Photovoltaics is Solar Electricity

Photovoltaics (PV)

- Direct conversion of sunlight to electricity

Advantages

- Modular (mW to many MW)
- No (or few) moving parts
- Noise and pollution free
- Reliable; low operating costs
- Abundant, indigenous resource ($30,000\ km^2$ PV for 800 GW)

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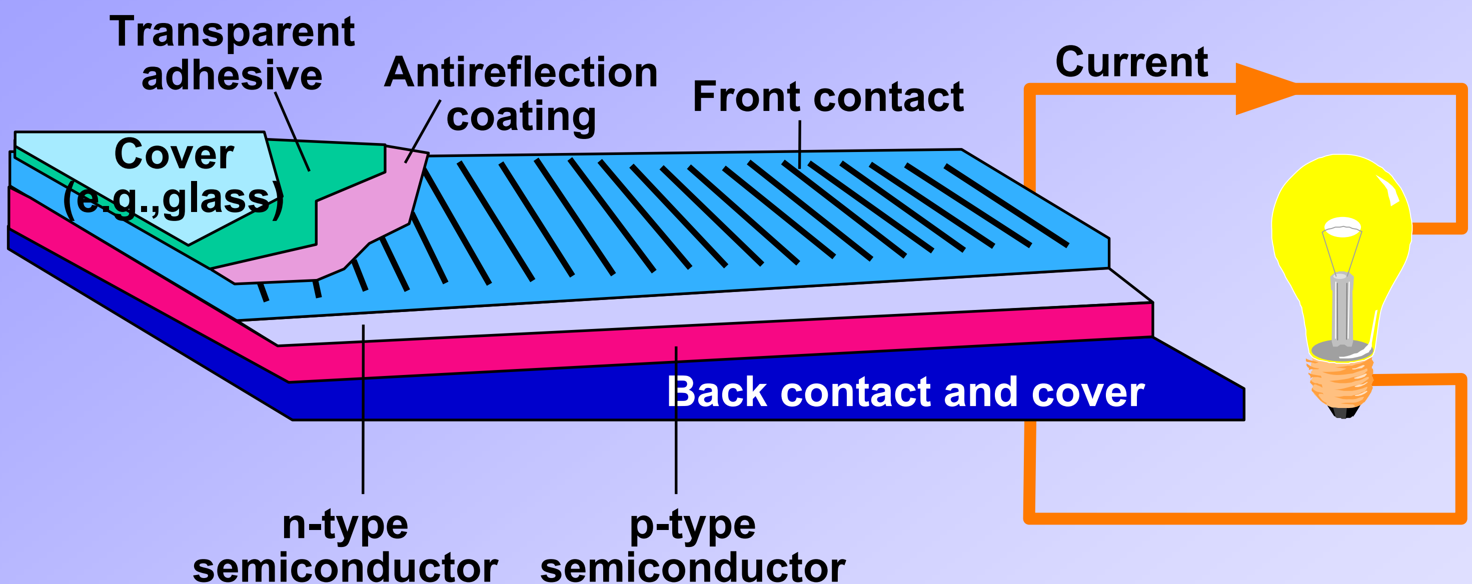
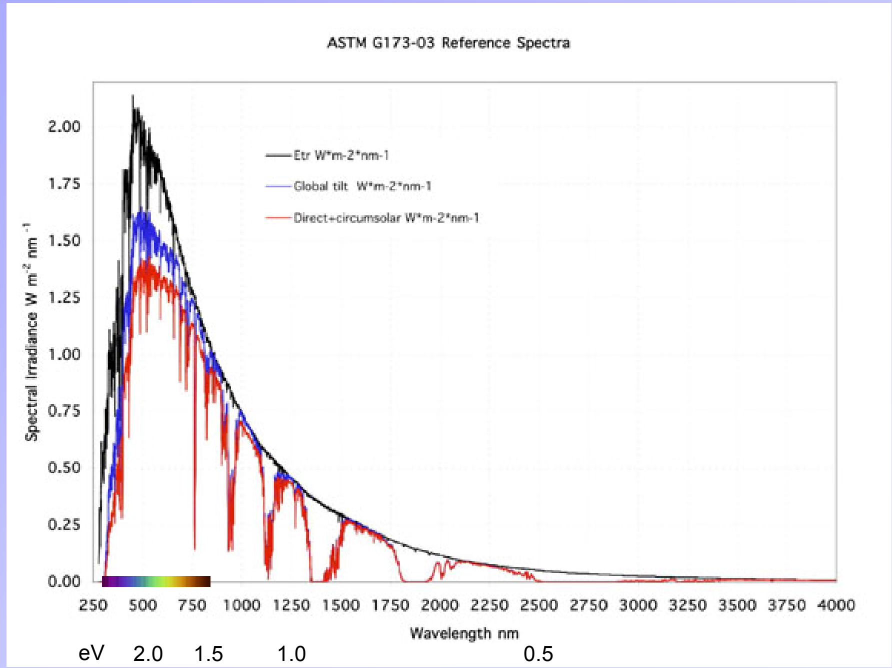
Solar Cell Structure

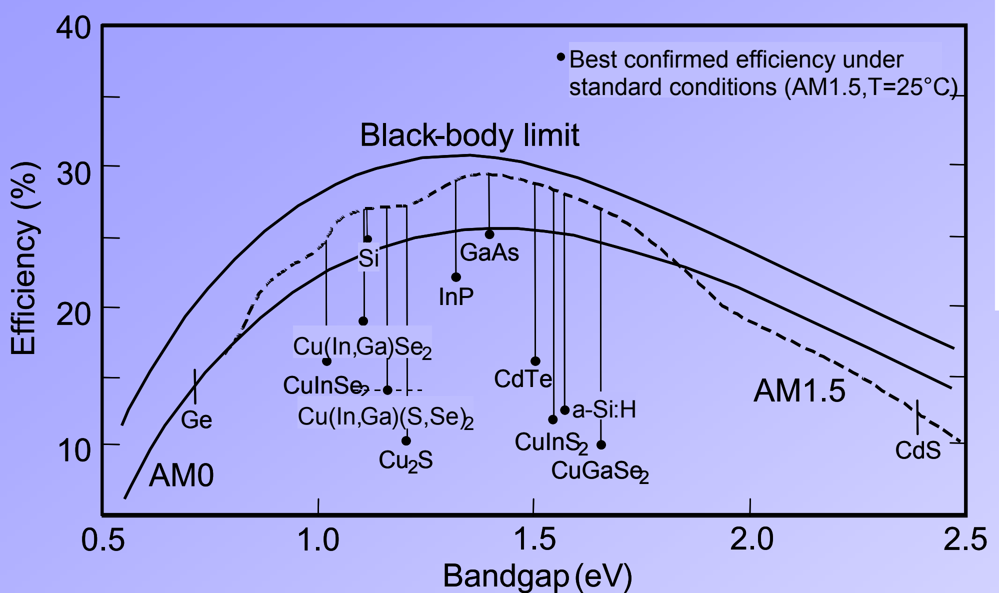


$$\text{Solar cell efficiency (\%)} = \frac{\text{Power out (W)} \times 100\%}{\text{Area (m}^2\text{)} \times 1000\ \text{W/m}^2}$$

10% efficiency = 100 W/m² or 10 W/ft²

How to select the semiconductor absorber material(s)?

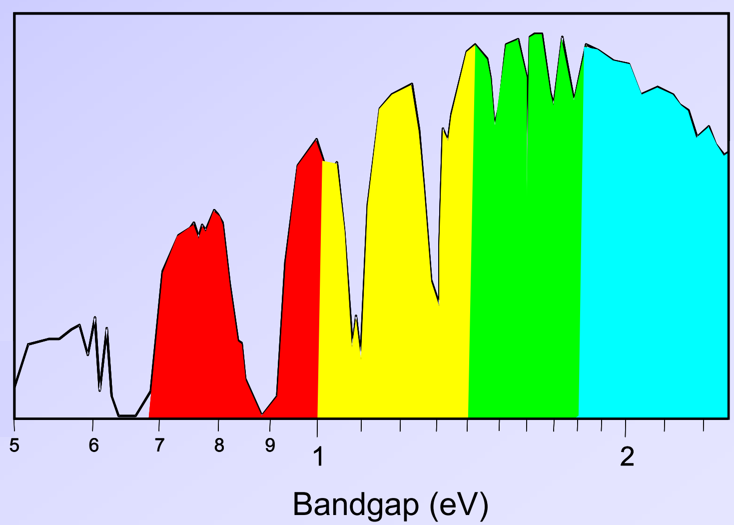


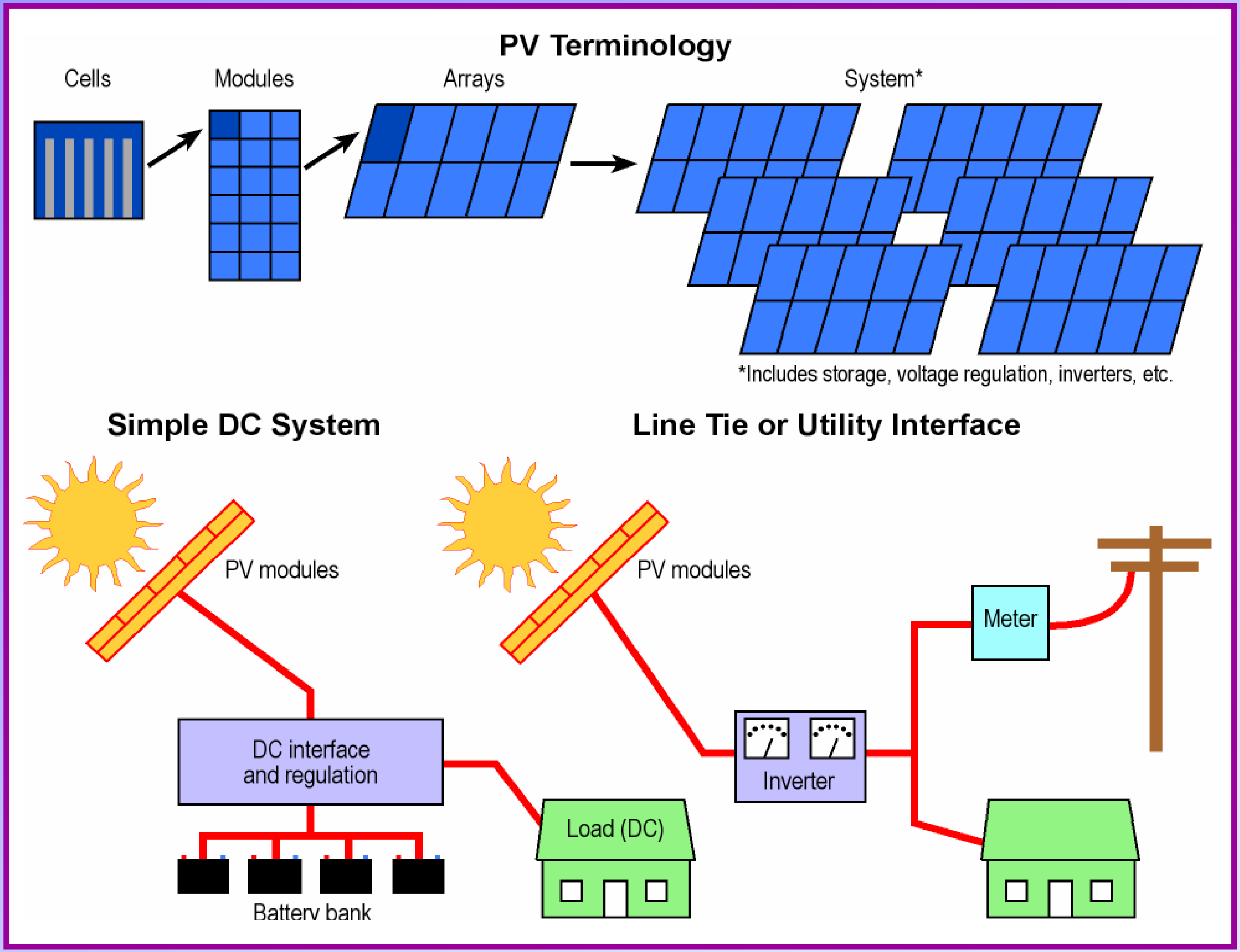


Four-junction device with bandgaps

1.8 eV/1.4 eV/1.0 eV/0.7 eV

Theoretical efficiency > 52%




PV Terminology
Cells
Modules
Arrays
System*
*Includes storage, voltage regulation, inverters, etc.
Simple DC System
Line Tie or Utility Interface
PV modules
DC interface and regulation
Battery bank
Load (DC)
PV modules
Meter
Inverter

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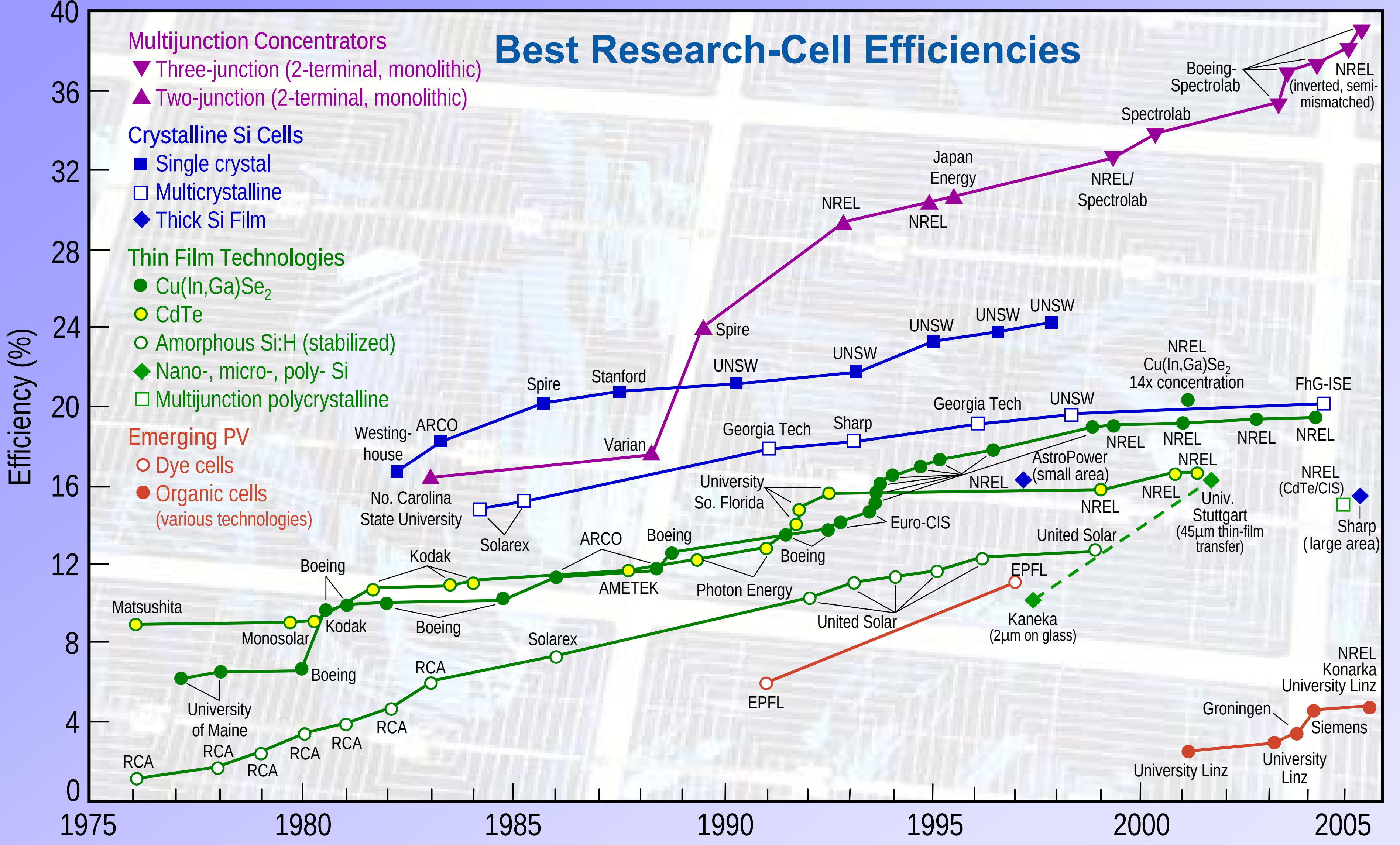


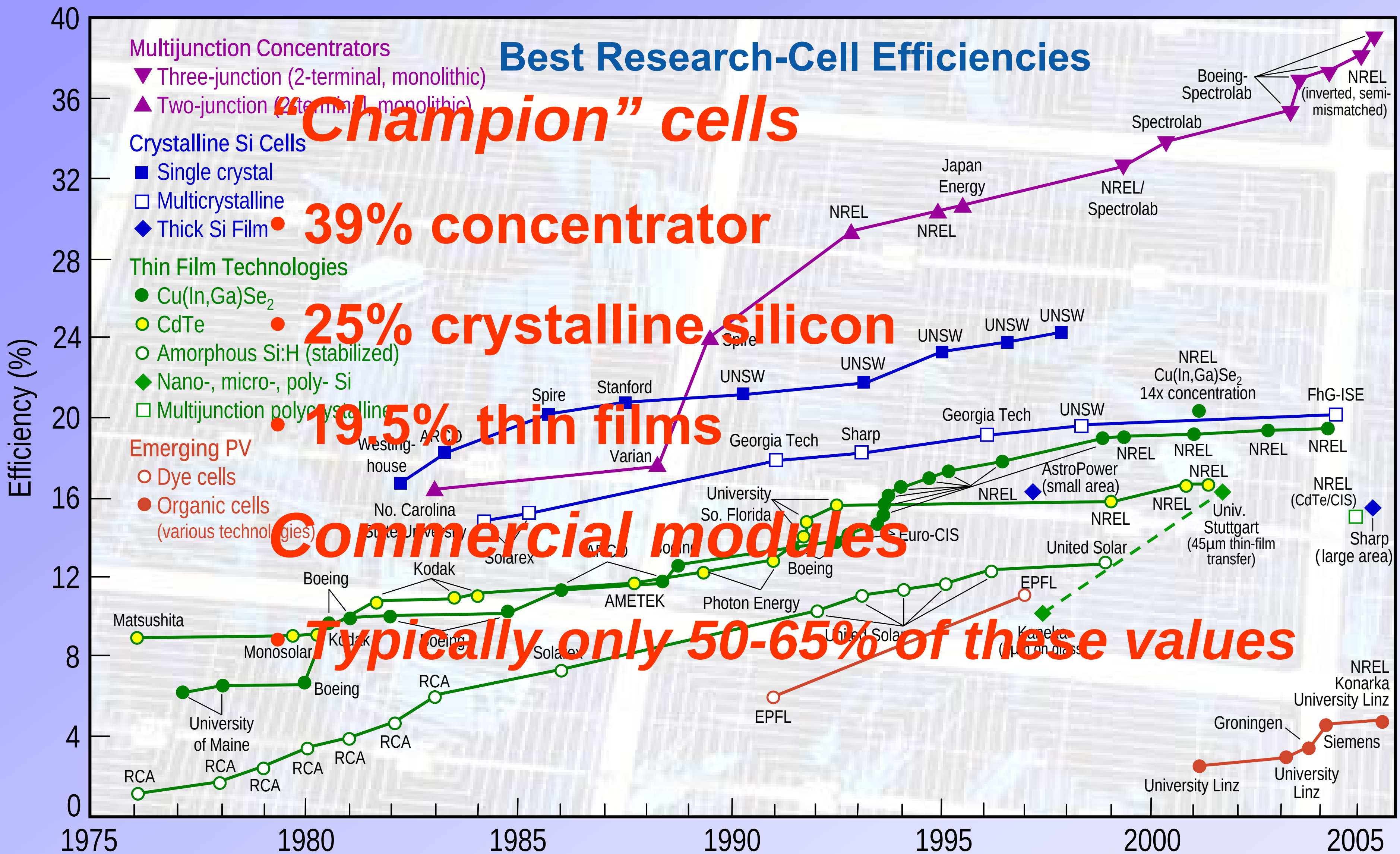
Best Research-Cell Efficiencies
Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Crystalline Si Cells
Single crystal
Multicrystalline
Thick Si Film
Thin Film Technologies
Cu(In,Ga)Se2
CdTe
Amorphous Si:H (stabilized)
Nano-, micro-, poly- Si
Multijunction polycrystalline
Emerging PV
Dye cells
Organic cells
(various technologies)
Efficiency (%)
0
4
8
12
16
20
24
28
32
36
40
1975
1980
1985
1990
1995
2000
2005
Boeing-
Spectrolab
NREL
(inverted, semi-
mismatched)
Spectrolab
NREL/
Spectrolab
Japan
Energy
NREL
NREL
Spire
Varian
UNSW
UNSW
UNSW
UNSW
UNSW
UNSW
Stanford
Spire
ARCO
Westing-
house
No. Carolina
State University
Solarex
Georgia Tech
Sharp
Georgia Tech
UNSW
FhG-ISE
NREL
Cu(In,Ga)Se2
14x concentration
NREL
NREL
NREL
NREL
AstroPower
(small area)
NREL
NREL
NREL
NREL
NREL
(CdTe/CIS)
Univ.
Stuttgart
(45μm thin-film
transfer)
Sharp
(large area)
University
So. Florida
Euro-CIS
United Solar
Boeing
Boeing
ARCO
AMETEK
Photon Energy
Kodak
Boeing
Matsushita
Monosolar
Kodak
Boeing
Boeing
Solarex
United Solar
EPFL
Kaneka
(2μm on glass)
EPFL
RCA
RCA
RCA
RCA
RCA
RCA
RCA
University
of Maine
NREL
Konarka
University Linz
Groningen
Siemens
University Linz
University
Linz

"Champion" cells

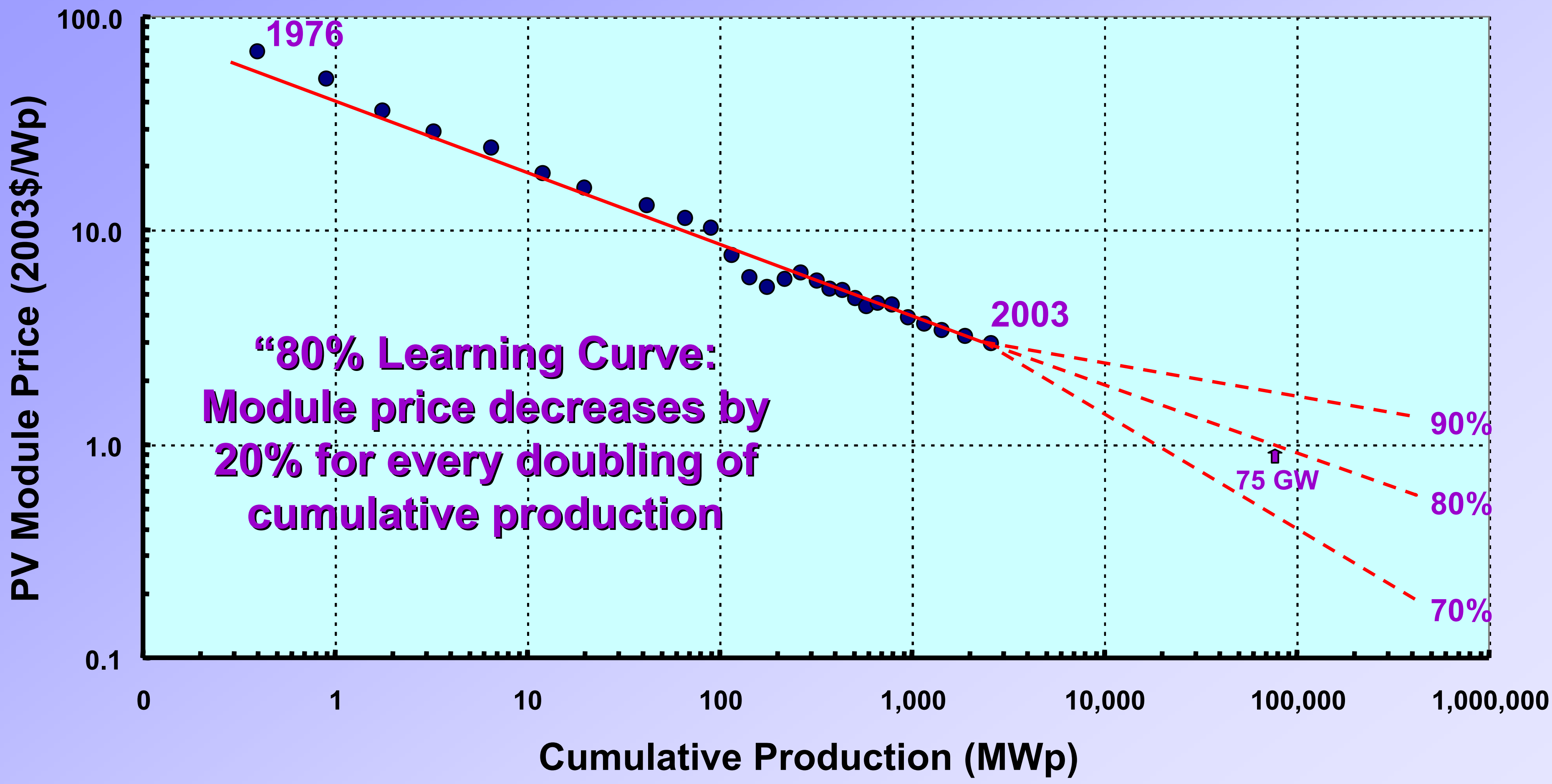
- 39% concentrator
- 25% crystalline silicon
- 19.5% thin films

Commercial modules

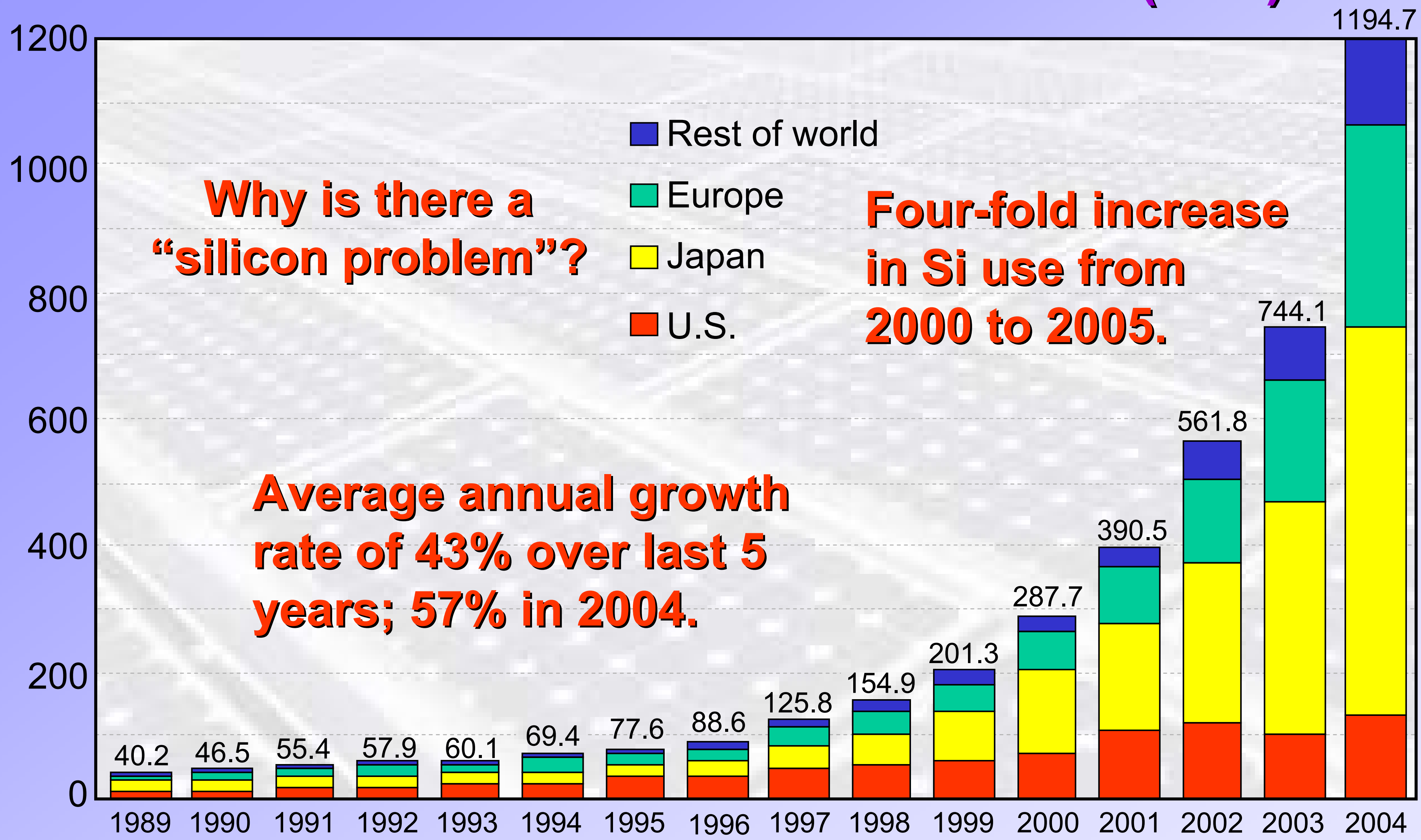
- Typically only 50-65% of these values



PV Module Production Experience (or "Learning") Curve



World PV Cell/Module Production (MW)



Source: Paul Maycock, *PV News*, February 2005

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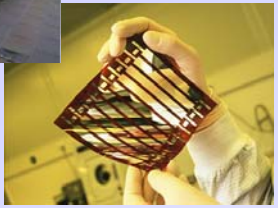
PV Technology Options

Flat plates
- Crystalline silicon
- Thin films
- New technologies



Concentrators
- Silicon
- Multijunctions (III-Vs)

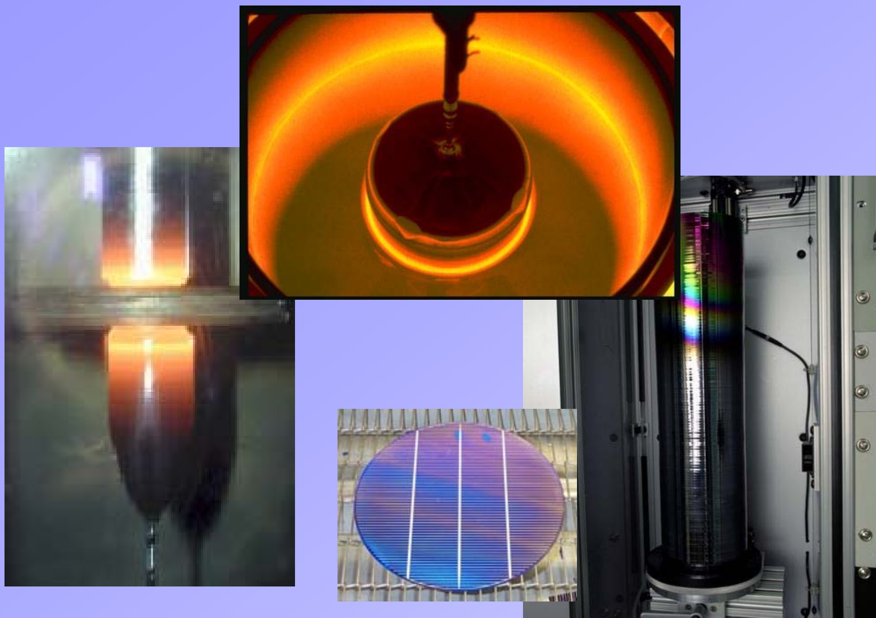
PV Module Production in 2004 by Technology Type *

Technology Type	MW	%
Flat plates – Single crystal silicon	403.5	33.8
Cast polycrystalline silicon	669.1	56.0
Ribbon silicon	41.0	3.4
Thin film amorphous silicon	64.6	5.4
Thin film cadmium telluride	13.0	1.1
Thin film CIGS	3.0	0.3
Concentrators – Silicon	0.5	<0.05
TOTALS	**1194.7**	**100**

>93% (single crystal, cast polycrystalline and ribbon silicon)

* Source: *PV News*, March 2005

Crystalline Silicon – Ingots

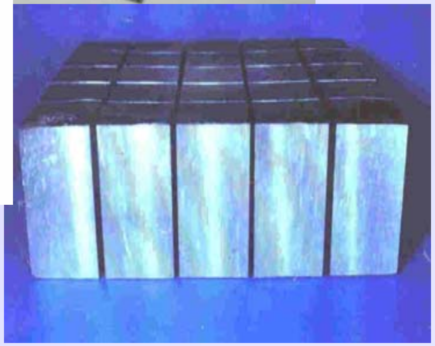


- Crystal growth developments: larger ingots (to 60 kg CZ, 20 cm diameter), reduced consumables costs (energy, crucibles, ambient gases, hot zones), batch melt recharge for multiple ingots
- PV-specific growth of CZ; starting low-cost FZ
- Highest efficiencies for single crystals: FZ > CZ

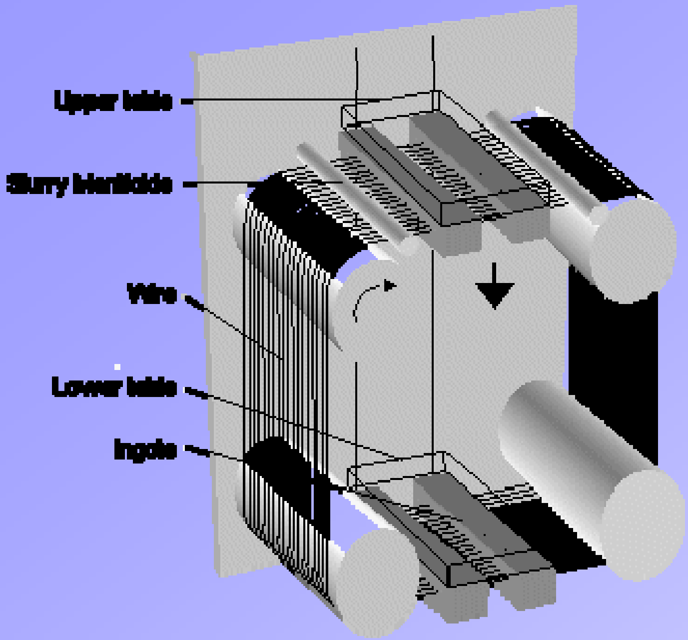
  24.7% laboratory cell (FZ)
  16-22% production cells
  13-17% commercial modules
  25-year warranties

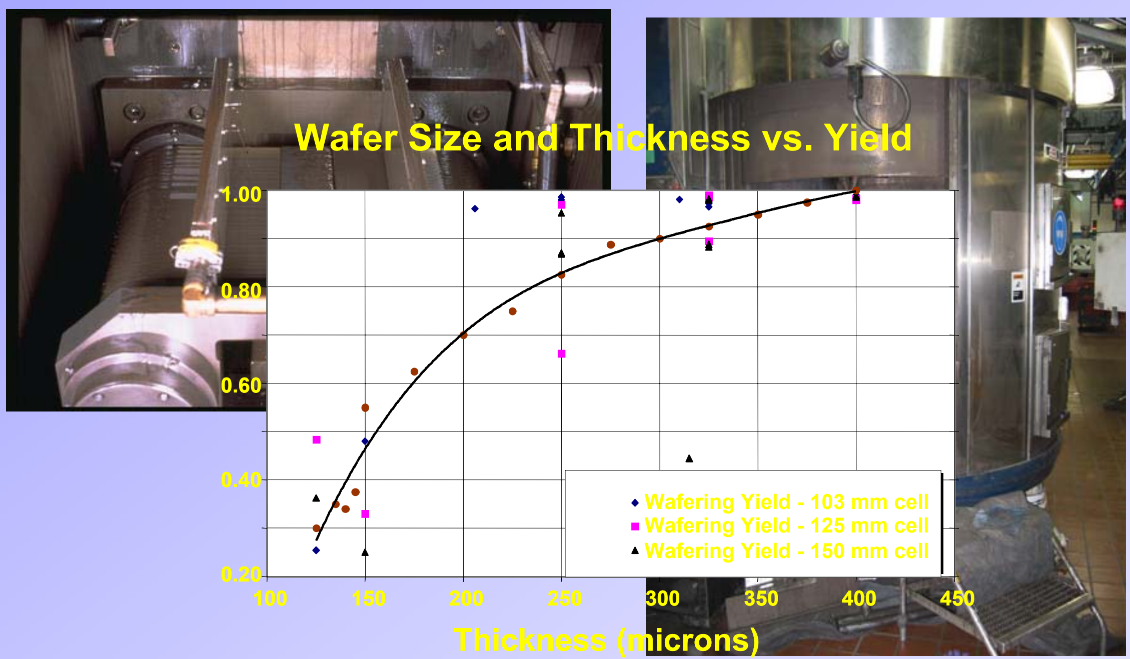
- Cast multicrystalline ingots are fastest growing segment of PV industry:
  - Commercial systems available
  - Up to 300 kg ingots
- Extensive development of thermal profiles, impurity distributions, crucibles, automation
- Efficiencies ~10% lower than single crystals
- Opportunities for new crystal growth developments: low-cost FZ and CZ for PV; larger cast ingots; control grain sizes, defects, and impurities

GT-DSS240 FURNACE

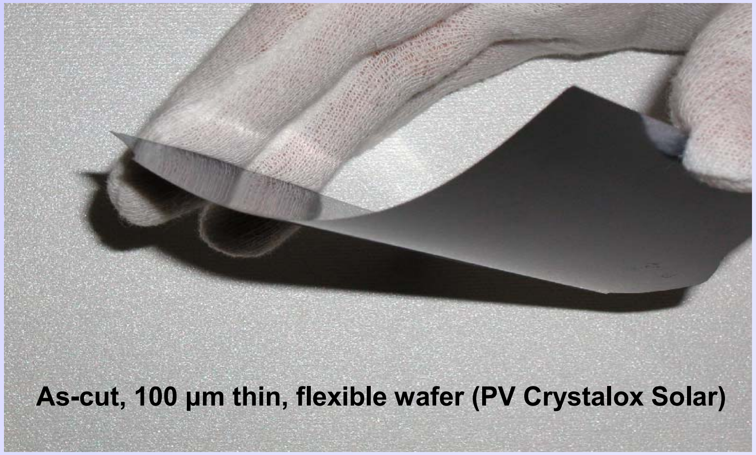


Crystalline Silicon – Wafering





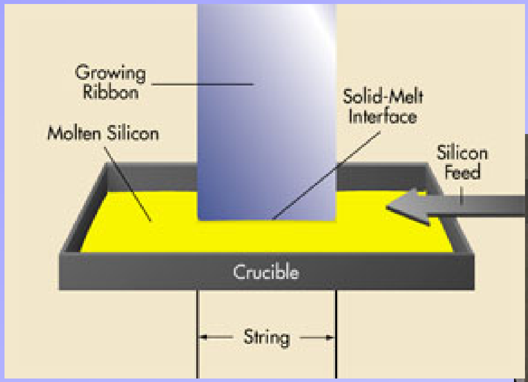
- Advent of wire-saw is a significant result of terrestrial PV research:
  - Faster than ID saw (1000 vs. 25 wafers/hour)
  - Less surface damage
  - 250-300 µm thickness, 200 µm kerf routine
- Ongoing advances needed:
  - Thinner, stronger wires
  - Slurry recycling, water-based slurries
  - Thin wafer handling in processing
  - Detecting microcracks in wafers



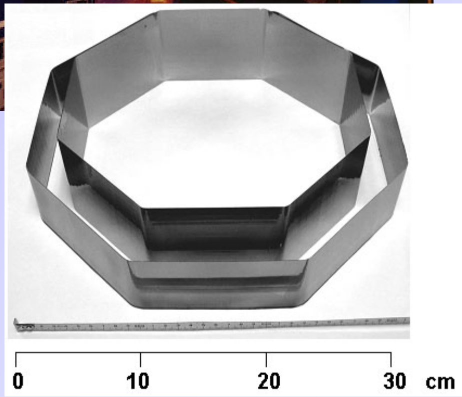
As-cut, 100 µm thin, flexible wafer (PV Crystalox Solar)

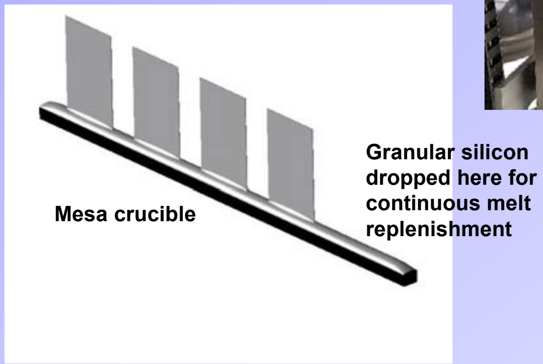
Crystalline Silicon – Ribbons

- First of new, terrestrial PV technologies to be commercialized
- More than 20 innovative ribbon/ sheet growth approaches researched
- Two leading techniques in production:
  - Edge-defined film-fed growth (EFG)
  - String Ribbon



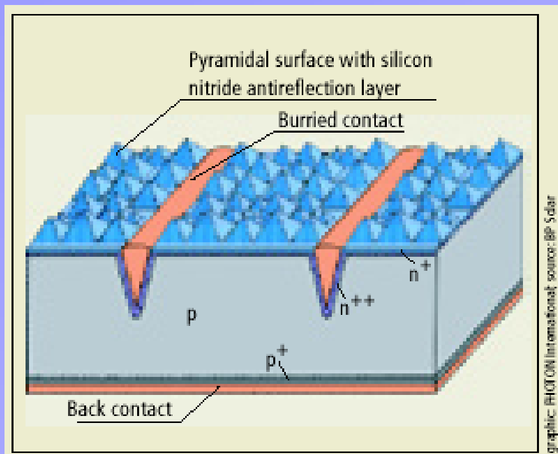
Efficiencies are similar to multicrystalline Si





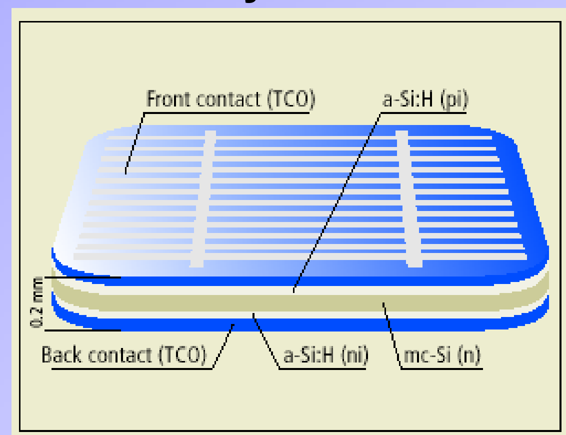
- Research issues:
  - Yield and throughput (growth rate, ribbon width)
  - Thin ribbons (~100 μm)
  - Thermal stress control
  - Melt replenishment
  - Continuous growth
  - Defects and impurities

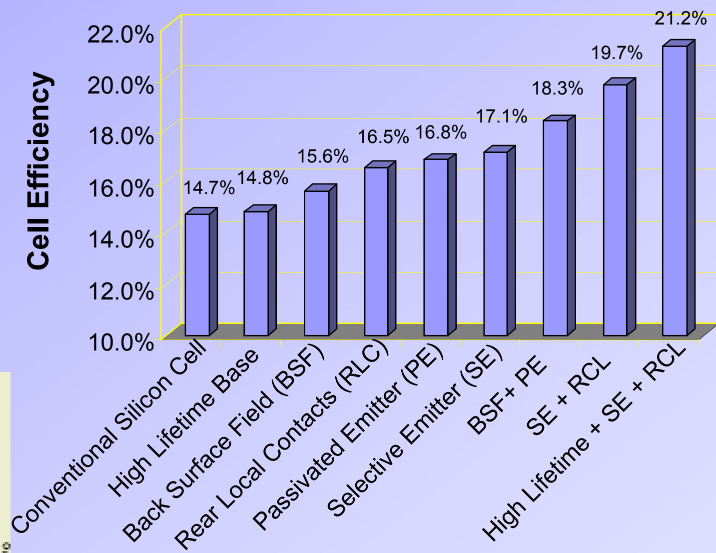
High-Efficiency Silicon Solar Cells



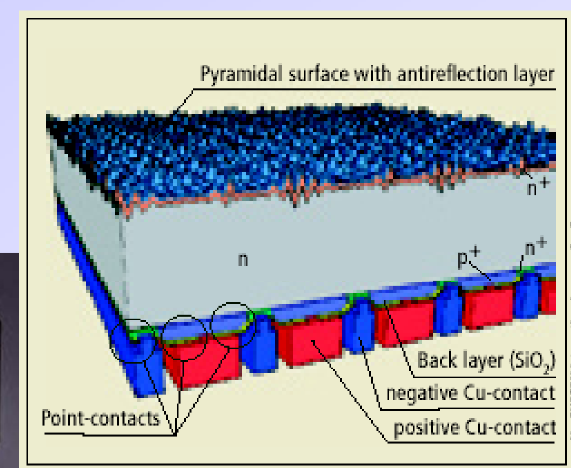
Buried-contact cell/UNSW BP Solar – 18.3%

HIT cell Sanyo – 21%

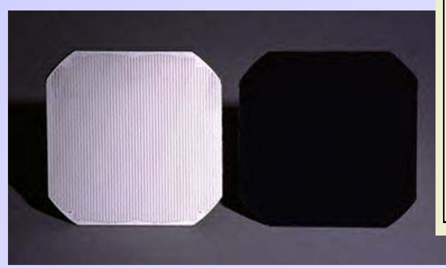




Point-contact cell SunPower – 21.5%

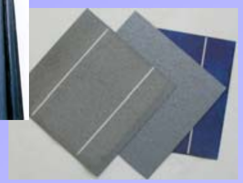


- Processing/lifetime relations
- Gettering/passivation of impurities/defects (Si_3N_x:H deposition for polycrystalline Si)
- Feedback to crystal growth
- High-throughput, low-cost (e.g., rapid thermal) processing
- **Selecting “cheapest” wafer or “cheapest” process will not always result in lowest-cost module**

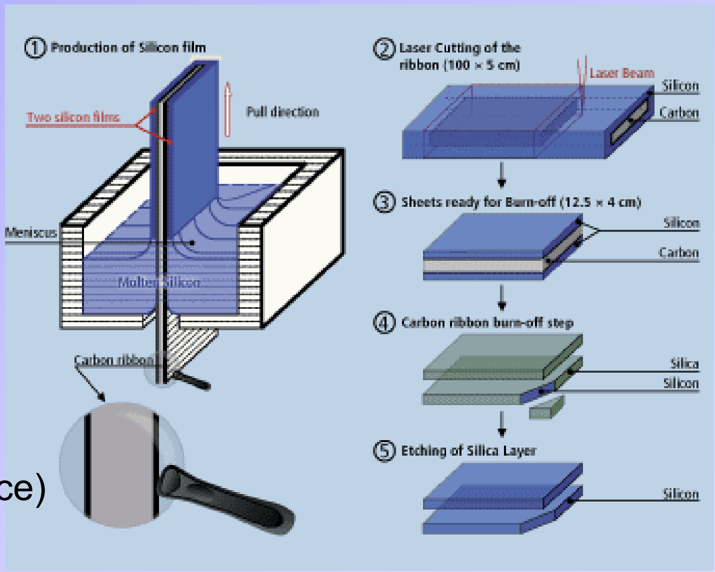


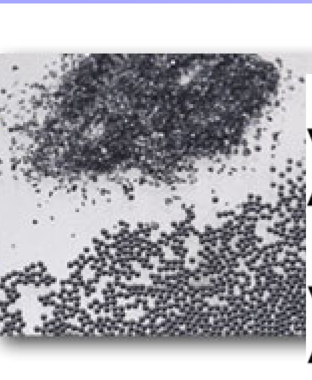
Crystalline Silicon – Sheets, etc.

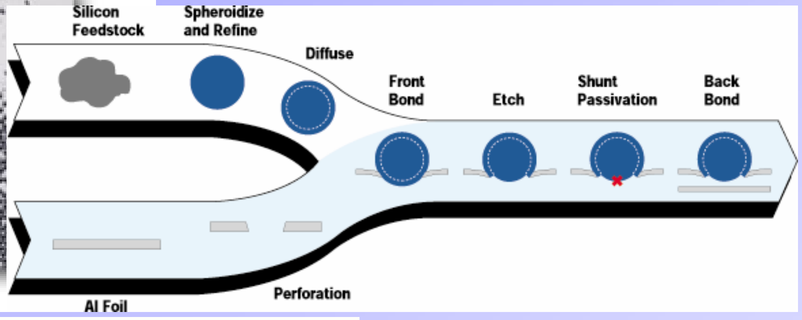
- Silicon Film™ process (AstroPower, now GE, U.S.)
  - Melt/solidify granular Si on reusable substrate
  - High throughput (3 m/min)
  - Small grain size (~ thickness)
  - Low module efficiency (<8%)

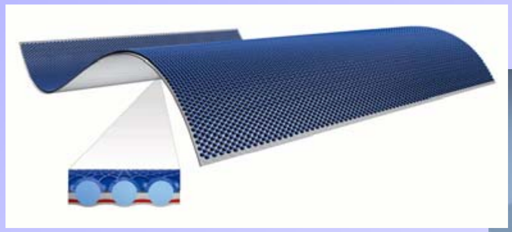


- RST technique (Solarforce, France)







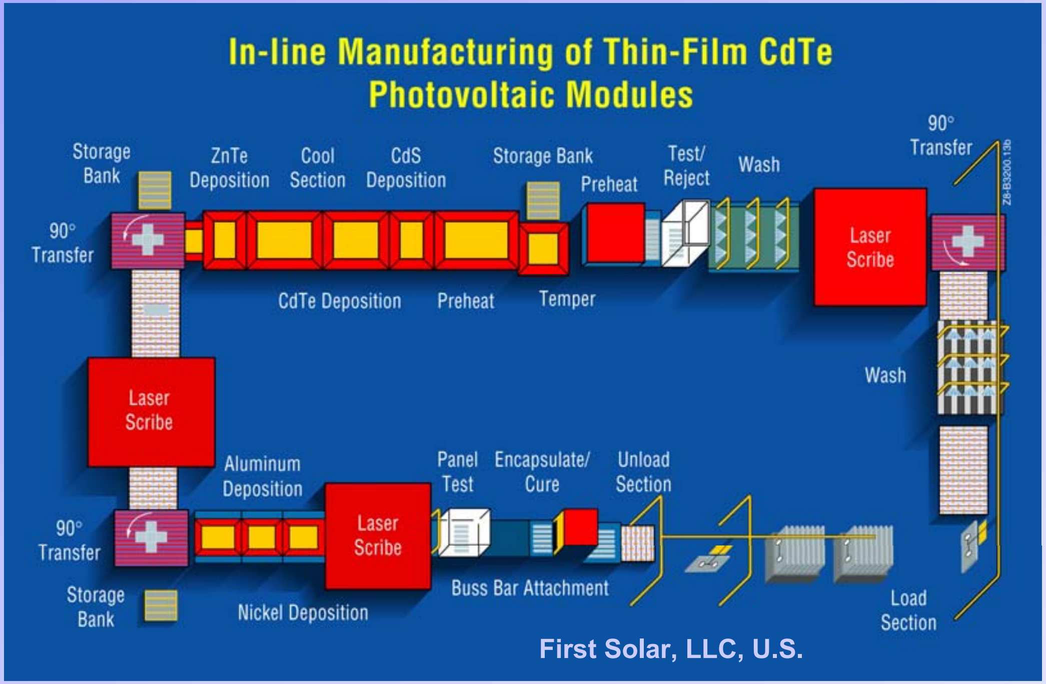


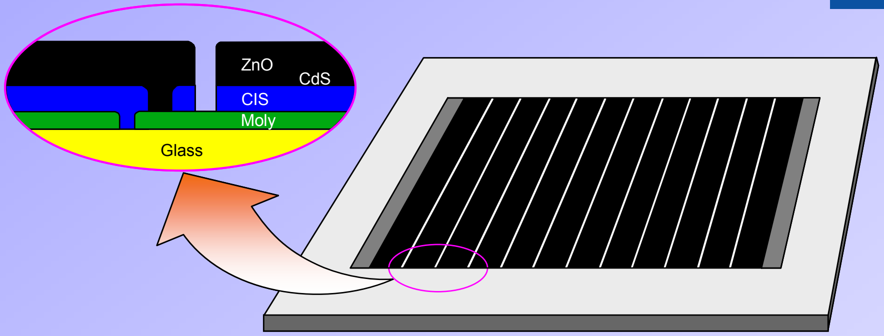
- Spheral Solar™ Power (Canada)
  - High Si utilization

- Sliver® cells (Origin Energy, Australia)
  - High utilization of single-crystal Si wafer

Thin-Film PV Technologies

- Low materials use (~1 µm vs. ~300 µm for Si) – direct bandgap absorbers
- Low-cost substrates (glass, stainless steel, plastics)
- High-throughput deposition processes (batch or continuous)
- Lower processing temperatures (less energy use); some non-vacuum
- Fewer processing steps for modules; integral interconnection of cells during film deposition

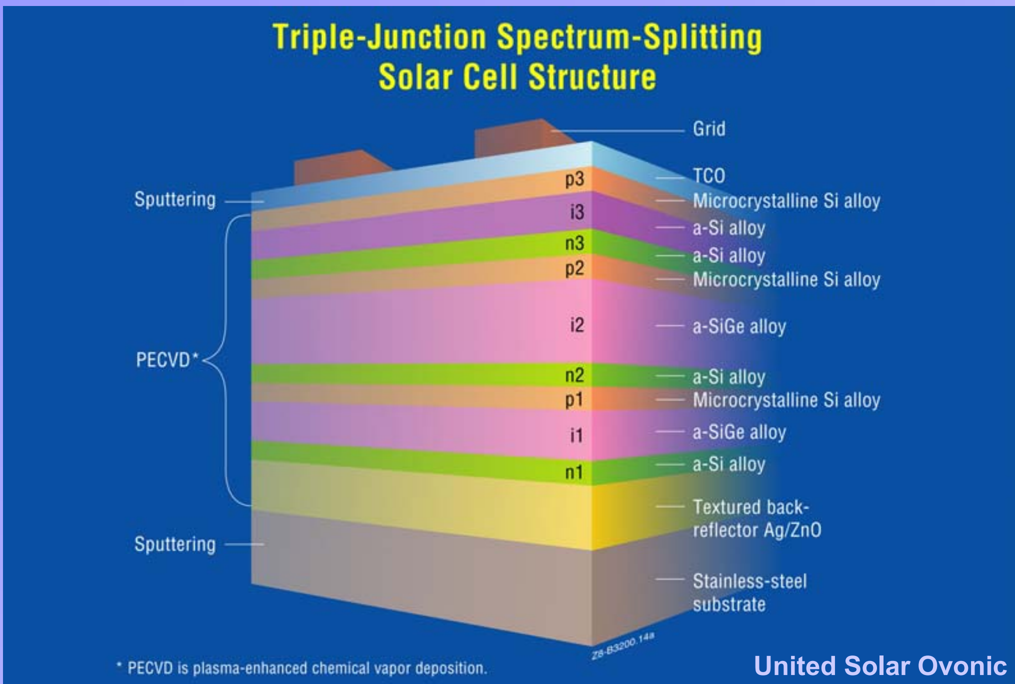




- Choice of materials dictated by efficiency, materials availability, ease of manufacturing, module reliability, market acceptance

- Leading technologies:
  - Amorphous silicon (a-Si:H)
  - Cadmium telluride
  - Copper indium gallium diselenide (CIGS)
- Future technologies:
  - Thin (polycrystalline) silicon
  - Polycrystalline multijunctions

Thin-Film Amorphous Silicon

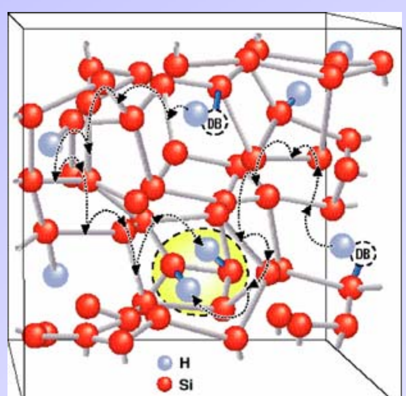


- Multi-MW/year in consumer products
- Substrate choices for unique products; lightweight (flexible), building-integrated (roofing tiles, semi-transparent windows)
- Engineered solution for “light-induced degradation”; thin absorber layers and multijunctions

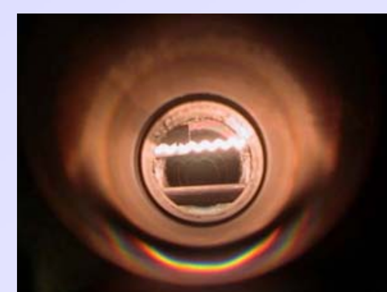
Stabilized efficiencies:
13% laboratory cell
10% best prototype module
5-8% commercial modules
Up to 20-year warranties

- Largest thin-film manufacturing facility: 30 MW/year (United Solar Ovonic, U.S.)

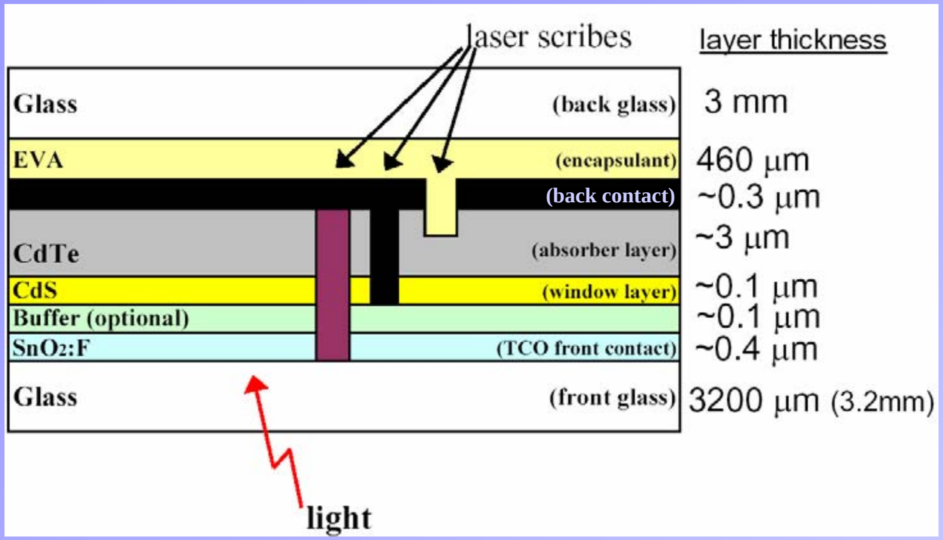
- Large research infrastructure leveraged by other applications
- Fundamental understanding of
  - Metastability
  - Roles of hydrogen and impurities
  - Microstructure (amorphous to microcrystalline)
  - Gas phase chemistry and control
  - Low-bandgap materials



- High-rate deposition (10-100 Å/s vs. 1-3 Å/s)
  - Hot-wire CVD
  - VHF plasma
  - Microwave plasma



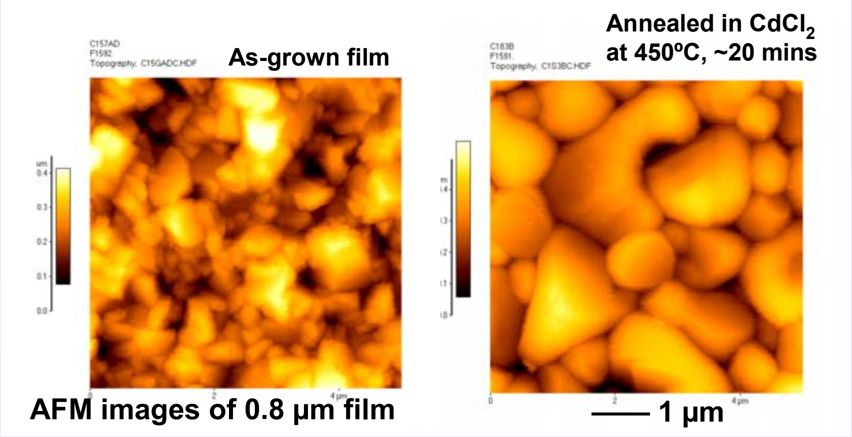
Thin-Film Cadmium Telluride



- Many scalable deposition approaches for >10% efficiency (high-rate vapor transport, electrodeposition, spraying, close-spaced sublimation, CVD, sputtering, etc.)
- Early consumer products (~1 MW/year)
- Large-scale manufacturing underway:
  - CdS/CdTe deposited in <1 min
  - Module start-to-finish in ~4 hrs
  - Up to 25 MW/year (First Solar, LLC, U.S.)

16.5% laboratory cell
11% best prototype module
7-9% commercial modules
10-20 year warranties

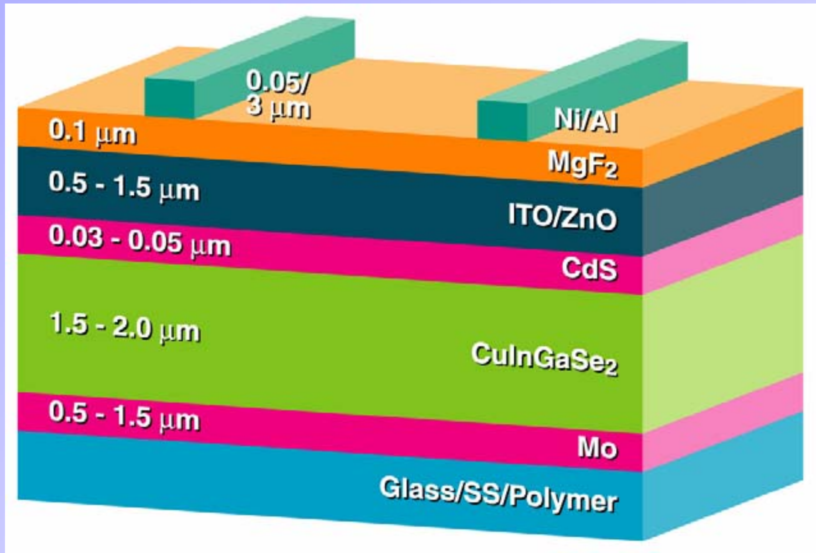
- Better understanding of film growth is key
  - Thin CdS and alternate buffer/window layers
  - CdTe nucleation and growth; thinner layer
  - Native defects and doping
  - CdS/CdTe interdiffusion
  - Annealing and heat treatment ($CdCl_2$)
  - Back contacts; role of Cu diffusion
- Compatibility of manufacturing process steps; simplified manufacturing processes
- EH&S issues extensively studied and under control (e.g., recycling) – Cd perception issue?

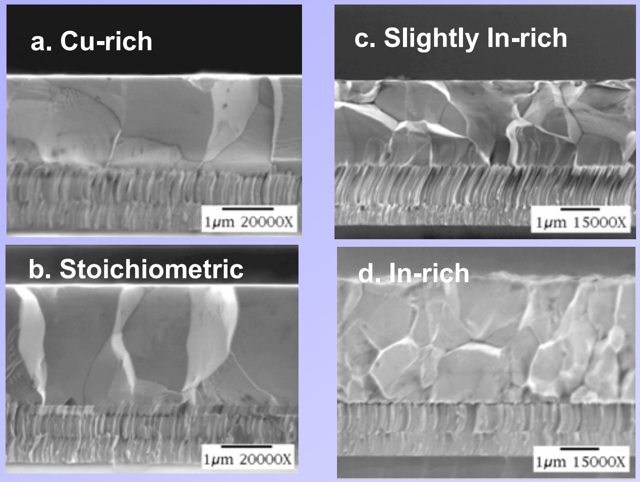


Thin-Film CIGS

- Varied deposition approaches: co-evaporation of elements, sputtering/selenization, non-vacuum/wet chemical, electrodeposition
- Glass or flexible substrates (stainless steel, polyimide) for varied products
- Manufacturing of several MW underway, with increasing interest worldwide

19.5% laboratory cell
18.6% with ZnS (“Cd-free” cell)
13% best prototype module
9-11% commercial modules
>10-year warranties





SEM images of stages of film growth (a → d)

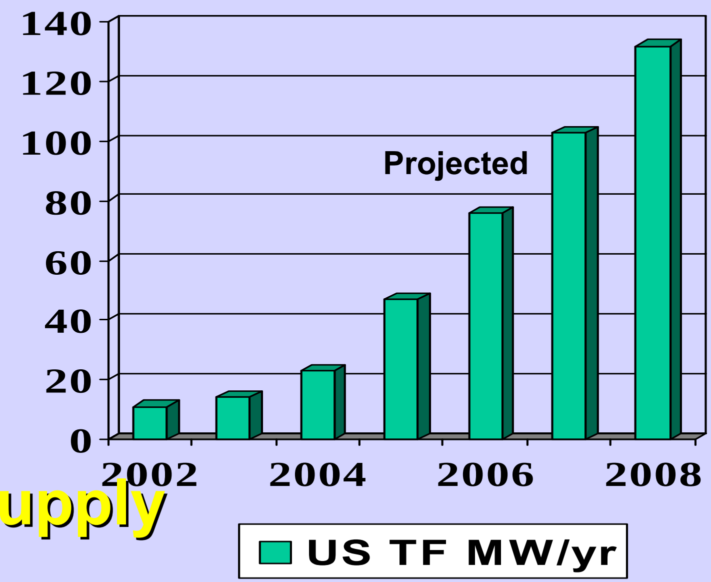
- Understanding of film growth, microstructures, defects, and device physics – complex but “tolerant” to processes
- Recipe for high-efficiency devices: Cu-rich step (large grains) followed by In-rich step (for target composition)
- Role of Na (necessary); higher bandgap alloys (Ga, S)
- Alternate, Cd-free window/buffer layers
- Process controls in manufacturing for uniform composition and thinner films (<1 µm); higher throughput and yield

Thin-Film PV Manufacturing and Applications

Thin-Film PV Manufacturing and Applications

Major challenges for technologies:

- Module reliability for >20 years outdoors
  - Accelerated life testing
  - Hot and humid climates testing
  - Advanced packaging materials



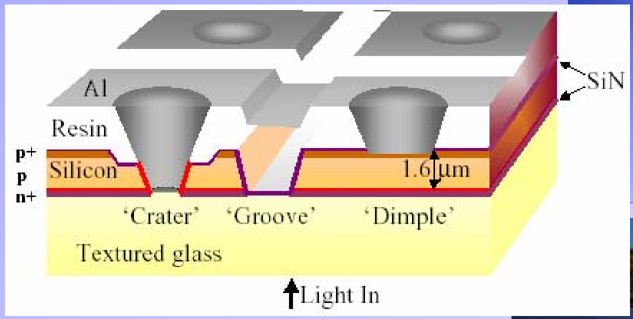
- Market acceptance of products
  - Niche, high-value applications
  - Power modules with demand > supply

- Competition from crystalline silicon
  - Can thin films stay ahead of ongoing improvements in c-Si?
  - Financial commitment of investors

New Thin-Film PV Research Directions

Thin Crystalline Silicon

- Microcrystalline Si bottom cells for a-Si:H multijunctions – in production
- Thin polycrystalline silicon (<10 μm) on low-cost substrates
  - Light-trapping designs
  - Many novel approaches (e.g., “lift-off” from re-usable wafers, recrystallizing amorphous or small-grained films, etc.)



Crystalline Silicon on Glass (CSG)

CSG Solar (Germany, Australia)

Transparent Conductors

n-type	p-type
ITO*	$CuAlO_2$
SnO_2: F, Cl, Sb*	$CuInO_2$
ZnO: Al, B, Ga, In*	Cu_2SrO_2
CdO: F	ZnO: N, Ga
Cd_2SnO_4	
In_2O_3	
In_2O_3: Mo	
Zn_2SnO_4	

* Commercial Products

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Key components for all thin-film technologies – opportunities for crystal growth research

Heterojunction Partners “Buffer Layers”

Material	Process	Material	Process
• Ga_2S_3	PVD	• SrF_2	PVD
• Ga_2Se_3	PVD	• $ZnIn_xSe_y$	PVD
• $(InGa)_2Se_3$	PVD	• Zn_xMg_yO	Sputter
• $In(HO)_3$	CBD	• ZnO	ALD, MOCVD
• In_xSe_y	PVD	• $Zn(O,S,OH)_x$	CBD
• In_2Se_3	ALCVD	• ZnS	CBD, PVD
• SnO_2	CBD	• ZnSe	Sputter
• $Sn(S,O)_2$	CBD	• ZrO_2	CBD

ALD - atomic layer deposition; **CBD** - chemical bath deposition; **PVD** - physical vapor deposition

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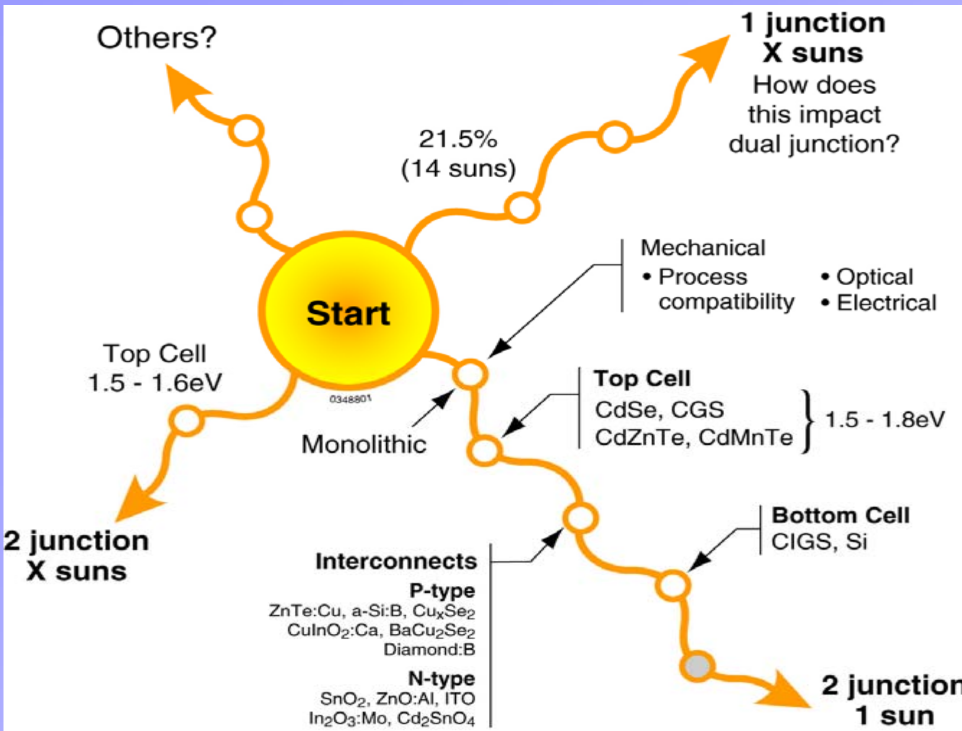
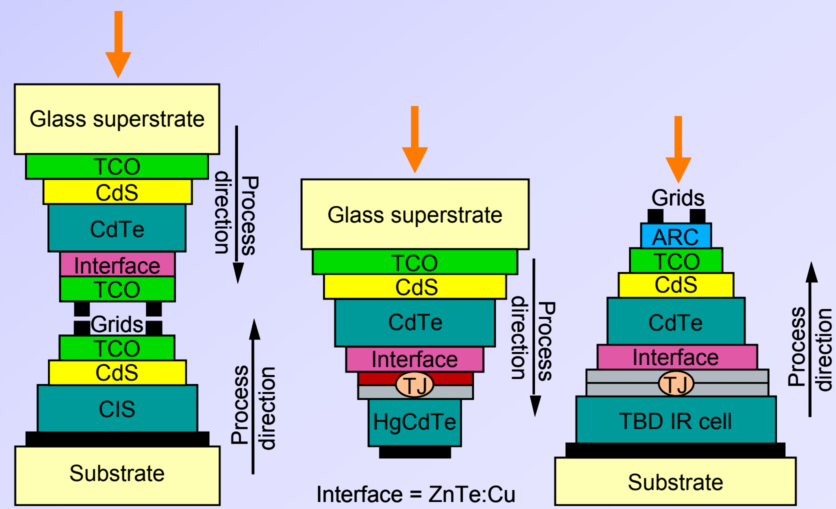
Polycrystalline Thin-Film Multijunctions



- Success of CIGS and CdTe is motivating new research toward higher efficiencies in thin films:
  - >25% solar cells
  - >20% modules
- Potential to improve flat-plate silicon efficiency with appropriate top cell or develop *top cell/thin Si* tandem
- Key research questions: efficient top cell (>15%) with bandgap of 1.5-1.8 eV; tunnel-junction interconnects; compatibility of film growth processes; monolithic versus mechanical-stack designs

- Early results validate some of the concepts:
  12.7% CdTe top cell (>50% transmission)
  9.7% mechanically-stacked CGS/CIS
  5.1% CGS/thin polycrystalline Si tandem
  All-sputtered CdTe/HgCdTe tandem (1.3%)
  21.5% CIGS cell under concentration (14 suns)
- Significant research needed to accomplish goals

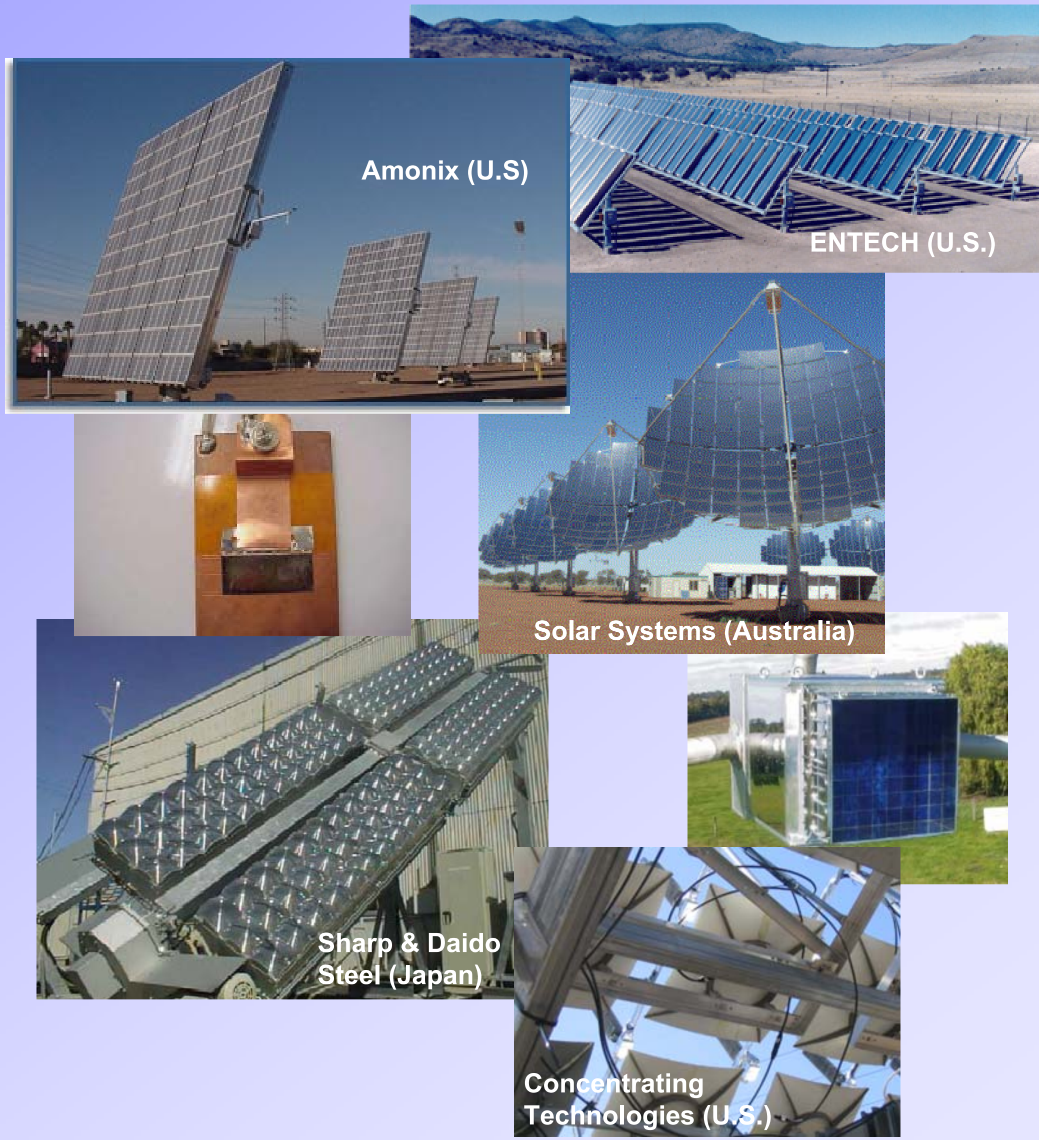


Concentrator PV Technologies

- Manufacturability demonstrated for all system components:
  - Low-concentration, line focus
  - High-concentration, point focus
  - Refractive and reflective optics
  - Secondary optics; passive/active cooling
  - Tracking and supports; installation
  - High-efficiency cells (Si, III-Vs) are in production – best cell efficiencies:

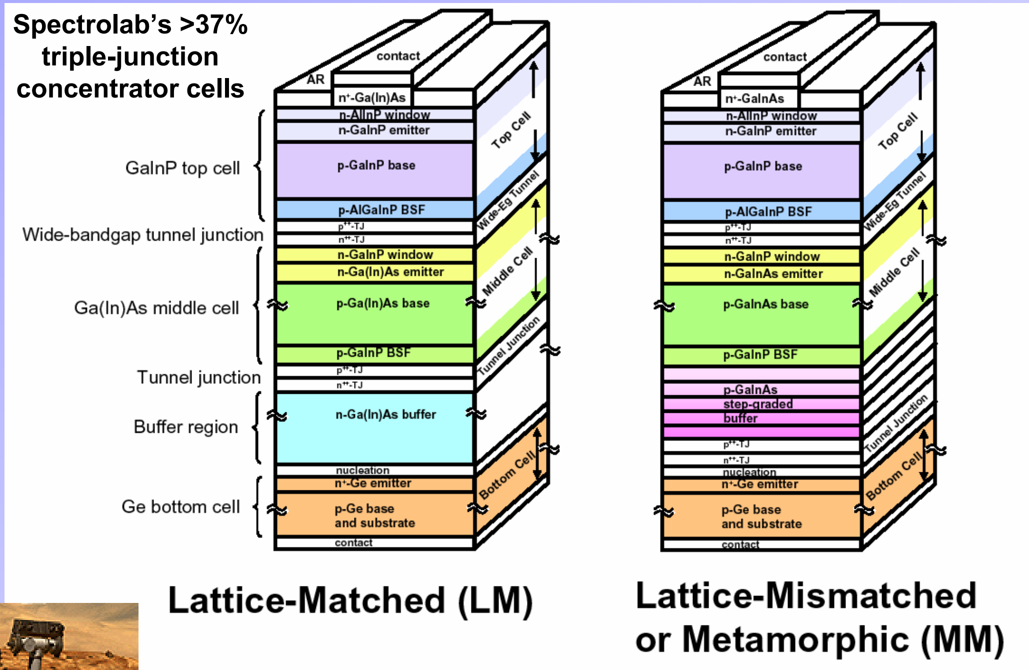
    27% Si (up to 400X)
    28% GaAs (up to 1000X)
    39% $GaInP_2$/Ga(In)As/Ge triple-junction (up to 600X)
    37.9% $GaInP_2$/GaAs/GaInAs at 10X

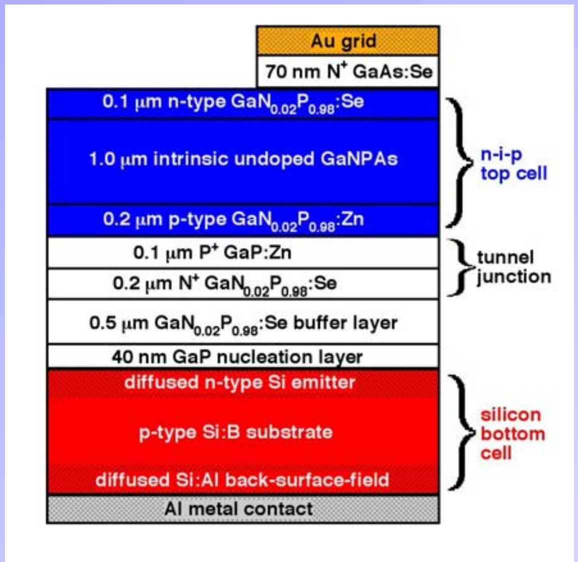
- Commercial modules: ~17% (Si)
- Best prototype modules: >20% (Si), >24% (GaAs), 28% ($GaInP_2$/GaInAs/Ge), >20% (Si dense-array)
- Predictable, low costs for large-scale manufacturing and deployment
  - Applications are limited to areas of high direct (not diffuse or global) solar radiation
  - Many of today's distributed PV markets are not suitable for concentrators (>25 kW units)



High-Efficiency Concentrator Cells

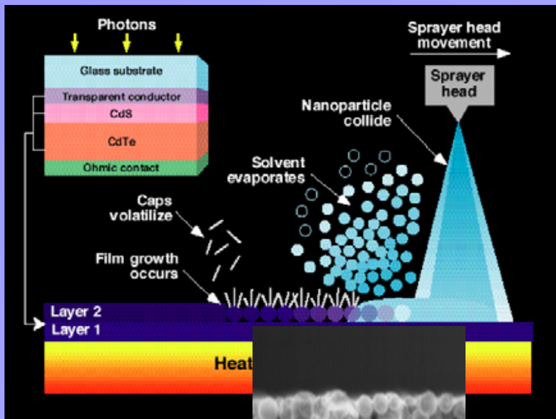
- Multijunction devices offer better utilization of solar spectrum
  - Highest efficiencies in III-V materials
  - Opportunity to tailor bandgaps
  - Lattice-matched or mismatched growth
  - Complex crystal growth challenges – alloying, doping, control of defects and impurities, compatibility and stability of successive layers, passivating layers and tunnel junctions
  - Commercial growth systems (MOCVD) produce cells for space markets
  - Early terrestrial tests promising

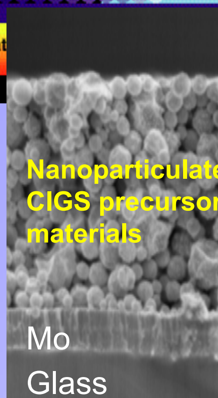




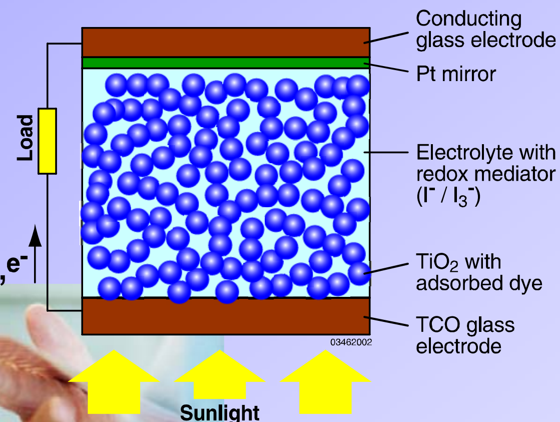
- Adding 1-eV cell in above structure should result in >40% efficiency (GaInAsN?)
- 5-junction and 6-junction cells are being investigated – easier to match lower currents but get higher voltages (mostly for space)
- Potential to improve silicon cell efficiency with appropriate top cell – recent results on lattice-matched GaNPAs-on-Si (with GaP tunnel junction) look promising

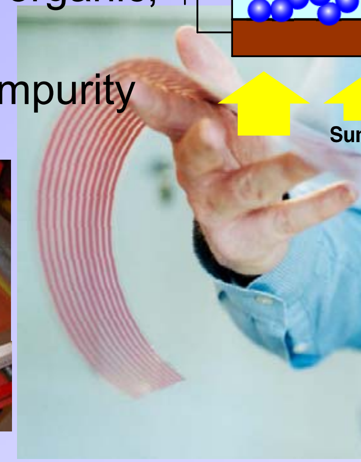
Future Generation PV Technologies

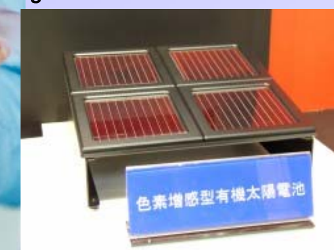


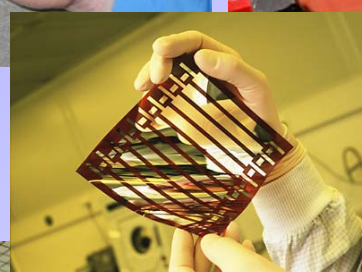


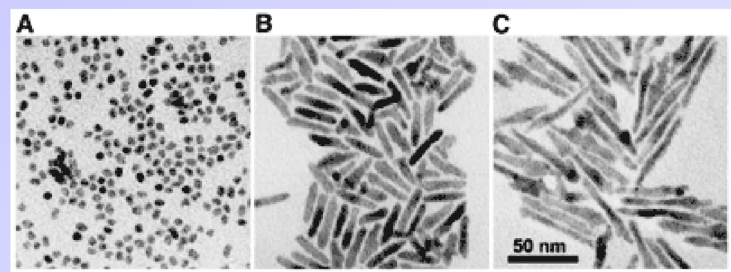
- Opportunities for innovation – ultra low cost, ultra high efficiencies, new materials, new device physics
  - Nanoparticle precursors
  - Exciton cells (dye, polymer, organic, small molecules, etc.)
  - Quantum dots, hot-carrier, impurity band cells

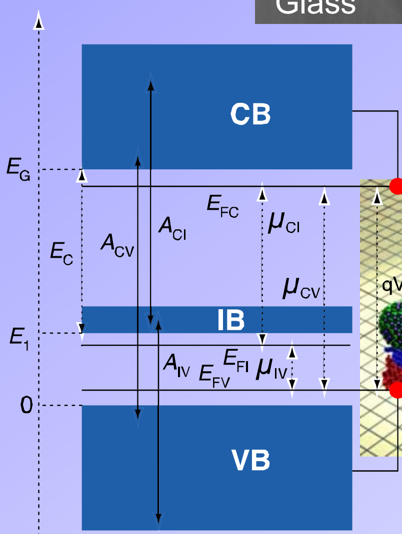


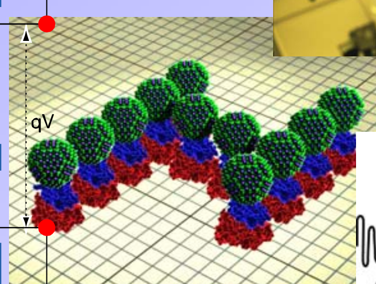


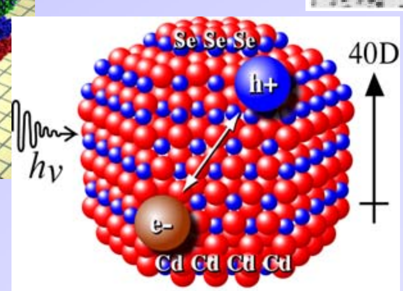


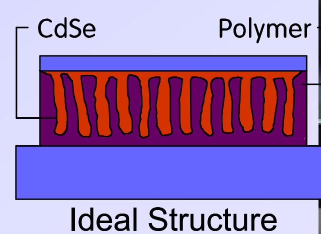


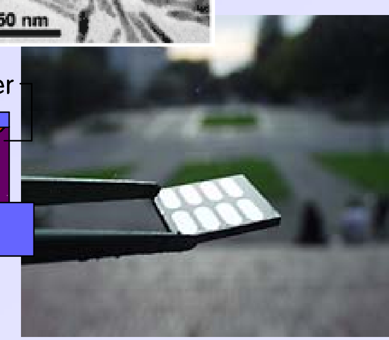




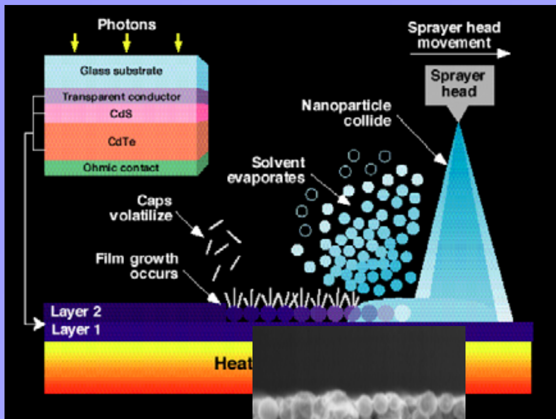








Future Generation PV Technologies



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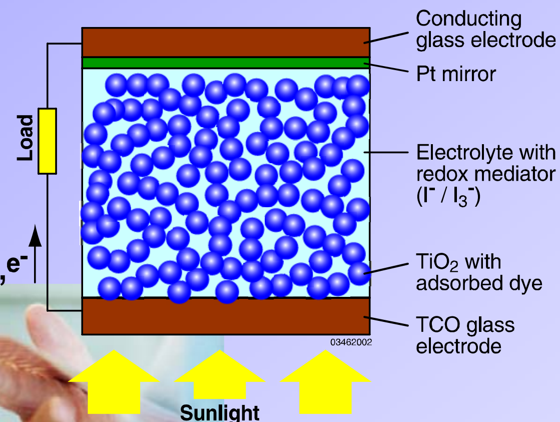
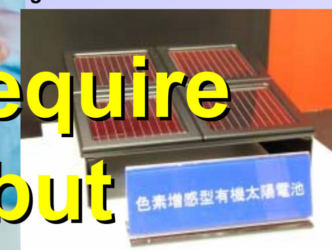
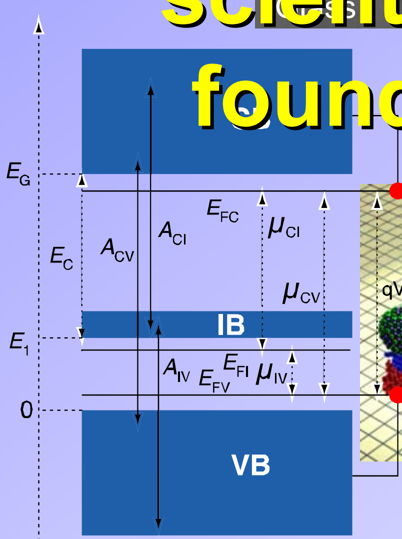
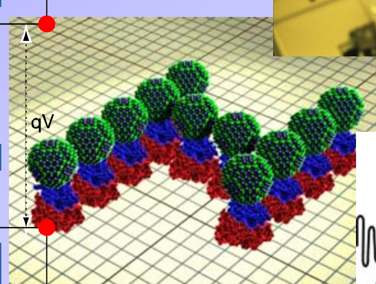
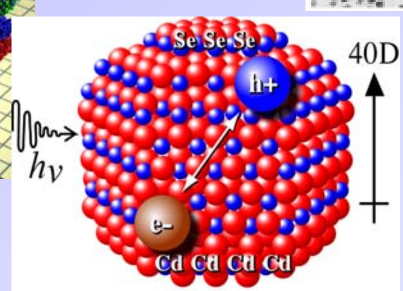


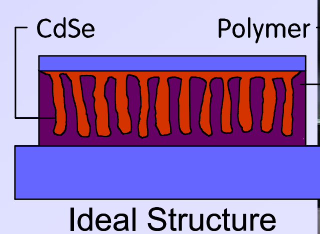


The "success" of PV does not require these ultimate discoveries – but scientific research and discovery are the foundations for technological progress







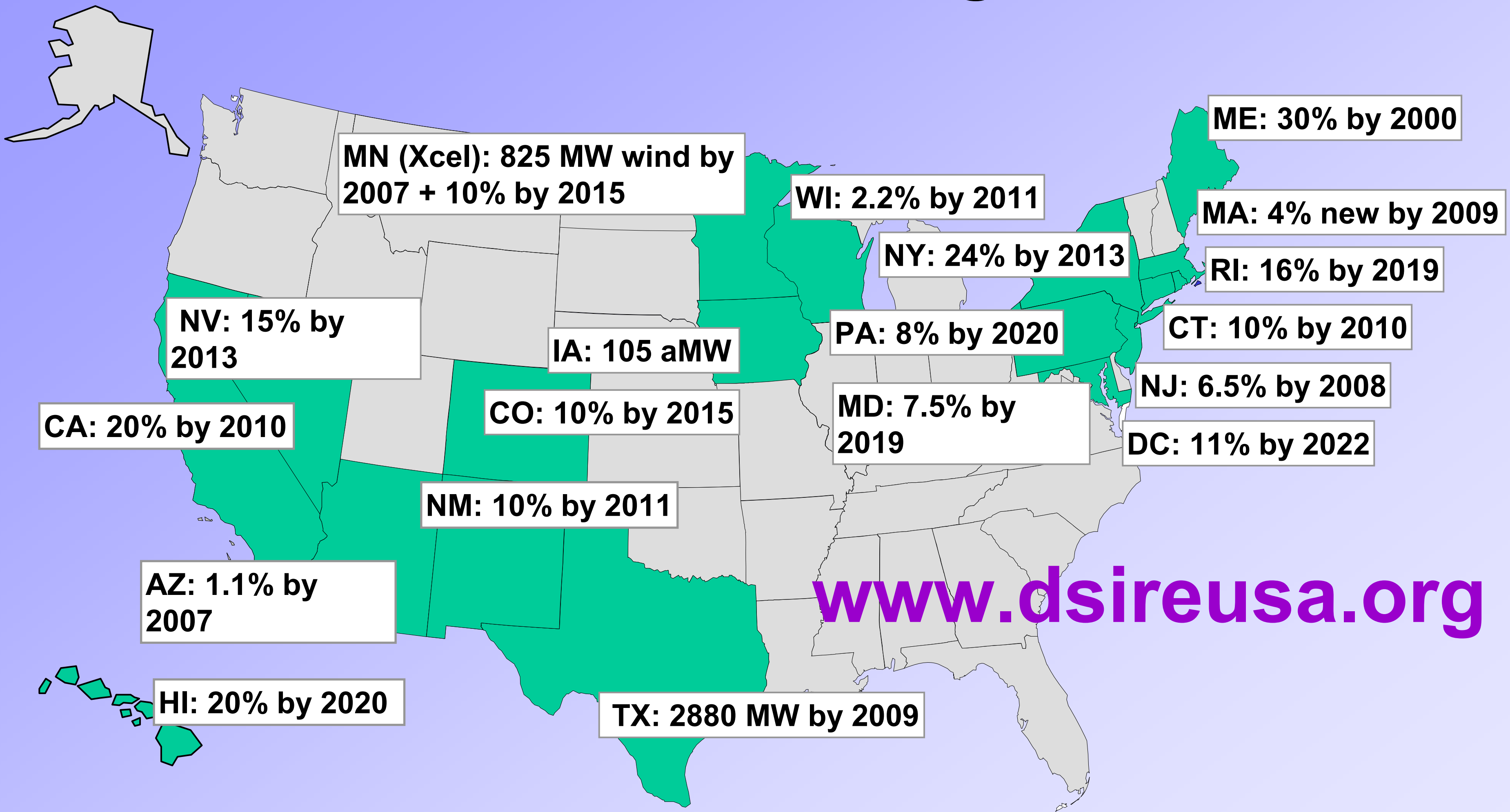


What is the future for PV?

- Market needs
- Technology projections
  - Crystalline silicon
  - Thin films/Concentrators
  - New technologies
- Solar future

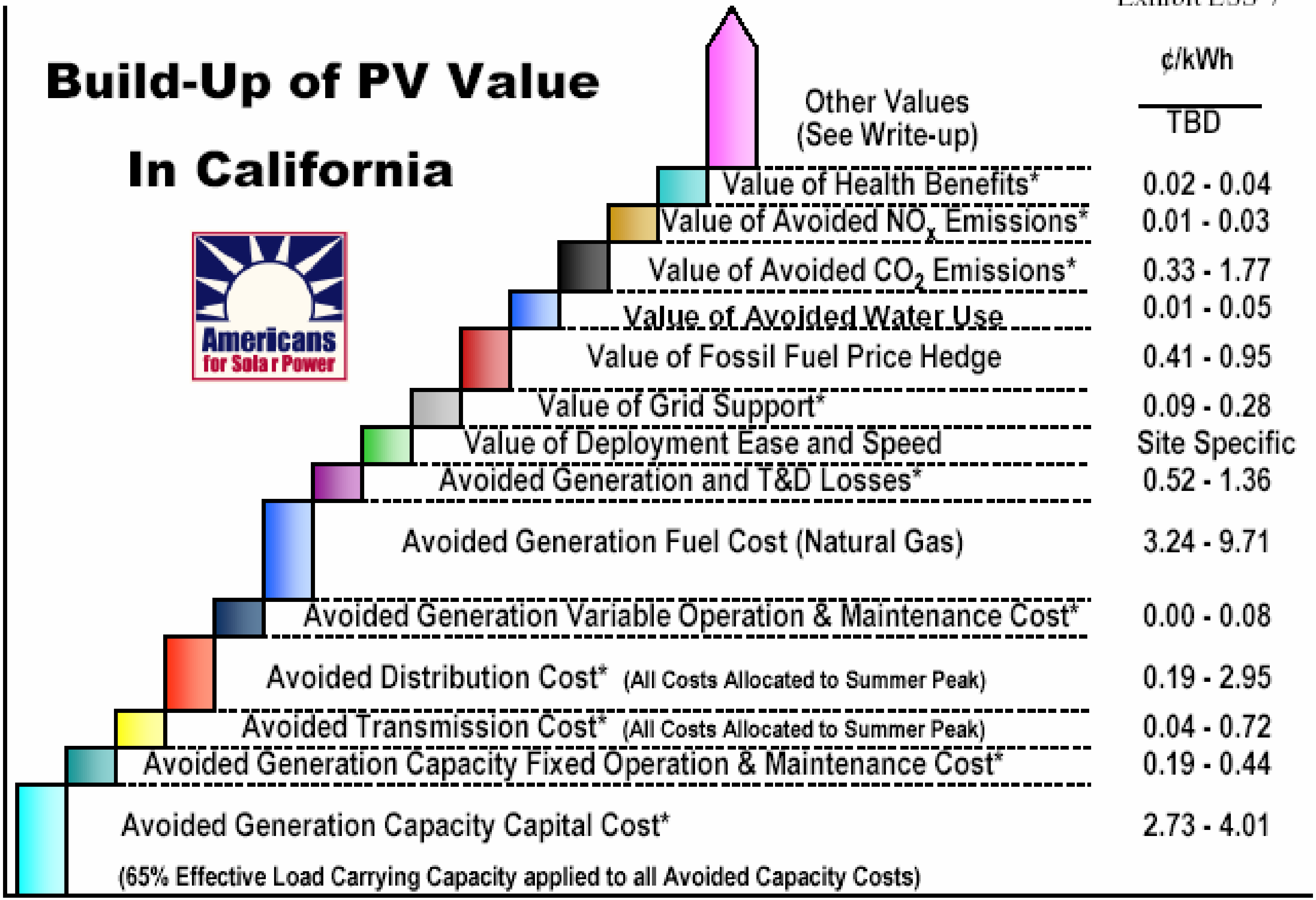
- **Market incentive programs – and government policies – are key to continued progress:**
  - **- Feed-in tariff (Germany, Spain, etc.)**
  - **- Subsidies – now only 15% (Japan)**
  - **- Portfolio standards/buydowns/tax credits (U.S.)**

Existing State RPS Requirements: 18 States and Washington, D.C.



www.dsireusa.org

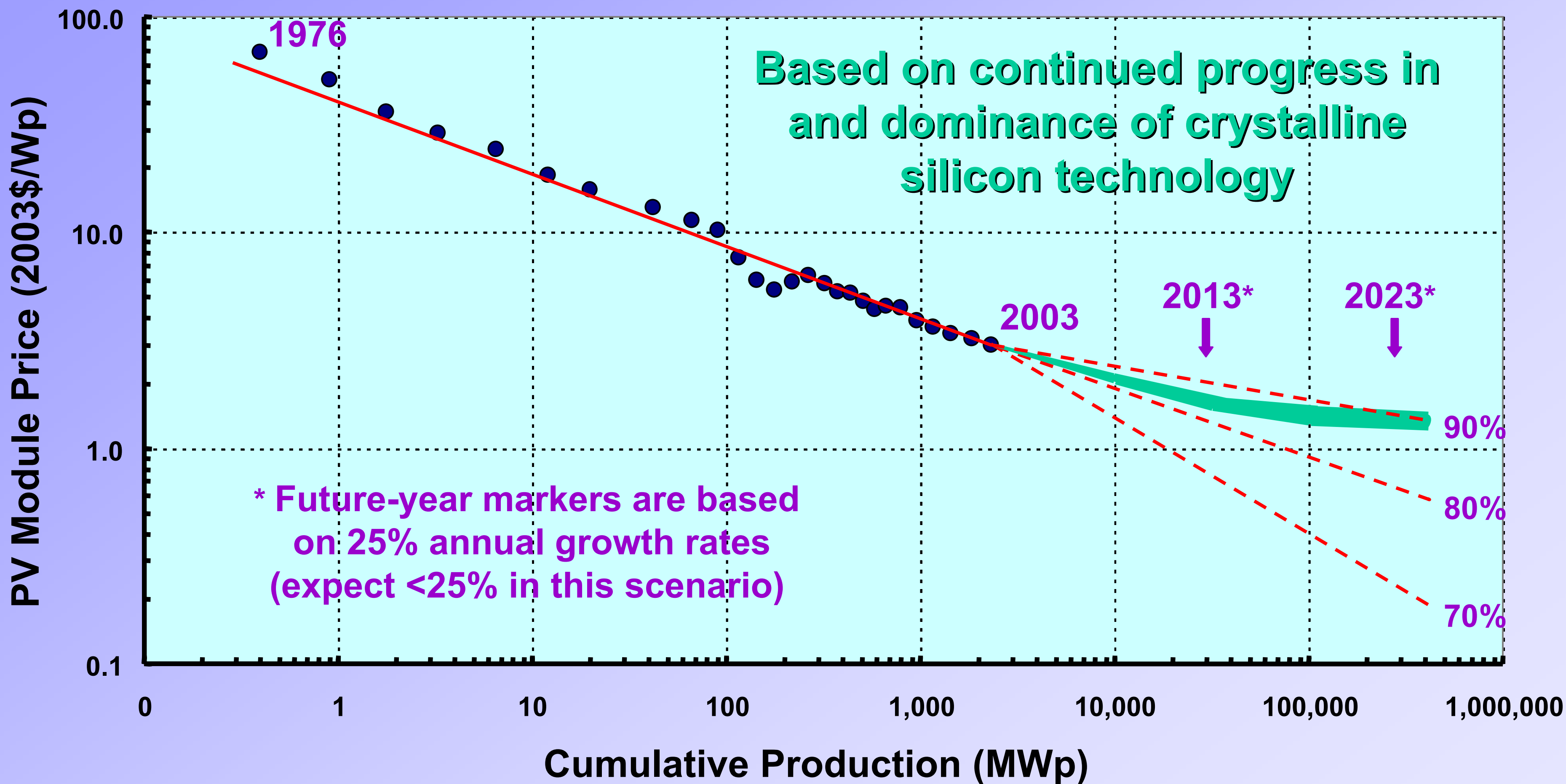
Exhibit LSS-7



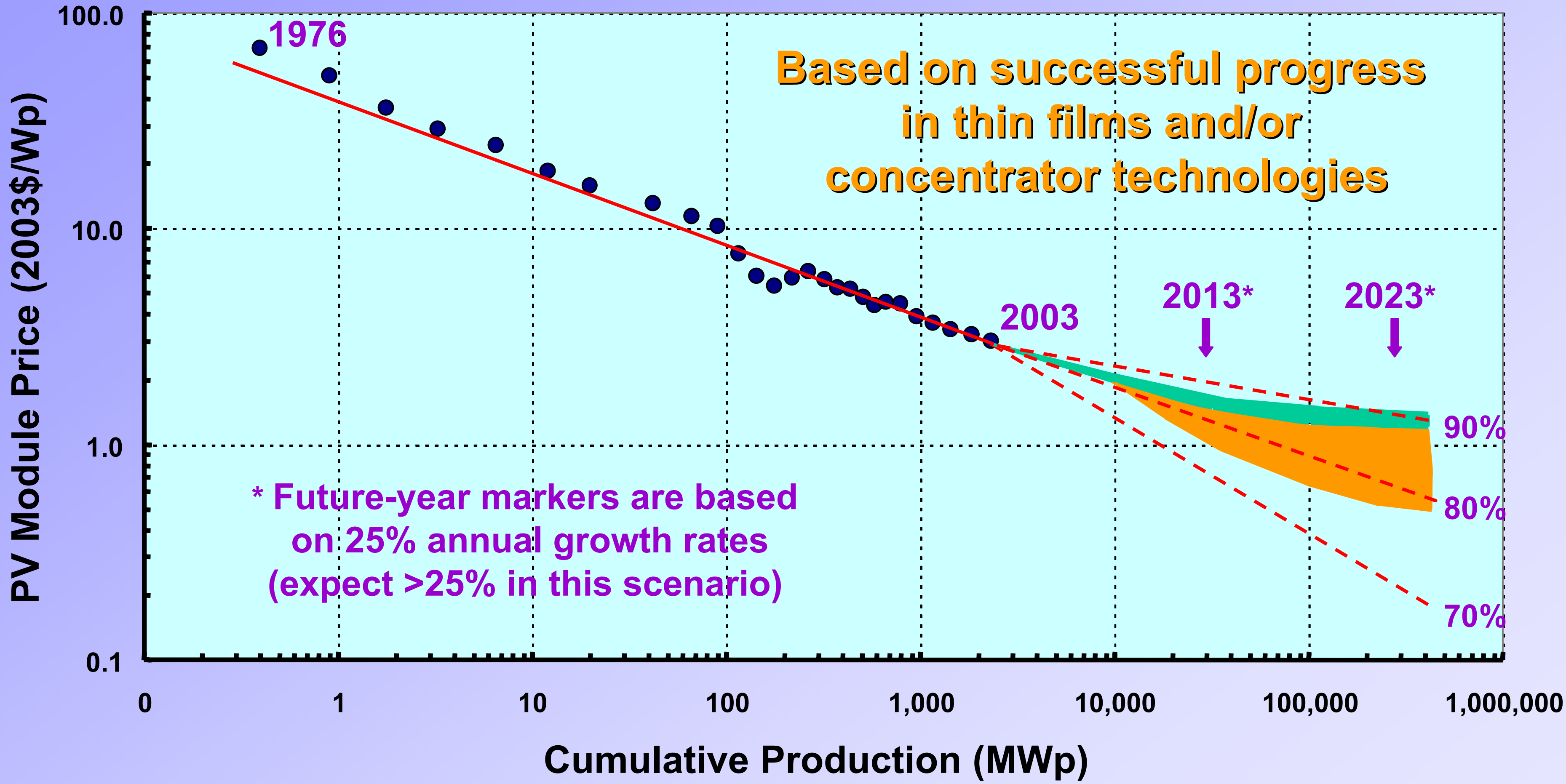
CPUC R1 4/13/05

RANGE OF TOTAL VALUE OF PV: **7.8 – 22.4 ¢/kWh**

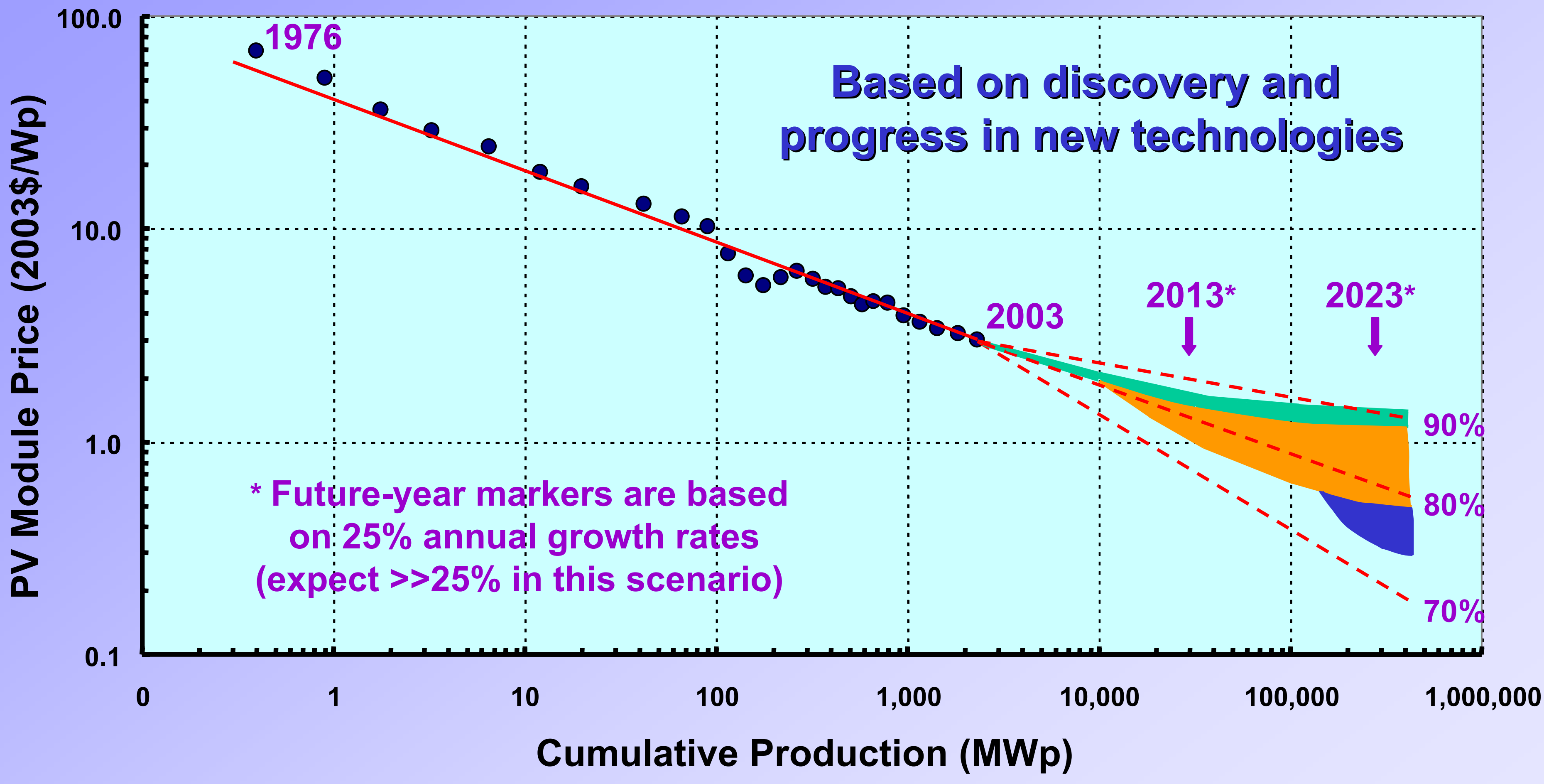
PV Module Production Experience (or "Learning") Curve
… The "near-term" scenario



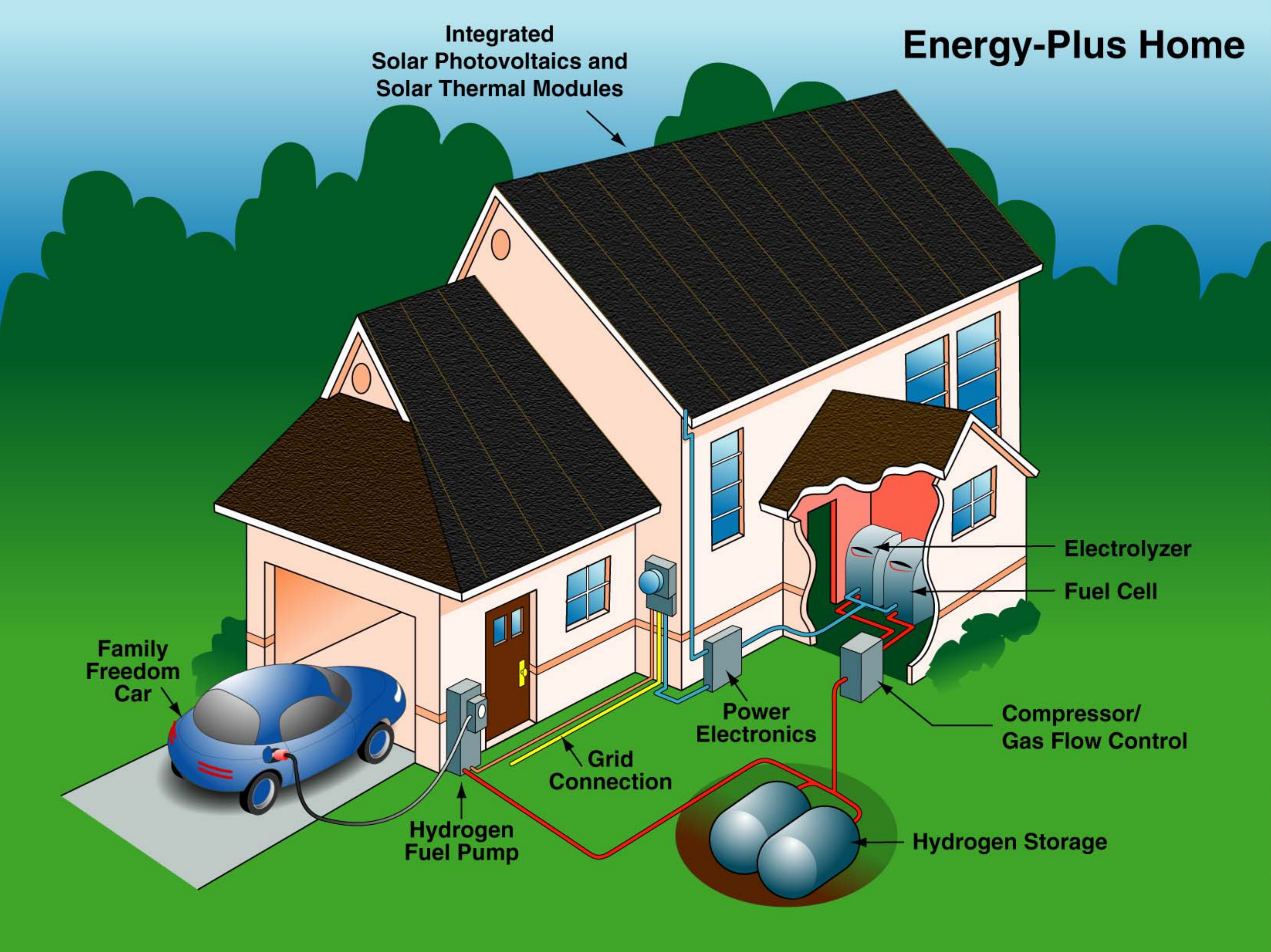
PV Module Production Experience (or "Learning") Curve
… The "mid-term" scenario

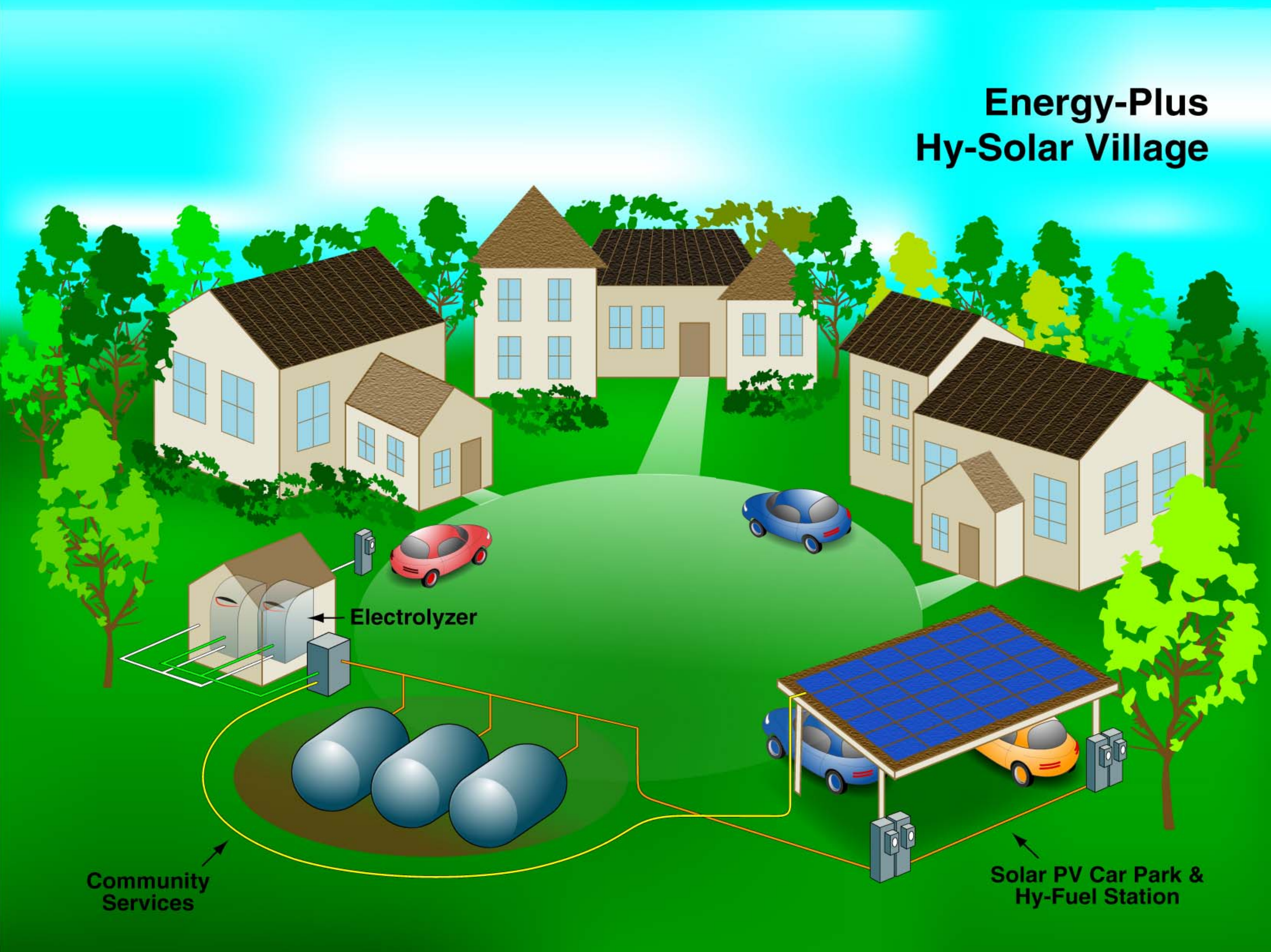


PV Module Production Experience (or "Learning") Curve
… The "long-term" scenario




Solar Decathlon II
October 7-16, 2005
Solar Street


Energy-Plus Home
Integrated
Solar Photovoltaics and
Solar Thermal Modules
Electrolyzer
Fuel Cell
Family
Freedom
Car
Power
Electronics
Compressor/
Gas Flow Control
Grid
Connection
Hydrogen
Fuel Pump
Hydrogen Storage



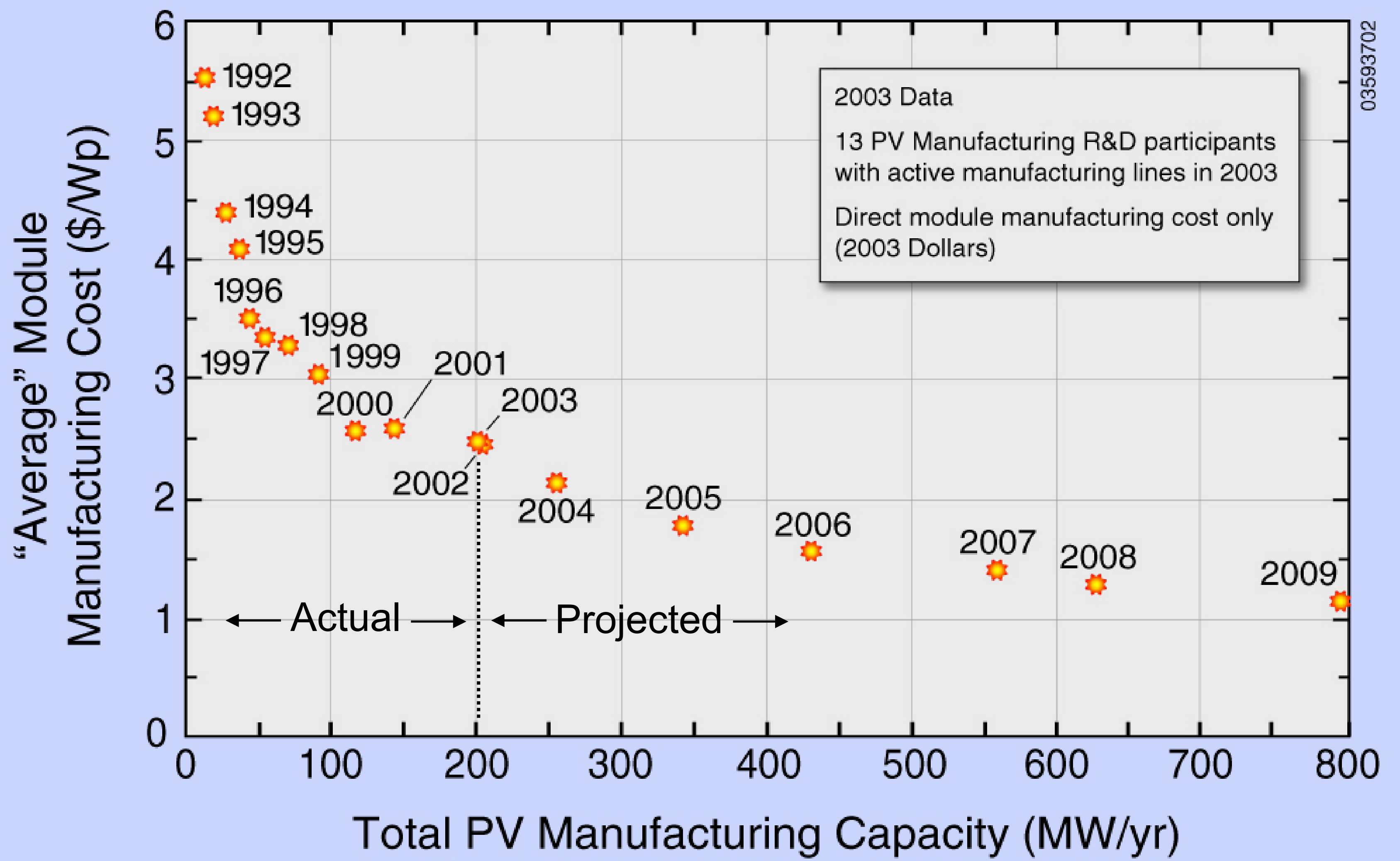
Energy-Plus
Hy-Solar Village
Electrolyzer
Community
Services
Solar PV Car Park &
Hy-Fuel Station

Are there enough materials for energy-significant PV production?

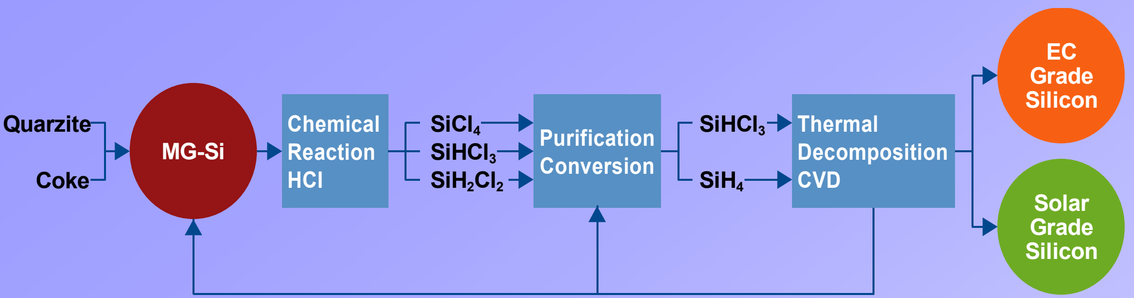
Technology	Material	World Production[a]	Materials Required[a,b]	% of Current Production	Annual Growth Needed (%)
Crystalline silicon	Purified silicon	25,000 MT/yr[b]	130,000 MT	520%	3.7%[c]
	Silver (grids/cell pads)	20,000 MT/yr	6,000 MT	30%	0.53%
Thin-film Cu (In, Ga) Se_2 alloys	Indium	250 MT/yr (byproduct)	400 MT	160%	2.0%[d]
	Selenium	2,200 MT/yr	800 MT	36%	0.6%[e]
	Gallium	150 MT/yr	70 MT	47%	0.9%[f]
Thin-film cadmium telluride	Tellurium	450 MT/yr (2,000 unused byproduct)	933 MT	38% (of total, including unused)	2.2%
	Cadmium	26,000 MT/yr (byproduct)	800 MT	3%	0.06%
Thin-film silicon	Germanium	270 MT/yr (3,200 unused byproduct)	40 MT	1% (of total, including unused)	0.7%

[a]Necessary production for each type of PV technology to produce 20 GW/yr by 2050.
[b]Metric Tons
[c]Elemental silicon is not constrained by supply; current production is low because of low demand.
[d]Indium is a byproduct of zinc, which has been growing at 3%/yr for 50 years. Indium growth will probably exceed demand because of growth in zinc extraction. Indium production would only have to increase 2%/yr to keep pace with demand.
[e]Selenium is a byproduct of copper; an increase of only 0.16%/yr would keep pace with demand.
[f]Gallium is not constrained by supply; current production is low because of low demand.

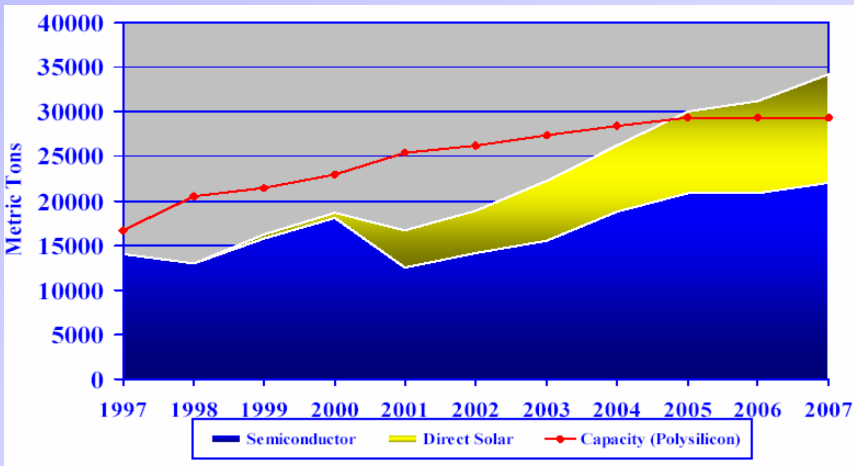
PV Manufacturing R&D Cost/Capacity
(DOE/U.S. Industry Partnership)



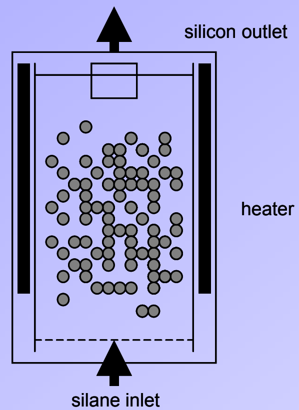
Silicon Feedstock – Is there a problem?

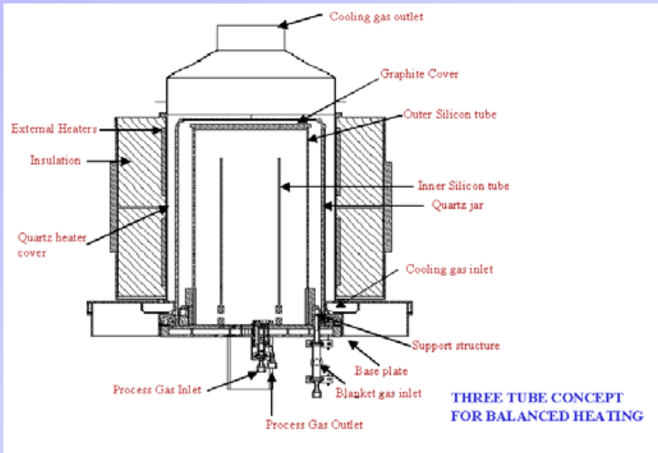


- Historically, PV industry used "low-cost" end of electronic-grade Si
- "Scraps" and "off-spec" approx. 5% of total (<$20/kg)
- In 2003, ~9,000 MT for PV out of ~26,000 MT silicon produced



- With annual growth of 10% in IC industry and 35% in PV industry, shortages are expected by 2005
- Adding new EC capacity requires price of >$60/kg
- "Solar-grade" silicon by modified Siemens process:
  - Fluidized-bed reactor (granular feedstock)
  - Silicon tube to replace slim-rod (high-rate dep'n)
  - ~$30/kg should be possible and be available
- Feedstock only ~5%-7% of PV system cost today





- Purifications of MG-silicon possible (acid-leaching, slagging, alcohol dissolution, reactive gas blowing, directional solidifications, etc.)
- Not likely to result high-enough quality for high-efficiency solar cells
- Area for extensive materials research