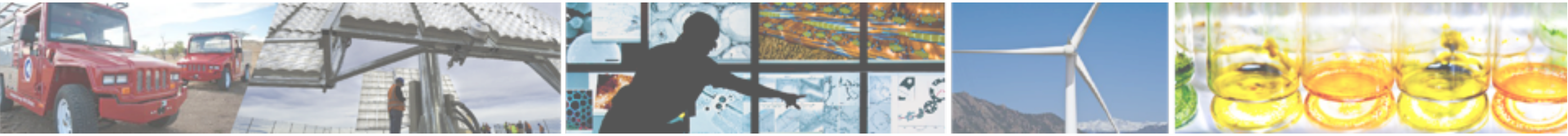


The Multi-TW Scale Future for PV

University of Chicago
Physics of Sustainable Energy Short Course

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

National Renewable Energy Laboratory
Golden, Colorado - USA

17 June, 2016

Overview

1. Brief introduction of NREL, the MCST Directorate and NREL's PV Program.
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

NREL’s Program Portfolio

Strategic Analysis

Efficient Energy Use

- Buildings Technologies
- Vehicle Technologies

Delivery & Storage

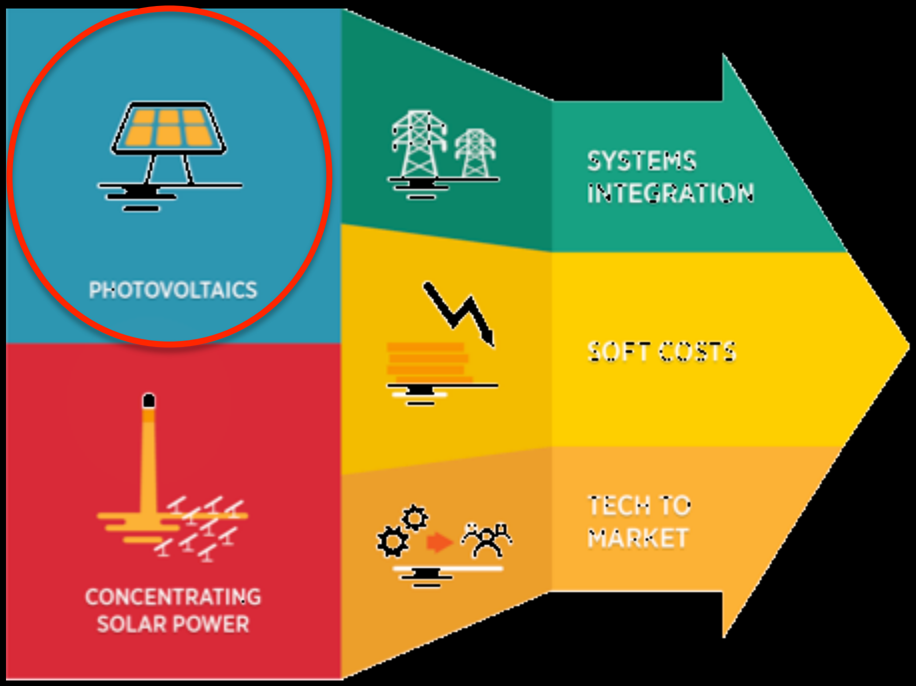
- Battery and Thermal Storage
- Hydrogen
- Smart Grid and Grid Integration

Renewable Resources

- Solar
- Wind and Water
- Biomass
- Geothermal

Foundational Science

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



6¢/kWh

SunShot 2020 Goal

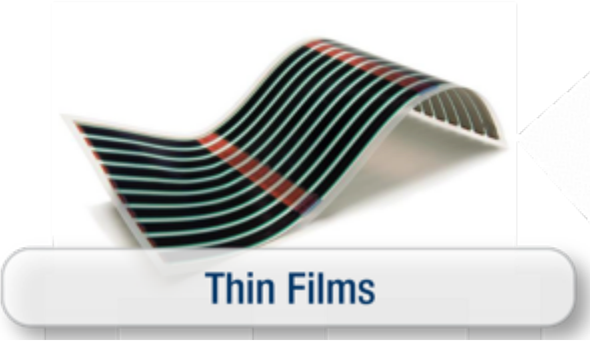
Multiple PV Technologies

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%.

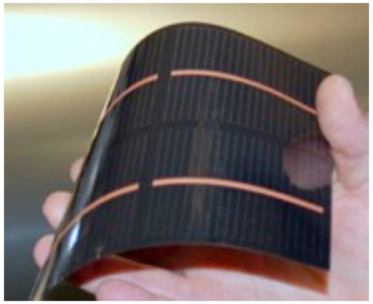
•20x-100x

•500x

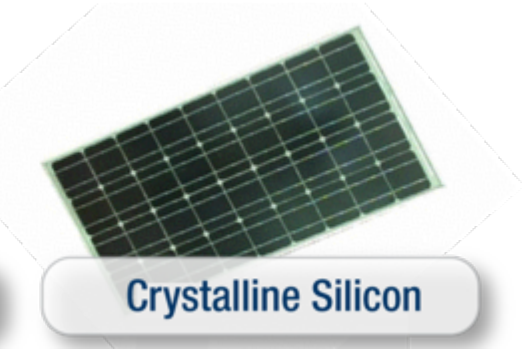


Thin Films

- 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.

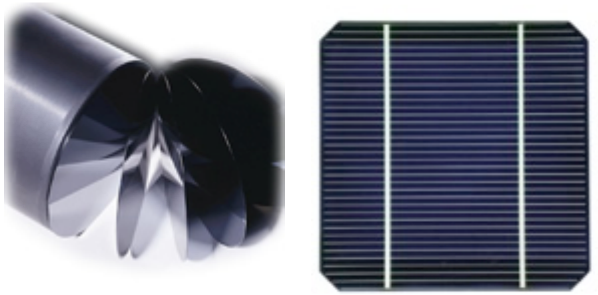


•$Cu(In,Ga)Se_2$ ~ 1-2 um



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%.



•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**

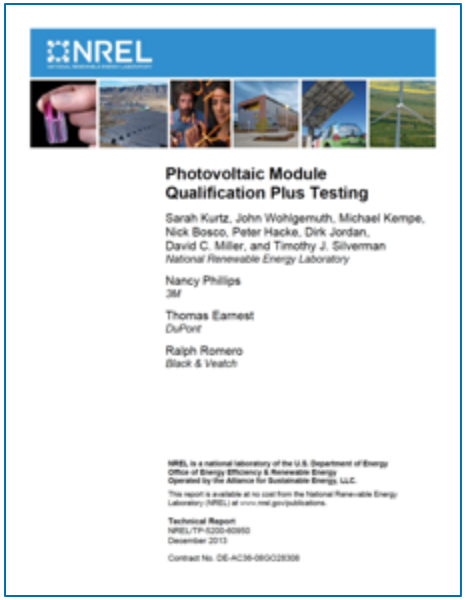
PV Cross-Cutting R&D

- **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



NREL

Photovoltaic Module Qualification Plus Testing

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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
Operated by the Alliance for Sustainable Energy, LLC

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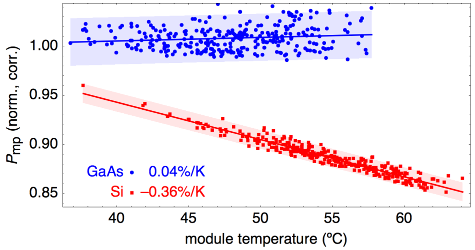
Technical Report
NREL/TP-5200-60950
December 2013

Contract No. DE-AC36-08GO28308



Module Performance

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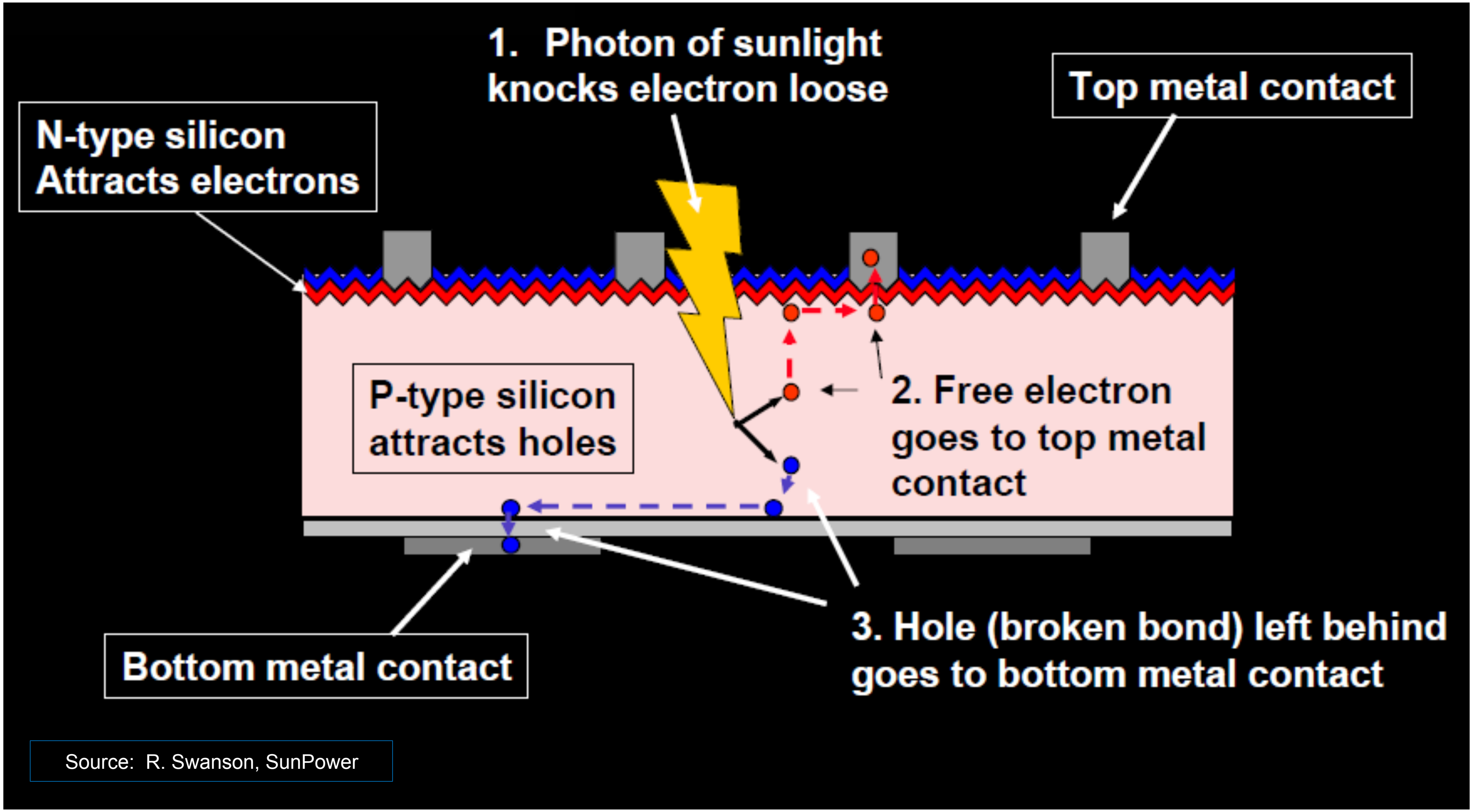
A Brief History of Photovoltaics

- **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



1. Photon of sunlight knocks electron loose

Top metal contact

N-type silicon Attracts electrons

P-type silicon attracts holes

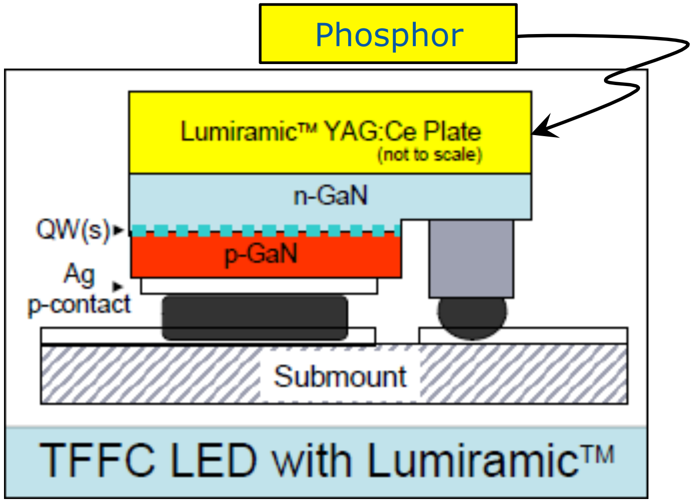
2. Free electron goes to top metal contact

3. Hole (broken bond) left behind goes to bottom metal contact

Bottom metal contact

Source: R. Swanson, SunPower

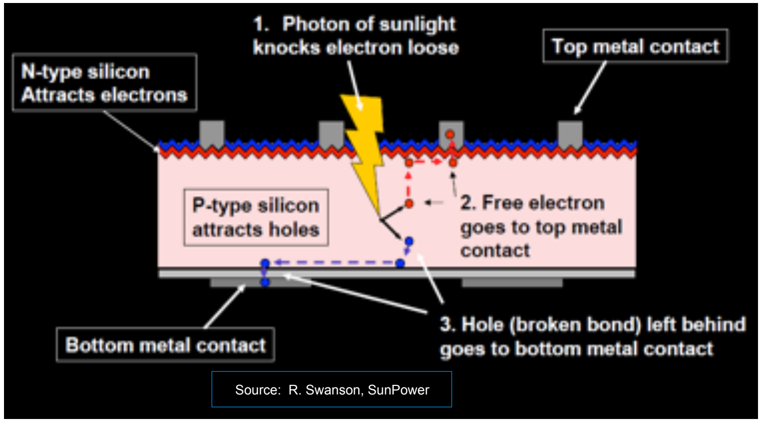
LED vs. PV Cell



Source: Philips Lumileds

LED

- Applying voltage across p-n junction excites electrons that then produce photons (light) as they fall back to their ground state.
- The wavelength of the light produced is directly related to the **bandgap** of the semiconductor that is used.



Source: R. Swanson, SunPower

PV Cell

- Light (photons) passing through the absorber knocks electrons from their atomic orbits creating electron-hole pairs.
- Electrons are collected by contacts on the emitter and holes (absence of electrons) are collected by contacts on the absorber.
- The wavelength of light absorbed to produce current is directly related to the **bandgap** of the semiconductor that is used.

Energy and Light

Candle

Light Temperature: ~ 1850K

Efficiency: ~ 0.3 lm/W

Incandescent Lamp

Light Temperature: ~ 3000K

Efficiency: 10 - 15 lm/W

Compact Fluorescent Lamp

Light Temperature: ~ 3000K

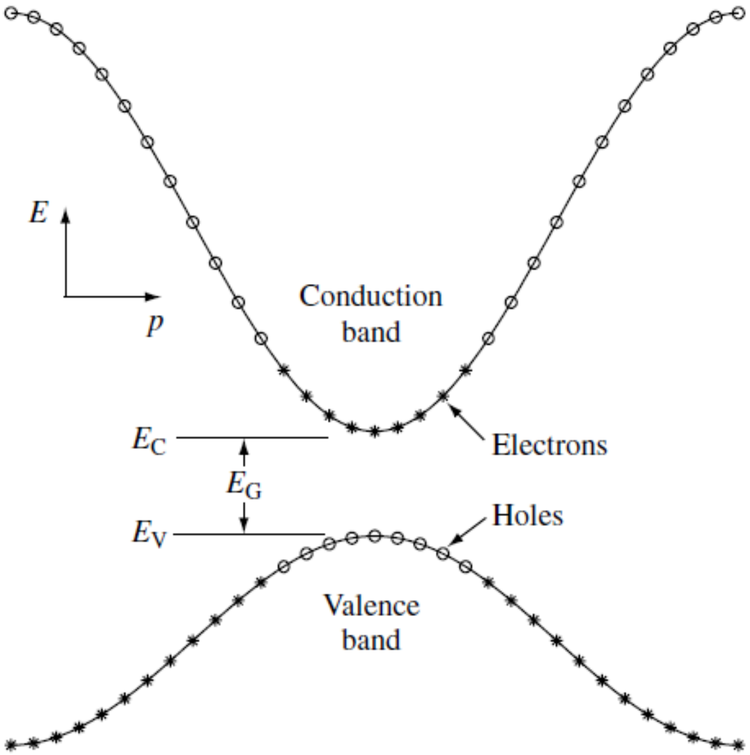
Efficiency: 60 - 75 lm/W

LED Lamp (Blue LED + Phosphors)

Light Temperature: ~ 3000K

Efficiency: 100 - 130 lm/W

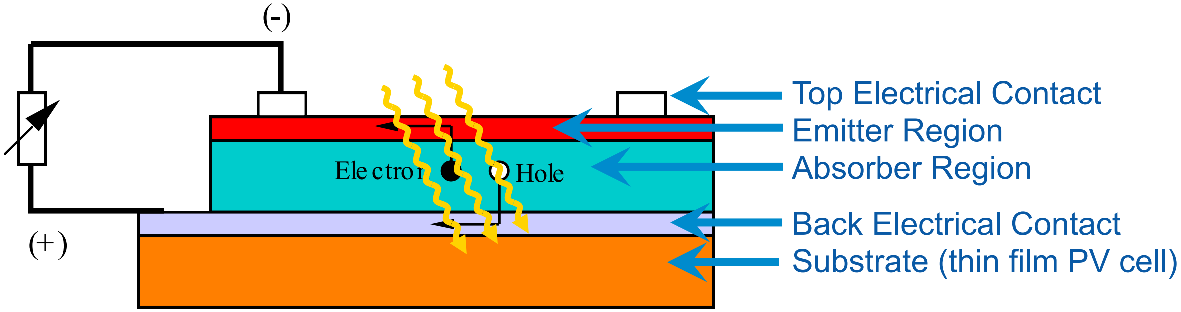
Bandgap??



Source: "Handbook of Photovoltaic Science and Engineering", edited by Antonio Luque and Steven Hegedus (2003).

- The bandgap of a semiconductor is the energy required for an electron to "jump" from its lowest energy state (valence band) to its highest energy state (conduction band).
- For metals, the conduction and valence bands overlap so they conduct electricity.
- For insulators, the bandgap is very large so no electricity can flow.
- For semiconductors, the bandgap is smaller and can be manipulated by the addition of impurities called "dopants". This is the reason a semiconductor can act like a <u>conductor</u> and an <u>insulator</u>.

PV Cell Nomenclature



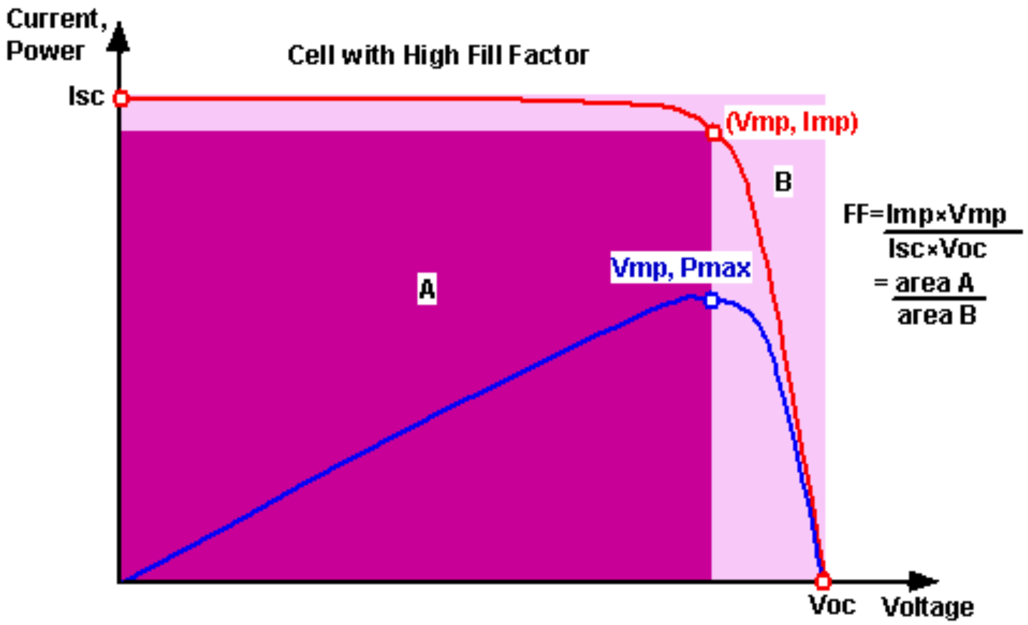
Absorber – Can be made from any number of semiconductors and is commonly p-type (collects positive charges).

Emitter – Usually formed by doping the semiconductor used as the absorber in order to produce the opposite type, in this example n-type (collects negative charges).

Substrate – Not used in the case of wafer silicon. For thin film PV cells the substrate is usually glass or metal.

Efficiency of a PV cell depends on many things but mostly the quality of the semiconductor material, the quality of the surface “passivation” and the quality of the electrical contacts.

I-V Curve and PV Cell Efficiency



Cell Efficiency = η

$\eta = P_{OUT}/P_{IN}$

P_{IN} is the power of the incoming light (usually 1000 W/m^2)

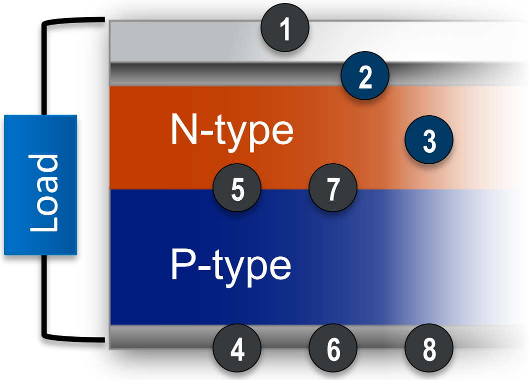
P_{OUT} is the product of the max power voltage and current.

Fill Factor is defined as the ratio of the cell's max power, $I_{MP}xV_{MP}$ and $I_{SC}xV_{OC}$.

PV Cell Efficiency

$$\eta = FF\frac{(J_{sc} \cdot V_{oc})}{1000\,W/m^2}$$

h = solar cell efficiency
J_{sc} = short-circuit current
V_{oc} = open-circuit voltage
FF = fill factor



Solar cell efficiency is determined by **inherent losses** (i.e., solar photons with energies below the bandgap of the host material) and those primarily due to **optical or electrical losses** (i.e., reflectance, series resistance, etc.).

J_{sc}, V_{oc}, and FF are intimately and fundamentally tied. It is difficult to affect one without changing the others.

Factors Affecting **CURRENT**

① Electrical resistance and transmission loss of the transparent conducting materials and contacts

② Reflection and optical transmission loss through the glass and/or encapsulant

③ Charge carrier recombination (related to carrier mobility, lifetime, defect density)

④ Back contact and bulk series resistance

Factors Affecting **VOLTAGE**

⑤ Absorber and emitter semiconductor choice, doping, and crystallinity

⑥ Bulk and surface carrier recombination

Factors Affecting **FILL FACTOR**

⑦ Carrier Recombination in the depletion region

⑧ Series and shunt resistance

Definitions: Energy & Power

Energy

Basic unit is Joule

3.6e6 J = 1 kW-hr

Power

Basic unit is Watt

1 W = J/s

1 W = V*A

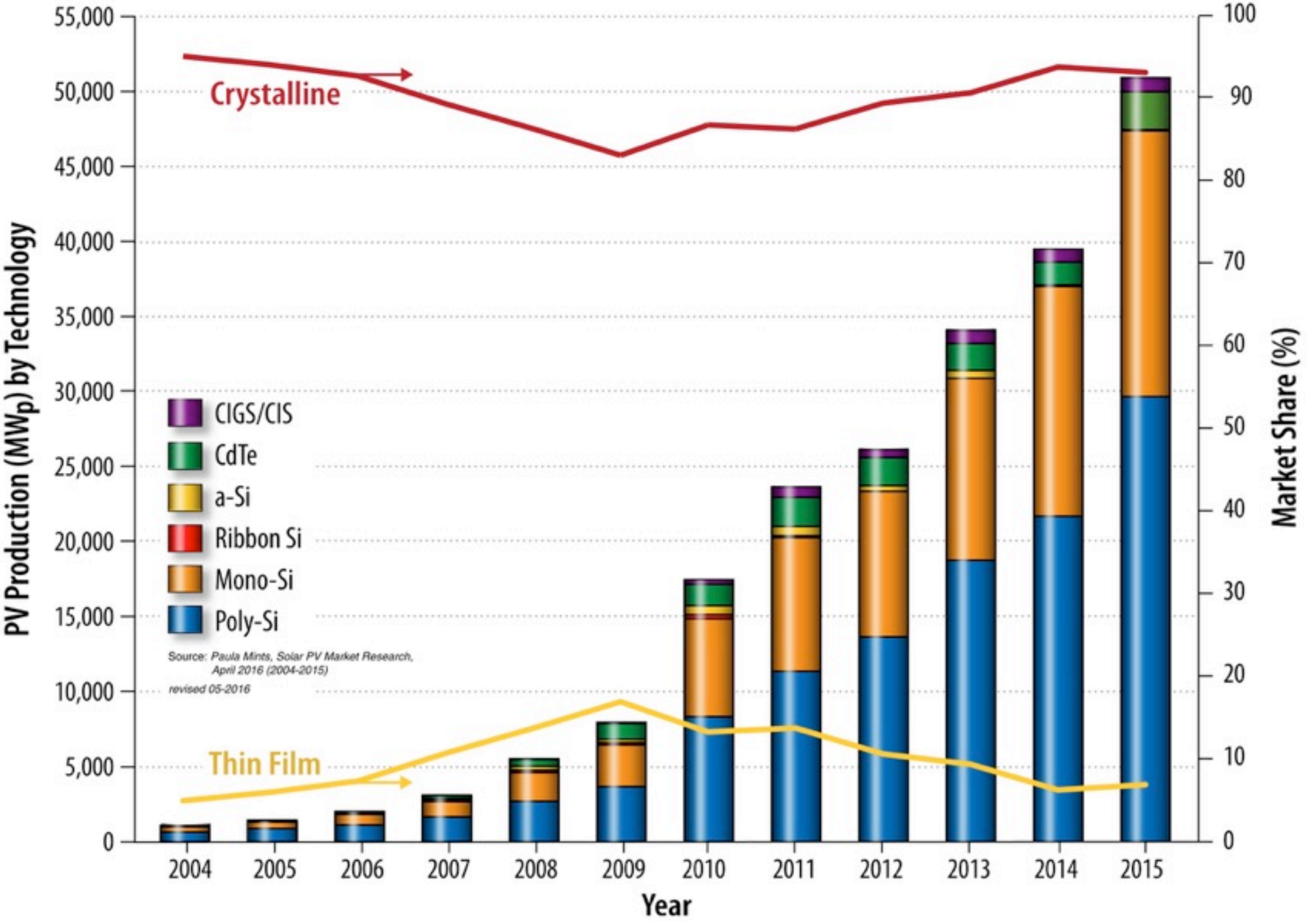
∴ Power is energy transferred per unit time.

Solar Constant = 1,366 W/m^2

Average Earth Insolation = 1,000 W/m^2

(sea level, normal incidence)

PV Industry Growth – By Technology



Source: *Paula Mints, Solar PV Market Research, April 2016 (2004-2015)*

revised 05-2016

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Earth

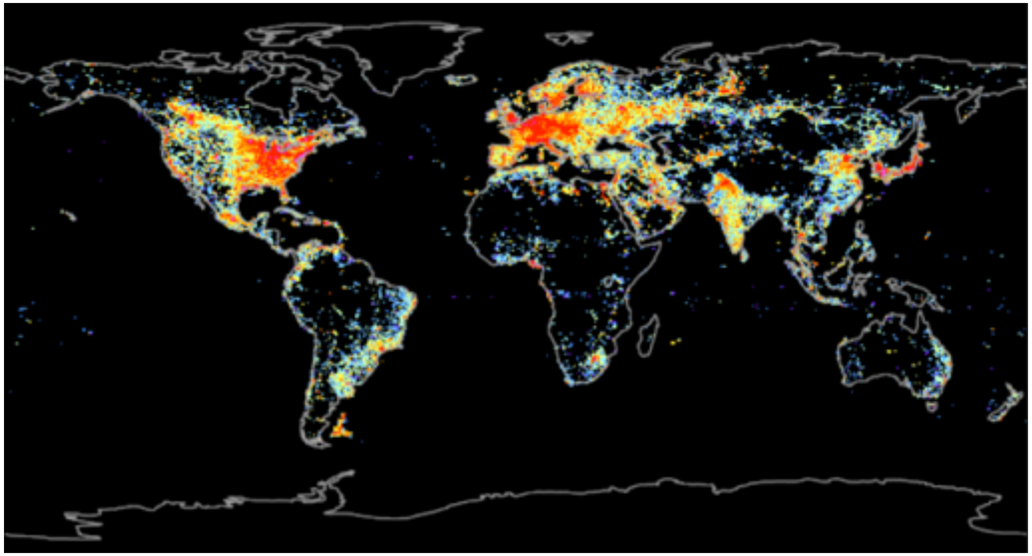
Human Population = 7.3 B

Annual Electricity Demand = 23,300 TWh

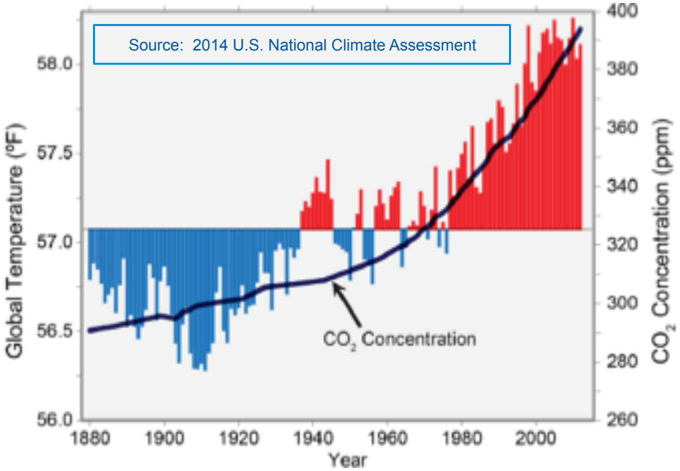
Annual CO2 Emissions = 32.2 Gt

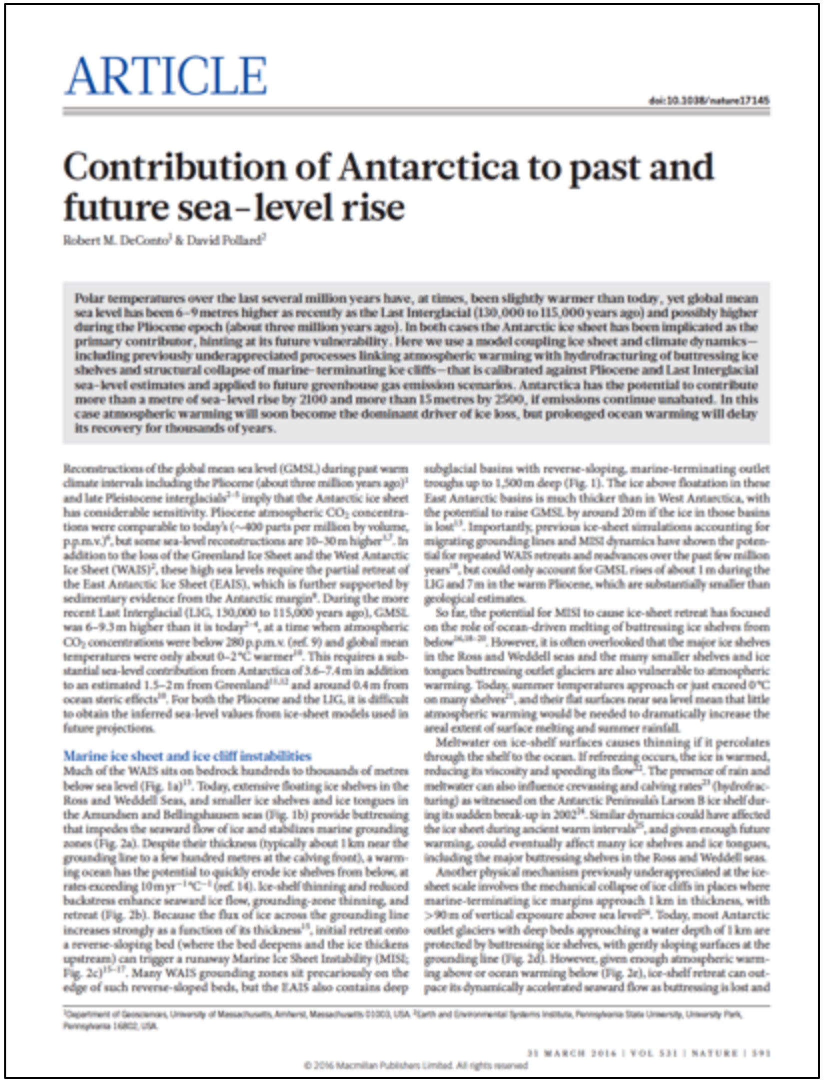
Fraction of GHG Emissions from Energy Use ≈ 68%

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.**


Source: 2014 U.S. National Climate Assessment



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 shelves and structural collapse of marine-terminating ice cliffs—that is calibrated against Pliocene and Last Interglacial sea-level estimates and applied to future greenhouse gas emission scenarios. Antarctica has the potential to contribute more than a metre of sea-level rise by 2100 and more than 15 metres by 2500, if emissions continue unabated. In this case atmospheric warming will soon become the dominant driver of ice loss, but prolonged ocean warming will delay its recovery for thousands of years.

Reconstructions of the global mean sea level (GMSL) during past warm climate intervals including the Pliocene (about three million years ago)[1] and late Pleistocene interglacials[2–5] imply that the Antarctic ice sheet has considerable sensitivity. Pliocene atmospheric CO_2 concentrations were comparable to today's (~400 parts per million by volume, p.p.m.v.)[6], but some sea-level reconstructions are 10–30 m higher[1,7]. In addition to the loss of the Greenland Ice Sheet and the West Antarctic Ice Sheet (WAIS)[2], these high sea levels require the partial retreat of the East Antarctic Ice Sheet (EAIS), which is further supported by sedimentary evidence from the Antarctic margin[8]. During the more recent Last Interglacial (LIG, 130,000 to 115,000 years ago), GMSL was 6–9.3 m higher than it is today[2–4], at a time when atmospheric CO_2 concentrations were below 280 p.p.m.v. (ref. 9) and global mean temperatures were only about 0–2 °C warmer[10]. This requires a substantial sea-level contribution from Antarctica of 3.6–7.4 m in addition to an estimated 1.5–2 m from Greenland[11,12] and around 0.4 m from ocean steric effects[10]. For both the Pliocene and the LIG, it is difficult to obtain the inferred sea-level values from ice-sheet models used in future projections.

Marine ice sheet and ice cliff instabilities

Much of the WAIS sits on bedrock hundreds to thousands of metres 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 subglacial basins with reverse-sloping, marine-terminating outlet troughs up to 1,500 m deep (Fig. 1). The ice above floatation in these East Antarctic basins is much thicker than in West Antarctica, with the potential to raise GMSL by around 20 m if the ice in those basins is lost[13]. Importantly, previous ice-sheet simulations accounting for migrating grounding lines and MISI dynamics have shown the potential for repeated WAIS retreats and readvances over the past few million years[18], but could only account for GMSL rises of about 1 m during the LIG and 7 m in the warm Pliocene, which are substantially smaller than geological estimates.

So far, the potential for MISI to cause ice-sheet retreat has focused on the role of ocean-driven melting of buttressing ice shelves from below[14,18–20]. However, it is often overlooked that the major ice shelves in the Ross and Weddell seas and the many smaller shelves and ice tongues buttressing outlet glaciers are also vulnerable to atmospheric warming. Today, summer temperatures approach or just exceed 0 °C on many shelves[21], and their flat surfaces near sea level mean that little atmospheric warming would be needed to dramatically increase the areal extent of surface melting and summer rainfall.

Meltwater on ice-shelf surfaces causes thinning if it percolates through the shelf to the ocean. If refreezing occurs, the ice is warmed, reducing its viscosity and speeding its flow[22]. The presence of rain and 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

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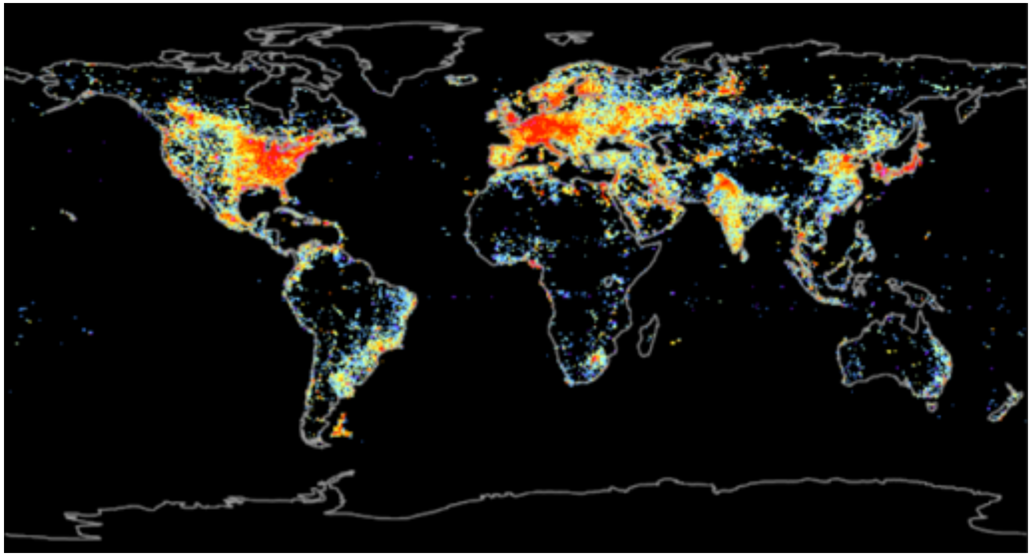
Nature - 31 March, 2016

Motivation is Clear – Energy Needs vs. CO_2



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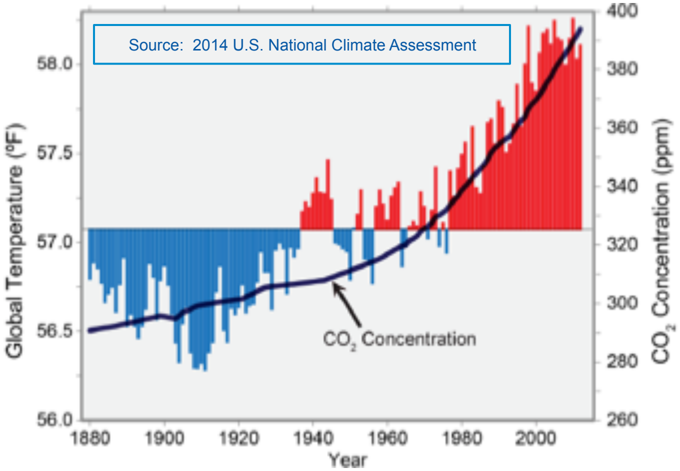
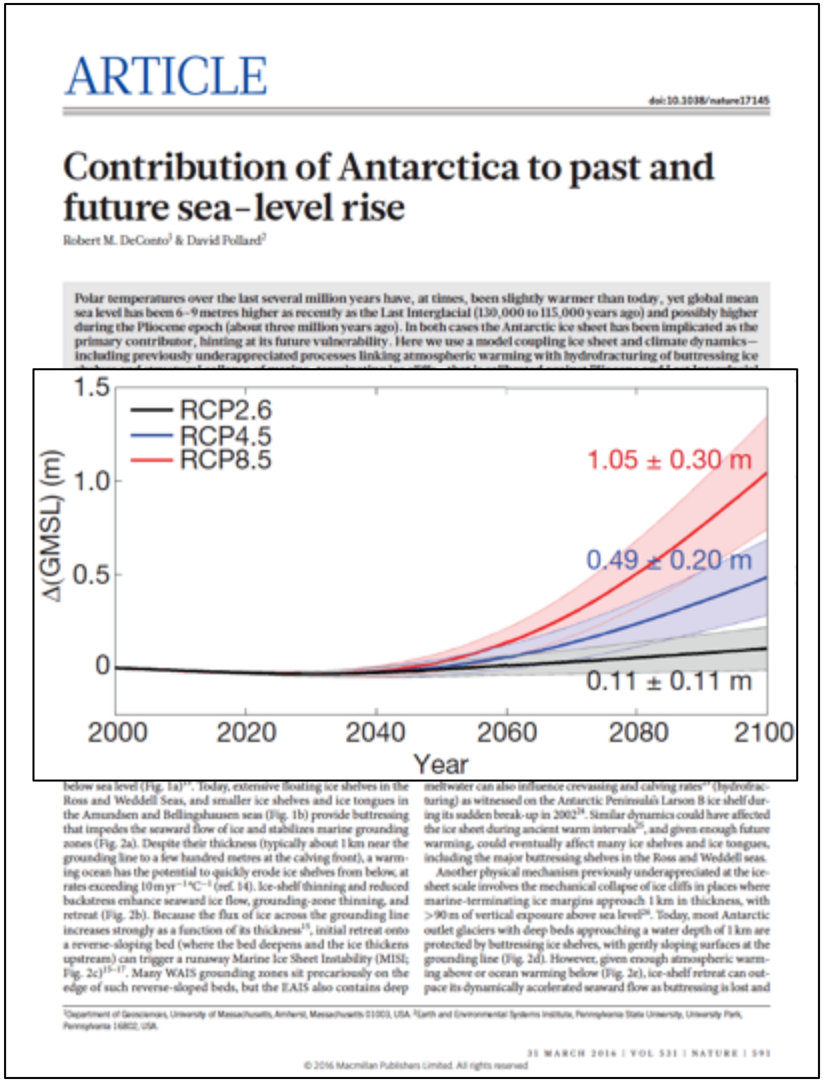


Source: 2014 U.S. National Climate Assessment



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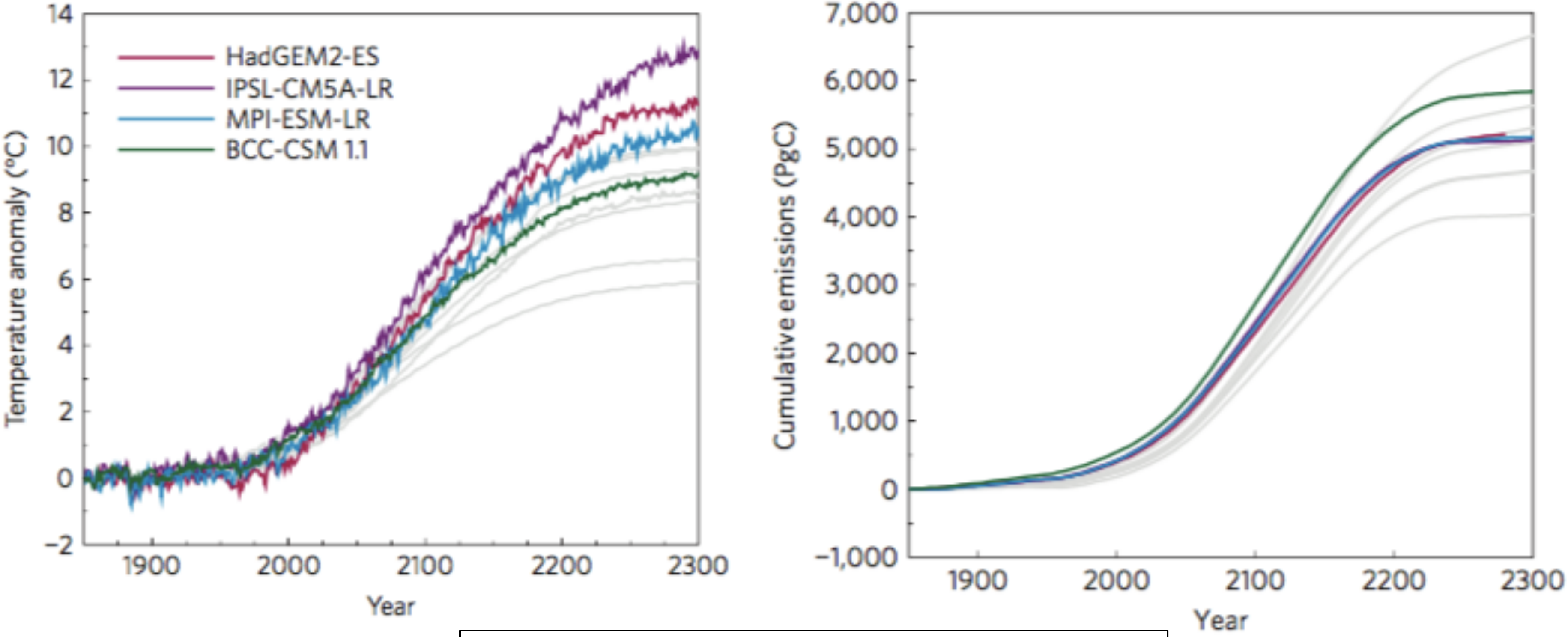
31 MARCH 2016 | VOL 531 | NATURE | 591

Nature - 31 March, 2016

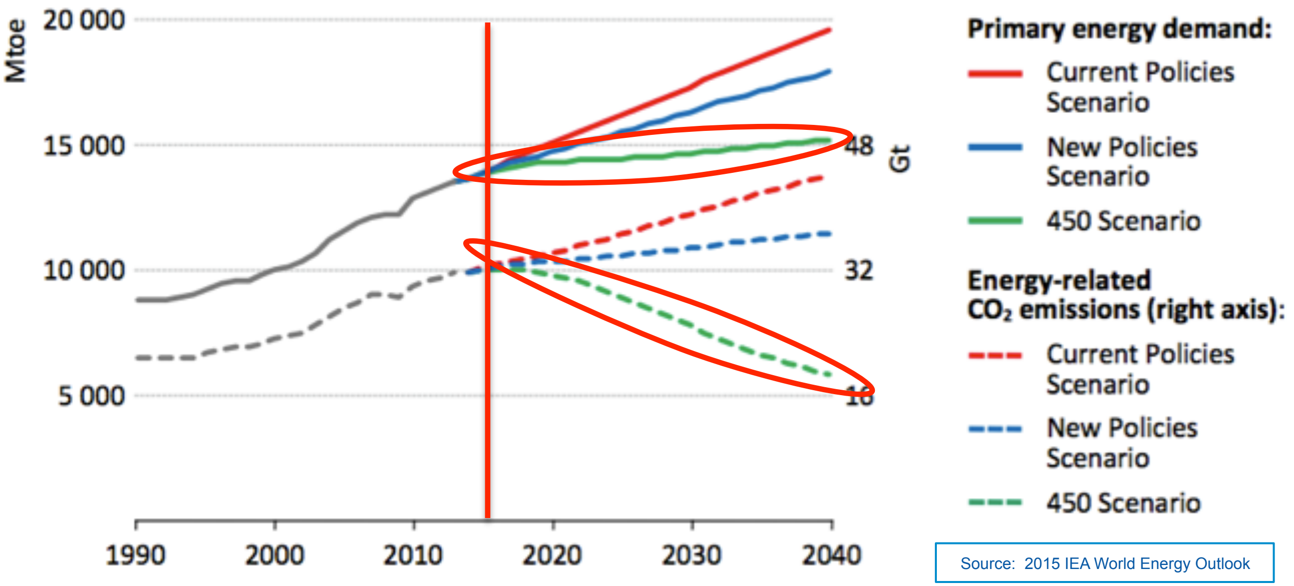
Latest Earth System Model Results

- Predicted global average surface temperature has gone up, not down, with increasingly sophisticated earth system models.
- Warming and CO2 emissions are in fact roughly linear.
- Burning all of earth’s fossil fuel resources, projected by ~2200 given current trends, would result in global average warming of 6.4–9.5° C, **mean Arctic warming of 14.7–19.5° C.**



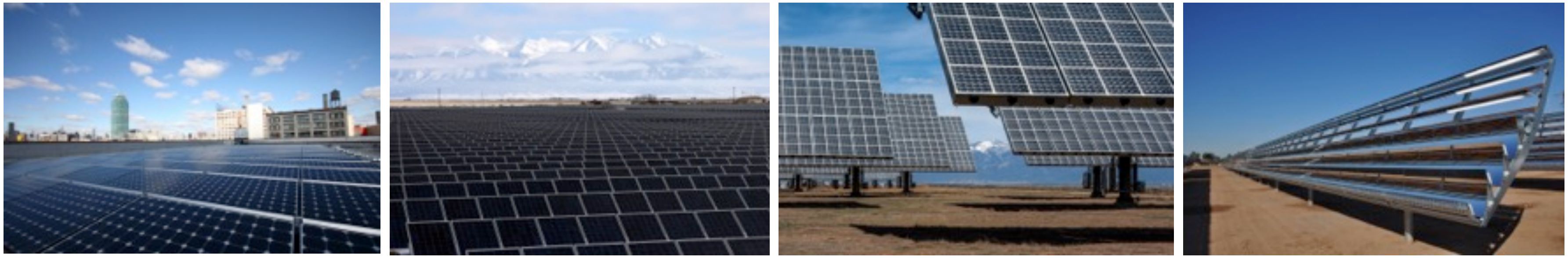
Source: Tokarska et al., *Nature Clim Change*, 23MAY16

450ppm Goal: Dramatic Change Needed

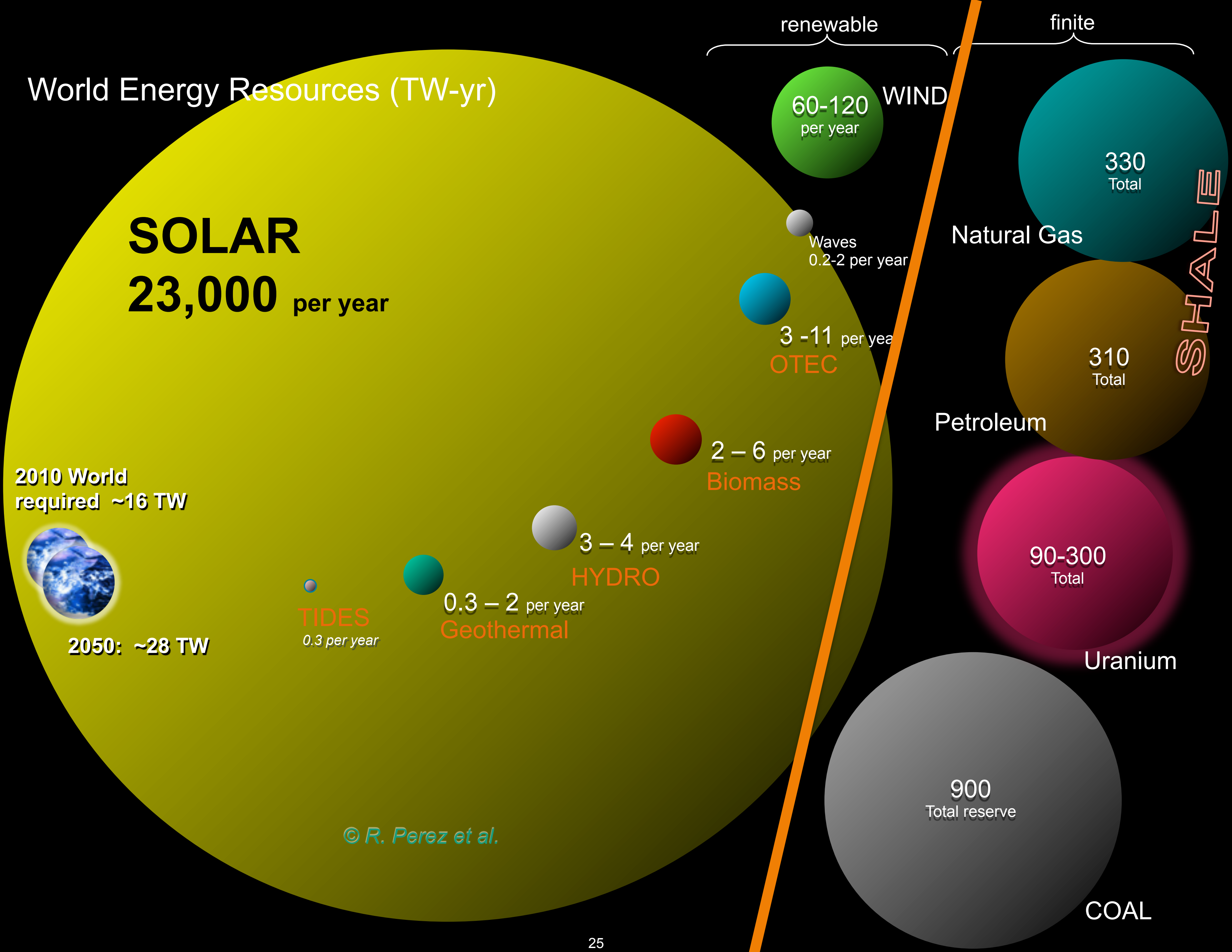


Source: 2015 IEA World Energy Outlook

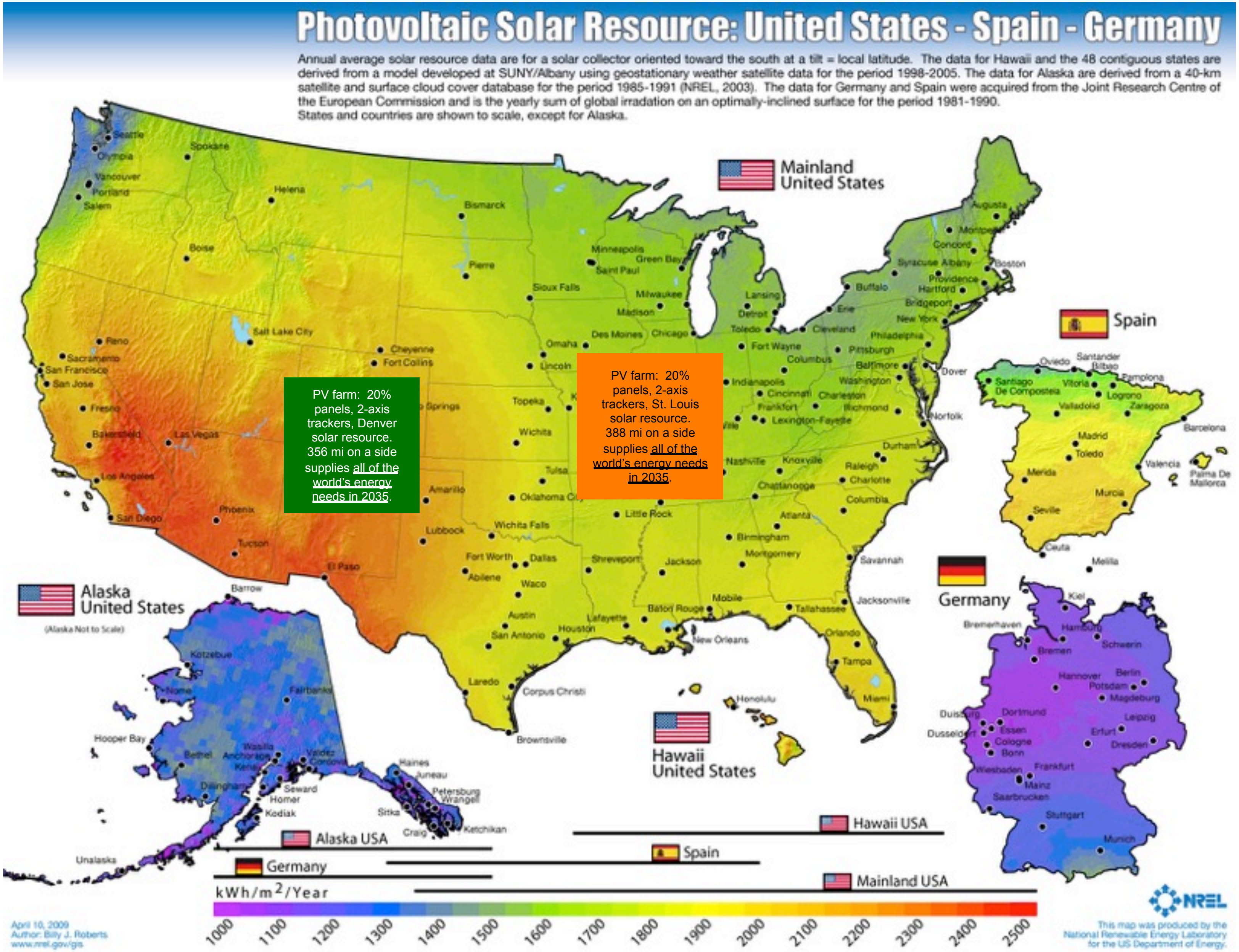
- Must hold overall energy consumption essentially flat for the next 25 years through major gains in energy efficiency.
- Must begin a major shift to zero carbon generation immediately, with measurable reductions by 2020.



World Energy Resources (TW-yr)



Solar Insolation – U.S.



Photovoltaic Solar Resource: United States - Spain - Germany

Annual average solar resource data are for a solar collector oriented toward the south at a tilt = local latitude. The data for Hawaii and the 48 contiguous states are derived from a model developed at SUNY/Albany using geostationary weather satellite data for the period 1998-2005. The data for Alaska are derived from a 40-km satellite and surface cloud cover database for the period 1985-1991 (NREL, 2003). The data for Germany and Spain were acquired from the Joint Research Centre of the European Commission and is the yearly sum of global irradiation on an optimally-inclined surface for the period 1981-1990. States and countries are shown to scale, except for Alaska.

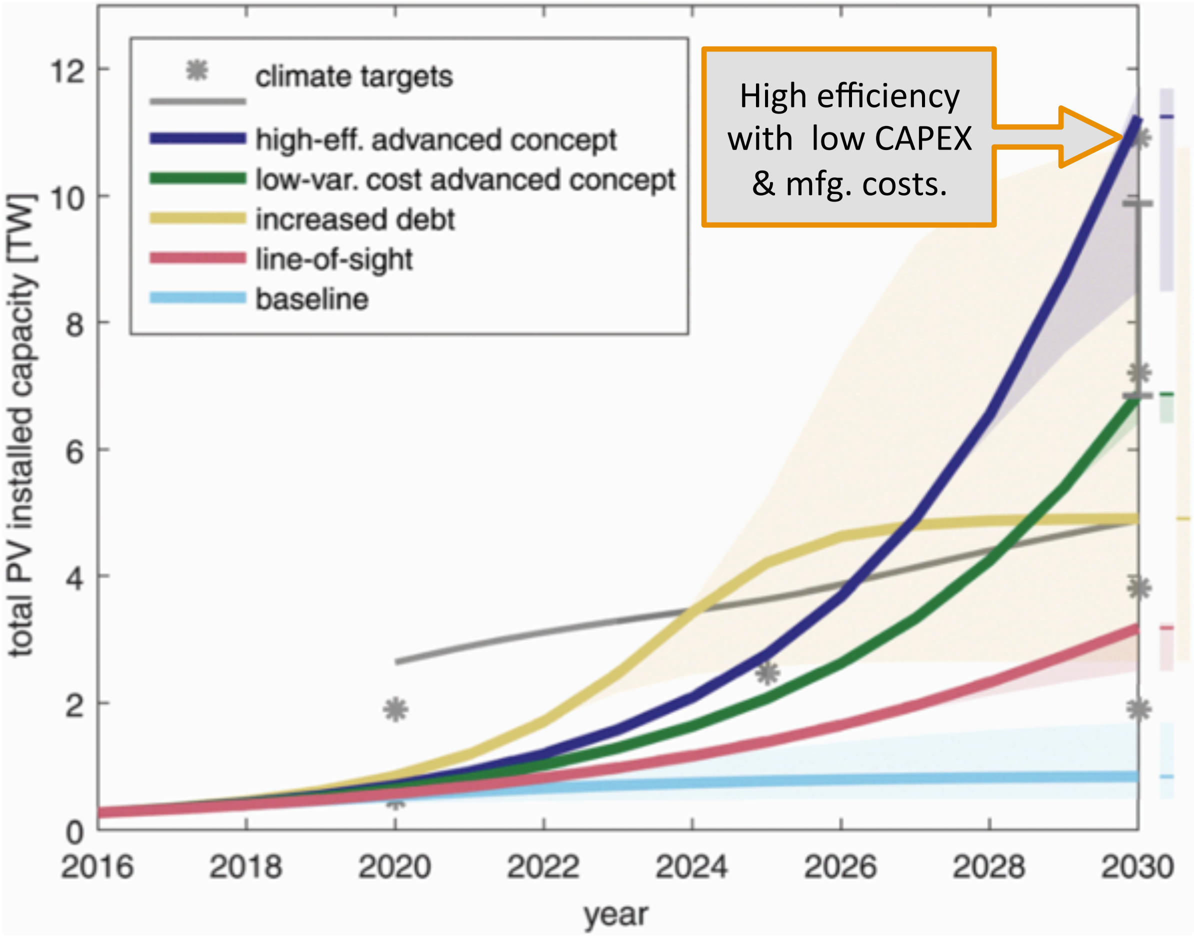
PV farm: 20% panels, 2-axis trackers, Denver solar resource. 356 mi on a side supplies <u>all of the world's energy needs in 2035</u>.

PV farm: 20% panels, 2-axis trackers, St. Louis solar resource. 388 mi on a side supplies <u>all of the world's energy needs in 2035</u>.

April 10, 2009
Author: Billy J. Roberts
www.nrel.gov/gis

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

PV & Carbon Emissions Reduction



High efficiency with low CAPEX & mfg. costs.

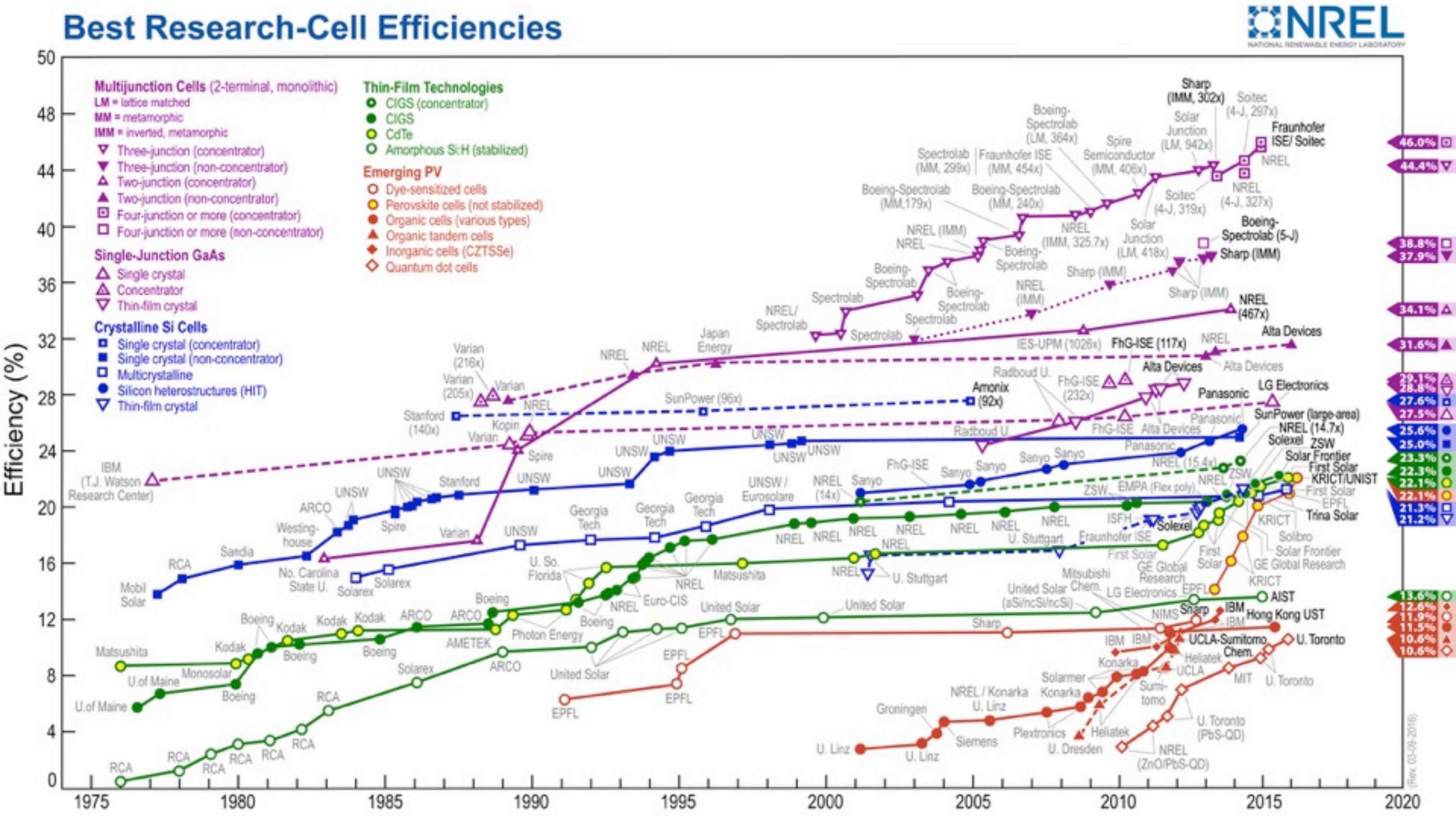
- This paper focused on industry growth constrained by technology, mfg. capacity and demand. Energy storage, demand shifting and grid modernization not considered directly but incorporated into assumed demand curve.
- High efficiency, advanced concept case based on 24% module efficiency, very thin absorber and ultra-low CAPEX. This case included to show potential impact of innovation alone on future PV market size.

Source: Needleman et al., *E&ES*, 21APR16

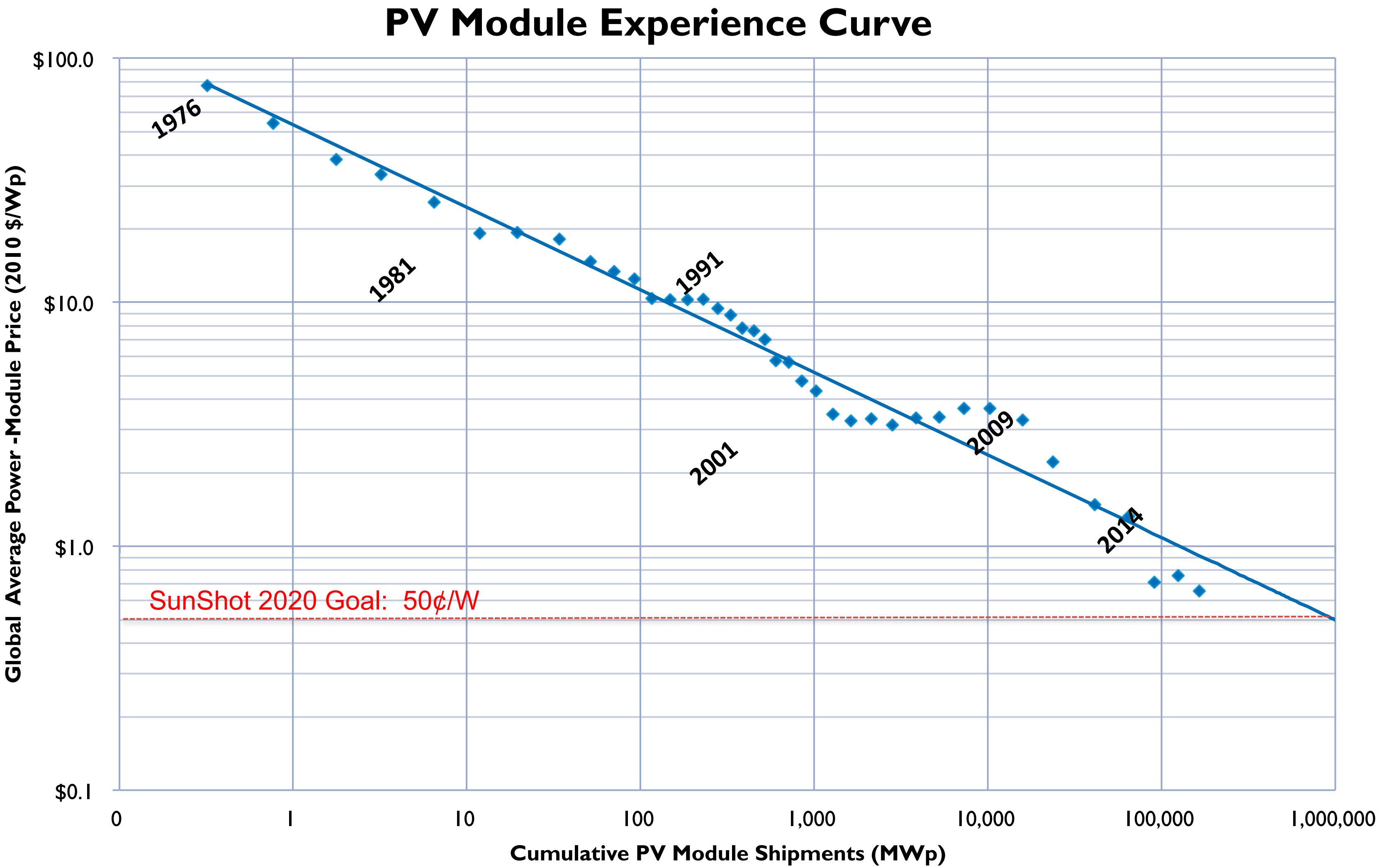
Overview

1. Brief introduction of NREL, the MCST Directorate and NREL’s PV Program.
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.

PV Research – Dramatic Progress

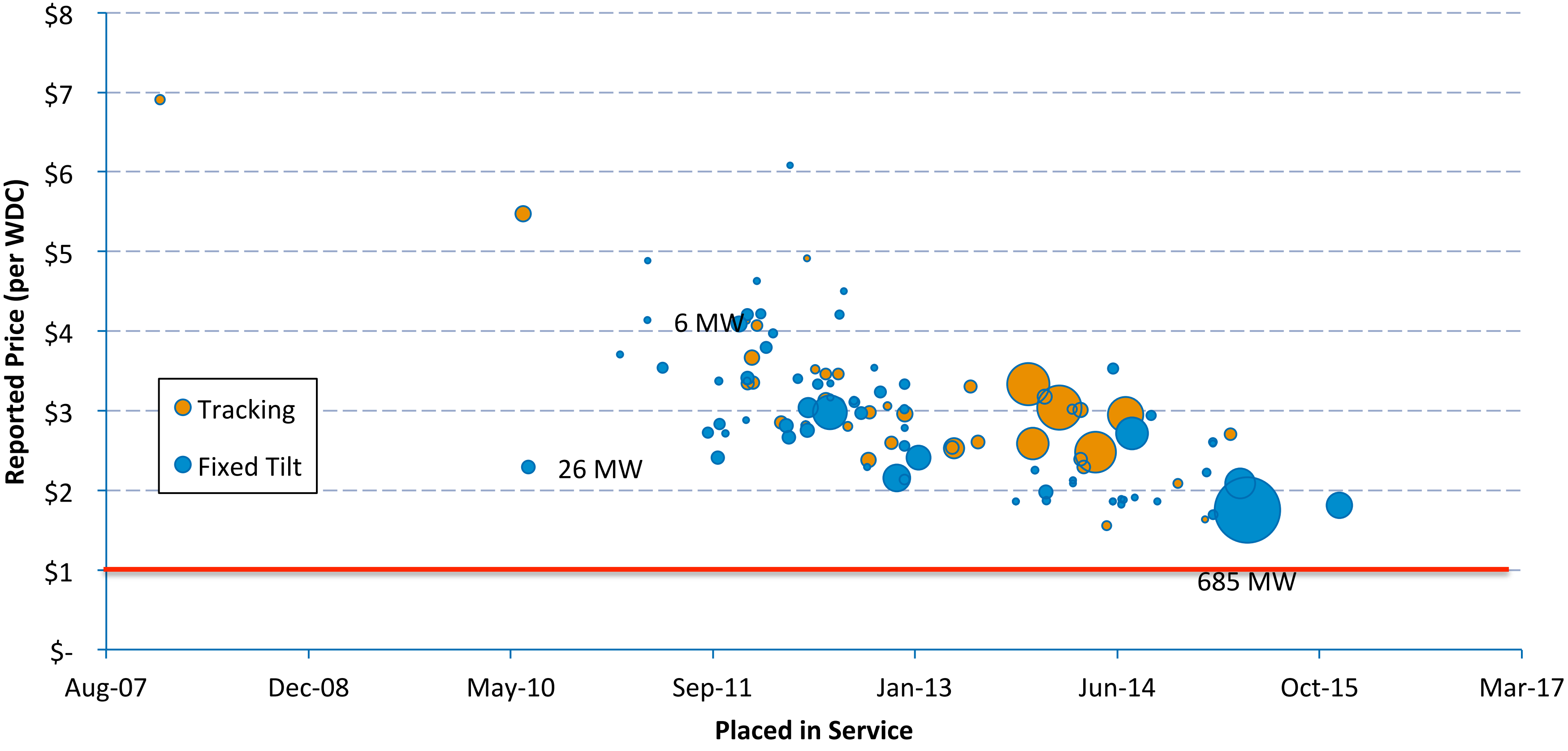


PV Module Cost Decline



Sources: Strategies Unlimited, Navigant Consulting & Paula Mints

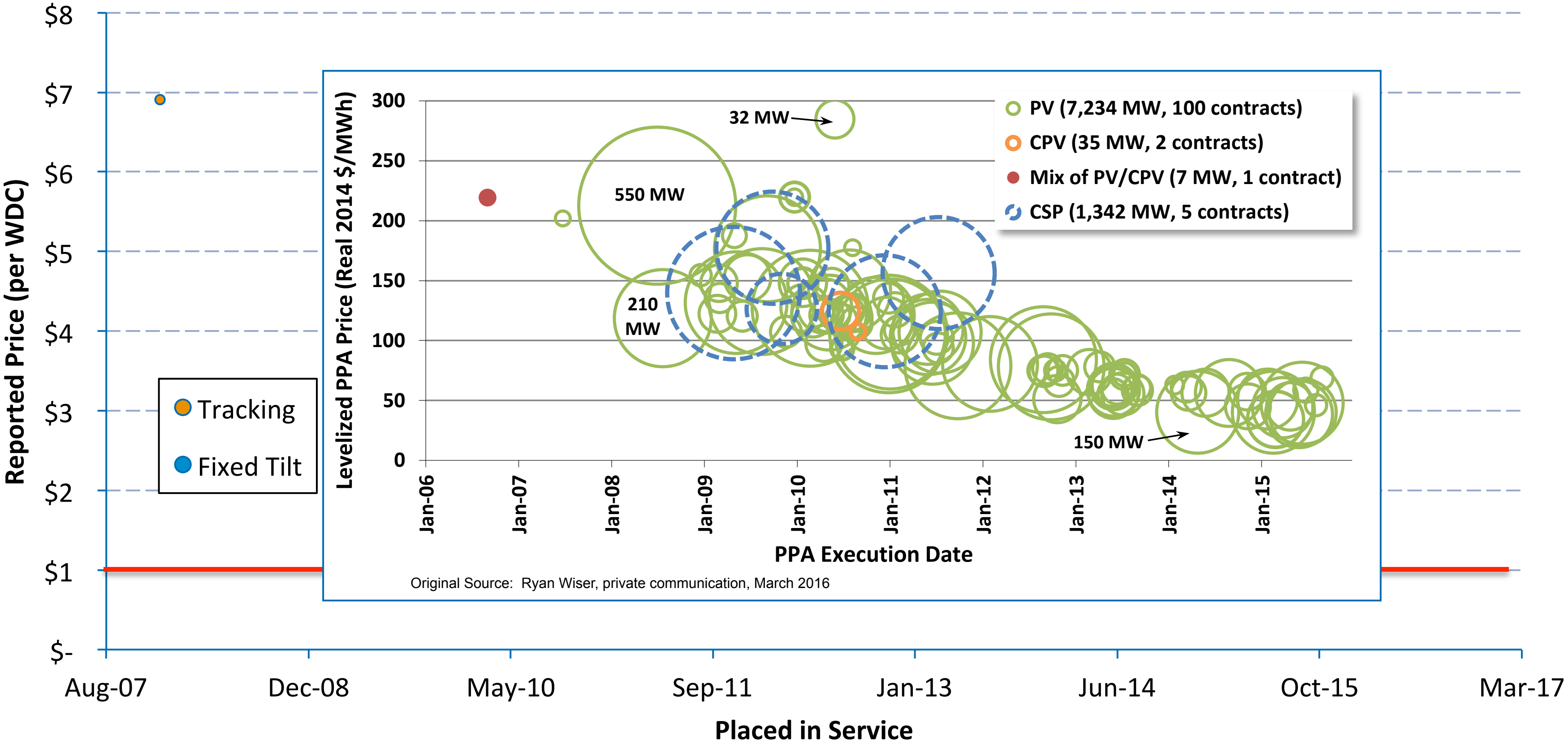
US System Pricing – Utility Scale >5 MW



- 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

US System Pricing – Utility Scale >5 MW



Original Source: Ryan Wiser, private communication, March 2016

- PV system costs at all scales declining rapidly.
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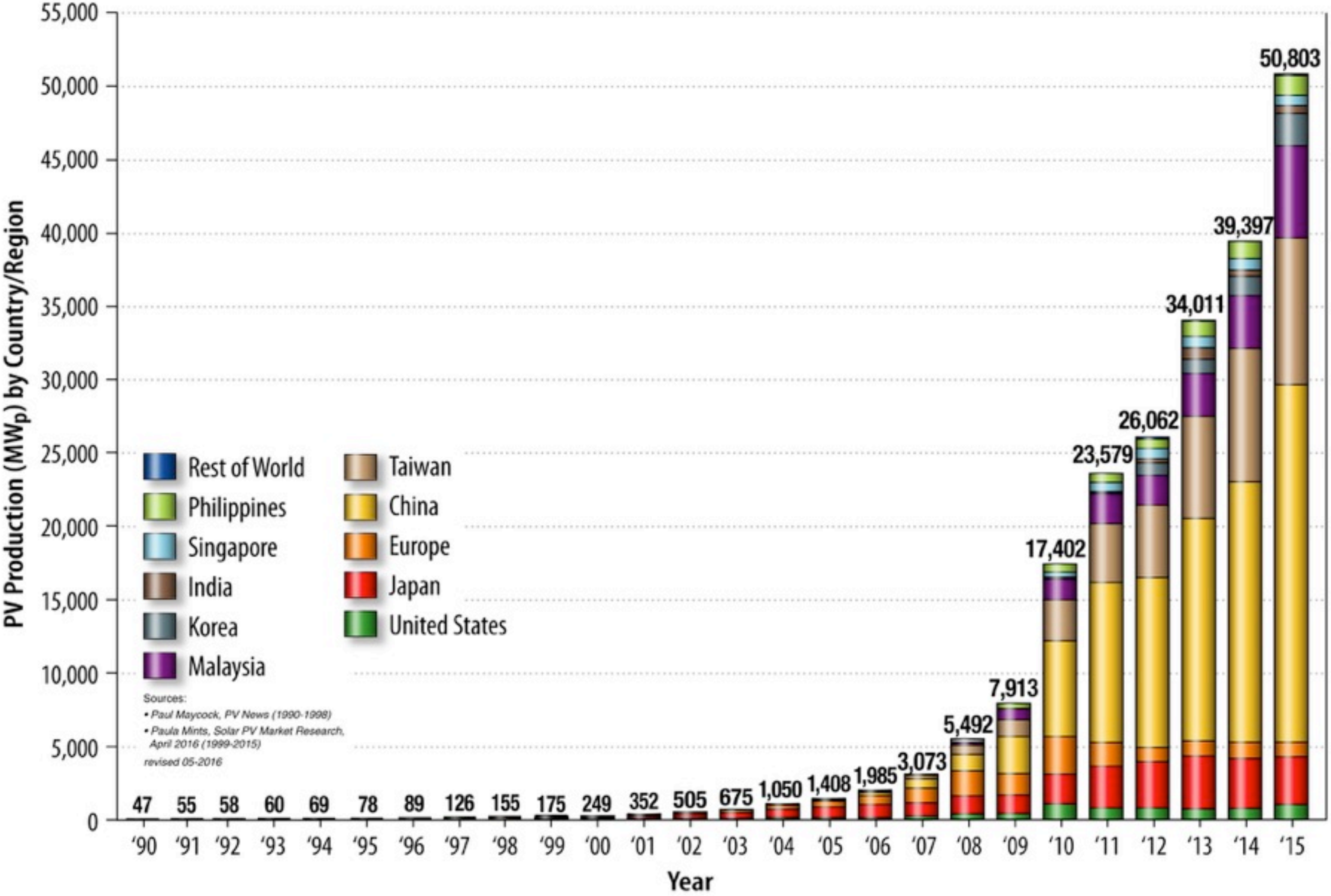
Original Source: NREL 3Q15 Solar Update, Feldman et al., 19JAN16

PV Annual Production: 1990 - 2015

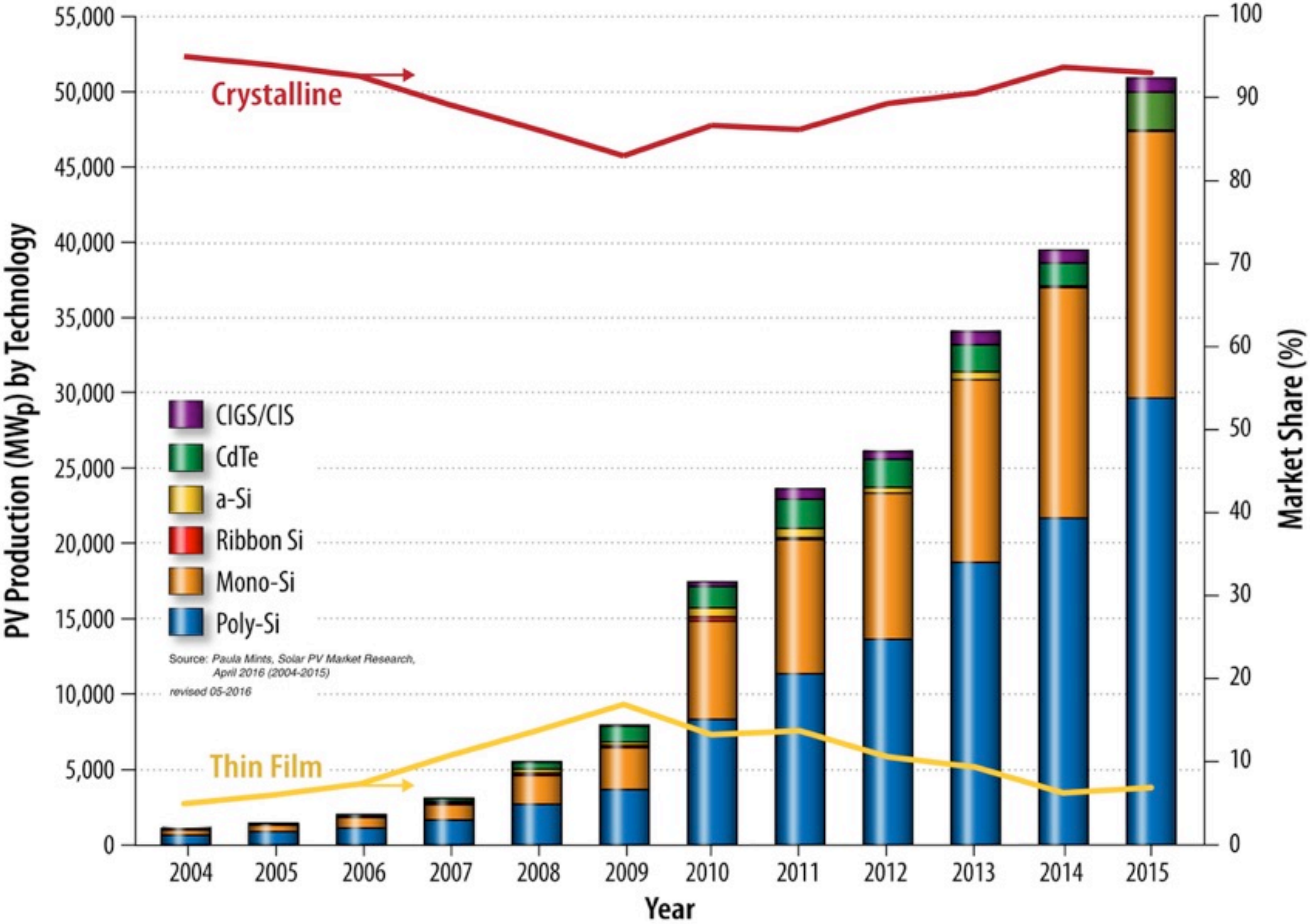


Sources:

- *Paul Maycock, PV News (1990-1998)*
- *Paula Mints, Solar PV Market Research, April 2016 (1999-2015)*

revised 05-2016

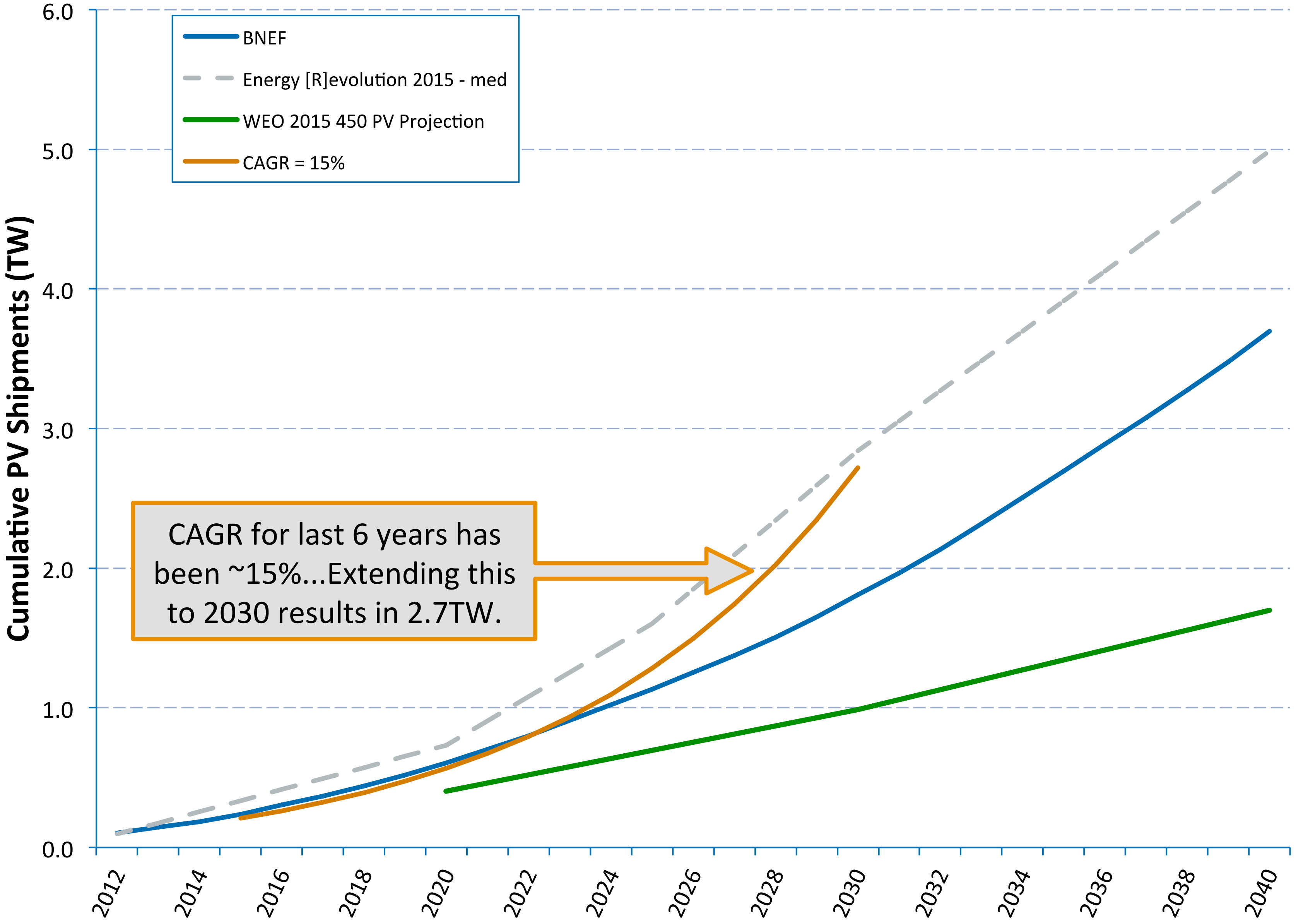
PV Industry Growth – By Technology



Source: Paula Mints, Solar PV Market Research, April 2016 (2004-2015)

revised 05-2016

Global PV Capacity - Forecasts



CAGR for last 6 years has been ~15%...Extending this to 2030 results in 2.7TW.

Overview

1. Brief introduction of NREL, the MCST Directorate and NREL's PV Program.
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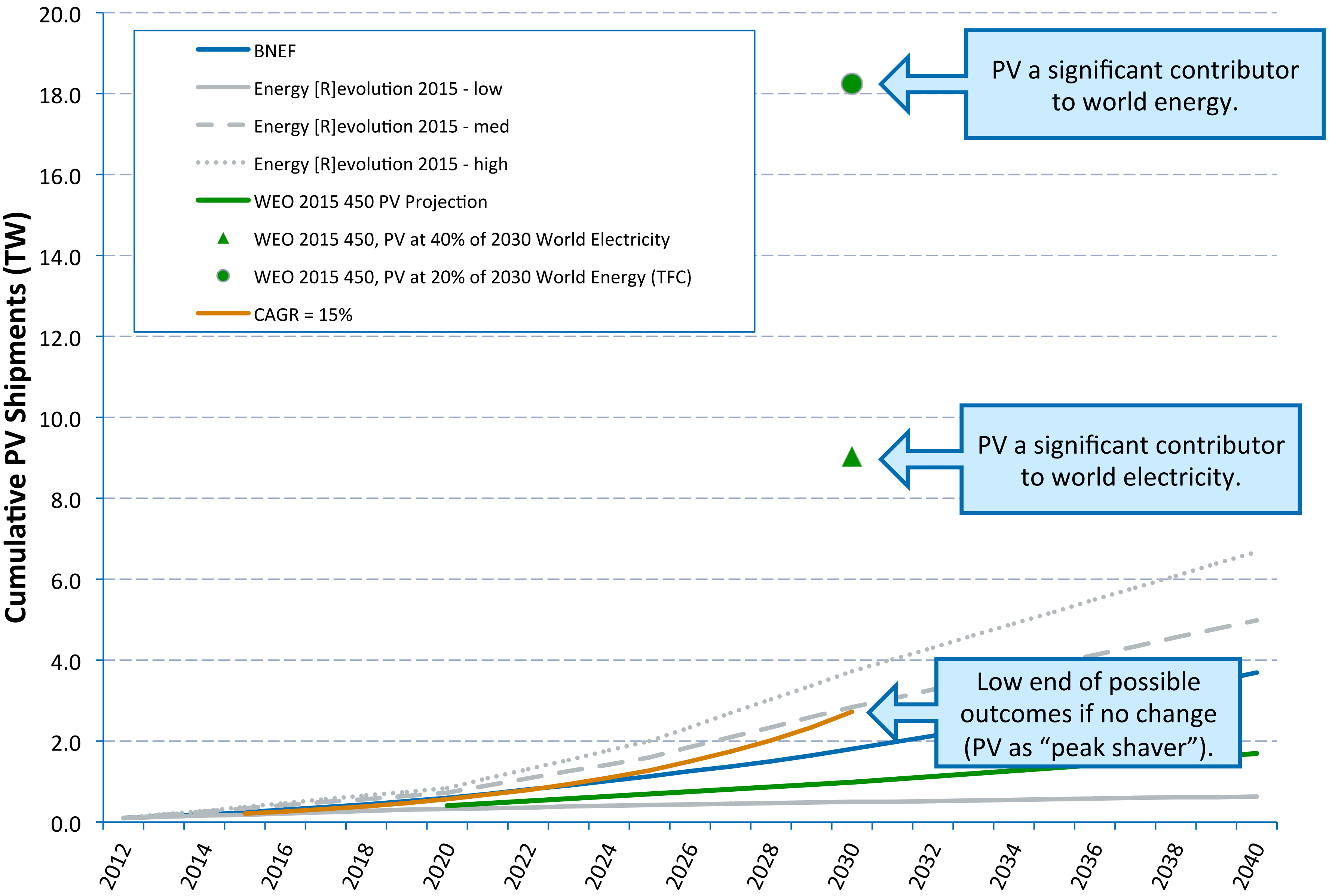
GA-SERI: The TW Workshop

GA-SERI
The Terawatt Workshop

AIST
ISE
NREL

Global Alliance of Solar Energy Research Institutes

Global PV Growth & CO_2 Emission Goals

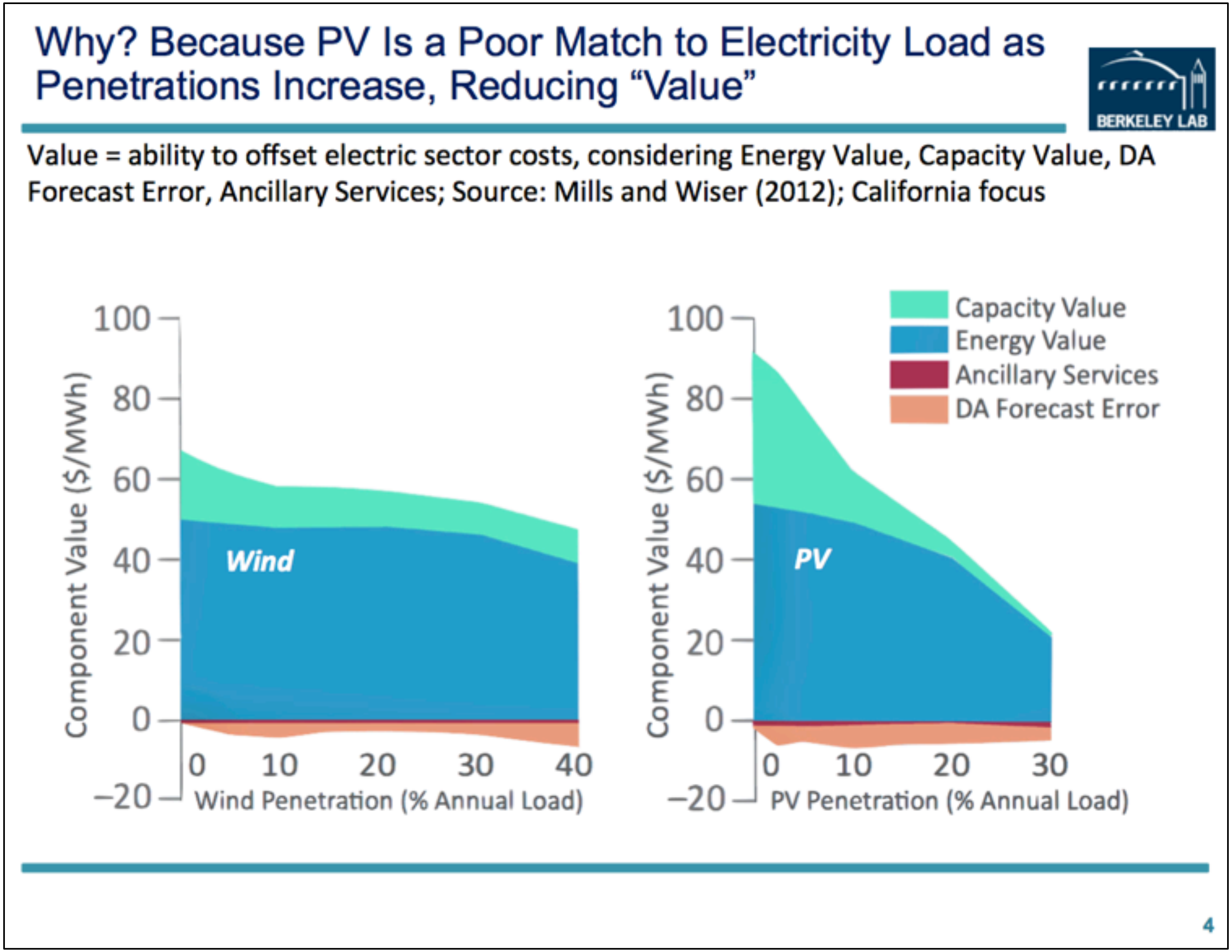


PV a significant contributor to world energy.

PV a significant contributor to world electricity.

Low end of possible outcomes if no change (PV as “peak shaver”).

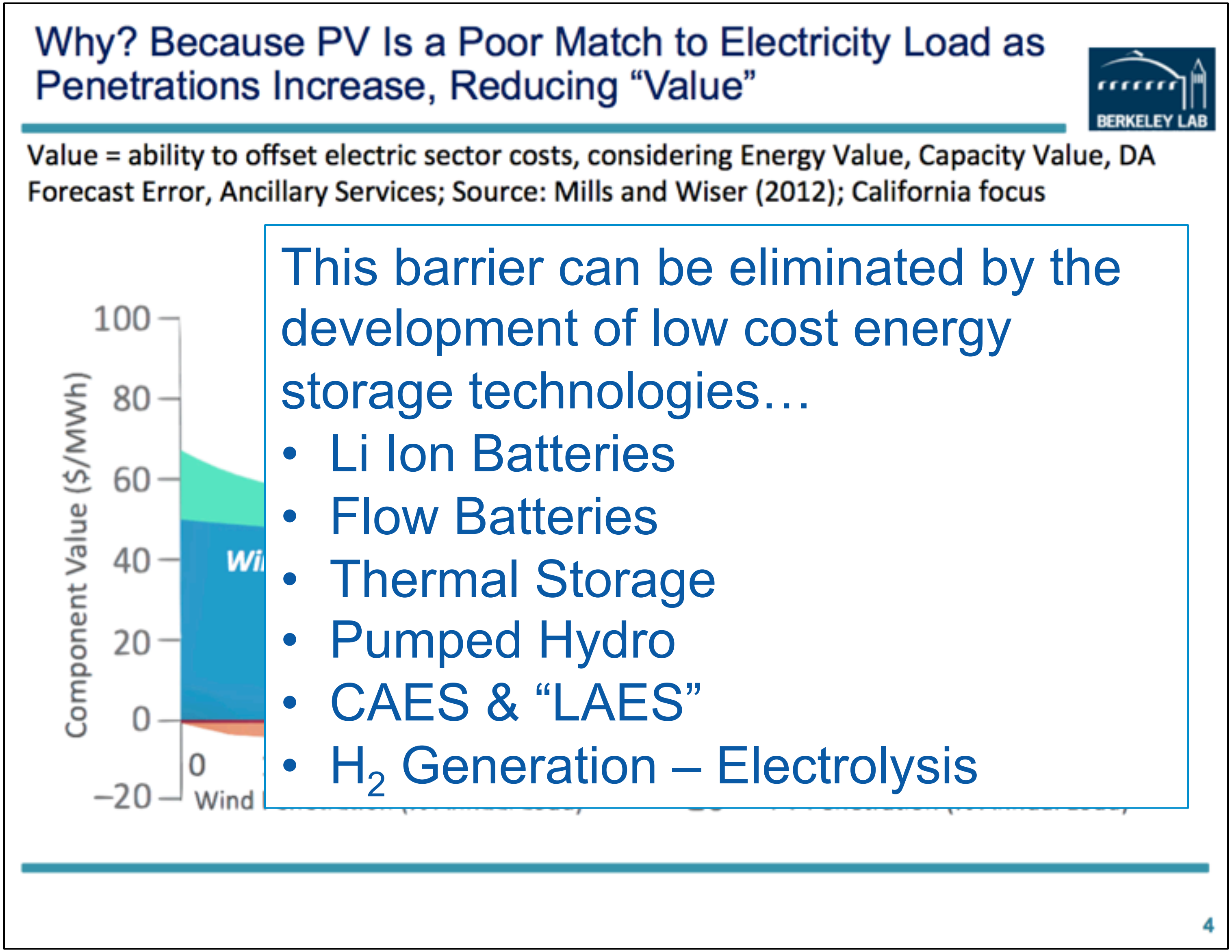
Barrier: Devaluation of PV Electrons



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

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

Barrier: Devaluation of PV Electrons



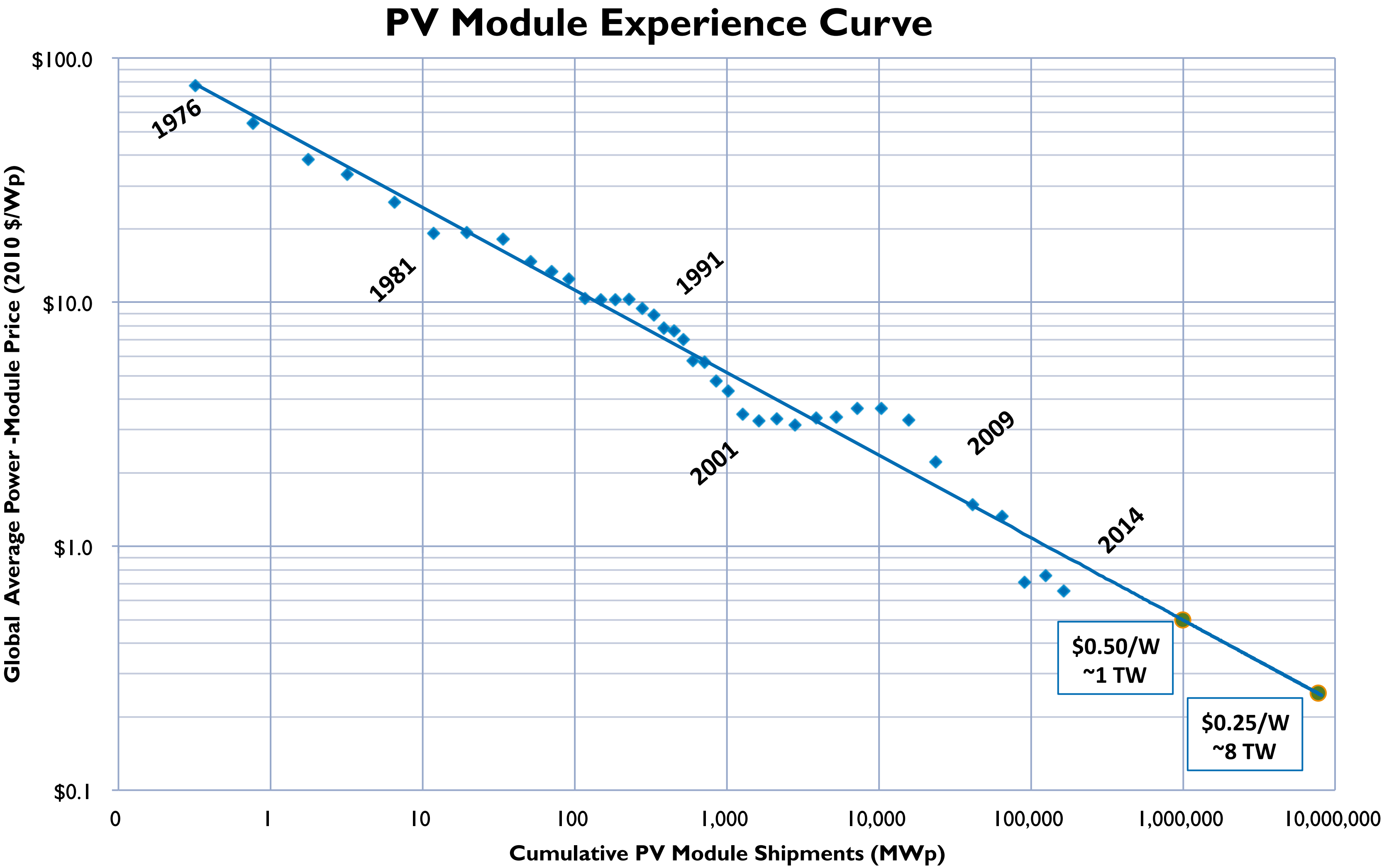
Why? Because PV Is a Poor Match to Electricity Load as Penetrations Increase, Reducing “Value”

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

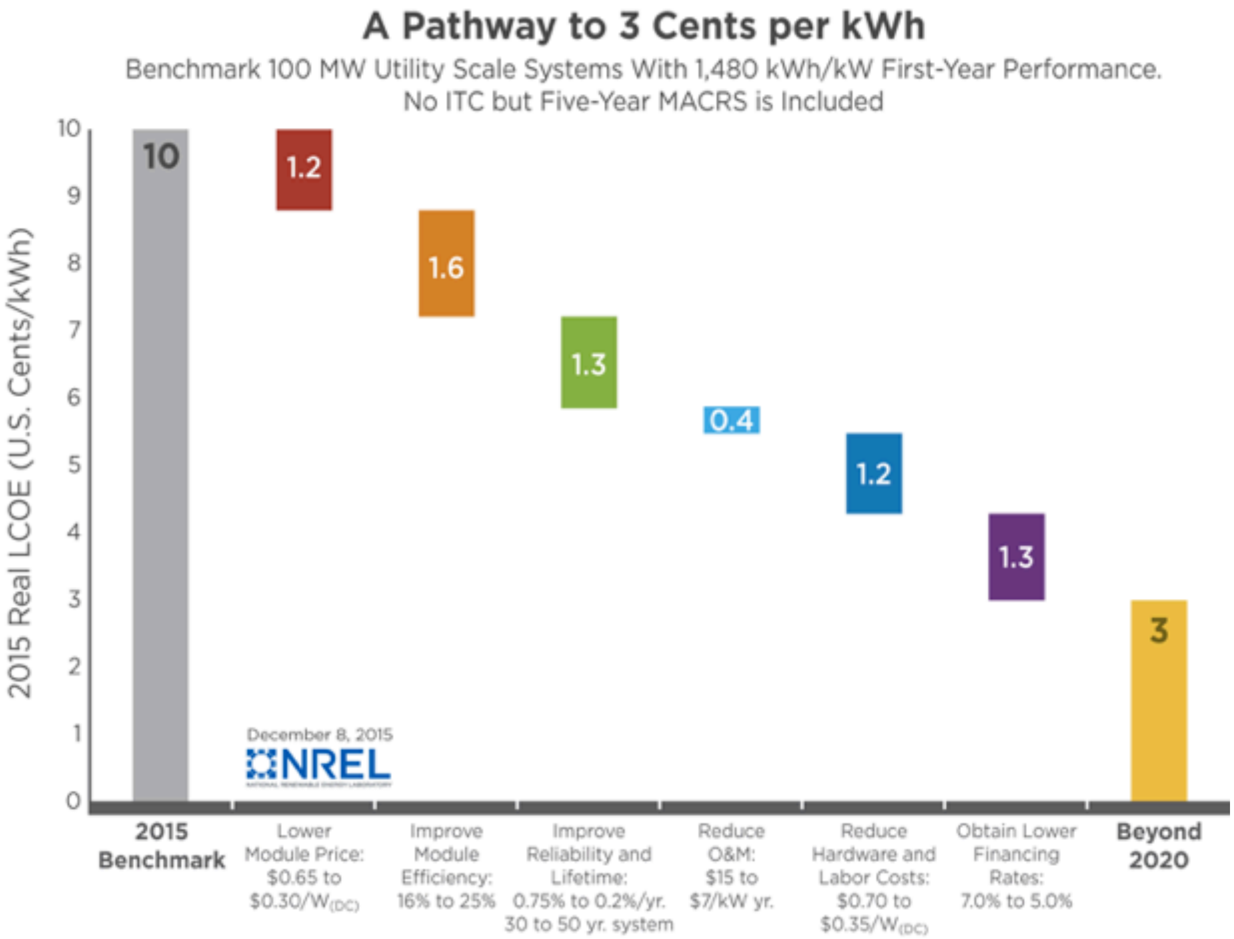
This barrier can be eliminated by the development of low cost energy storage technologies…

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

Multi-TW Scale PV: Projected Module Price

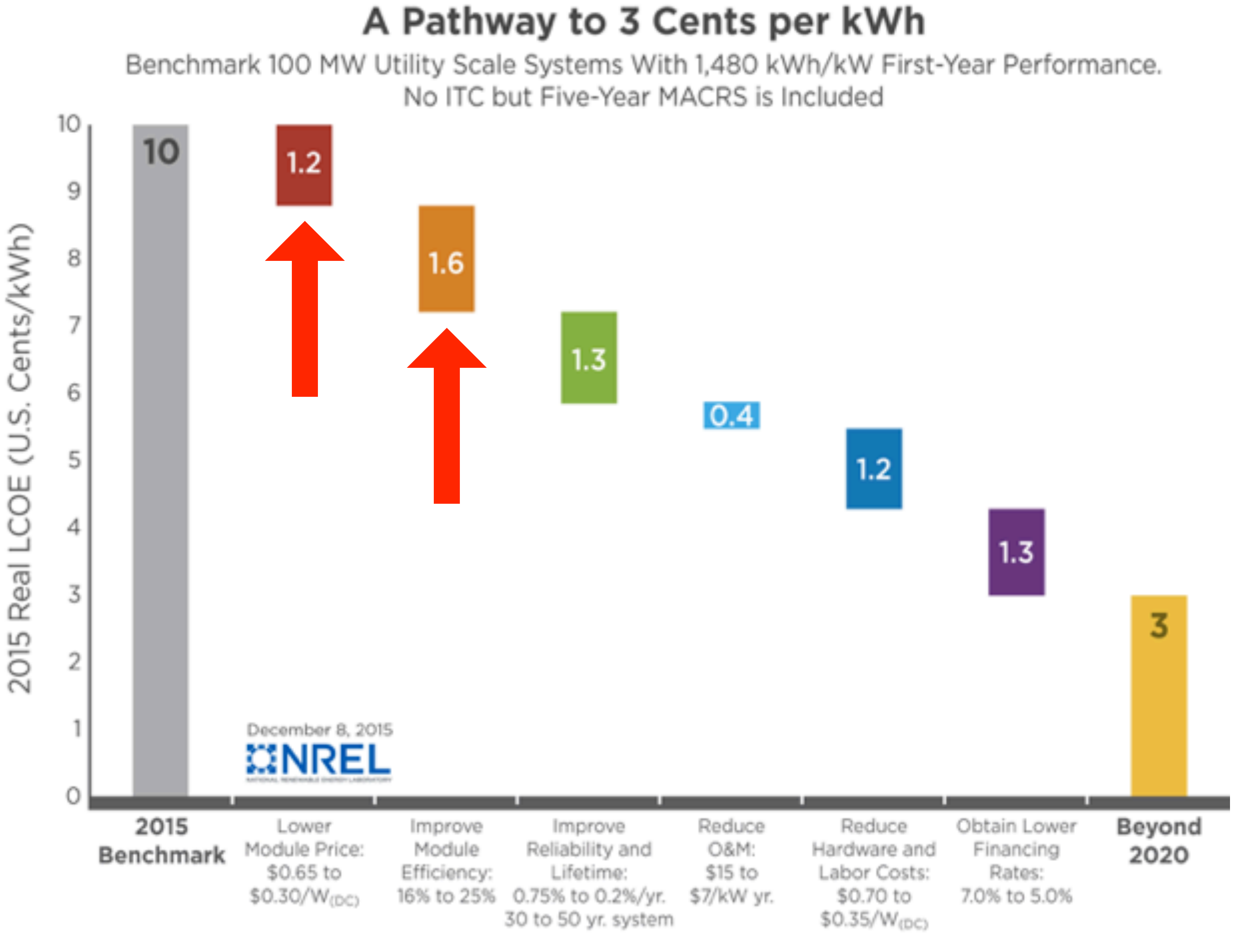


Example – Path to 3¢/kWh LCOE Target



Module cost, efficiency and reliability will be the focus of major new R&D efforts.

Example – Path to 3¢/kWh LCOE Target



Module **cost, efficiency** and reliability will be the focus of major new R&D efforts.

Silicon

Developing Next-Gen Si Solar Cells to Enable Higher-Efficiency Modules at Today's Cost

Systems **Engineering** & Integration

Decision Science & Analysis

Power Systems & Electrical Engineering

Applied Materials Science & Engineering

Chemical Engineering

Advanced Computer Science, Visualization & Data

INTEGRATION TO IMPACT

Impact entire c-Si PV market

NREL as US-based, internationally recognized Si PV research hub

Creates Si industry workforce

FhISE

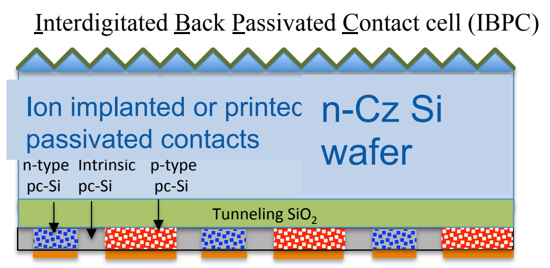
UNSW

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

INNOVATION TO APPLICATION

High-efficiency >23%, low-cost industrial-size cell on n-Cz wafer by 2018; currently 21.5%

Exploring novel transparent and conductive micro-composites



Interdigitated Back Passivated Contact cell (IBPC)

MIT

GIT

CSM

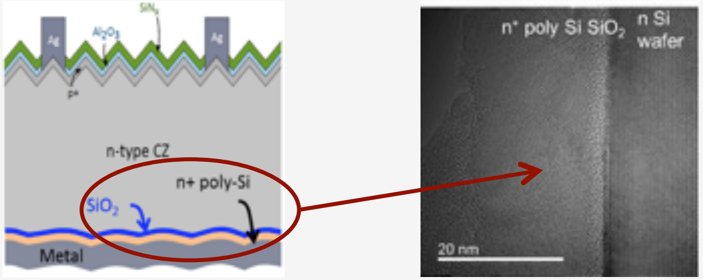
ASU

NIST

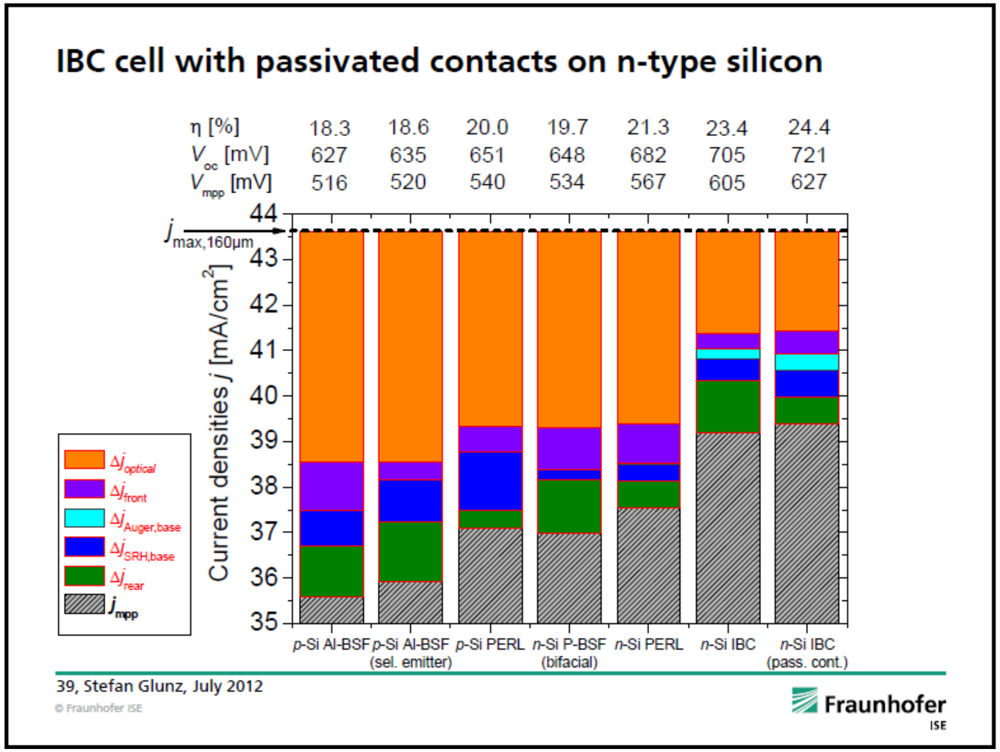
FOUNDATIONAL KNOWLEDGE

Developed passivated tunnel contacts for advanced cell architecture

Developed Tabula Rasa wafer treatment to prevent O-precipitation



Si Tandem Cells



IBC cell with passivated contacts on n-type silicon

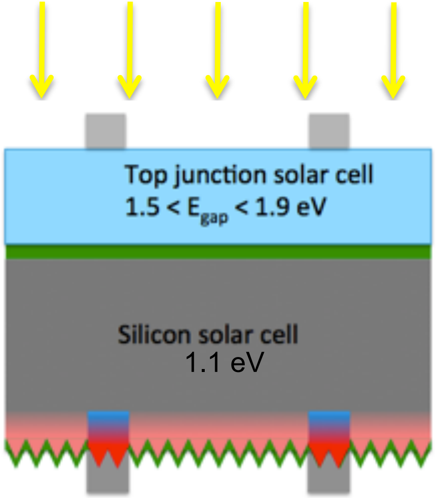
	p-Si Al-BSF	p-Si Al-BSF (sel. emitter)	p-Si PERL	n-Si P-BSF (bifacial)	n-Si PERL	n-Si IBC	n-Si IBC (pass. cont.)
η [%]	18.3	18.6	20.0	19.7	21.3	23.4	24.4
V_{oc} [mV]	627	635	651	648	682	705	721
V_{mpp} [mV]	516	520	540	534	567	605	627

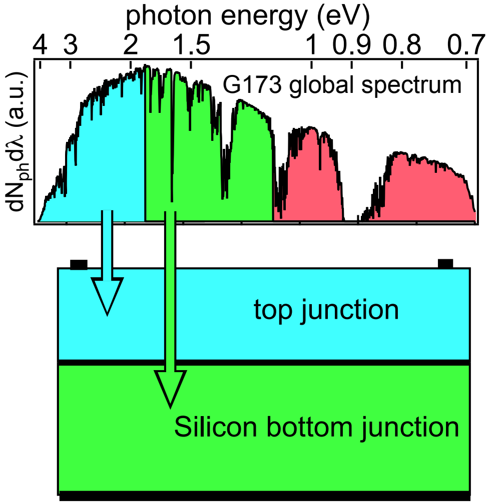
39, Stefan Glunz, July 2012

© Fraunhofer ISE

Fraunhofer ISE

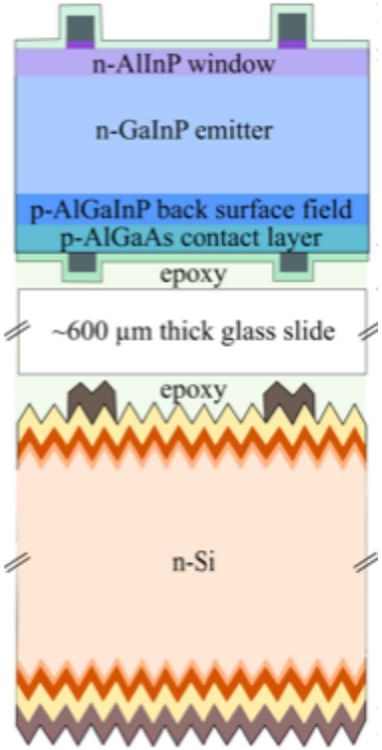
Source: Stefan Glunz presentation, NREL Si Workshop in Vail, CO, July, 2012

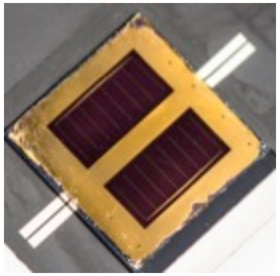




- Path to > 30% efficiency for Si wafer based cells.
- Top cell requirements:
  - Lattice & CTE match to Si if epitaxially grown
  - ~1.7 eV band gap
- Perovskites may evolve into good polycrystalline choice.

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

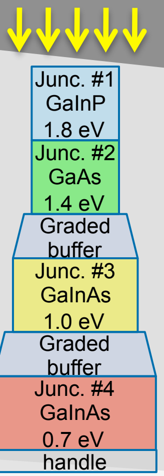
All commercial cells for space and concentrator PV based on NREL multijunction technology

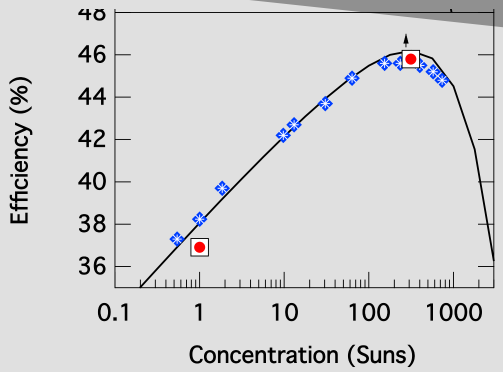
R&D 100 Awards:

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

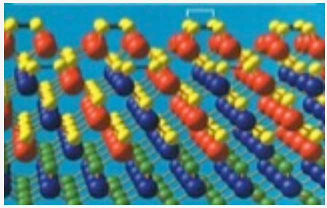
INNOVATION TO APPLICATION

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

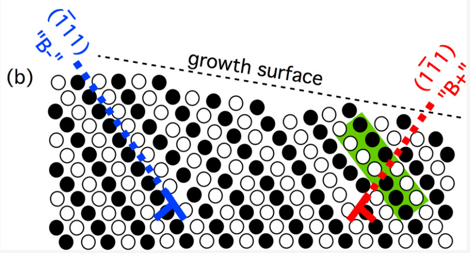




FOUNDATIONAL *KNOWLEDGE*

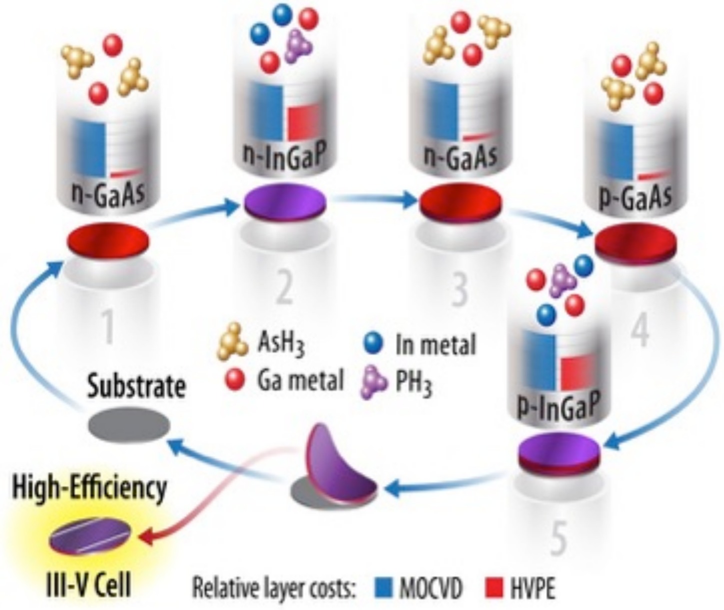


Superstructure ordering modifies the energy band and tailored optical properties



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)

Cadmium Telluride

CdTe Solar Technology Leading the Way to Grid Parity

Systems **Engineering** & Integration

Decision Science & Analysis

Power Systems & Electrical Engineering

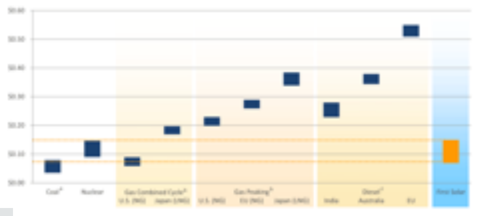
Applied Materials Science & Engineering

Chemical Engineering

Advanced Computer Science, Visualization & Data

INTEGRATION TO IMPACT

NREL contributed to CdTe technology for 20 years and held world-record efficiency for 10 years



First Solar

REEL Solar

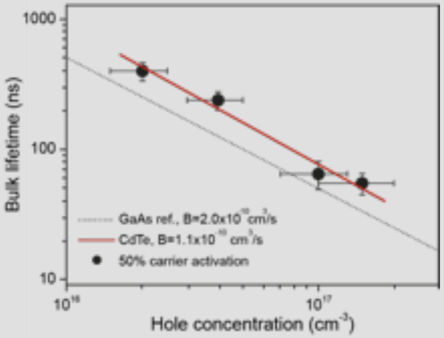
LucinTech

EPIR

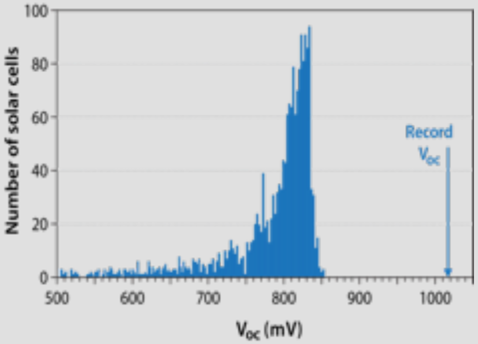
Calyxo

A small group of companies and research groups has led to CdTe competing directly with conventional energy sources

INNOVATION TO APPLICATION



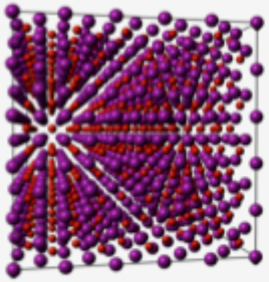
By shifting to Cd-rich stoichiometry and placing P on Te sites, we have attained defect-free lifetimes with ideal conductivity for solar cells



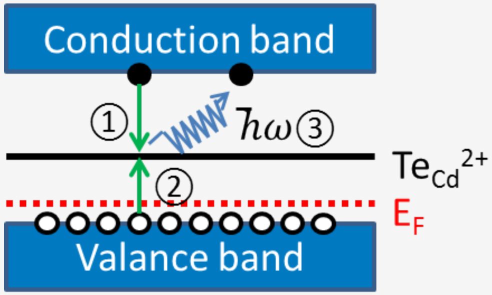
These improvements helped NREL break the 60-year voltage barrier

FOUNDATIONAL KNOWLEDGE

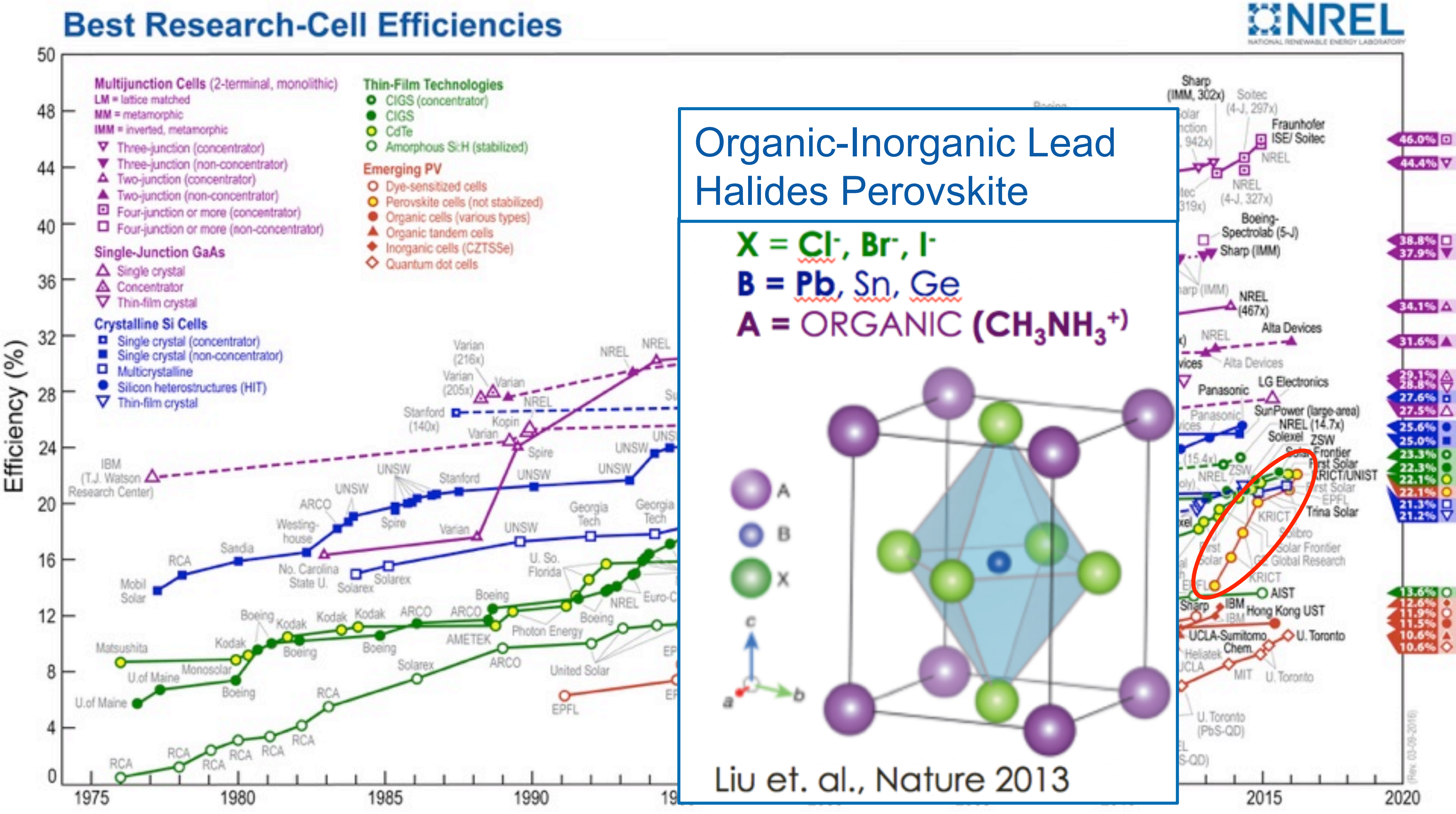
After years of empiricism, NREL has been systematically studying the fundamentals of II-VI material



Atomistic calculations and experiment indicate that Te on Cd sites limit lifetime



Perovskite PV Cells



Organic-Inorganic Lead Halides Perovskite

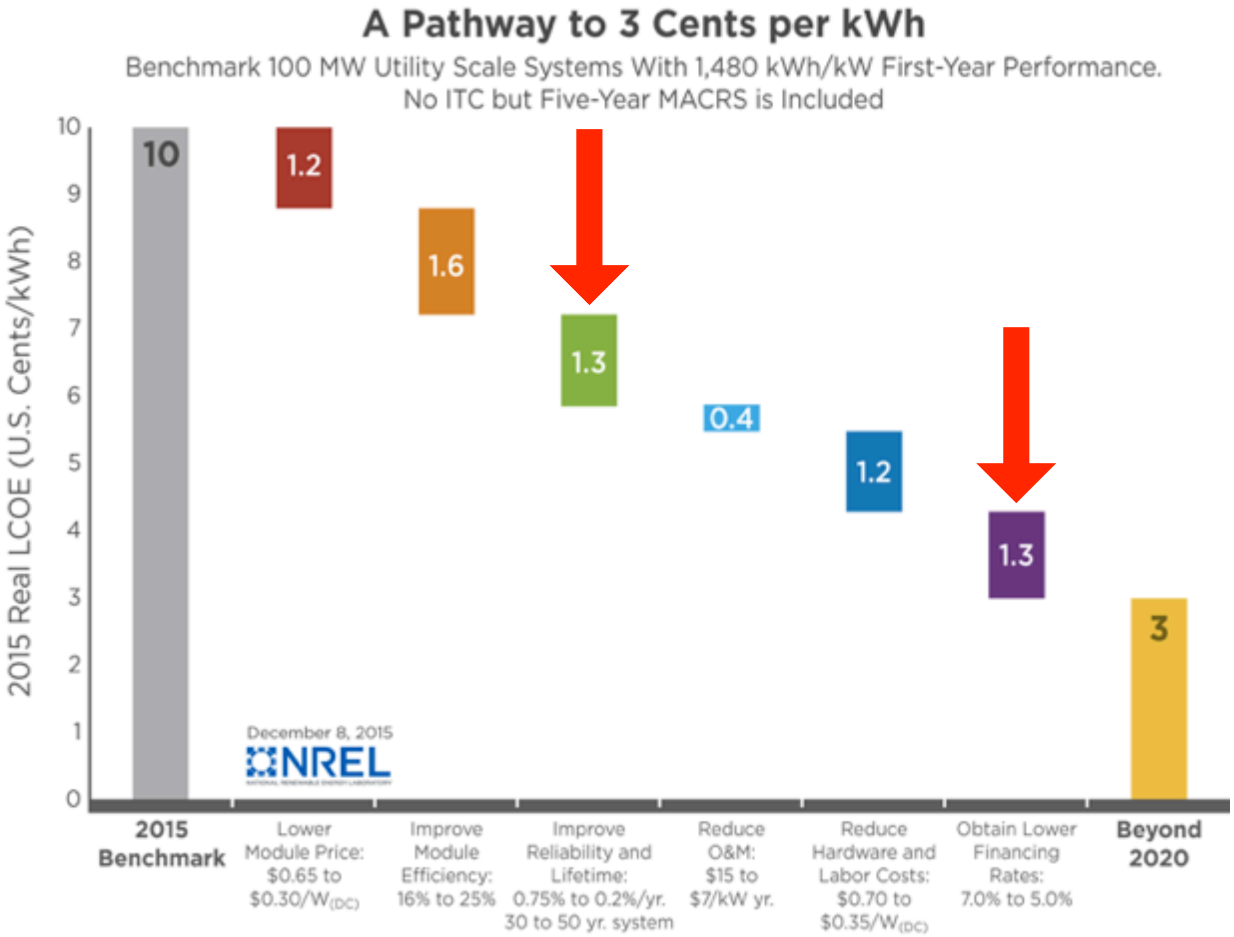
$X = Cl^-, Br^-, I^-$

$B = Pb, Sn, Ge$

$A =$ ORGANIC $(CH_3NH_3^+)$

Liu et. al., Nature 2013

Example – Path to 3¢/kWh LCOE Target



Module cost, efficiency and **reliability** will be the focus of major new R&D efforts.

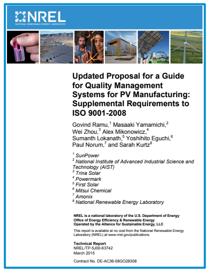
PV Reliability

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



NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Updated Proposal for a Guide for Quality Management Systems for PV Manufacturing: Supplemental Requirements to ISO 9001-2008

Govind Ramu,[1] Masaaki Yamamichi,[2] Wei Zhou,[3] Alex Mikonowicz,[4] Sumanth Lokanath,[5] Yoshihito Eguchi,[6] Paul Norum,[7] and Sarah Kurtz[8]

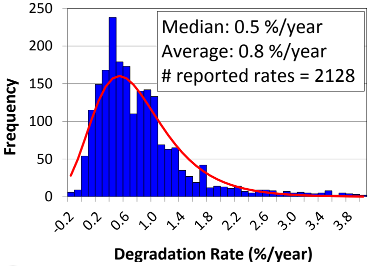
[1] *SunPower*
[2] *National Institute of Advanced Industrial Science and Technology (AIST)*
[3] *Trina Solar*
[4] *Powermark*
[5] *First Solar*
[6] *Mitsui Chemical*
[7] *Amonix*
[8] *National Renewable Energy Laboratory*

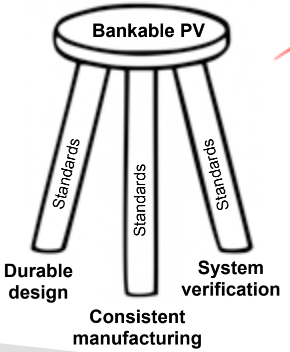
NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Technical Report
NREL/TP-5J00-63742
March 2015

Contract No. DE-AC36-08GO28308





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

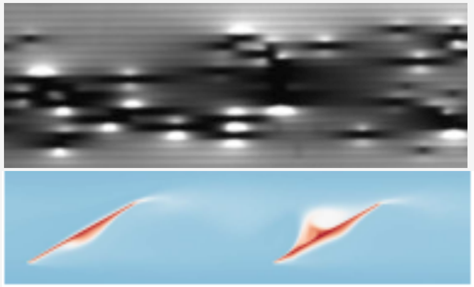
SUNPOWER

First Solar.

Sandia National Laboratories
STION
EPRI ELECTRIC POWER RESEARCH INSTITUTE

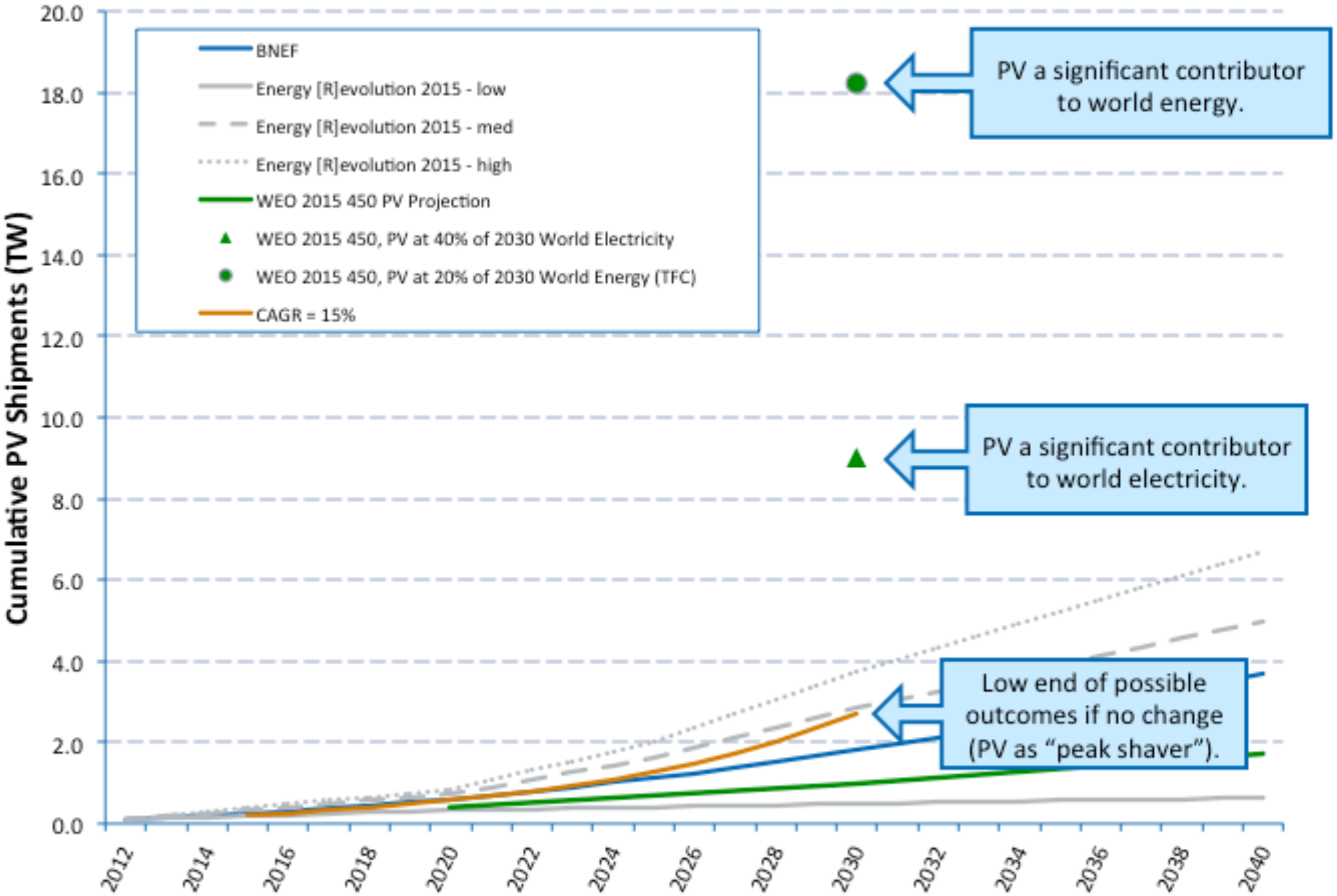
FOUNDATIONAL KNOWLEDGE

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



ATLAS MATERIAL TESTING SOLUTIONS
Stanford University
ASU

Low Cost Energy Storage



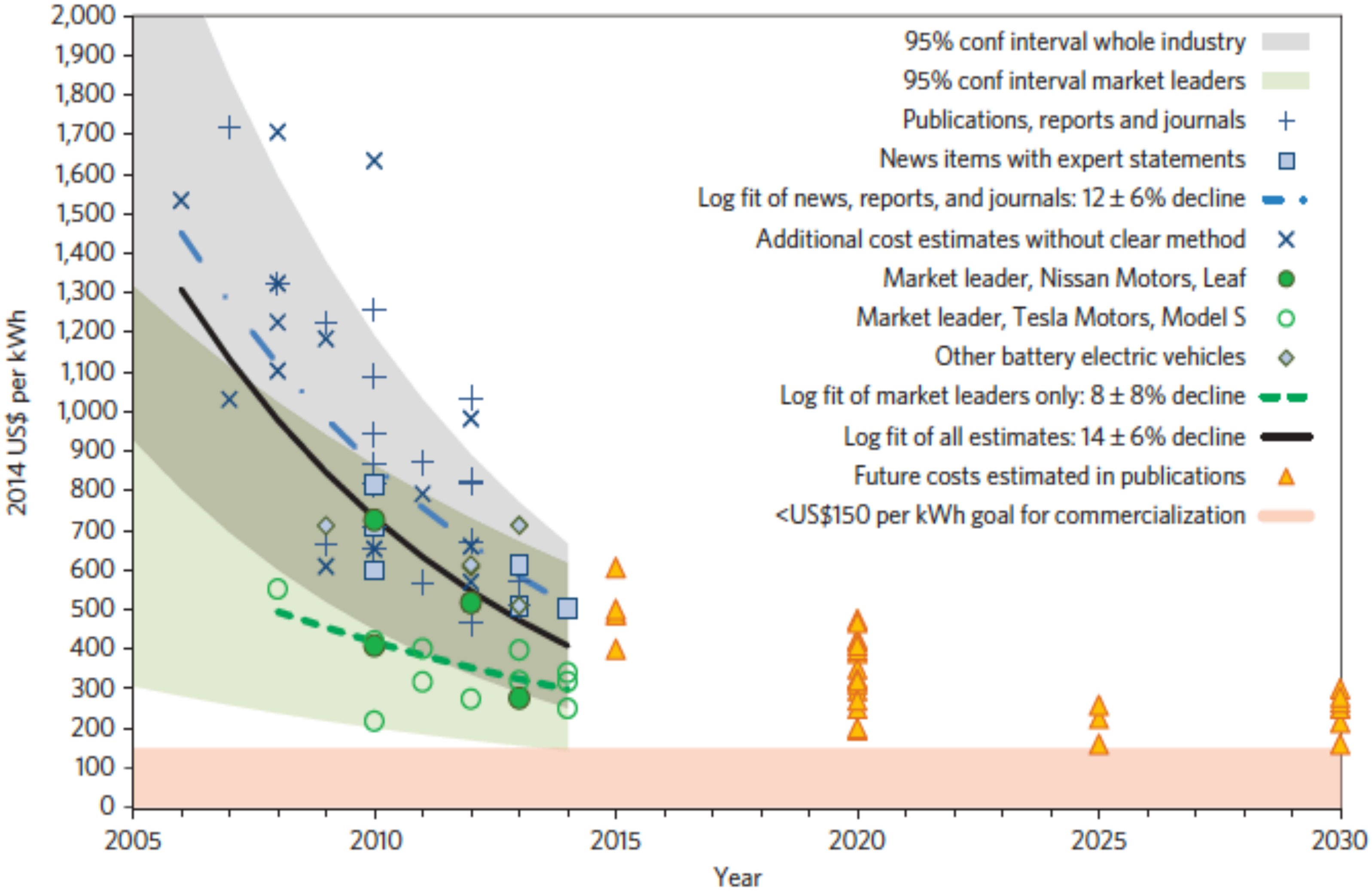
PV a significant contributor to world energy.

PV a significant contributor to world electricity.

Low end of possible outcomes if no change (PV as "peak shaver").

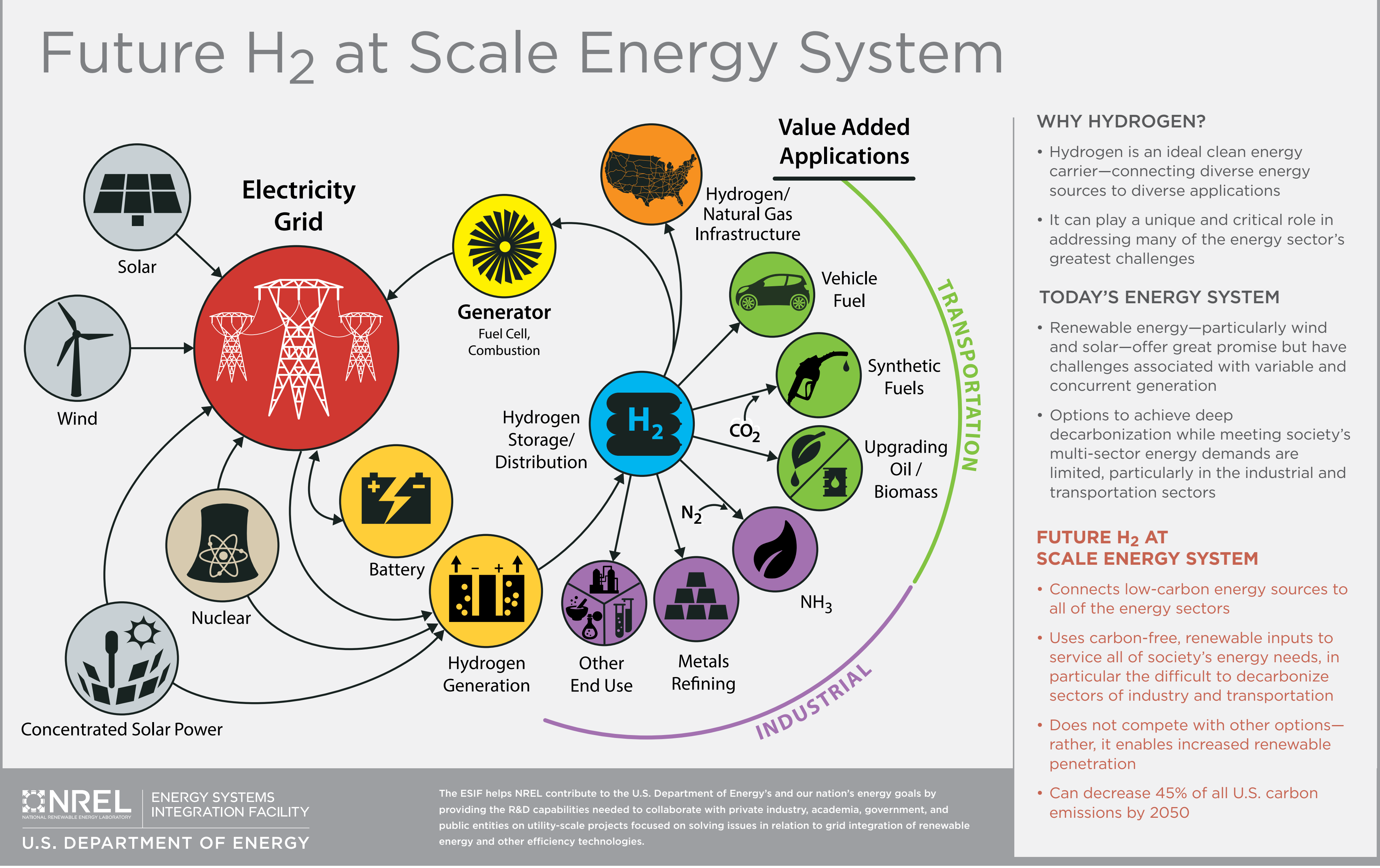
For 2 growth scenarios beyond peak shaving, R&D directed at **storage in all forms** will also be needed.

Li Ion Batteries - Cost Declines



Source: Nykvist & Nilsson, *Nature Climate Change*, 23MAR15

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

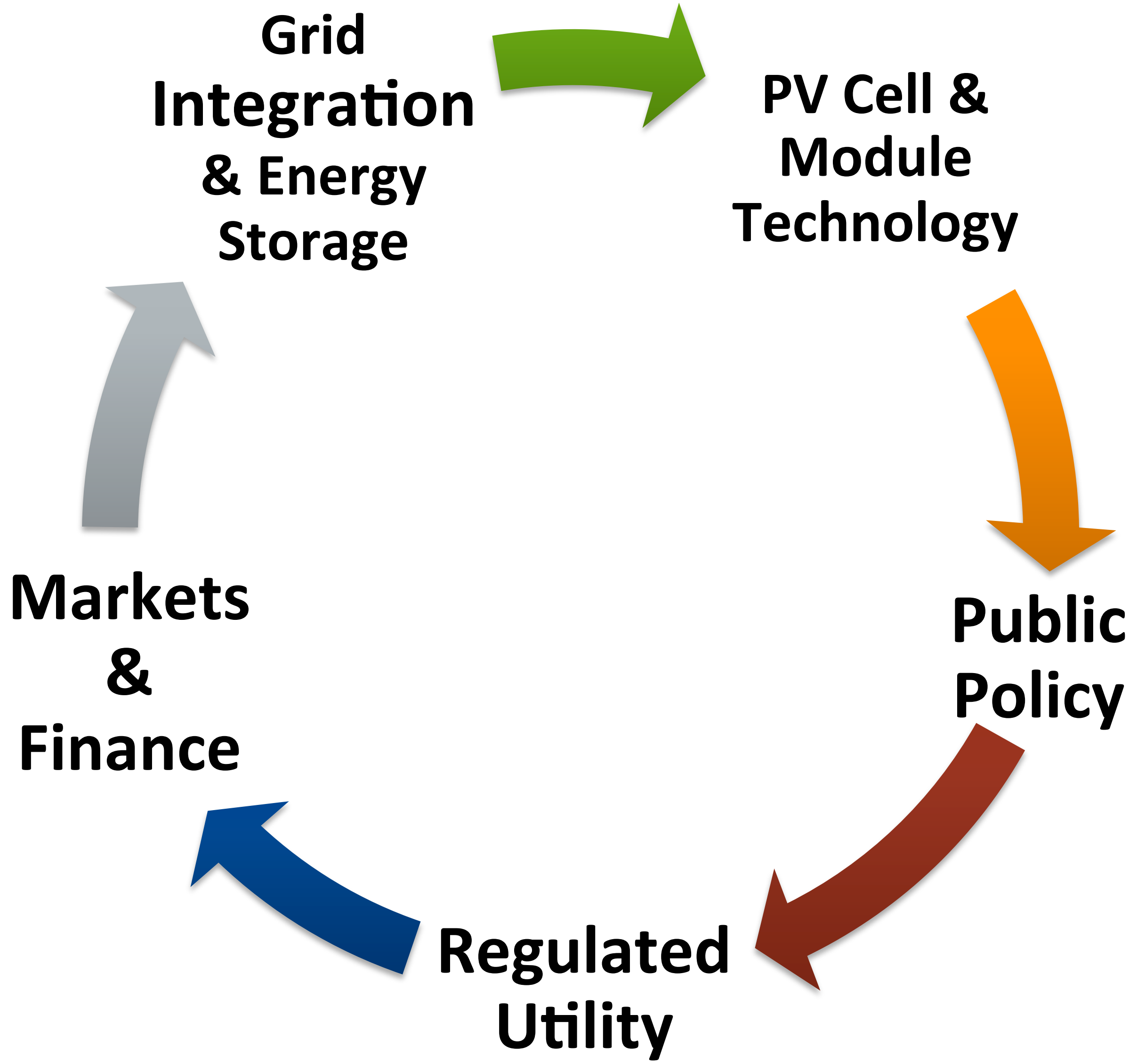
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
ENERGY SYSTEMS INTEGRATION FACILITY
U.S. DEPARTMENT OF ENERGY

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.

Overview

1. Brief introduction of NREL, the MCST Directorate and NREL's PV Program.
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.

PV & Storage R&D – Not the Only Problem



Grid Integration & Energy Storage

PV Cell & Module Technology

Public Policy

Regulated Utility

Markets & Finance

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Thank You