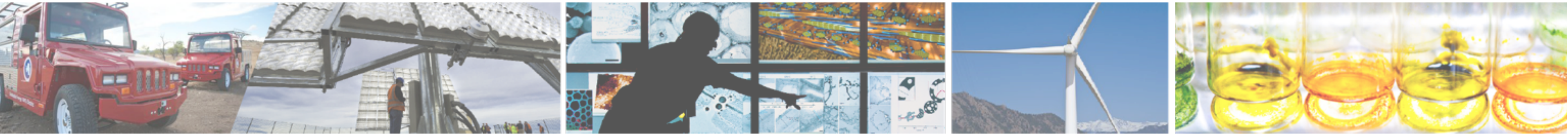
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

U.S. DEPARTMENT OF ENERGY



The Multi-TW Scale Future for PV

Sustainable Energy Conference
St. Louis University - St. Louis, Missouri

Greg Wilson
Director, Center for Materials Applications & Performance
Co-Director, National Center for Photovoltaics

National Renewable Energy Laboratory
Golden, Colorado - USA

14 April, 2016

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.

Overview

1. Brief introduction of NREL and NREL's PV and Energy Materials Programs.
2. PV101
3. Energy and climate change.
4. Cell efficiency and module cost - 39 years of progress.
5. Enabling PV as a global carbon emissions reduction tool.
6. Final comments.

National Renewable Energy Laboratory

Dedicated Solely to Advancing Energy Efficiency and Clean Energy Research toward Enabling Deployment onto a Modernized Grid

- Physical Assets Owned by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy
- Operated by the Alliance for Sustainable Energy under Contract to DOE
- 1700 permanent staff and world-class facilities
- More than 350 active partnerships annually
- Campus is a living model of sustainable energy

Alliance for Sustainable Energy—Partnering with Excellence

NREL's Program Portfolio

Strategic Analysis

Efficient Energy Use

- Buildings Technologies
- Vehicle Technologies

Delivery & Storage

- Battery and Thermal Storage
- Hydrogen
- Smart Grid and Grid Integration

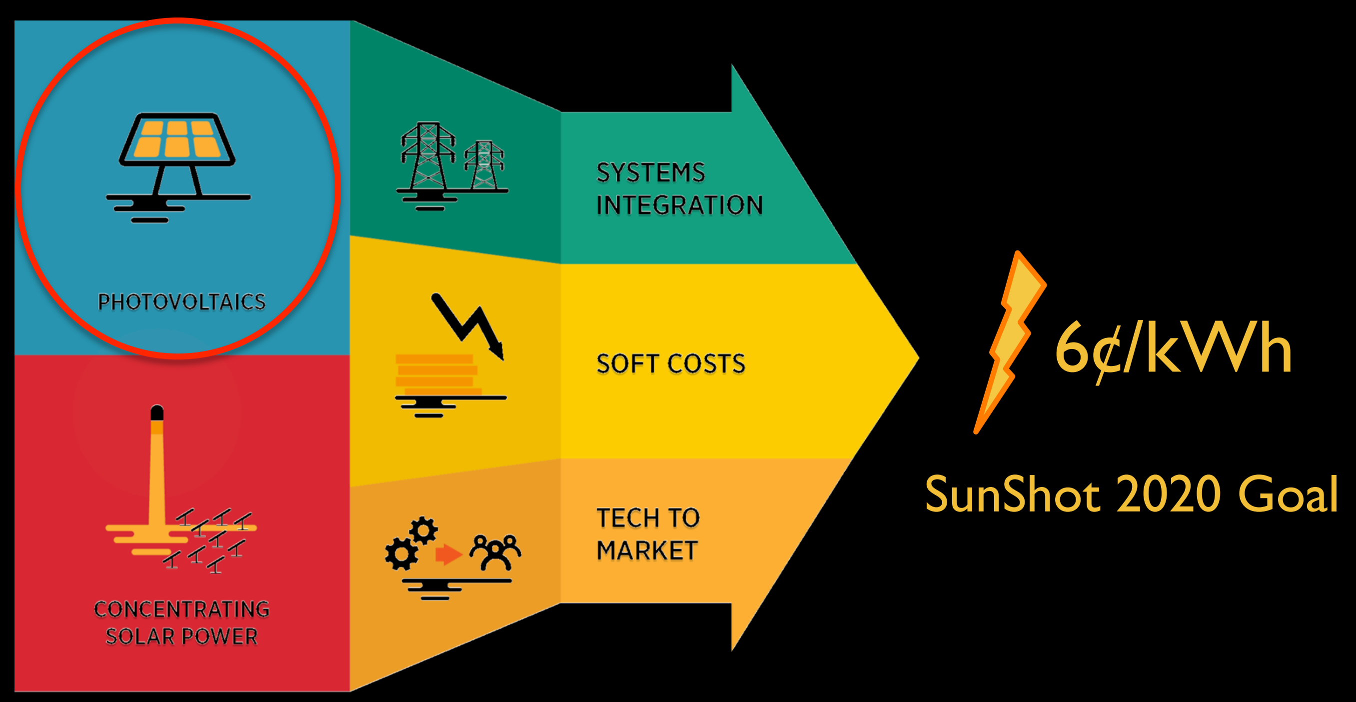
Renewable Resources

- Solar
- Wind and Water
- Biomass
- Geothermal

Foundational Science

NATIONAL RENEWABLE ENERGY LABORATORY | National Center For Photovoltaics

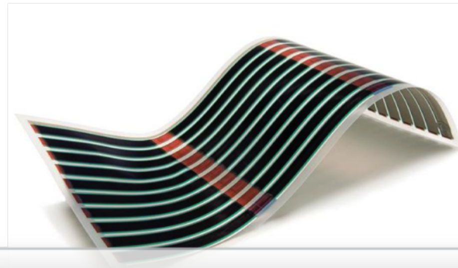
NREL's PV Program: Originating as SERI in 1977, today a key component of the U.S. DOE SunShot Initiative.



Multiple PV Technologies

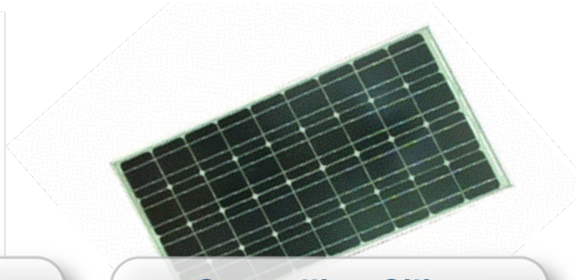
CPV

- Ground mount with 2-axis tracking.
- Concentration of up to 1000x.
- Utilizes the most advanced III-V multi-junction cells.
- Highest efficiency terrestrial PV solution - ~35%.



Thin Films

- CdTe and CIGS are most common today. Future could be Perovskites.
- CIGS can be very light so focus is rooftop and BIPV applications.
- CdTe panels today are widely used in ground mount applications.
- Many new inorganic, organic and hybrid PV absorbers are possible.

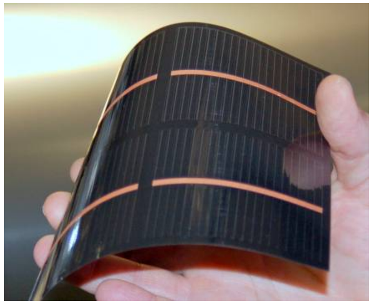


Crystalline Silicon

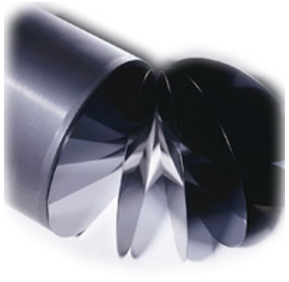
- Silicon PV controls >90% of terrestrial PV market.
- Consists of 2 forms, multi-crystalline and single crystal.
- Highest efficiency rooftop PV technology is cSi - ~22.5%.

•20x-100x

•500x



•$Cu(In,Ga)Se_2$ ~ 1-2 um



•c-Si ~ 180 um

NREL's PV Research Portfolio

PV Research at NREL

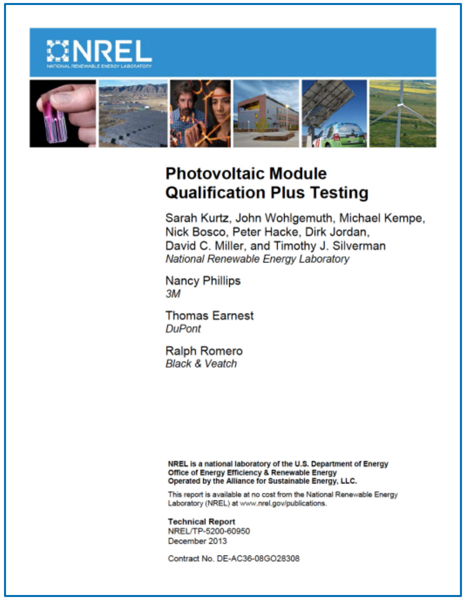
PV Technologies
- Thin Film PV — CIGS / CdTe / Novel
- III-V — MJ & 1J
- Silicon — cSi 1J & Tandems
- Perovskites & OPV

PV Cross-Cutting R&D
- Measurements & Characterization
- Module Reliability & Systems Engineering

Extensive Capabilities and PV Experience Under One Roof

PV Conversion Technology R&D

- III-V Multijunction — Demonstrate > 50% 4J device
- Crystalline Si — Develop low cost, industrial n-CZ cells >23%
- cSi Tandem — Demonstrate cSi based 2J cells > 30%
- CdTe — Materials questions, enable >16% production module
- CIGS — Materials questions, enable >16% production module
- Organic PV — Build on BES prog., demonstrate market viability
- III-V 1J via HVPE — Develop low-cost, 1-sun III-V cells
- Novel PV Absorbers — Build on EFRC, identify new absorbers
- Perovskites — Answer industrial processing and stability questions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Photovoltaic Module Qualification Plus Testing

Sarah Kurtz, John Wohlgemuth, Michael Kempe, Nick Bosco, Peter Hacke, Dirk Jordan, David C. Miller, and Timothy J. Silverman
National Renewable Energy Laboratory

Nancy Phillips
3M

Thomas Earnest
DuPont

Ralph Romero
Black & Veatch

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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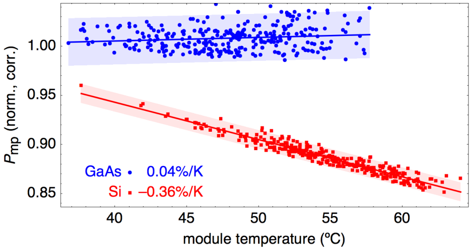
Technical Report
NREL/TP-5200-60950
December 2013

Contract No. DE-AC36-08GO28308

Module Performance



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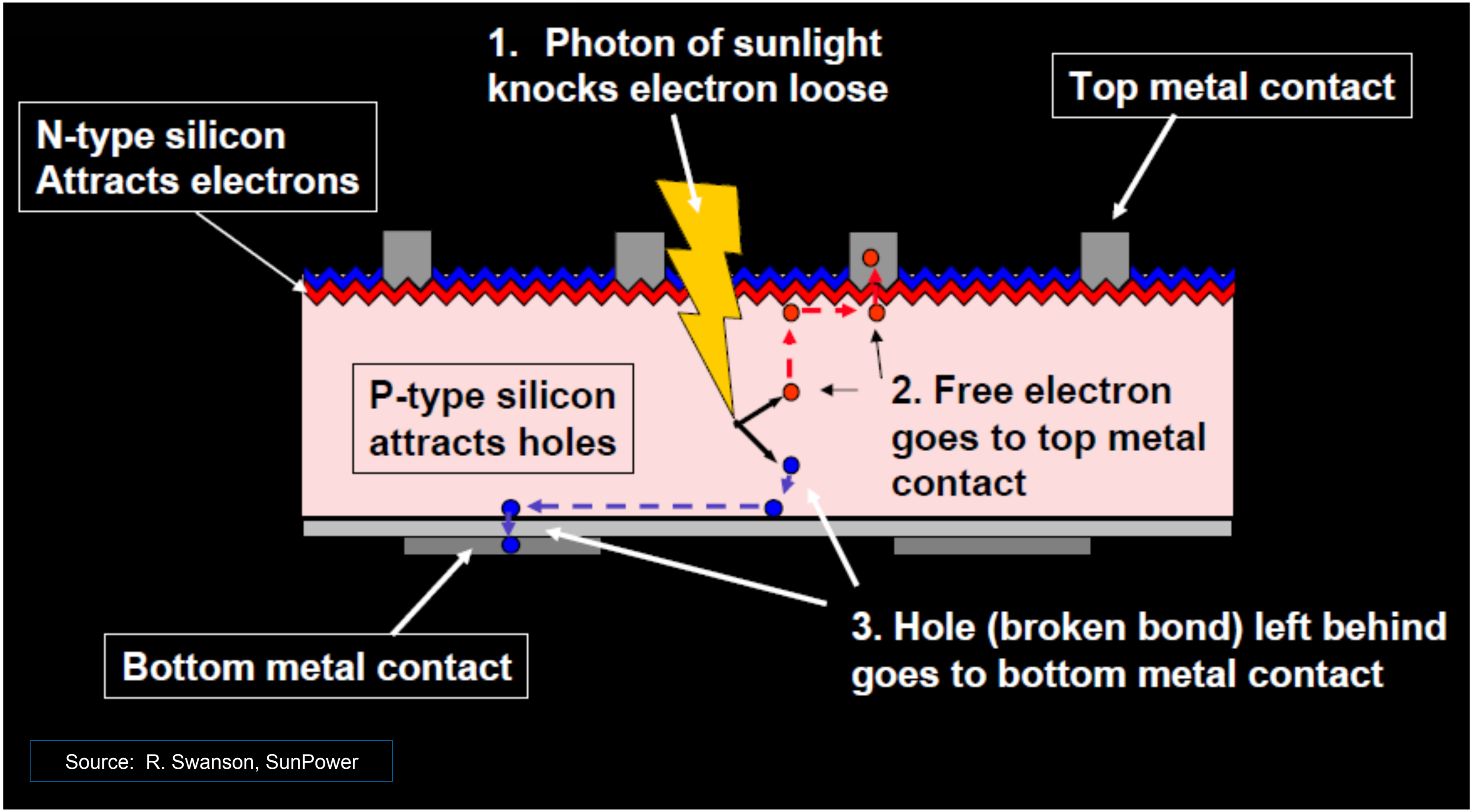
A Brief History of Photovoltaics

- **1839 - French scientist Edmond Becquerel discovers the photovoltaic effect** while experimenting with an electrolytic cell made up of two metal electrodes placed in an electricity-conducting solution—electricity generation increased when exposed to light.
- **1883** - Charles Fritts, an American inventor, described the first solar cells made from selenium wafers.
- **1905 - Albert Einstein published his paper on the photoelectric effect** (along with a paper on his theory of relativity).
- **1921 - Albert Einstein wins the Nobel Prize** for his theories (1904 research and technical paper) explaining the photoelectric effect.
- **1954 - Photovoltaic technology is born in the United States** when Daryl Chapin, Calvin Fuller, and Gerald Pearson develop the silicon photovoltaic (PV) cell at Bell Labs. Bell Telephone Laboratories produced a silicon solar cell with 4% efficiency and later achieved 11% efficiency.
- **1958 - The Vanguard I space satellite used a small (less than one watt) array to power its radios**. Later that year, Explorer III, Vanguard II, and Sputnik-3 were launched with PV-powered systems on board.

Physics of a PV Cell



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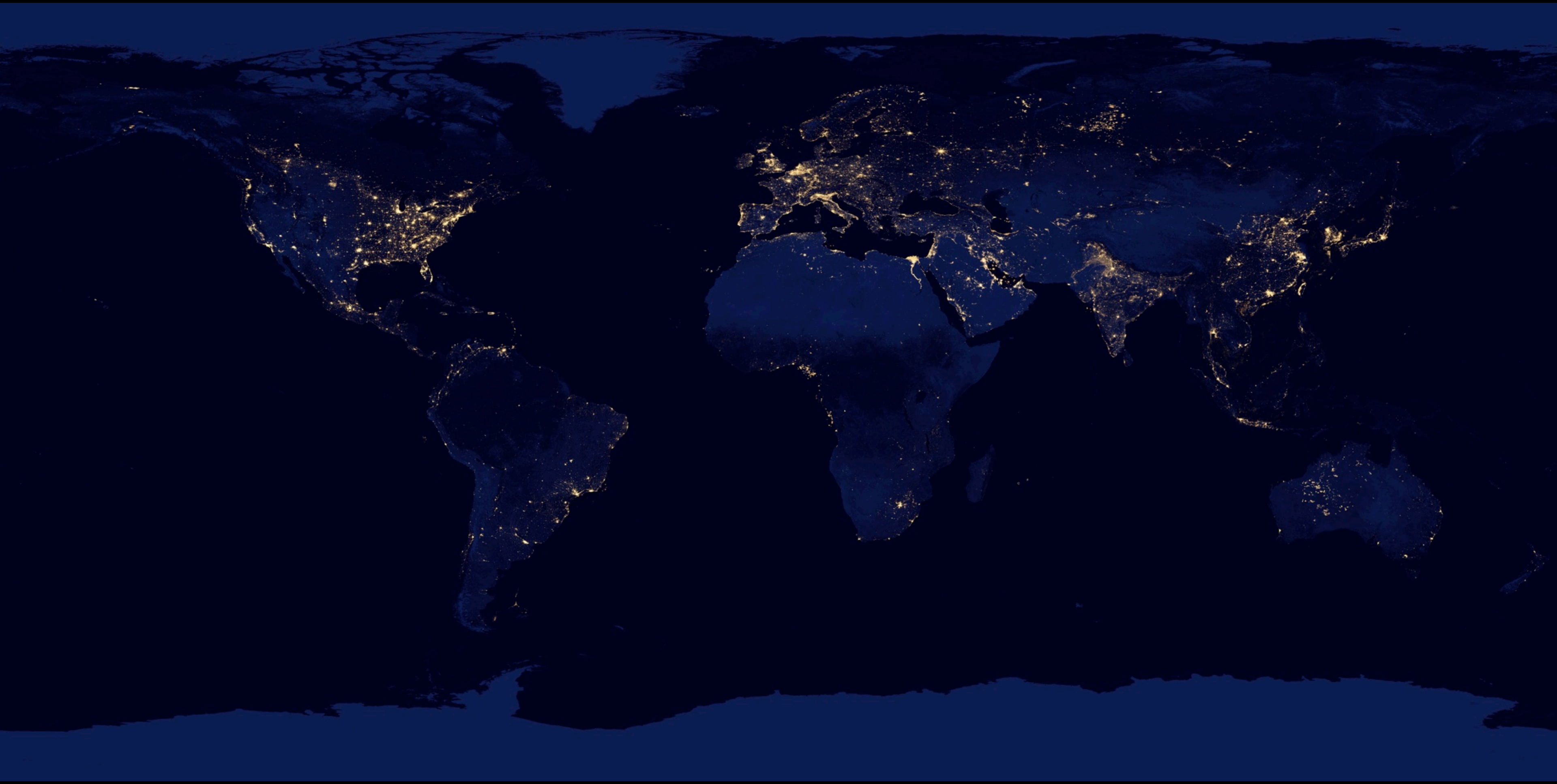


Earth

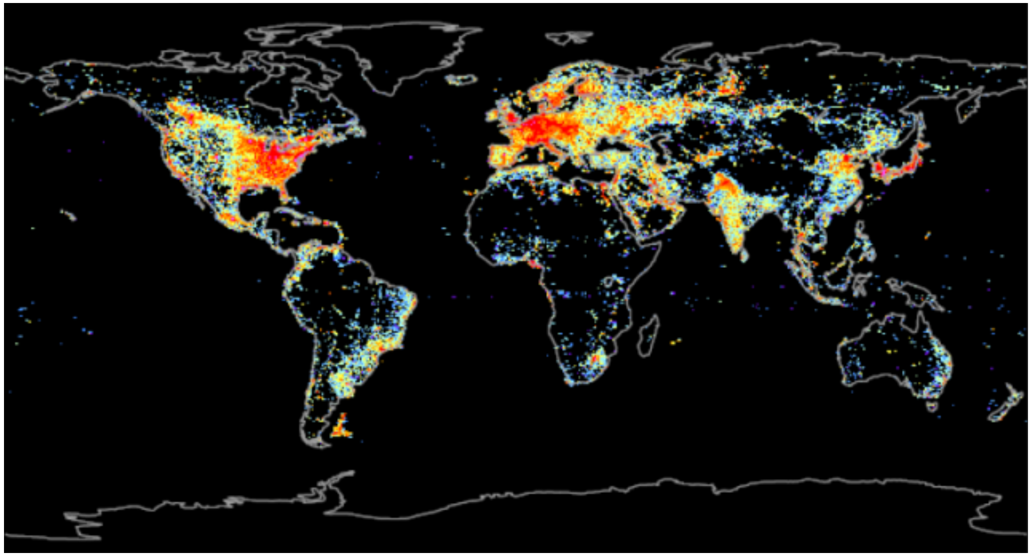
Human Population = 7.3 B

Annual Electricity Demand = 22,800 TWh

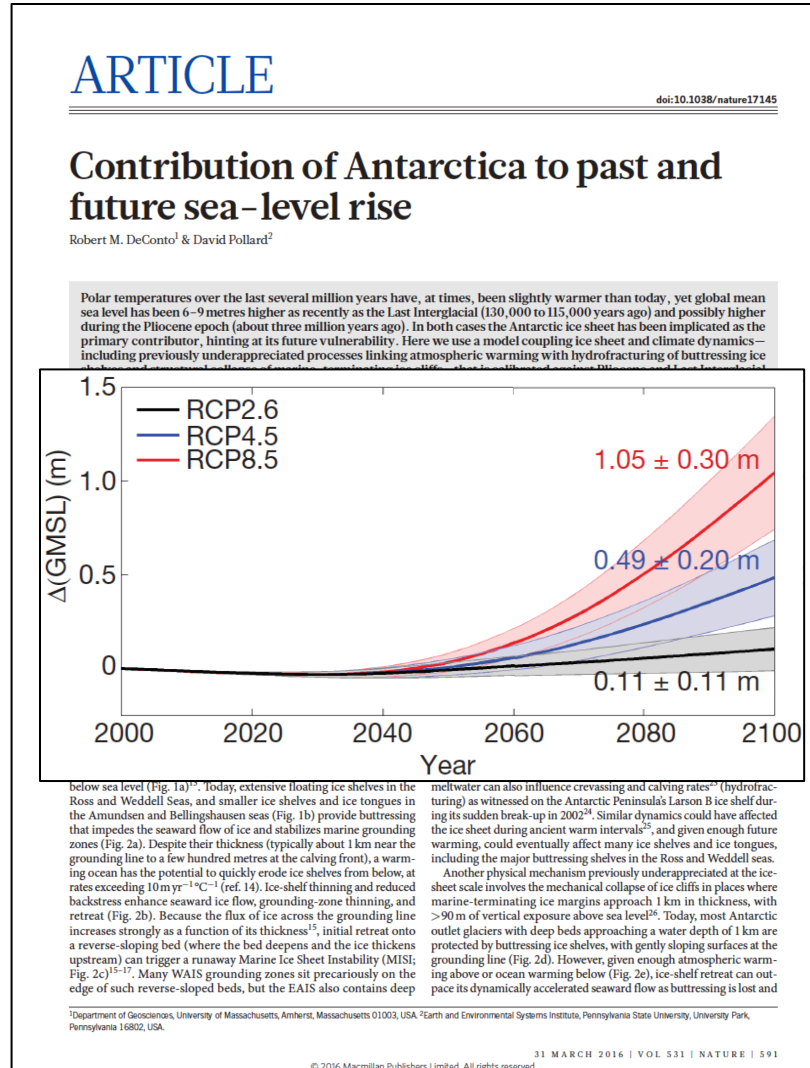
Annual CO_2 Emissions = 32.2 Gt

Fraction of GHG Emissions from Energy Use ≈ 68%

Motivation is Clear – Energy Needs vs. CO_2



- **Earth uses ~6 TW of electricity, ~2/3 from fossil fuels.**
- **$[CO_2]$ ~402 ppm and rising.**



ARTICLE

doi:10.1038/nature17145

Contribution of Antarctica to past and future sea-level rise

Robert M. DeConto[1] & David Pollard[2]

Polar temperatures over the last several million years have, at times, been slightly warmer than today, yet global mean sea level has been 6–9 metres higher as recently as the Last Interglacial (130,000 to 115,000 years ago) and possibly higher during the Pliocene epoch (about three million years ago). In both cases the Antarctic ice sheet has been implicated as the primary contributor, hinting at its future vulnerability. Here we use a model coupling ice sheet and climate dynamics—including previously underappreciated processes linking atmospheric warming with hydrofracturing of buttressing ice

below sea level (Fig. 1a)[13]. Today, extensive floating ice shelves in the Ross and Weddell Seas, and smaller ice shelves and ice tongues in the Amundsen and Bellingshausen seas (Fig. 1b) provide buttressing that impedes the seaward flow of ice and stabilizes marine grounding zones (Fig. 2a). Despite their thickness (typically about 1 km near the grounding line to a few hundred metres at the calving front), a warming ocean has the potential to quickly erode ice shelves from below, at rates exceeding $10\,m\,yr^{-1}\,°C^{-1}$ (ref. 14). Ice-shelf thinning and reduced backstress enhance seaward ice flow, grounding-zone thinning, and retreat (Fig. 2b). Because the flux of ice across the grounding line increases strongly as a function of its thickness[15], initial retreat onto a reverse-sloping bed (where the bed deepens and the ice thickens upstream) can trigger a runaway Marine Ice Sheet Instability (MISI; Fig. 2c)[15–17]. Many WAIS grounding zones sit precariously on the edge of such reverse-sloped beds, but the EAIS also contains deep

meltwater can also influence crevassing and calving rates[23] (hydrofracturing) as witnessed on the Antarctic Peninsula's Larson B ice shelf during its sudden break-up in 2002[24]. Similar dynamics could have affected the ice sheet during ancient warm intervals[25], and given enough future warming, could eventually affect many ice shelves and ice tongues, including the major buttressing shelves in the Ross and Weddell seas.

Another physical mechanism previously underappreciated at the ice-sheet scale involves the mechanical collapse of ice cliffs in places where marine-terminating ice margins approach 1 km in thickness, with >90 m of vertical exposure above sea level[26]. Today, most Antarctic outlet glaciers with deep beds approaching a water depth of 1 km are protected by buttressing ice shelves, with gently sloping surfaces at the grounding line (Fig. 2d). However, given enough atmospheric warming above or ocean warming below (Fig. 2e), ice-shelf retreat can outpace its dynamically accelerated seaward flow as buttressing is lost and

[1]Department of Geosciences, University of Massachusetts, Amherst, Massachusetts 01003, USA. [2]Earth and Environmental Systems Institute, Pennsylvania State University, University Park, Pennsylvania 16802, USA.

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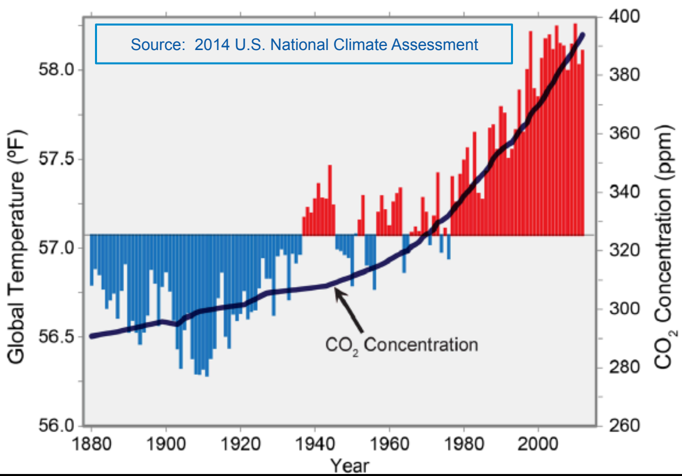
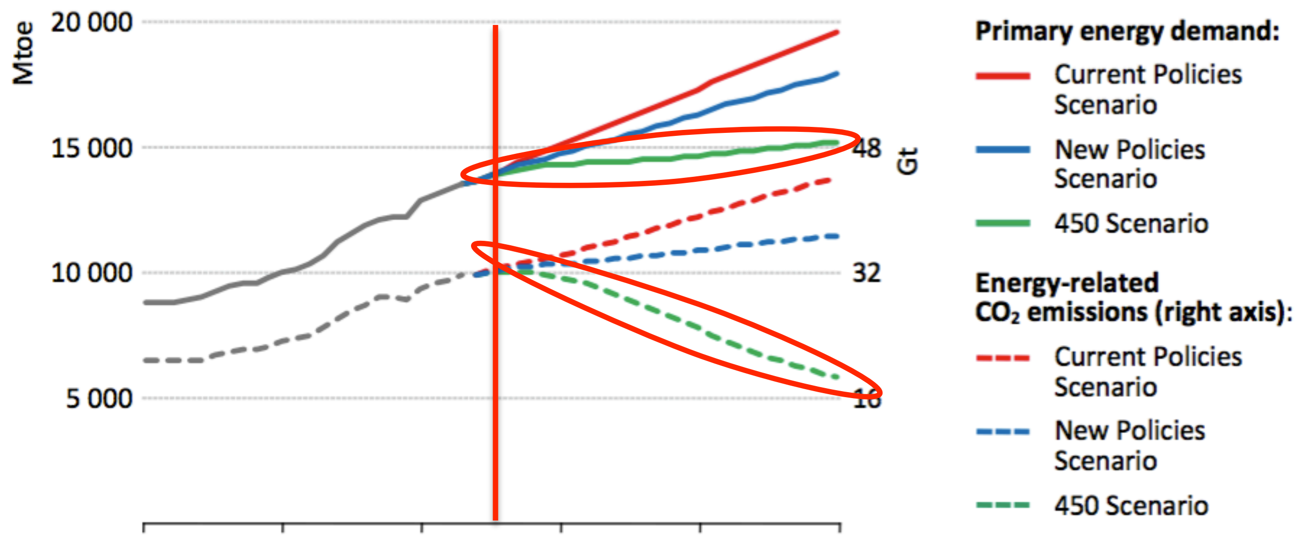


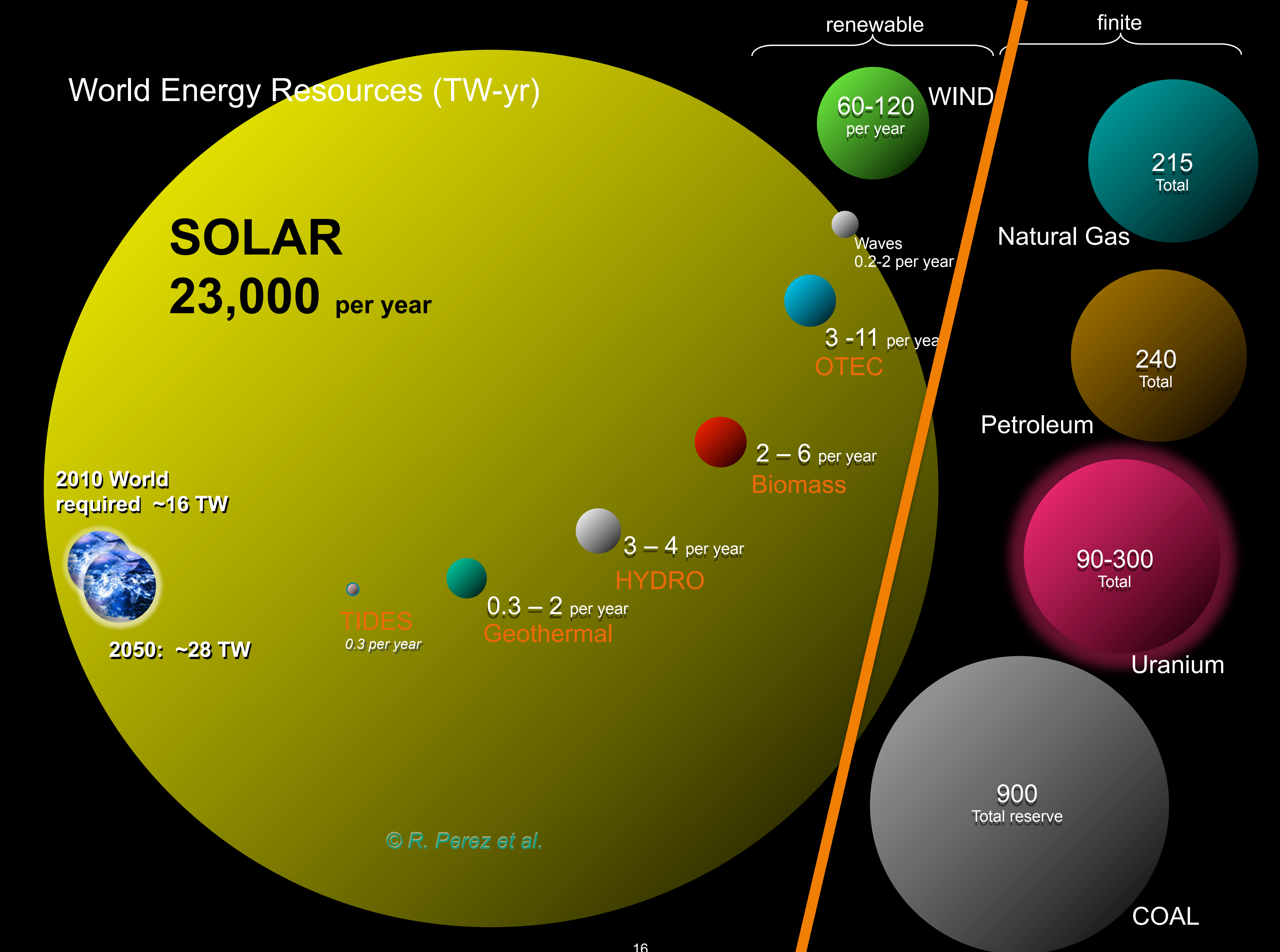
450ppm Goal: Dramatic Change Needed

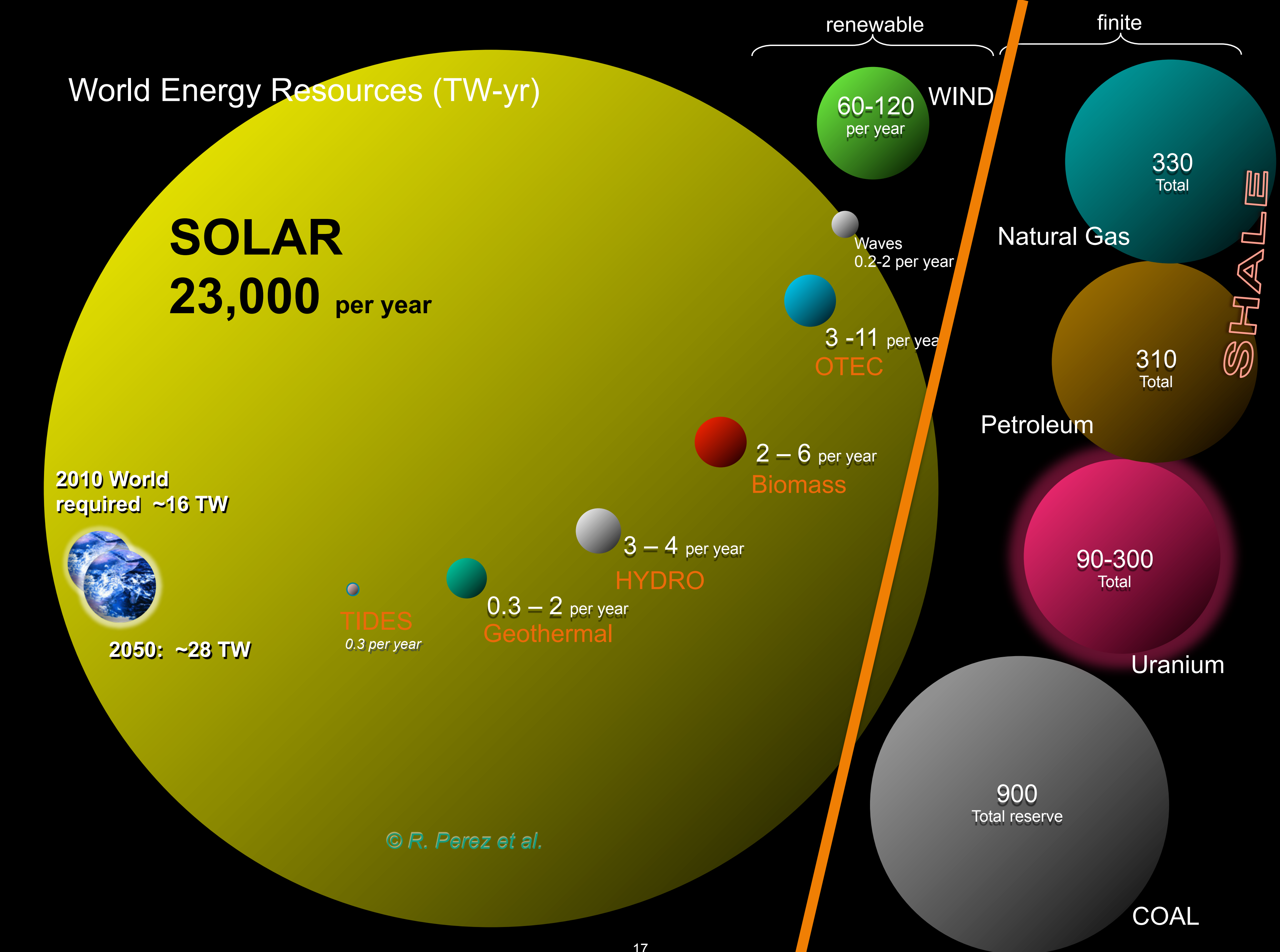


Source: 2015 IEA World Energy Outlook

- Must hold overall energy consumption essentially flat for the next 25 years through major gains in energy efficiency.
- Must begin a major shift to zero carbon generation immediately, with measurable reductions by 2020.

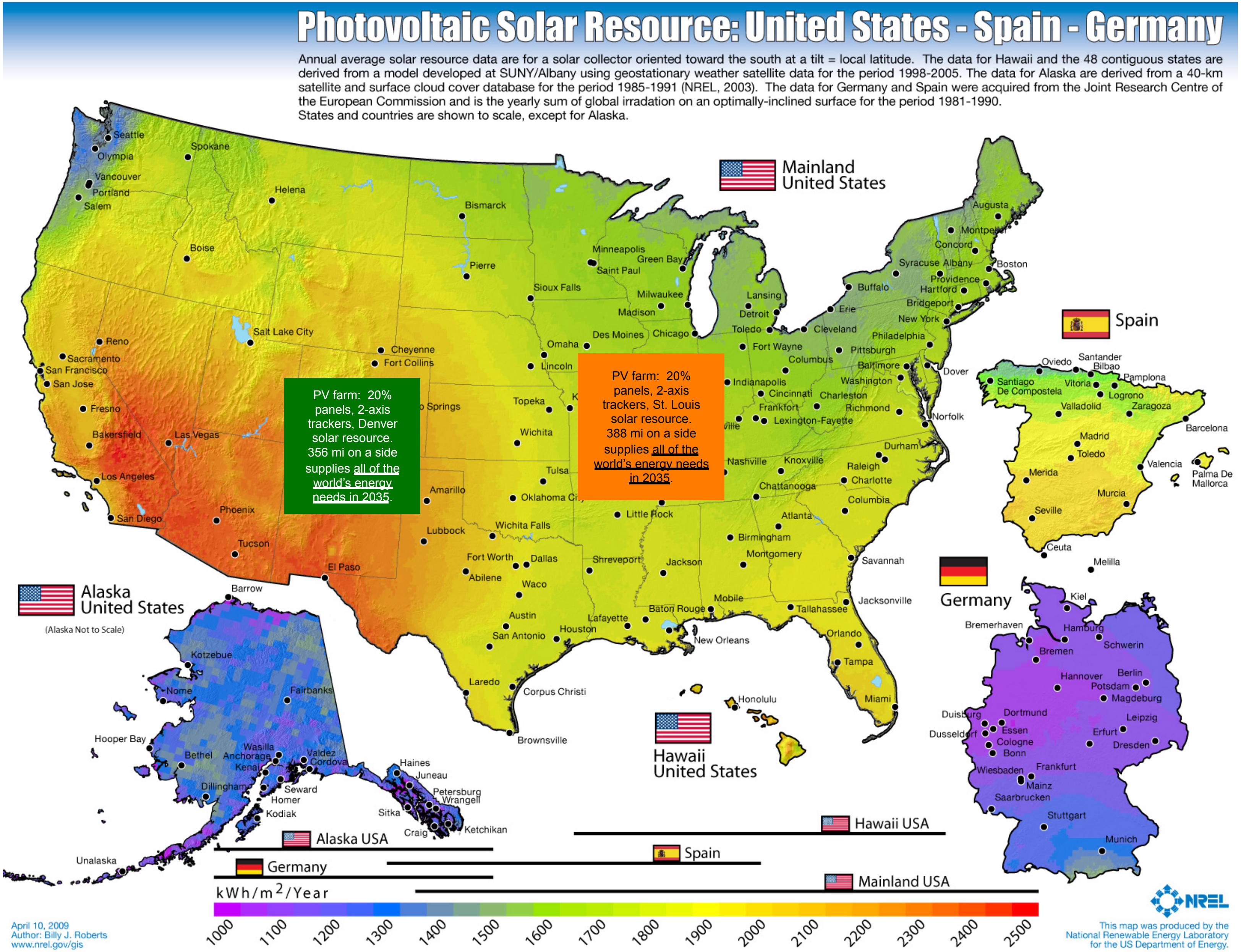




World Energy Resources (TW-yr)
renewable
finite
SOLAR
23,000 per year
60-120 per year
WIND
Waves
0.2-2 per year
3 -11 per yea
OTEC
2 – 6 per year
Biomass
3 – 4 per year
HYDRO
0.3 – 2 per year
Geothermal
TIDES
0.3 per year
2010 World
required ~16 TW
2050: ~28 TW
215
Total
Natural Gas
240
Total
Petroleum
90-300
Total
Uranium
900
Total reserve
COAL
© R. Perez et al.



World Energy Resources (TW-yr)
renewable
finite
SOLAR
23,000 per year
2010 World
required ~16 TW
2050: ~28 TW
TIDES
0.3 per year
0.3 – 2 per year
Geothermal
3 – 4 per year
HYDRO
2 – 6 per year
Biomass
3 -11 per year
OTEC
Waves
0.2-2 per year
60-120
per year
WIND
330
Total
Natural Gas
SHALE
310
Total
Petroleum
90-300
Total
Uranium
900
Total reserve
COAL
© R. Perez et al.

Solar Insolation – U.S.



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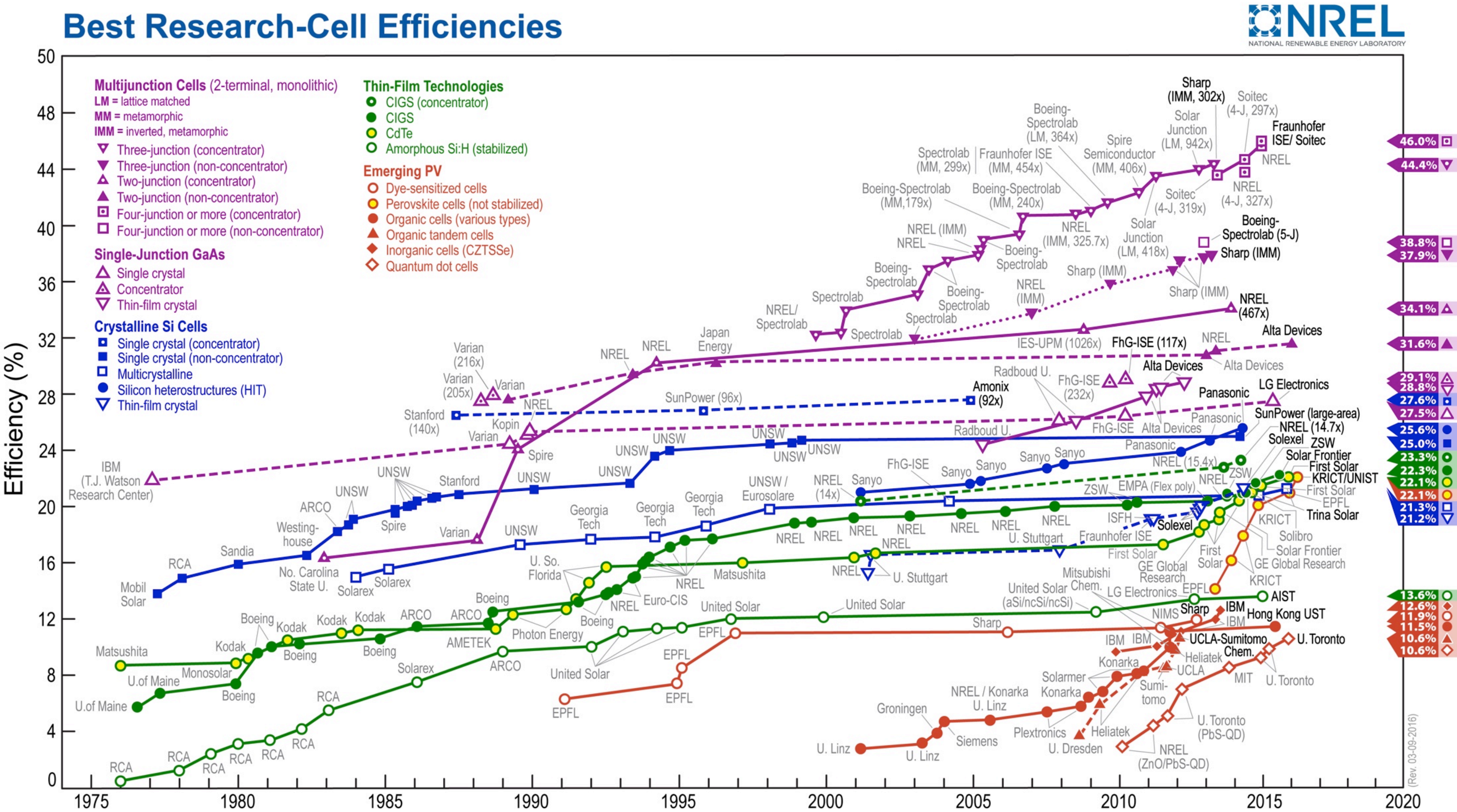
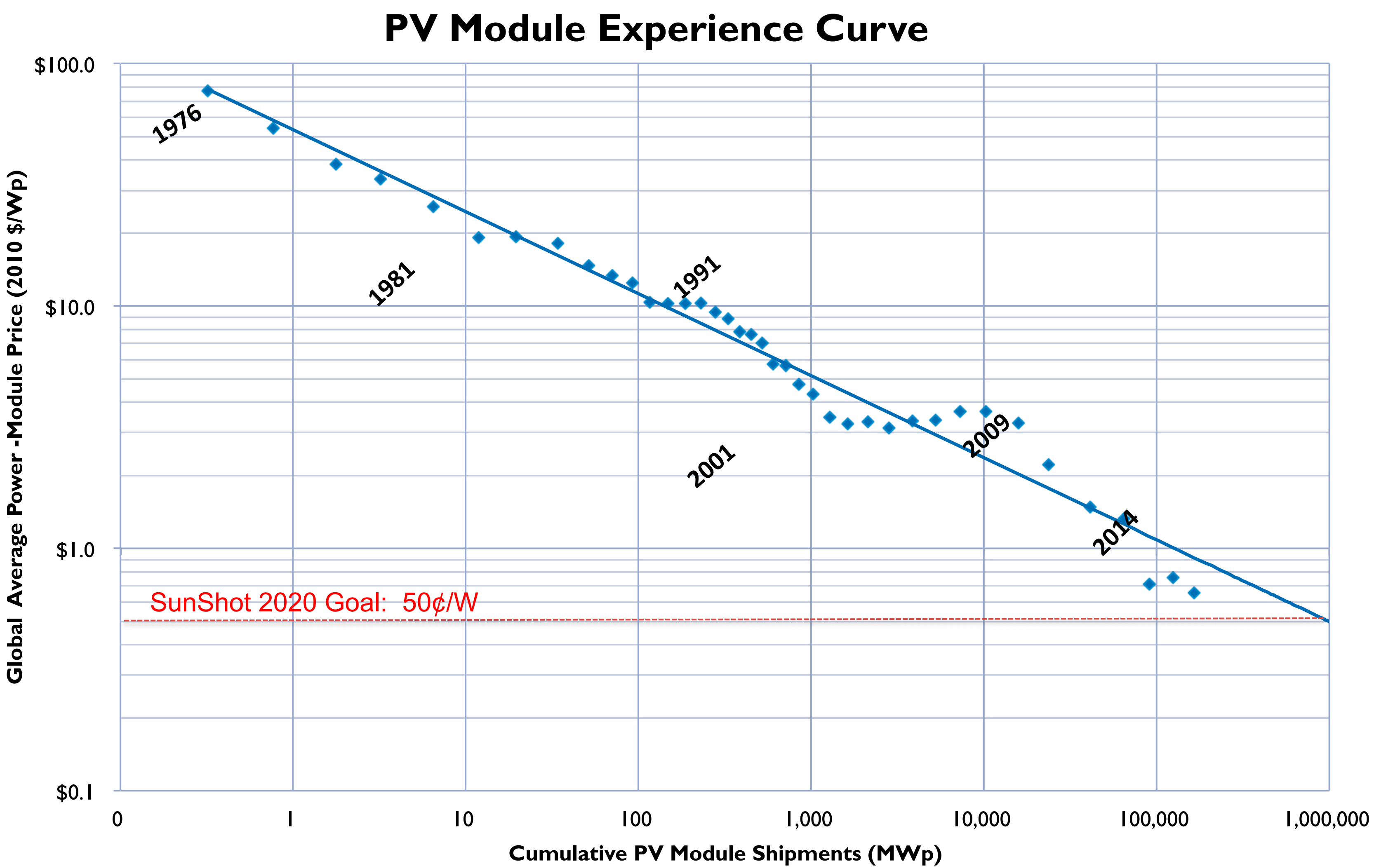
PV Research – Dramatic Progress

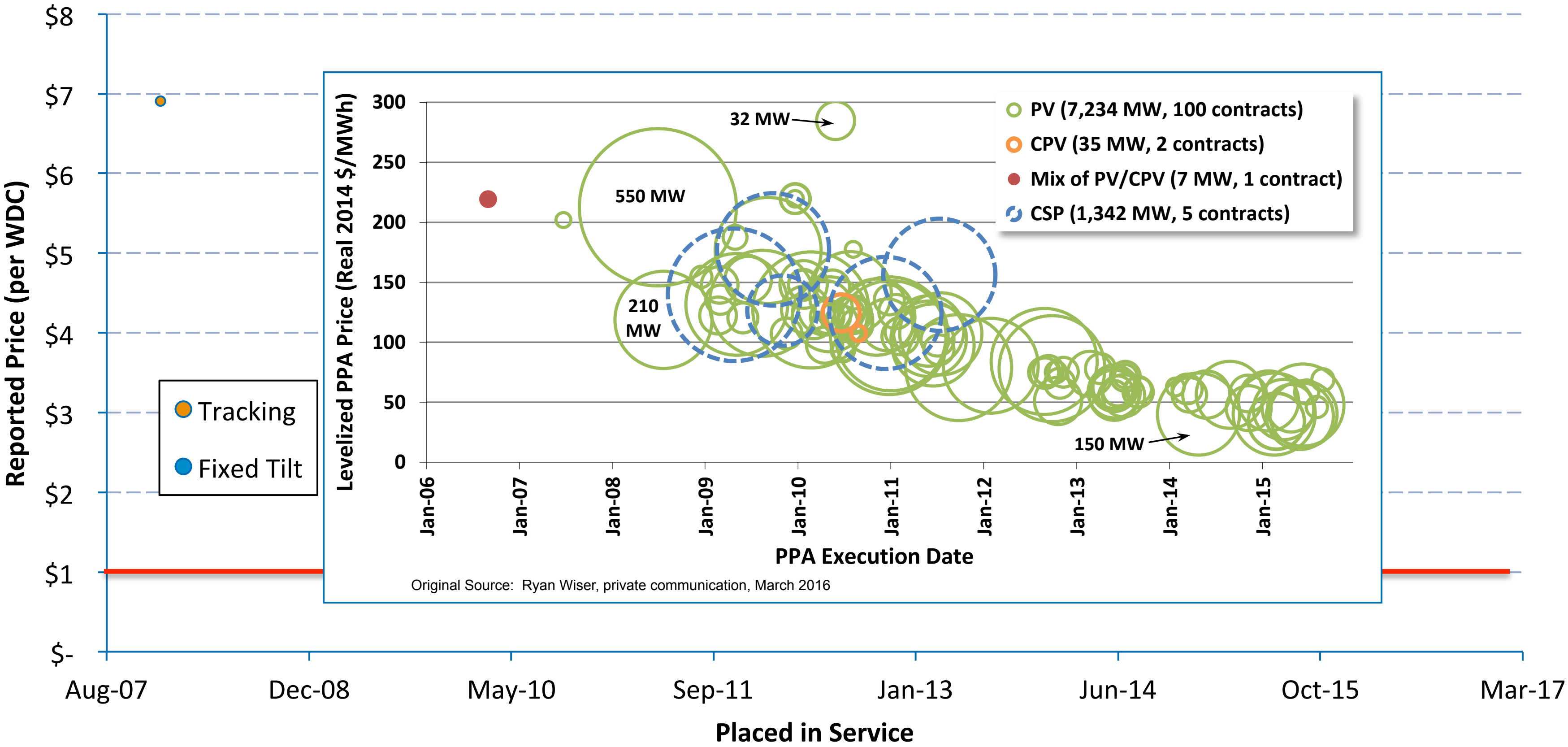


PV Module Cost Decline



Sources: Strategies Unlimited, Navigant Consulting & Paula Mints

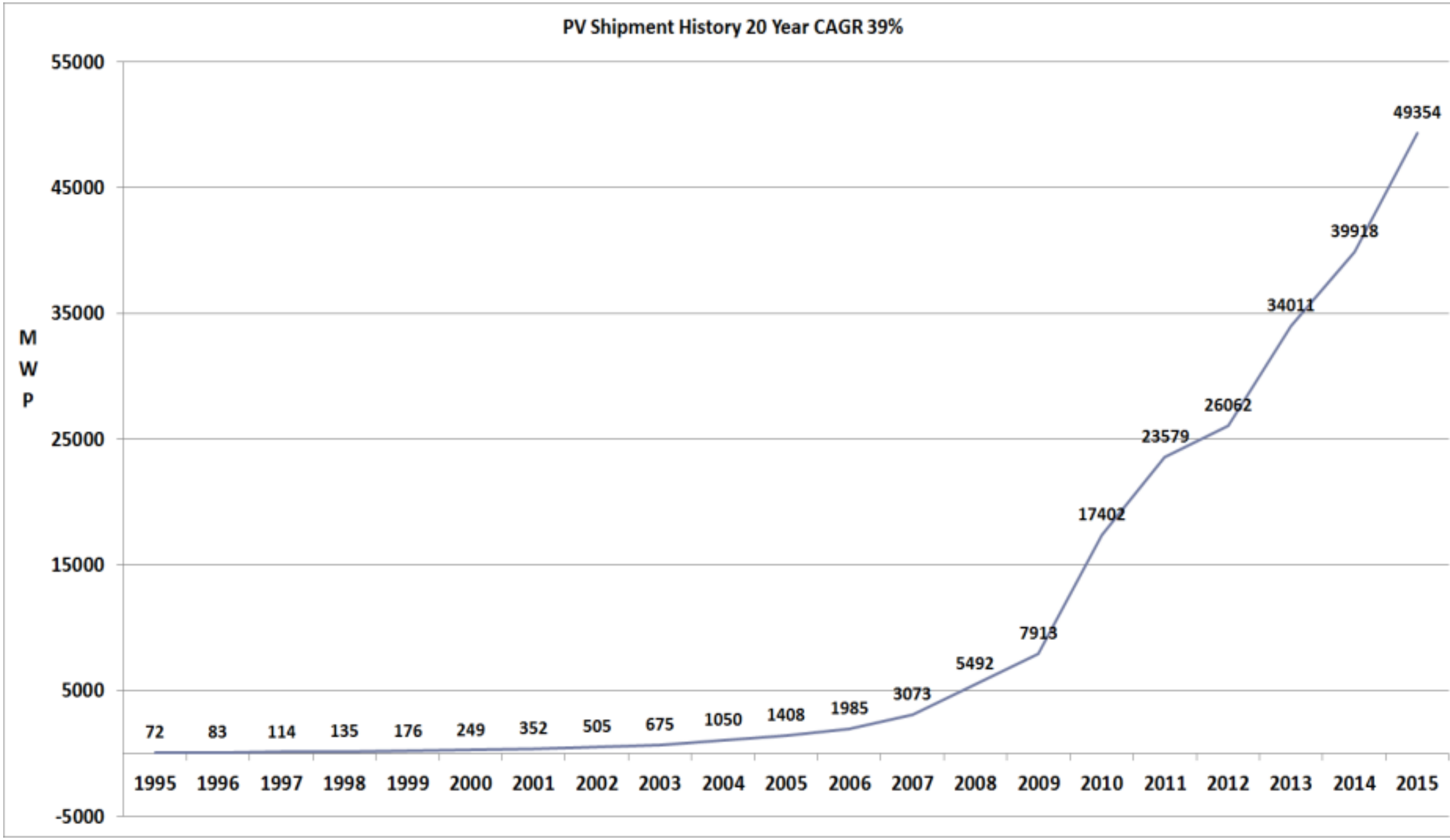
US System Pricing – Utility Scale >5 MW



- PV system costs at all scales declining rapidly.
- SunShot goal of $1/W corresponds to LCOE of 6 ¢/kWh.

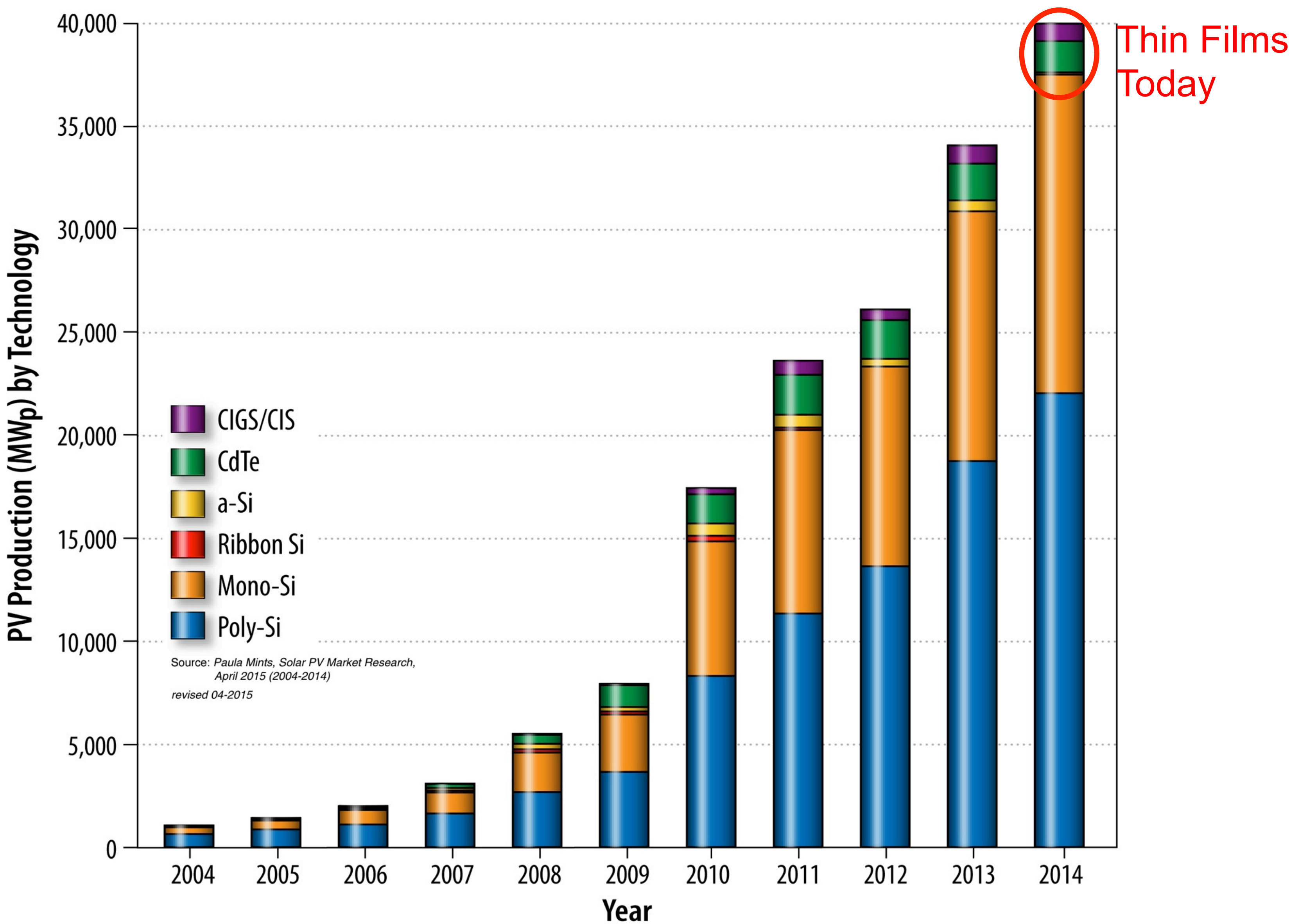
Original Source: NREL 3Q15 Solar Update, Feldman et al., 19JAN16

PV Annual Installations: 1995 - 2015

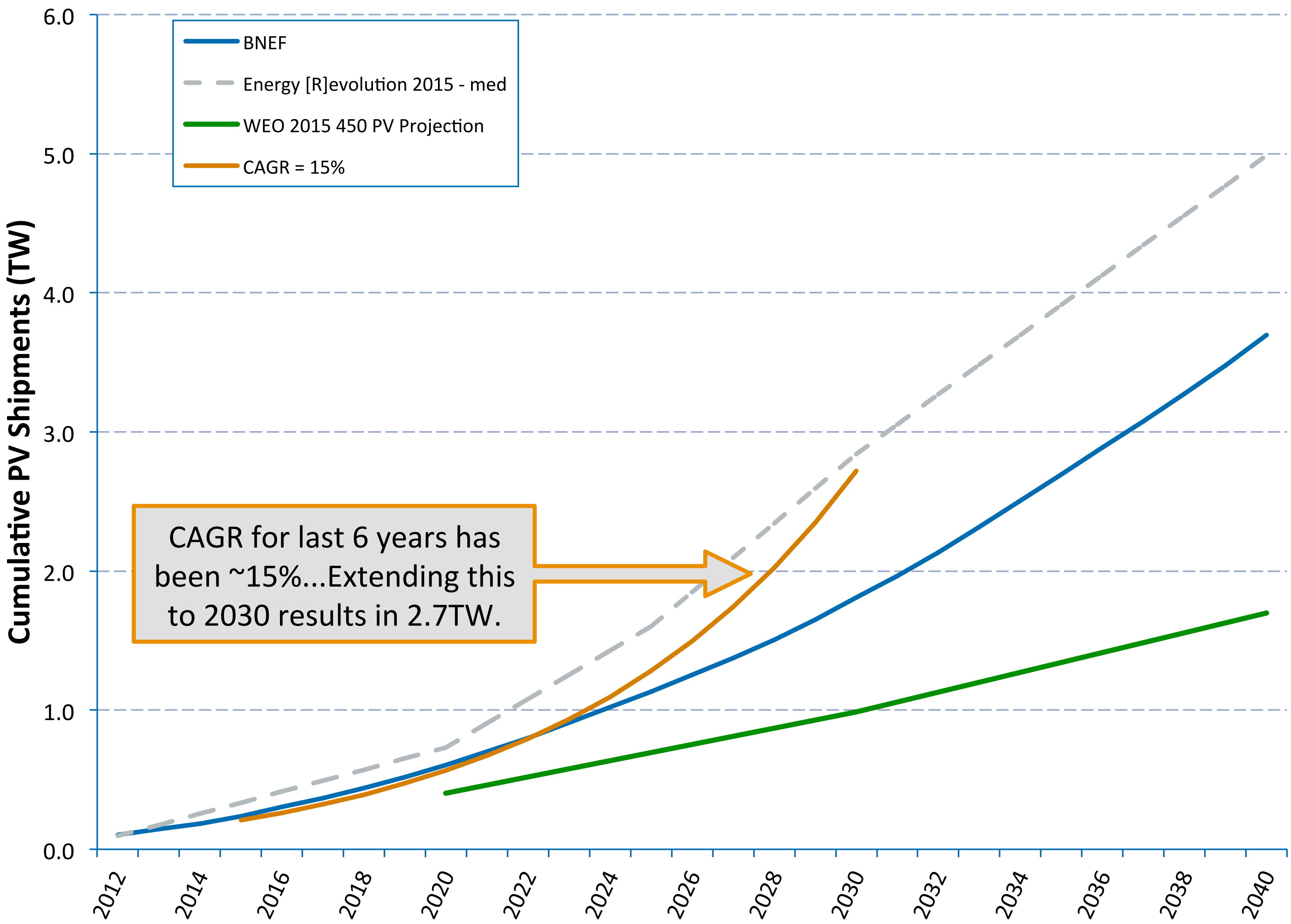


Source: Paula Mints, NREL Internal Workshop, 27JAN16

PV Industry Growth – By Technology



Global PV Capacity - Forecasts



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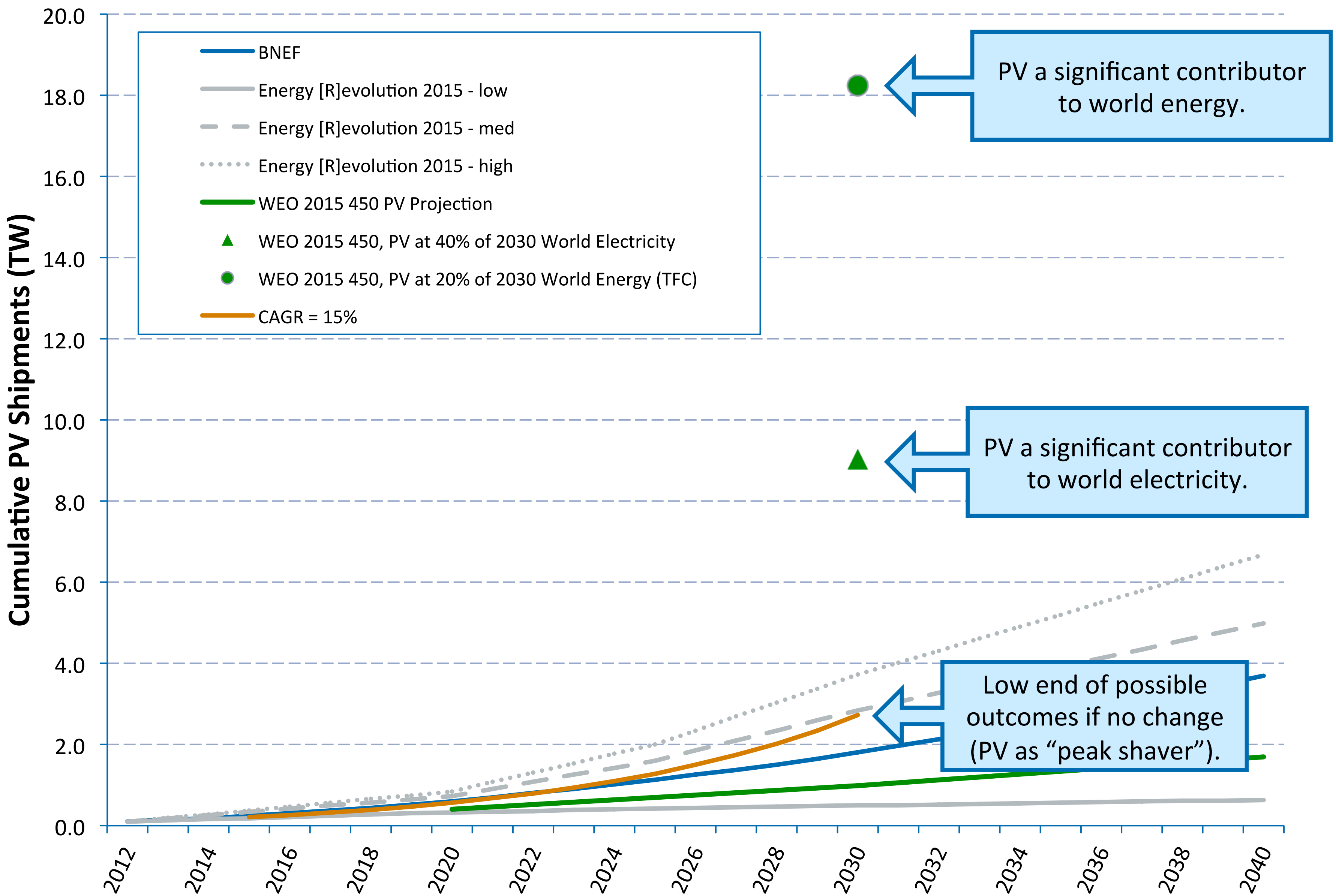
GA-SERI: The TW Workshop

GA-SERI

The Terawatt Workshop

Global Alliance of Solar Energy Research Institutes

Global PV Growth & CO_2 Emission Goals

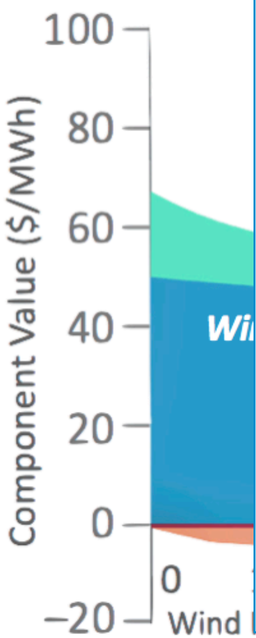


Barrier: Devaluation of PV Electrons

Why? Because PV Is a Poor Match to Electricity Load as Penetrations Increase, Reducing "Value"

BERKELEY LAB

Value = ability to offset electric sector costs, considering Energy Value, Capacity Value, DA Forecast Error, Ancillary Services; Source: Mills and Wiser (2012); California focus

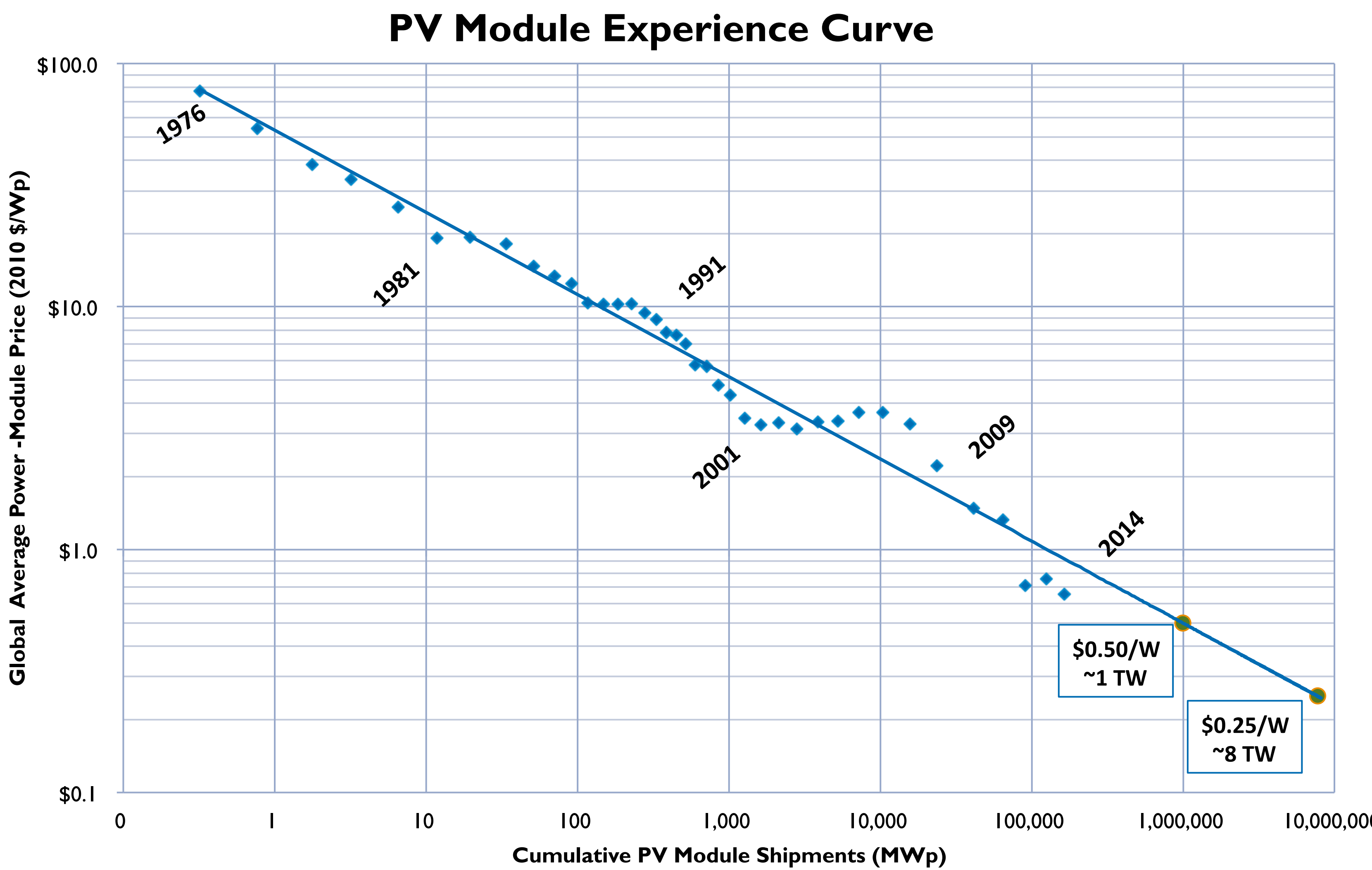


This barrier can be eliminated by the development of low cost energy storage technologies…

- Li Ion Batteries
- Flow Batteries
- Thermal Storage
- Pumped Hydro
- CAES & "LAES"
- H_2 Generation – Electrolysis

4

Multi-TW Scale PV: Projected Module Price



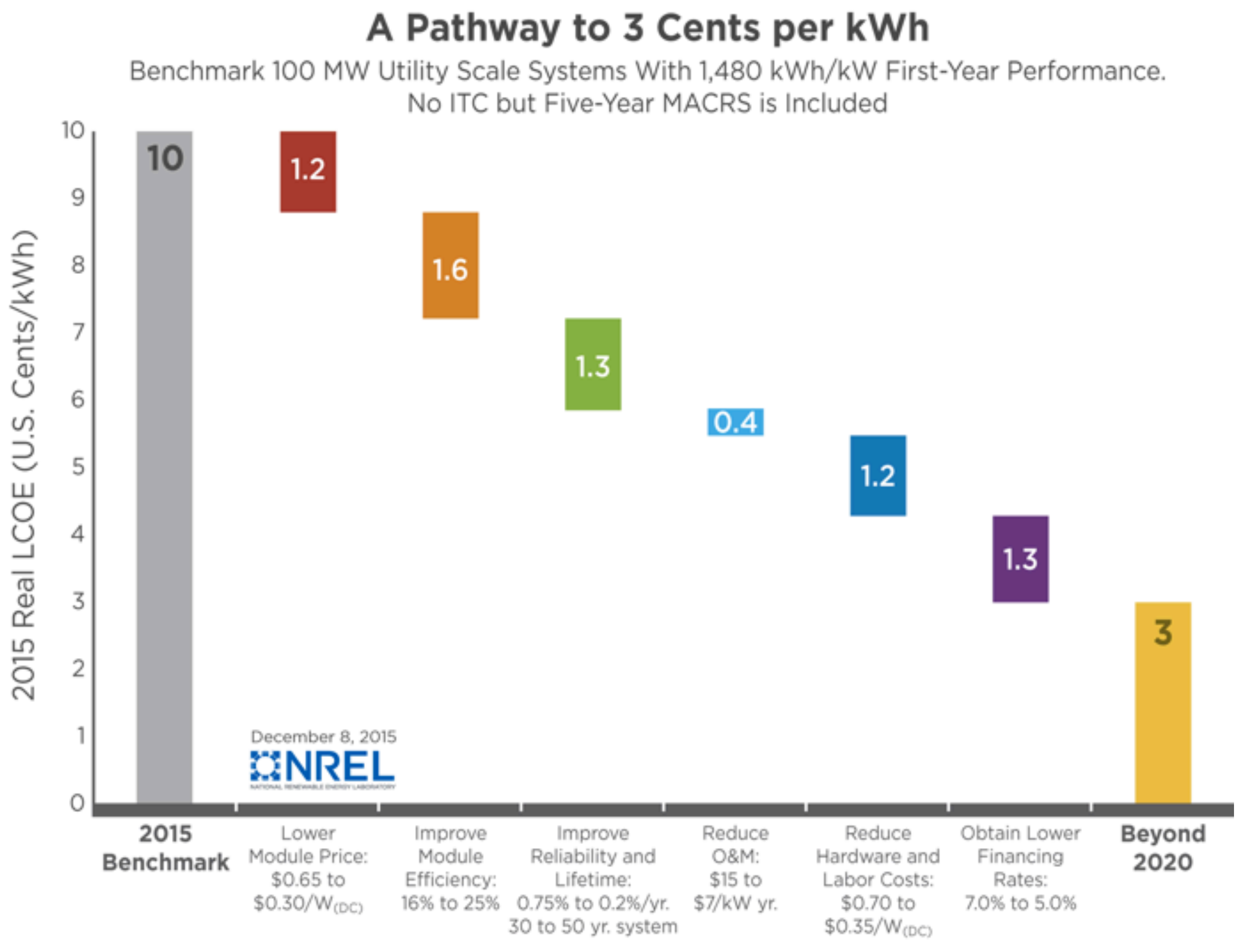
GA-SERI: The TW Workshop

GA-SERI
The Terawatt Workshop
AIST ISE NREL
Global Alliance of Solar Energy Research Institutes

Conclusions:

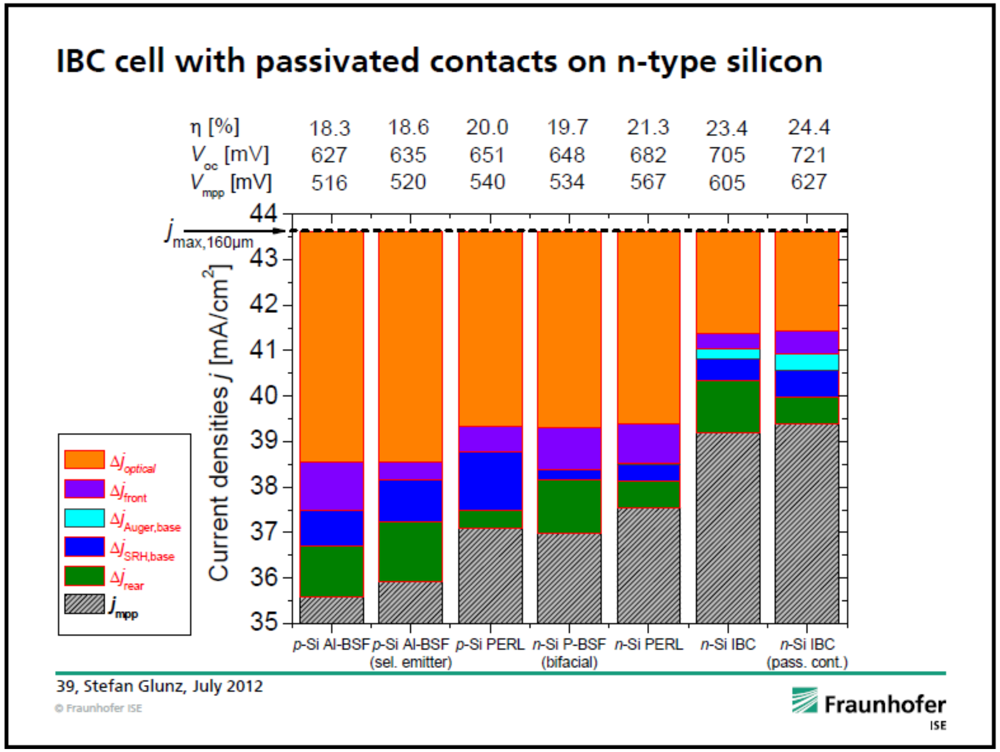
- Cumulative capacity of 3 TW PV by 2030 is anticipated (line of sight).
- Requires 500 GW/year market by 2030.
- 5 - 10 TW is achievable, 20 TW in 2040 is needed for climate goals.
- Requires further, continuous reduction of Cap-Ex (and Op-Ex) for stable business models.
- Requires flexible grid, demand side management, lower cost of storage, batteries, especially to go beyond 5 TW.
- Requires adequate and innovative funding mechanisms, especially for developing world.
- Requires stable R&D support, increasing R&D support to go beyond 5 TW in 2030 by industry & public institutions, including systemic R&D geared at increasing efficiencies, durability, and decreasing production costs.
- Increased attention to public, political support in view of resistance of incumbents.

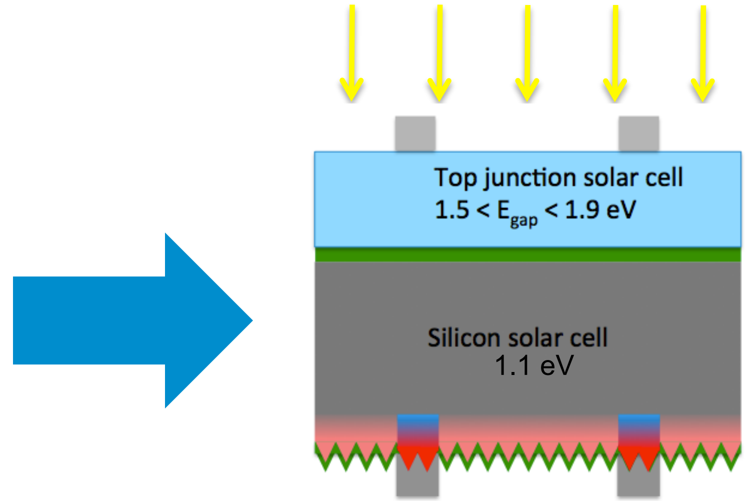
Example – Path to 3¢/kWh LCOE Target



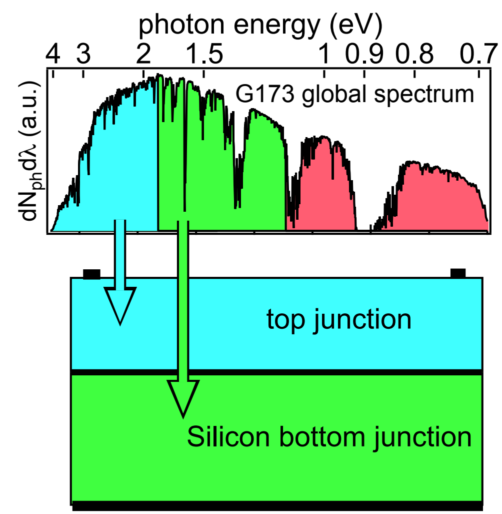
- Module cost, efficiency and reliability will be the focus of major new R&D efforts.
- For 2 growth scenarios beyond peak shaving, R&D directed at storage in all forms will also be needed.

Si Tandem Cells



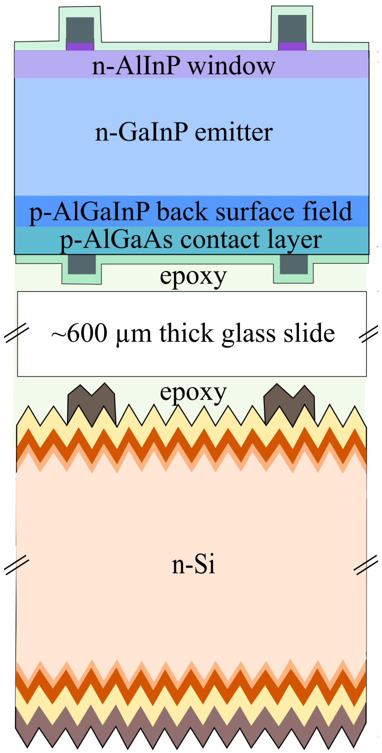


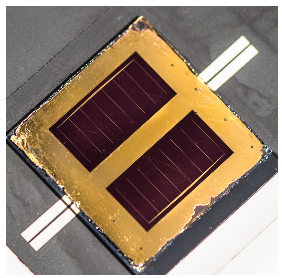
Source: Stefan Glunz presentation, NREL Si Workshop in Vail, CO, July, 2012



- Path to > 30% efficiency for Si wafer based cells.
- Top cell requirements:
  - Lattice & CTE match to Si if epitaxially grown
  - ~1.7 eV band gap
- Perovskites may evolve into good polycrystalline choice.

Development of World Record GaInP/Si Dual-Junction, One-Sun Solar Cell





The device structure integrates a 1.8-eV GaInP top junction with a silicon bottom junction, with a four-terminal interconnection. The resulting device is pictured at right.

- Cost-effective solar cells with efficiency greater than possible with conventional silicon could enable a very large market for low-concentration photovoltaics.
- A two-junction structure with a silicon bottom junction is an attractive path to this goal.
- NREL developed a new device structure combining a III-V GaInP top junction and a silicon bottom junction, and demonstrated a world record 29.8% efficiency – significantly exceeding the best conventional silicon efficiency of 25.6%.
- The four-terminal structure allows ease of construction, and optimal energy production under real-world operating conditions.
- We are presently developing an improved, manufacturable bonding technique to enable transfer of this structure to industry.

S. Essig et al, Energy Procedia 77, p. 464 (2015).

High-Efficiency Multi-junction Solar Cells

Integrating Capabilities to Bring Advanced Technology from Space to Earth

- Systems Engineering & Integration
- Decision Science & Analysis
- Power Systems & Electrical Engineering
- Applied Materials Science & Engineering
- Chemical Engineering
- Advanced Computer Science, Visualization & Data

Integration to Impact

All commercial cells for space and concentrator PV based on NREL multijunction technology

Solar Junction

SPECTROLAB A BOEING COMPANY

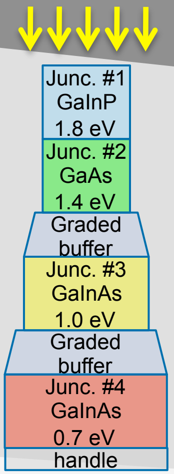
emcore empower with light

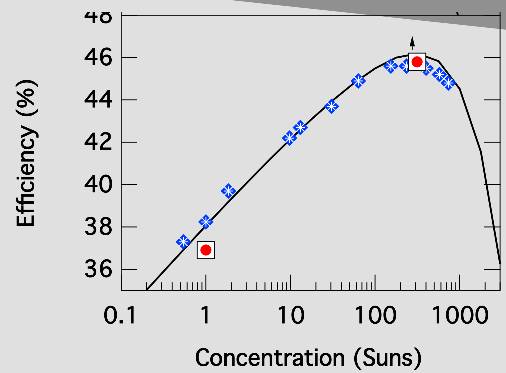
R&D 100 Awards:

- **2012, with Solar Junction**
- **2008, with Emcore**
- **2001, with Spectrolab**

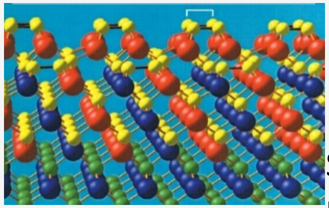
Innovation to Application

Devices with "engineered" multilayered structures have ~46% conversion efficiency

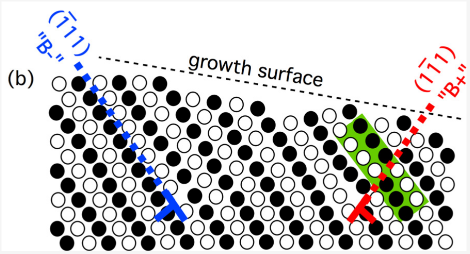




Foundational *Knowledge*

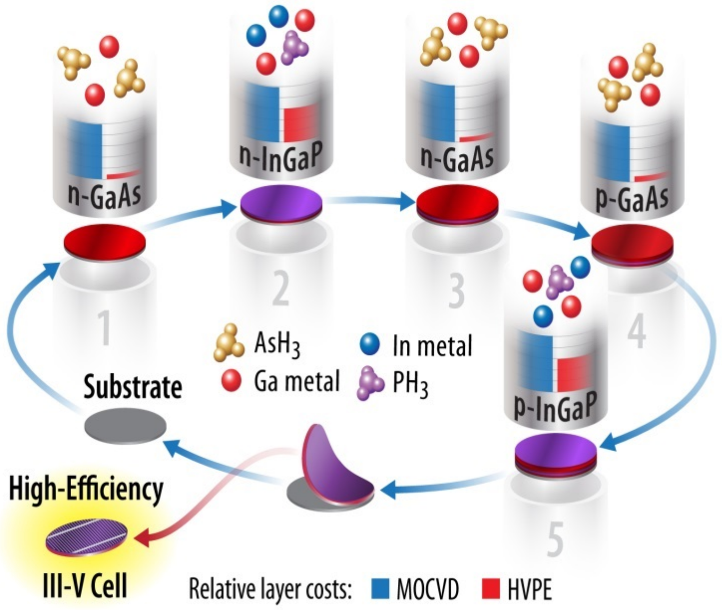


Superstructure ordering modifies the energy band and tailored optical properties



Cation site order affects Dislocation glide energetics in alloys – allows rational design of multijunctions

High-Efficiency III-V Solar Cells at Unprecedented Low Costs



Schematic of an in-line HVPE reactor with continual substrate reuse that eliminates metal-organic sources and uses cheap elemental metals. Our reactor is a major step to this ultimate goal.

- High efficiency is critical to lowering photovoltaic costs. III-V PV is the most efficient, but most expensive. We aim to radically lower III-V costs to make III-V cells the preferred photovoltaic technology.
- Our approach to reduction of III-V growth cost is use of hydride vapor-phase epitaxy (HVPE), which drastically lowers both capital and materials costs while maintaining high efficiency.
- We also address cost of the expensive substrates, through strategies for reusing them.
- We have developed and are operating a novel HVPE reactor capable of growing >25% solar cells; 20.6% already demonstrated.

Simon et al, IEEE J. Photovolt. v.6, p. 191 (2016);
Schulte et al, J. Cryst. Growth v. 434 p. 138 (2016)

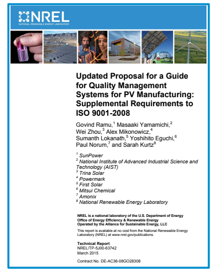
PV Reliability

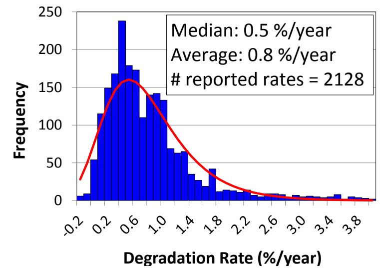
Reducing Cost of PV by Increasing PV Lifetime and Confidence in Long-Term Performance

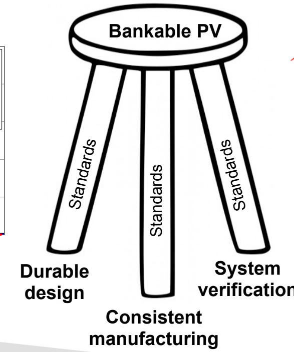
- Systems Engineering & Integration
- Decision Science & Analysis
- Mechanical Design & Engineering
- Power Systems & Electrical Engineering
- Materials Science & Engineering
- **Advanced Computer Science, Visualization & Data**

Integration to Impact

Develop international standards in partnership with manufacturers, test labs, installers, and international standards organizations





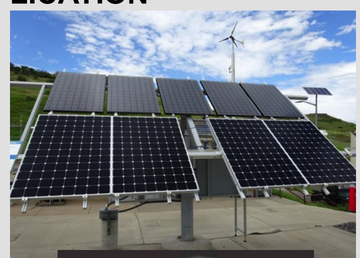


AIST · JRC European Commission · IEC · 3M

Innovation to Application

Study field and accelerated testing of PV products to quantify performance and long-term reliability

Regional Test Centers are managed jointly with Sandia



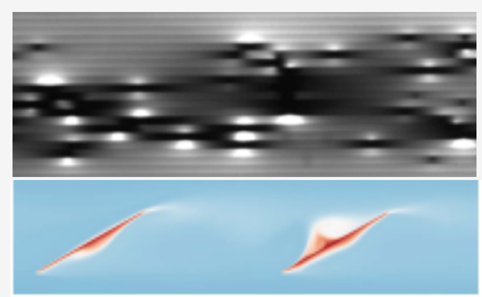
SUNPOWER

First Solar

Sandia National Laboratories · STION · EPRI Electric Power Research Institute

Foundational Knowledge

Fundamental understanding of adhesion, UV aging, moisture ingress, thermal management, reverse bias



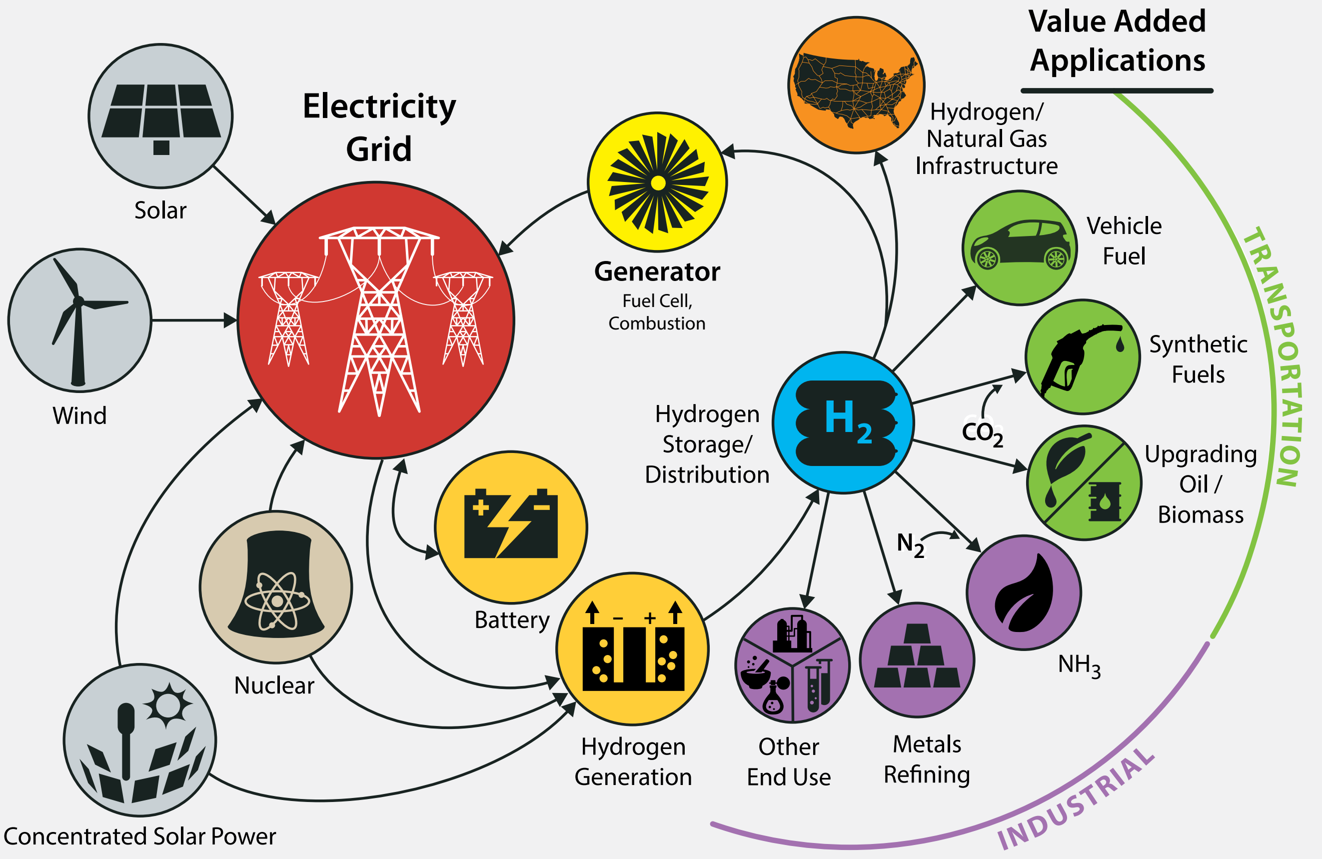
ATLAS Material Testing Solutions · Stanford University · ASU

Overview

1. Brief introduction of NREL and NREL's PV and Energy Materials Programs.
2. PV101
3. Energy and climate change.
4. Cell efficiency and module cost - 39 years of progress.
5. Enabling PV as a global carbon emissions reduction tool.
6. Final comments.

Future Energy System – Commodity H_2

Future H_2 at Scale Energy System



WHY HYDROGEN?

- Hydrogen is an ideal clean energy carrier—connecting diverse energy sources to diverse applications
- It can play a unique and critical role in addressing many of the energy sector's greatest challenges

TODAY'S ENERGY SYSTEM

- Renewable energy—particularly wind and solar—offer great promise but have challenges associated with variable and concurrent generation
- Options to achieve deep decarbonization while meeting society's multi-sector energy demands are limited, particularly in the industrial and transportation sectors

FUTURE H_2 AT SCALE ENERGY SYSTEM

- Connects low-carbon energy sources to all of the energy sectors
- Uses carbon-free, renewable inputs to service all of society's energy needs, in particular the difficult to decarbonize sectors of industry and transportation
- Does not compete with other options—rather, it enables increased renewable penetration
- Can decrease 45% of all U.S. carbon emissions by 2050

NREL NATIONAL RENEWABLE ENERGY LABORATORY | ENERGY SYSTEMS INTEGRATION FACILITY

U.S. DEPARTMENT OF ENERGY

The ESIF helps NREL contribute to the U.S. Department of Energy's and our nation's energy goals by providing the R&D capabilities needed to collaborate with private industry, academia, government, and public entities on utility-scale projects focused on solving issues in relation to grid integration of renewable energy and other efficiency technologies.

Global R&D Cooperation & New Funding

INTRODUCING THE

BREAKTHROUGH ENERGY COALITION

THE WORLD NEEDS WIDELY AVAILABLE ENERGY that is reliable, affordable and does not produce carbon. The only way to accomplish that goal is by developing new tools to power the world. That innovation will result from a dramatically scaled up public research pipeline linked to truly patient, flexible investments committed to developing the technologies that will create a new energy mix. The Breakthrough Energy Coalition is working together with a growing group of visionary countries who are significantly increasing their public research pipeline through the Mission Innovation initiative to make that future a reality.

- THE PRINCIPLES
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Thank You