Billy J. Stanbery
2015 APS Spring Meeting
Workshop on Energy Research and Applications
1 March, 2015

Materials Challenges for Photovoltaics

Outline

- The Terawatt Challenge
- Economics and Distributed Nature of Solar Resource Drive PV Adoption
- Cost Challenges to Economically Competitive PV
- Performance Challenges to Economically Competitive PV

The Terawatt Challenge

"Any source of energy that is not available to humanity on a terawatt scale is not a relevant part of the solution to the problem of supplying our future energy needs."

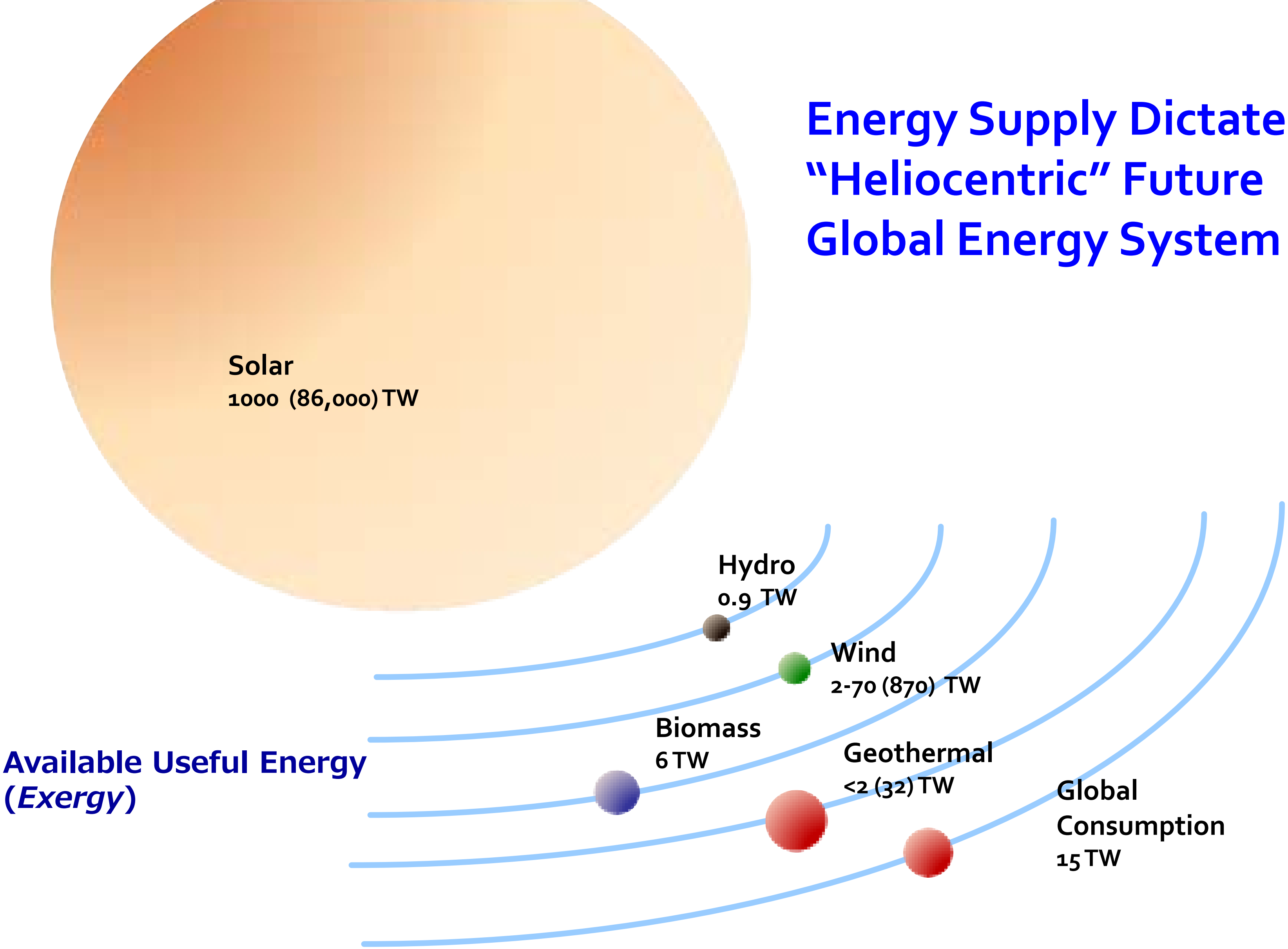
Richard Smalley

The Terawatt (TW) Challenge of Rick Smalley and Nate Lewis

- Humanity uses 15 TW of power today
- World will need 30 TW by 2040
- Only 5 known sources of energy are available on a TW scale*
  - Fossil fuels: Coal, oil, gas
  - Nuclear fuels
  - Solar is the largest, and only inherently distributed TW-scale resource
    - No fuel cost, but intermittent

*Prof. Nathan Lewis, http://nsl.caltech.edu/

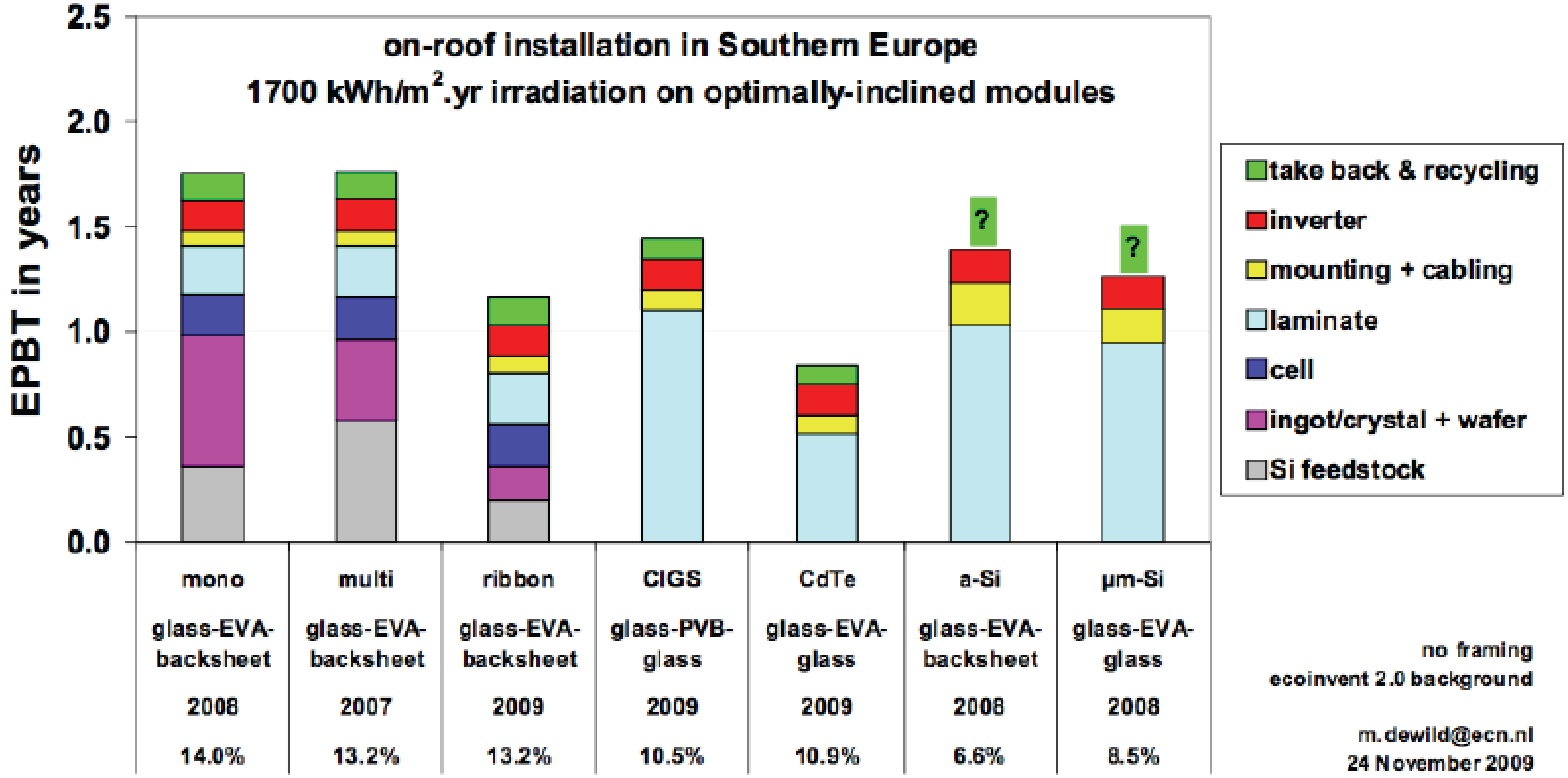
Energy Supply Dictates a "Heliocentric" Future Global Energy System



Courtesy of
Harry Atwater

Solar, Hydro, Wind, Biomass resources based on siting

Energy Payback Time



- It is a myth that solar PV never generates more power than is required to produce it:
  - Current payback time <2 years and standard product warranties are 25 years

Economics of PV

Cost is not the same as Value

Different Value to Utilities and their Customers lead to Conflicts of Interest

Economics of PV: What is the Product?

- PV ultimately used to generate electrical power
  - Applications can be divided broadly into consumer electronics and power generation
    - Market for power generation dwarfs consumer electronics
- PV device efficiency optimization always involves trade-off between device size and parasitic internal Ohmic losses, limiting individual device size
- PV devices are low voltage and must be configured into higher voltage circuits for power generation applications to match power conditioning electronics
  - PV modules are the product sold to system integrators, typically for installation in system arrays

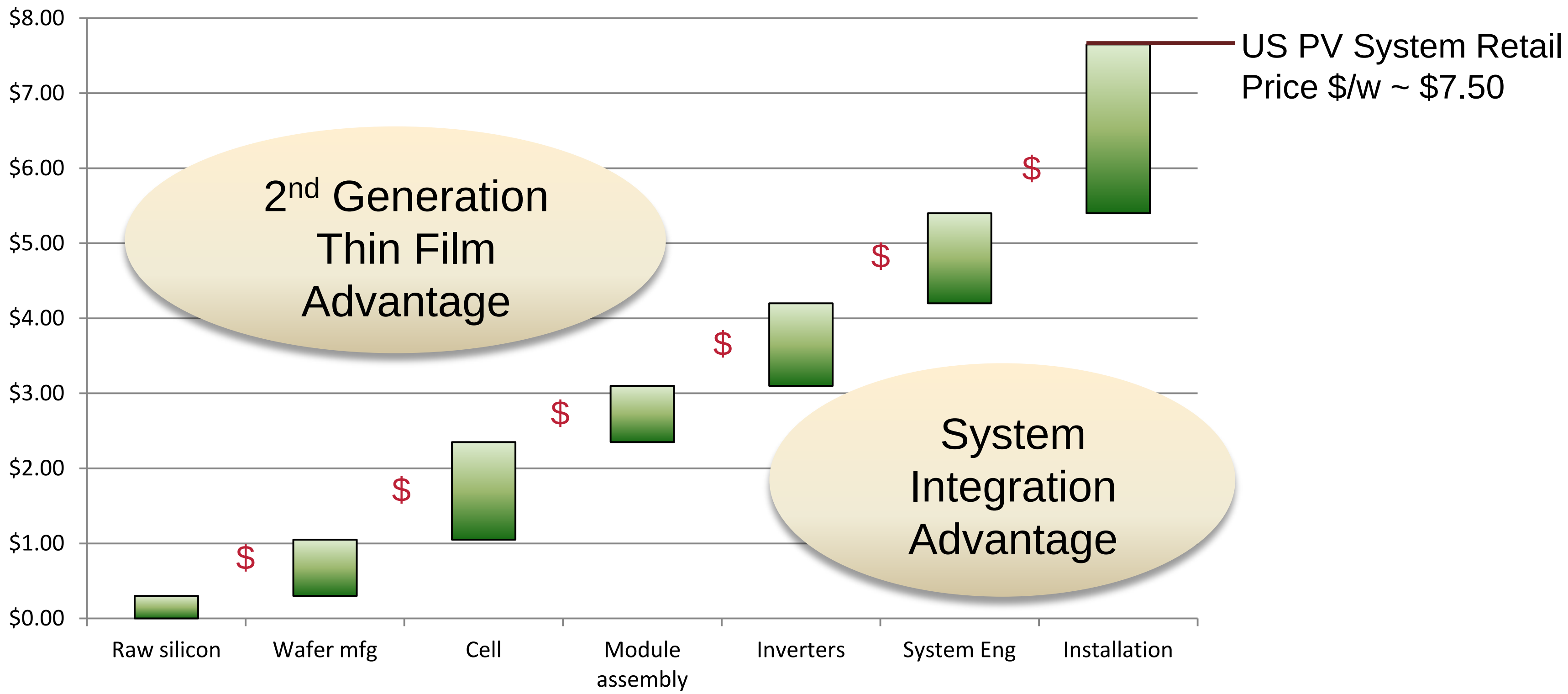
Levelized Cost of Energy

LCOE evaluates the life cycle energy cost and production of a power plant, allowing alternative technologies to be compared in principle

$$\text{LCOE (\$/kWh)} = \left(\frac{\text{Installed Cost} + \text{Total Lifetime Cost of System (\$)}}{\text{Total Lifetime Energy Output (k/Wh)}} \right)$$

- **Initial Cost:** Installed costs are comprised of costs of the solar panels and balance of system costs
- **Total Lifetime Cost of System:** Lifetime costs are comprised of ongoing operating and maintenance costs and project finance costs, net of tax or other government incentives: **RELIABILITY is Essential**
- **Total Lifetime Energy Output:** The lifetime electricity output of a photovoltaic system depends on the collection and conversion of sunlight into electricity over the lifetime of the system: **RELIABILITY is Essential**

Systems Capital Costs Divided Equally Between Modules & Balance-of-Systems



- Module efficiency provides system price leverage
  - Market studies range from 25-41 ¢/% (declining)

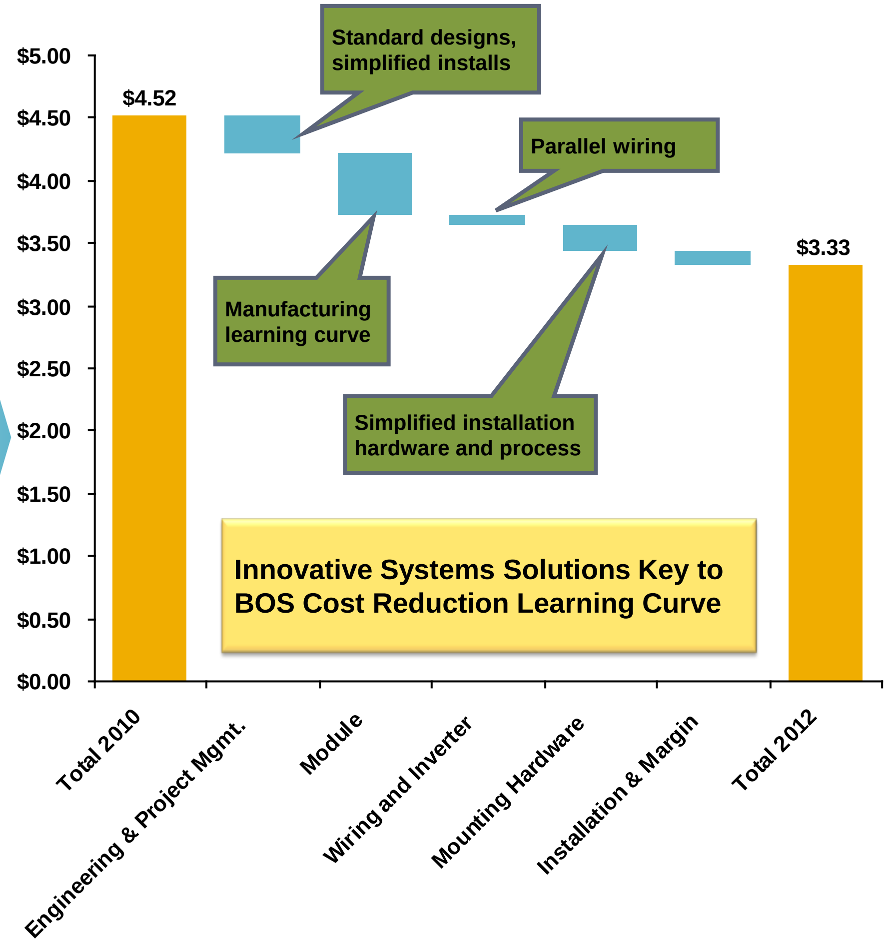
Installed Systems Cost Comprised of Module Costs and Balance-Of-Systems

Key Components of Balance of Systems

Cost of Area/Land
\+
Engineering Costs
\+
Mounting Hardware
\+
Power Management
\+
Installation Labor
=
Total BOS Cost

Module Efficiency at Installed Normal Operating Temperature (INOCT) Is a Key Driver of Balance of System Costs

Case Study – Commercial Rooftop



Illumination and Temperatures Vary in Real Applications, and Modules Degrade

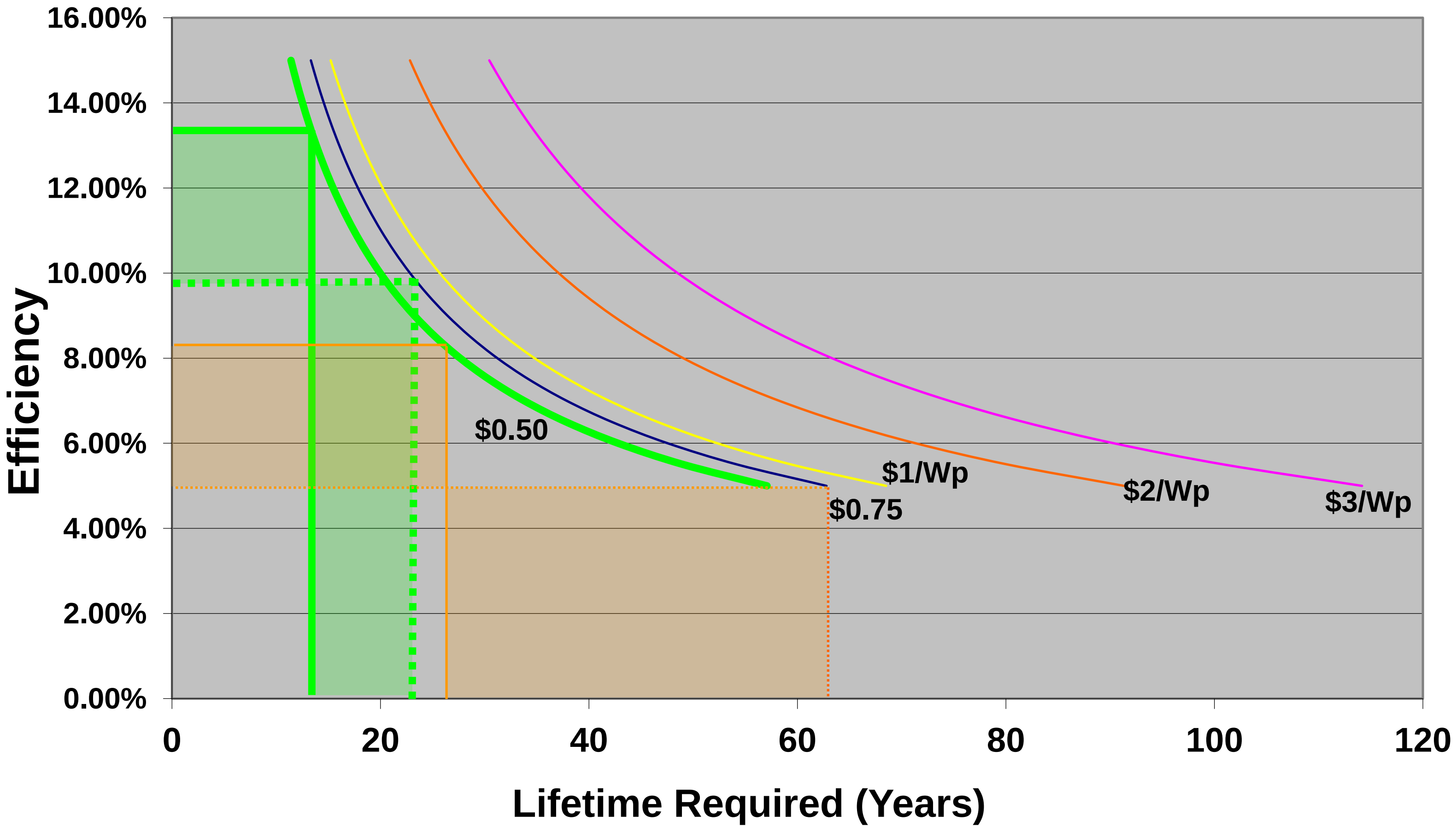
Device Technology	Module Rated Efficiency	Avg Annual Yield (kWh/m^2)
mc-Si	14%	229
CIGS	12%	223
a-Si (sj)	7%	126

- STC Efficiency not a good indicator of energy yield (harvest): kWh/kW_{STC}
- Degradation effects vary among different technologies
- Complex non-linear interactions of temperature effects, solar angle-of-incidence, collection of diffuse light, and spectral shifts make prediction of actual power generation from STC ratings and linear coefficients of response unreliable.

Source: Pecan Street Project Final Report.

Low Cost PV Electricity Requires Hardware Reliability

- Performance and Lifetime trade-offs required to achieve 10¢/kW·h LCOE for various CIGS module costs



The Value of PV Generated Electricity

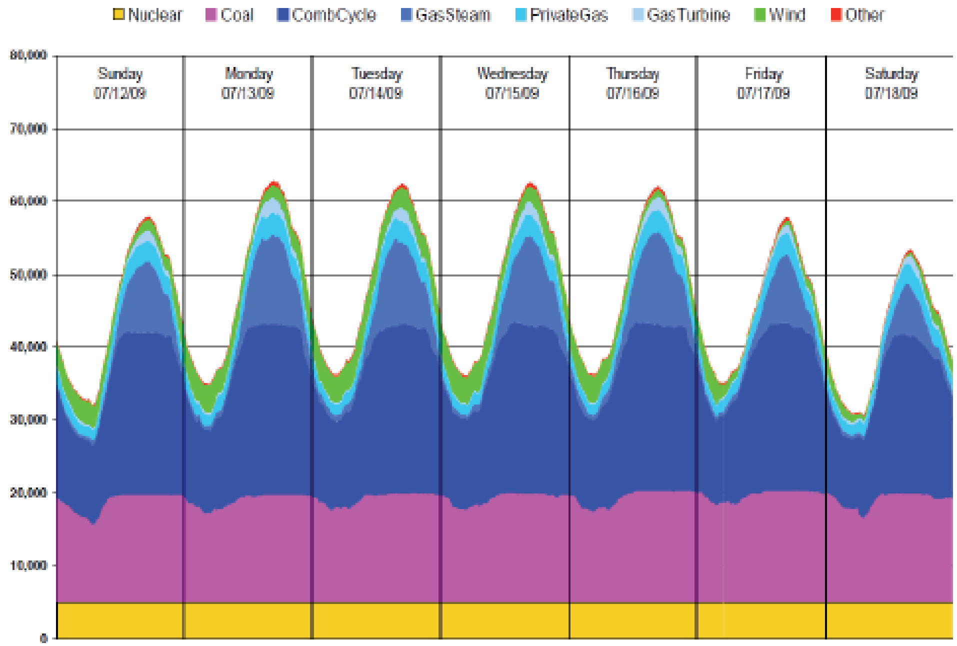
- Discussions about the future of the PV industry are dominated by the **cost** of electricity
  - The **value** of PV generated electricity isn't appreciated
- Analysis of commercial rooftop PV-generated electricity in Austin, TX (2008) at wholesale ERCOT clearing prices shows peak demand premium value
  - Wholesale value averaged 9.6 ¢/kWh, far greater than the average cost of electricity because of peak demand coincidence, otherwise supplied by low-utilization natural gas combined cycle "peakers."

Source: Pecan Street Project Final Report.

Electrical Grid Power Consumption is Highly Variable and Generation Follows

Typical Summer Week Load Shape with Generation Resources

- Base-load supplies represent 20,000 MW, primarily coal & nuclear generation.
- Natural Gas units provide shaping/ load following. They are the marginal unit – they set the price for the next MW of generation needed to meet demand.



Source: ERCOT/PUCT

9

- PV generation would reduce natural gas usage for peaking load
- Wind generation reduces nighttime coal base-load generation

PV Supply/Electrical Cost Overlap

Average Load Day

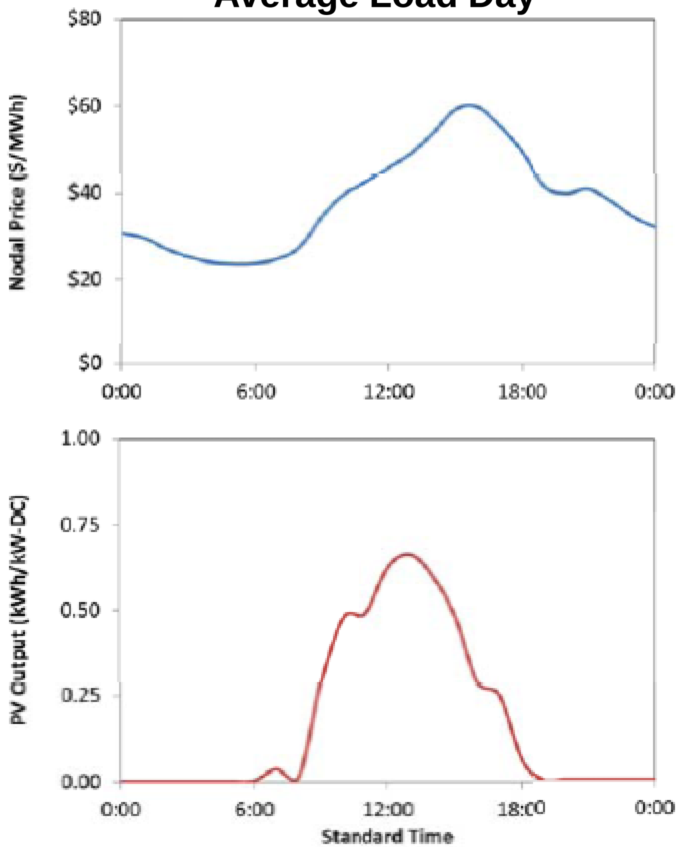


Fig. 1: Nodal price and PV output for July 30, 2011.

Peak Load Day

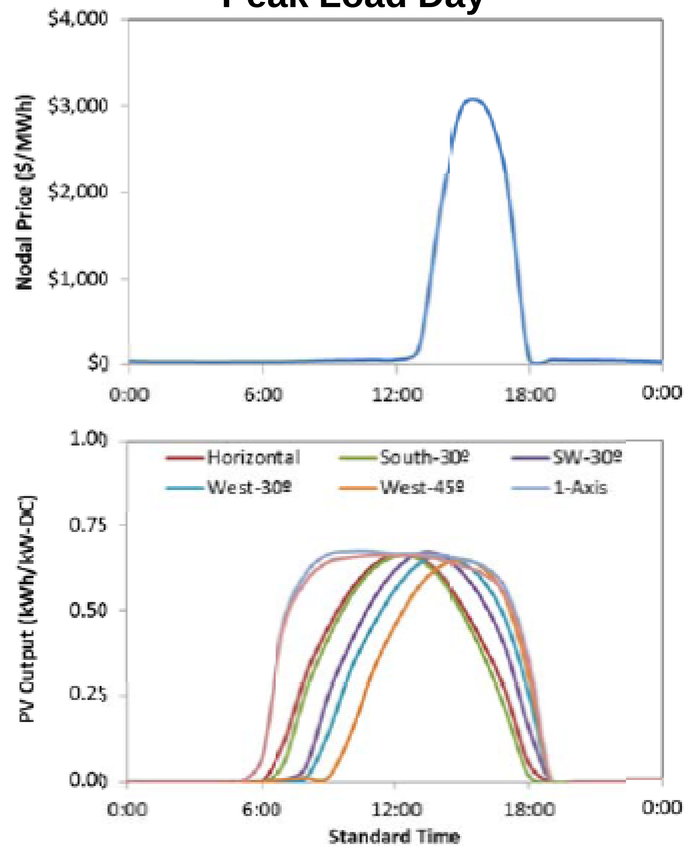


Fig.2: Nodal price and PV output for August 3, 2011.

"Designing Austin Energy's Solar Tariff Using a Distributed PV Value Calculator," Rábago et al, 2012.

Value of Utility Scale *vs.* Distributed Solar PV to Utilities

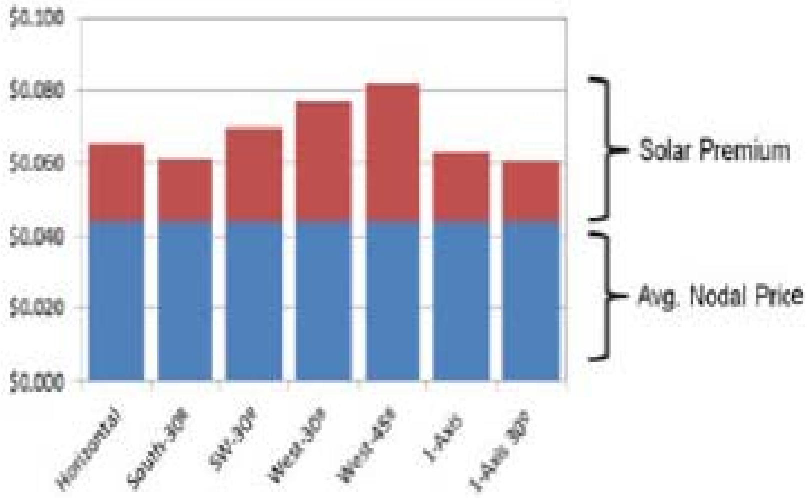


Fig. 3: Annual generation value and the solar premium.

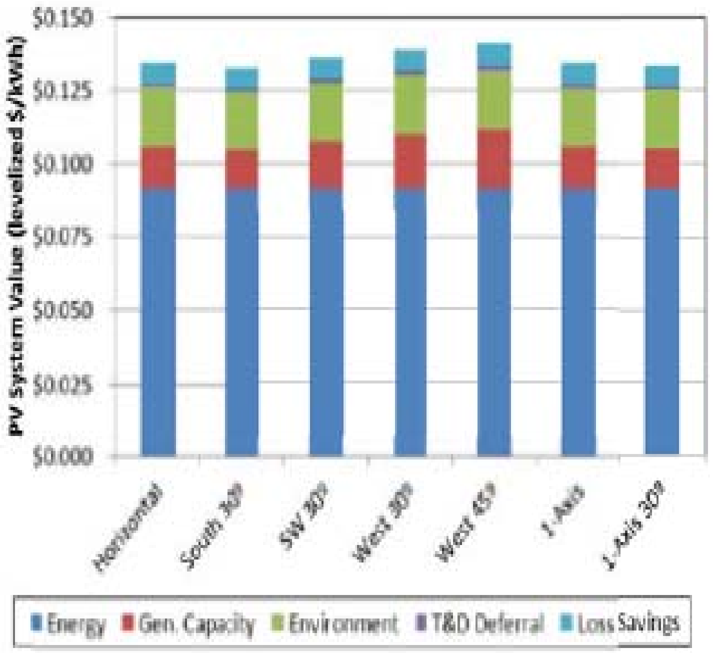


Fig. 4: PV value results by component and configuration.

"Designing Austin Energy's Solar Tariff Using a Distributed PV Value Calculator," Rábago et al, 2012.

Solar Today:

Central Power Generation Dominates, Commercial Rooftop Growing Faster Residential Rooftop Growing Fastest (US)

Utility Scale

Solar farm in Amstein, Germany

Commercial Rooftop Systems

Google HQ - Solar Project

The Future of Solar PV: Growth of Distributed PV Generation

Commercial Rooftop Systems

Office building and school roof top examples

Building Integrated Photovoltaic Systems

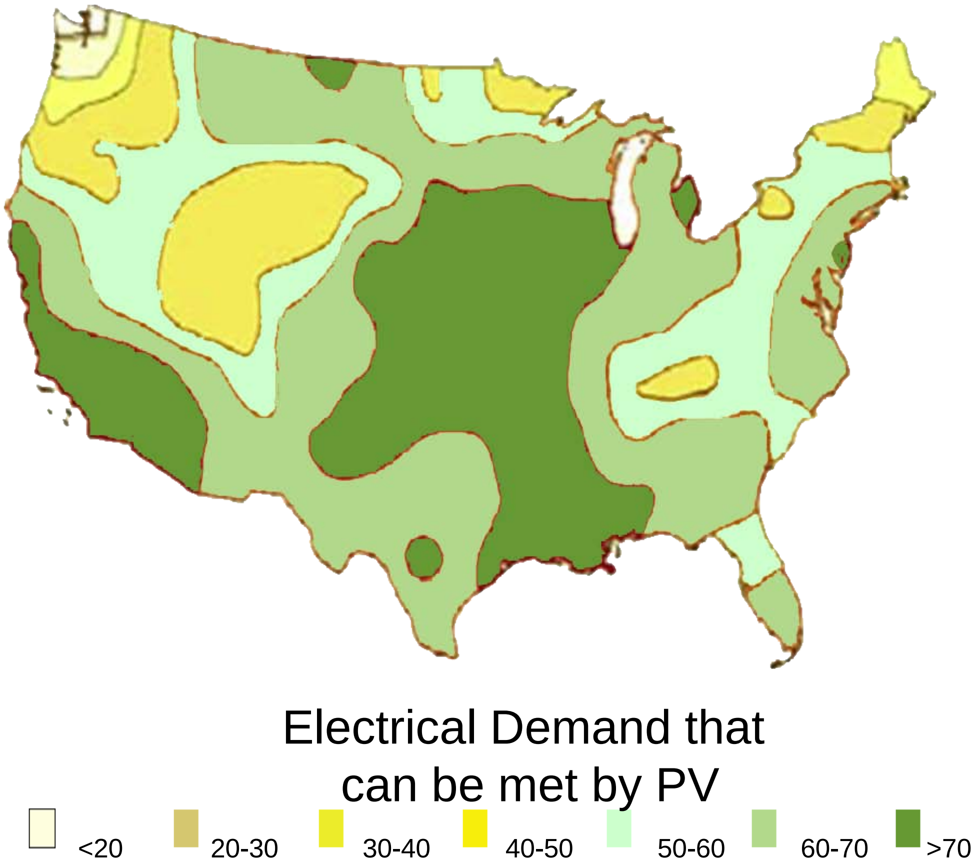
Residential roof tile and façade examples

TW-Scale PV Solar Generation is a Match for Buildings

- How many things does humanity do which cover 40,000 km^2 or more?
  - Agriculture
  - Transportation infrastructure
  - Buildings
- Current electricity infrastructure is based on central power generation using coal, gas, oil, or nuclear fuels, with T&D to point of use
  - >60% of all electricity is used in buildings

Building-Integrated PV: Power Buildings Market Potential

- Power Buildings are expected to become a multi-$T market
  - PV as an integrated electronic component
  - Integration reduces system installation cost
- Huge latent demand
  - $150 billion per year value of 60% of US electricity
- Multiple segments
  - Architectural Glass
  - Windows and skylights
  - Roofing



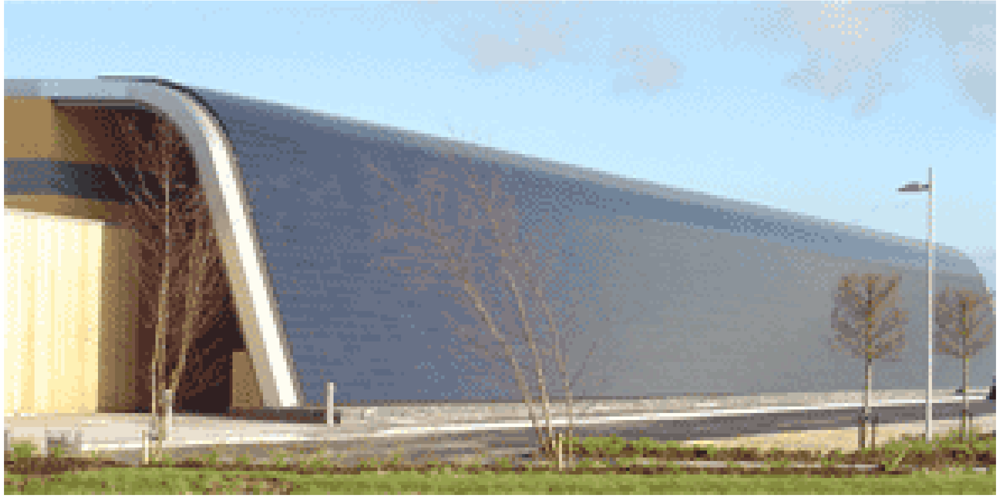
Electrical Demand that can be met by PV

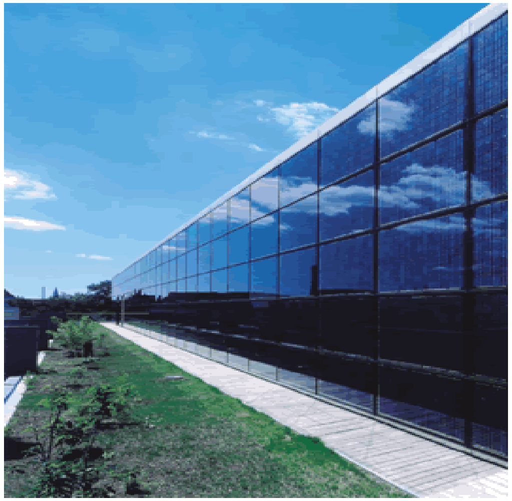
% Capacity

Source: U.S. Department of Energy.

Building Integration for PV System Cost Reduction Is the Future

PV as an integrated electronic component in building construction materials



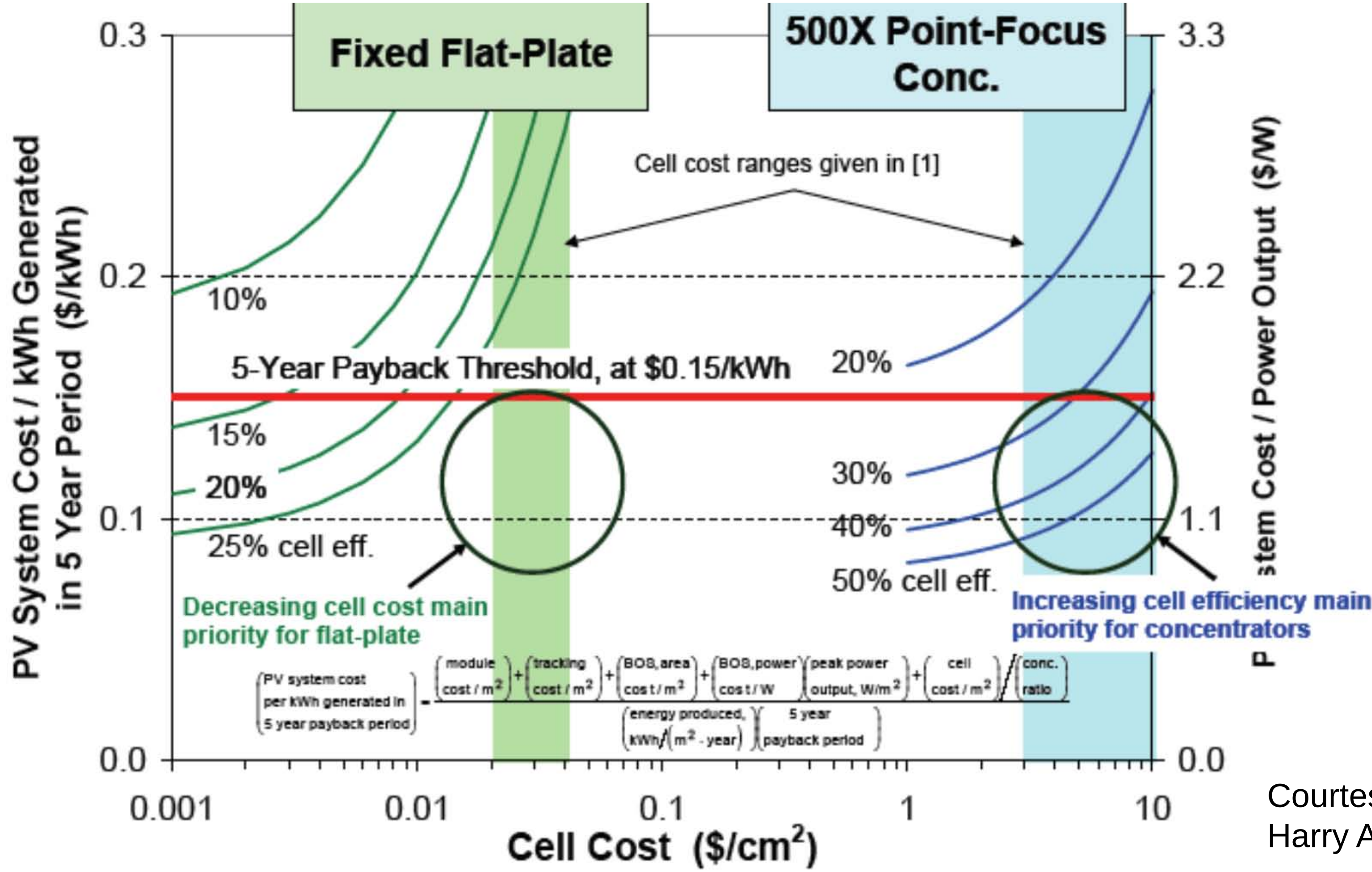


- Despite its intermittency and non-dispatchability, the value of solar PV electricity is disproportionate to its cost compared to conventional electrical generating assets due to its high temporal correlation with demand.
- Distributed solar PV is poised to create an existential crisis for the utility industry in the US because their business models and grid infrastructure cannot yet accommodate high penetration, and utility customers with rooftop solar don’t need high-priced utility supplied peaking power.

Measuring Cost of PV Modules As Electrical Power Generating Assets

- Traditional metric is $/Wp= $\frac{\text{Cost / m}^2}{\text{Watt / m}^2}$
- Scientists and engineers tend to focus on technical performance metrics like conversion efficiency
  - Watts/m2 = Efficiency x 1kW/m2 (AM1.5 Global, 21°C)
- Manufacturers must also focus on production cost
  - Cost/m2 = ((Direct Materials + Labor + Consumables + Capital Amortization + Overhead) /m2)/Yield
- Which is a better approach in manufacturing:
  - increase efficiency
  - reduce materials and operating expenses
  - improve yield

Cost per Watt and Levelized Cost of Electricity in Flat Plate vs. Concentrator



$$\begin{pmatrix}\text{PV system cost}\\ \text{per kWh generated in}\\ \text{5 year payback period}\end{pmatrix} = \frac{\begin{pmatrix}\text{module}\\ \text{cost}/m^2\end{pmatrix}+\begin{pmatrix}\text{tracking}\\ \text{cost}/m^2\end{pmatrix}+\begin{pmatrix}\text{BOS, area}\\ \text{cost}/m^2\end{pmatrix}+\begin{pmatrix}\text{BOS, power}\\ \text{cost}/W\end{pmatrix}\begin{pmatrix}\text{peak power}\\ \text{output, }W/m^2\end{pmatrix}+\begin{pmatrix}\text{cell}\\ \text{cost}/m^2\end{pmatrix}\Big/\begin{pmatrix}\text{conc.}\\ \text{ratio}\end{pmatrix}}{\begin{pmatrix}\text{energy produced,}\\ \text{kWh}/(m^2\text{-year})\end{pmatrix}\begin{pmatrix}\text{5 year}\\ \text{payback period}\end{pmatrix}}$$

Courtesy of Harry Atwater

Module and BOS cost assumptions from: [1] Swanson, Prog. Photovolt. Res. Appl. ***8****, 93-111 (2000).*

Cost Challenges to Economically Competitive PV

Cost per Unit Area ($/m²) Reduction has Contributed More to Solar PV's Success than Technological Improvements in Efficiency

Solar is a Ubiquitous Resource but PV Must Cover Vast Areas Economically

- Sunlight is a generous resource
  - 117,000 TW falls on the earth continuously
- Sunlight is an inherently distributed resource
  - 1 kW/m2 = 1 GW/km2 = 1 TW/1000 km2
  - 8,000 km2 for 1 TW electricity (12% net AC)
  - Sun only shines full brightness equivalent of 20% of the time (capacity factor)
  - ~40,000 km2 for 1 TW continuous power capacity equivalent to dispatchable coal or nuclear
  - Grid Infrastructure evolution required

Power Loss Competition: Absorption vs. Collection

- Typical 15% silicon solar module inefficiencies

Power loss cause:	**% lost**
Over-energetic *e*$^-$ [heat]	**32**
Under-energetic light [not absorbed]	**24**
Recombination loss [not collected]	**21**
Surface reflection [not absorbed]	**3**
Contact shading [not absorbed]	**3**
Cell spacing [not absorbed]	**2**
Total	85

Power Loss Mechanism Management: PV Solution Approaches

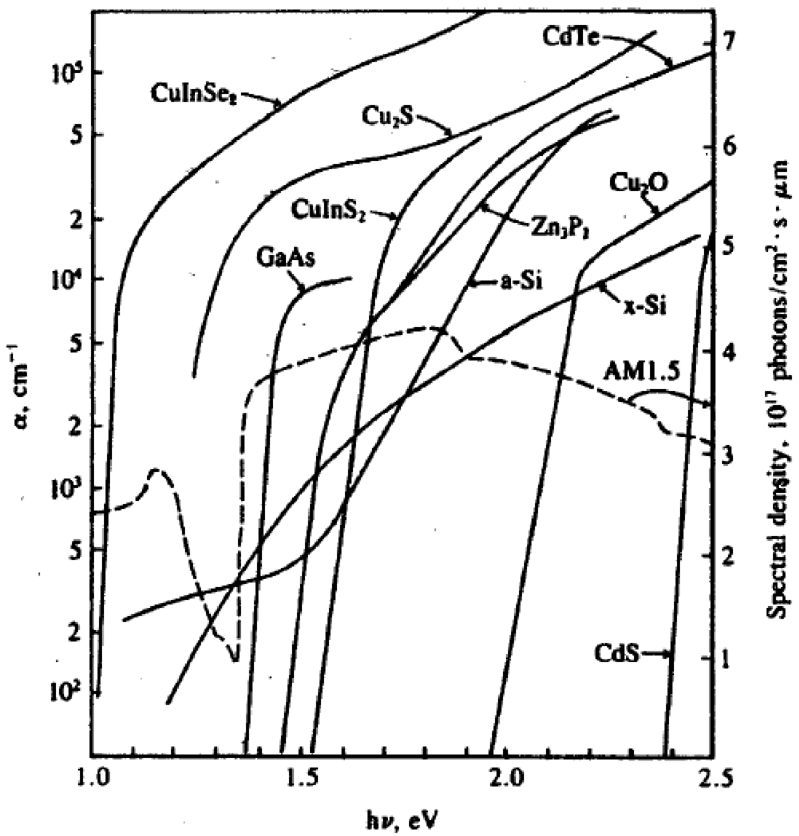
- Over- & under-energetic electrons
  - Multi-junction (tandem or cascade) cell structures
  - Multi-electron generation processes
- Recombination (collection loss)
  - Concentrator Solar Cells
    - Increased voltage, but increased temperature & system complexity/cost; poor indirect light collection
  - Excitonic solar cells
  - Bulk heterojunctions
    - spontaneously form in CIGS
    - Engineered structure in many Organic PV structures

Thin Film PV Historical Redux

- Thin Film PV (TFPV) technologies have been under development since the 1950's as an alternative to crystalline silicon (c-Si).
- Primary motivation was materials cost reduction
- Two principal technical challenges:
  - Performance
  - Reliability
- More recently sustainability and scalability have been recognized as potential advantages
  - Potential not yet fully realized

Direct-Bandgap Semiconductors Reduce TFPV Thickness For Solar Absorption

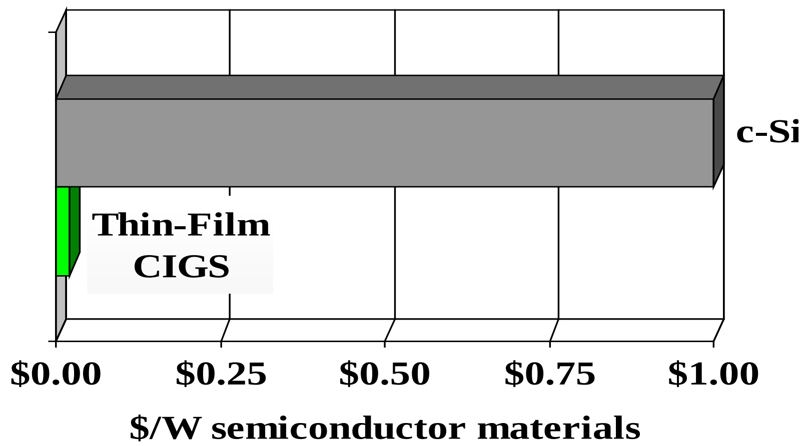
ABSORPTION COEFFICIENT OF SEMICONDUCTOR PV MATERIALS AND AM1.5 SPECTRUM

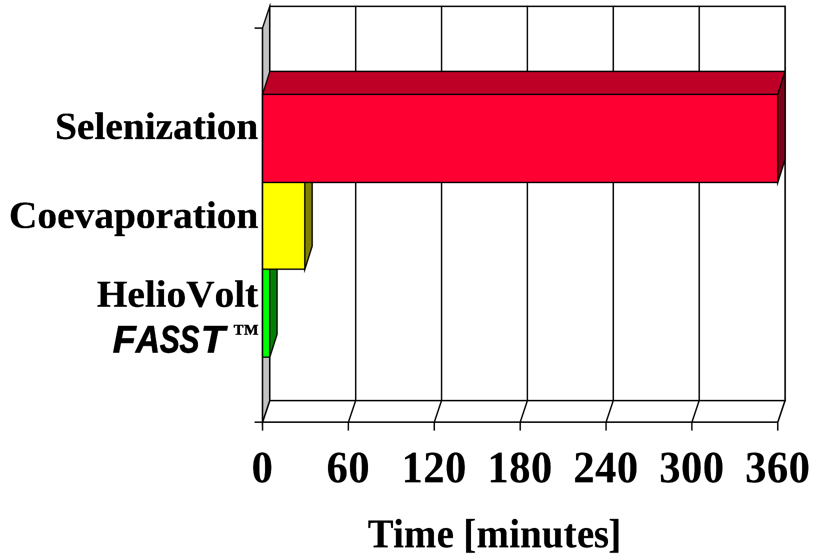


THICKNESS OF SEMICONDUCTOR NEEDED TO ABSORB SOLAR SPECTRUM VARIES DRAMATICALLY

- Film thickness roughly equal to α^{-1} near band edge used to absorb most of the solar spectrum without light trapping
- Useful dimensionless constant to characterize semiconductor material quality is α*L, product of absorption coefficient (α) and collection length (L)

TFPV Amortization and Direct Materials Cost Reduction Strategies





- Rapid film deposition and processing methods significantly reduces **capital amortization**
  - Vapor Transport Deposition (VTD) First Solar's key CdTe manufacturing technology breakthrough
- Thin-film materials can significantly reduces **direct materials** wafer module cost component if raw materials utilization is efficient

CIGS TFPV Characteristics

- Copper-Indium-Gallium Selenide (CIGS)
  - Highest efficiency of all single-junction TFPV technologies
    - Current world cell record 21.7% (ZSW)
      - Commercially dominant mc-Si device record only 20.4%
    - Current world module record 17.5% (Solar Frontier)
  - Intrinsically stable thin film solar cell
    - Other intrinsically stable technologies: silicon & III-V's
  - Challenges:
    - Extrinsic instability due to water vapor corrosion of TCO
    - Known indium reserves with recycling limit production to ~30-50 GW/year

CIGS Complex Non-Stoichiometric Thermochemical Phase Structure

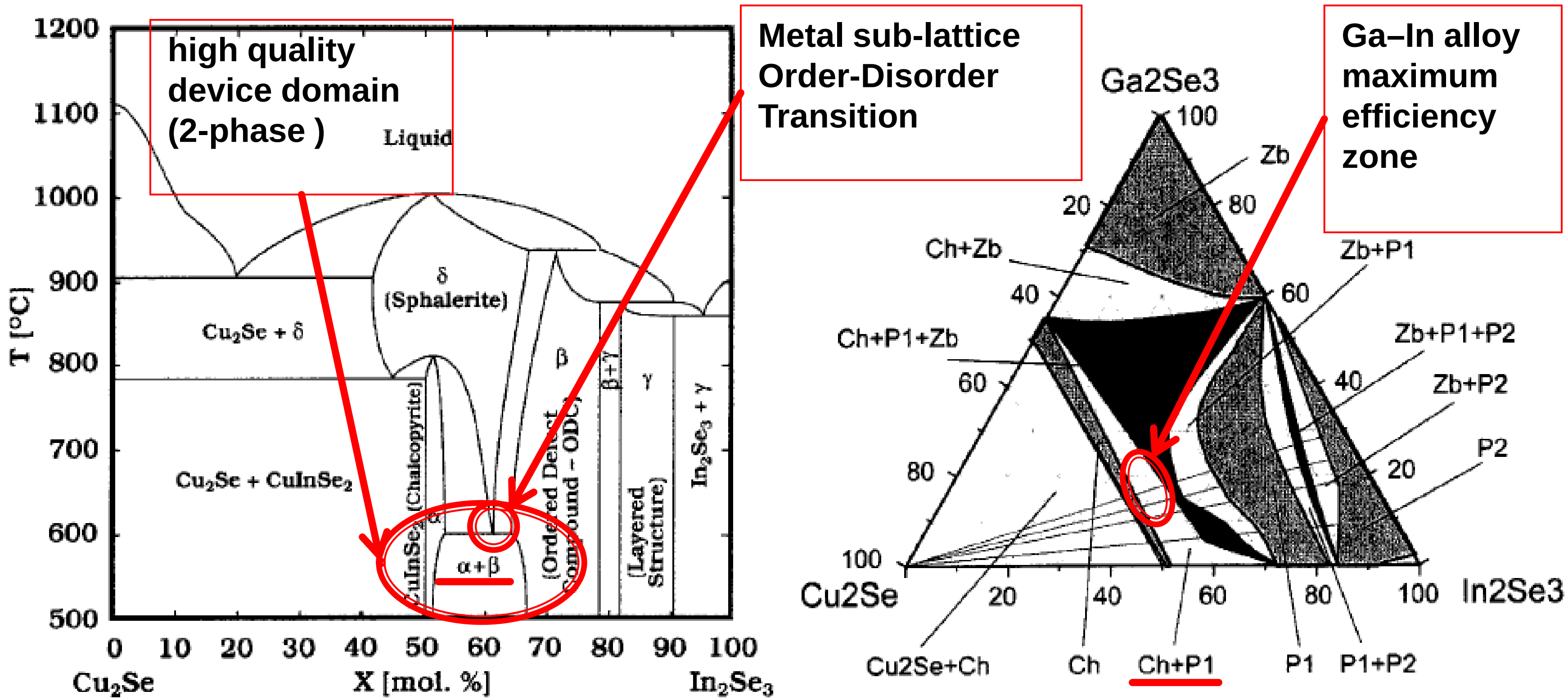


FIGURE 1. Adapted from a published assessment of the phase diagram along the Cu_2Se – In_2Se_3 pseudobinary section of the Cu–In–Se chemical system.[33]

FIGURE 4. Predominance diagram for the Cu_2Se–In_2Se_3–Ga_2Se_3 pseudoternary phase field at room temperature.[135] In that author's notation, Ch is the α phase, P1 is the β phase, P2 is the γ phase, and Zb is the δ phase.

- <u>All</u> of the stable thermodynamic phases in the CIGS material system are crystalline but can vary in composition

Polycrystallinity and Recombination

- Grain boundaries (g.b.'s) in polycrystalline materials dramatically increase the surface-to-volume ratio leading to demanding requirements on effective grain boundary passivation to prevent excessive minority carrier surface recombination
- It has long been recognized that the high efficiencies of CIGS TFPV are indicative of intrinsic mechanisms for g.b. surface passivation
- CIGS surfaces have been shown to be deficient in copper to an extent sufficiently large to be characterized as the formation of the β-phase (sometimes called an Ordered Defect Compound, or ODC)
  - Formation of this surface β-phase boundary does not introduce another grain boundary because the α and β phases are crystallographically coherent, sharing the same FCC Se sublattice
- Recent studies have unequivocally confirmed that a key distinction between the highest and lower efficiency devices is the uniformity of positively charged g.b.'s*

† C.-S. Jiang *et al.*, Proc. 38th IEEE PVSC, 2012.

CIGS Non-Stoichiometry and Atypical Device Behavior

- Peculiar semiconductor behavior:
  CIGS PV devices insensitive to ±% atomic composition variations & extended defects
  >19% efficiencies recently reported† over range:
    - $0.69 \leq [Cu]/([In]+[Ga]) \leq 0.98$ (Group I/III ratio)
    - $0.21 \leq [Ga]/([Ga]+[In]) \leq 0.38$ (Group III alloy ratio: E_g)
- Empirical Observations
  - CIGS PV devices are always copper deficient compared to α-$CuInSe_2$
  - Compositions lie in the equilibrium $\alpha+\beta$ 2-phase domain
  - CIGS PV devices usually have near-theoretical limit internal QE currents, even when voltages are low

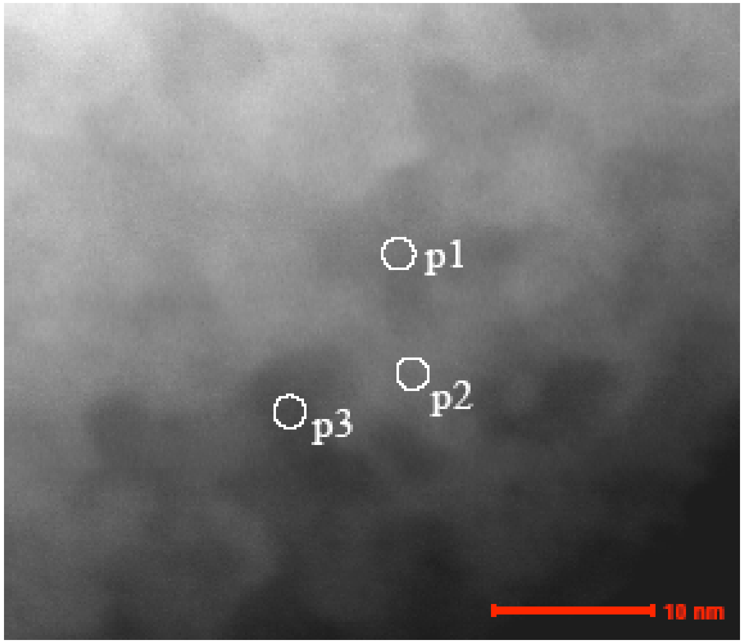
† Jackson *et al.*, Prog. PV, Wiley & Sons, 2007.

Intra-Absorber Junction (IAJ) Model

- Device-quality CIGS is a two-phase mixture of p-type α-CIS and n-type β-CIGS, which are depleted
- Contravariant band fluctuations result from the bandgap difference of *p*- α-CIGS and *n*- β-CIGS
- These internal junctions separate charge carrier pairs first, followed by injection of each into the corresponding contact.
- The n-type β-CIGS surface layer on the absorber reduces hole recombination that would result from direct contact with the α-CIGS domains

Composition Fluctuations and Carrier Transport in CIGS PV Absorbers

- Theoretical model *a priori* predicted preferential Ga-In distribution between segregated phases
- Experimental results* HAADF-TEM & nano-EDS
  - 5-10 nm characteristic domain size (2-D)
  - Pearson product-moment statistical correlation between the two variables Cu/(In+Ga) and Ga/(In+Ga) is 0.72 (null P=0.3%)



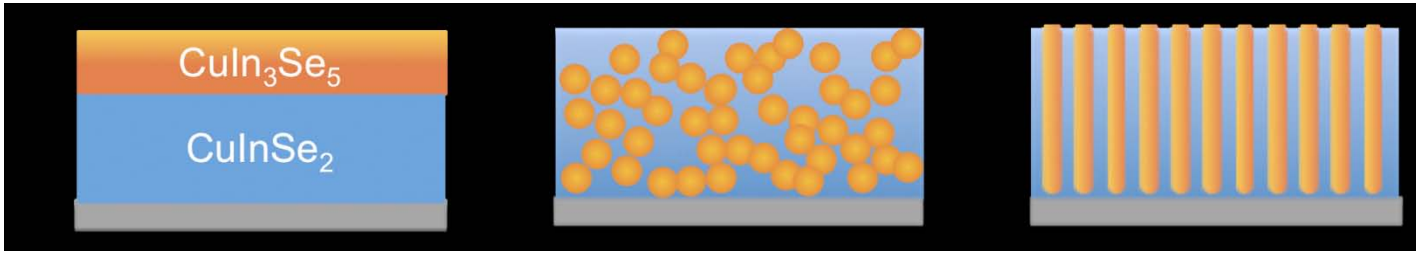
*Applied Physics Letters, 87, 2005, 121904

CIGS: Spontaneous 'Bulk Heterojunction' Formation

- Inherent to CIGS PV semiconductor
  - Spontaneous nanostructuring
    - Driven by phase segregation
  - Forms internal nano-scale junctions
    - Two phases form different interpenetrating percolation networks for each carrier type
    - Physical separation of ambipolar currents reduce recombination, explaining CIGS performance & robustness
- Suggests novel pathways for
  cost & performance improvement

Role of Nano-Engineering in Next-Generation CIGS PV Device Technology

- Intra-Absorber Junction (IAJ) model
  - Device-quality CIGS is a two-phase mixture of *p*-type α-CIGS and *n*-type β-CIGS phases, forming a nanoscale bulk heterojunction.
  - These internal junctions form an interpenetrating percolation network, allowing positive and negative charges to travel to the contacts in physically separated paths, reducing recombination.
- Presents opportunity for optimization of nanostructures in CIGS by engineered nanostructure synthesis



•single heterojunction between Cu-rich and Cu-deficient phases,
•randomly oriented bulk heterojunction formed by spontaneous nucleation, and
•an ideal vertically oriented bulk heterojunction.

PV Material Resources at TeraWatt Scale

Construct 1 TW of PV with optically thick cells at 15% efficiency

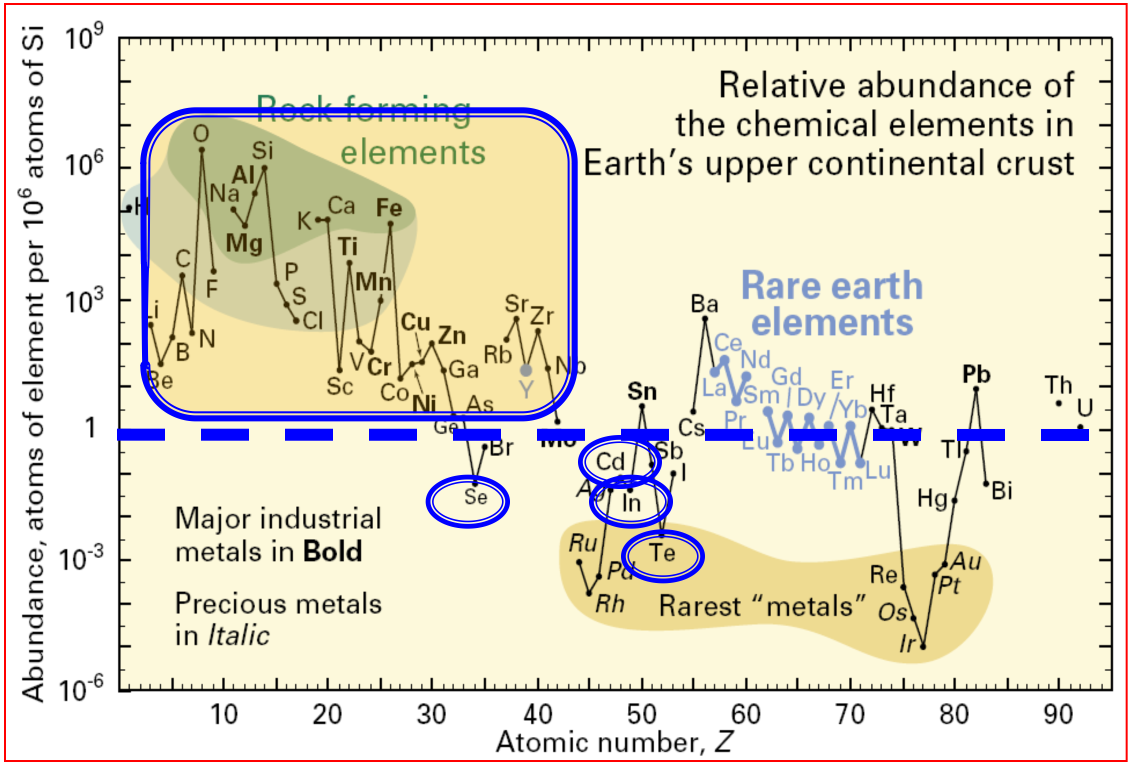
Many current thin film PV materials have resource limitations that prevent this!

Solutions:

1) Earth Abundant Semiconductors (Si,Cu_2O, Zn_3P_2, FeS_2;)

2) Enhance Light Absorption/reduce semiconductor volume

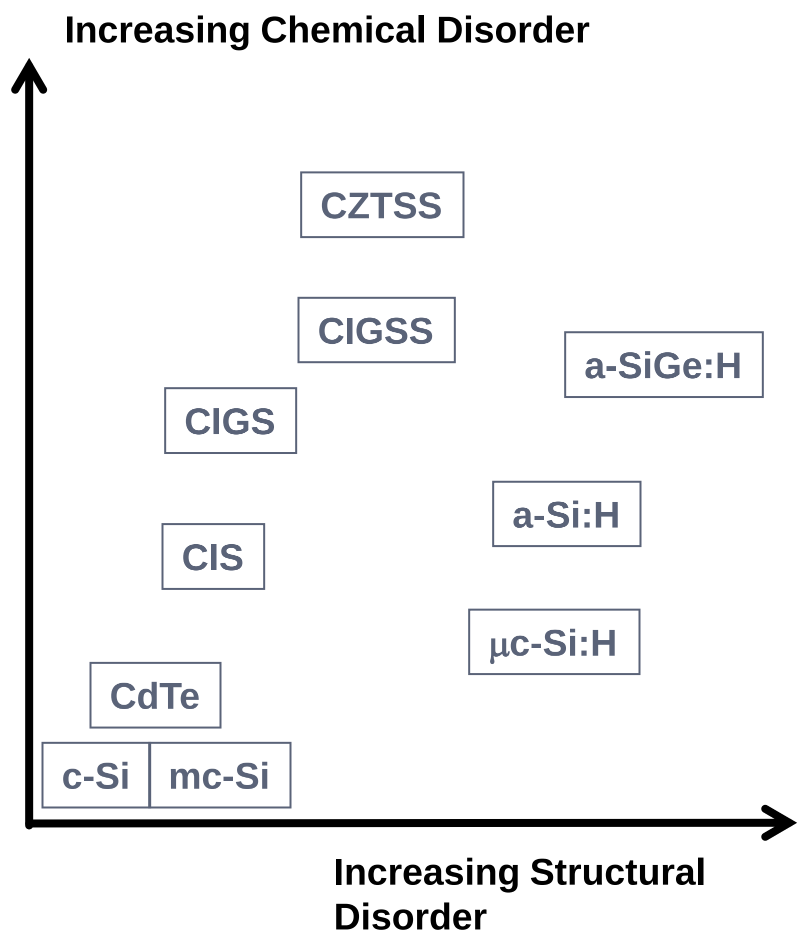
Relative abundance of elements vs. atomic number*



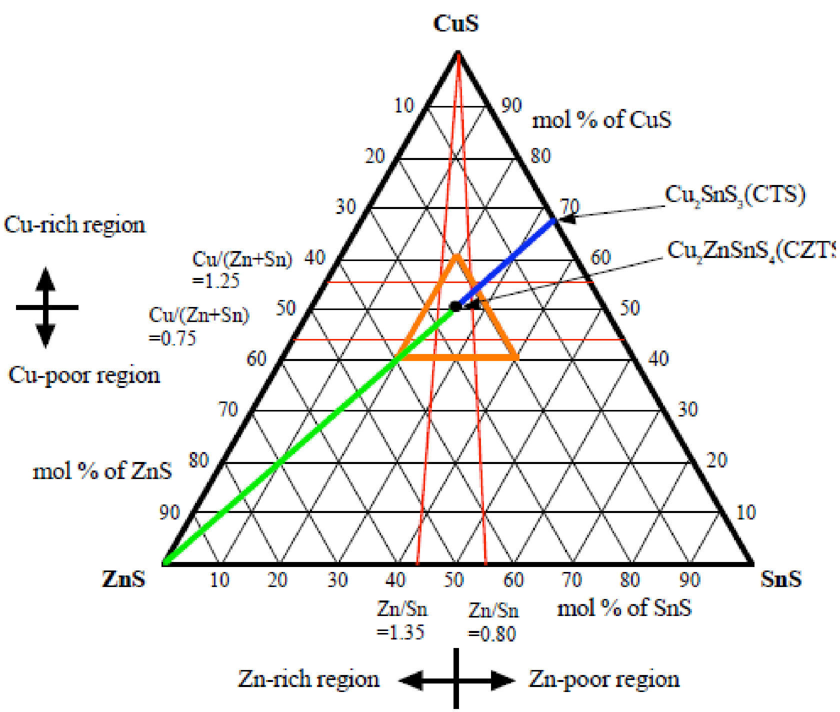
*from P.H. Stauffer et al, Rare Earth Elements - Critical Resources for High Technology, USGS (2002)

Structural vs. Chemical Disorder in TFPV Materials

- Mainstream TFPV materials vary from nearly conventional (CdTe) to amorphous and complex multinary compounds
- Disorder does not appear to be an insurmountable obstacle to high PV performance
- Studies of the mechanisms by which recombination centers in disordered TFPV materials are passivated suggest that combinations of extrinsic impurities and native defect complexes are involved
  - H in mc-Si and a-Si
  - Na and ($2V_{Cu}$+In_{Cu}) neutral cation defect complex in CIGS



CZTS Phase Field and Efficiency



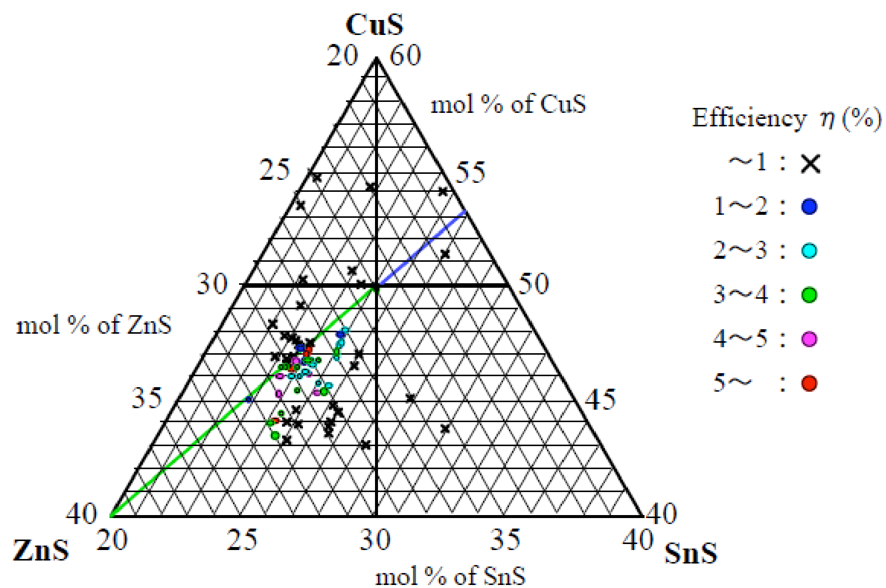


Figure 5. Efficiency map on the pseudo-ternary phase diagram. The green line looks like a boundary between the high conversion efficiency cells and the others.

- Much like CIGS, the highest efficiencies for CZTS are achieved with compositions far from the stoichiometric ideal. This is almost certainly indicative of the need to adjust stoichiometry to control the formation of electrically deleterious native defect complexes.

Katigari, H., et al., Mater. Res. Soc. Symp. Proc. Vol. 1165 (2009)

Adamantine Crystallographic Structures

- **Tetrahedral**
  - Single element
    - e.g.: silicon, diamond
- **Zincblende**
  - 2-element compound
  - e.g.: GaAs (III-V) and ZnSe (II-VI)
- **Chalcopyrite**
  - 3-element compound
  - e.g.: $CuFeS_2$ and $CuInSe_2$ (I-III-VI_2)
- **Kesterite**
  - 4-element compound
  - e.g.: $Cu_2ZnSnSe_4$ (I_2-II-IV-VI_4)

- Each successive category is a crystallographic superstructure of the preceding
- Each in an ideal lattice would be "Normal Valence Compounds" wherein there are two electrons available for each bond in the tetrahedrally-coordinated structures with each atom in its normal valence state
- Heterogeneous bond ionicity drives tetragonal lattice distortion (2+ metals)
- Entropy drives formation of lattice defects and non-tetrahedral equilibrium polytopes in equilibrium (lowest free energy) crystal structures
- Increasing number of elements allows more modes for crystallographic defects to accommodate non-ideal stoichiometry in equilibrium, resulting in increasingly broad composition within individual thermochemical phase domains

CZTS Crystallographic Structure

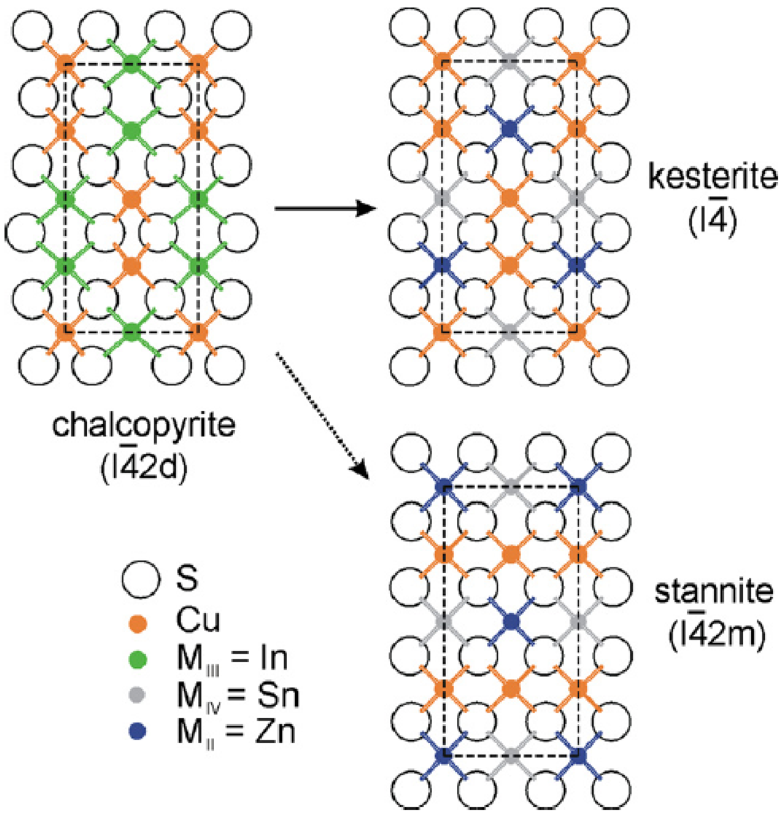
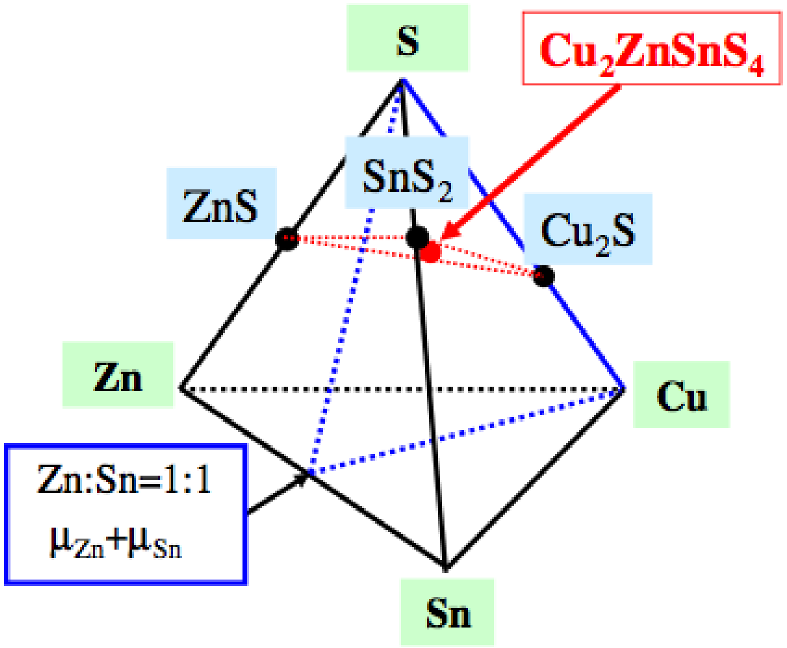


Fig. 1. Schematic representation of the chalcopyrite structure (drawn with M_{III}=In), and kesterite and stannite structures (drawn with M_{II}=Zn, M_{IV}=Sn). The unit cell boundaries are denoted with dashed lines and the space group for each structural type is also provided.



CZTS Kesterite Phase Identification

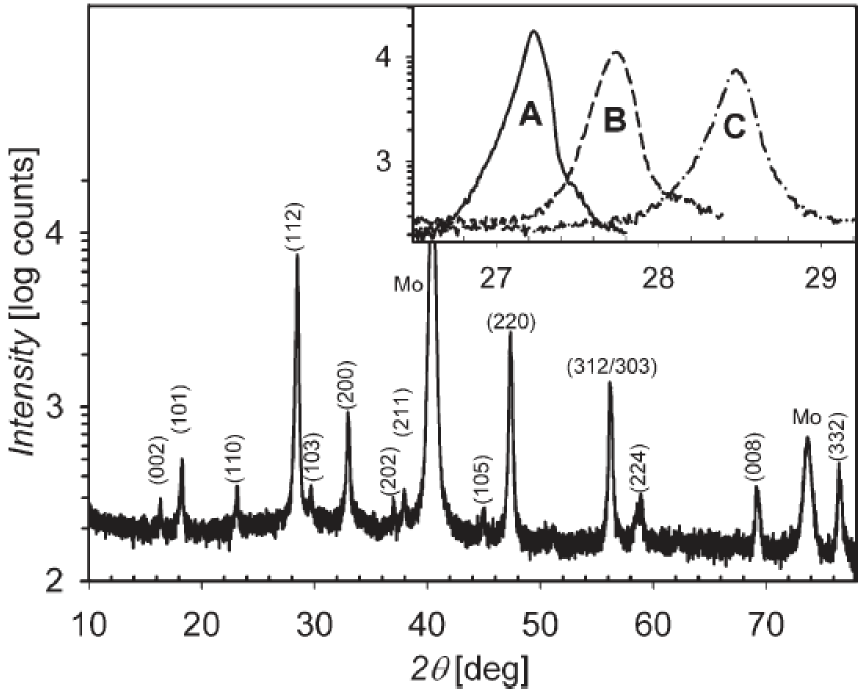


Figure 2. X-ray diffraction pattern of sulfide sample C, Cu_2ZnSnS_4, identified as kesterite, JCPDS 26-0575. Peaks arising from the Mo underlayer are noted. Inset: (112)-peak shift with progressively increased sulfur content in samples A, B and C (same axis labeling as for the main figure). The fitted tetragonal lattice constants (using full diffraction profile) for each of the samples are—Sample A: $a = 5.668(2)$ Å, $c = 11.349(5)$ Å; Sample B: $a = 5.567(1)$ Å, $c = 11.168(2)$ Å; Sample C: $a = 5.432(1)$ Å, $c = 10.840(3)$ Å.

"Phase pure" materials from evaporation, sputtering, solution, MBE etc.

CIGS experience is that in complex multinary compounds phase identification by XRD can be unreliable because thermochemistry dominated by short-range defect complexes which may not have sufficient long-range order to yield coherent scattering from X-ray sources

Sn and Zn loss a major problem

Solution routes are best to date

Mitzi, Solar Energy Materials & Solar Cells 95 (2011) 1421–1436

The Challenge of Understanding CZTSS: From Isolated Point Defects to Associates

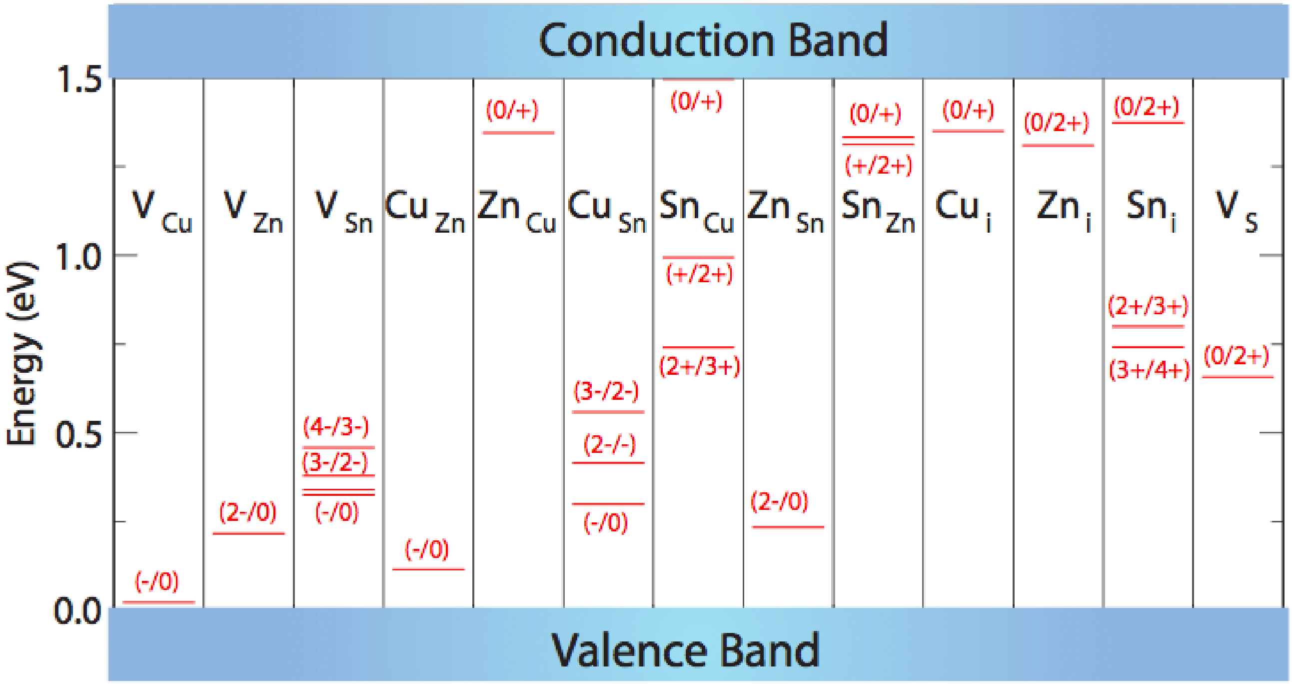


FIGURE 1. Calculated transition energy levels of intrinsic defects in the band gap of Cu_2ZnSnS_4.

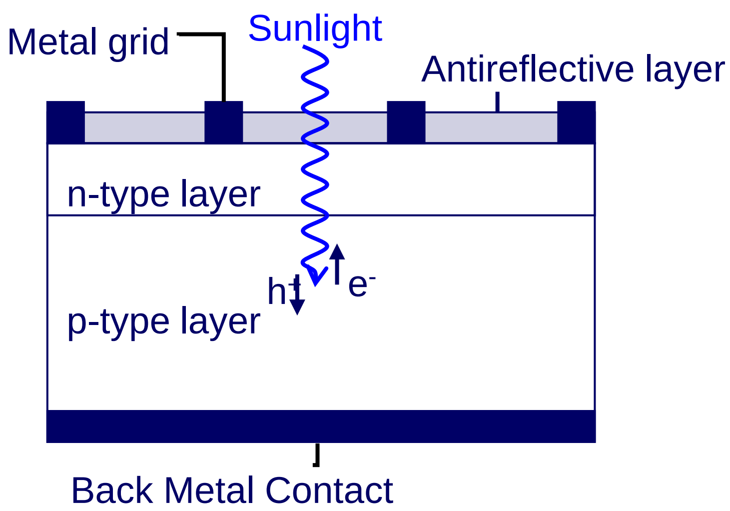
Physics of Semiconductors AIP Conf. Proc. 1399, 63-64 (2011)

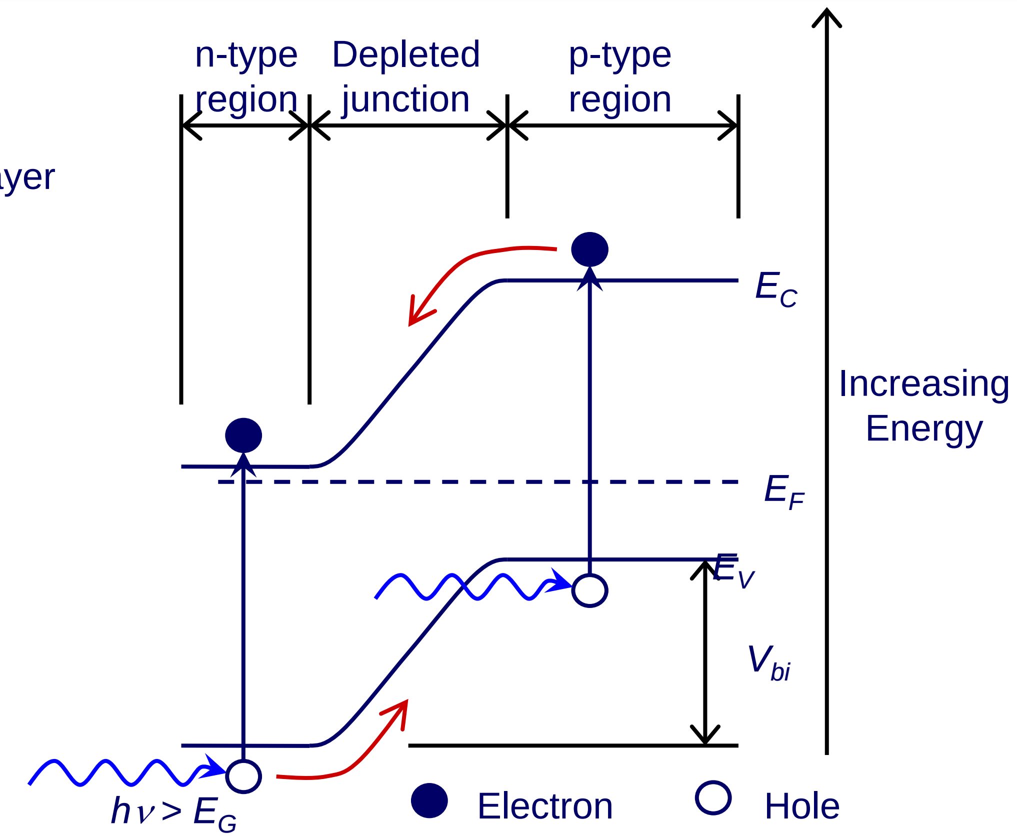
- The experience in CIGS has been that a comprehensive understanding of electrical properties requires an understanding of the energetics of defect associates (complexes), which forms as the lattice equilibrates towards its lowest free energy state.

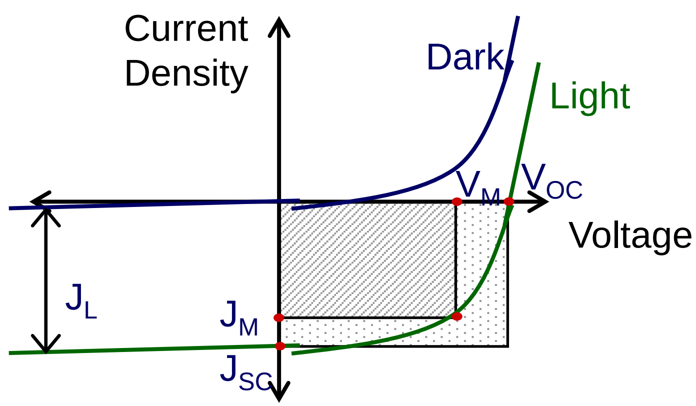
Performance Challenges to Economically Competitive PV

Many Strategies for Increasing Efficiency Have Been Successfully Demonstrated, but Most Are Not Cost-Effective Because of Materials Issues

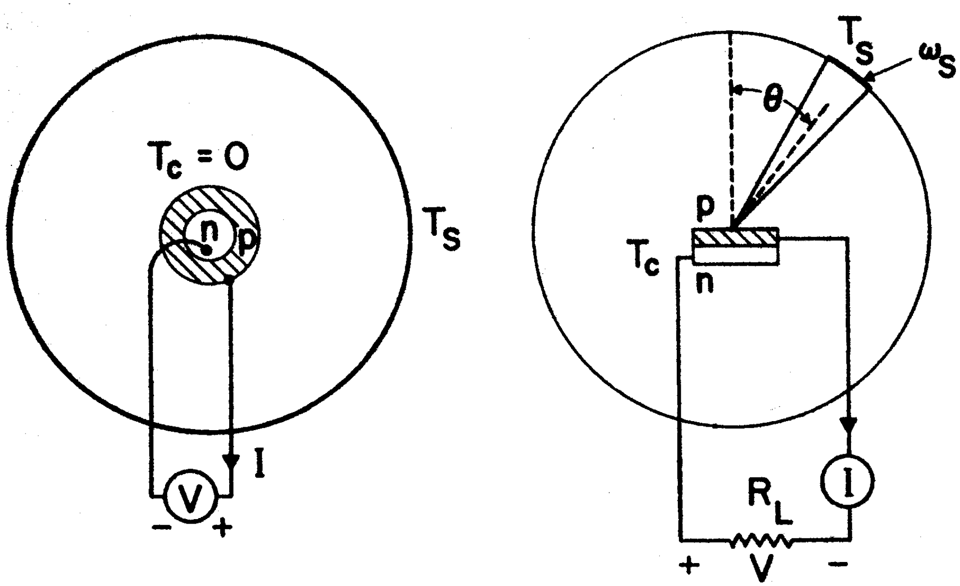
Solar Cell Schematic



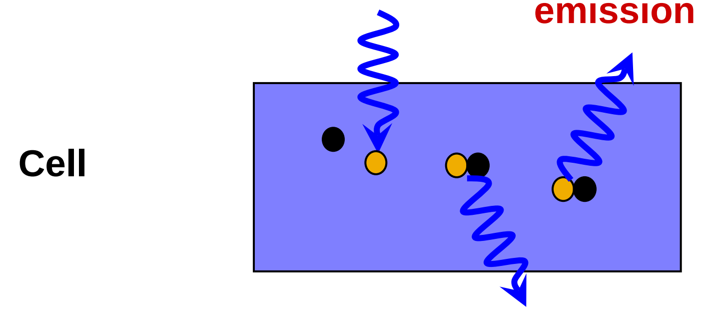




Detailed Balance Limit for Solar Cell Efficiency



(a) (b)



$$\frac{J_1}{q} = {}^{AM1.5}N - {}^{rad}N_1$$

charge carrier flux

generation rate by sunlight absorption

radiative recombination rate

Shockley and Queisser, **J. Appl. Phys**. (1961)

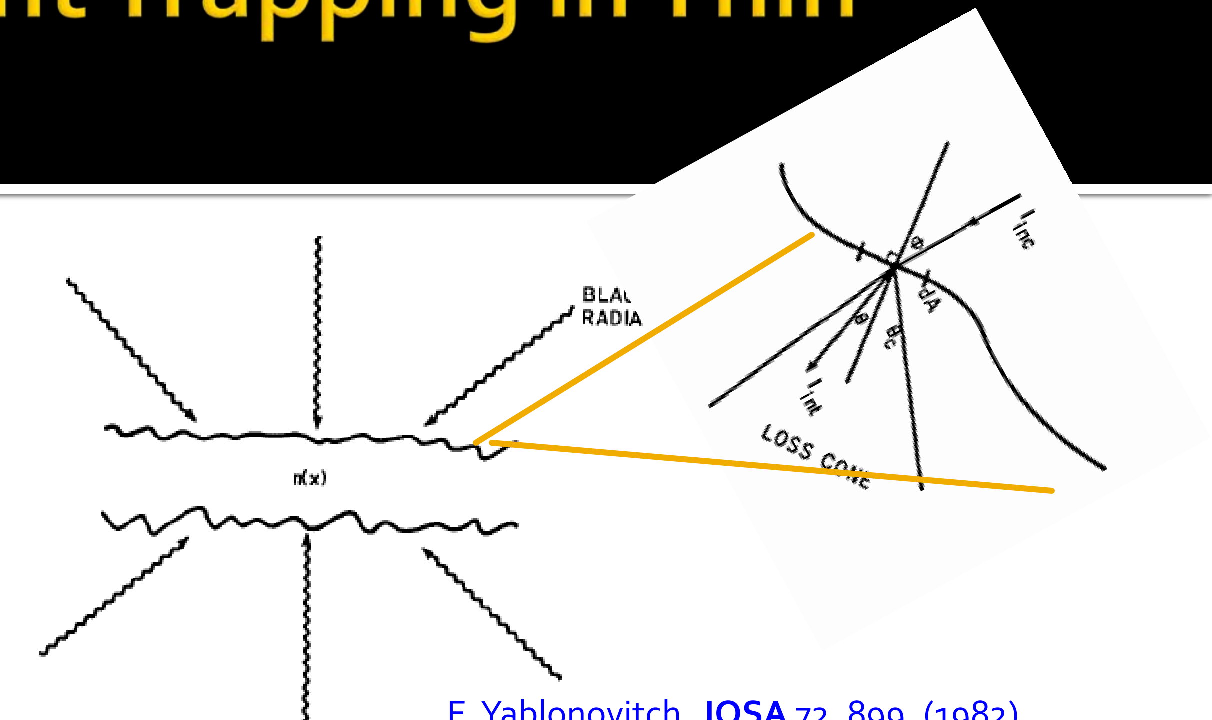
‘Ergodic’ Light Trapping in Thin Sheets

Assumptions:

geometrical ray optics

optically thin sheet

random texture



E. Yablonovitch, **JOSA** 72, 899, (1982)

Detailed balance between absorption and emission cones

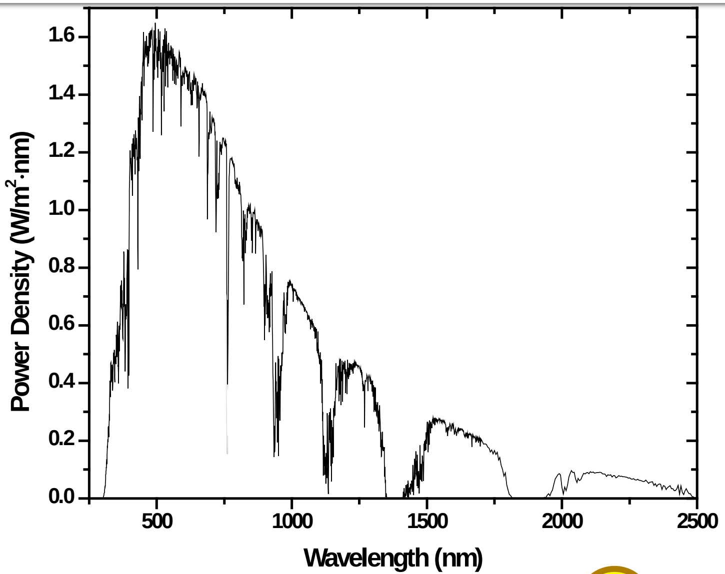
Results:

light in medium will be randomized in direction

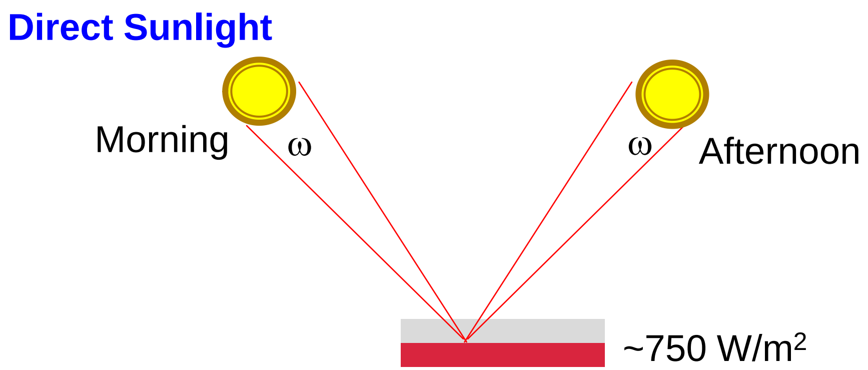
In medium, $2n^2(x)$ times greater intensity than incident light (for Si, ~25x)

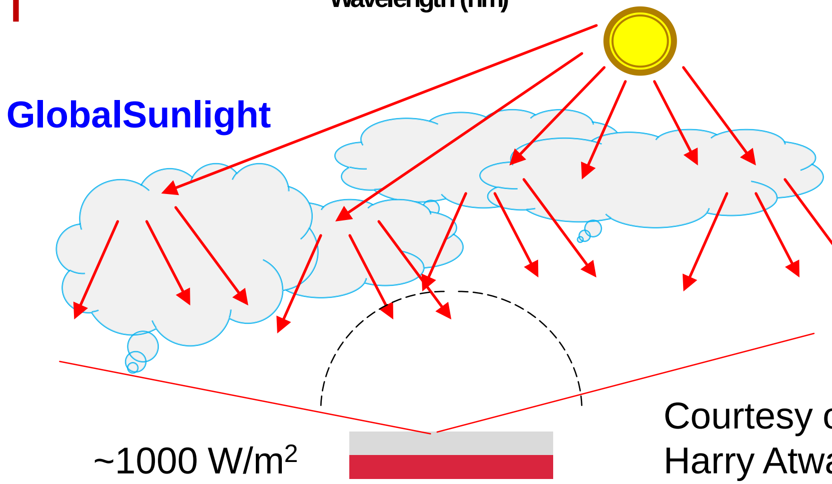
Photovoltaic Absorber Requirements

Spectrally Broad Absorption



Angle-Independent Absorption

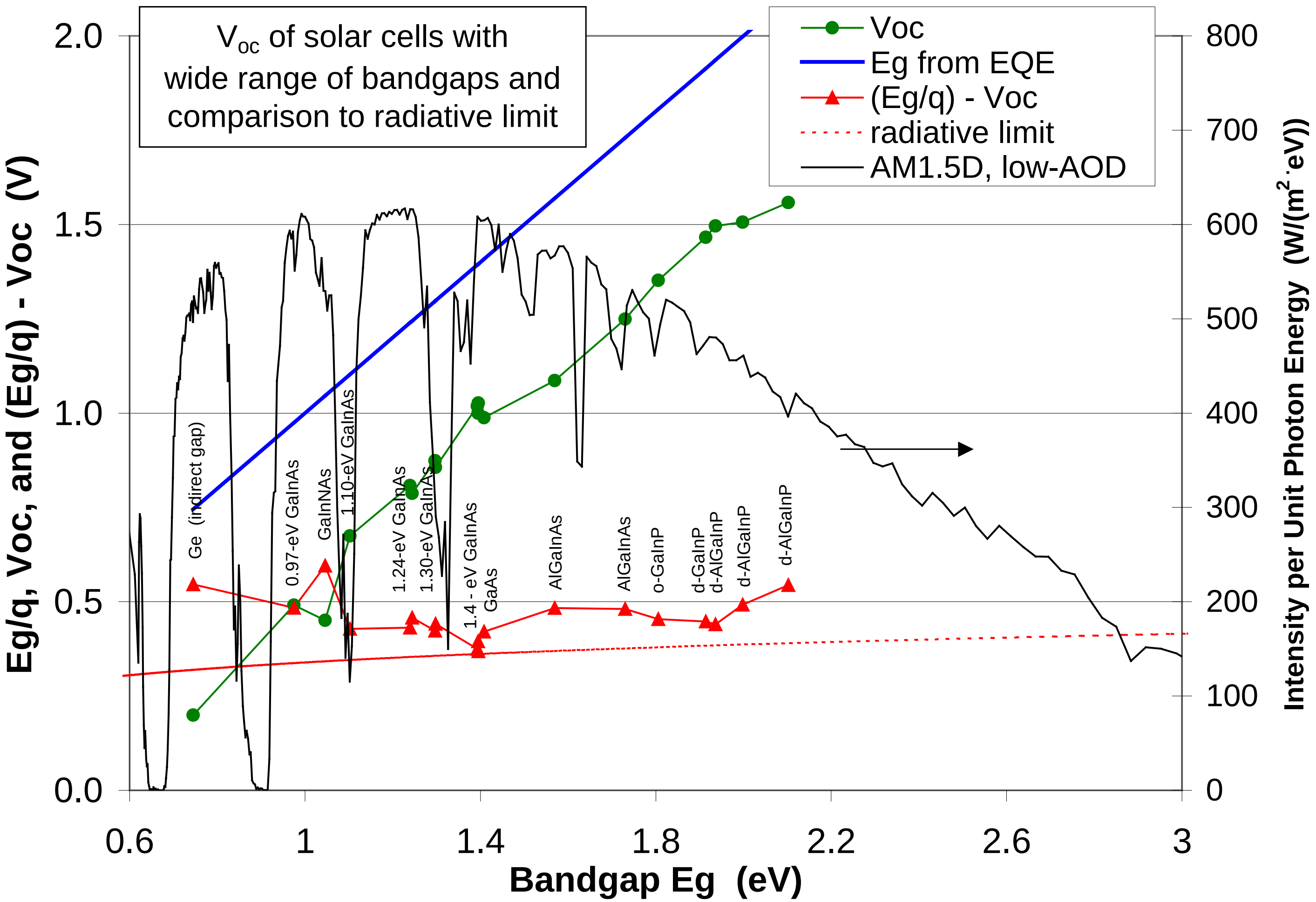




Courtesy of Harry Atwater

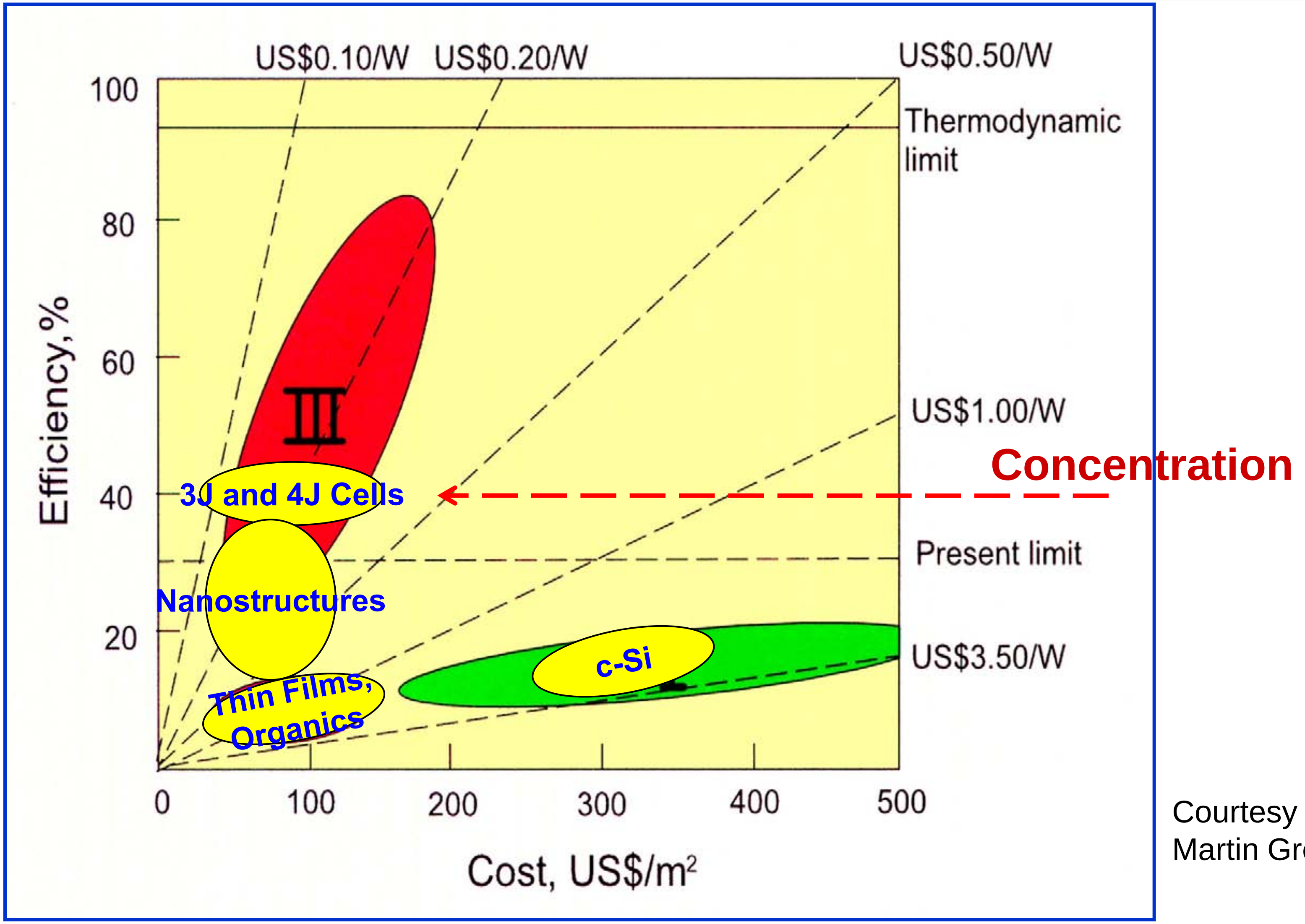
Open Circuit Voltage Offset from Bandgap: Photon Entropy

$\Delta F = \Delta H - T\Delta S = qV_{oc} = E_g - T\,k\ln\Omega = E_g - kT\ln 46{,}200 = E_g - 10.7\,kT =$ 279 meV @ 300K



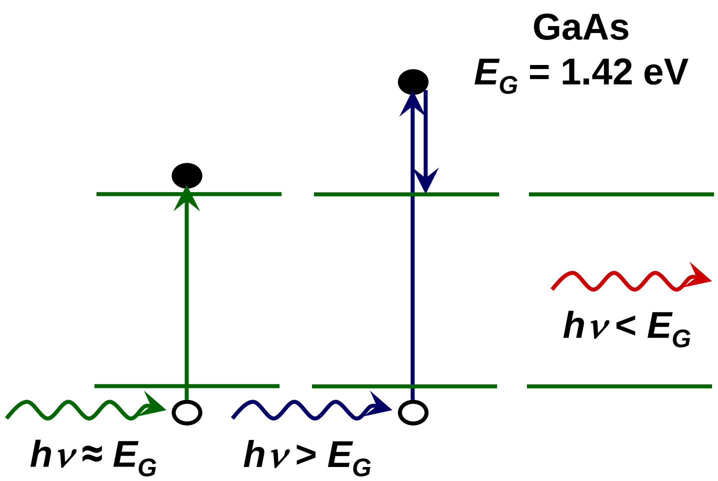
Courtesy of Richard King

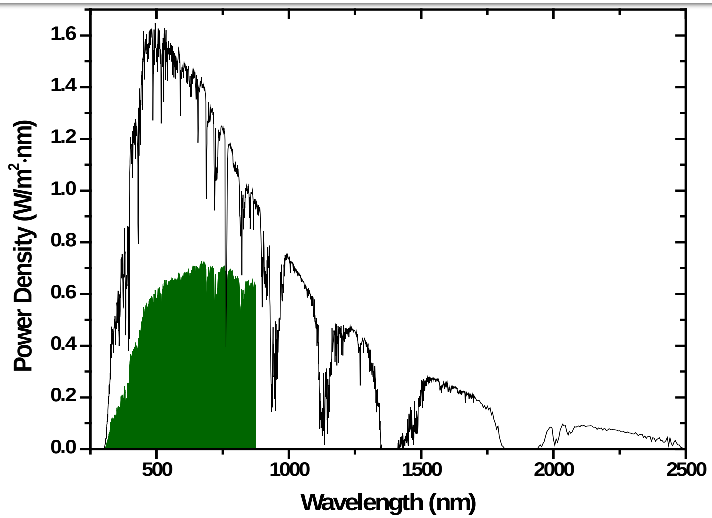
Cost/Efficiency Roadmap for Photovoltaic Technologies

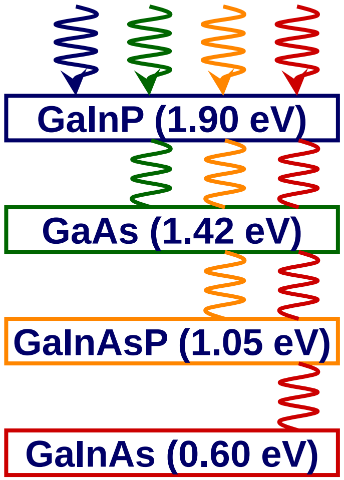


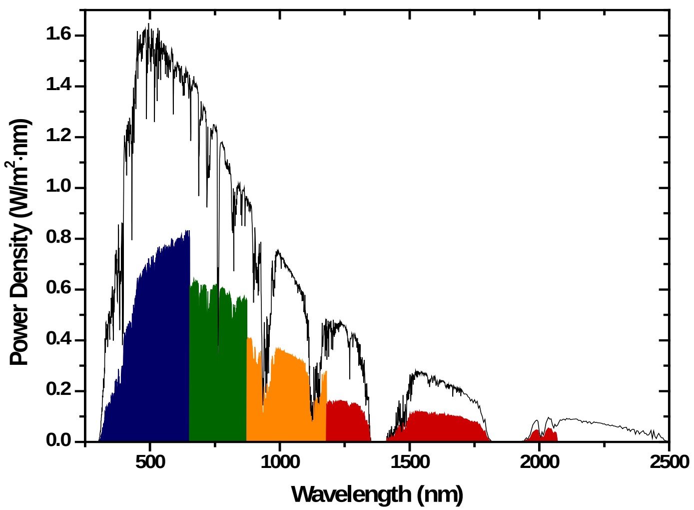
Courtesy of Martin Green

Spectral Splitting: Single-junction vs. Multijunctions









Summary

Solar Energy is the Earth's Greatest Energy Resource and its Further Development is Essential to the Sustainability of Human Life

There are Many Unresolved Challenges!

- Despite its intermittency and non-dispatchability, the value of solar PV electricity is disproportionate to its cost compared to conventional electrical generating assets due to its high temporal correlation with demand.
- Distributed solar PV is poised to create an existential crisis for the utility industry in the US because their business models and grid infrastructure cannot yet accommodate high penetration
- Large-scale penetration of PV into the global electrical power infrastructure requires multi-disciplinary advances throughout the value chain from materials science, device physics, as well as various engineering disciplines (electrical, mechanical, industrial).
- Many intellectually challenging fundamental issues in the field of non-stoichiometric compound semiconductors and their application to PV
- Equally important challenges remain in the development of manufacturing methods to economically produce suitable semiconductor materials at scale.