The Present and Future of Photovoltaic Manufacturing

Fondúireacht Eolaíochta Éireann
Science Foundation Ireland

Colin A. Wolden
E.T.S. Walton Visiting Fellow
University College Dublin
School of Chemical and Bioprocess Engineering
Belfield, Dublin 4, Ireland

Permanent Address
Department of Chemical Engineering
Colorado School of Mines
Golden, CO 80401 USA

SEC
Advanced Biomimetic Materials for
SOLAR ENERGY CONVERSION
SFI Strategic Research Cluster

UCD DUBLIN

MINES

Outline

Energy: Resources & Needs

- Survey of Conventional and Renewable Resources
- The Scope of the Sustainable Energy Challenge
- A Little Science

Status & Prospects for PV Manufacturing Technologies

- Single and Multi-crystalline Silicon
- Thin Film: (CdTe, a-Si, CIGSS)
- Dye-sensitized Solar Cells (DSC)

Meeting the Terawatt Challenge

- Areas for Research Investment
- Broader Issues

Sustainable Energy: The Grand Challenge

Humanity's Top Ten Problems for next 50 years

1. ENERGY
2. WATER
3. FOOD
4. ENVIRONMENT
5. POVERTY
6. TERRORISM & WAR
7. DISEASE
8. EDUCATION
9. DEMOCRACY
10. POPULATION

2003	6.3	Billion People
2050	8-10	Billion People

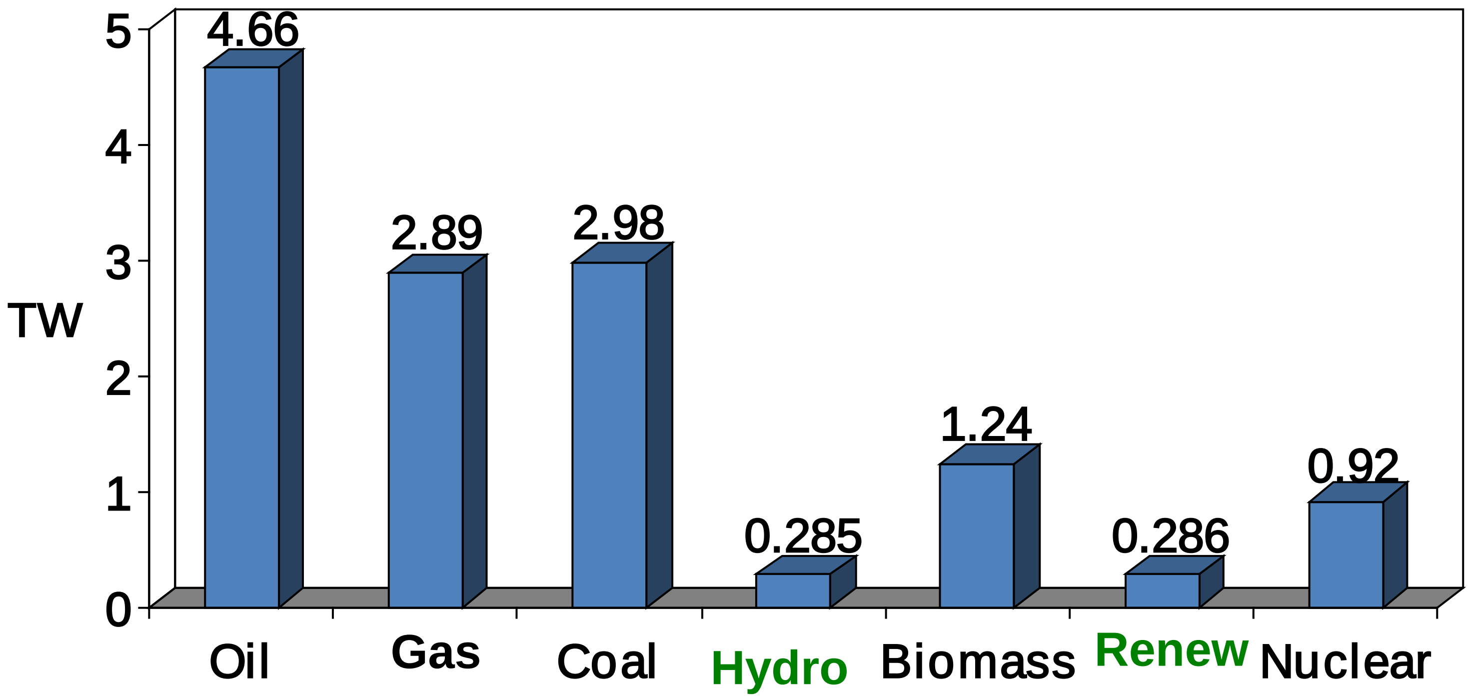
Source Richard Smalley Energy & Nanotechnology Conference
Rice University, Houston May 3, 2003

see also R.E. Smalley, MRS Bulletin 30 412 (2005)

Current Energy Portfolio

Global Total ~ 15 Terawatts

- $1\ TW = 10^{12}\ W$
- Predominantly through the combustion of fossil fuels



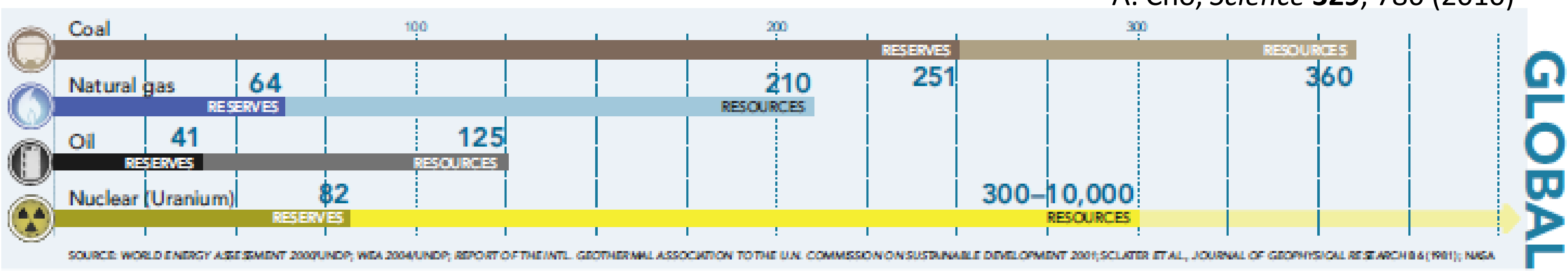
N. S. Lewis, *MRS Bulletin* **32**, 808 (2007)

Conventional Energy Resources

How much is left?

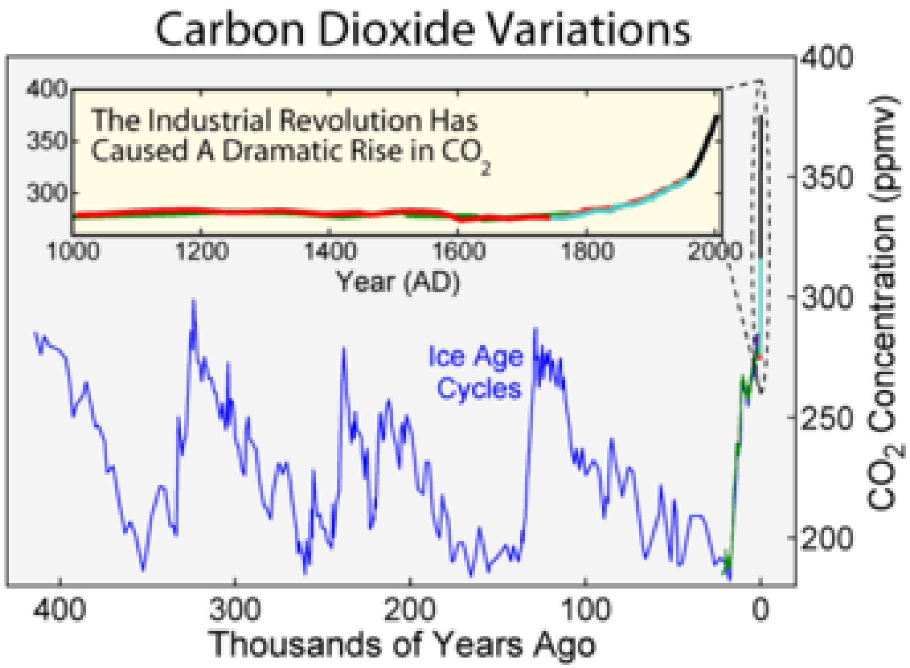
- Oil: 40 – 125 years
- Natural Gas: 65 - 210 years
- Coal: 250 – 360 years
- Nuclear: 80 – 300

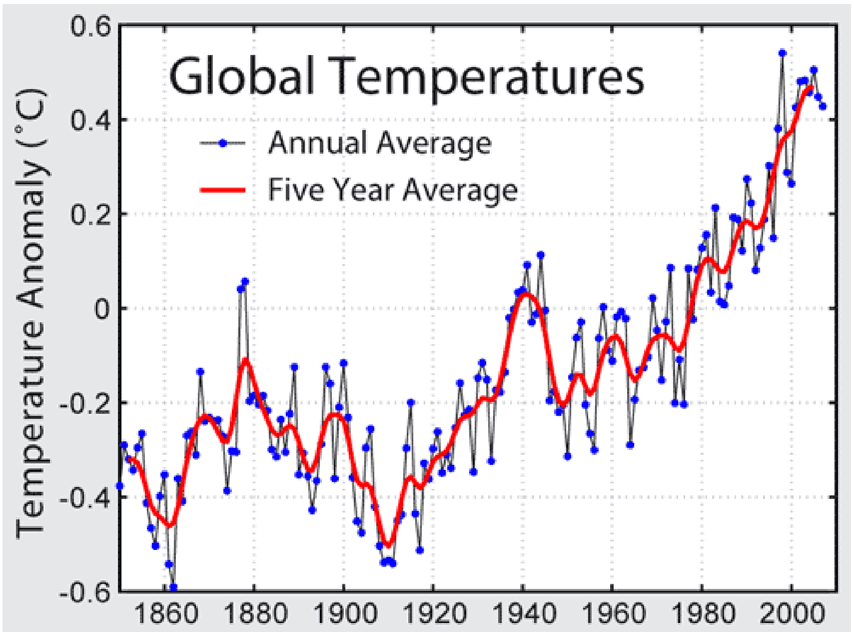
A. Cho, *Science* **329**, 786 (2010)

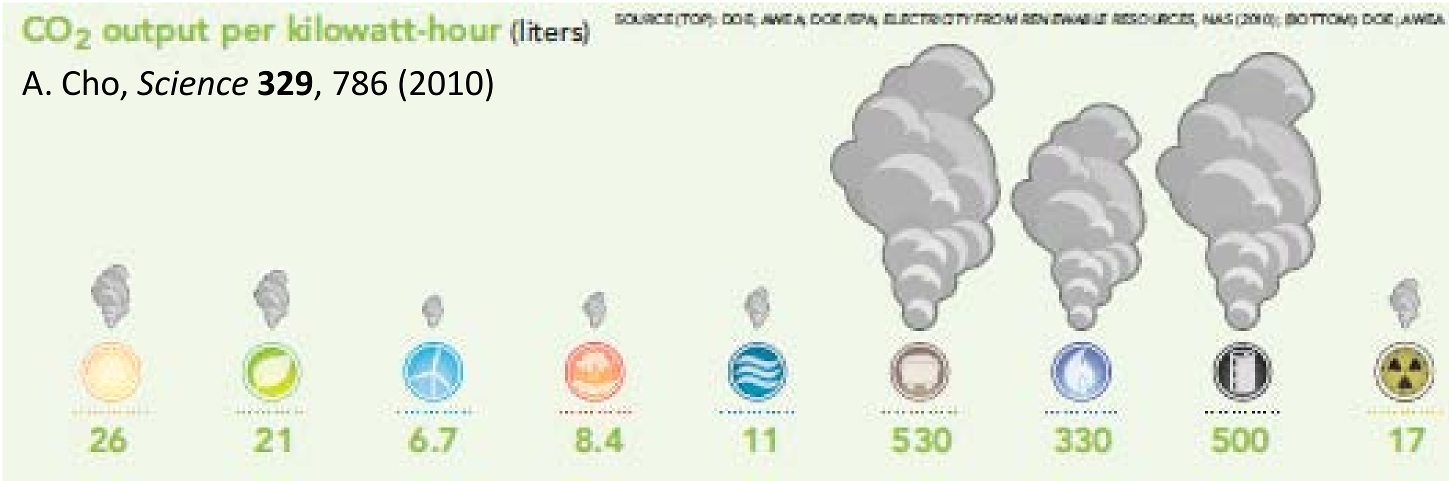


More Difficult/Costly

CO_2 & Climate Change



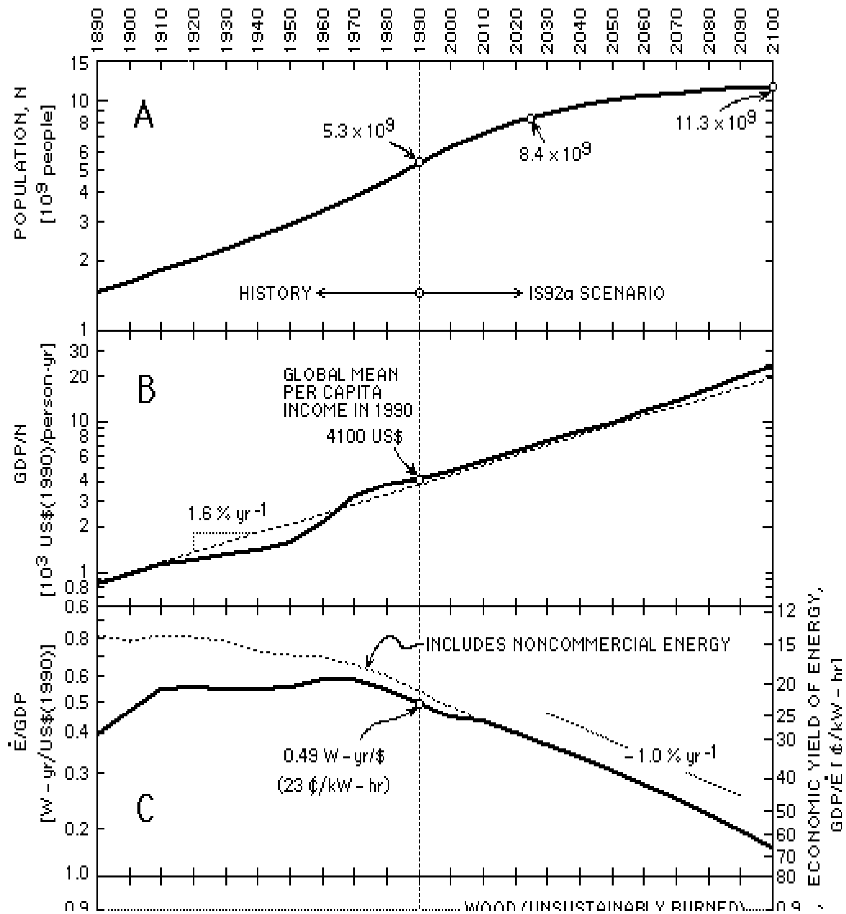




A. Cho, *Science* **329**, 786 (2010)

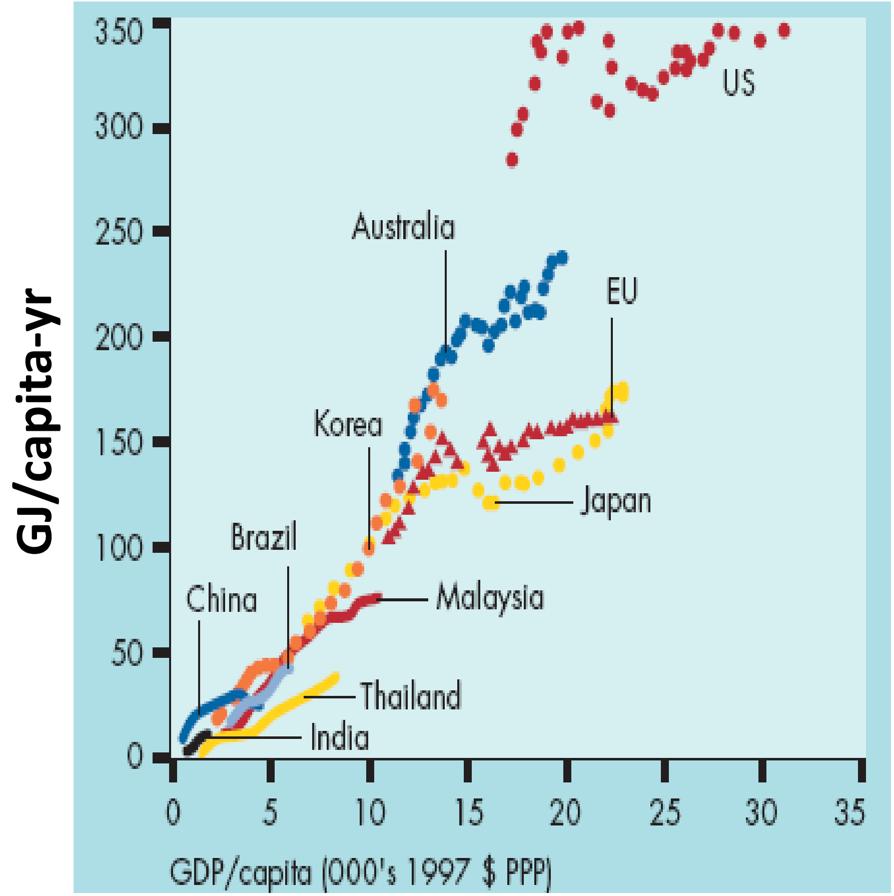
Population & Wealth

2050: > 10 Billion



Hoffert et al., *Nature* **385**, 881 (1998)

Consumption vs. Wealth



N. S. Lewis, *MRS Bulletin* **32**, 808 (2007)

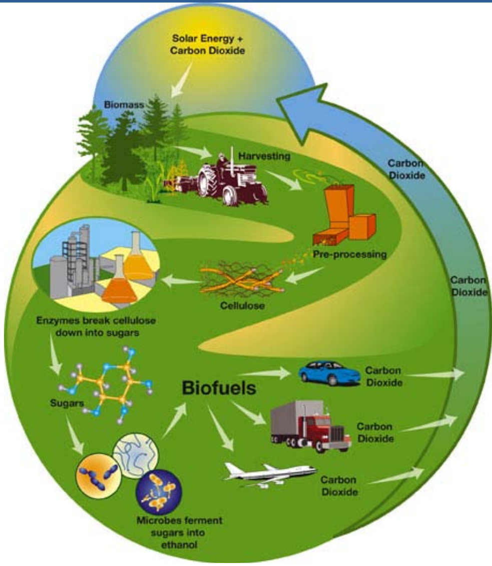
To Stabilize CO_2: 30 TW of carbon-free energy by 2050

Renewable Energy Resources

- **Hydroelectric**
- **Wind**
- **Biomass**
- **Geothermal**
- **Ocean/Tides**
- Solar

Global Potential

- Current: ~2 TW
- Practical: ~10 TW

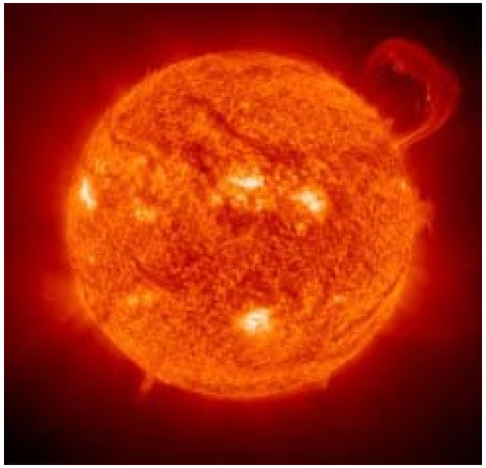


Source: WEA 2000

Renewable Energy Resources: Solar

Solar Energy Potential

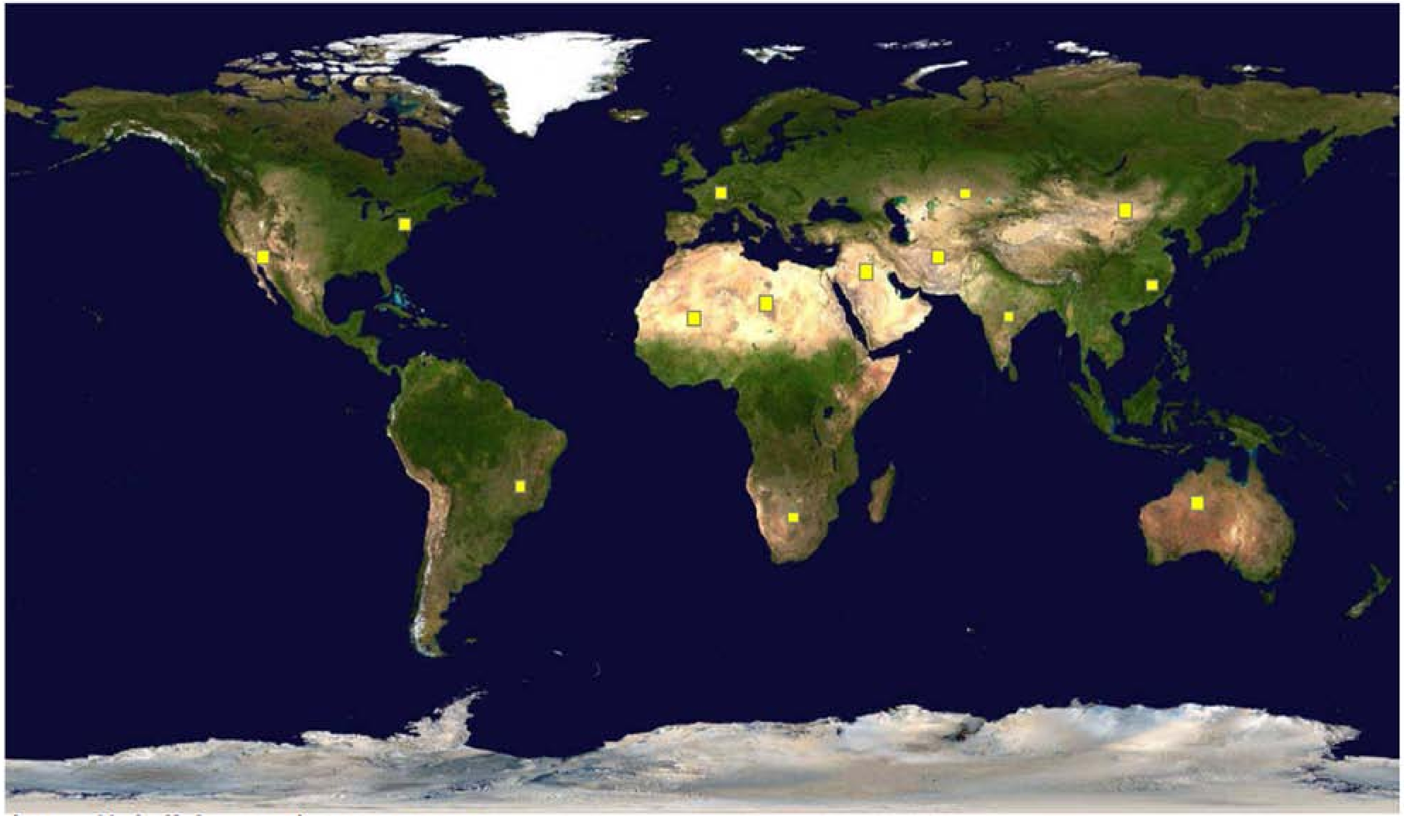
- Solar Flux: 1.1 x 10^5 TW
- I hour Sunlight = Annual Global Consumption
- Practical Potential: 600 TW
- Infinite Supply



Solar Energy Conversion Options

- Solar Thermal: Photons to Heat
- **Solar Photovoltaic: Photons to Electrons**
- Solar Fuels: Photons to Chemicals
  - Water Splitting: $2H_2O + h\nu \rightarrow 2H_2 + O_2$
  - CO_2 Reduction: $CO_2 + 2H_2O + h\nu \rightarrow 2CH_3OH + O_2$

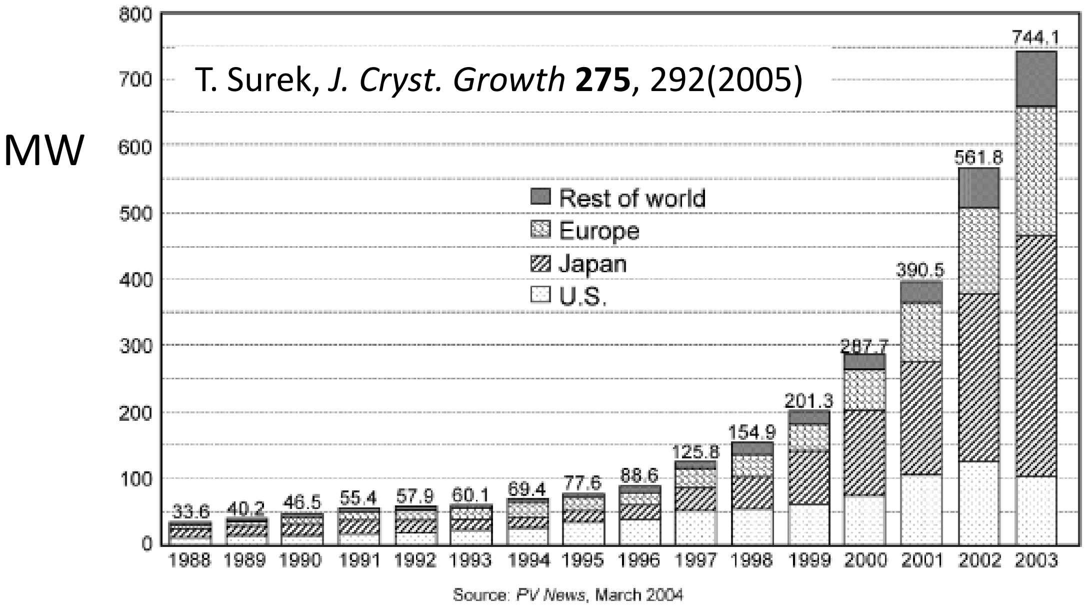
Terawatt Challenge



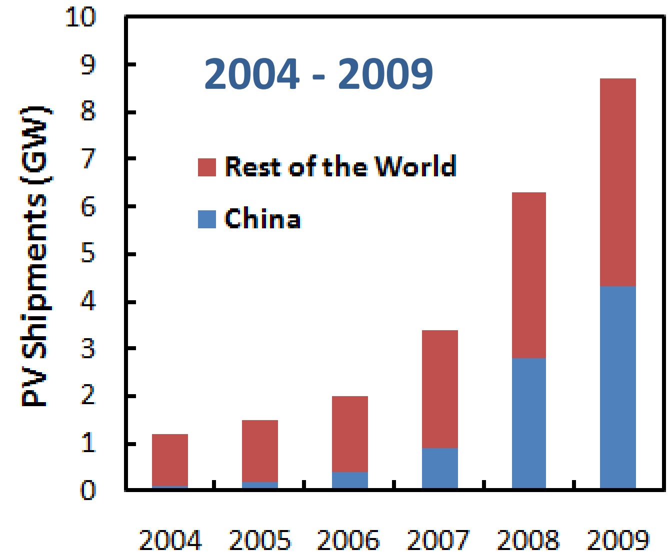
http://visibleearth.nasa.gov

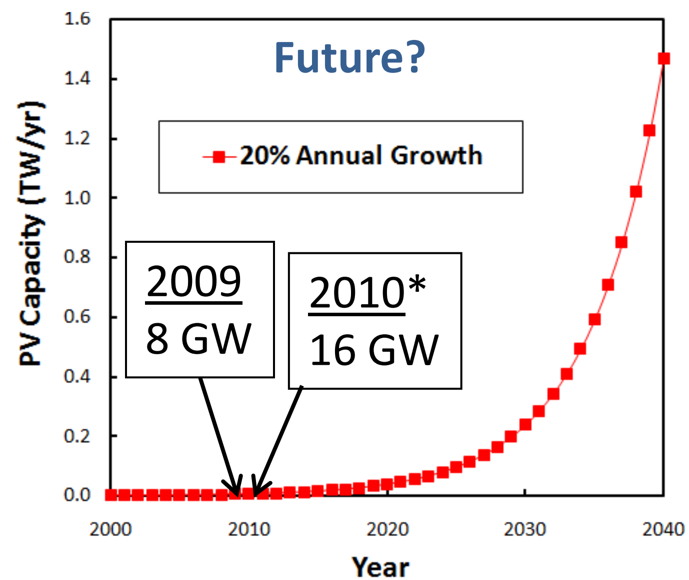
- 30 TW of clean, renewable energy by 2050
- Require 1 TW/year capacity

Growth of the PV Market



1988 - 2003

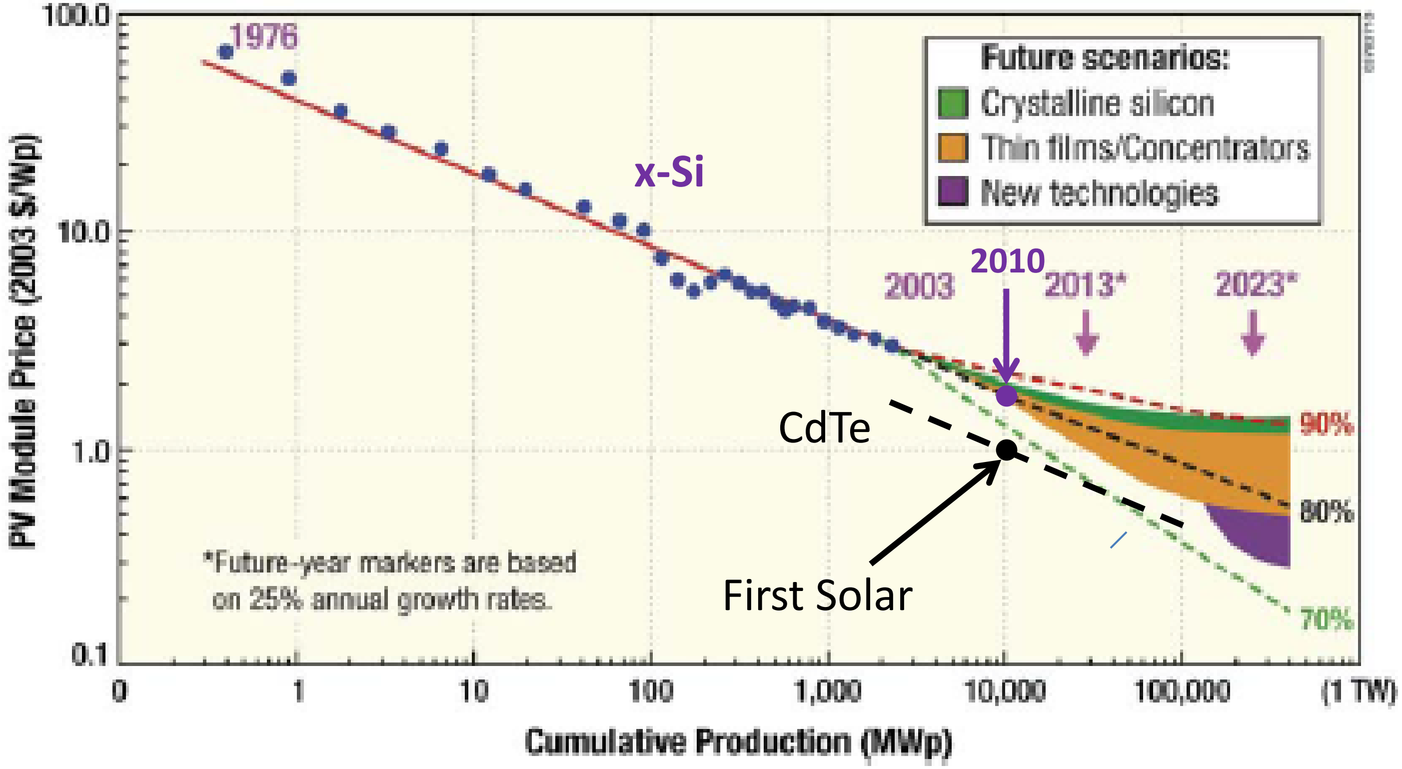




- Is 20% growth sustainable?
- What about costs?

PV Costs are Dropping

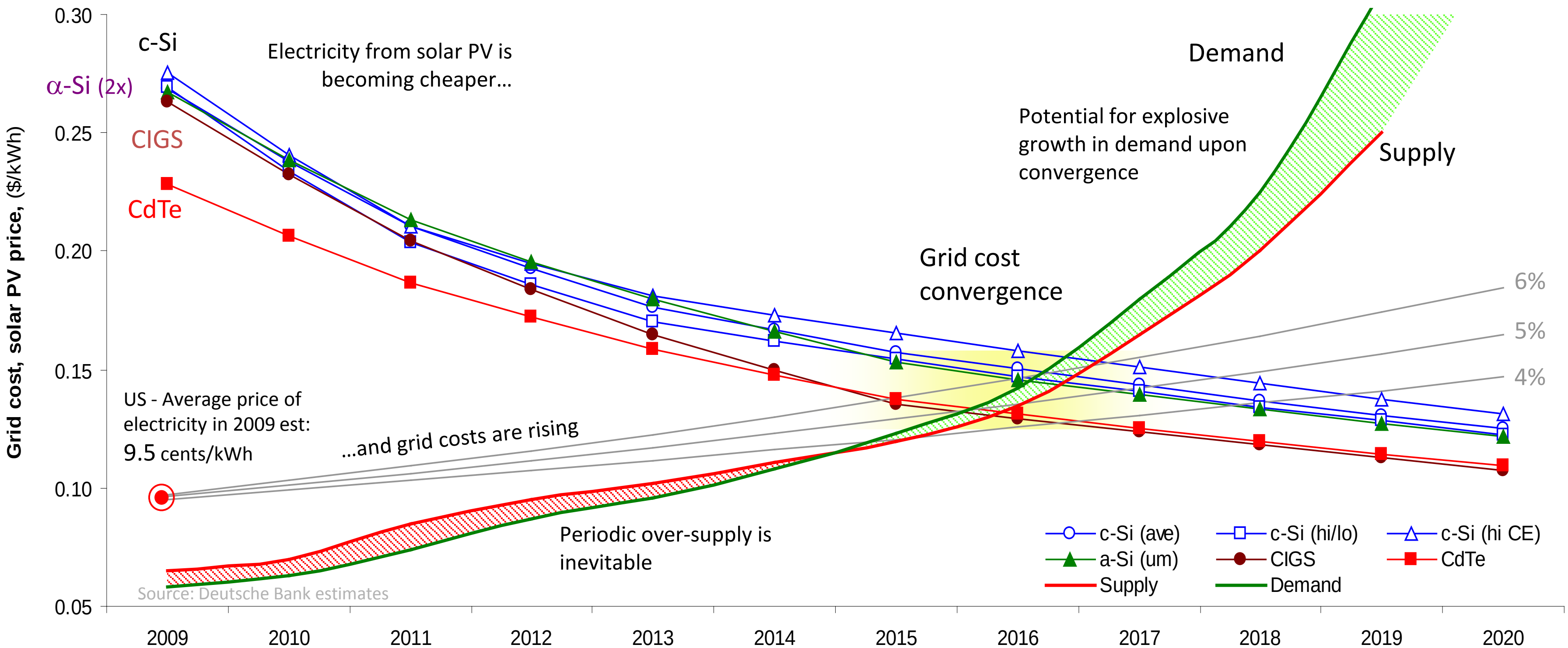
The Experience Curve: 80%



T. Surek, *J. Cryst. Growth* **275**, 292 (2005)

- x-Si: $2/$W_p$, $1.3/$W_p$ (China)
- CdTe (First Solar): $1/$W_p$

Convergence



❑ No technical breakthroughs are required to achieve solar PV cost reduction curve(s)

Source: Steven O'Rourke, "Solar Photovoltaic Industry", Deutsche Bank, May 2009

- Market poised for explosive growth this decade
- Are we ready for it?

Catalyzing Innovation in PV Manufacturing

An NSF Workshop

May 6-7th, 2010

Golden, CO

Workshop Goal

“Identify the potential technologies and innovations that offer *low-cost, high-conversion-efficiency and sustainable* photovoltaic materials.”

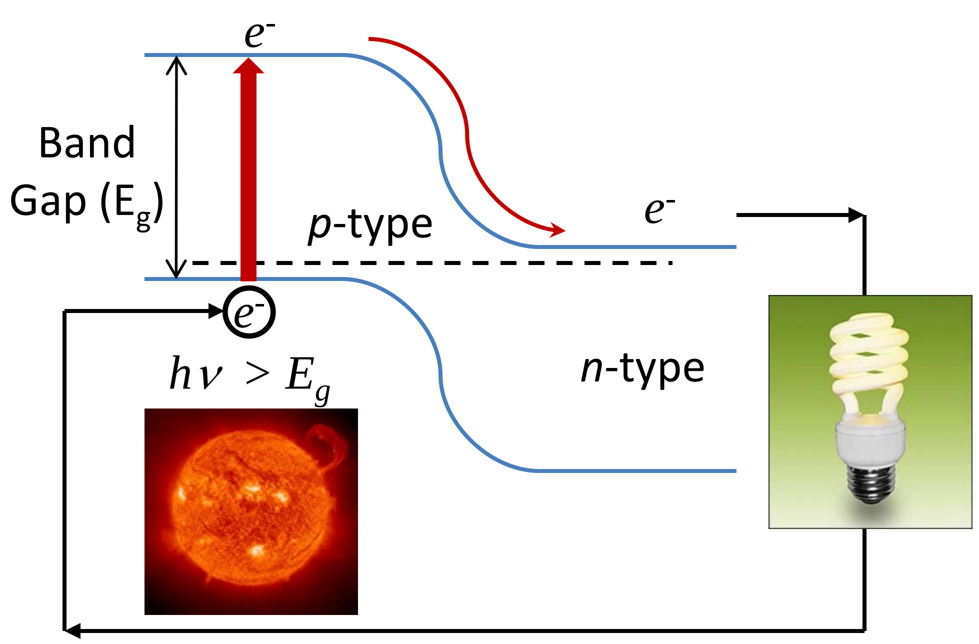
Reviewed Each Technology

- Current Status
- Identify the short/long term needs
- Recommend/prioritize areas for R & D Investment

Principle of Solar Photovoltaics

Solid State *pn* Junction: The Electron Pump

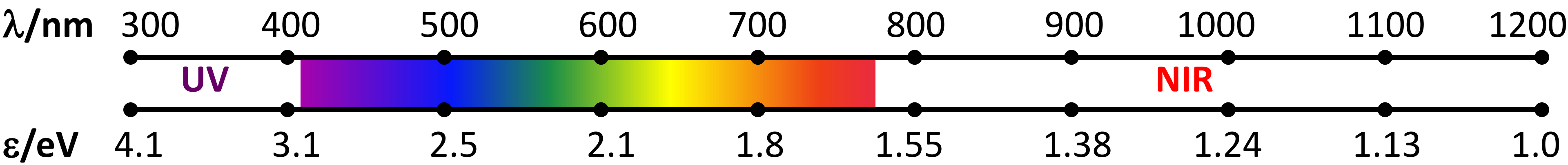
- Join to dissimilar semi-conductors: A diode
- Absorb Photon: Generate Electron- Hole Pair
- Junction provides a internal bias

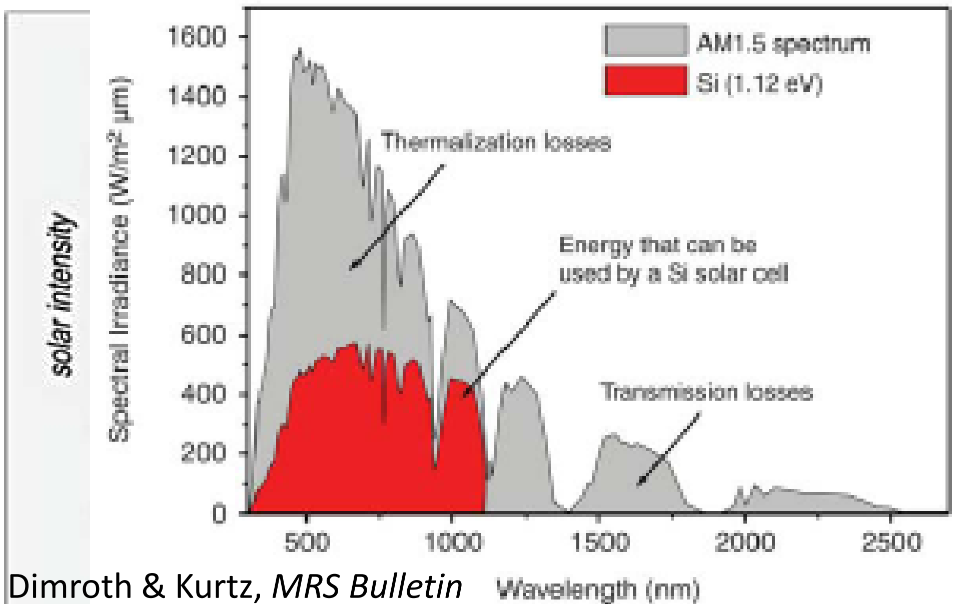


Why is Solar so Inefficient?

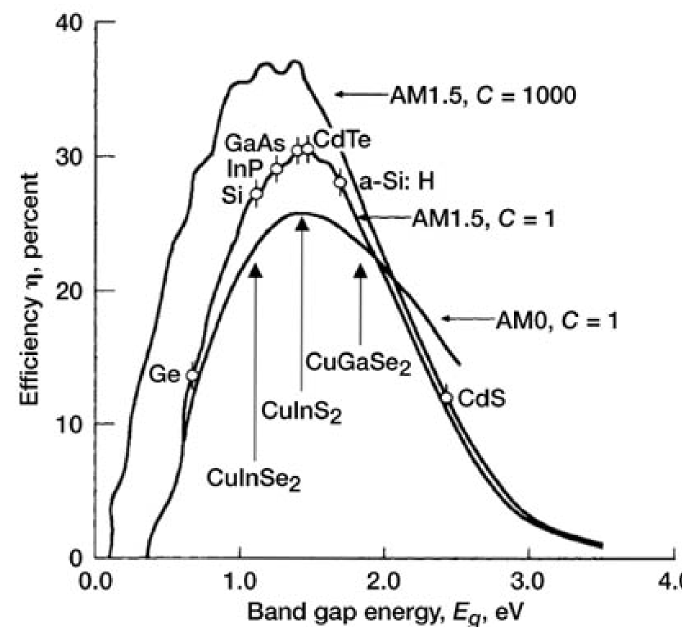
Thermodynamic Limit: 30% Conversion

- Photons below band gap are not absorbed
- Photon energy in excess of band gap wasted





Dimroth & Kurtz, *MRS Bulletin* **32**, 242 (2007)



Shockley & Quiesser, *JAP* **32**, 510 (1961)

Technology Classification

1^{st} Generation

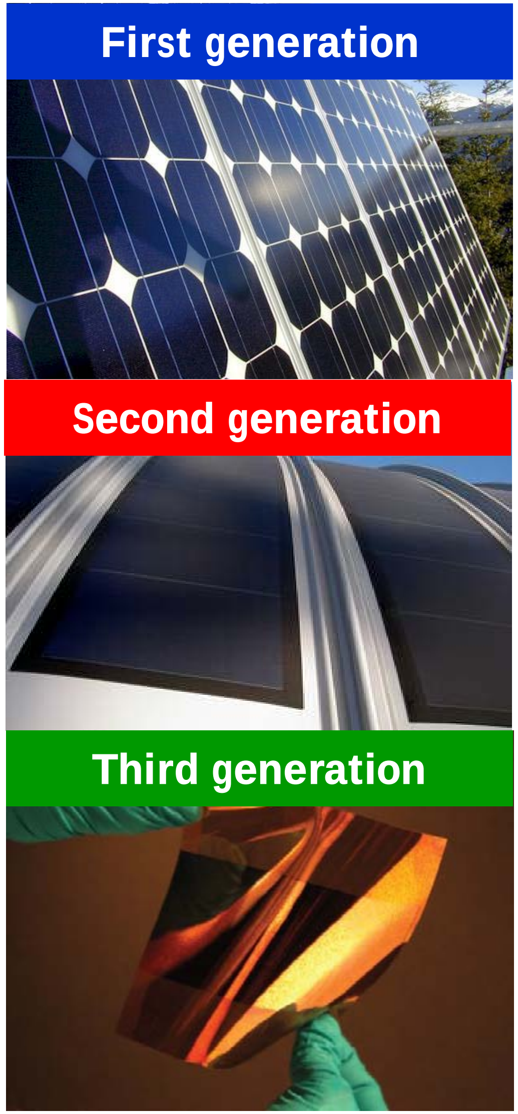
- Crystalline silicon, relatively thick (100s μm)
- Higher efficiency, relatively expensive

2^{nd} Generation

- Thin Film Technology (1 – 10 μms)
- Flexible, low cost, lower efficiency
- CdTe, CIGS, a-Si, DSC

"Next Generation"

- Organic PV (OPV), plastic solar cells
- Earth abundant inorganics (CZTS, pyrite)
- Quantum-dot (3^{rd} Generation)

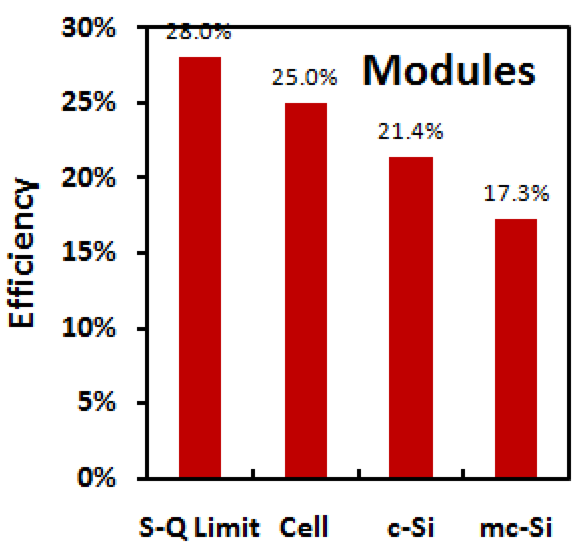


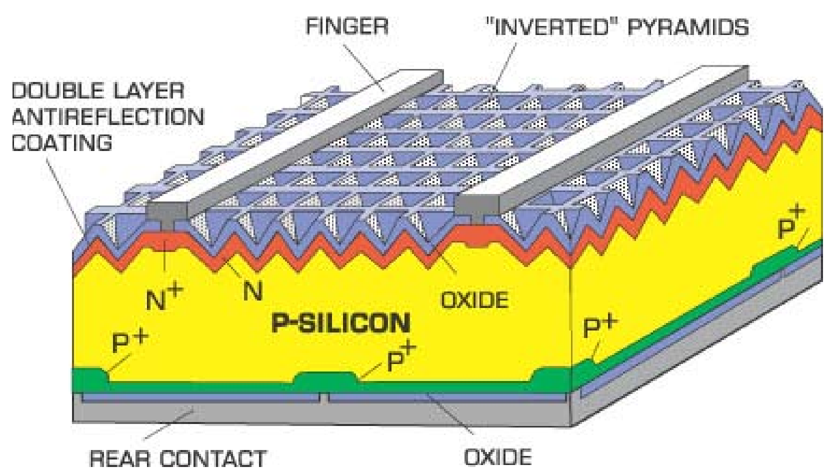
Courtesy Richard van de Sanden, TU Eindhoven

Crystalline Silicon

"1st Generation" Photovoltaics

- Invented 1954
- Dominates Market (~85%)
- Single Crystal (c-Si)
- Multi-crystalline (mc-Si)
- Mature, Earth Abundant
- 10 Companies Dominate





PERT Cell, UNSW

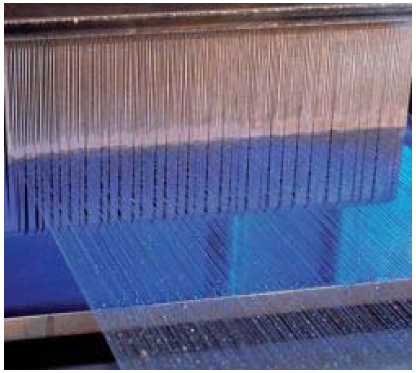
Chapin, Fuller & Pearson, *JAP* **25**, 676 (1954)

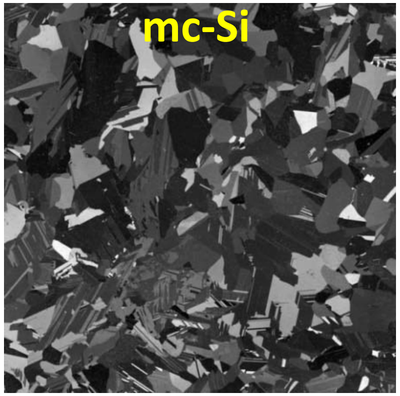
Crystalline Silicon

Cast Brick

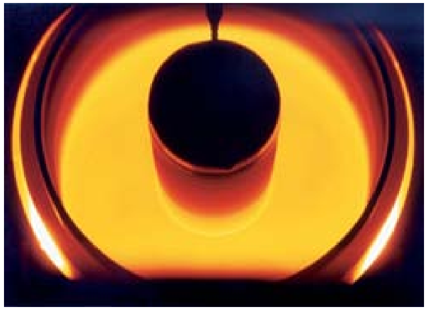
Cut & Grind Bricks

Wire-Cut Wafers





Clean & Polish



Czochralski Growth

Ingot

Big Problem

50% Loss

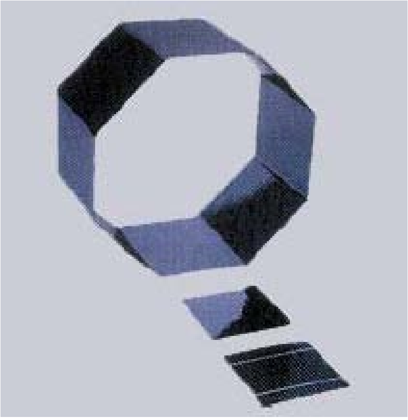
Improve Feedstock

Metallurgical	Solar Grade	Electronic
99%	???	< 1 ppb

Ribbon Silicon

EFG Si

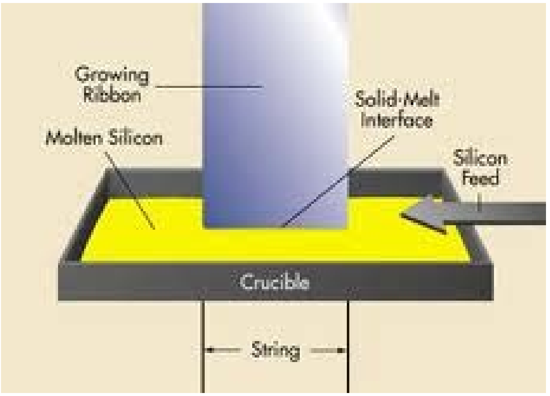
Edge-defined film-fed growth

ASE Americas

SCHOTT solar

String Si



evergreensolar
Think Beyond.

Kerfless Wafers

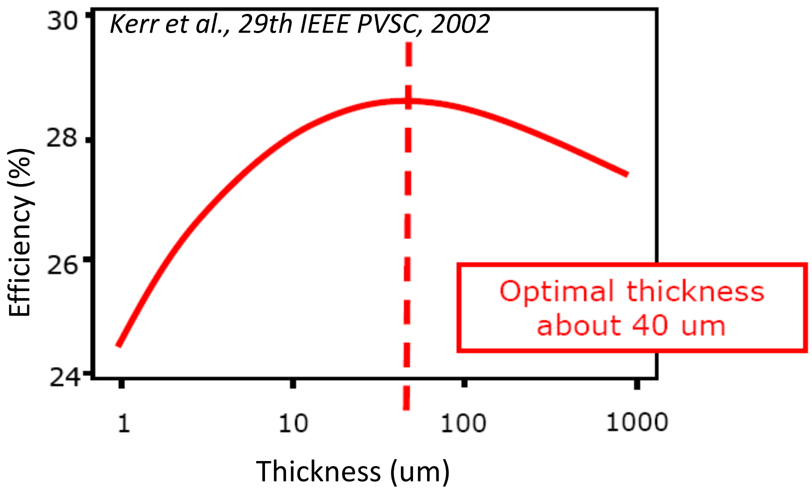
- Invented in the 1970s
- mc-Si: 200-300 μm thick
- Passivation of defects critical
- Record Cells ~18%, Modules 14.5%
- **Energy payback < 1 year**
- Reduce thickness, improve throughput

Ciszek, *Mater. Res. Bull.* **7**, 731 (1972)
Ciszek et al., *J. Electrochem. Soc.* **129**, 2838 (1982).

c-Si: Opportunities & Challenges

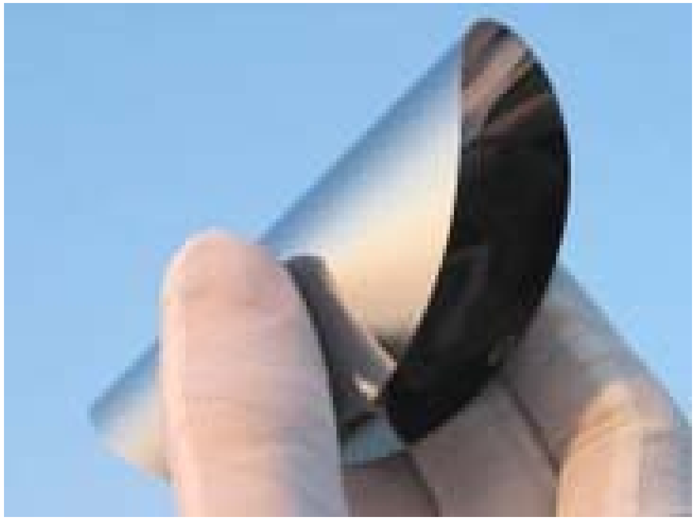
Ultrathin Silicon (5 – 50 μm)

- Current wafers: ~200 μm
- Optimum Thickness: ~40 μm
- **10X Improvement Possible**



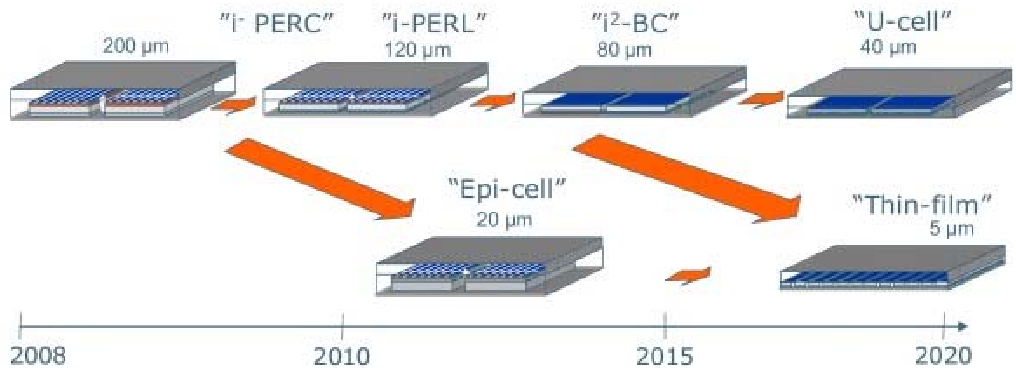
Maintain High Efficiency

- Optical Enhancement
- Surface Passivation
- Wafer Handling



Production of Ultrathin Silicon

Strategies for Production

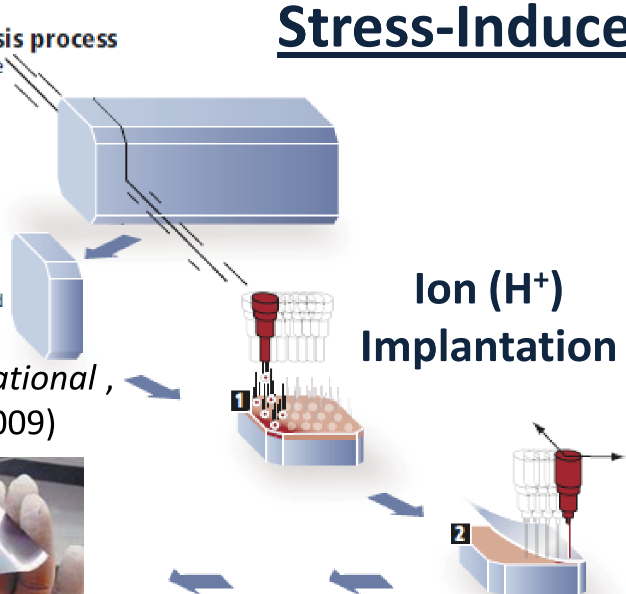


Liftoff

Hetero-epitaxy

J. Poortmans, IMEC

Stress-Induced Liftoff



Photon International , p.116 (May, 2009)

Thermal Treatment

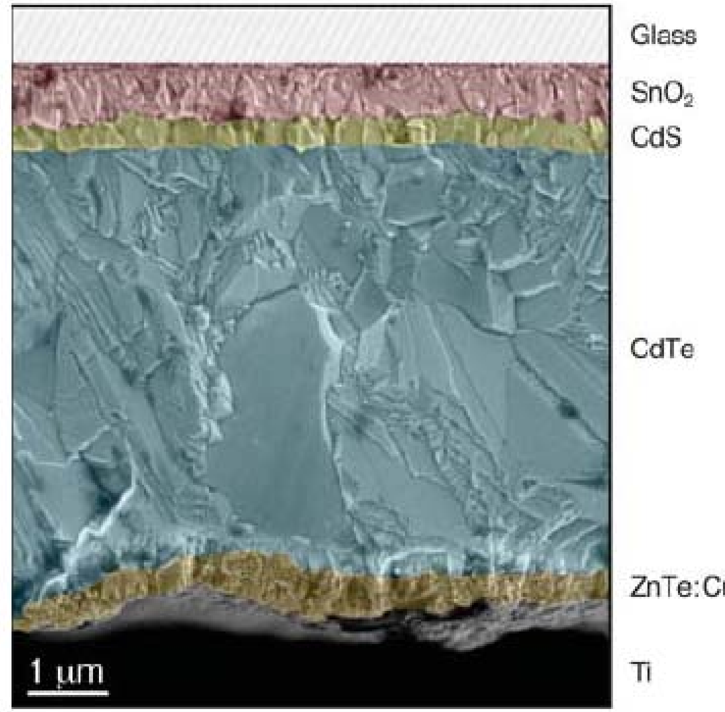
Unanswered Questions

- Reduce T requirements?
- Low cost sacrificial substrate?
- Throughput?
- **Economics**
- Trading Process vs. Material Costs?

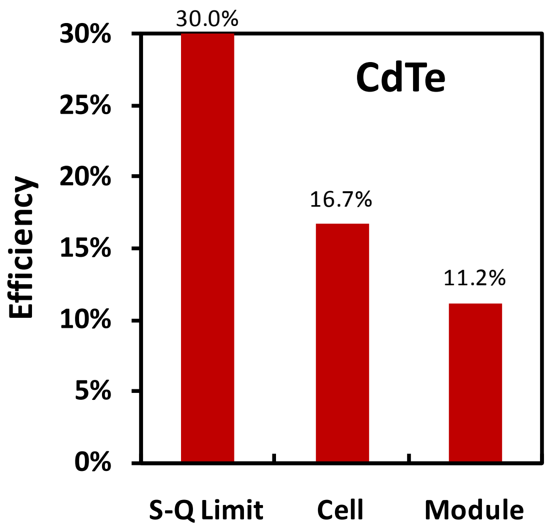
Thin Film CdTe

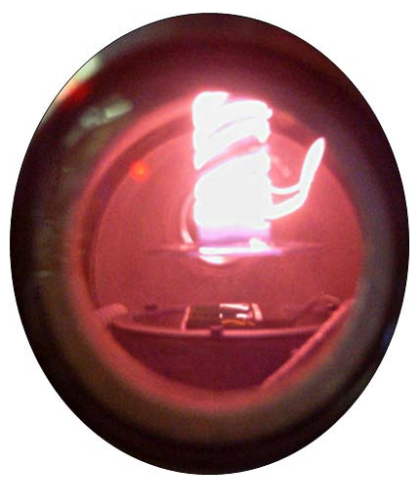
"2nd Generation" Photovoltaics

- Invented 60s, developed 80s, 90s
- Major Player (~12% of market)
- First Solar + Dozen Startups
- Ideal band gap, high absorption
- Simple deposition: Evaporation
- Compatible with float line glass
- **Low Cost Leader ($1/W$_p$)**



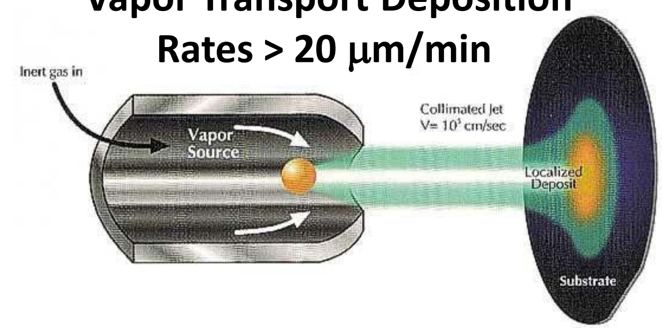
Fortunato et al, *MRS Bulletin* **32**, 242 (2007)





Vapor Transport Deposition

Rates > 20 µm/min



Kestner et al, *Solar Energy Mater. Solar Cells* **83**, 55 (2004)

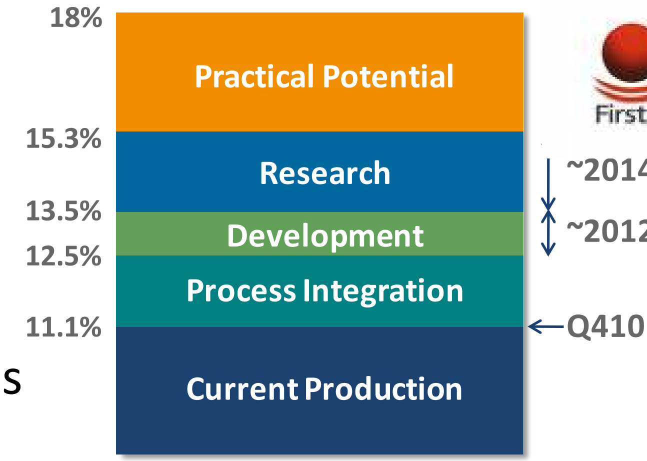
Thin Film CdTe Manufacturing

First Solar

CdTe: Opportunities & Challenges

Improve Efficiency

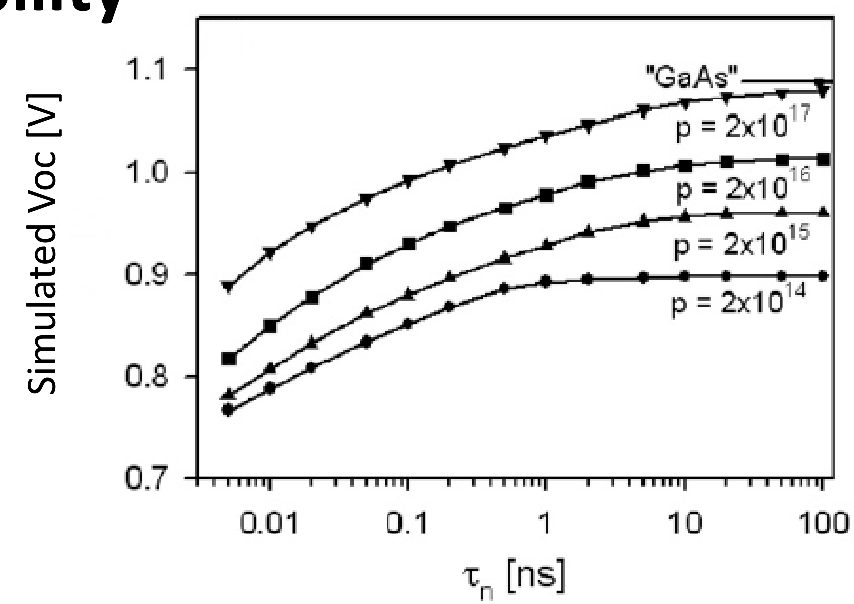
- Advanced front contact, J_{sc}
- Need to Increase V_{oc}
- Carrier Lifetime/Density
- Understand/Control of Grain Boundaries



Courtesy Markus Beck

Concerns about Toxicity/Availability

- Hotly debated questions
- Not volatile, no leaching
- Recycling programs in place
- Cd byproduct of Zn Mining
- PV panels: Cd Sequestration
- Te is a relatively scarce material

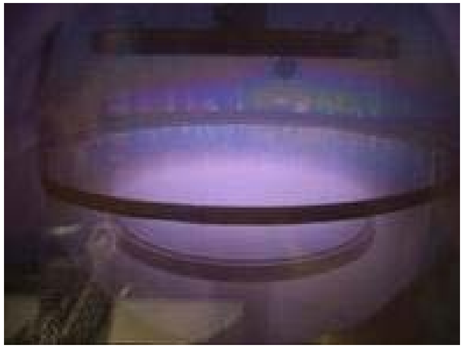


Sites et al, *Thin Solid Films* **515**, 2007

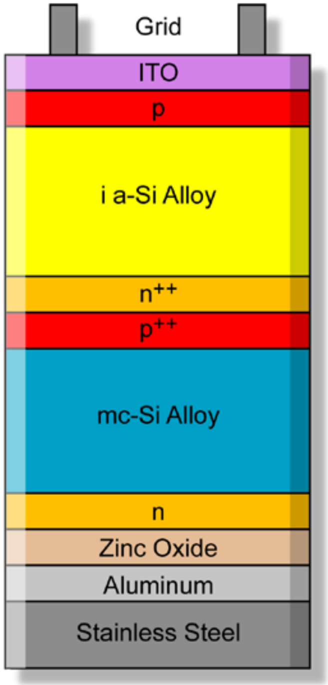
Amorphous-Nanocrystalline Silicon

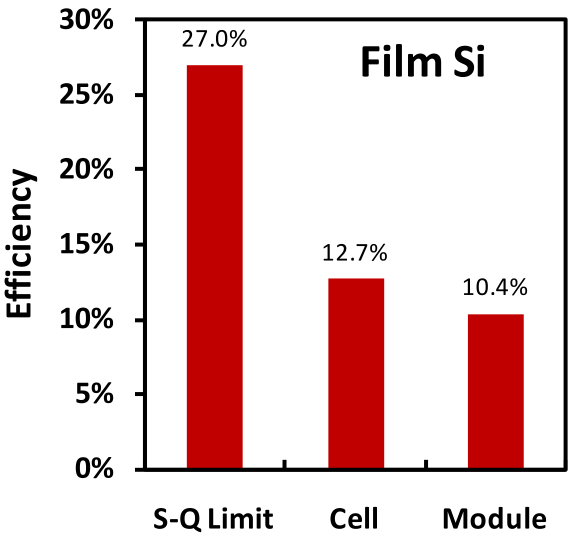
Synthesis & Attributes

- Carlson and Wronski (1976)
- Sharp, United Solar, Oerlikon
- Plasma-enhanced CVD using SiH_4/H_2
- Low temperature (<150 °C)
- **Low weight, flexible laminates**
- Multi-junction compatible



UNI-SOLAR
United Solar Ovonic



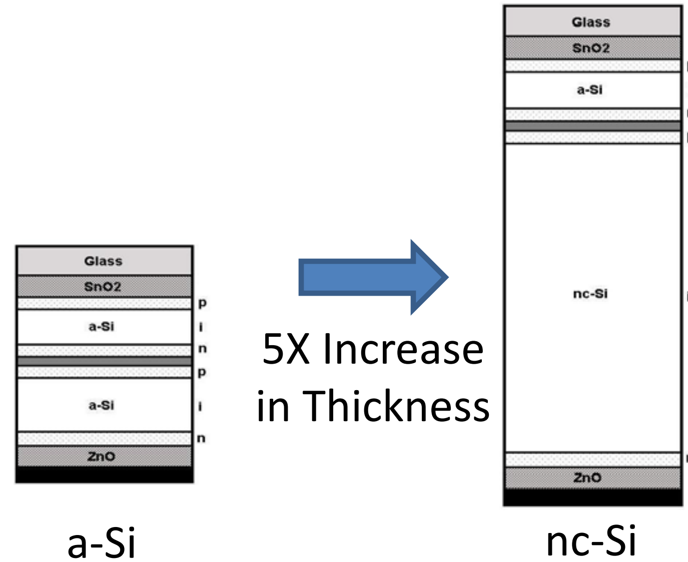


Carlson & Wronski, *APL* **28**, 671 (1976)

a-Si/nc-Si: Opportunities & Challenges

High Rate Manufacturing

- a-Si Unstable: Staebler-Wronski Effect
- nc-Si Stable: Slow rate, low absorption
- VHF (100 MHz) plasma, new linear sources

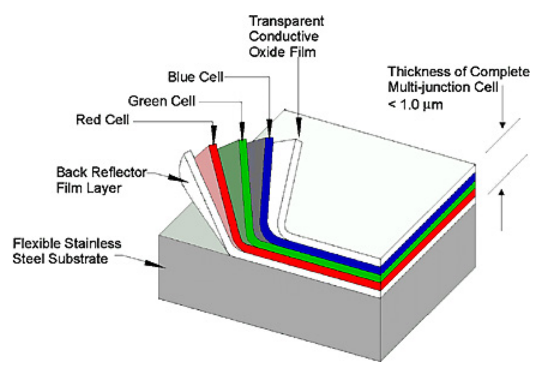


Advanced Photon Management

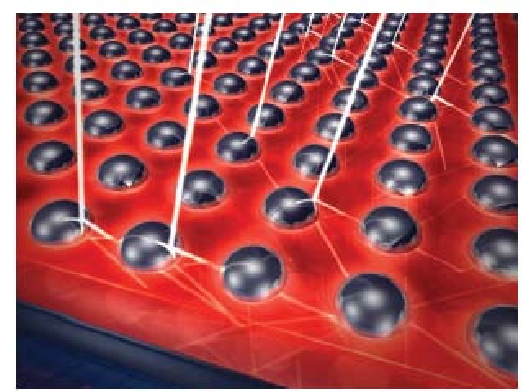
- Increase light collection
- Reduce thickness requirements
- Texturing, plasmonics, index matching

Increase Efficiency

- Triple junction cells
- Introduce SiGe alloys
- Targeting 15%



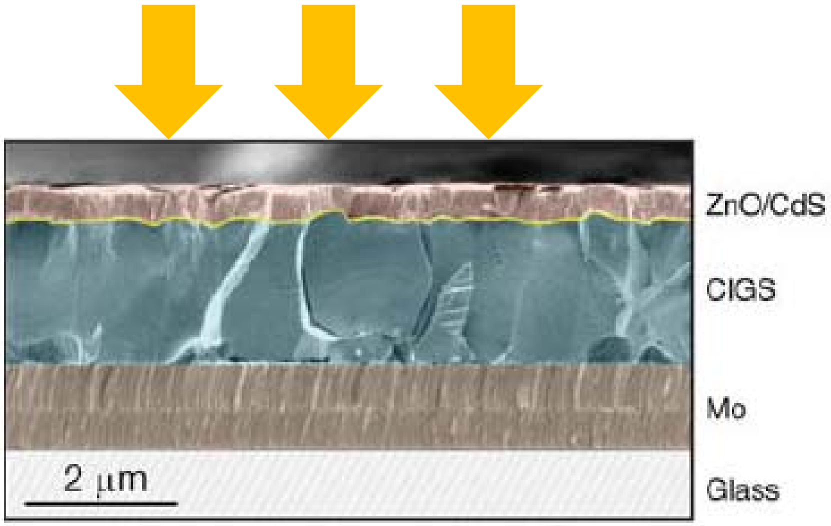
Plasmonics



CIGSS: $CuIn_xGa_{1-x}Se_{2-y}S_y$

Attributes

- Kazmerski et al. (1976)
- Tunable Band gap (1 – 2 eV)
- **Thin Film Efficiency Leader (20.1%)**



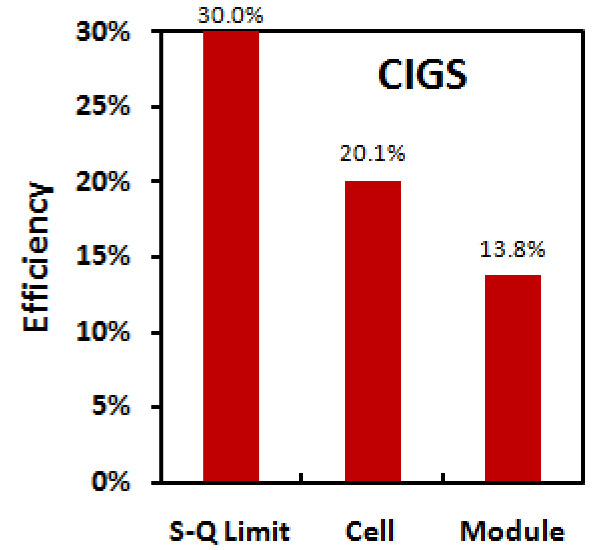
Fortunato et al, *MRS Bulletin* **32**, 242 (2007)

Many Companies/Many Techniques

- Co-Evaporation
- Sputtering/Anneal in Se Vapor
- Screen Print /Anneal in Se Vapor

Kazmerski et al., *APL* **29**, 268 (1976)

CIGS: Opportunities & Challenges

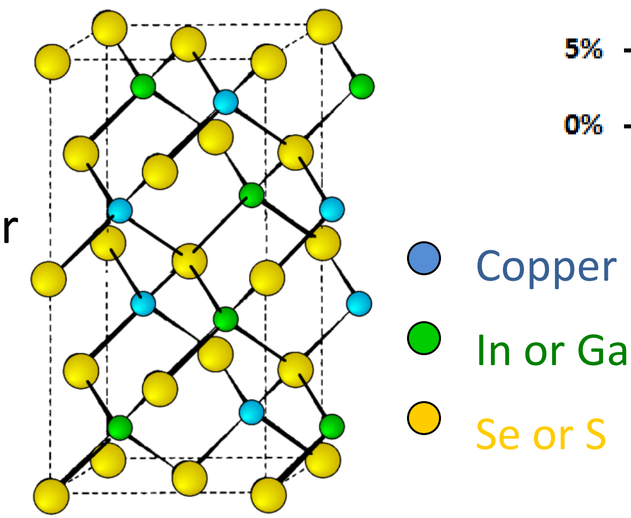


Robust Manufacturing Process

- Translate cell record into module performance
- Could compete with c-Si

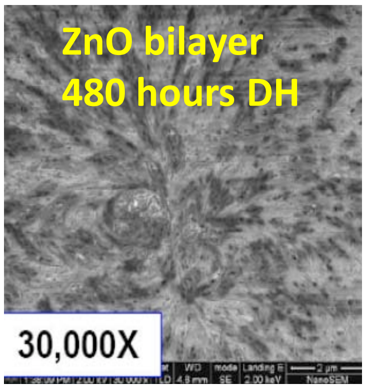
Materials Chemistry

- Optimizing Chalcopyrite
- Replace CdS as window layer
- Reduce/replace In
- Understand the role of Na



Improved Stability

- Reduced sensitivity to moisture (replace ZnO?)
- New moisture barriers (WVTR < 10^{-6} g/m^2/day)

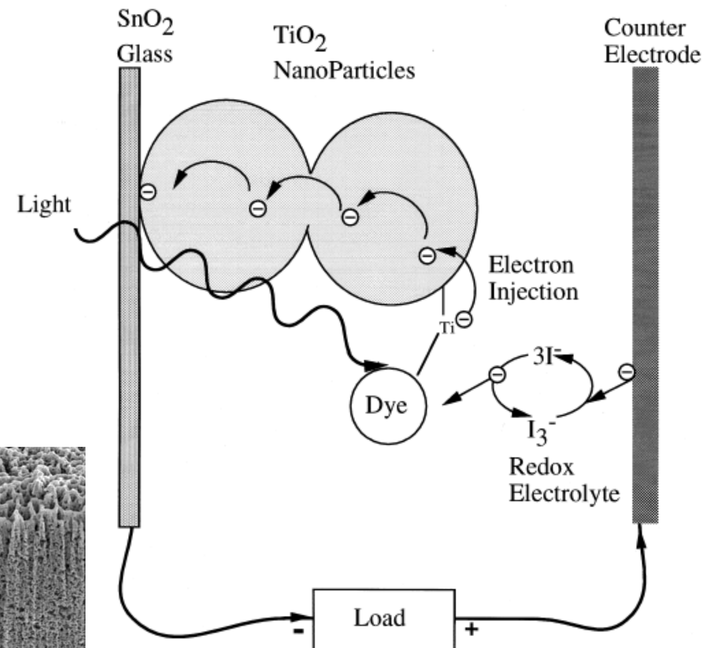


Pern et al, 2nd WCPVSEC, 1998.

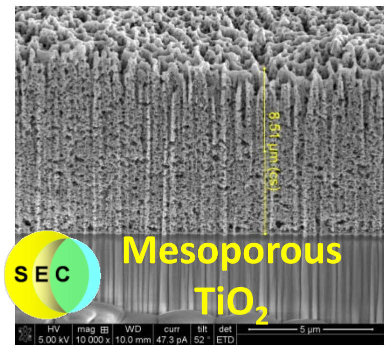
DSC: Dye Sensitized Cell

Photoelectrochemical Cell

- Discovered by Becquerel (1839)
- Invented by Grätzel (1990)
- SolarPrint, G24i, Dye-sol
- **Works in diffuse light (indoors, cloudy)**
- Low T, Flexible, Lightweight



G. P. Smestad, *Optoelectronics of Solar Cells* (2002).

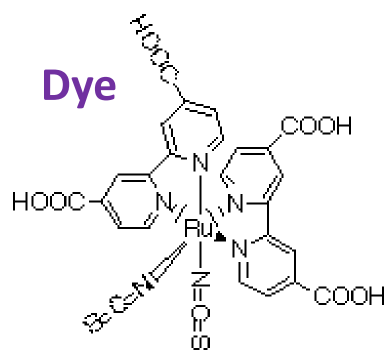


Many Steps

- Photon absorbed by dye
- e^- "hops" TiO_2 particles
- Redox Reaction

$$I_3^- + 2e^- \longrightarrow 3I^-$$

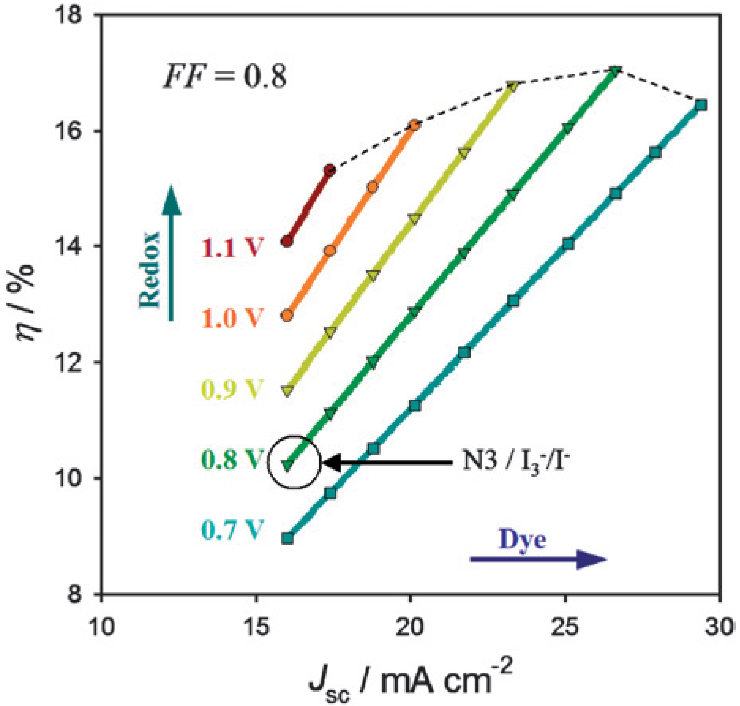
- Diffuse across electrolyte
- Regenerate dye



DSC: Opportunities & Challenges

Increase Efficiency: Stagnant at ~11%

- Unchanged since 1995
- New Dyes: Improve J_{SC}
- New Redox Couple: Improve V_{oc}



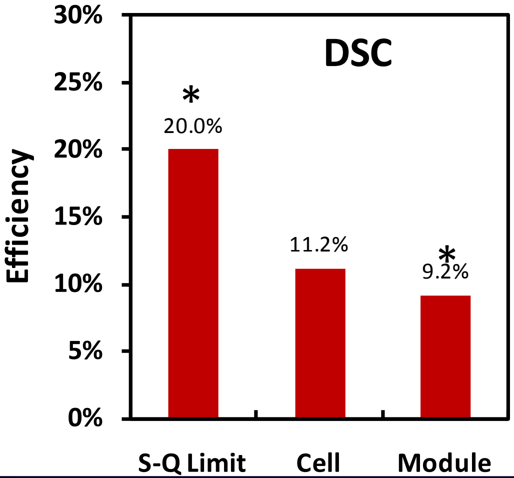
Hamann et al, *Energy Environ. Sci.* **1**, 68 (2008)

Improved Stability

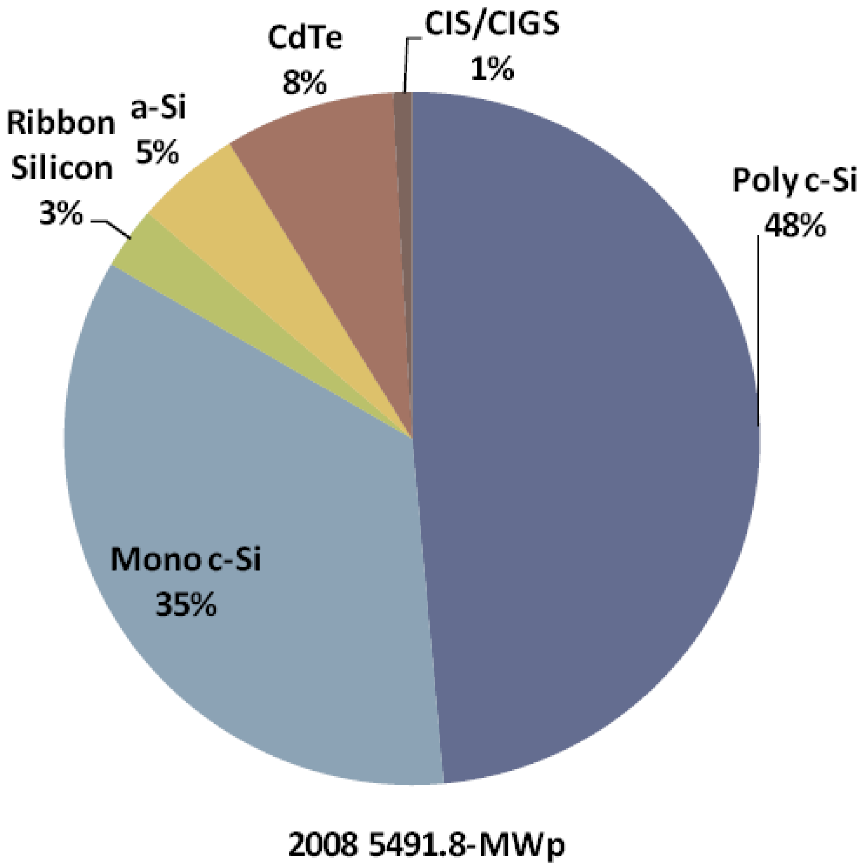
- New Dyes (>10^8 turnovers)
- New Electrolyte (Ionic liquids/Gels)
- Simultaneous Optimization

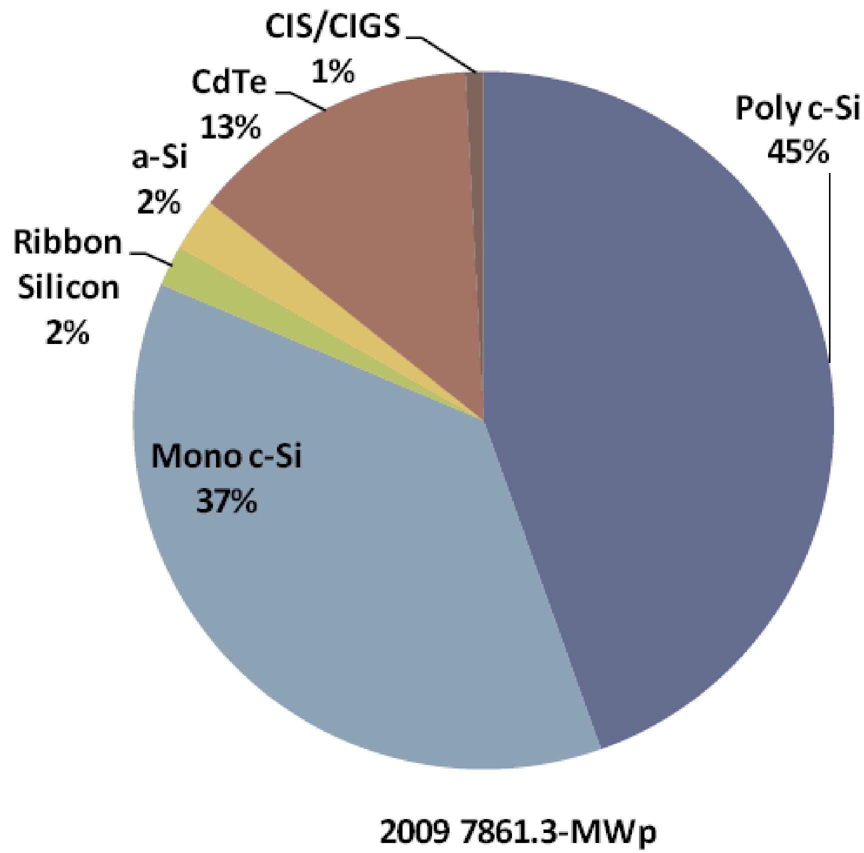
R2R Processing

- Eliminate Glass
- Encapsulation



Dynamic PV Marketplace





Source: Navigant Consulting

All Technologies Continue to Grow

- CdTe and Si Growing Fastest
- Other Technologies Getting Squeezed

3 Possible Future Scenarios

Status Quo

- Continued dominance by c-Si, mc-Si
- CdTe an important component of utility market
- Others: Niche markets in consumer/aerospace

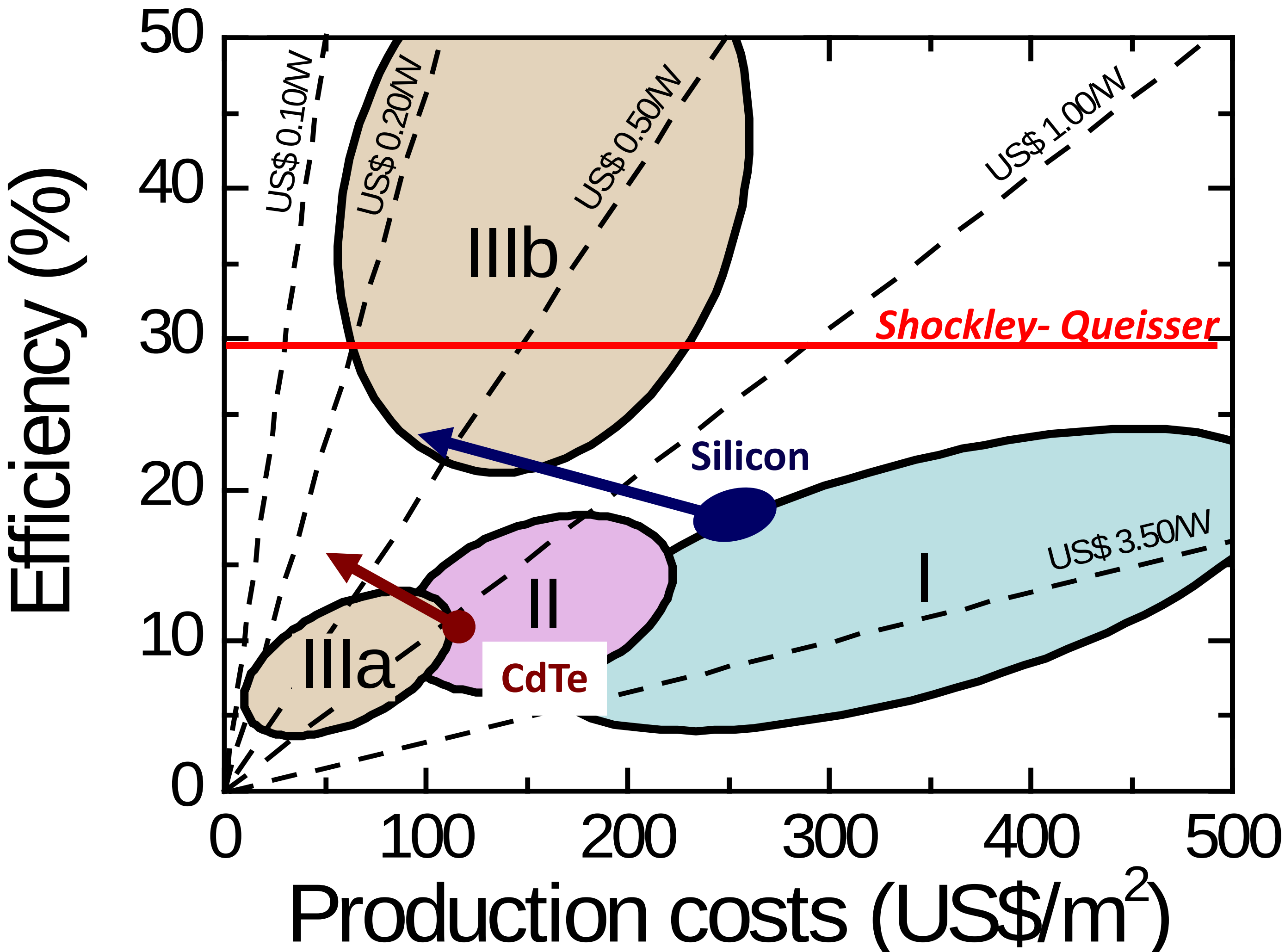
Transition to New Forms of Crystalline Silicon

- Ribbon silicon
- Ultrathin silicon

Breakthrough in Thin Film Technology

- CIGS: Compete with x-Si, CdTe in power sector
- DSC: Consumer products, BIPV, selected climates

Time to Redefine "3rd Generation"?



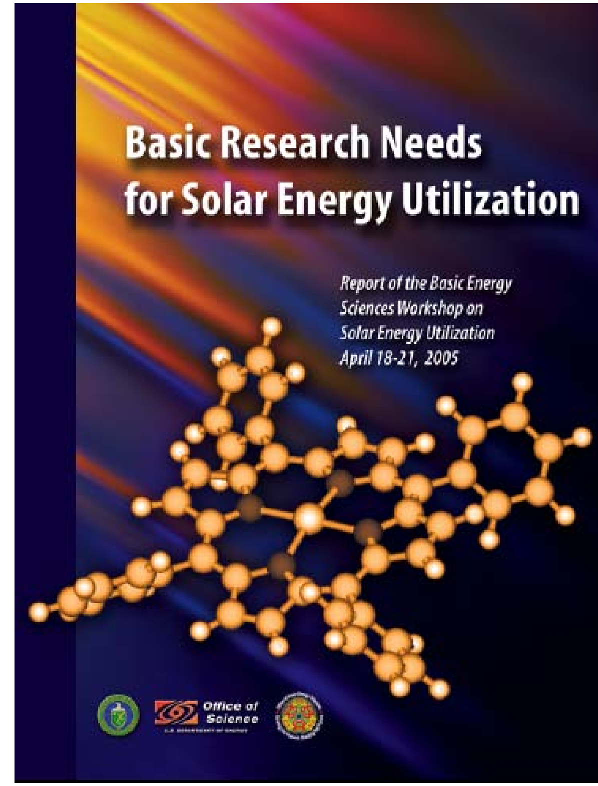
Adapted from M. A. Green, "3rd Generation Photovoltaics", *Prog. Photovolt.: Res. Appl.* **9**, 133 (2001)

Revolution Through Evolution?

Areas for Investment

NSF/DOE

- Predominantly supported 3rd Generation
- Little for x-Si, thin films



Fundamental Challenges Remain

- Developing thin Si (< 100 μm)
- Increase CdTe/DSC efficiency
- Improve CIGS/a-Si manufacturing

Cross Cutting Issues

- Advanced Photon Management
- Effective Encapsulation/Compatibility with R2R Processing
- Manufacturing Science: Metrology/Reliability

Transportation & Storage

Geographic/Diurnal Variations

- Common to most renewables
- Management challenge

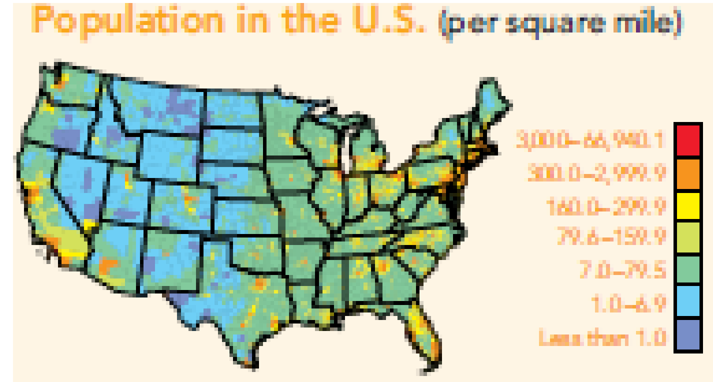
New Grid

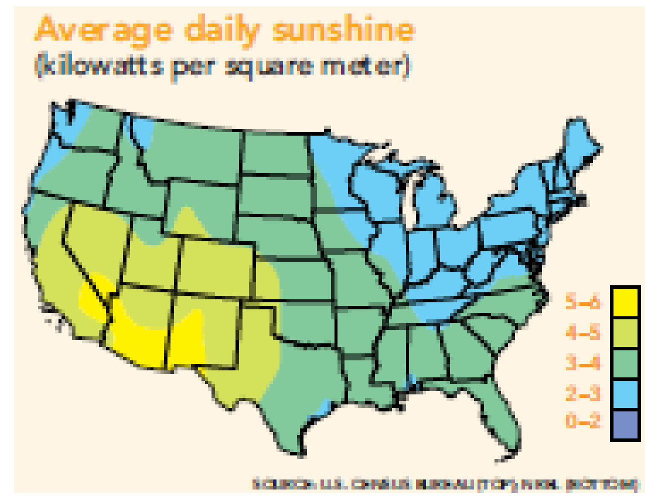
- From concentrated to distributed
- From continuous to variable
- Increased capacity
- Coal/Nuclear/Natural Gas
- Wind/ Hydroelectric/Solar

} **All Produce Electricity**

Energy Storage

- Batteries, Hydrostatic , Mechanical
- Solar Fuels: Chemical





A. Cho, *Science* **329**, 786 (2010)

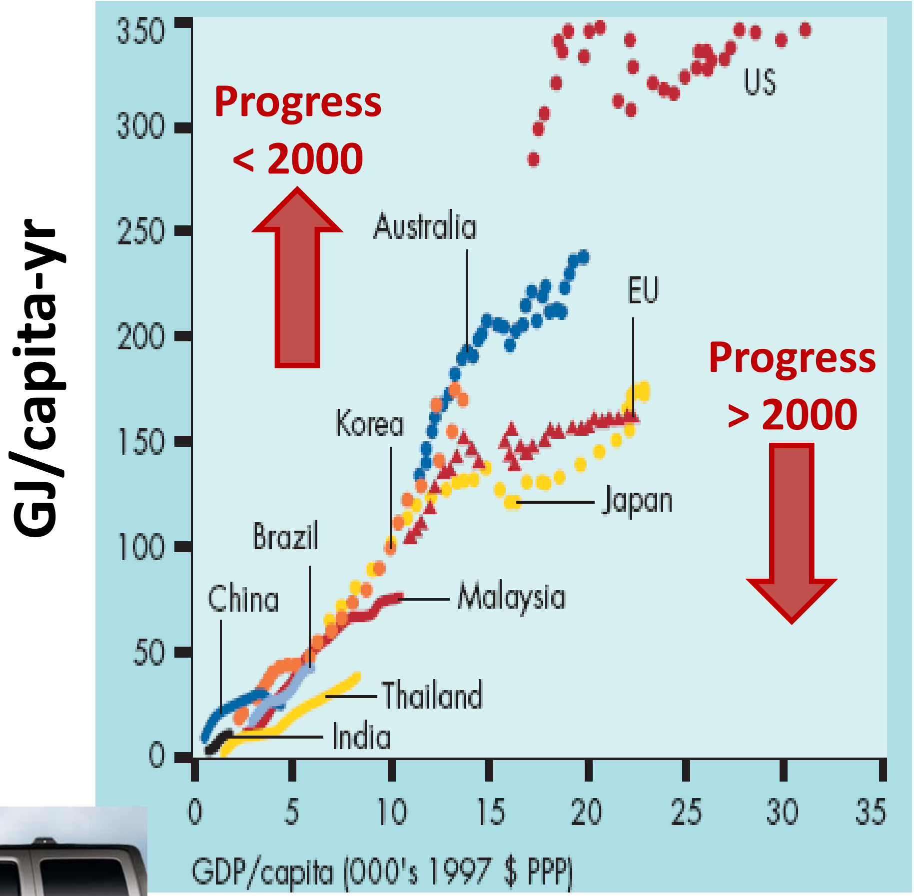
Meeting the Sustainability Challenge

50% from New Energy Sources

- Solar PV, Solar Thermal
- Wind, Hydroelectric
- Nuclear: Bridge Technology

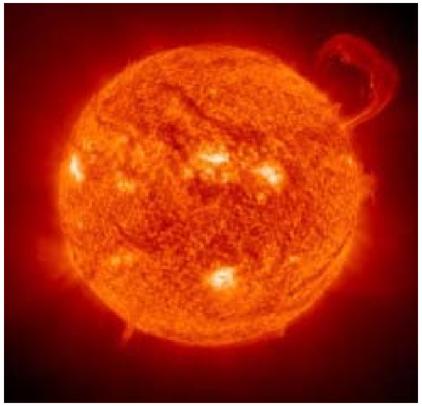
50% Increased Efficiency

- More with less
- Technology exists
- Maintain quality of life



The Future is Bright!

Solar Energy



- Critical contributor to a sustainable future
- PV poised for explosive growth

Future Outlook: No silver bullet

- x-Si: Leader in utility & residential markets, large upside remains
- CdTe: Fast growing, expect to increase share of utility market
- a/nc-Si: Improved deposition rate/cost critical to keep up with CdTe, low weight laminates a differentiator
- CIGS: Potential to challenge x-Si, awaiting a break through
- DSC: Consumer products, BIPV where weight and flexibility are key drivers and lifetime less of a concern

Renewables + Increased Efficiency = Sustainability

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science foundation ireland

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