Introduction to Fundamentals of Photovoltaics

Lecture 1 – Introduction

MIT Fundamentals of Photovoltaics
2.626/2.627 – Fall 2011

Prof. Tonio Buonassisi

Why Solar?

Energy: Fuel for Development

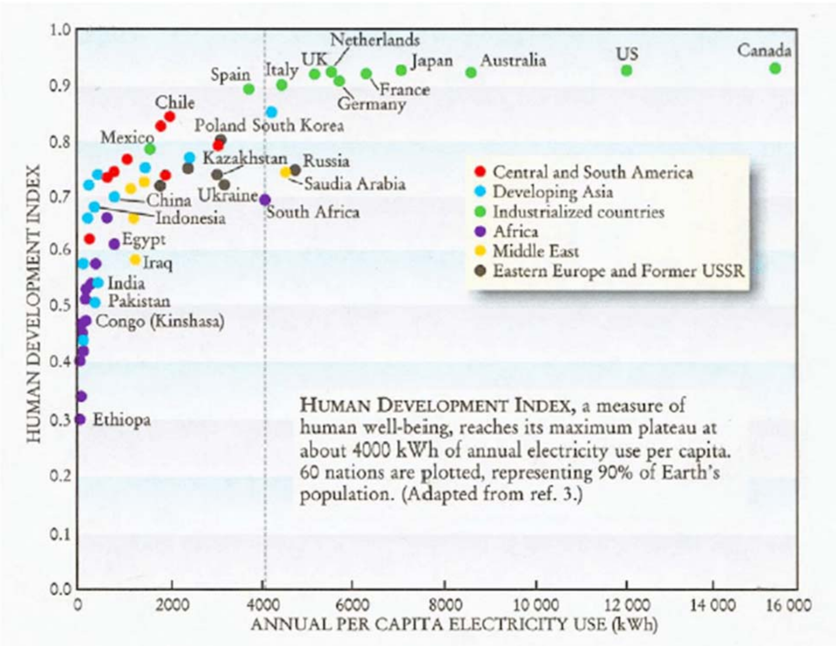
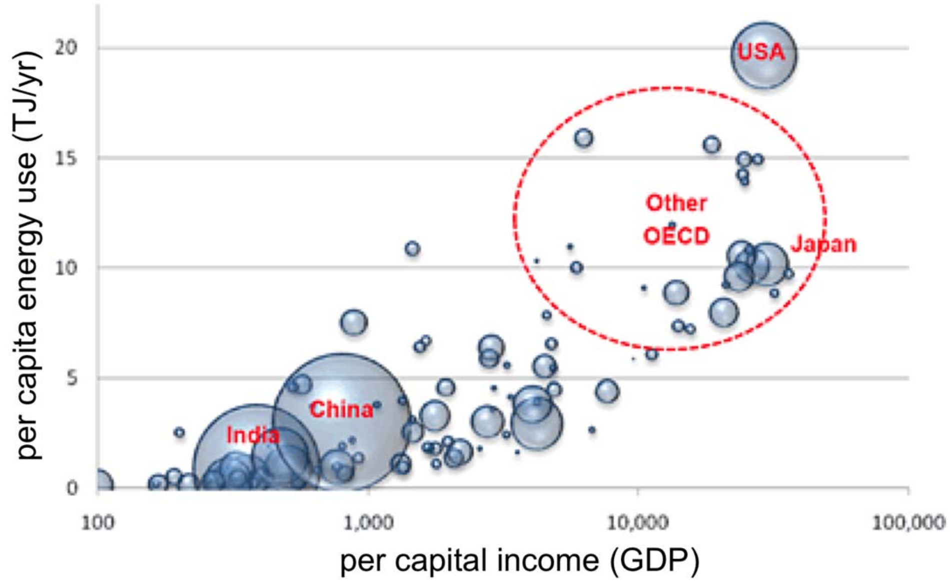


Figure 1.2. Human development index vs. per capita electricity use for selected countries. Taken from S. Benka, *Physics Today* (April 2002), pg 39, and adapted from A. Pasternak, Lawrence Livermore National Laboratory rep. no. UCRL-ID-140773.

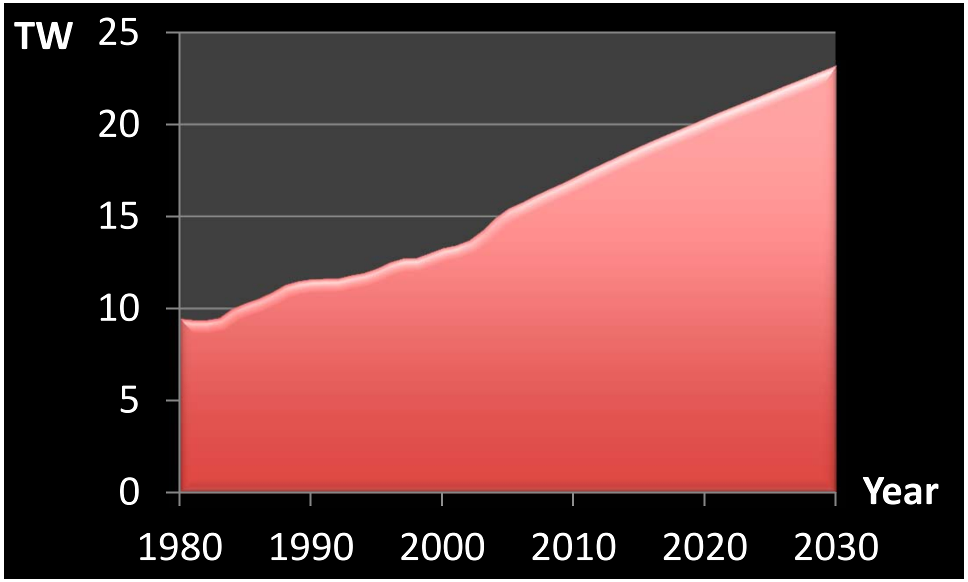
Source: Benka, Stephen G. "The Energy Challenge." *Physics Today* 55 (April 2002): 38-39.

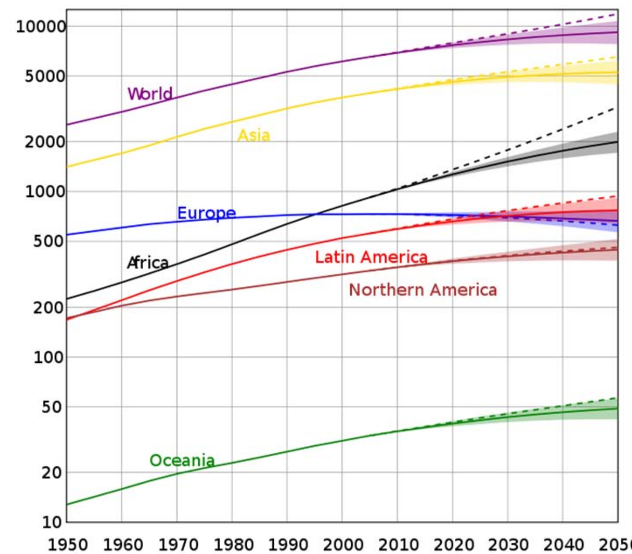


Source: David Roland-Holst, based on World Bank and IEA data

2011: 7 Billion People
2050: 7.5–11 Billion People

Human Energy Use





Solar Resource

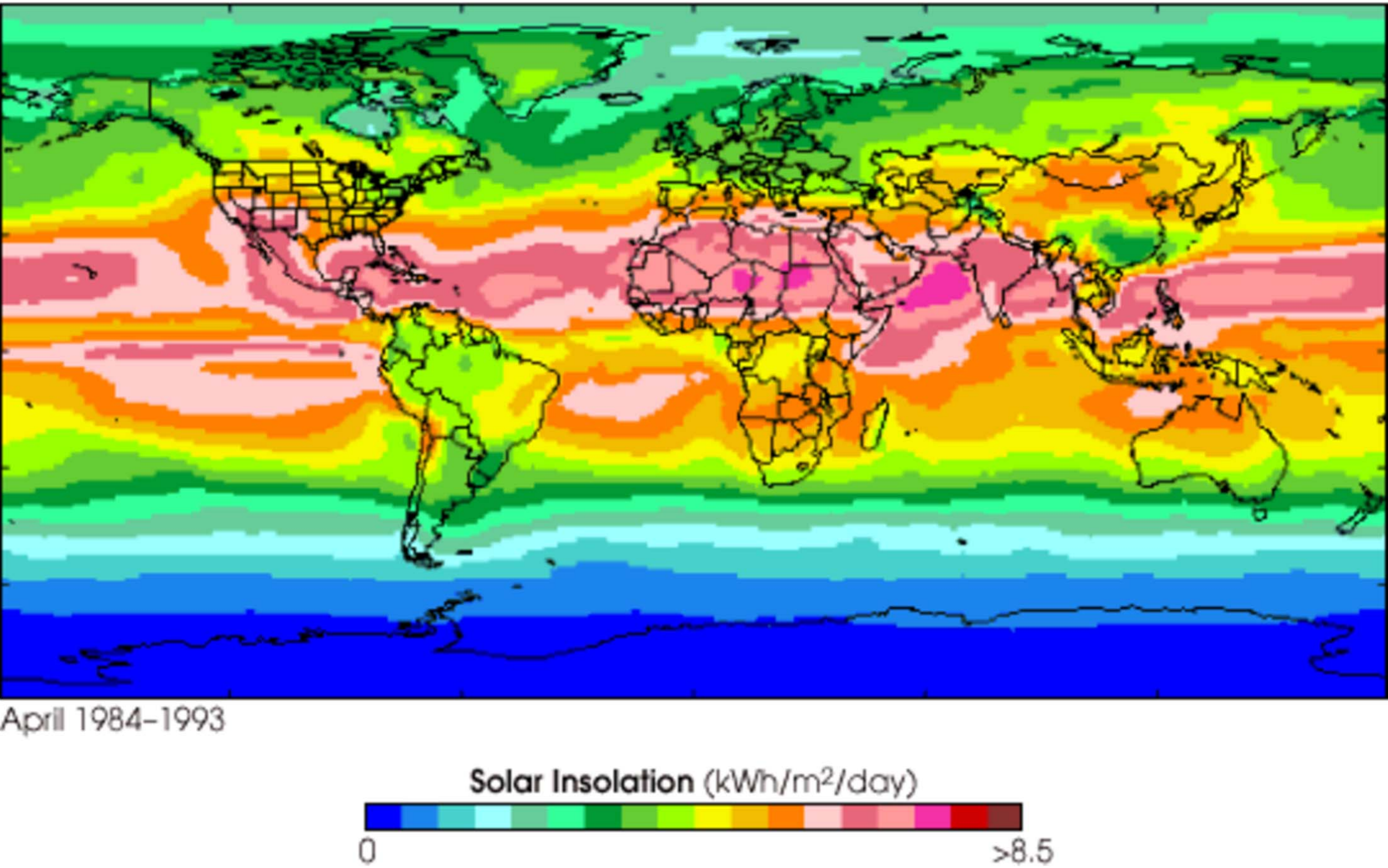
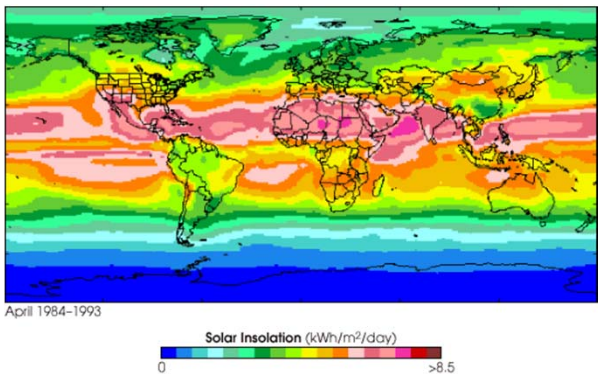


Image courtesy NASA Earth Observatory.

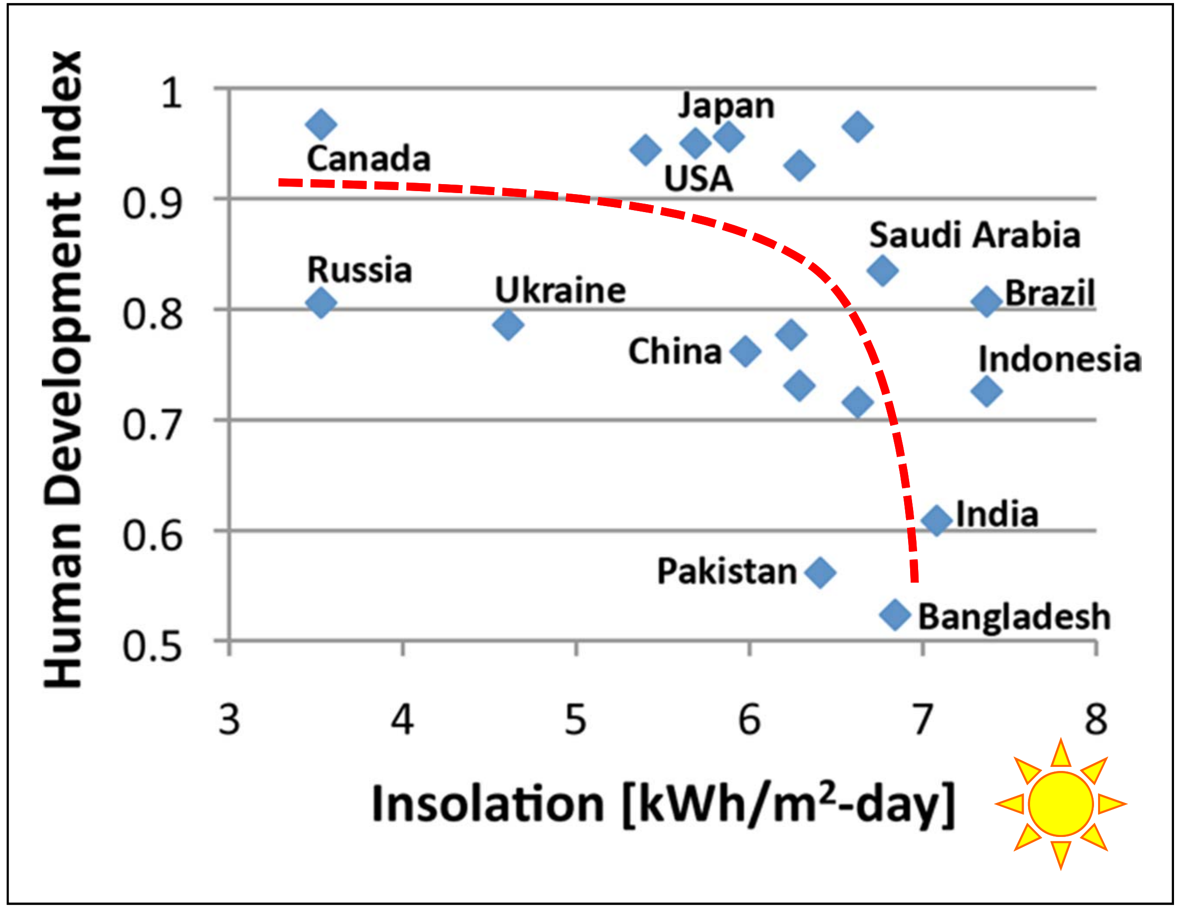
http://neo.sci.gsfc.nasa.gov/Search.html

Solar Supply Well Matched to Future Energy Demand



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

Image courtesy NASA Earth Observatory.



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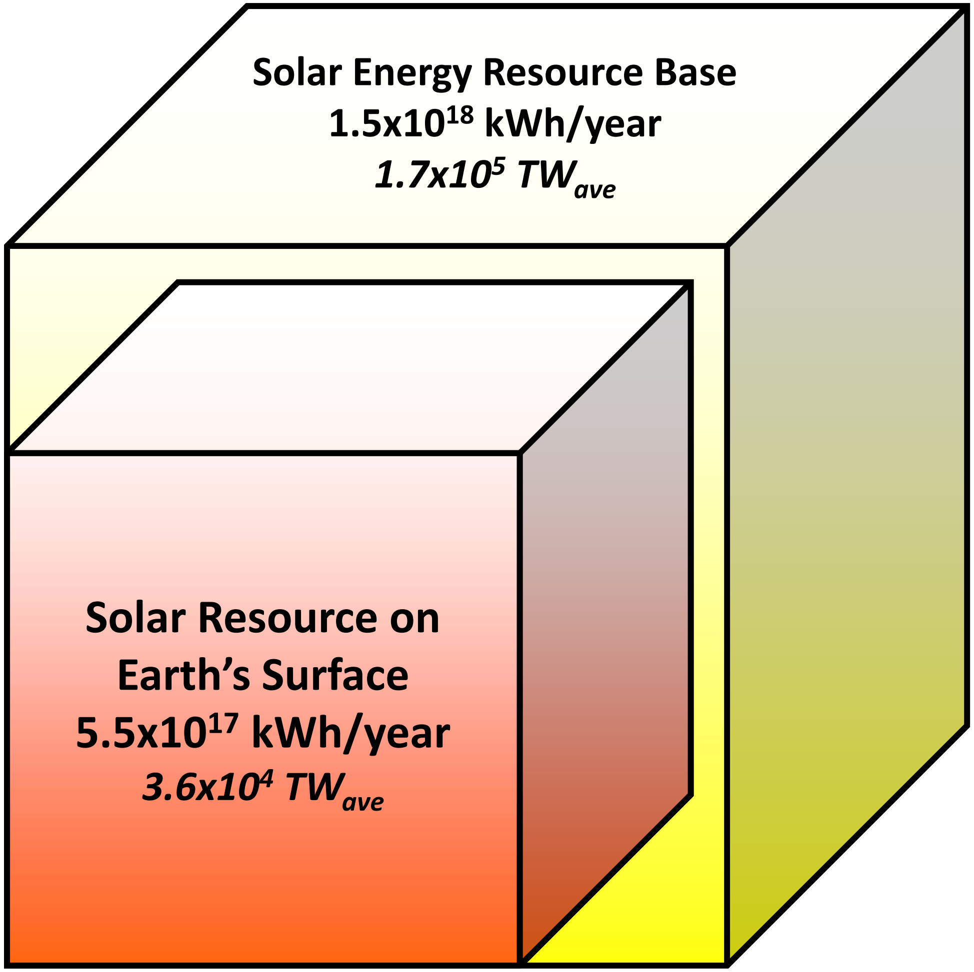
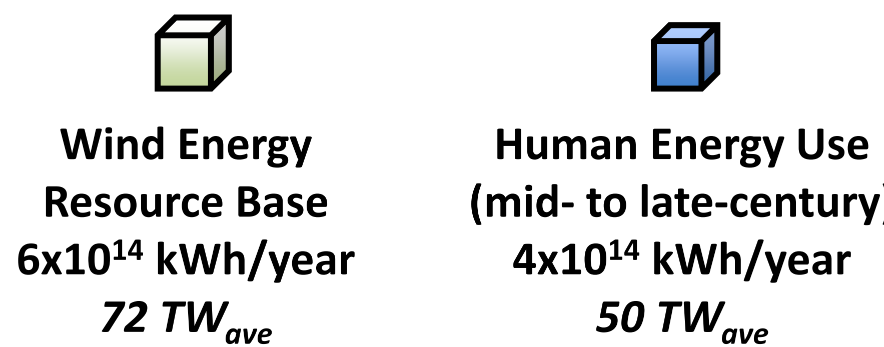
Solar Resource Base



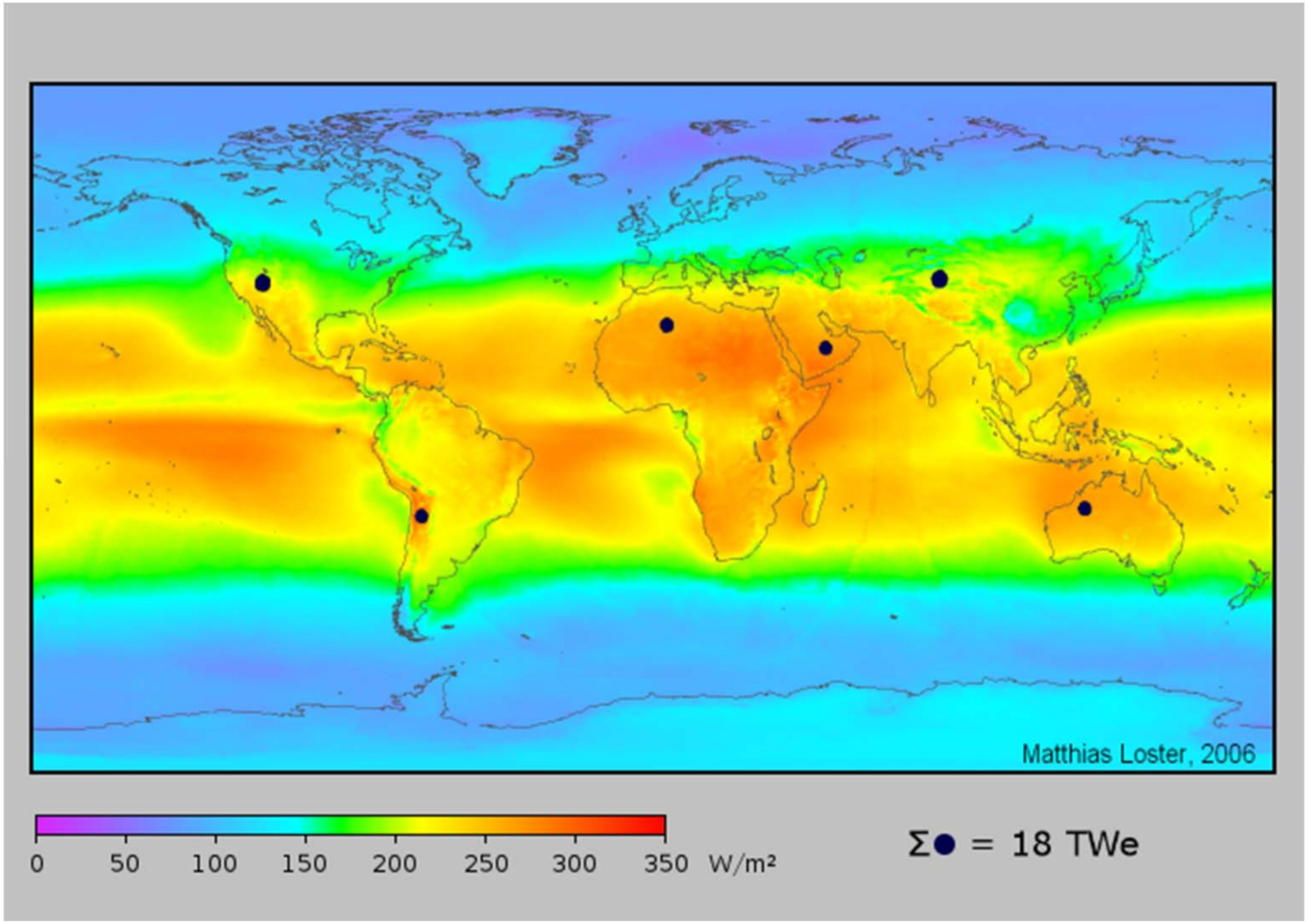


References:
Wind Energy: C.L. Archer and M.Z. Jacobson, *J. Geophys. Res.* **110**, D12110 (2005).

Potential of Solar Energy

The Sun is able to support TWs of demand:

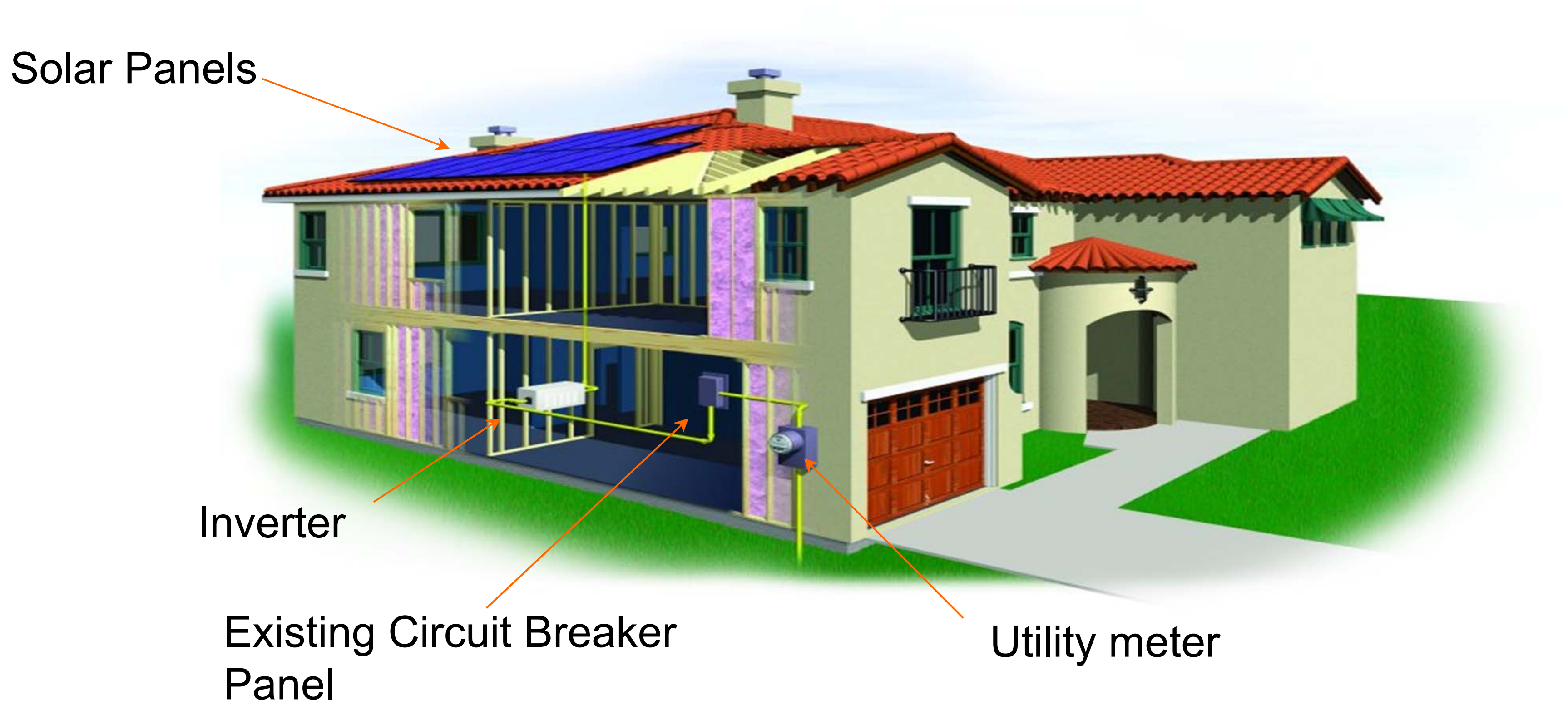
Average 9×10^4 TW incident on Earth; 450 TW practical to recover.



http://www.answers.com/topic/solar-power-1

18 TW = 6 Dots at 3 TW Each

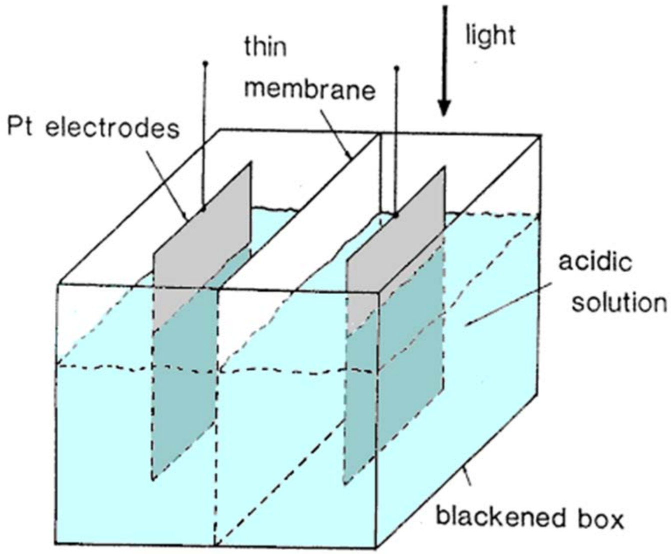
Residential Installations



Photovoltaics: Historical Perspective and Current Challenges

Rich History of Innovation

1839: Discovery of photovoltaic effect



http://pvcdrom.pveducation.org/MANUFACT/FIRST.HTM

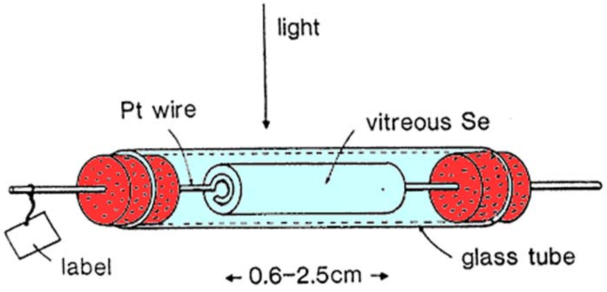
Mémoire sur les effets électriques produits sous l'influence des rayons solaires; par M. **Edmond Becquerel.**

E. Becquerel, "Mémoire sur les effets électriques produits sous l'influence des rayons solaires," *Comptes Rendus* **9**, 561–567 (1839)

http://en.wikipedia.org/wiki/File:Alexandre_Edmond_Becquerel,_by_Pierre_Petit.jpg

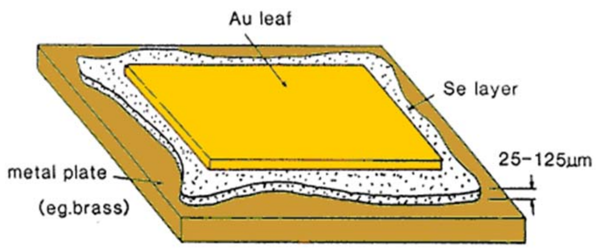
Rich History of Innovation

1877: Photoelectric effect in solid system



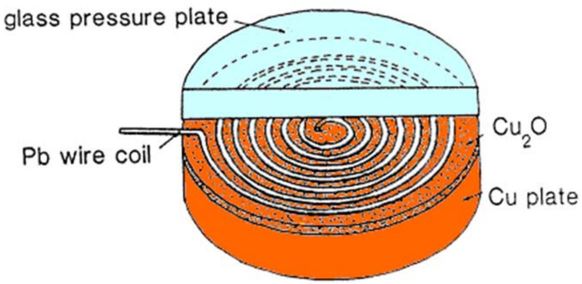
W.G. Adams and R.E. Day, “The Action of Light on Selenium,” *Proceedings of the Royal Society* **A25**, 113 (1877)

1883: Photovoltaic effect in sub-mm-thick films



C.E. Fritts, "On a new form of selenium photocell", *Proc. of the American Association for the Advancement of Science* **33**, 97 (1883)

1927: Evolution of solid-state PV devices



L.O. Grondahl, "The Copper-Cuprous-Oxide Rectifier and Photoelectric Cell", *Review of Modern Physics* **5**, 141 (1933).

Images from: http://pvcdrom.pveducation.org/MANUFACT/FIRST.HTM

Photovoltaic Device Fundamentals

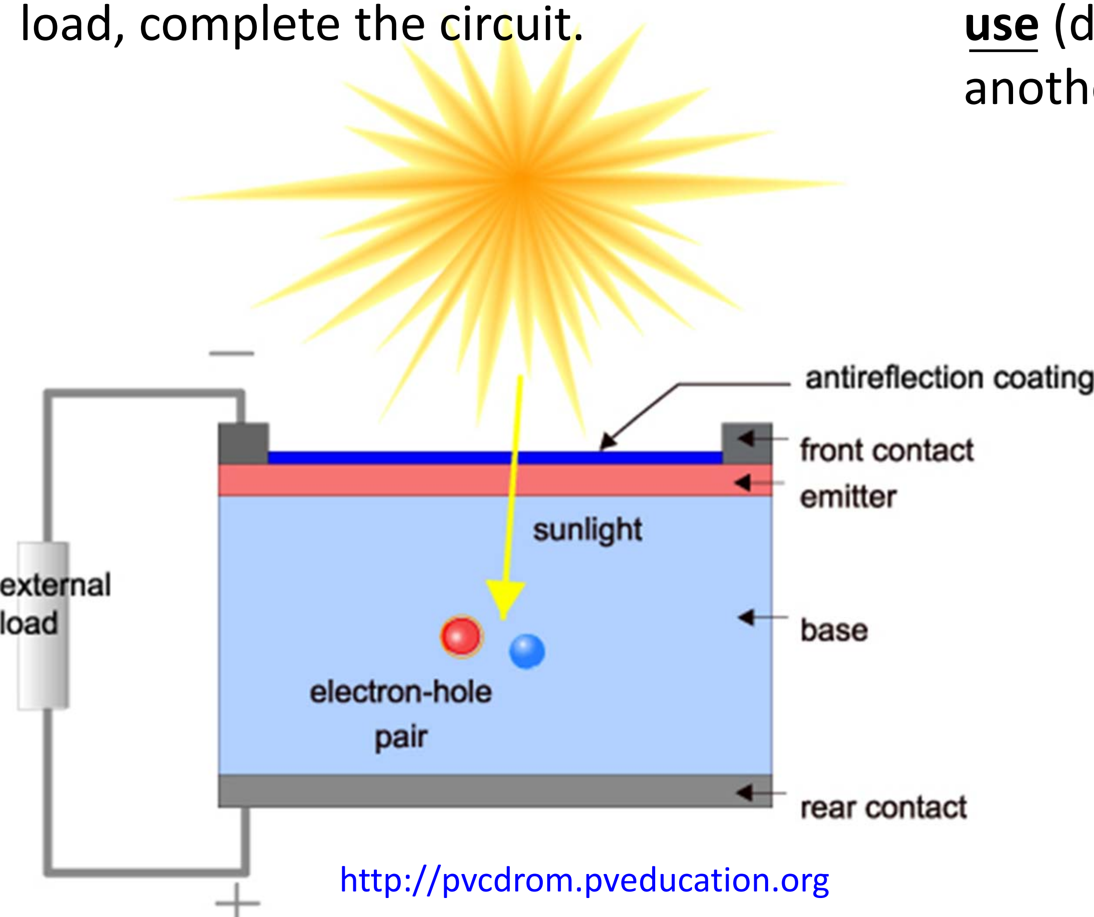
(1) Charge Generation: Light excites electrons, freeing them to move around the crystal.

(2) Charge Separation: An electric field engineered into the material (pn junction) sweeps out electrons.

(3) Charge Collection: Electrons deposit their energy in an external load, complete the circuit.

Advantages: There are no moving parts and no pollution created at the site of use (during solar cell production, that's another story).

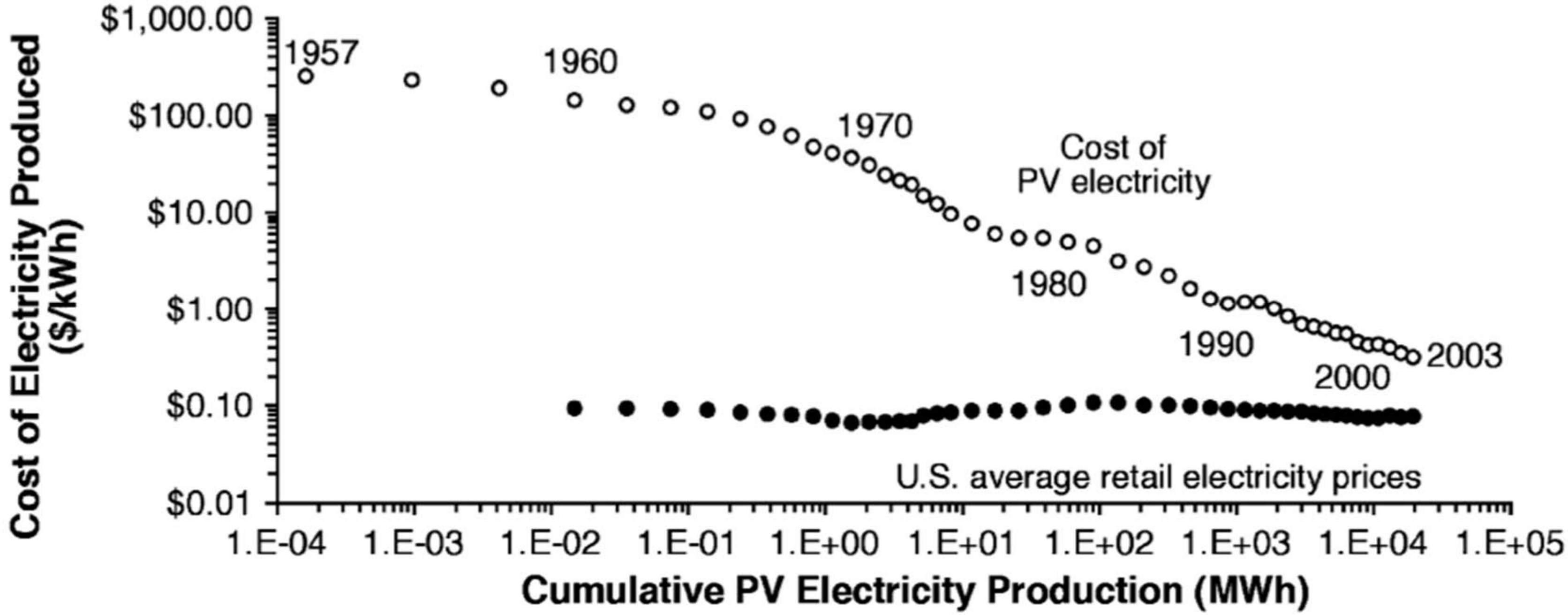
Disadvantages: No output at night; lower output when weather unfavorable.



http://pvcdrom.pveducation.org

How Solar Has Evolved Since Your Parents First Heard of It

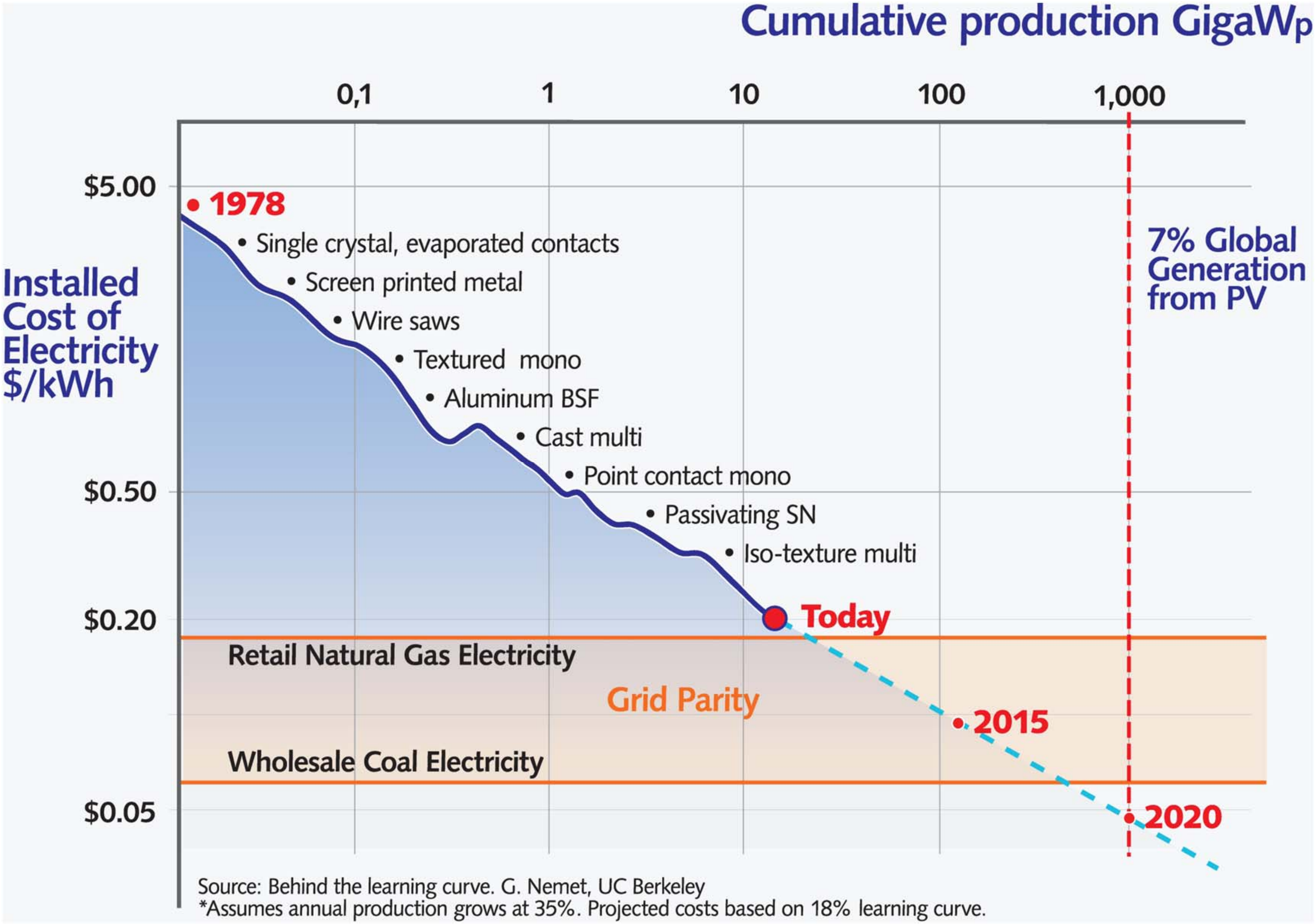
Convergence Between PV and Conventional Energy



US electricity prices and levelized cost of electricity produced from PV modules. Source: G.F. Nemet, *Energy Policy* **34**, 3218–3232 (2006).

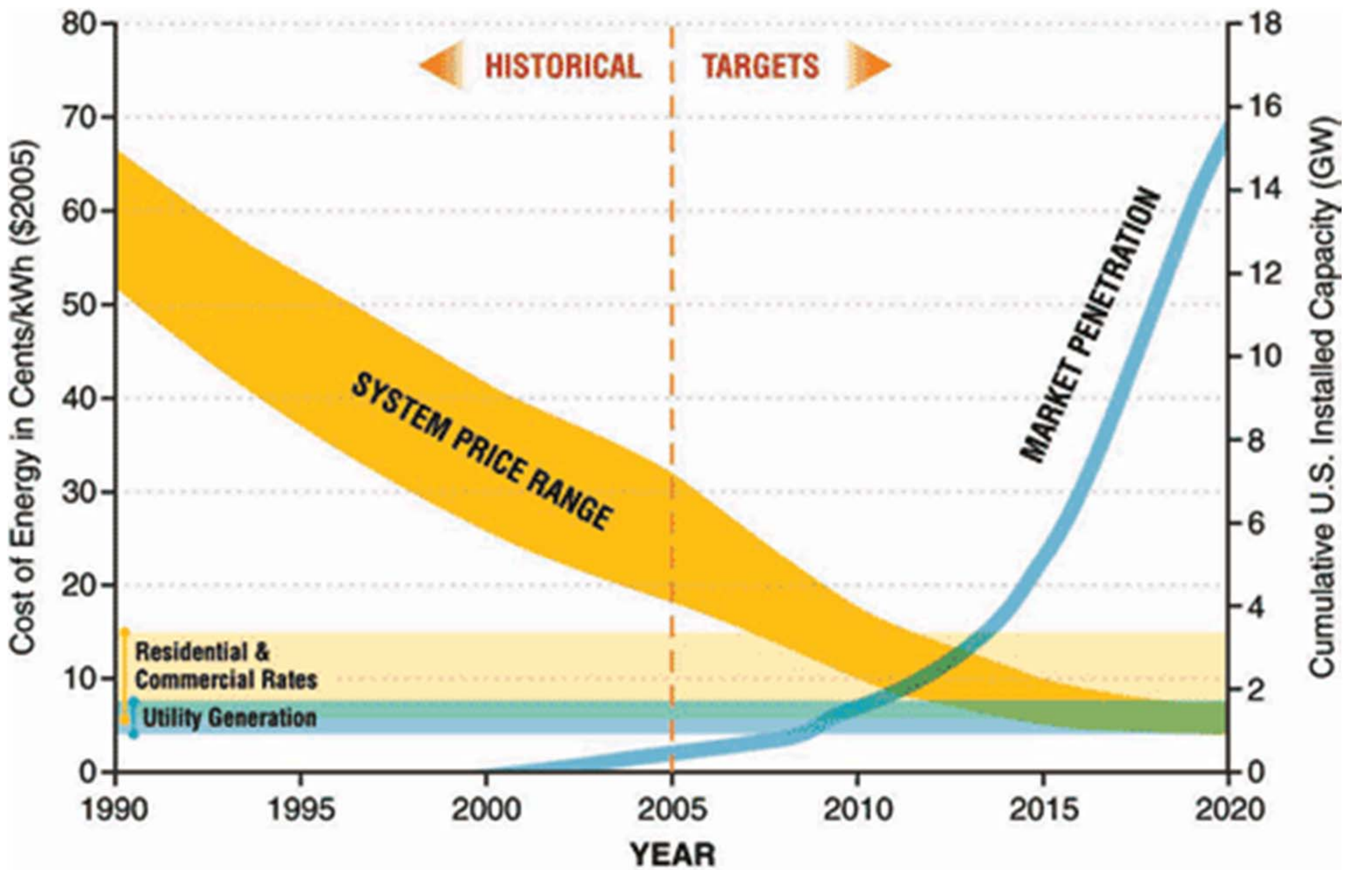
Large PV cost reductions over the past few decades were driven by (1) innovation in technology, manufacturing, and deployment, (2) increased scale, and (3) lower-cost materials.

Innovation: Driving Force in PV Cost Reduction



Source: 1366 Technologies, presented at hearing of the US House Select Committee on Energy Independence and Global Warming, July 28, 2009.

Convergence Between PV and Conventional Energy

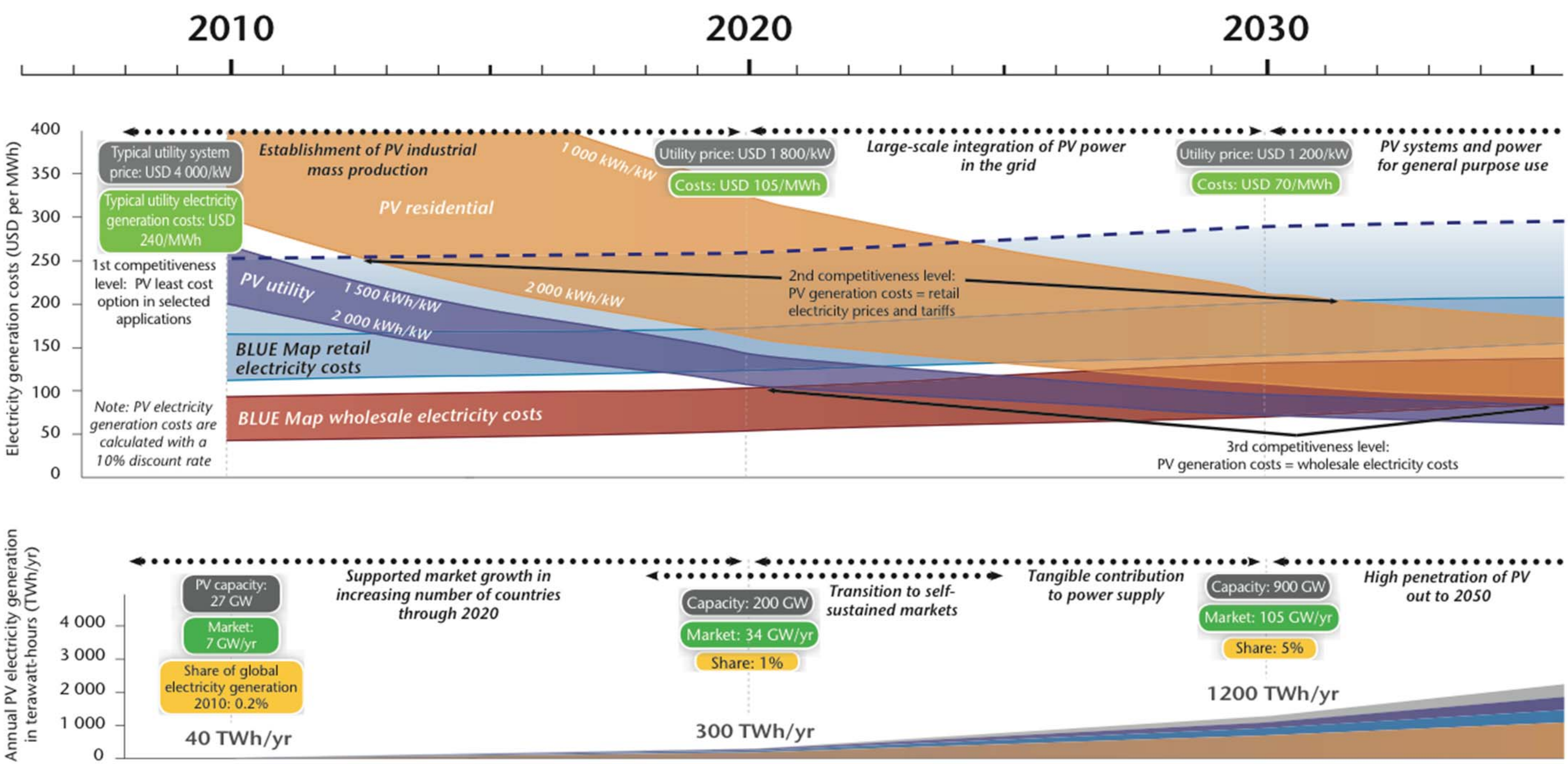


Market Sector	Currenet U.S. Market Price Range (¢/kWh)	Cost (¢/kWh) Benchmark 2005	Cost (¢/kWh) Target 2010	Cost (¢/kWh) Target 2015
Residential	5.8-16.7	23-32	13-18	8-10
Commercial	5.4-15.0	16-22	9-12	6-8
Utility	4.0-7.6	13-22	10-15	5-7

Source: US Department of Energy (ca. 2006)

Convergence Between PV and Conventional Energy

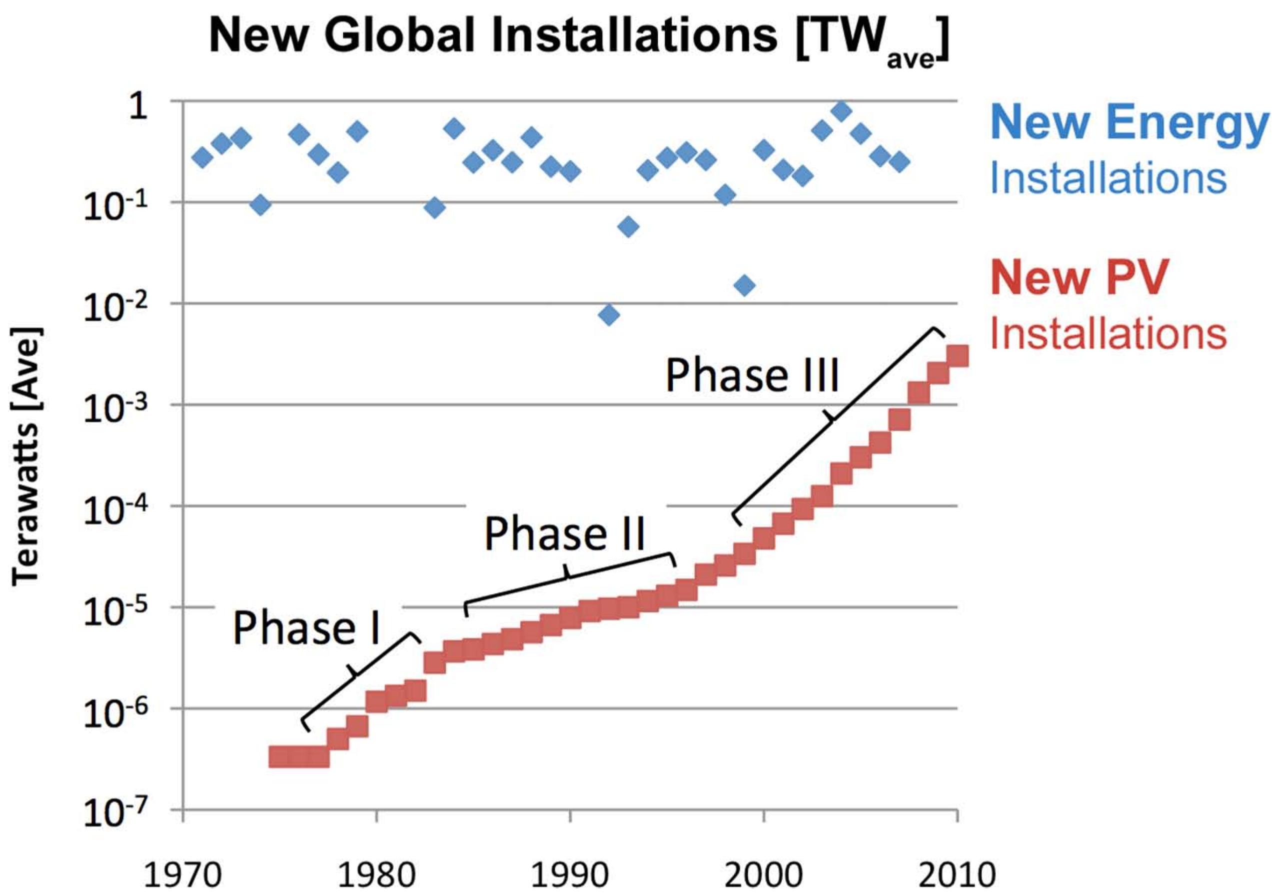
Figure 8: PV market deployment and competitiveness levels



Assumptions: Interest rate 10%, technical lifetime 25 years (2008), 30 years (2020), 35 years (2030) and 40 years (2050); O&M costs 1%.

Source: http://www.iea.org/papers/2010/pv_roadmap.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).

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Plot on previous page: "The coming convergence." Data sources used:

- World primary energy usage: http://www.eia.gov/totalenergy/data/annual/index.cfm#international
- PV production: Various, including Paul Maycock's PVNews, http://www.iea-pvps.org/index.php?id=trends, http://iet.jrc.ec.europa.eu/remea/pvnet-european-roadmap-pv-rd, and http://www.pv-tech.org/news/solarbuzz_pv_installations_reached_18.2gw_in_2010.
  Websites accessed 2011.
- For PV, TW_{peak} to TW_{ave} conversion assumes 1/6 PV capacity factor.

Solar Energy Technology Framework

Motivation, explanation, and rationale of framework

Framework for the Solar Energy Technology Universe

Motivation:

Several hundreds of technologies exist to convert solar radiant energy into other usable forms that perform work for humanity.

To make sense of this technology space, and to produce meaningful technology assessments and projections, a technology framework is helpful.

Please see lecture video for example images of each type of solar panel.

Framework for the Solar Energy Technology Universe

Design Principles for the Technology Framework:

Exhaustive categorization
Our technology framework must provide a meaningful framework to categorize 90+% of solar energy technologies today.

30 years challenge
The framework should be time-immutable, useful also in 30 years (within which time solar may “come of age”).

Useful analysis tool
The framework must provide a tool to economists and social scientists, to divide the solar space into meaningful units that can be analyzed independently.

Please see lecture video for example images of each type of solar panel.

Division 1: According to Conversion Technology

Solar Energy Conversion Technology			
Solar to Electricity	**Solar to Heat Electricity**	**Solar to Heat**	**Solar to Fuels**

Rationale:

Output-oriented
Focus on the delivered product (electricity, heat, fuels) naturally lumps similar technologies together.

Exhaustive categorization(?)
There are only a limited number of known energy products useful to humanity. Barring unexpected discoveries and harnessing of other energy forms (e.g., the "gravity wave" scenario), this framework should continue to be useful in 30 years.

Division 2: According to Moving Mechanical Parts

Solar Energy Conversion Technology							
Solar to Electricity		**Solar to Heat Electricity**		**Solar to Heat**		**Solar to Fuels**	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

Rationale:

Input-oriented
Focus on the method that solar energy is captured and converted into a usable form.

Moving parts
Tracking systems imply moving parts, which add to the complexity, cost, and maintenance of solar systems, while increasing the output.

Why not "concentrating / non-concentrating"?
"Tracking" and "concentrating" are non synonymous. While concentrator systems add extra capital equipment expenditure (capex), tracking systems add both extra capex and operating expenses (opex).

on to the assessment…

Solar Energy Conversion Technology

Solar to Electricity	Solar to Heat Electricity	Solar to Heat	Solar to Fuels

Embodiments:

- Photovoltaic device (solar cell).
- Thermoelectric device

Photovoltaic Device Fundamentals

(1) Charge Generation: Light excites electrons, freeing them from atomic bonds and allowing them to move around the crystal.

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(3) Charge Collection: Electrons deposit their energy in an external load, complete the circuit.

Advantages: There are no moving parts and no pollution created at the site of use (during solar cell production, that's another story).

Disadvantages: No output at night; lower output when weather unfavorable.

For animation, please see http://micro.magnet.fsu.edu/primer/java/solarcell/

Technological Diversity

Please see lecture video for example images of each type of solar technology.

Kerfless Silicon

Multijunction Cells

Copper Indium Gallium Diselenide (CIGS)

Amorphous Silicon

Dye-sensitized Cells

Silicon Sheet

Cadmium Telluride

Hybrid (nano)

Monocrystalline Silicon

Multicrystalline Silicon

High-Efficiency silicon

Organics

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

Two Sub-Groups:

1. Non-concentrating

2. Concentrating

Please see lecture video for example images of each type of solar technology.

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

1. Non-concentrating, non-tracking

a. Roof-mounted

b. Ground-mounted

Please see lecture video for example images of each type of solar technology.

Solar Energy Conversion Technology							
Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

2. Concentrating, non-tracking

a. External (mounted) reflectors

Please see lecture video for example images of each type of solar technology.

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

2. Concentrating, non-tracking

b. Internal reflectors

Please see lecture video for example images of each type of solar technology.

Sliver Cell (A.N.U.)

Solyndra

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

2. Concentrating, non-tracking

c. Photon conditioning, internal reflectors

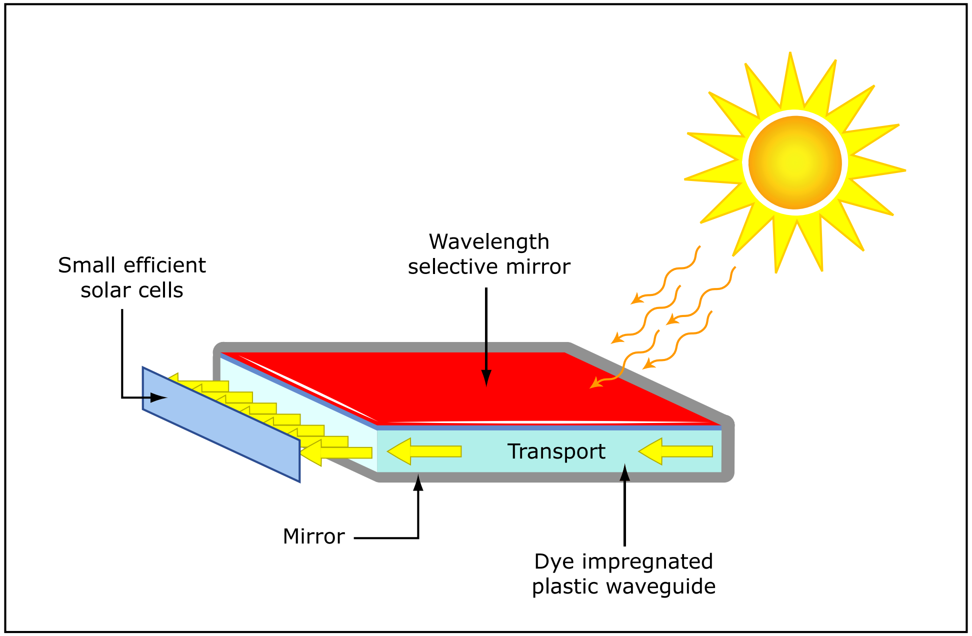


Image by MIT OpenCourseWare.

Luminescent Concentrator

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

The Basics of Tracking Systems:

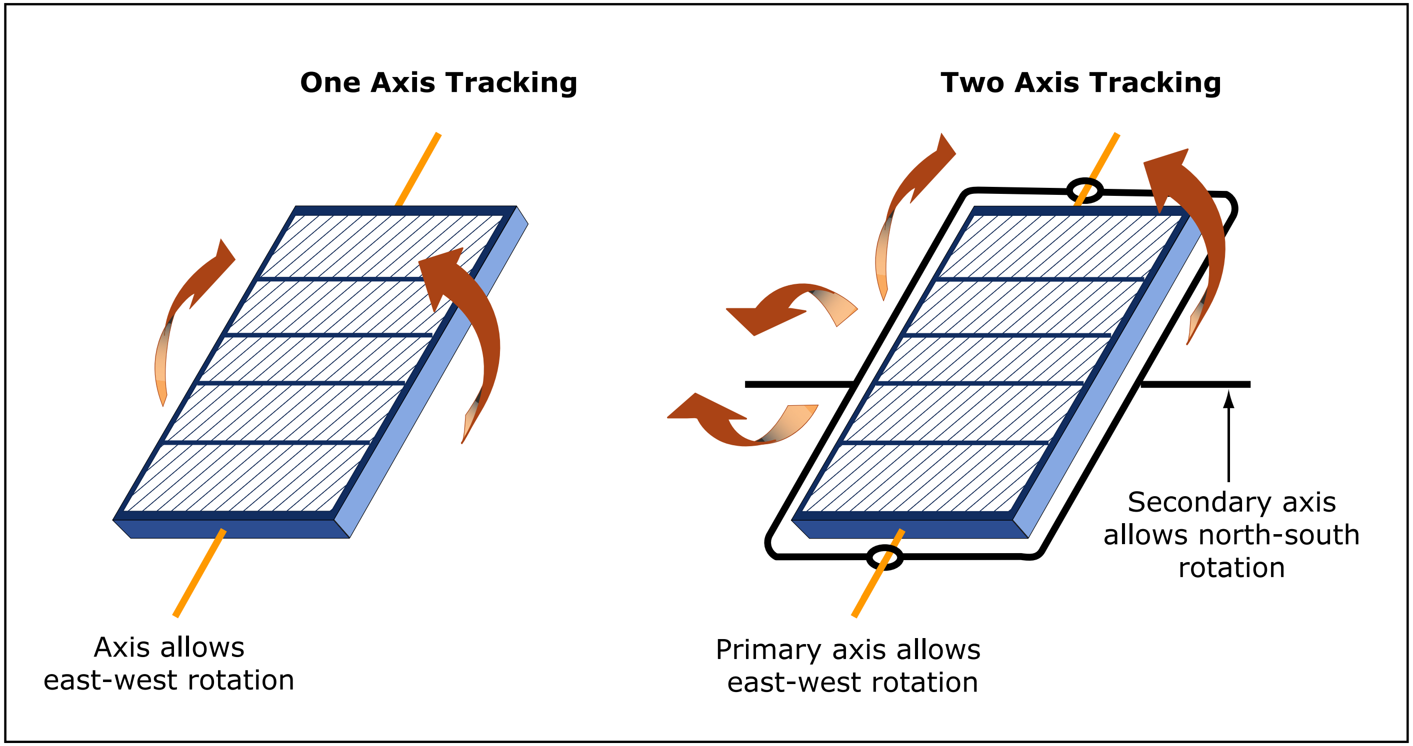


Image by MIT OpenCourseWare.

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

Two Sub-Groups:

1. Not Concentrating

2. Concentrating

Please see lecture video for example images of each type of solar technology.

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

1. Not concentrating, tracking

a. Photovoltaics

Please see lecture video for example images of each type of solar technology.

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

2. Concentrating, tracking

a. (Frenel) Lenses

Please see lecture video for example images of each type of solar technology.

SunCube Mark 5 Solar Appliance
Green and Gold Energy of Australia

Solar Energy Conversion Technology

Solar to Electricity	Solar to Heat Electricity	Solar to Heat	Solar to Fuels

Current embodiments

1. **Heat Engines*:** Sunlight heats a fluid (e.g., pressurized water, nitrate salt, hydrogen), which moves a turbine or piston, either directly or via heat exchanger.
2. **Heat Exchangers***
3. **Thermoelectrics**:** Visible sunlight converted into heat; temperature difference between leads drives an electrical current.
4. **Long-λ PV:** Visible sunlight converted into heat, which powers IR-responsive photovoltaic devices.

* Hybrids Possible (e.g., combined cycle power plant): The above, in tandem with another fuel (e.g., natural gas).

** Hybrids Possible (e.g., with solar cells)

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

Non-tracking and Concentrating

Solar Updraft Tower

Please see lecture video for example images of each type of solar technology.

50 kW Solar Chimney in Manzanares, Spain

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

Tracking and Concentrating

a. Reflectors (Parabolic Troughs)

Please see lecture video for example images of each type of solar technology.

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

Tracking and Concentrating

b. Parabolic Dish / Sterling Engines

Please see lecture video for example images of each type of solar technology.

http://www.stirlingenergy.com/technology/suncatcher.asp

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

Tracking and Concentrating

c. Solar Towers (a.k.a. "Power Towers")

Please see lecture video for example images of each type of solar technology.

PS10, 11 MW Solar Tower (Sanlucar la Mayor, Seville)

Current embodiments

Use heat to…

1. Heat water.
2. Desalinate water.
3. Cook food.

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

1. Non-tracking and Non-concentrating

Solar Hot Water Heaters

Please see lecture video for example images of each type of solar technology.

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

2. Non-tracking and Concentrating

Solar Hot Water Tubes

Please see lecture video for example images of each type of solar technology.

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

Tracking Solar to Heat

Solar Oven

Please see lecture video for example images of each type of solar technology.

Current embodiments

Enthalpy

1. **Solar catalysis:** Use sunlight to split (stable) molecules into more volatile species (e.g.: $2H_2O + \text{Energy} \rightarrow 2H_2 + O_2$).
2. **Photosynthesis:** Use sunlight to combine (stable) molecules into long-chain hydrocarbons (e.g.: $6CO_2 + 6H_2O + \text{Energy} \rightarrow C_6H_{12}O_6 + 6O_2$).

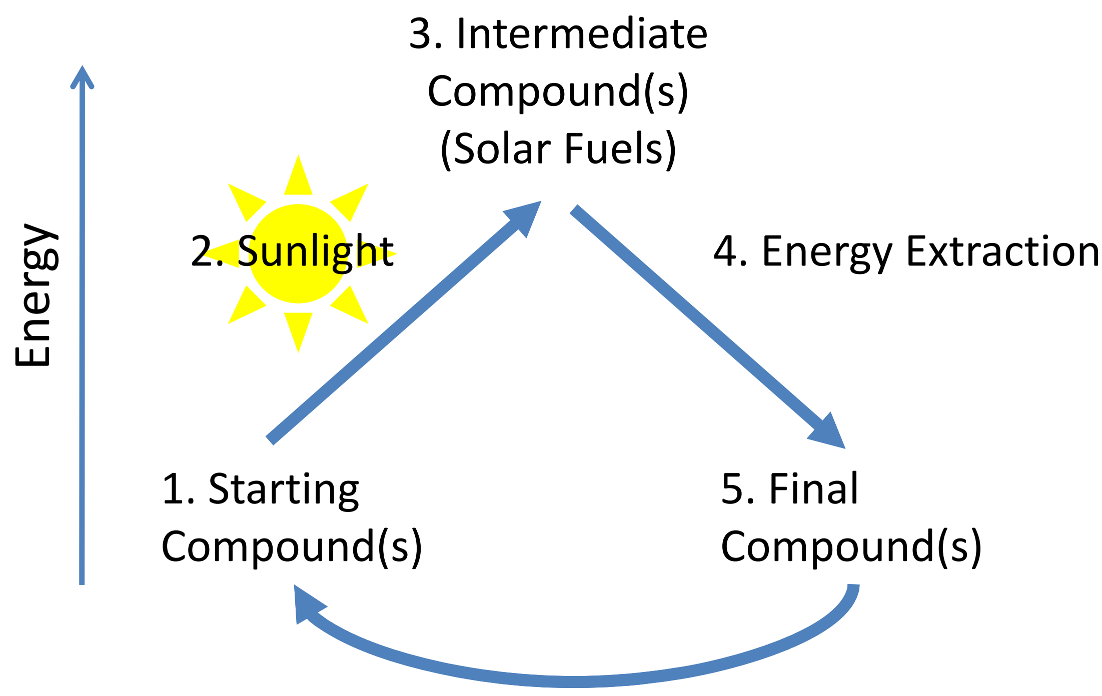
Entropy

1. **Separation of phases:** E.g., desalination.

Solar Energy Conversion Technology

Solar to Electricity	Solar to Heat Electricity	Solar to Heat	Solar to Fuels

Example of a Renewable Solar Fuels Cycle



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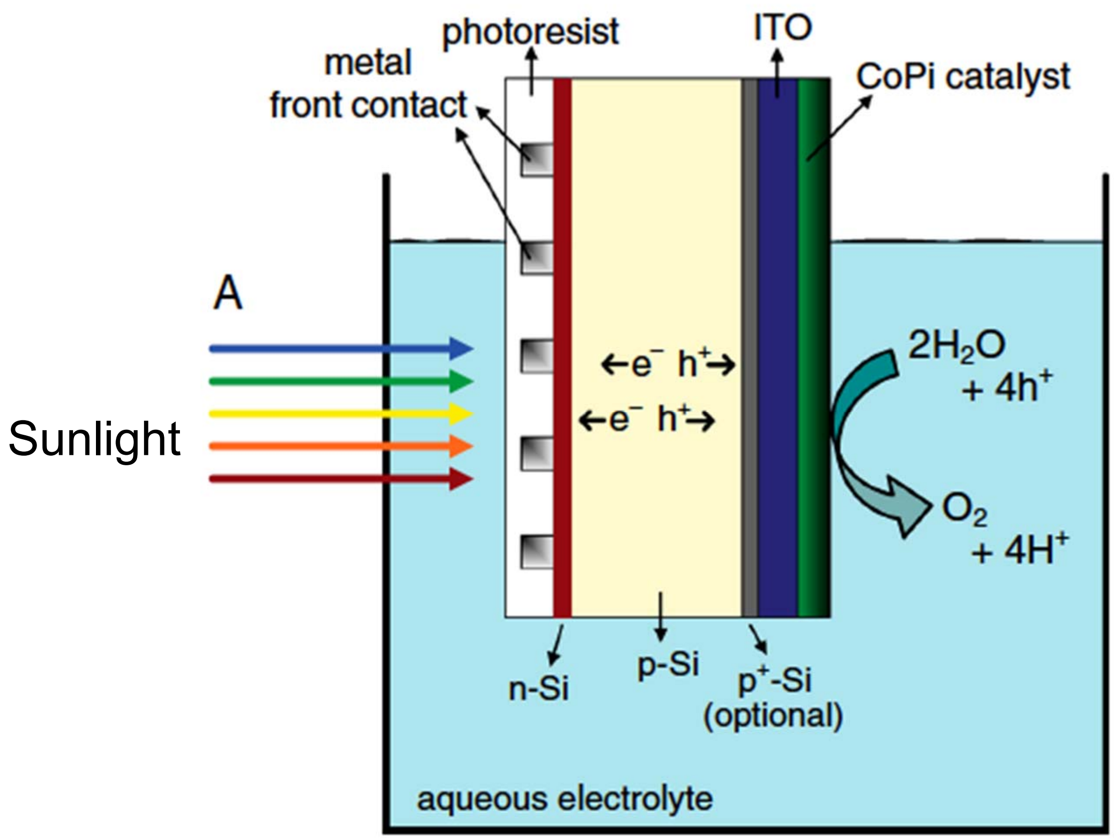
Example of a Renewable Solar Fuels Cycle



Solar Energy Conversion Technology

Solar to Electricity	Solar to Heat Electricity	Solar to Heat	Solar to Fuels

Reducing Entropy

Solar Desalination

Please see lecture video for example images of each type of solar technology.

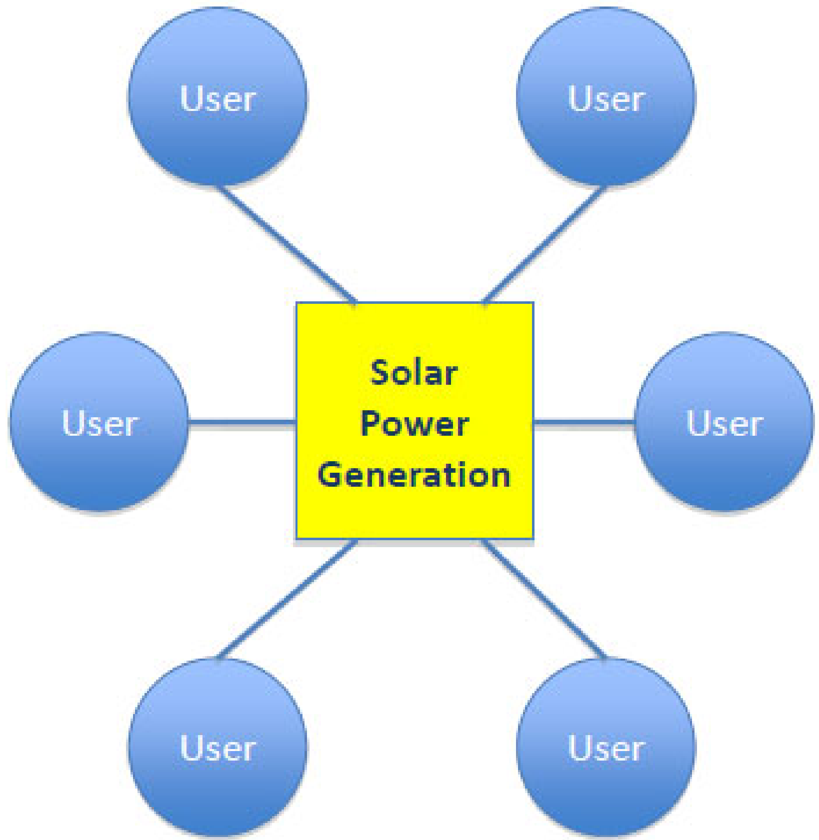
Footnote: Some discussion occurred on 6/30 as to whether this should fall under “solar to fuels”, or “solar to heat”.

Balance of Systems
(Infrastructure Beyond Conversion Devices)

Systems	
Energy Production Centralized	**Energy Production Distributed**

Systems

Energy Production Centralized	Energy Production Distributed



Today's typical centralized installation typically exceeds 500 kW_p.

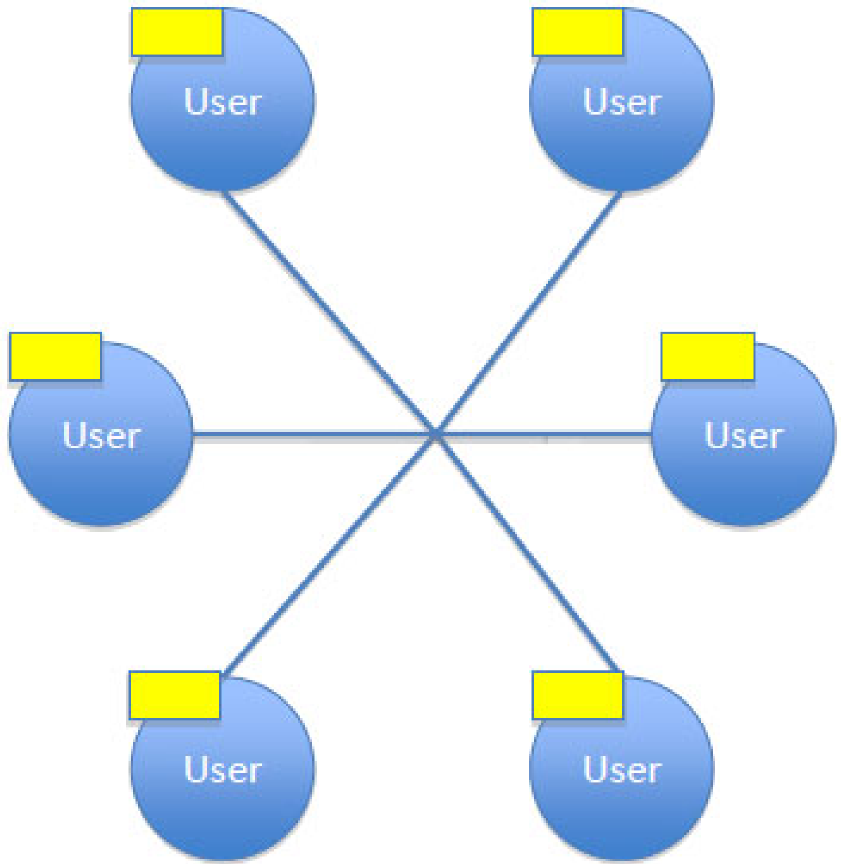
Systems

Energy Production Centralized	Energy Production Distributed

Please see lecture video for example images of each type of solar technology.

Systems

Energy Production Centralized | **Energy Production Distributed**



Today's typical distributed installation is typically less than 10 kW_p, but can 675 kW_p or larger.

Systems

Energy Production Centralized	Energy Production Distributed

Please see lecture video for example images of each type of solar technology.

Systems

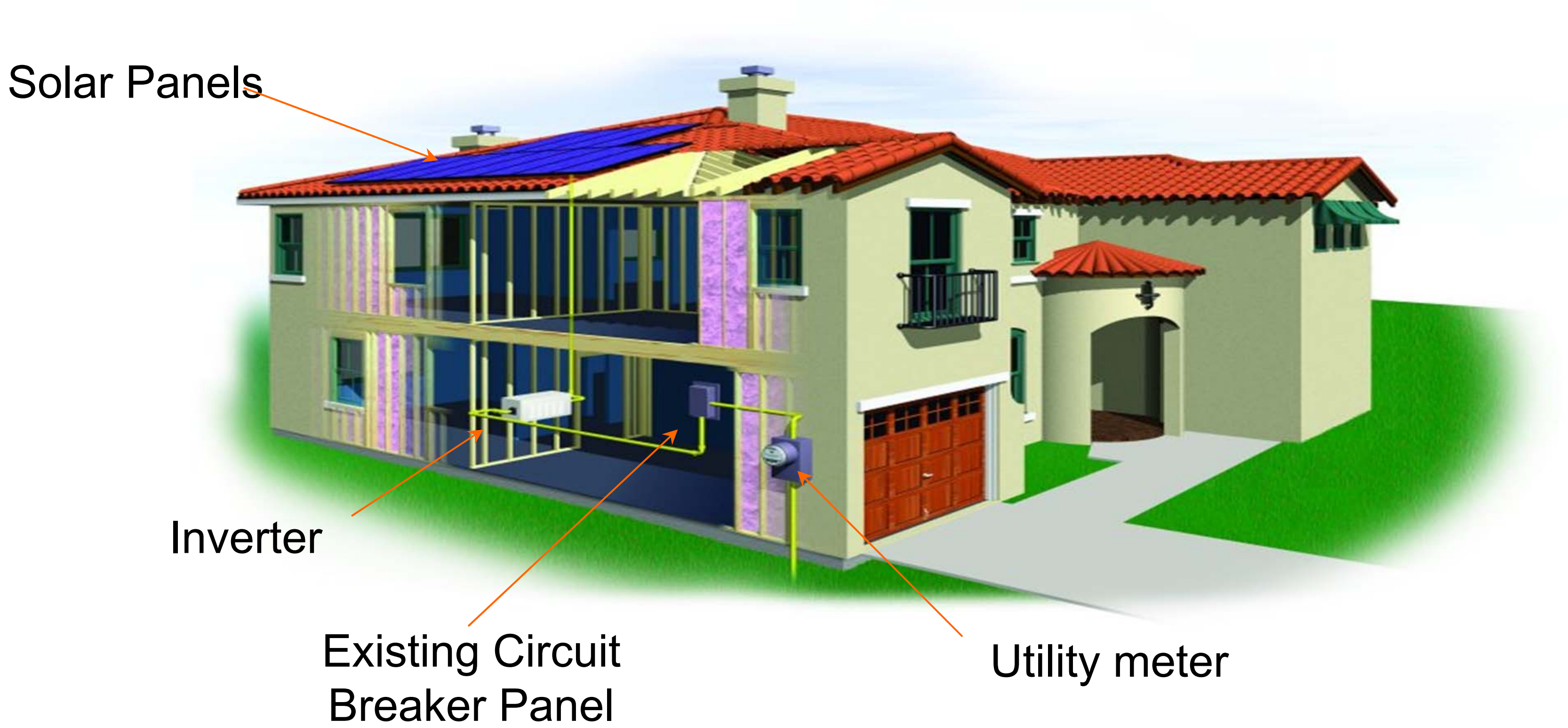
Energy Production Centralized	Energy Production Distributed

Please see lecture video for example images of each type of solar technology.

Zero energy homes, Rancho Cordova, CA
http://www.smud.org/news/multimedia.html

Systems

Energy Production Centralized	**Energy Production Distributed**



What about energy storage?

Energy storage, current embodiments

1. **Chemical:** Batteries (Pb, NiMH, Li), redox flow, fuels…
2. **Electromagnetic:** Capacitors, supercapacitors, SMES…
3. **Mechanical:** Fly-wheels, pneumatic, elastic, graviational…
4. **Thermal:** Storage tanks…

Systems			
Energy Production Centralized		Energy Production Distributed	
Storage Distributed	Storage Centralized	Storage Distributed	Storage Centralized

Please see lecture video for example images of each type of technology.

Fuel cells (x2)

Batteries (lead acid)

Systems

Energy Production Centralized		Energy Production Distributed	
Storage Distributed	Storage Centralized	Storage Distributed	Storage Centralized

Please see lecture video for example images of each type of technology.

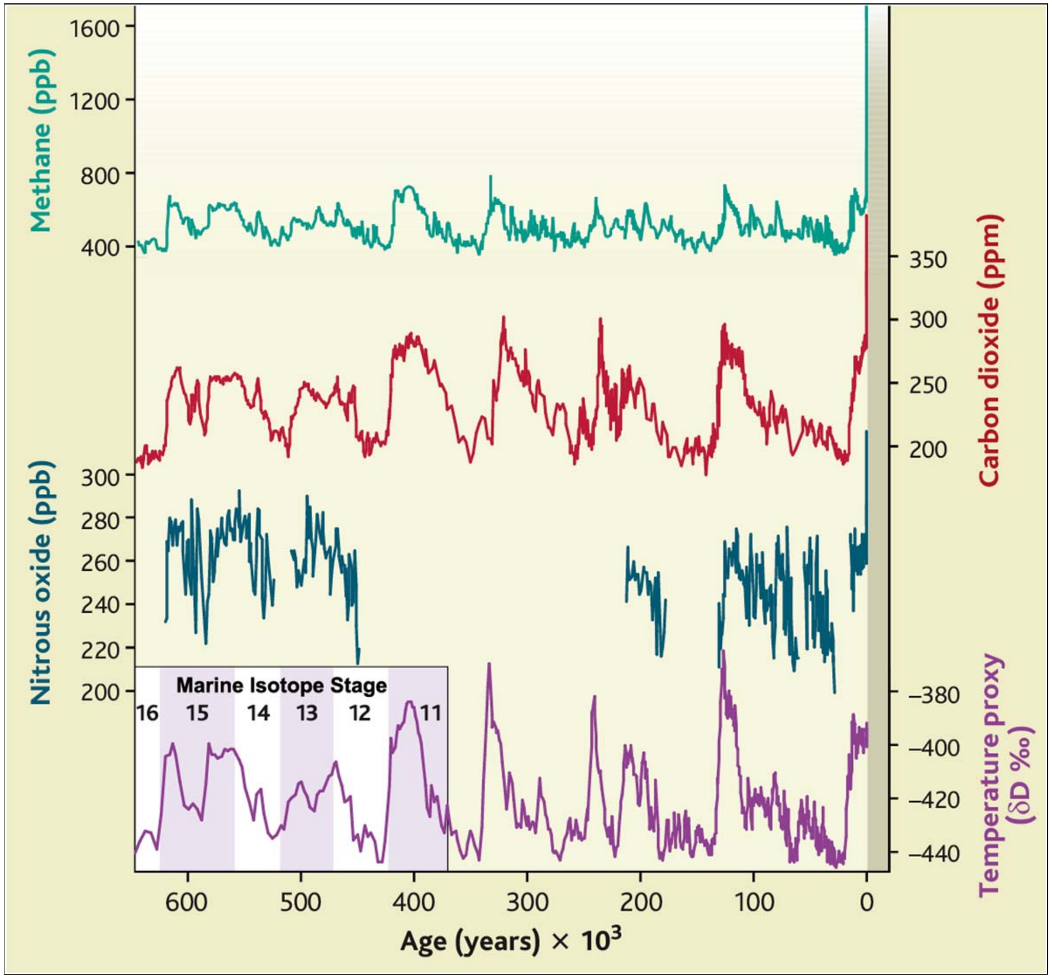
"Utility-scale" energy storage

The Grid*
**non-dispatchable storage solution!*

			Solar Energy Conversion Technology							
			Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
			Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Trackin g	Tracking
Systems	Energy Production Distributed	Storage Centralized								
		Storage Distributed								
	Energy Production Centralized	Storage Centralized								
		Storage Distributed								

CO_2, Energy, and Climate Change

Greenhouse Gasses and Mean Global Temperature



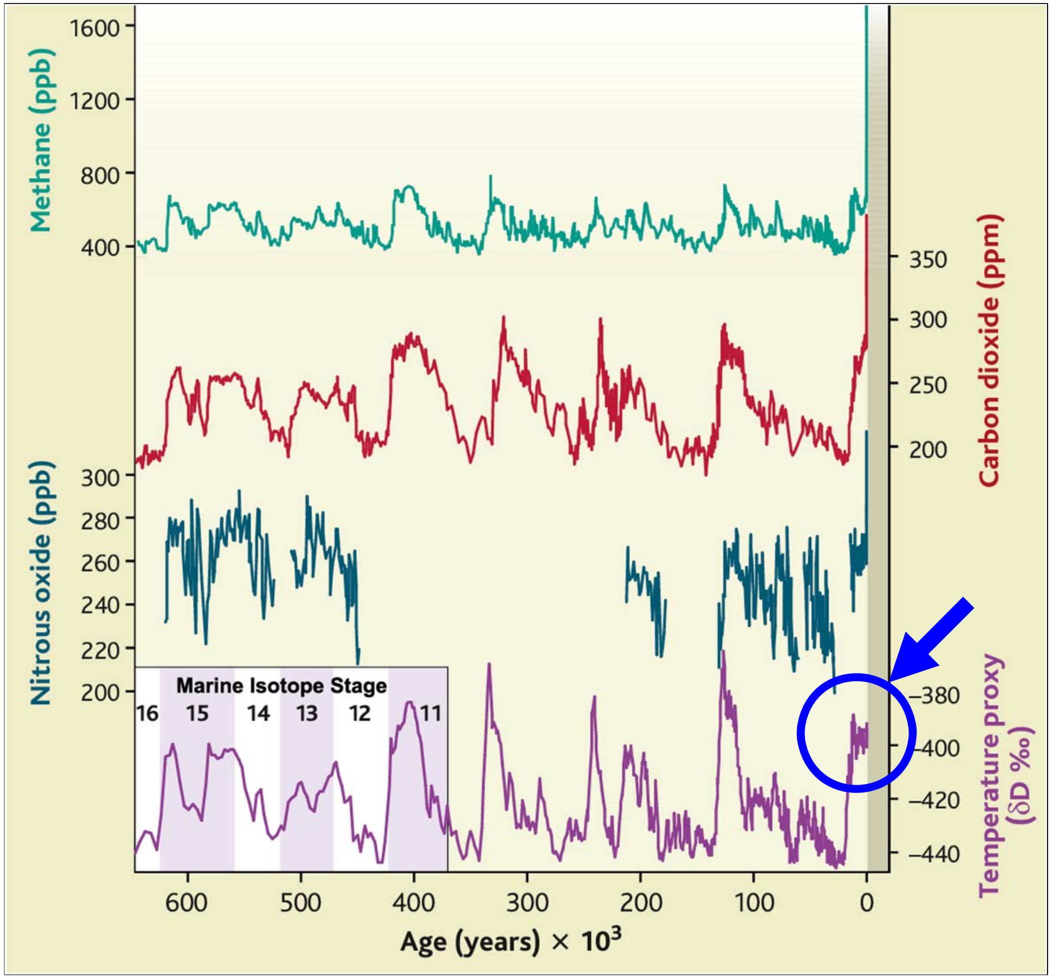
For over 600,000 years, a strong correlation between greenhouse gasses and global temperature exists.

Source: Brook, E."Tiny Bubbles Tell All." *Science* 310 (2005): 1285-7.

See also:

J.R. Petit, J. Jouzel, D. Raynaud, et al., *Nature* **399**, 429 (1999)
U. Siegenthaler, T.F. Stocker, E. Monnin, et al., *Science* **310**, 1313 (2005)
Renato Spahni, J. Chappellaz, T.F. Stocker, et al., *Science* **310**, 1317 (2005)

Greenhouse Gasses and Mean Global Temperature



For over 600,000 years, a strong correlation between greenhouse gasses and global temperature exists.

For the last 12,000 years, global temperatures have been stable, coincident with the rise of human civilizations.

Source: Brook, E. "Tiny Bubbles Tell All." *Science* 310 (2005): 1285-7.

See also:

J.R. Petit, J. Jouzel, D. Raynaud, et al., *Nature* **399**, 429 (1999)
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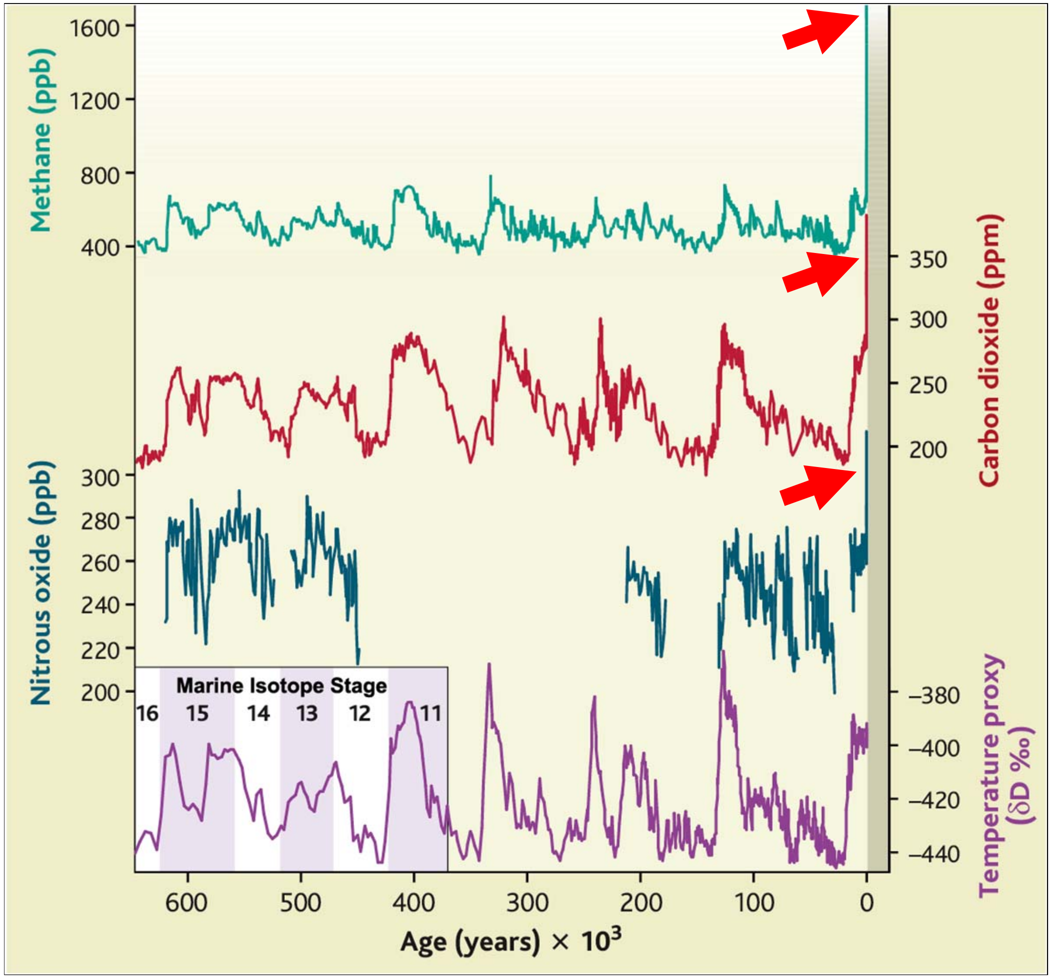
Greenhouse Gasses and Mean Global Temperature



Source: Brook, E. "Tiny Bubbles Tell All." *Science* 310 (2005): 1285-7.

For over 600,000 years, a strong correlation between greenhouse gasses and global temperature exists.

For the last 12,000 years, global temperatures have been stable, coincident with the rise of human civilizations.

Recently, greenhouse gas levels have greatly exceeded naturally-occurring watermark – in some cases, by >2x.

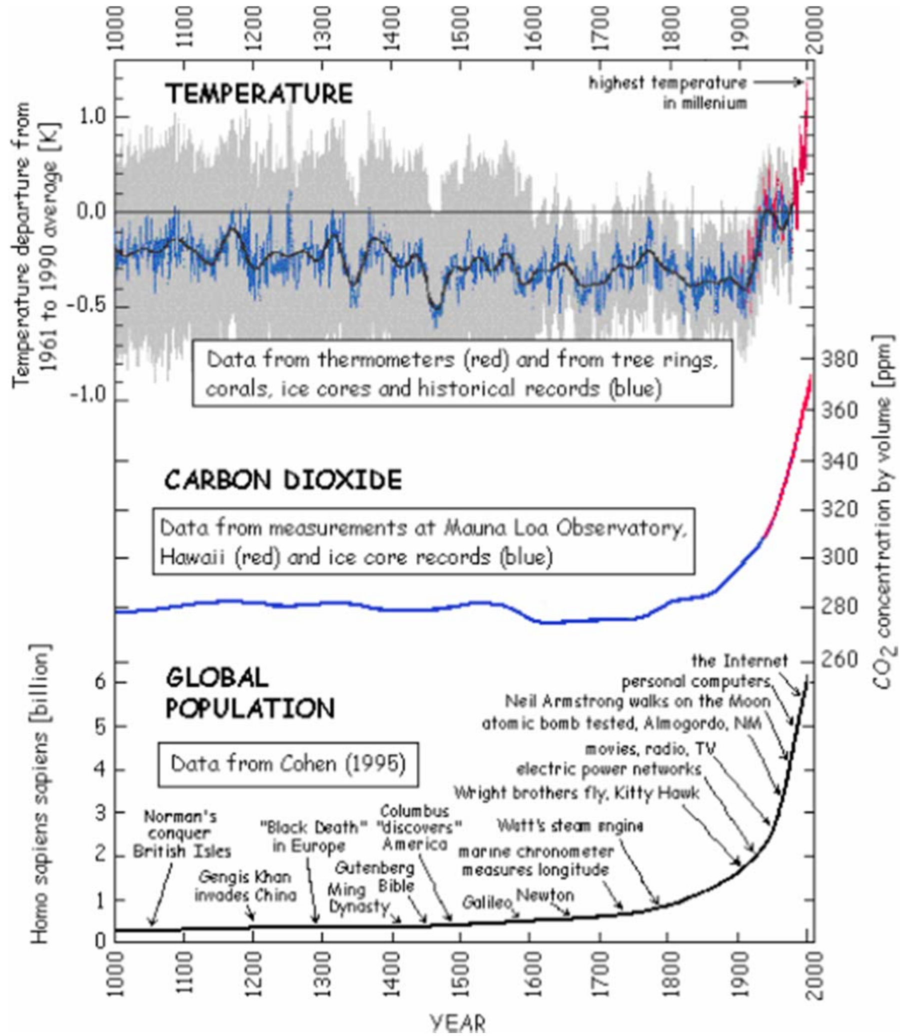
What recently disrupted this natural cycle?

See also:
J.R. Petit, J. Jouzel, D. Raynaud, et al., *Nature* **399**, 429 (1999)
U. Siegenthaler, T.F. Stocker, E. Monnin, et al., *Science* **310**, 1313 (2005)
Renato Spahni, J. Chappellaz, T.F. Stocker, et al., *Science* **310**, 1317 (2005)

Greenhouse Gasses, Mean Global Temperature, and Humans

The past two centuries experienced a rapid rise in human population, concomitant with a rise in atmospheric CO_2 levels. Shortly thereafter, average global temperatures began to rise.

Does the coincidence between population and CO_2 levels imply causality?



Courtesy of Martin Hoffert. Used with permission.

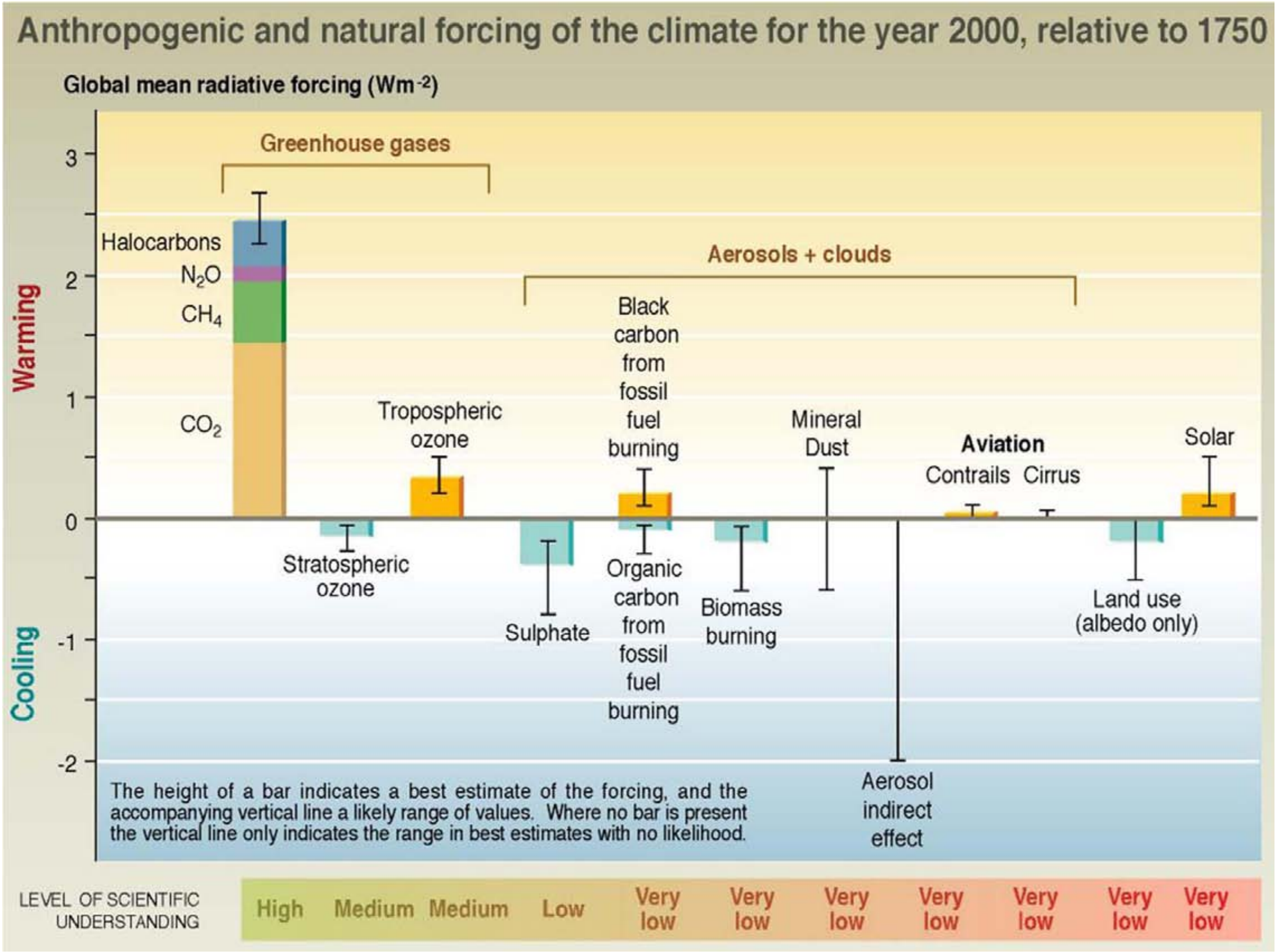
See also:
D.M. Etheridge et al., *J. Geophys. Res.* **101**, 4115 (1996).

Energy and Greenhouse Gasses

Please see lecture video for relevant interaction with graph.

- >85% global energy from fossil fuels
- Energy, GDP, and CO_2 are strongly correlated.
- Global energy needs are predicted to steadily increase.
- Business as usual: CO_2 levels will continue to increase.
- >20% increase in atmospheric CO_2 content!

The Magnitude of Global Warming



Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Figure 2-2; Figure SPM-2; Figure SPM-10b; Figure SPM-10a; Figure SPM-6. Cambridge University Press.

Scientific Consensus re: Global Warming

"Consensus as strong as the one that has developed around this topic is rare in science."
*D. Kennedy, Science **291**, 2515 (2001)*

"Human activities … are modifying the concentration of atmospheric constituents … that absorb or scatter radiant energy. … [M]ost of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations" p.21
(a.k.a. 2001 IPCC Report) J. J. McCarthy et al., Eds., Climate Change 2001: Impacts, Adaptation, and Vulnerability (Cambridge Univ. Press, Cambridge, 2001)

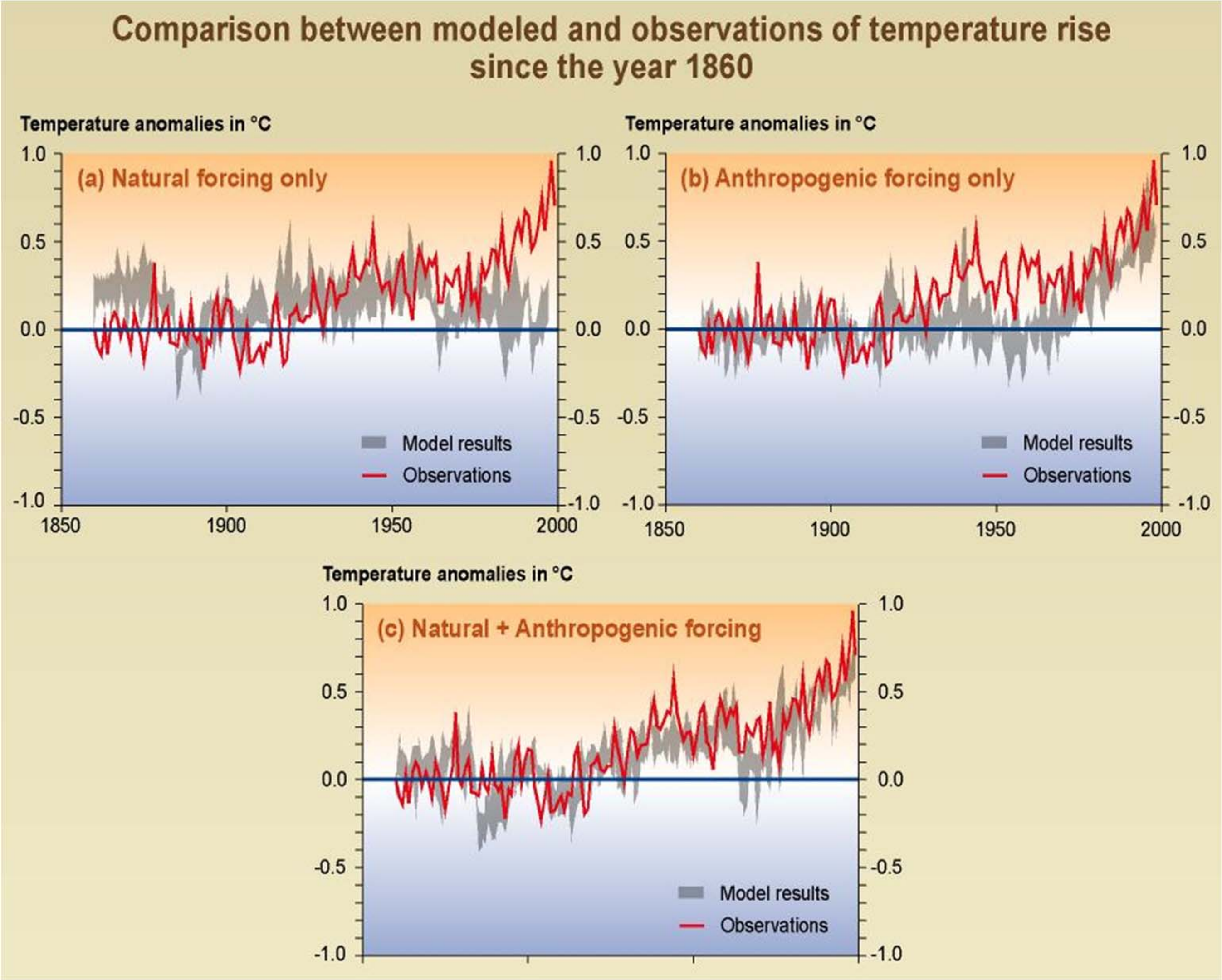
"Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise." p.1
(a.k.a. 2001 NAS Report) National Academy of Sciences Committee on the Science of Climate Change, Climate Change Science: An Analysis of Some Key Questions (National Academy Press,Washington, DC, 2001).

928 [peer-reviewed] papers were divided into six categories: explicit endorsement of the consensus position, evaluation of impacts, mitigation proposals, methods, paleoclimate analysis, and rejection of the consensus position. Of all the papers, 75% fell into the first three categories, either explicitly or implicitly accepting the consensus view; 25% dealt with methods or paleoclimate, taking no position on current anthropogenic climate change. Remarkably, none of the papers disagreed with the consensus position… [or argued] that current climate change is natural.
*N. Oreskes, Science **304**, 1686 (2004).*

"One of the reasons scientists consider the evidence so compelling is that it draws on such a broad range of sources. In addition to climate specialists who use sophisticated computer models to study climatic trends, researchers from an array of disciplines, including atmospheric scientists, paleoclimatologists, oceanographers, meteorologists, geologists, chemists, biologists, physicists, and ecologists have all corroborated global warming by studying everything from animal migration to the melting of glaciers. Evidence of a dramatic global warming trend has been found in ice cores pulled from the both polar regions, satellite imagery of the shrinking polar ice masses, tree rings, ocean temperature monitoring…" p.29

Union of Concerned Scientists. *ExxonMobil Report: Smoke Mirrors & Hot Air* (PDF). 2007.

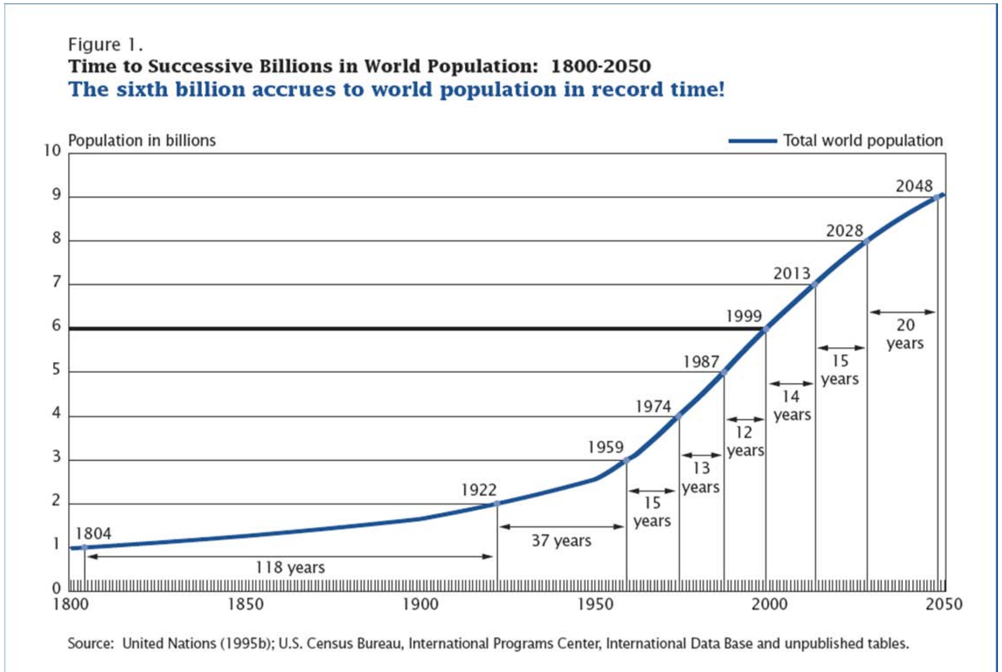
Anthropogenic Forcing



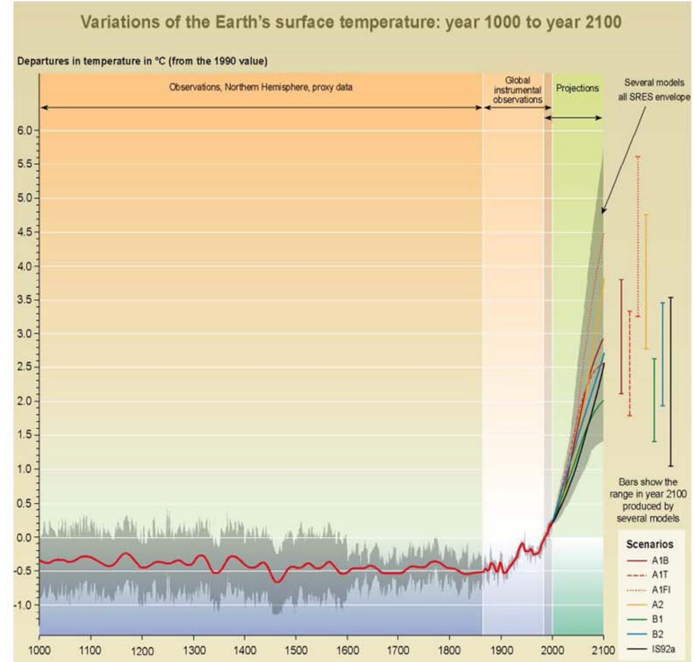
Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Figure 2-2; Figure SPM-2; Figure SPM-10b; Figure SPM-10a; Figure SPM-6. Cambridge University Press.

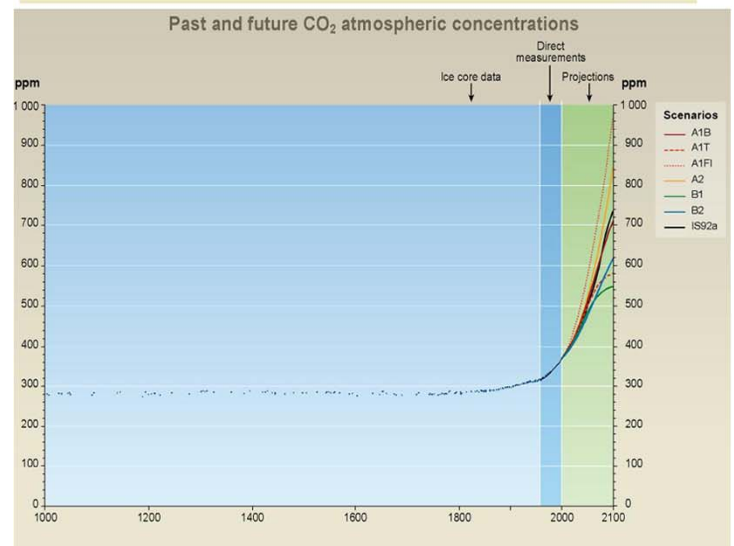
Future Predictions

Current trends predicted to continue.



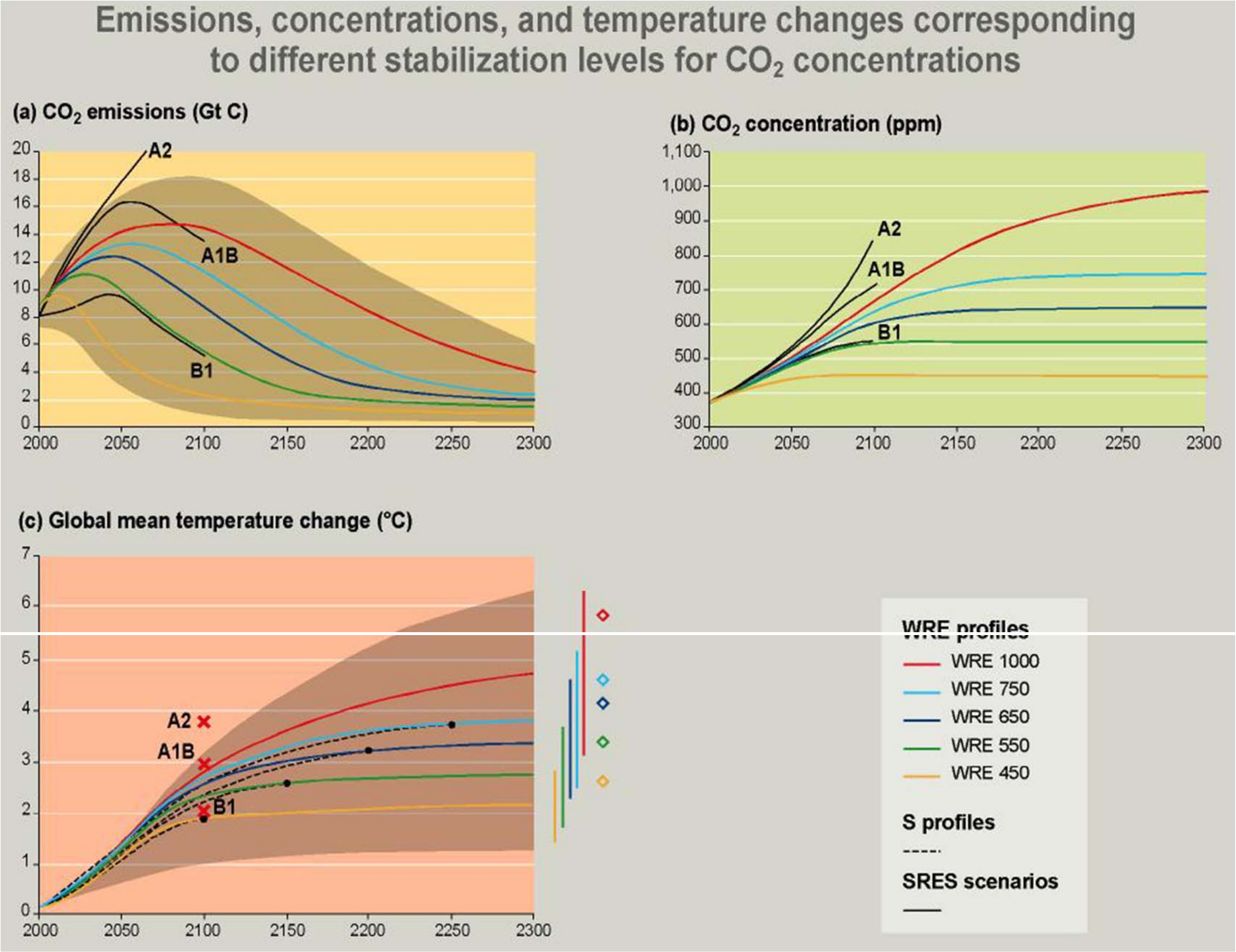
http://www.census.gov/ipc/prod/wp02/wp-02003.pdf





Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Figure 2-2; Figure SPM-2; Figure SPM-10b; Figure SPM-10a; Figure SPM-6. Cambridge University Press.

The Renewable Energy Imperative



Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Figure 2-2; Figure SPM-2; Figure SPM-10b; Figure SPM-10a; Figure SPM-6. Cambridge University Press.

2.626/2.627 in perspective

Recap

Why Solar?

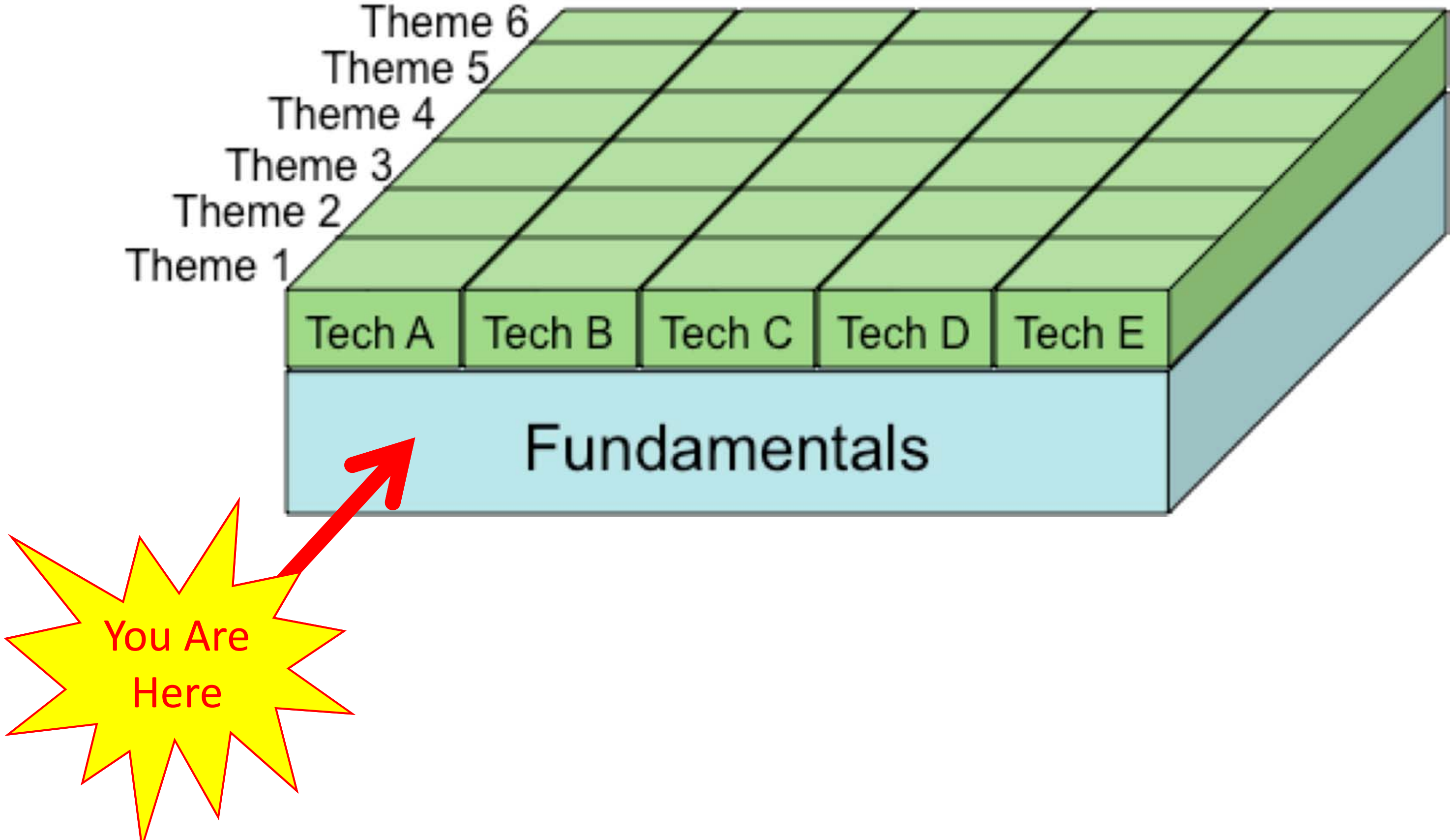
1. Energy is a necessary ingredient for human development.
2. The solar resource is abundant.
3. The solar resource distribution is well matched to growing human energy demand.
4. Solar is renewable, and is a 5-10x lower-carbon energy source than fossil fuels. [1]

How Solar?

1. Solar is on a rapid path to convergence with conventional fossil-fuel-based energy sources, both in cost and scale.
2. Many challenges inhibiting wide-scale solar adoption are identified.
3. Solutions to these challenges are rooted in PV technology, manufacturing, and deployment innovations.
4. To train future leaders to develop these solutions, a solid fundamental understanding of the science, technology, and cross-cutting themes is necessary.

[1] V.M. Fthenakis *et al*., *Environmental Science & Technology* **42**, 2168 (2008)

2.626/2.627 Roadmap



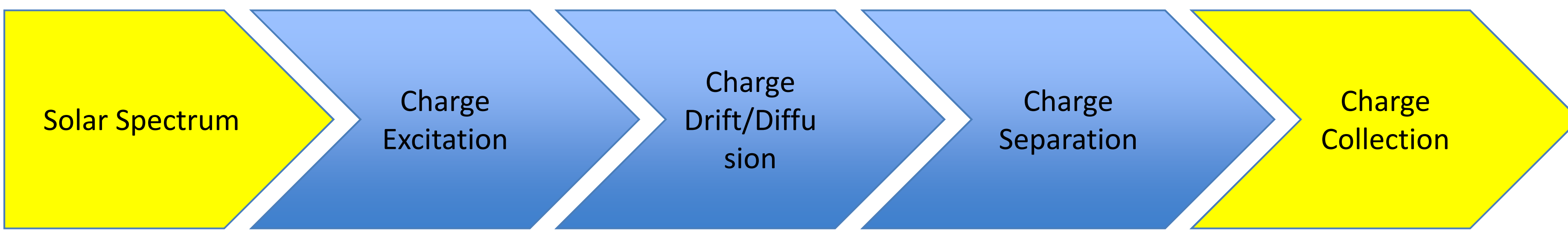
2.626/2.627: Fundamentals

<u>Every</u> 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



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

2.627 / 2.626 Fundamentals of Photovoltaics
Fall 2013