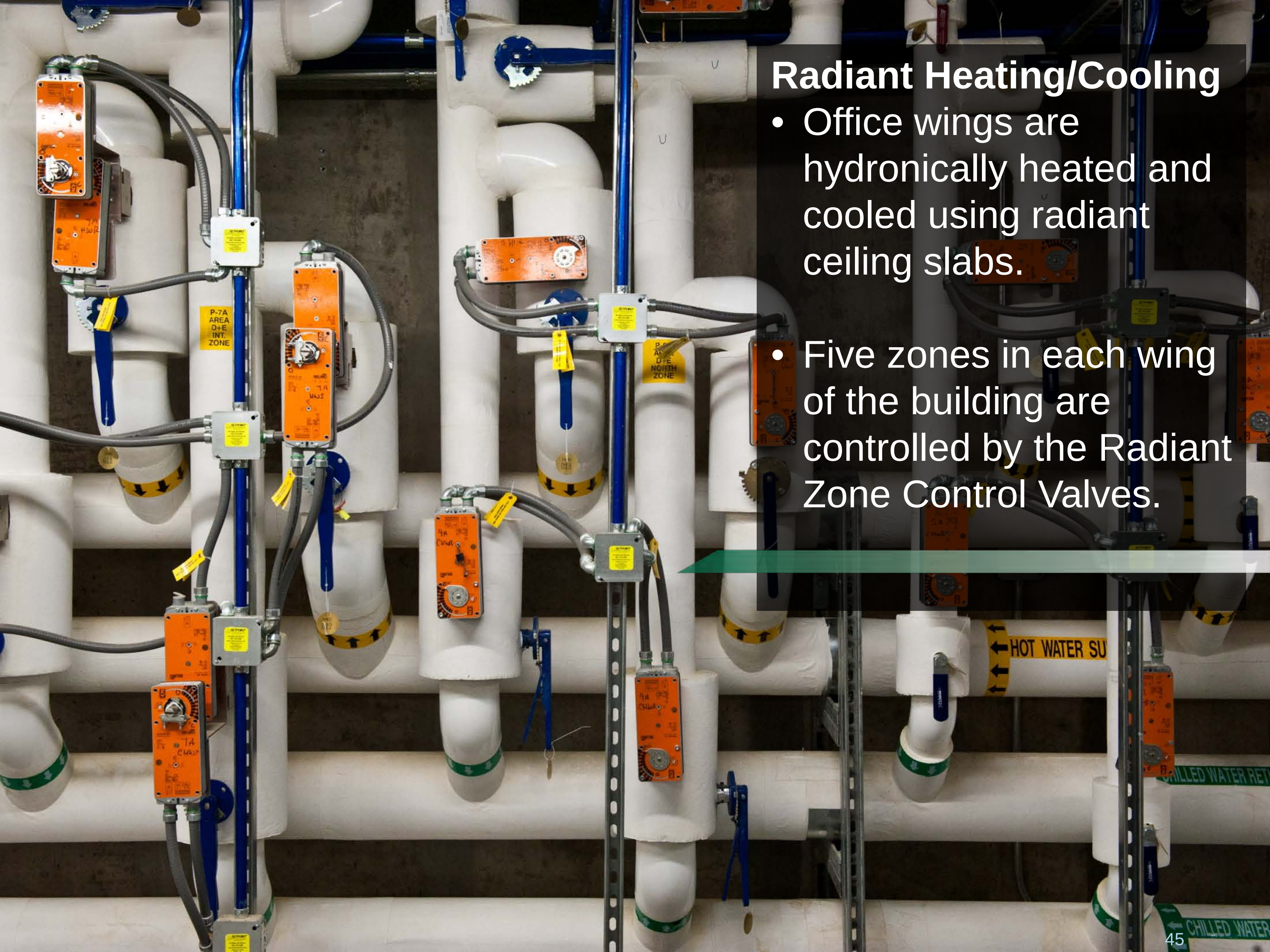
- During mild weather, operable windows allow for natural ventilation.
- Automatic windows are controlled and operated primarily to support nighttime precooling.
- Occupants are notified when conditions allow for manual windows to be opened.

Triple-glazed windows with individual overhangs maximize daylighting and minimize glare, as well as heat loss and gain.

Window Technologies

The west elevation windows feature NREL-developed **electrochromic technology** in which the windows tint in response to a small electric current, reducing heat gain in the afternoon hours.

Thermochromic windows on the eastern balcony windows react to temperature change and have glass resistant to heat transfer.



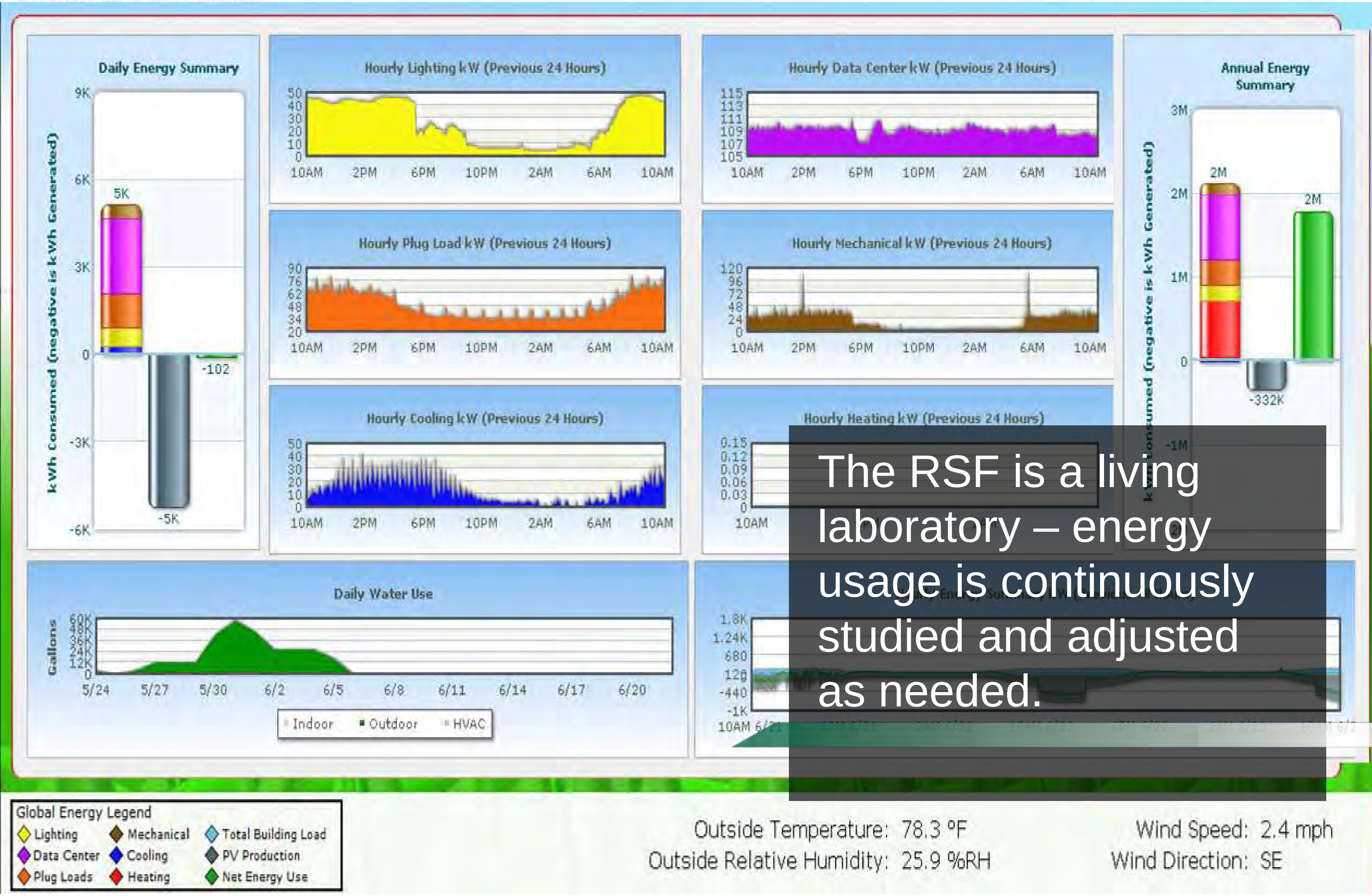
Radiant Heating/Cooling

- Office wings are hydronically heated and cooled using radiant ceiling slabs.
- Five zones in each wing of the building are controlled by the Radiant Zone Control Valves.

RSF Net Zero Energy PV Arrays

NATIONAL RENEWABLE ENERGY LABORATORY

RSF Energy Monitoring

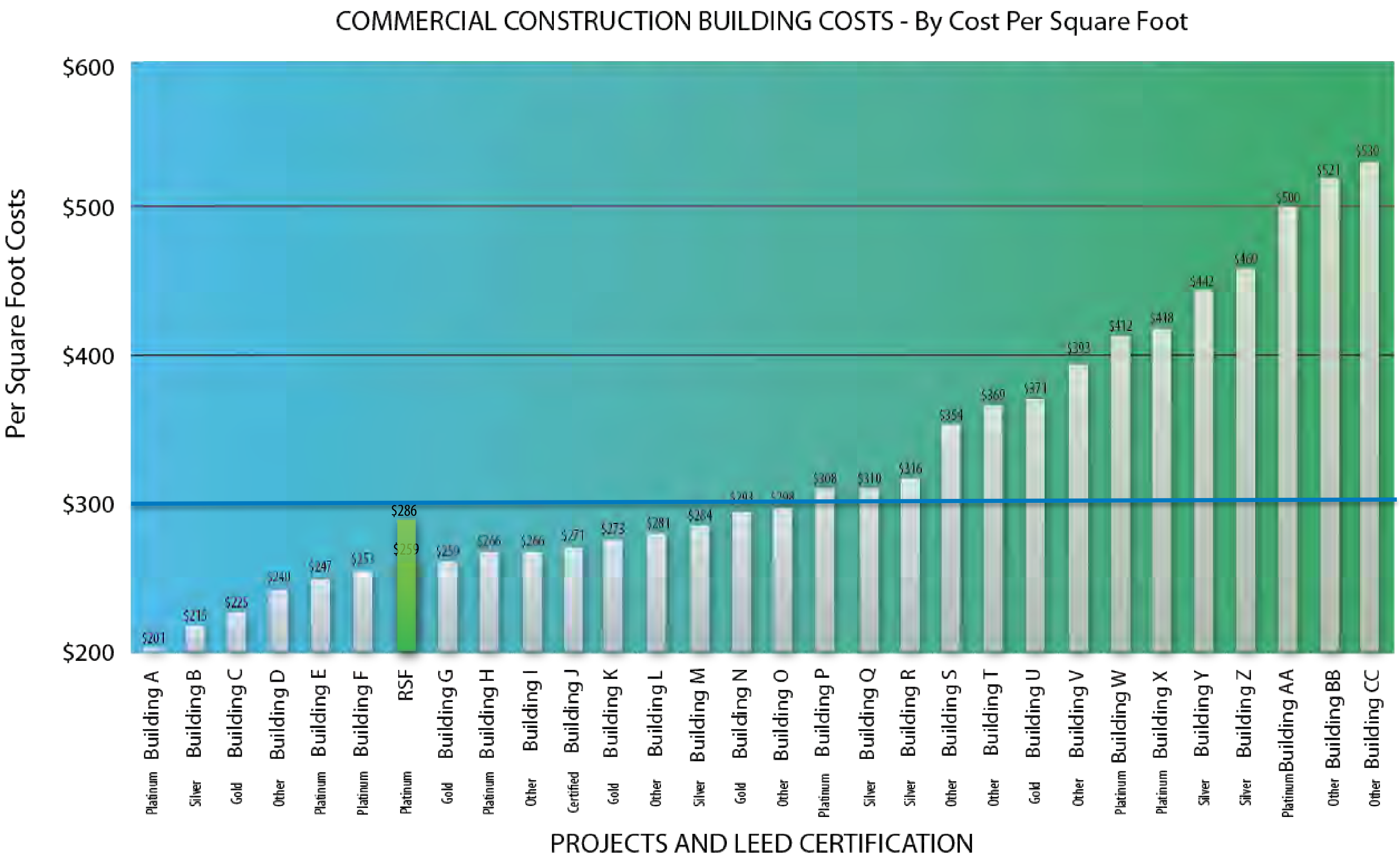


The RSF is a living laboratory – energy usage is continuously studied and adjusted as needed.

A glimpse into the future

If all commercial buildings operated in this fashion, the percent renewable energy – specifically solar – contribution to the energy mix would be a game changer.

Construction Costs



To achieve this vision, we must…

- Invent the future we desire
- Invest in innovation
- Improve access to capital
- Partner on a global scale

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