R&D Investment & Innovation in PV

Lecture 20

MIT Fundamentals of Photovoltaics

2.626/2.627 – 12/6/2011

Prof. Tonio Buonassisi

High-Efficiency Concepts

Very High-Efficiency Solar Cells

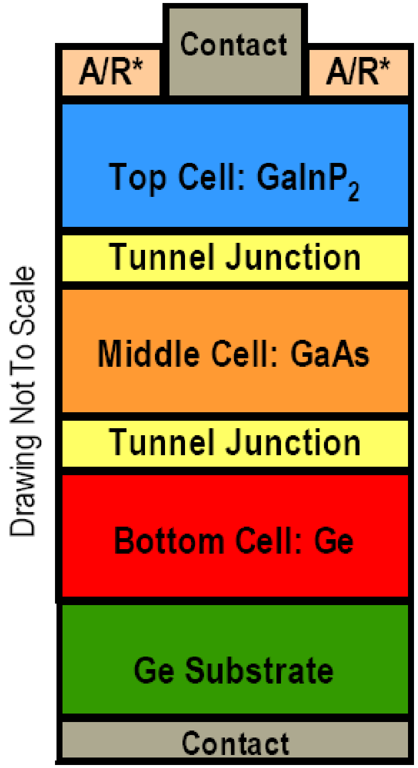
Advantages:

- Very high efficiencies

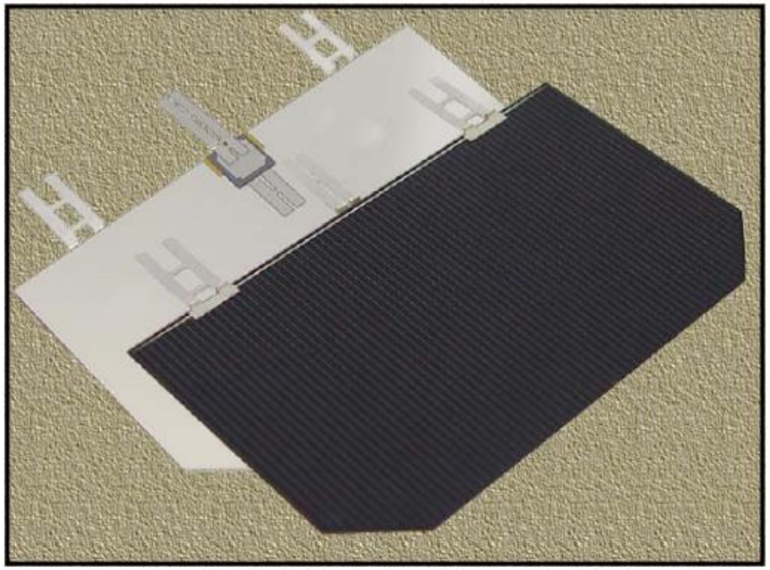
Challenges:

- High cost (often used in concentrators, where PV device is small % of total system cost)
- Manufacturability: Slow, expensive epitaxial growth methods

Tandem (Heterostructure) Cells



*A/R: Anti-Reflective Coating



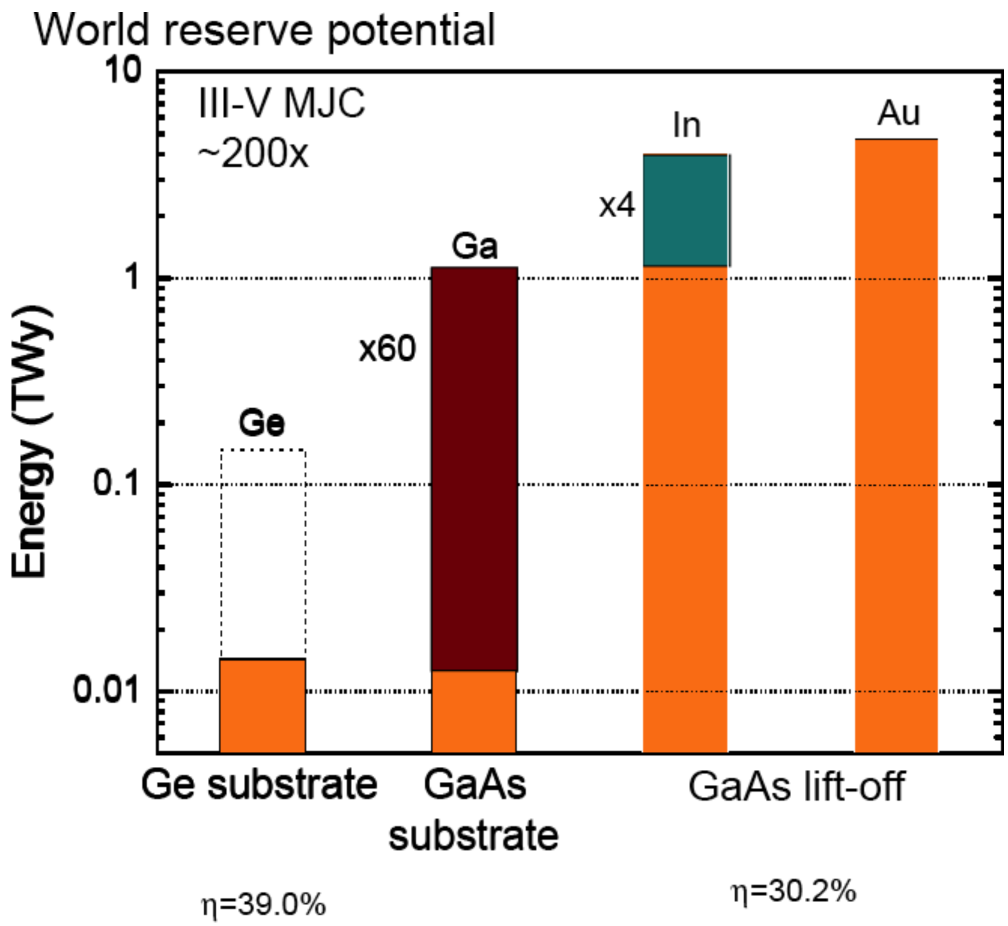
http://www.spectrolab.com/DataSheets/TNJCell/utj3.pdf

- Stack of lattice-matched materials with decreasing bandgaps.
- Spectrolab Cells: $GaInP_2$/GaAs/Ge. Eff_{max}=32%, Eff_{ave}=28%. 375 kW in orbit!
- Theoretical efficiency limit for infinite tandem cell: 86.8%
- *Heteroepitaxial growth slow and expensive!*

Materials Availability

Most experts agree: not enough Ge to produce TW of PV.

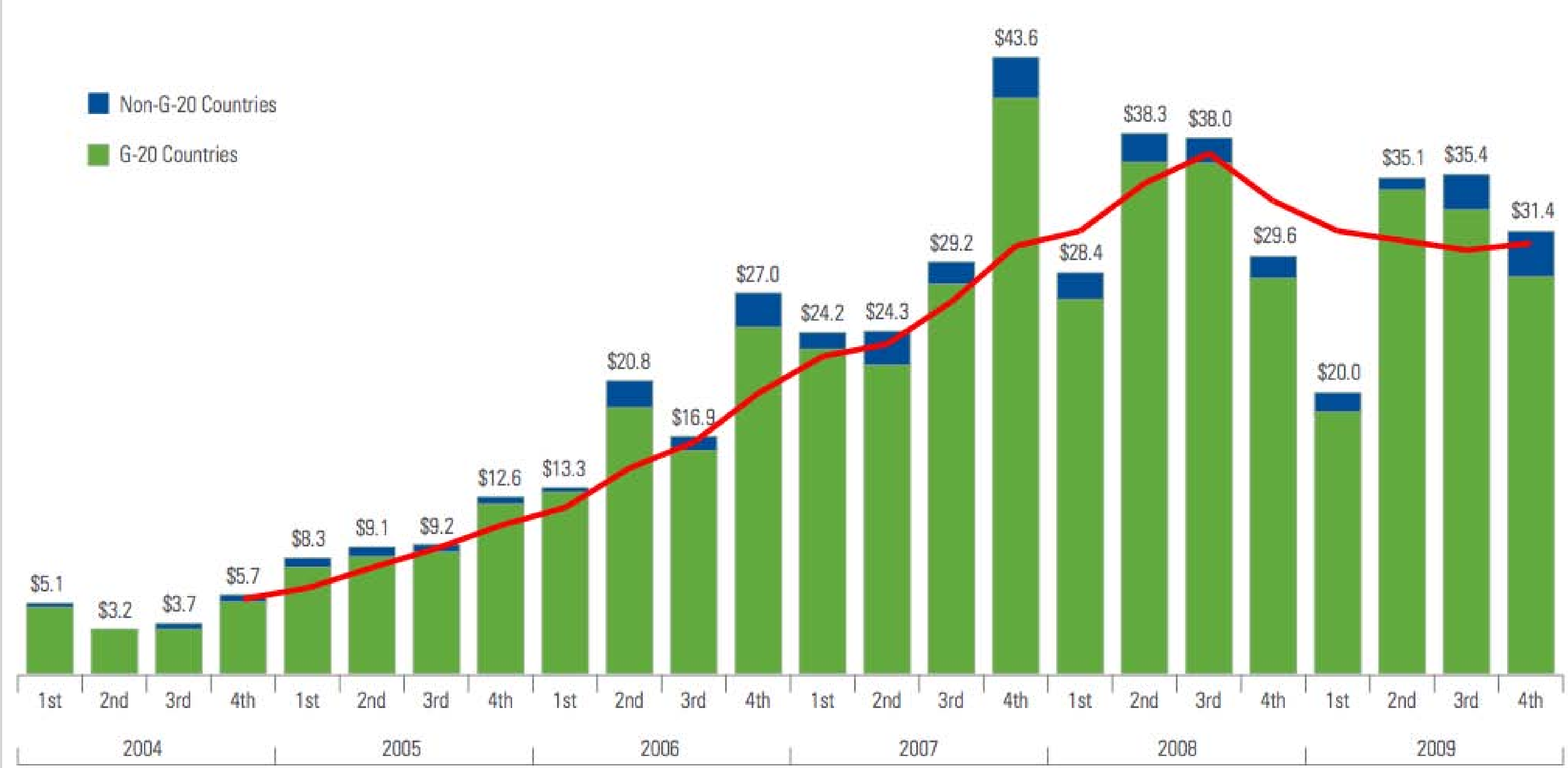
Development of new low-bandgap materials.



Source: A. Feltrin, A. Freundlich, "Material Considerations for Terawatt Level Deployment of Photovoltaics." *Renewable Energy* 33 (2008): 180-185. Courtesy of Alex Freundlich. Used with permission.

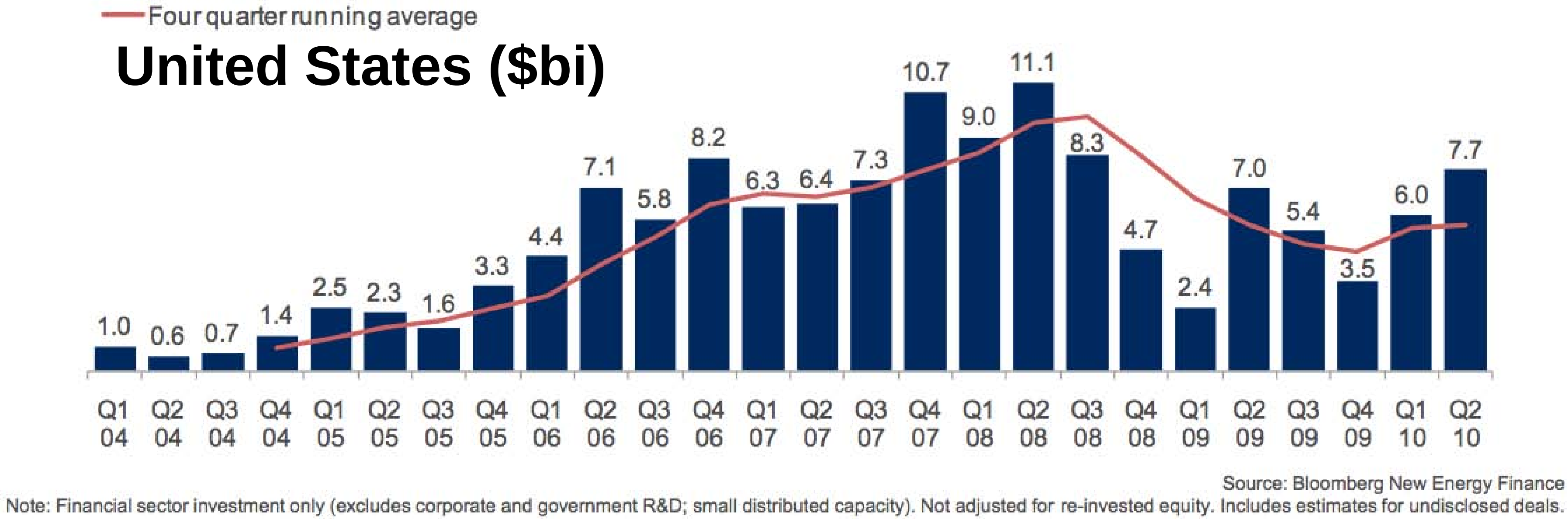
Global Investment Trends in Solar & Other Renewables

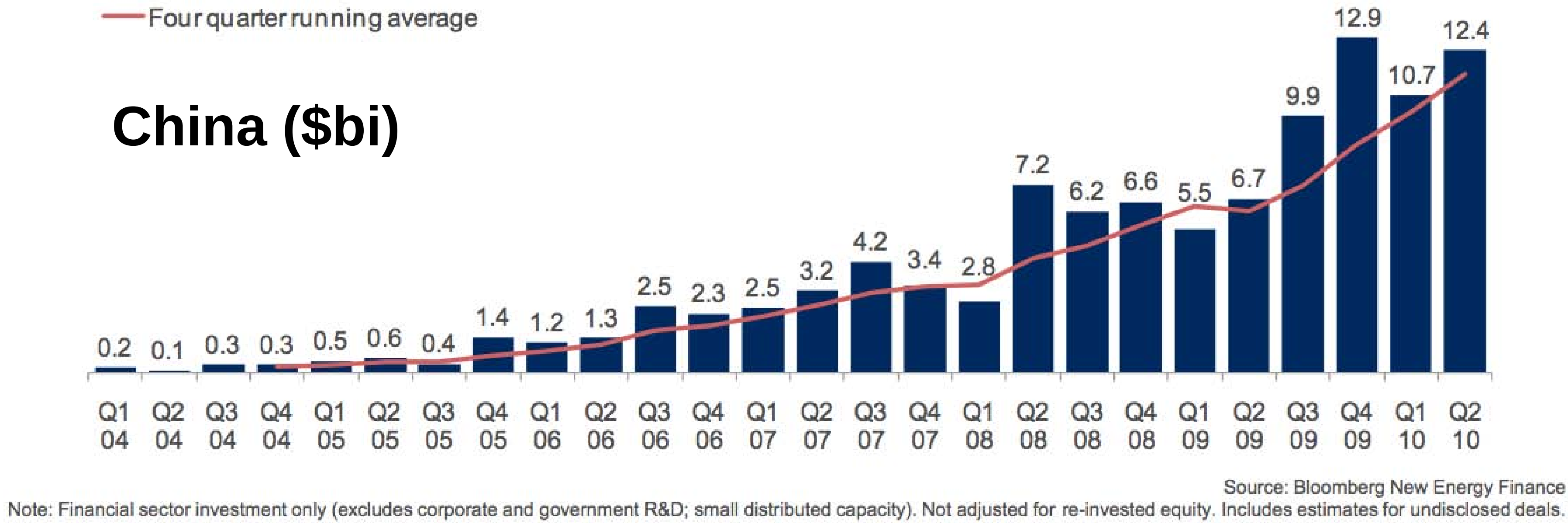
FIGURE 1. FINANCIAL INVESTMENT IN CLEAN ENERGY: GLOBAL TRENDS BY QUARTER (billions of $)



Investment to Rise 25 Percent
The ongoing priority for energy security, global warming pollution reduction and job creation will drive investment up 25 percent to a record $200 billion in 2010, Bloomberg New Energy Finance forecasts.

Source: "Who's Winning the Clean Energy Race? G-20 Clean Energy Factbook." Pew Charitable Trusts, 2010. (PDF)



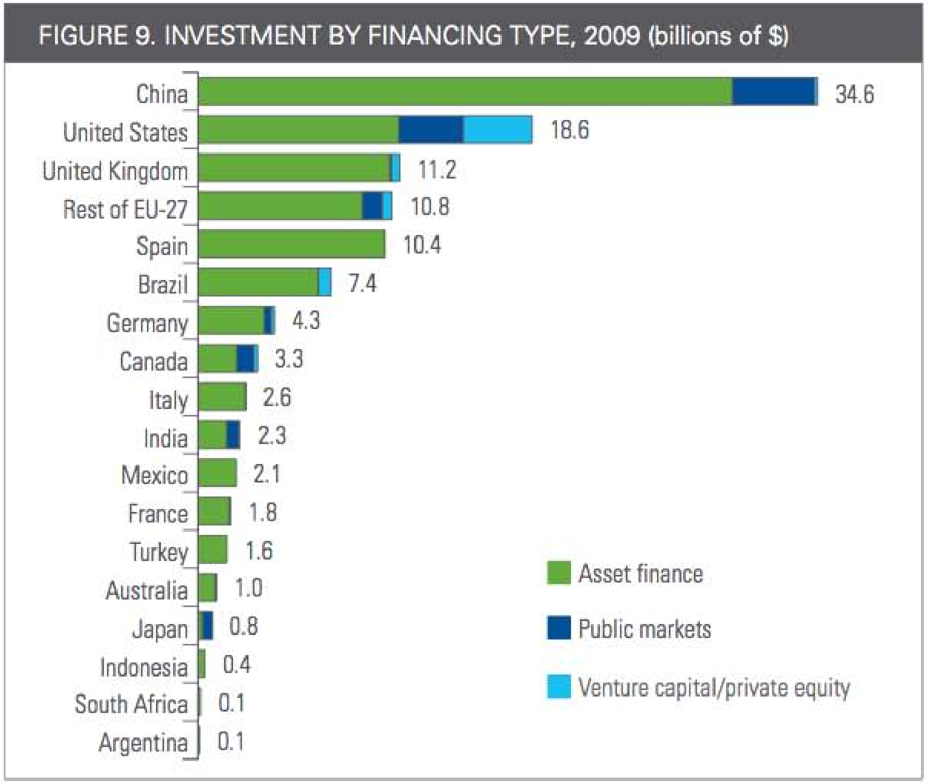


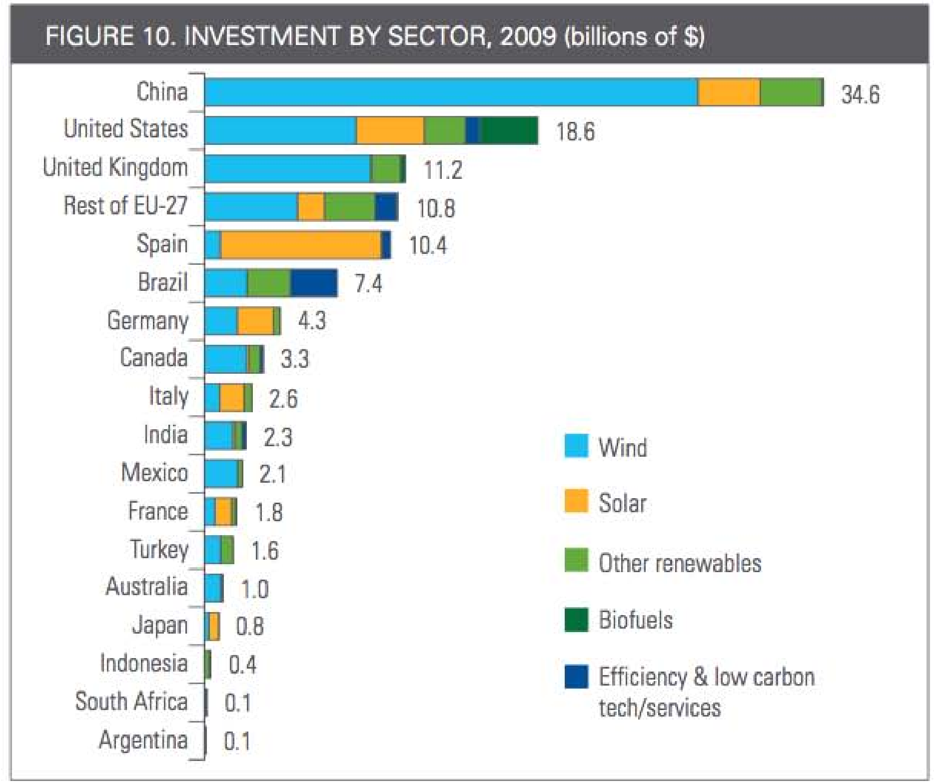
Source: Michael Liebreich (chief executive, Bloomberg New Energy Finance) testimony at "The Global Clean Energy Race," hearing of House Select Committee on Energy Independence and Global Warming, September 22, 2010. Testimony slides (PDF).

E.U. ($bi)

Source: Michael Liebreich (chief executive, Bloomberg New Energy Finance) testimony at "The Global Clean Energy Race," hearing of House Select Committee on Energy Independence and Global Warming, September 22, 2010. Testimony slides (PDF).

RE Investment, by Type and Sector



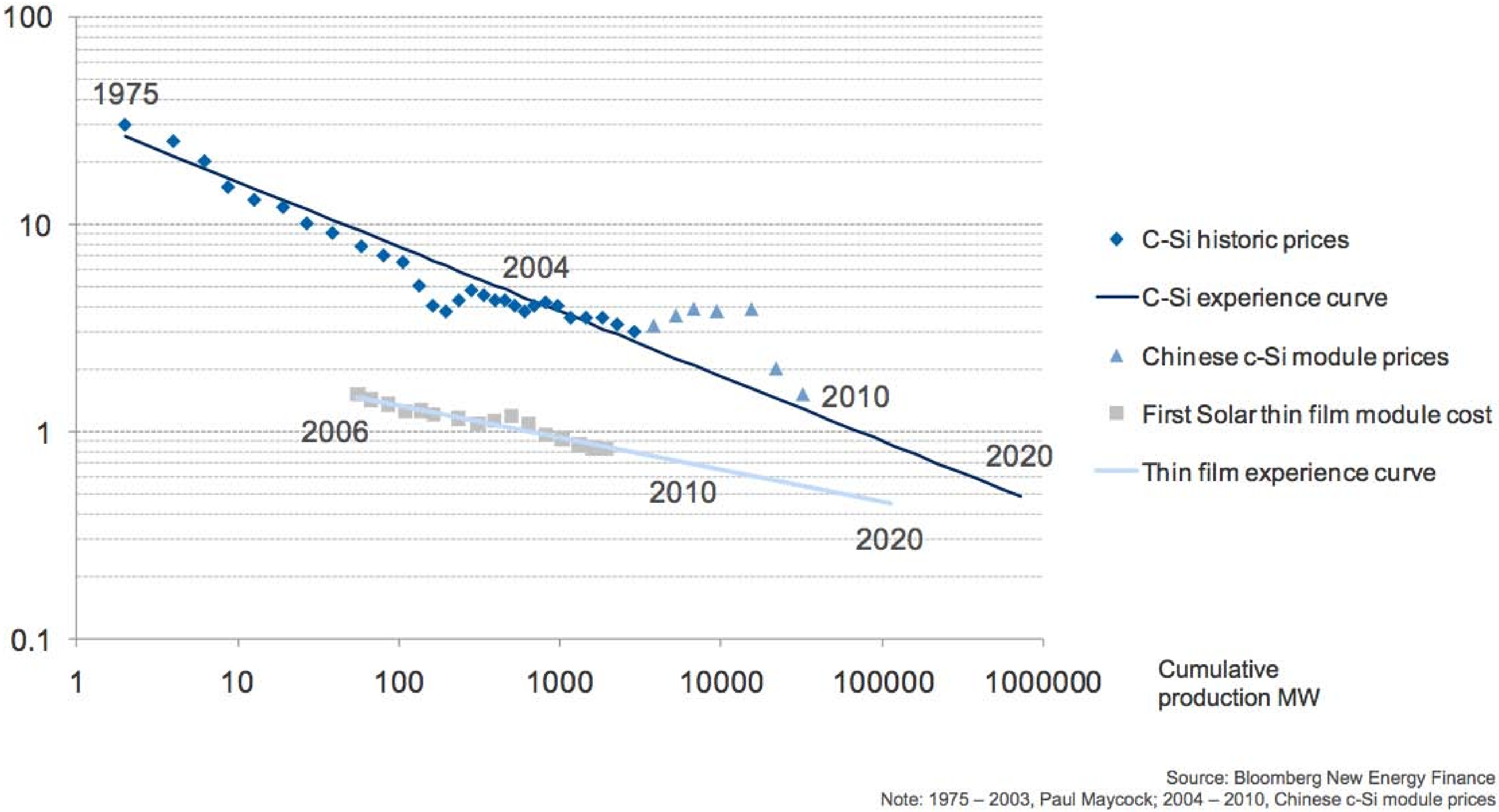


Source: "Who's Winning the Clean Energy Race? G-20 Clean Energy Factbook." Pew Charitable Trusts, 2010. (PDF)

Asset finance: Installation, capacity expansion…

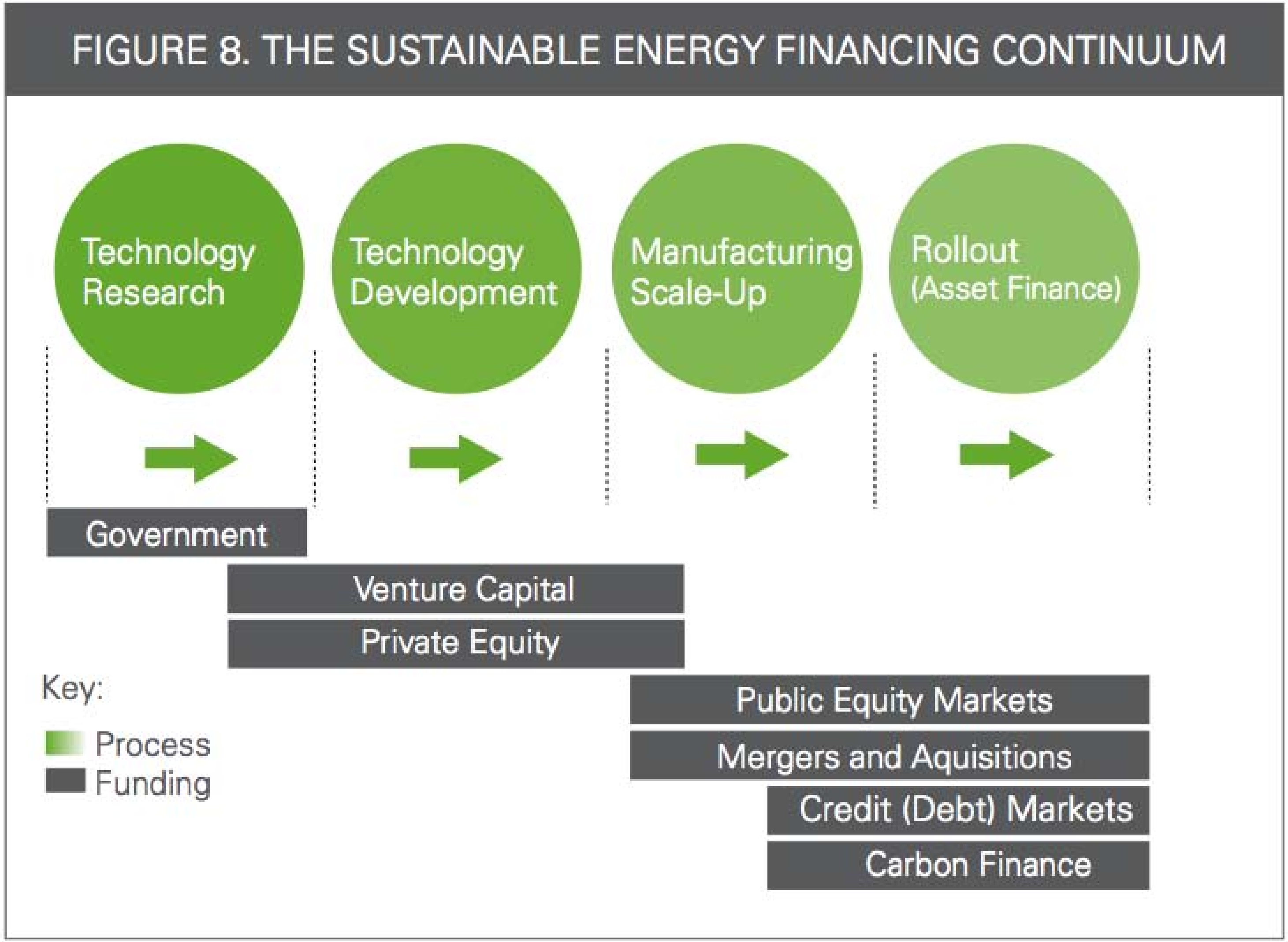
Public markets: Stock offerings, IPOs…

Solar PV module prices 1975 - 2010 ($/Wp)



Source: Michael Liebreich (chief executive, Bloomberg New Energy Finance) testimony at "The Global Clean Energy Race," hearing of House Select Committee on Energy Independence and Global Warming, September 22, 2010. Testimony slides (PDF).

Renewable Energy Technology Pipeline



Source: "Who's Winning the Clean Energy Race? G-20 Clean Energy Factbook." Pew Charitable Trusts, 2010. (PDF)

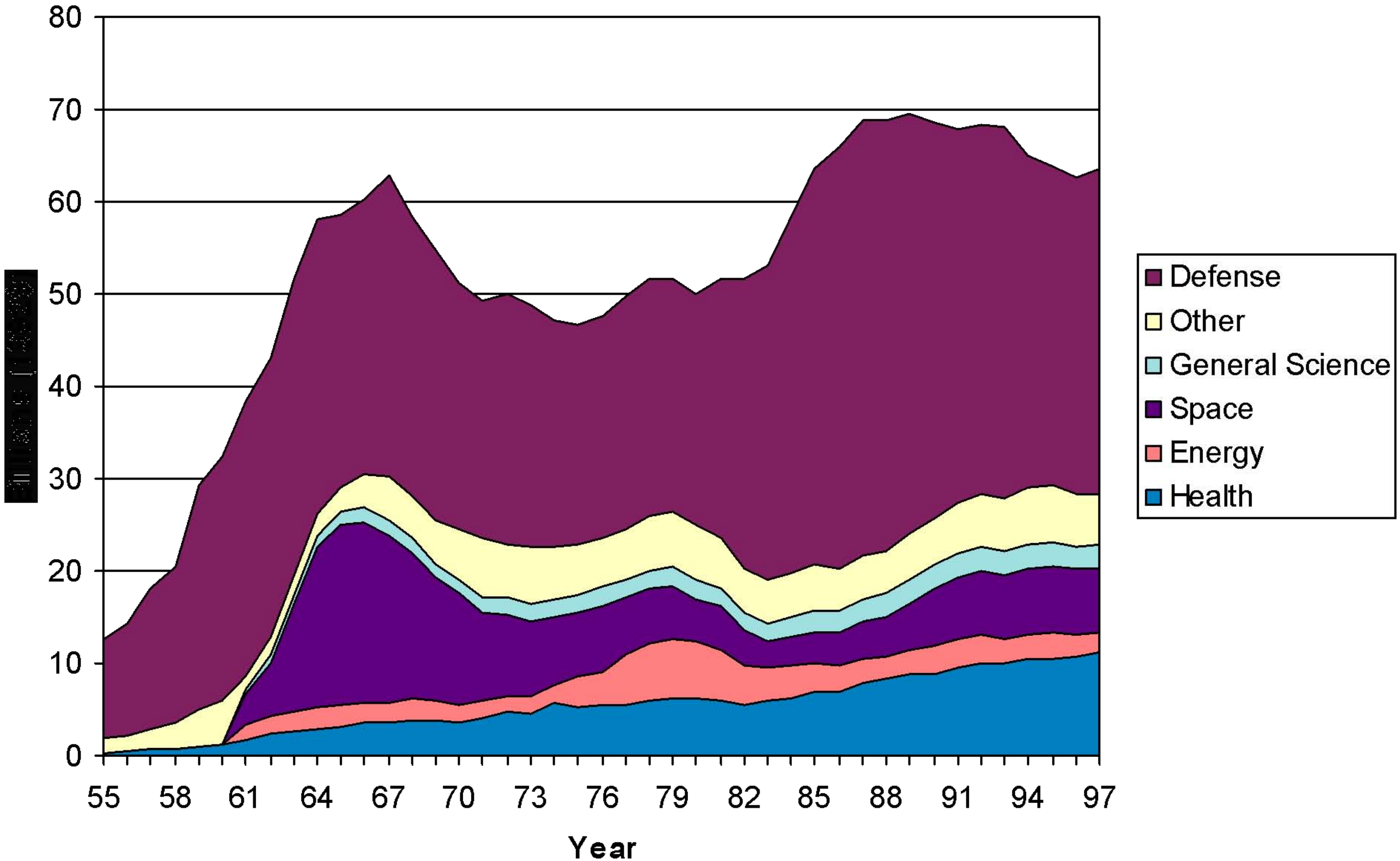
2009 Government Investment in Clean Energy

FIGURE 4. TOP 10 IN CLEAN ENERGY INVESTMENT	
China	$34.6 billion
United States	$18.6 billion
United Kingdom	$11.2 billion
Rest of EU-27	$10.8 billion
Spain	$10.4 billion
Brazil	$7.4 billion
Germany	$4.3 billion
Canada	$3.3 billion
Italy	$2.6 billion
India	$2.3 billion

FIGURE 5. FIVE-YEAR GROWTH IN INVESTMENT	
Turkey	178%
Brazil	148%
China	148%
United Kingdom	127%
Italy	111%
United States	103%
France	98%
Indonesia	95%
Mexico	92%
Rest of EU-27	87%

Source: "Who's Winning the Clean Energy Race? G-20 Clean Energy Factbook." Pew Charitable Trusts, 2010. (PDF)

U.S. Gov't R&D by Budget Function, 1955-1997



Source: DOE, Clean Energy Futures (2000)

Trends in Nondefense R&D by Function, FY 1953-2004

outlays for the conduct of R&D, billions of constant FY 2003 dollars

Source: DOE, Clean Energy Futures (2000)

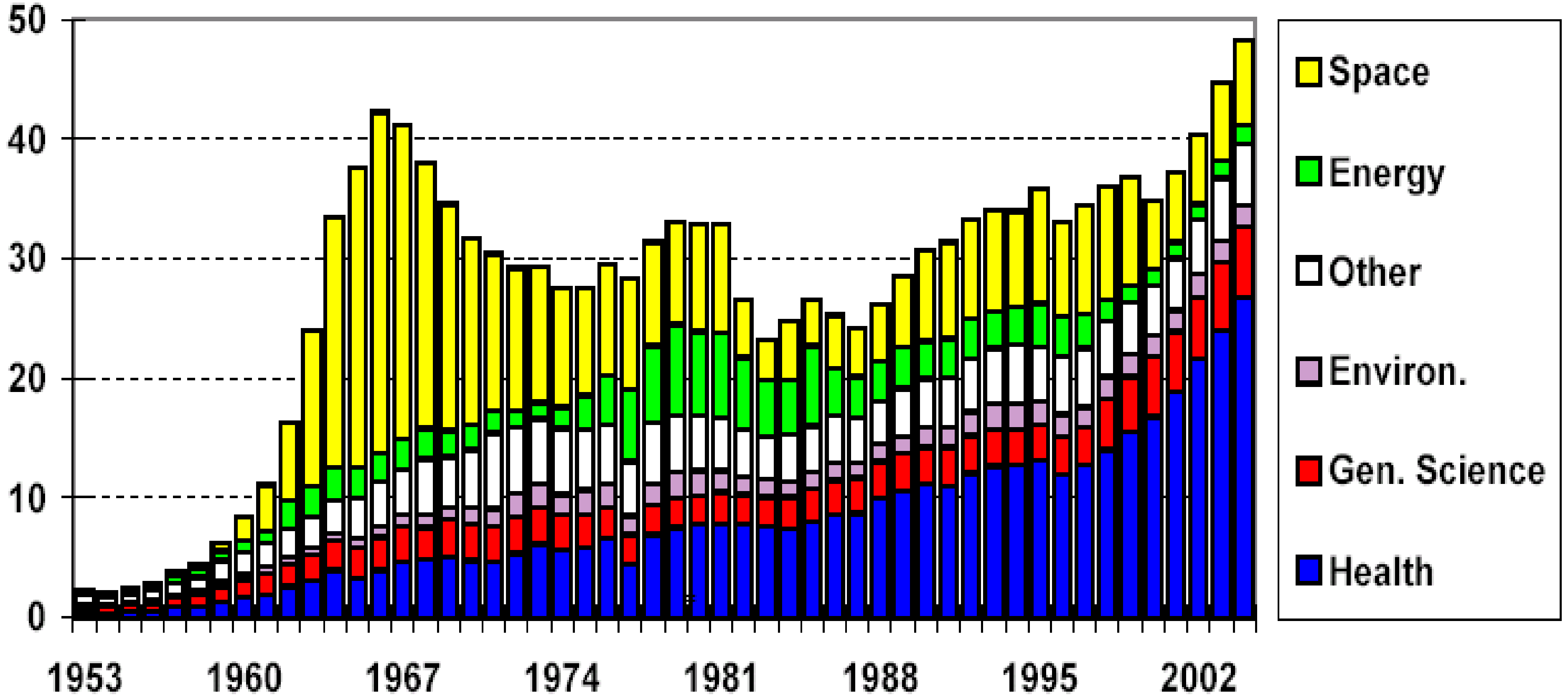


TABLE 1. Federal R&D budget authority by funding category, in order of FY 2011 proposed amounts: FY 2004–11
(Millions of dollars)

Fiscal year	All functions	National defense	Nondefense: Total	Health	General science	Space research/ technology	Natural resources/ environment	Energy	Transportation	Other[a]
Current $millions										
2004 actual	121,867	69,593	52,274	28,251	6,466	7,612	2,168	1,343	1,863	4,571
2005 actual	126,601	74,047	52,554	28,824	6,570	7,300	2,168	1,296	1,847	4,549
2006 actual	131,624	78,037	53,586	28,797	6,691	8,204	2,120	1,195	1,711	4,868
2007 actual	138,087	82,272	55,815	29,461	7,809	9,024	1,936	1,893	1,361	4,331
2008 actual	140,113	84,713	55,400	29,063	8,234	8,323	2,106	1,896	1,394	4,384
2009	156,009	85,166	70,843	40,389	11,840	6,891	2,245	3,318	1,440	4,720
Actual	140,903	84,866	56,037	30,827	8,885	6,205	2,171	2,014	1,336	4,599
ARRA preliminary	15,106	300	14,806	9,562	2,955	686	74	1,304	104	121
2010 preliminary	143,892	86,082	57,810	30,976	9,298	6,622	2,300	2,138	1,427	5,049
2011 proposed	143,404	81,969	61,434	31,917	9,945	7,364	2,490	2,450	2,046	5,223
% change 2010–11[b]	-0.3	-4.8	6.3	3.0	6.9	11.2	8.3	14.6	43.5	3.4
FY 2000 constant $millions										
2004 actual	111,600	63,730	47,870	25,871	5,921	6,971	1,985	1,230	1,603	4,289
2005 actual	112,335	65,703	46,631	25,576	5,830	6,477	1,924	1,150	1,615	4,059
2006 actual	113,050	67,025	46,025	24,733	5,747	7,046	1,821	1,026	1,605	4,045
2007 actual	115,506	68,818	46,688	24,643	6,532	7,548	1,620	1,583	1,553	3,209
2008 actual	114,979	69,517	45,462	23,850	6,757	6,830	1,728	1,556	1,530	3,212
2009	125,490	68,505	56,984	32,488	9,524	5,543	1,806	2,669	1,158	3,796
Actual	113,339	68,264	45,075	24,796	7,147	4,991	1,746	1,620	1,075	3,699
ARRA preliminary	12,151	241	11,910	7,691	2,377	552	60	1,049	84	97
2010 preliminary	113,479	67,888	45,591	24,429	7,333	5,222	1,814	1,686	1,125	3,982
2011 proposed	110,873	63,375	47,498	24,677	7,689	5,694	1,925	1,894	1,582	4,038
% change 2010–11[b]	-2.3	-6.6	4.2	1.0	4.8	9.0	6.1	12.3	40.6	1.4

ARRA = American Recovery and Reinvestment Act.

[a] Other functions include agriculture; veterans benefits and services; education, training, employment, and social services; income security; commerce and housing credit; international affairs; administration of justice; community and regional development; and medicare.

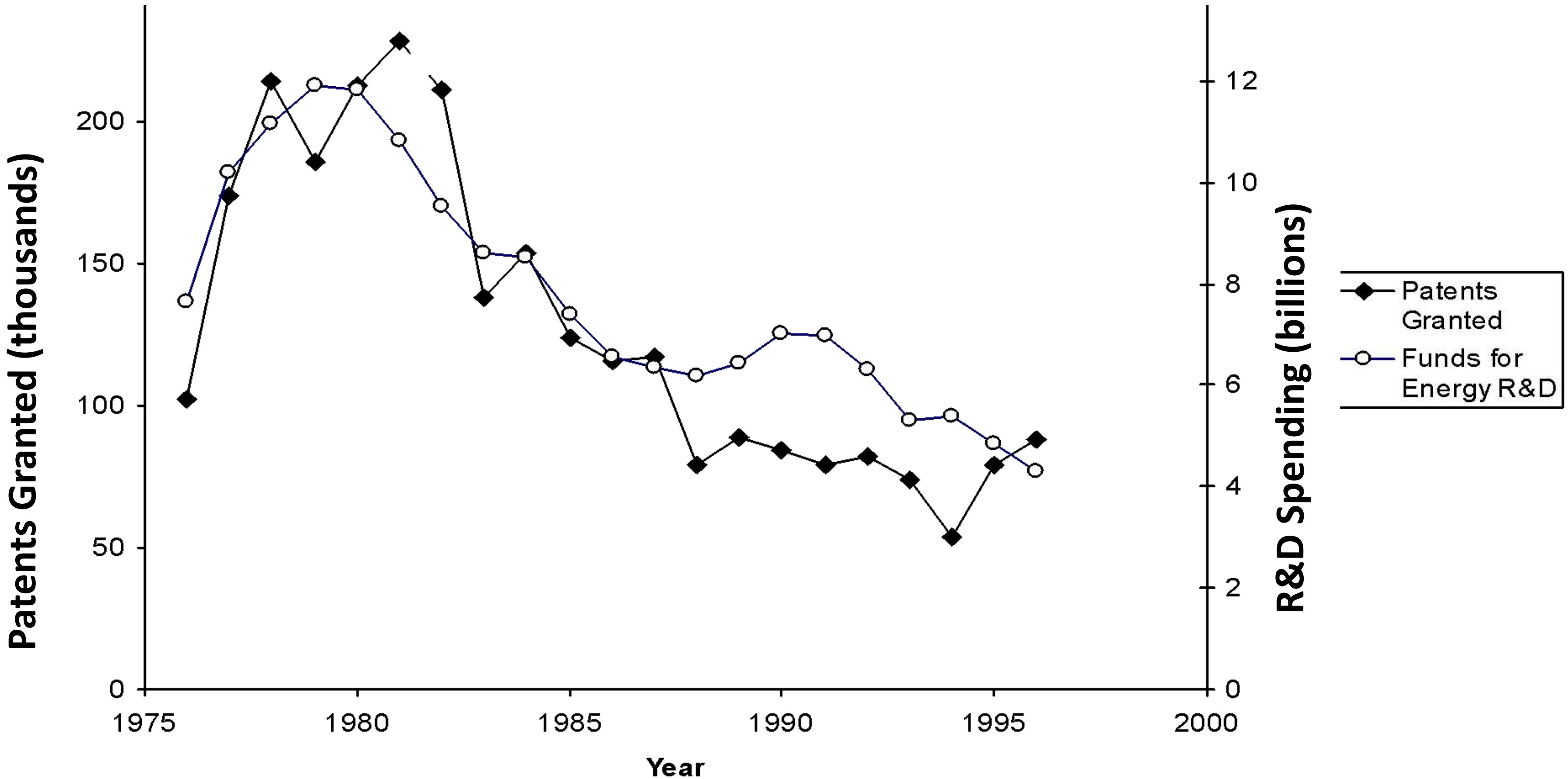
[b] Percentage change calculations are based on unrounded data.

NOTES: Budget information collected through May 2010. FY 2004–09 data are final appropriations except ARRA funding. ARRA funds may be obligated through FY 2010 and totals are preliminary. FY 2010 supplemental appropriations are included in FY 2010 preliminary budget authority. FY 2011 proposed budget authority from Obama administration will be revised to reflect congressional appropriation and actual program-funding decisions. Detail may not add to total because of rounding.

SOURCES: Agencies' submissions to the Office of Management and Budget; agencies' budget documents; and supplemental data obtained from agencies' budget offices.

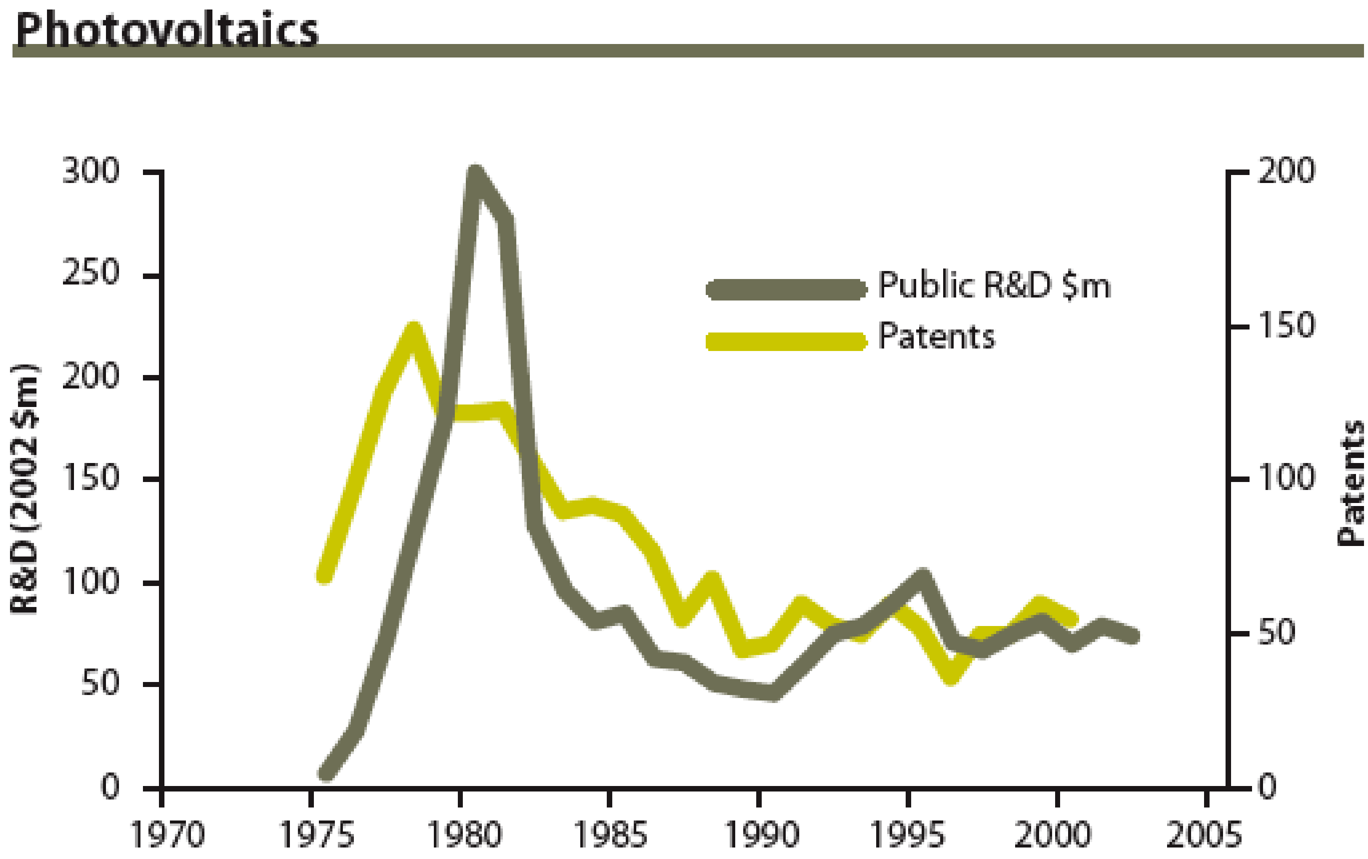
http://www.nsf.gov/statistics/infbrief/nsf10327/

Funding-Patent Correlation for Energy



R. Margolis and D. Kammen (1999). "Underinvestment: The energy technology and R&D policy challenge", *Science*, 285, 690 - 692.

Funding-Patent Correlation for PV



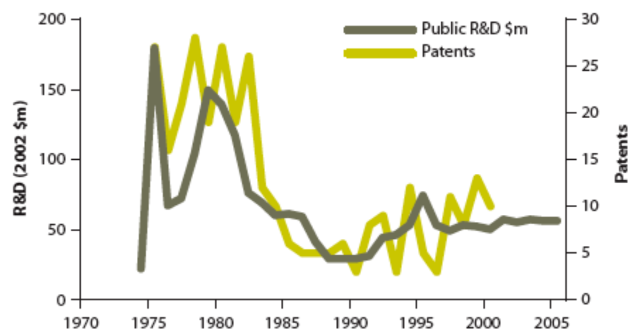
D. Kammen and G. Nemet, "Reversing the Incredible Shrinking Energy R&D Budget."
***Issues in Sci & Techn.*, Fall 2005, p. 84**

Funding-Patent Correlation for Energy

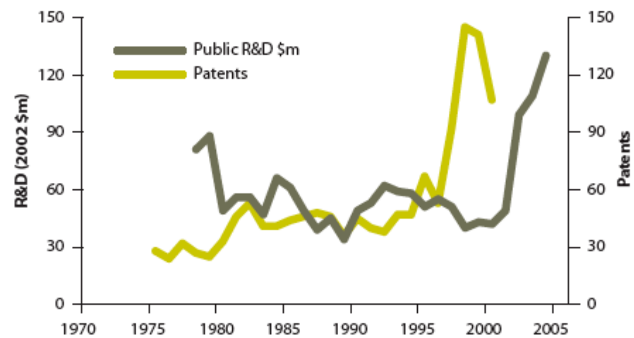
Patent data confirms problem

Patenting provides a measure of the outcomes of the innovation process. We use records of successful U.S. patent applications as a proxy for the intensity of innovative activity and find strong correlations between public R&D and patenting across a variety of energy technologies. Since the early 1980s, all three indicators—public sector R&D, private sector R&D, and patenting—exhibit consistently negative trends. The data include only U.S. patents issued to U.S. inventors. Patents are dated by their year of application to remove the effects of the lag between application and approval.

Wind



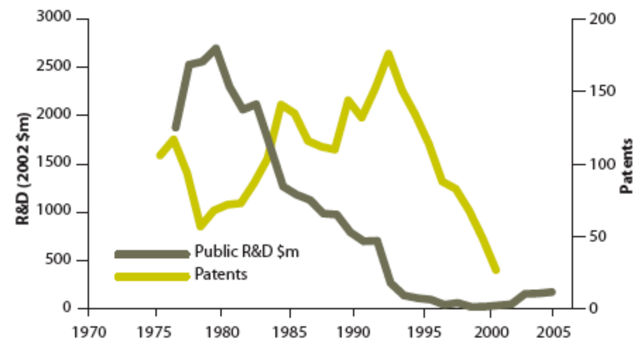
Fuel cells



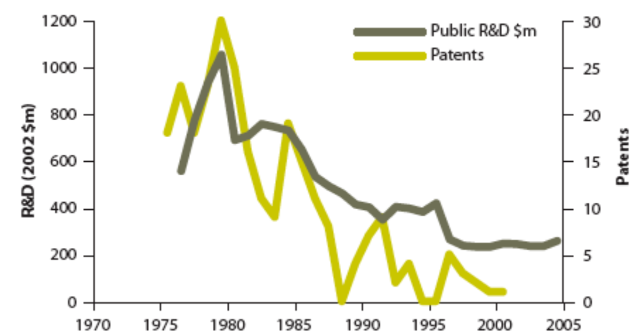
Source: U.S. Patent and Trademark Office patent database.

D. Kammen and G. Nemet, "Reversing the Incredible Shrinking Energy R&D Budget." *Issues in Sci & Techn.*, Fall 2005, p. 84

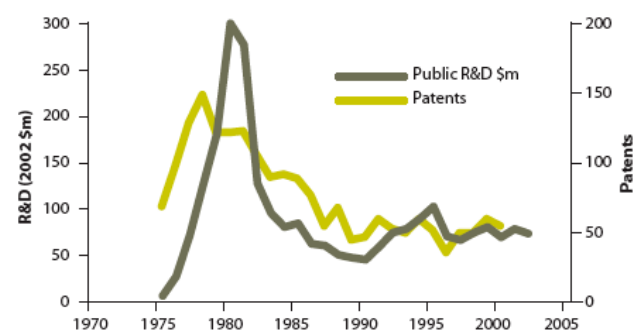
Nuclear fission



Nuclear fusion

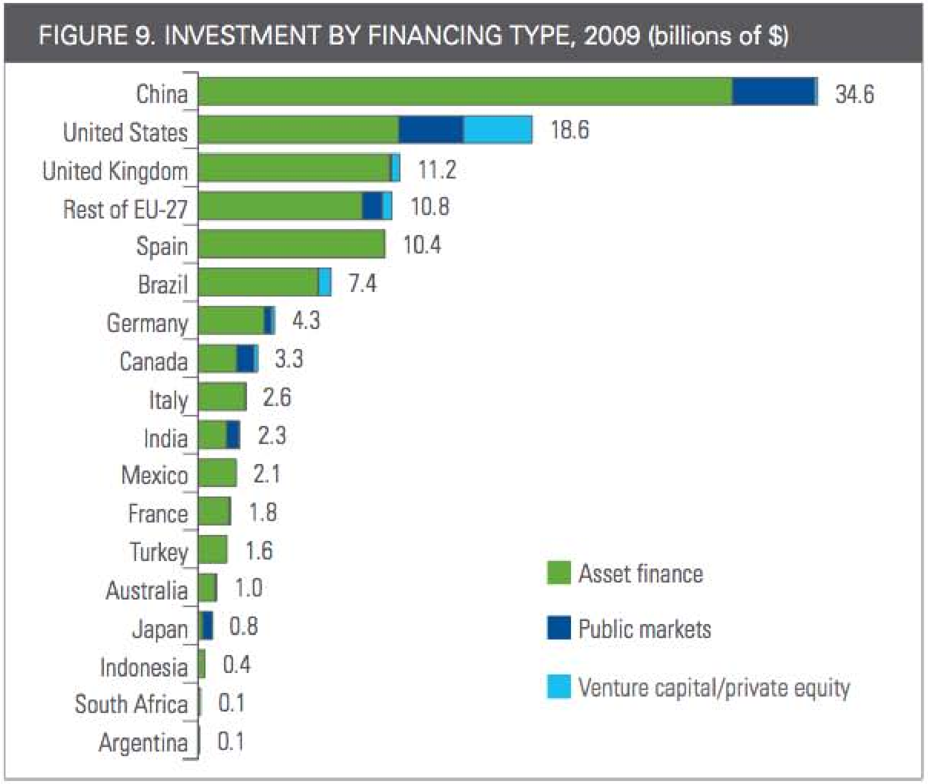


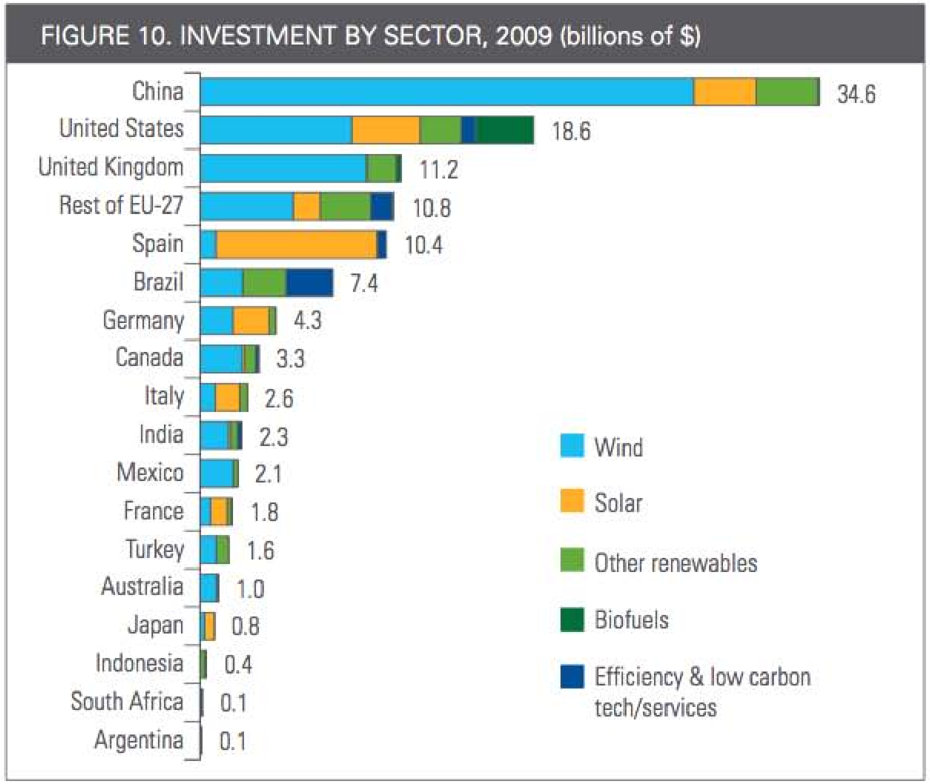
Photovoltaics



Global Trends in Venture Investing

RE Investment, by Type and Sector

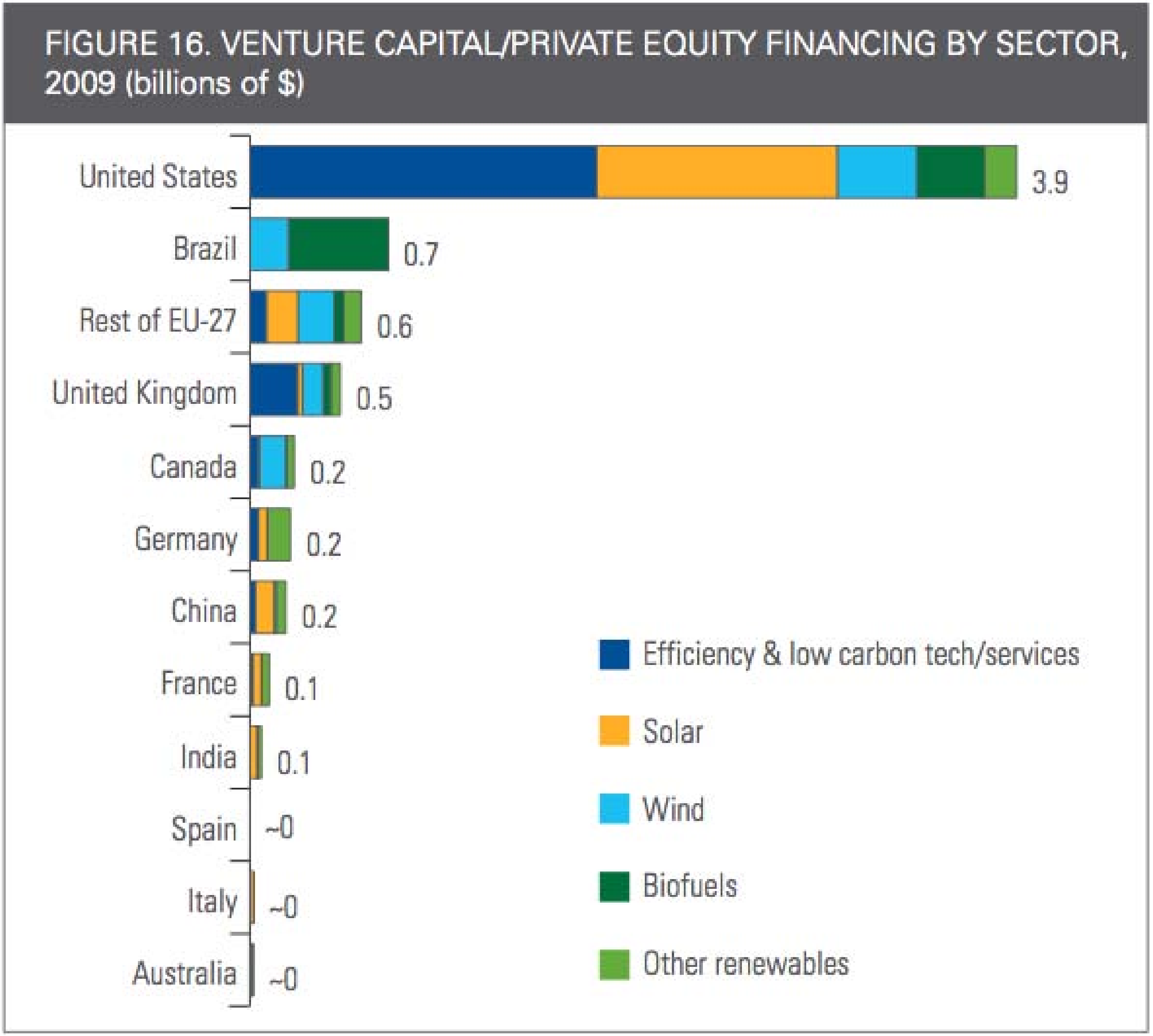




Source: "Who's Winning the Clean Energy Race? G-20 Clean Energy Factbook." Pew Charitable Trusts, 2010. (PDF)

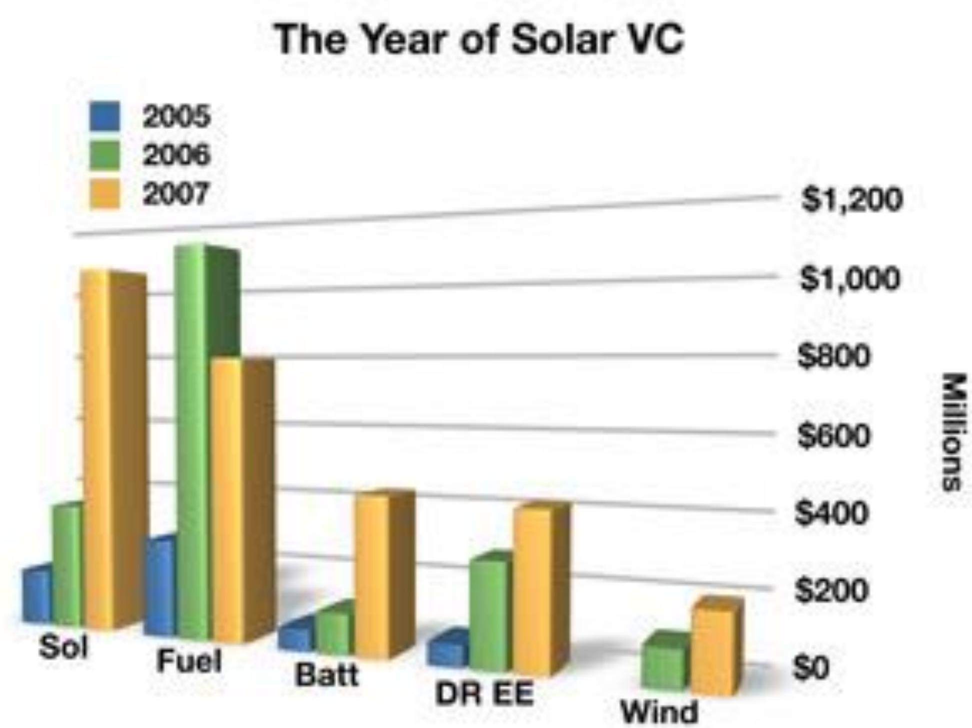
Asset finance: Installation, capacity expansion…
Public markets: Stock offerings, IPOs…

VC Investment, by Sector



Source: "Who's Winning the Clean Energy Race? G-20 Clean Energy Factbook." Pew Charitable Trusts, 2010. (PDF)

Solar Energy: Recent Boom



Eric Wesoff & Michael Kanellos
The Venture Power Report

http://www.greentechmedia.com/articles/read/the-master-list-of-early-stage-solar-startups-the-sequel/

Solar Start-Ups

- >200 solar start-ups worldwide.
- Few failed start-ups to date: Wakonda, Solasta, SV Solar, Senergen, Optisolar, Solyndra, SpectraWatt, Evergreen Solar.
- More failed start-ups coming (main cause: failure to raise capital for manufacturing, failure to reduce costs faster than state-subsidized production elsewhere, failure to secure investor confidence).
- Eric Wesoff (Greentech Media) keeps tabs on each, publishes list.
  - http://www.greentechmedia.com/articles/read/the-master-list-of-early-stage-solar-startups-the-sequel/
  - http://www.greentechmedia.com/articles/read/Solar-Start-Up-Bloodbath-2010/

1366 Technologies
6N Silicon
Advent Solar
AOS Solar
Blue Square
Calisolar
ET Solar
Norsun
RSI
SiC Processing
Silicon Genesis
Solar Notion
Solaicx
SpectraWatt
Wriota

Energy Recommerce
Envision
GreenSun Energy
GroSolar
Helio Mu
Recurrent Energy
Sierra Nevada Solar
Solaire
Solar Century
Solar City
Solar Notion
Soltage
Sun Edison
SunRun
Solar Power Partners
Sterling Planet
Tioga Energy

Extreme
Heliatek
Innovalight
Konarka
NanoGram
Nano Si
Orb energy
Orion
Plextronics
QuNano
Senergen
Semprius
Solexant
Solexel
Solel
Stion
Sunviva

Azure
Concentrix
Cool Earth
Cyrium
Day4
GreenVolts
Netcrystal
Prism Solar
Pyron
Pythagoras
QuantaSol
Skyline Solar
Solaria
Solbeam
SolFocus
Solar Junction
Solar Systems
Soliant
Sunrgi
SV Solar

Ausra
Brightsource Energy
Energy Innovations
eSolar
Heliodynamics
Infinia
Sopogy
Skyfuel
SolFocus
Solar Systems
Stirling

Ampulse
AVA Solar
CSG Solar
Energy PV
Flexcell
FTL Solar
Heliovolt
Miasole
Moser Baer
Nanosolar
Odersun

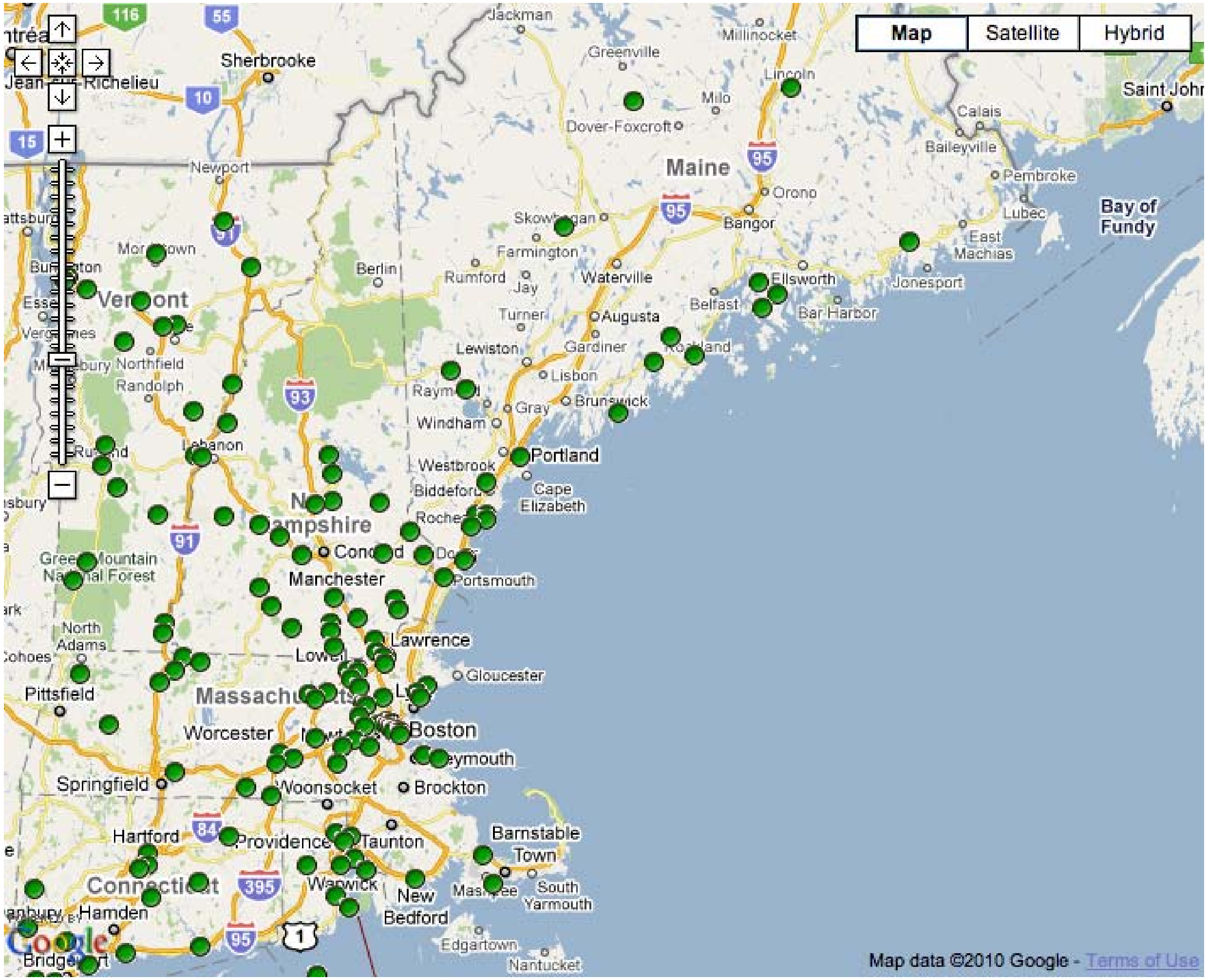
Optisolar
PrimeStar
Sencera
Sierra Solar
Signet
Solibro
Solopower
Solyndra
Sunovia
Sulfurfuel
Xunlight

BTI
Green Ray Solar
Petra Solar
PV Powered
SunLink
Solar Edge
SunRun
Tigo Energy

greentechmedia:

Source: Eric Wesoff, Greentech Media

RE Companies & Start-Ups in the New England Area



http://www.cleanenergycouncil.org/clustermap

U.S. Trends in RE Manufacturing

Solar Manufacturing in the United States

Figure removed due to copyright restrictions.
See lecture 20 video for details about where various PV technologies are manufactured.

http://www.gtmresearch.com/report/pv-manufacturing-in-the-united-states-market-outlook-incentives-and-supply

Solar Manufacturing Support in the United States

State Support

Figure removed due to copyright restrictions.
See lecture 20 video for details of state-by-state grants, loans, and tax incentives.

http://www.gtmresearch.com/report/pv-manufacturing-in-the-united-states-market-outlook-incentives-and-supply

Solar Manufacturing Support in the United States

Federal Support: Advanced Energy Manufacturing Tax Credit

30% of qualified investment, not to exceed US$2.3bi.

Global Trends in RE Installation

Market Incentives via RE Policy

NATIONAL CLEAN ENERGY POLICIES	Germany	U.S.	China
Carbon Cap			
Carbon Market	✓		
Renewable Energy Standard	✓		✓
Clean Energy Tax Incentives	✓	✓	✓
Auto Efficiency Standards	✓	✓	✓
Feed-in Tariffs	✓		✓
Government Procurement	✓	✓	
Green Bonds			✓

Source: "Who's Winning the Clean Energy Race? G-20 Clean Energy Factbook." Pew Charitable Trusts, 2010. (PDF)

RE Investment, by Type and Sector

FIGURE 9. INVESTMENT BY FINANCING TYPE, 2009 (billions of $)

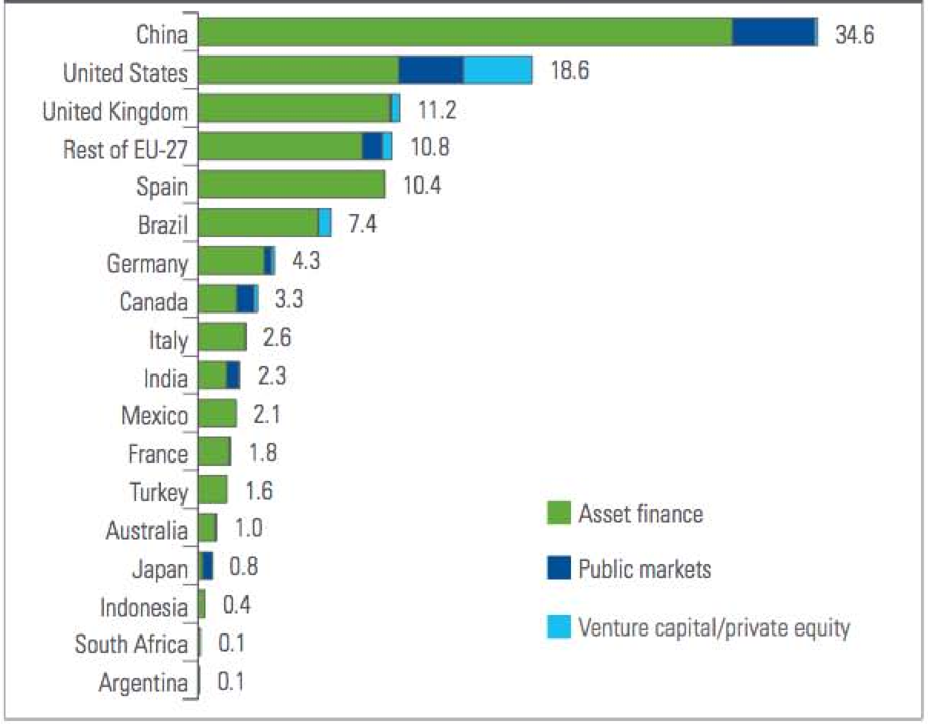
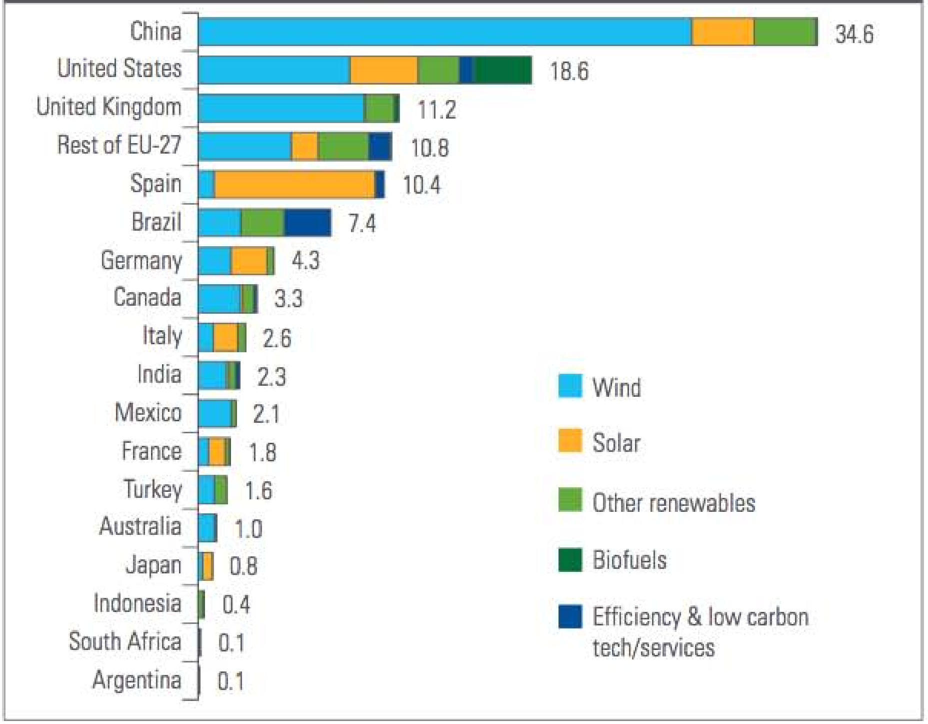


FIGURE 10. INVESTMENT BY SECTOR, 2009 (billions of $)

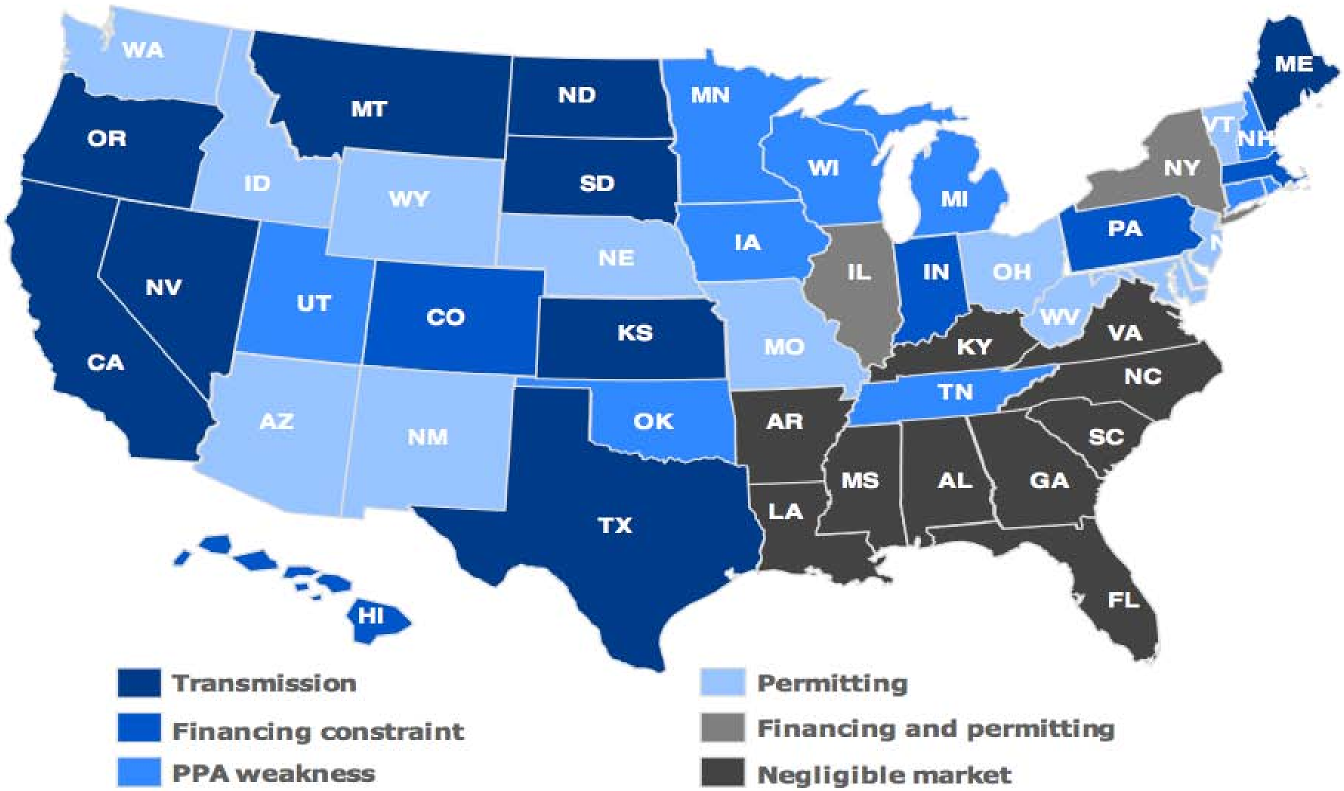


Source: "Who's Winning the Clean Energy Race? G-20 Clean Energy Factbook." Pew Charitable Trusts, 2010. (PDF)

Asset finance: Installation, capacity expansion…

Public markets: Stock offerings, IPOs…

Principal regional causes of project delay



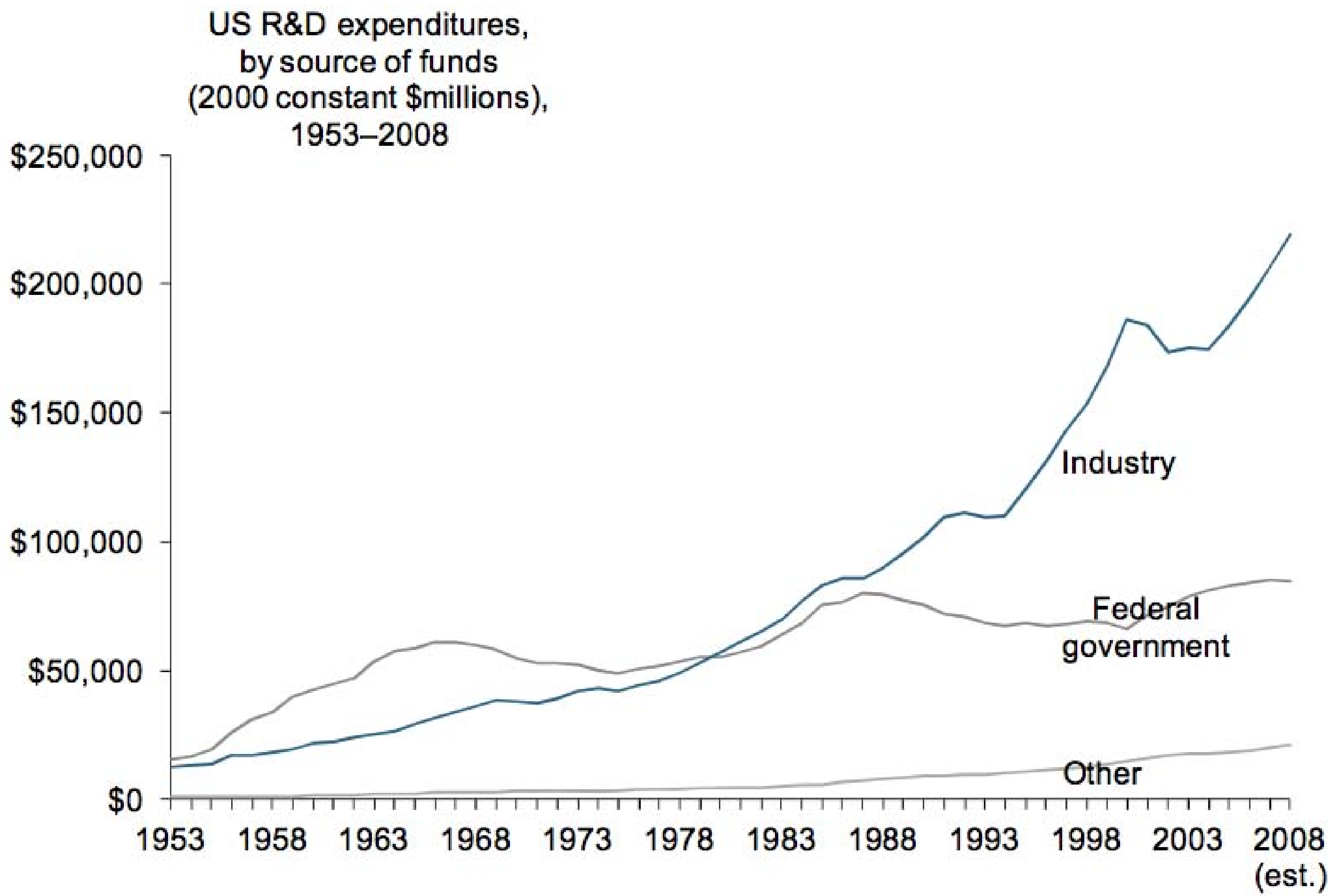
Note: States are coloured by leading cause of delay.

Source: Bloomberg New Energy Finance

Source: Michael Liebreich (chief executive, Bloomberg New Energy Finance) testimony at "The Global Clean Energy Race," hearing of House Select Committee on Energy Independence and Global Warming, September 22, 2010. Testimony slides (PDF).

Global Trends in R&D

Exhibit 4: The private sector finances a growing majority of total US R&D investment …

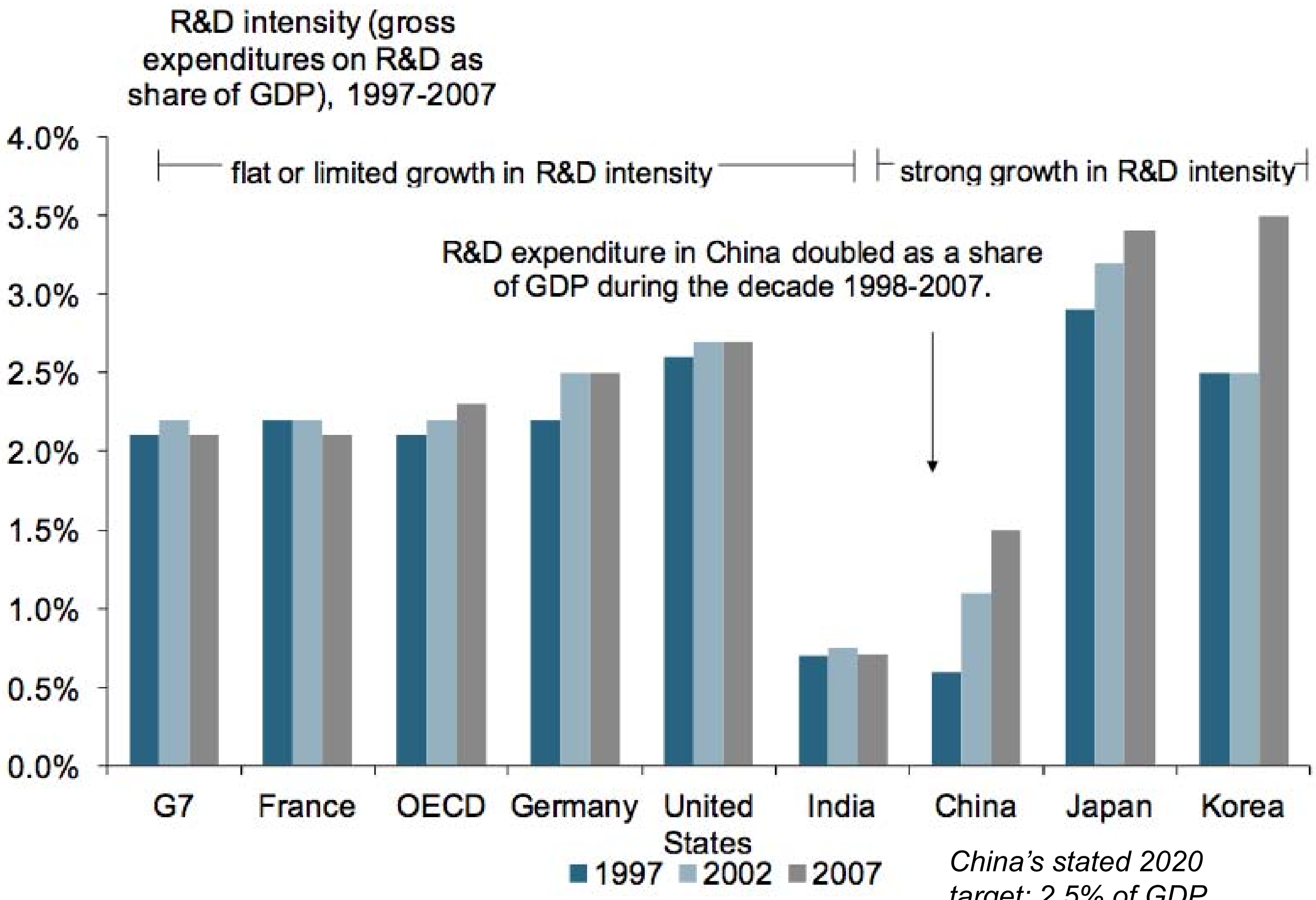


Source: National Science Foundation.

From Gilman, D. "The new geography of global innovation." Goldman Sachs Global Markets Institute, Sept. 20, 2010. (PDF)

Exhibit 2: Greatest R&D intensity gains are in Asia

China's investment has doubled as a share of GDP since '99

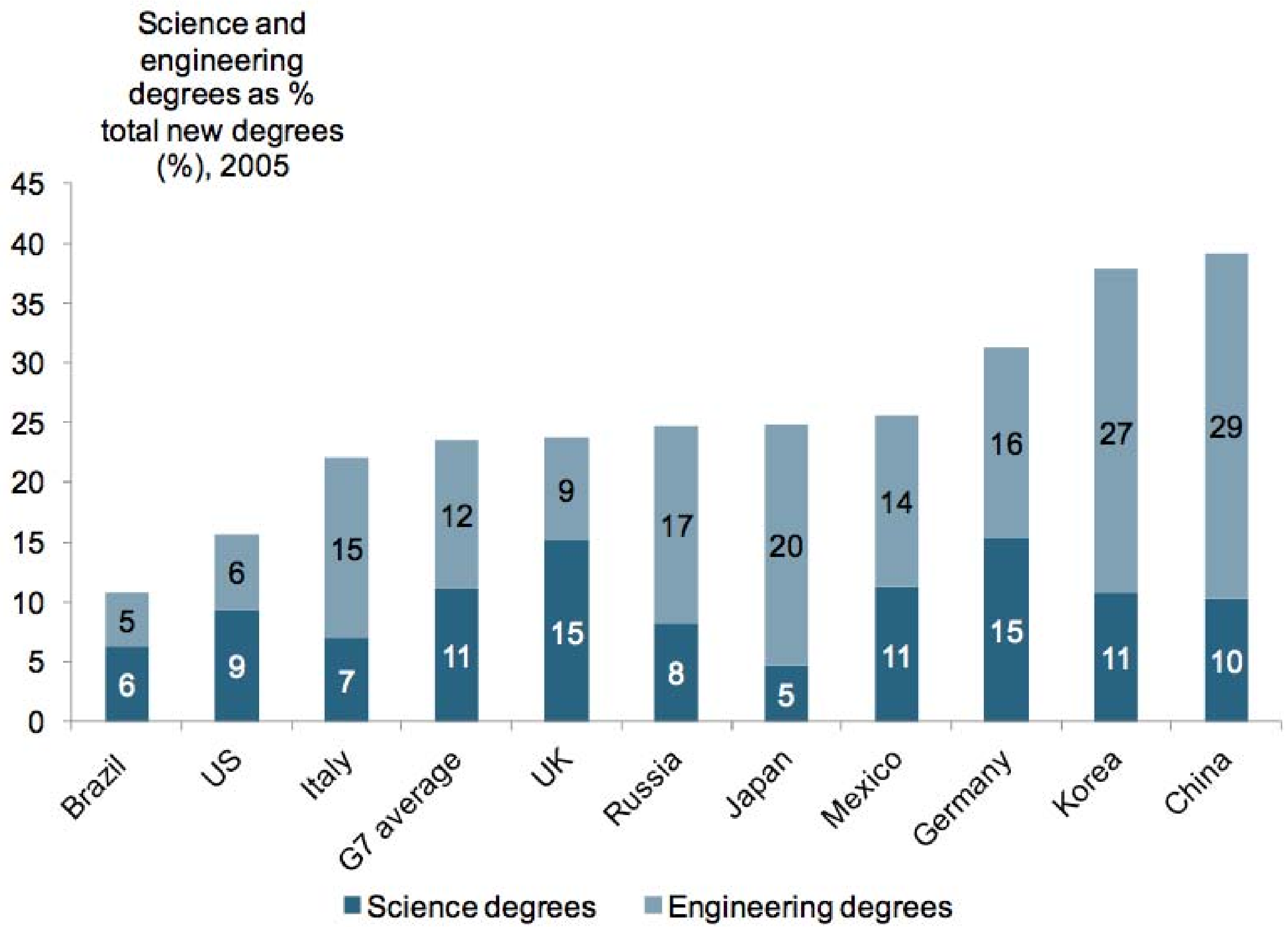


China's stated 2020 target: 2.5% of GDP

From Gilman, D. "The new geography of global innovation." Goldman Sachs Global Markets Institute, Sept. 20, 2010. (PDF)

Exhibit 12: S&E interest in Asia now 2.6X US levels ...

40% of all new degrees in China are in S&E fields, compared to 15% in the United States



Source: OECD, Global Markets Institute.

From Gilman, D. "The new geography of global innovation." Goldman Sachs Global Markets Institute, Sept. 20, 2010. (PDF)

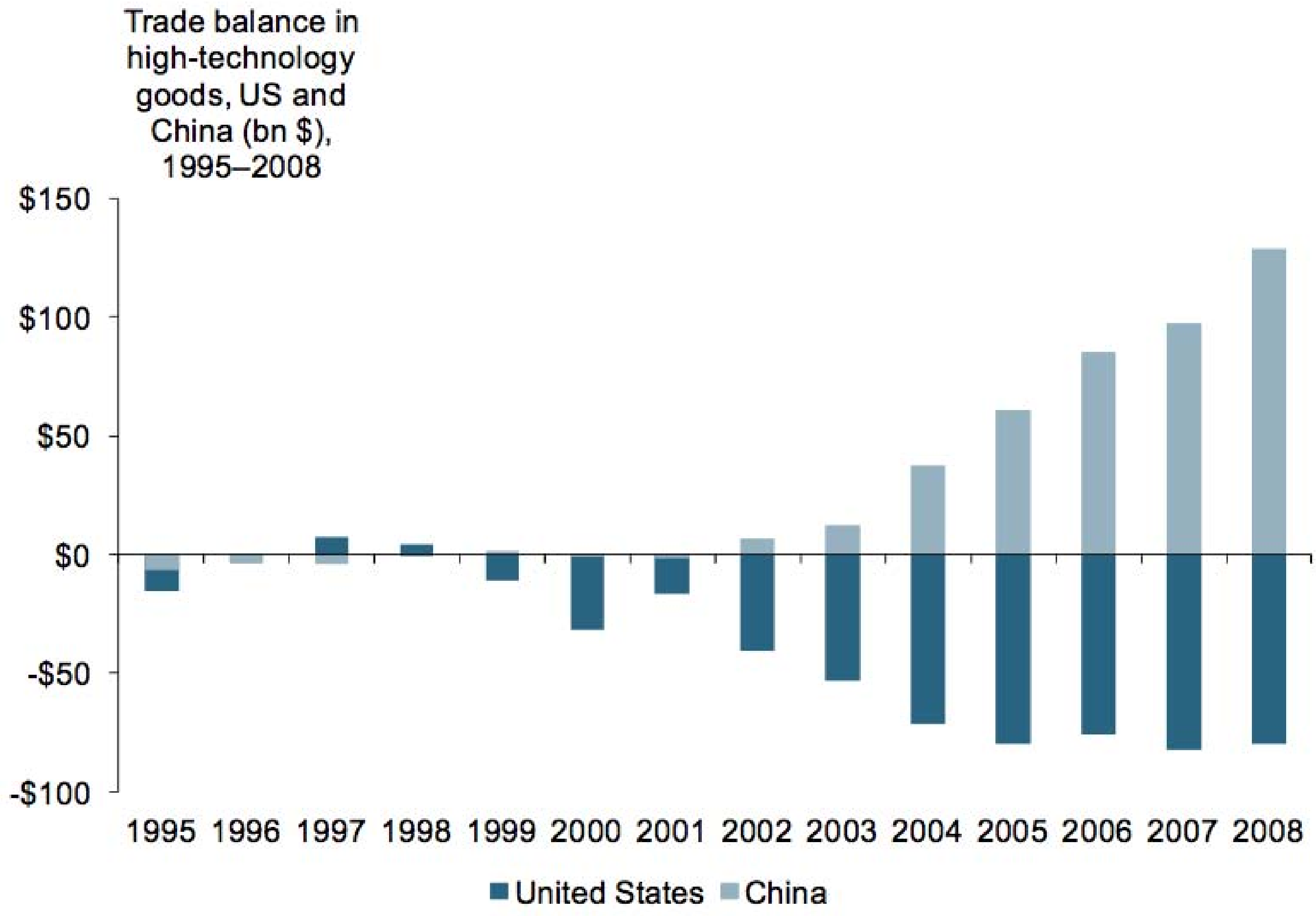
Exhibit 7: Global research output shifts toward Asia…

Source: National Science Foundation, Global Markets Institute.

From Gilman, D. "The new geography of global innovation." Goldman Sachs Global Markets Institute, Sept. 20, 2010. (PDF)

Exhibit 9: High-tech trade balances continue to widen …

China's trade balance in high-tech goods now $129 bn



Source: National Science Foundation.

From Gilman, D. "The new geography of global innovation." Goldman Sachs Global Markets Institute, Sept. 20, 2010. (PDF)

Technology Evaluation

Task: Evaluate a New PV Tech

- Why?
  - You’re a job applicant
  - You’re an inventor
  - You’re an investor
- How?
  - Analyze physics
  - Analyze cost, scale potential & manufacturing
  - Analyze markets

2.626/2.627: Fundamentals

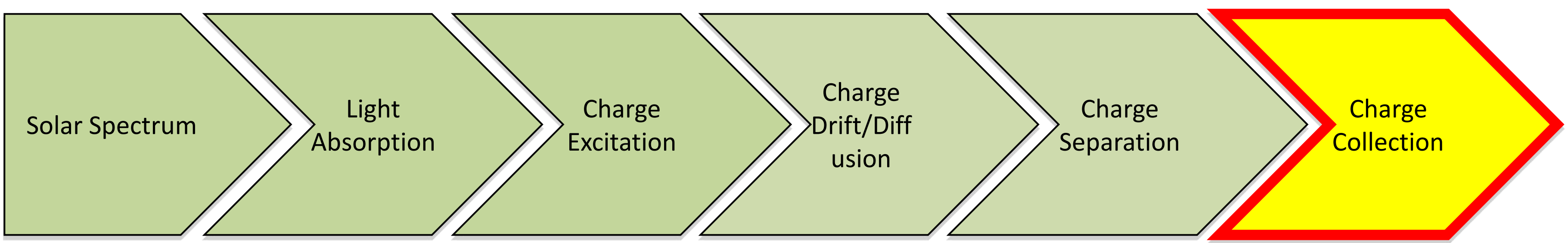
Every photovoltaic device must obey:

$$\text{Conversion Efficiency } (\eta) \equiv \frac{\text{Output Energy}}{\text{Input Energy}}$$

For most solar cells, this breaks down into:

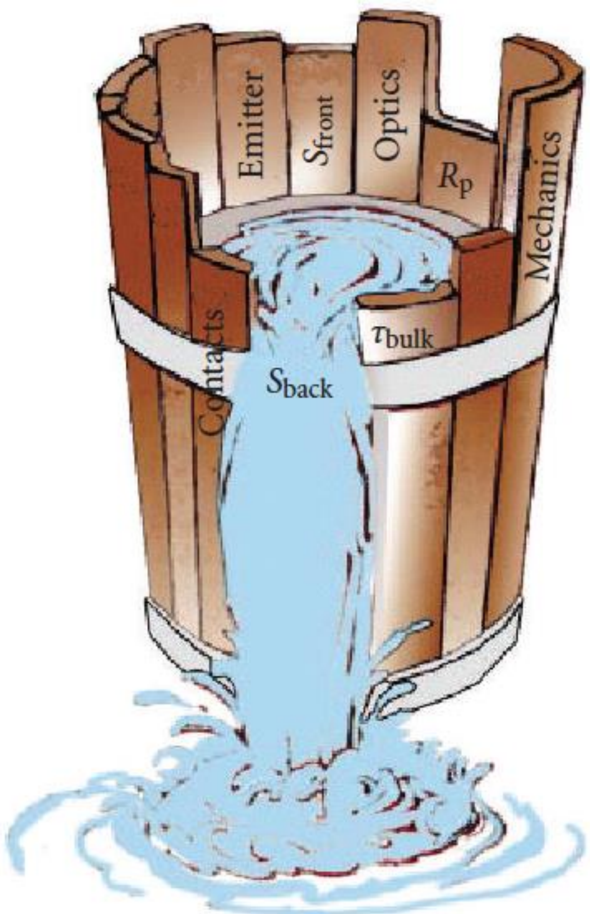
Inputs

Outputs



$$\eta_{\text{total}} = \eta_{\text{absorption}} \times \eta_{\text{excitation}} \times \eta_{\text{drift/diffusion}} \times \eta_{\text{separation}} \times \eta_{\text{collection}}$$

Liebig's Law of the Minimum



S. Glunz, *Advances in Optoelectronics* 97370 (2007)

$$\eta_{total} = \eta_{absorption} \times \eta_{excitation} \times \eta_{drift/diffusion} \times \eta_{separation} \times \eta_{collection}$$

Customer Needs

on-grid **off-grid** **consumer** **high efficiency**

Images removed due to copyright restrictions.
See the lecture 20 video.

Levers of Cost

Table 1: A simple model for module efficiency impacts on module cost.

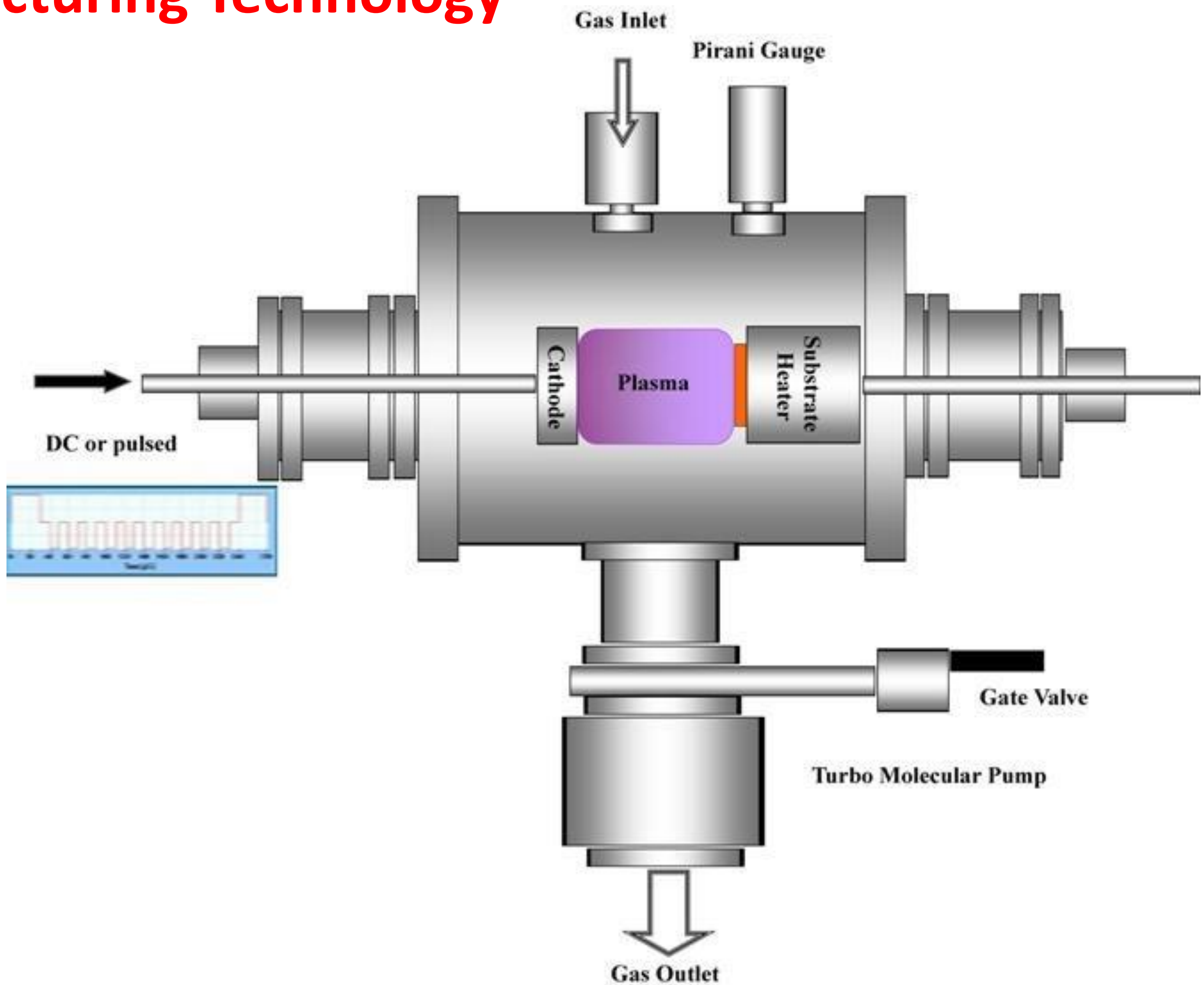
Wafer Cost ($/m²)	Cell Process Cost ($/m²)	Module Process Cost ($/m²)	Module Efficiency (%)	Module Manufacturing Cost ($/watt)
W_{hi}	$C \times W_{hi}$	$M \times W_{hi}$	η_{hi}	$W_{hi}(1 + C + M)/1000\eta_{hi}$
W_{low}	$C \times W_{hi}$	$M \times W_{hi}$	η_{low}	$(W_{low} + W_{hi}[C + M])/1000\eta_{low}$
Equating manufacturing costs: $W_{low}/W_{hi} = 1 - (1 - \eta_{low}/\eta_{hi})(1 + C + M)$				

T. Surek et al., Proc. 3rd World Conference on Photovoltaic Energy Conversion, Osaka, Japan (2009)

Cost Levers:

- Efficiency
- Processing Costs ($/m²)
- Manufacturing Yield
- Capital equipment cost
- Overhead…
- Other…

Manufacturing Technology



Vacuum Based: Large capex, Potential for high performance

Resource Availability, Scaling

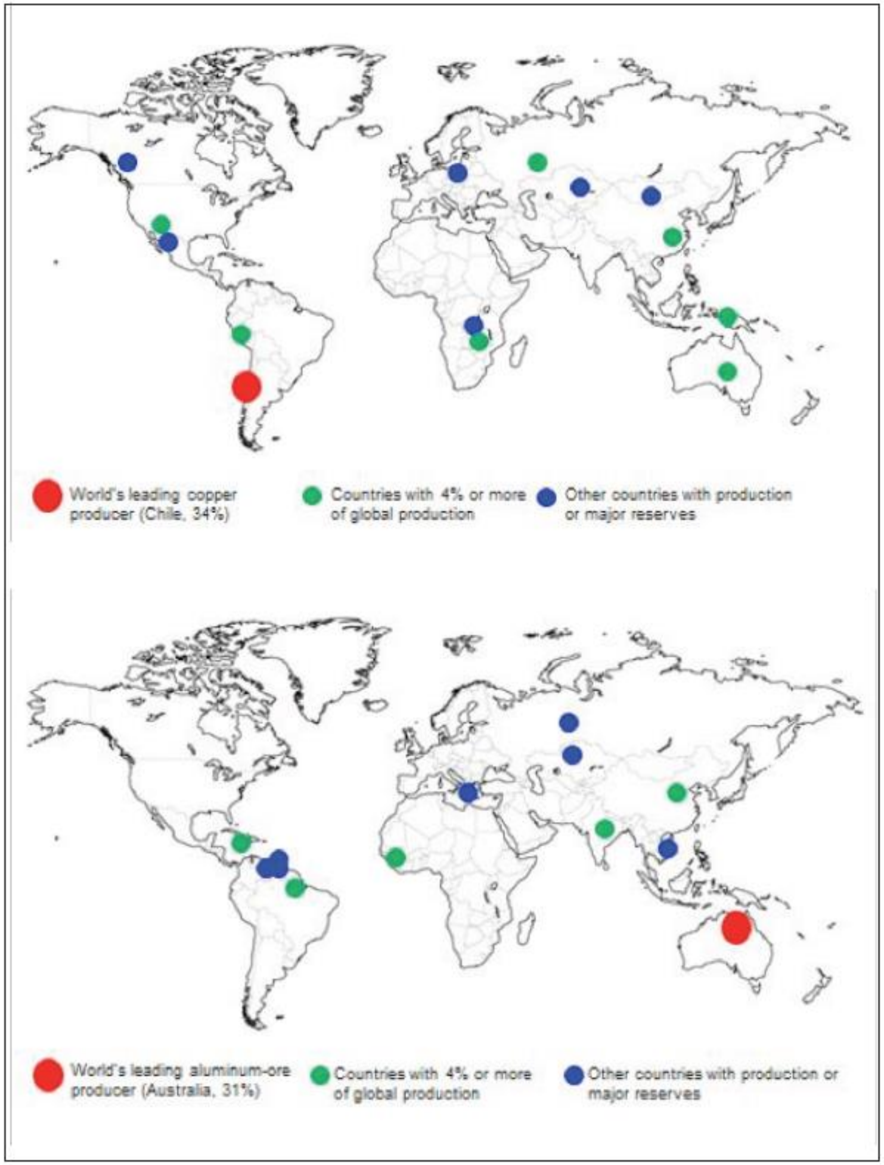
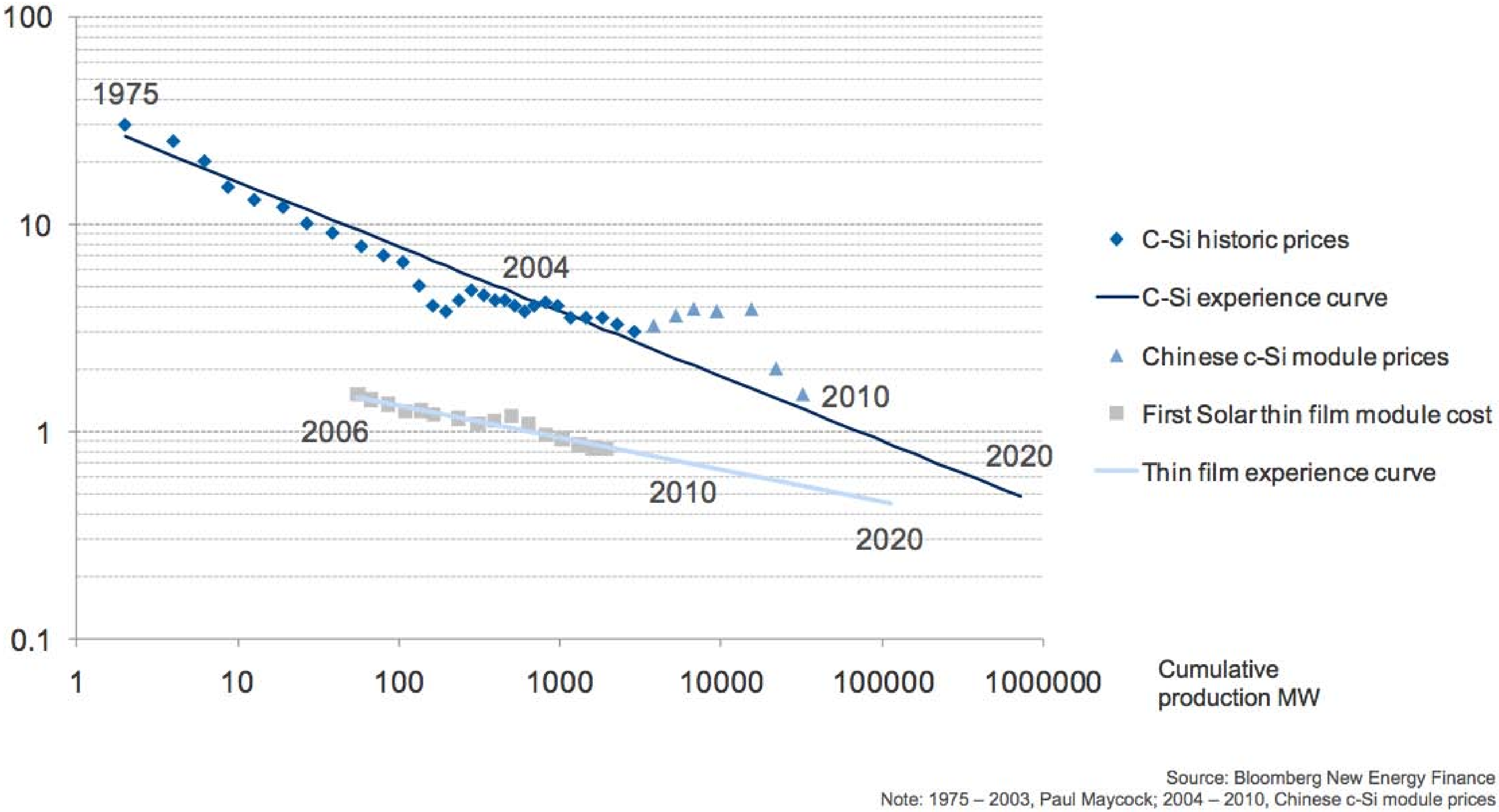


Figure 2. Leading copper producing countries in 2009 were Chile (34% of global production), Peru (8%), U.S. (8%), China (6%), Indonesia (6%), Australia (6%), Russia (5%), Zambia (4%), Canada (3%), Poland (3%), Kazakhstan (3%), and Mexico (2%); Mongolia and the Democratic Republic of Congo have major, recently discovered reserves. Leading aluminum-ore (bauxite) producing countries in 2009 were Australia (31%), China (18%), Brazil (14%), India (11%), Guinea (8%), Jamaica (4%), Kazakhstan (2%), Venezuela (2%), Suriname (2%), Russia (2%), Greece (1%), and Guyana (0.6%); Vietnam also has major reserves. Note that aluminum metal production (from bauxite) is concentrated in countries with inexpensive electricity (such as Iceland) due to the energy intensive nature of the aluminum production process. Production data are from the USGS (2010), plotted on a base map from http://english.freemap.jp/world_e/2.html.

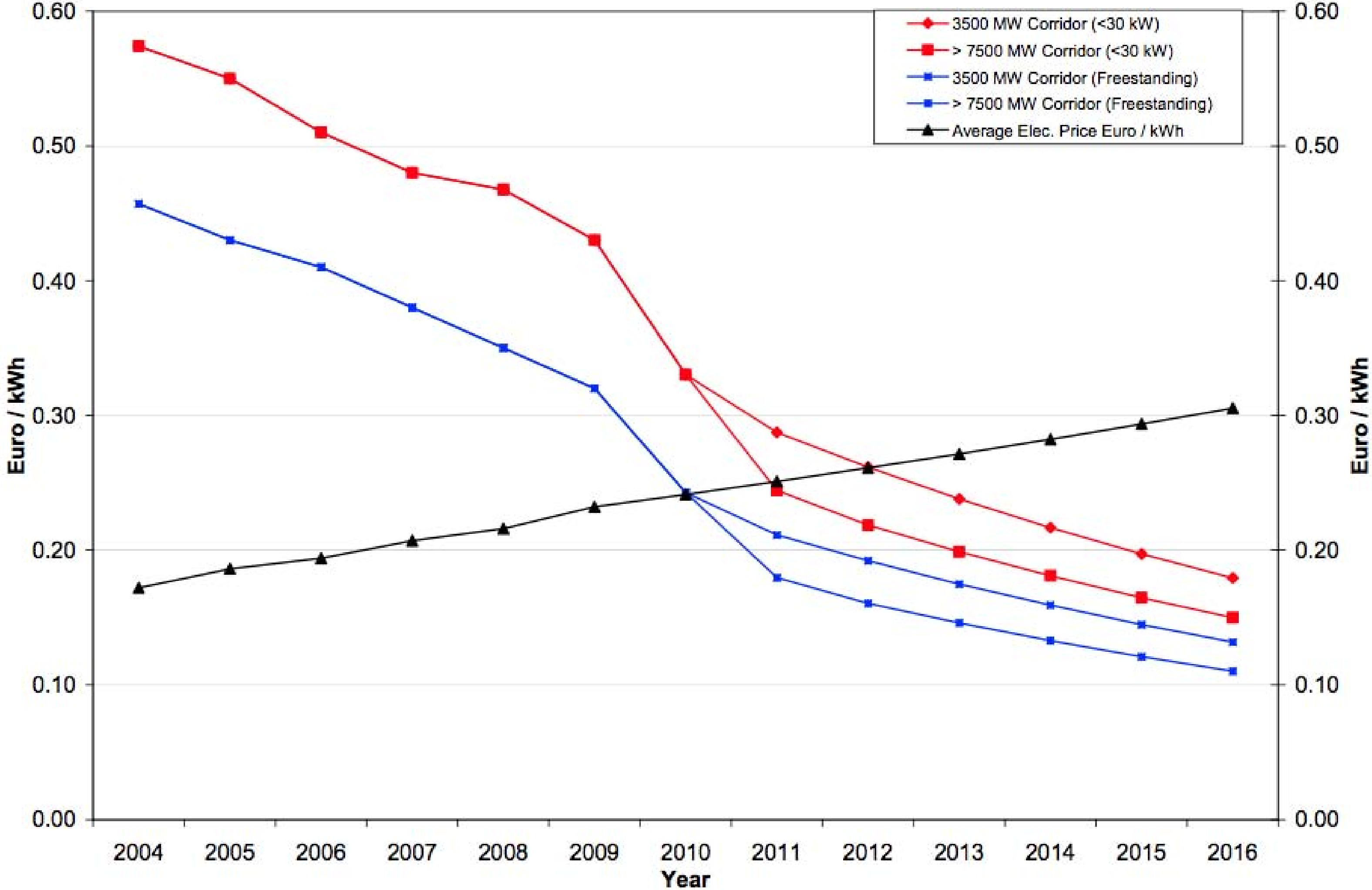
http://www.aps.org/publications/apsnews/201103/energycritical.cfm

Solar PV module prices 1975 - 2010 ($/Wp)



Source: Michael Liebreich (chief executive, Bloomberg New Energy Finance) testimony at "The Global Clean Energy Race," hearing of House Select Committee on Energy Independence and Global Warming, September 22, 2010. Testimony slides (PDF).

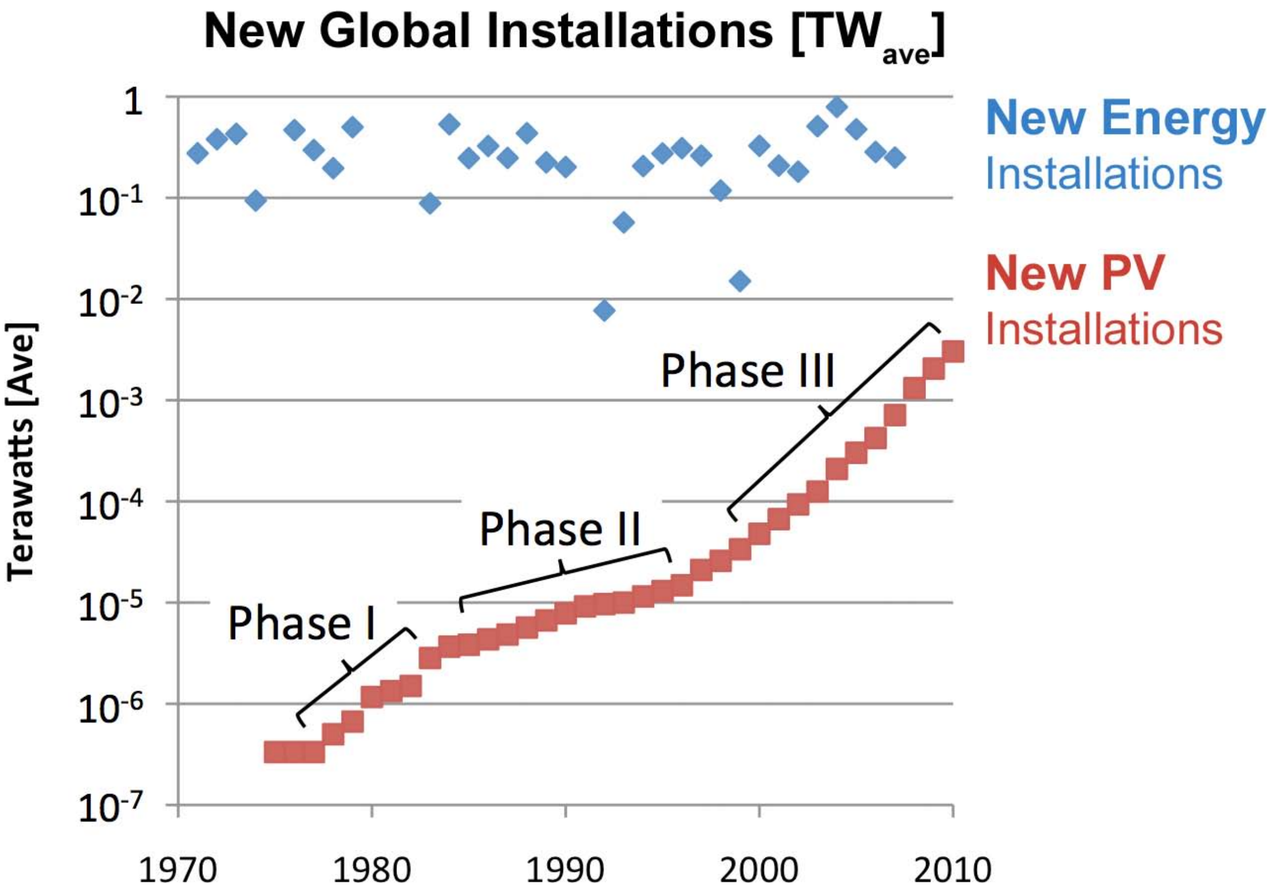
Exhibit 10: Retail rates vs. PV degression



Source: DBCCA research

Deutsche Bank Climate Change Advisors. "The German Feed-in Tariff for PV: Managing Volume Success with Price Response." May 23, 2011. (PDF)

Convergence Between PV and Conventional Energy Scale



Inception (Phase I: 1977–1981, 50% CAGR). Carter president, SERI ramps up.

Stagnation (Phase II: 1985–1995, 12% CAGR). Oil prices & government support plunge. PV manufacturing sustained by big oil (BP Solar, Mobil Tyco).

Scale (Phase III: 2000–2010, 48% CAGR) Strong government subsidies for installation & manufacturing in JPN, DE, US, EU, CN. PV manufacturing led by electronic (Sharp) & "pure-plays" (Q-Cells, First Solar, Suntech).

Other Intangibles

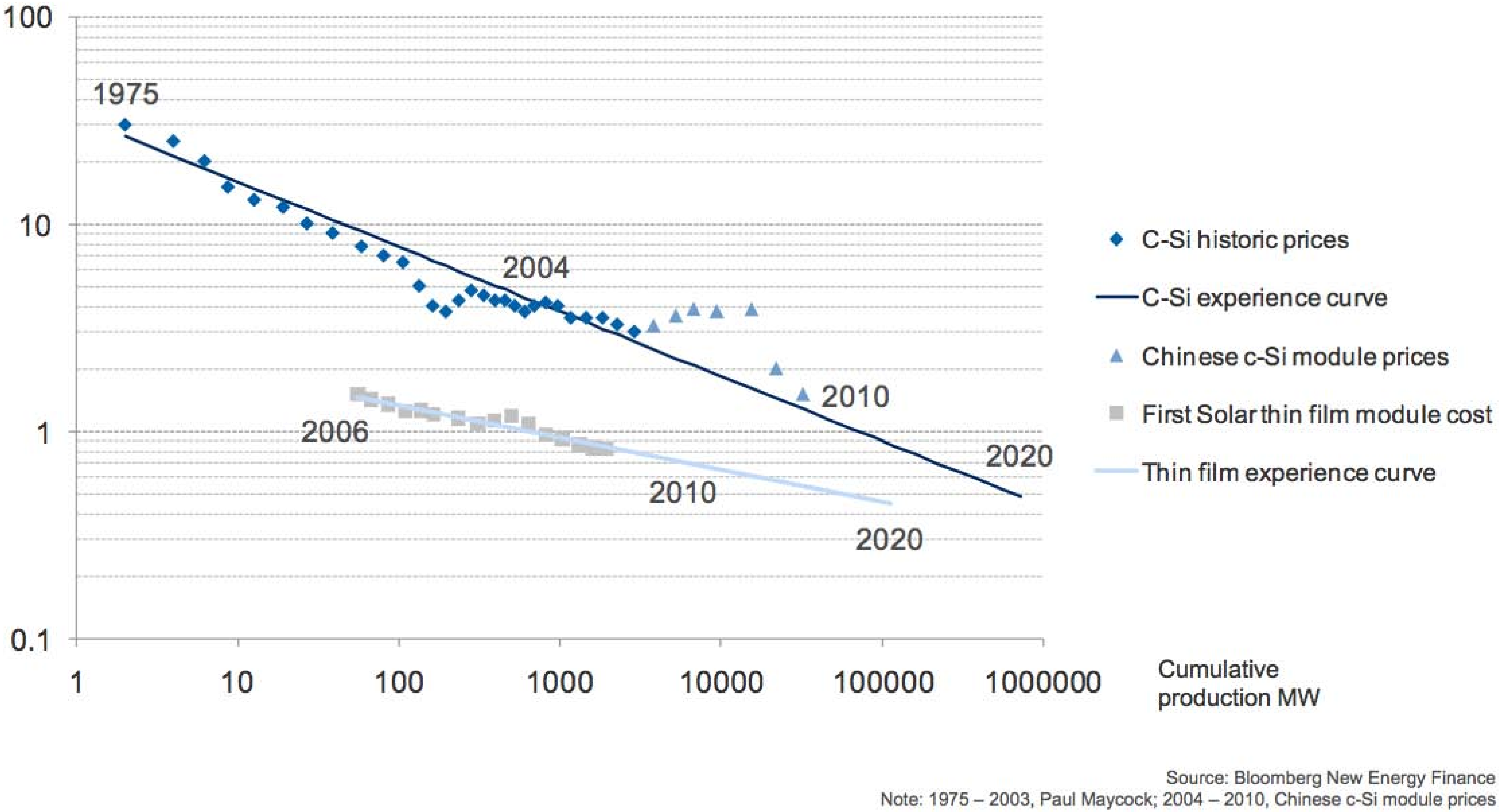
- Team
- Financing
- Patent Portfolio
- …

Examples

- Solar Paint
- Wundermaterial

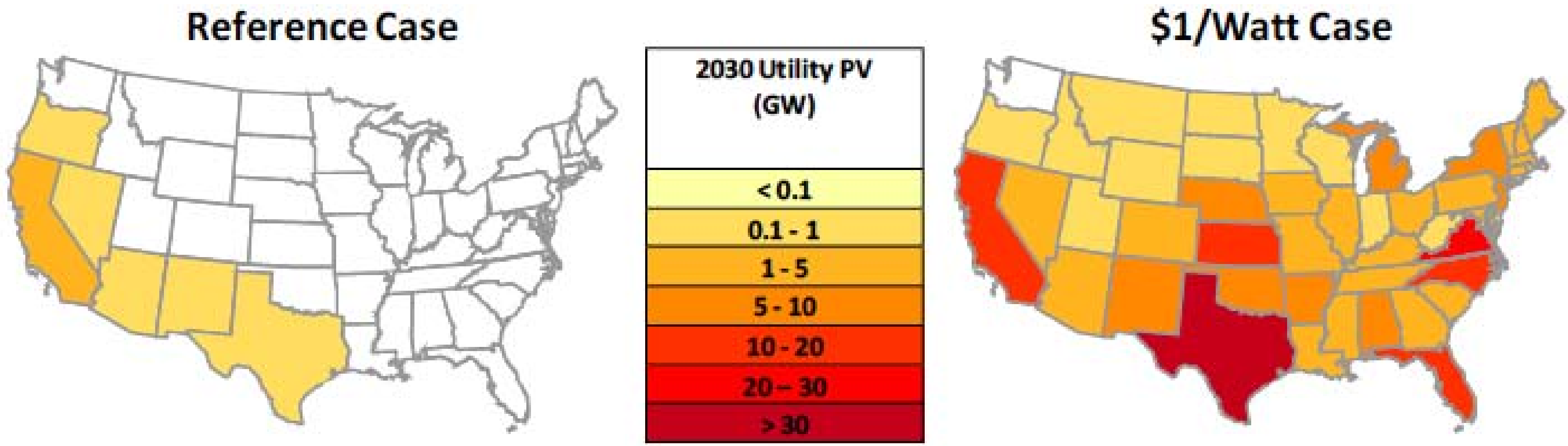
Path Forward

Solar PV module prices 1975 - 2010 ($/Wp)



Source: Michael Liebreich (chief executive, Bloomberg New Energy Finance) testimony at "The Global Clean Energy Race," hearing of House Select Committee on Energy Independence and Global Warming, September 22, 2010. Testimony slides (PDF).

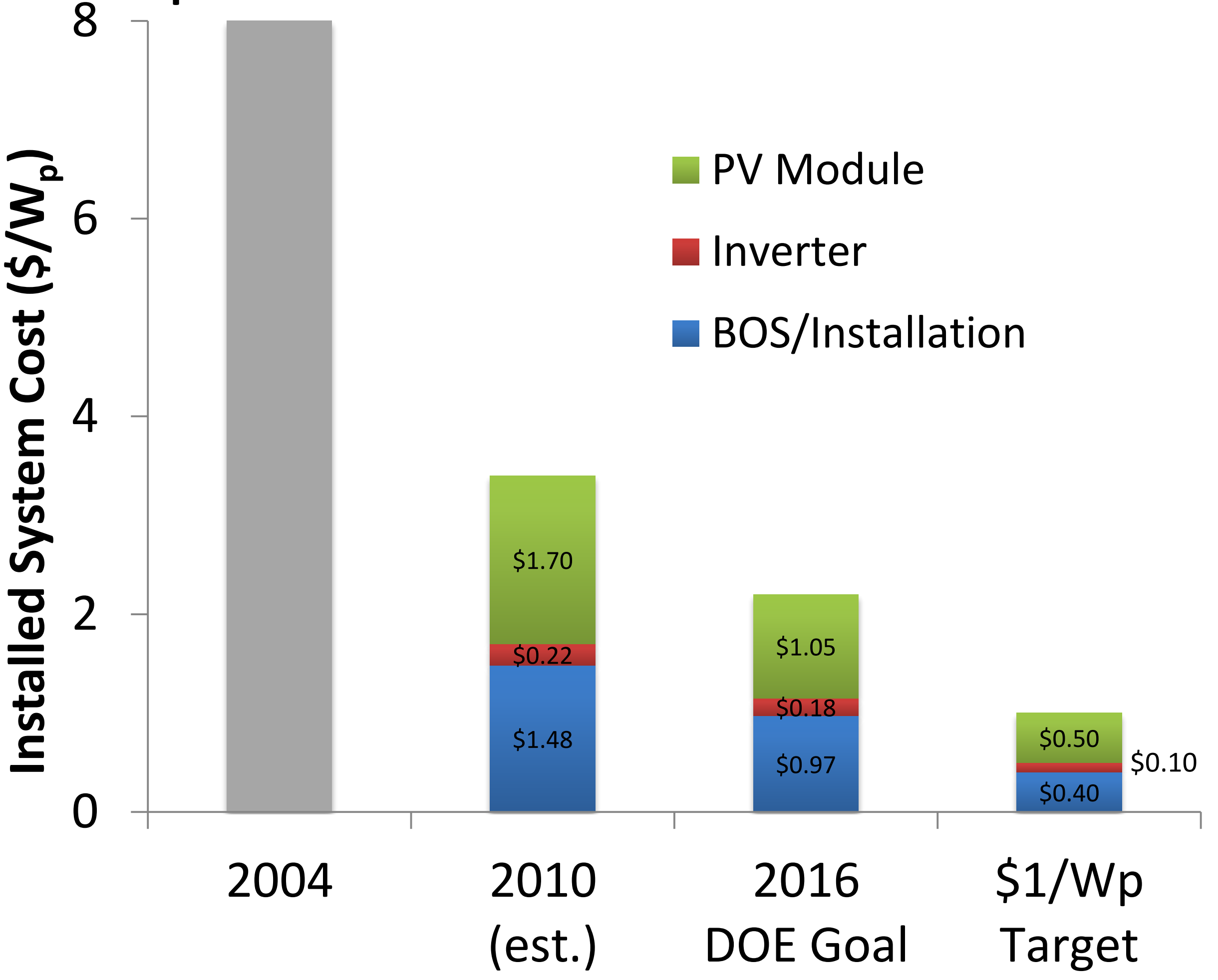
Cost Tipping Point



Source: U.S. Department of Energy

- Premise: High cost of PV limits market adoption.
- At $1 per peak watt ($W_p$), PV electricity ~5¢/kWh.
- At 5¢/kWh cost, PV cost-competitive with bulk electricity in most US states.

Towards $1/W_p$



>3x PV module cost reduction necessary for $1/W_p$.

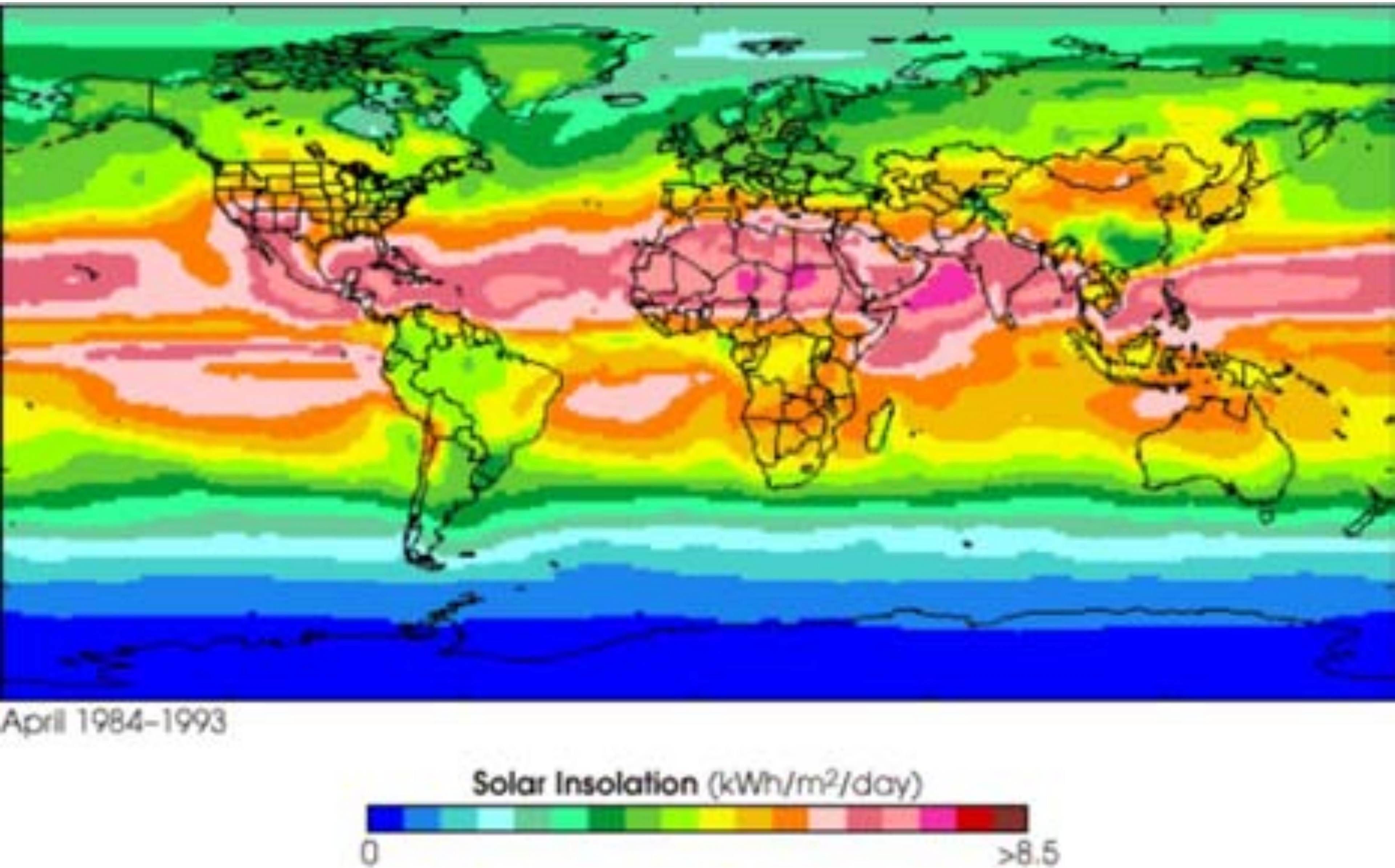
Buonassisi (MIT) 2011

Electricity Consumption

The World at Night

Source: NASA (public domain)

Solar Resource

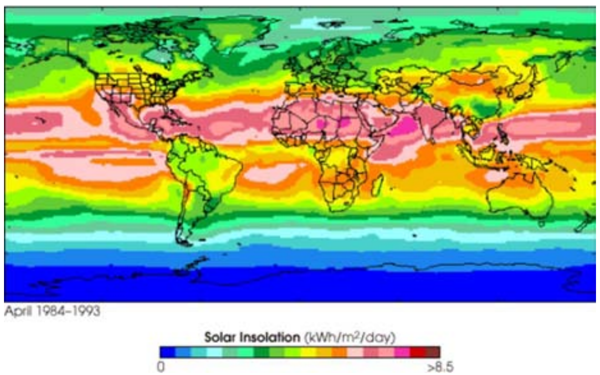


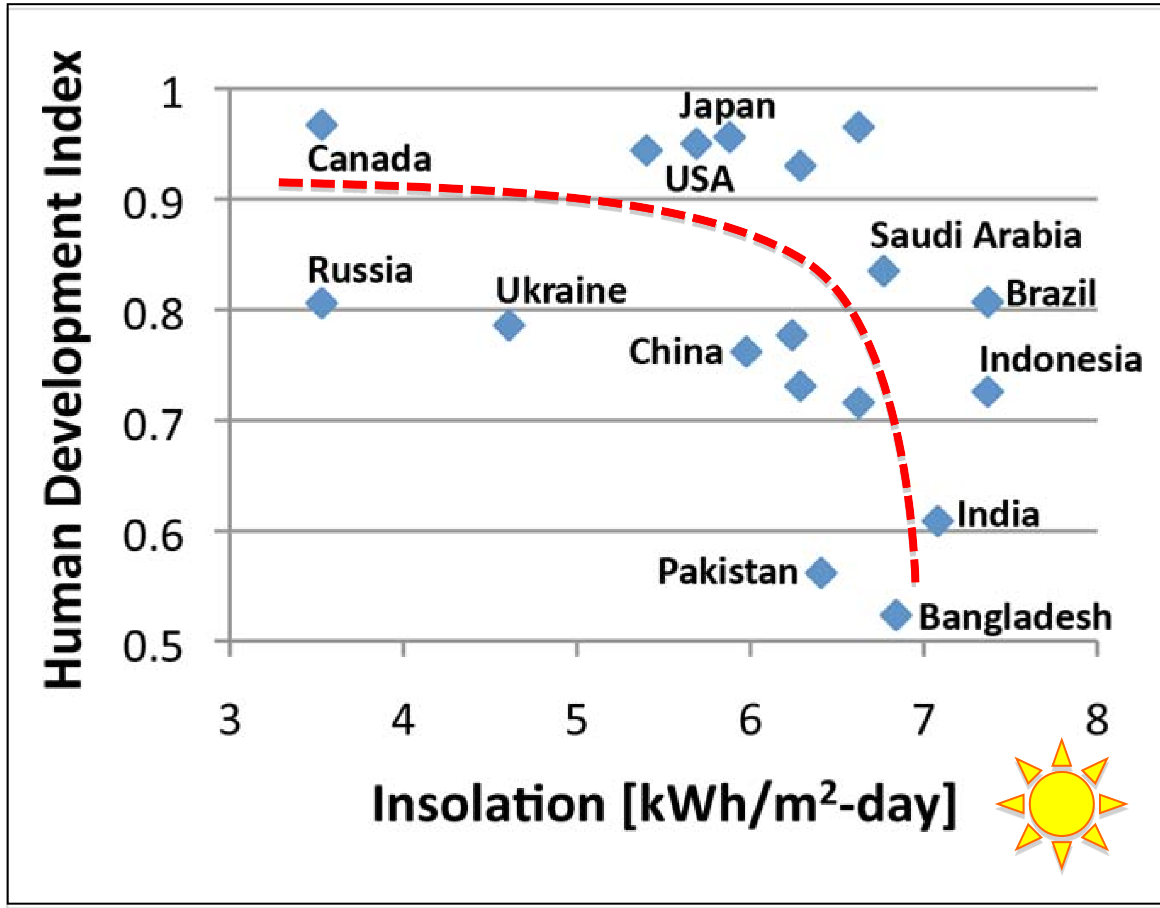
Source: NASA Earth Observations (public domain)

http://neo.sci.gsfc.nasa.gov/Search.html

Solar Supply Well Matched to Future Energy Demand

Source: NASA Earth Observations (public domain)





http://eosweb.larc.nasa.gov/sse/

Need for Innovation in PV

- 99% of solar panels have yet to be produced.
- $6bi VC investment lost is drop in bucket compared to GDP. (There will be others).
- Momentum, capital, innovation culture.

BUT…

- Rest of world catching up fast, increased competition.
- Need concerted R&D efforts focused on key targets. Better investments, smarter choice of technologies.
- Need to change the way we innovate: leverage collaborative work, pooled resources, improve industry-university-lab relations, direct-to-manufacturing innovation.
- Need for a steady, predictable market necessitates progressive & steady industrial policy.
- Need more investment in education.

How You Can Get Involved

- Expose yourself to new ideas, learn how the system works
  - Intern at the DOE
    - Advanced Research Projects Agency • Energy (DOE ARPA-E)
    - Solar Energy Technologies Program (DOE-EERE)
  - Do a UROP
    - Many options: http://pv.mit.edu/your-involvement/students/
    - http://web.mit.edu/MISTI/
  - Intern at a company
- Know your fundamentals (physics, chemistry, and biology). Become comfortable applying these to interdisciplinary problems.
- Choose meaningful use-inspired scientific project(s) grounded in solid economic motivation.
- Develop a strong interest in a value-added field, leverage any and all resources available to you, and excel at something you're passionate about (so you'll become 20x more productive than your global competitor).