Photovoltaics

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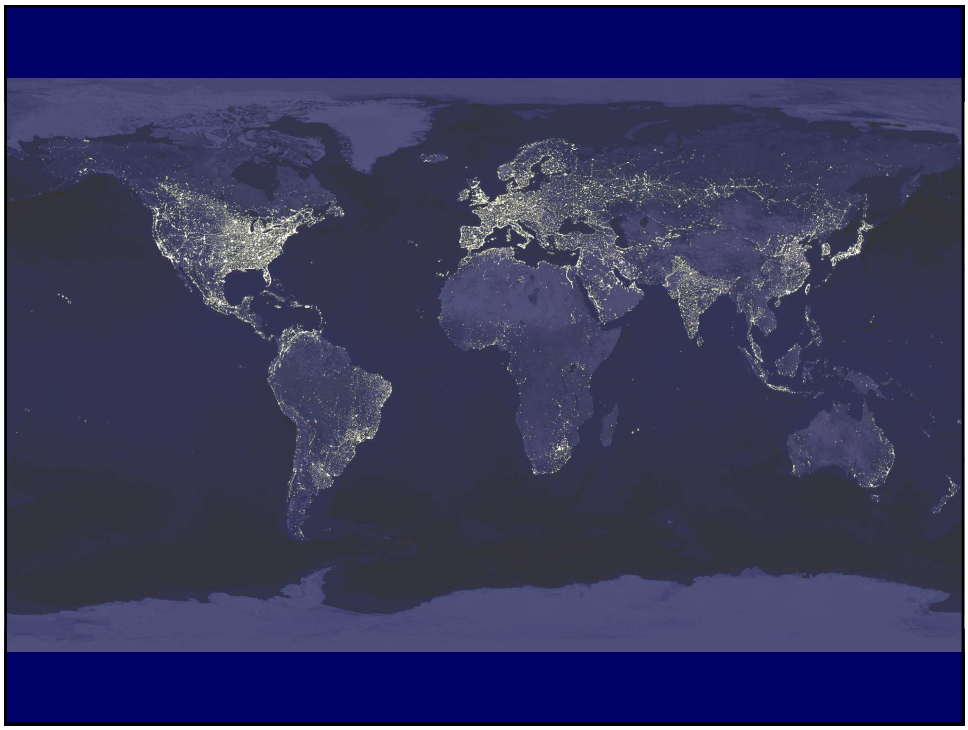
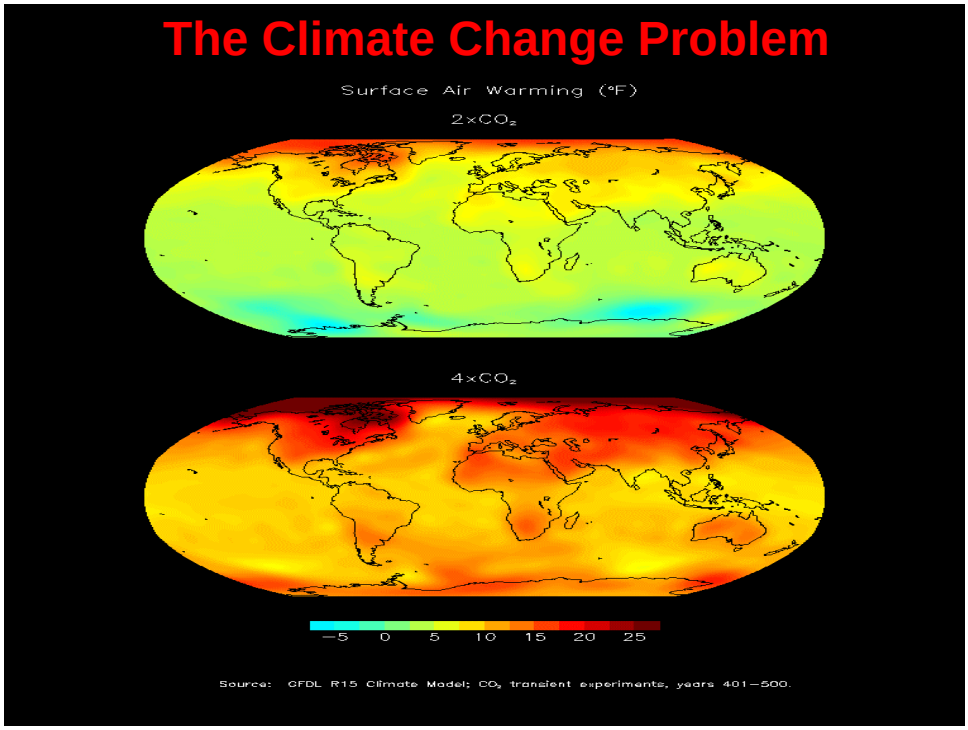
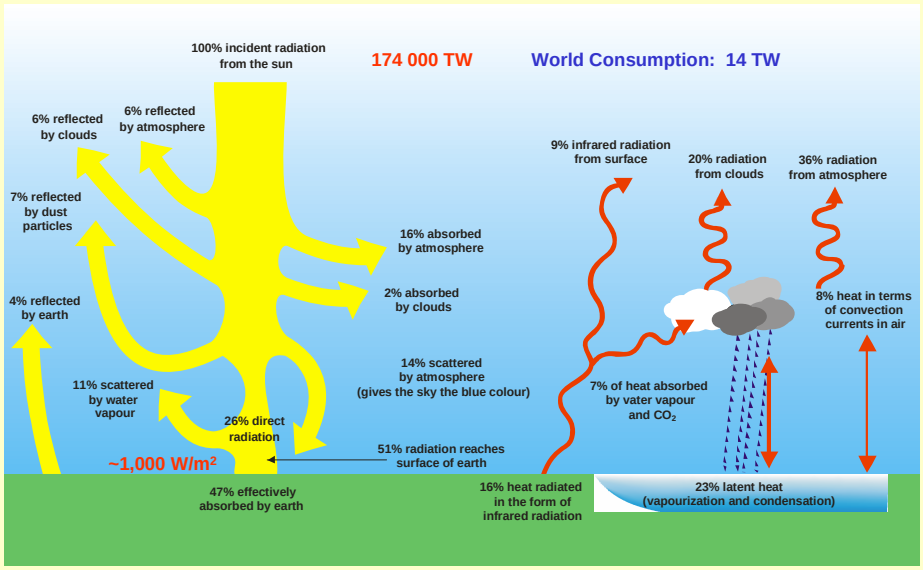
Economic Growth, Wealth

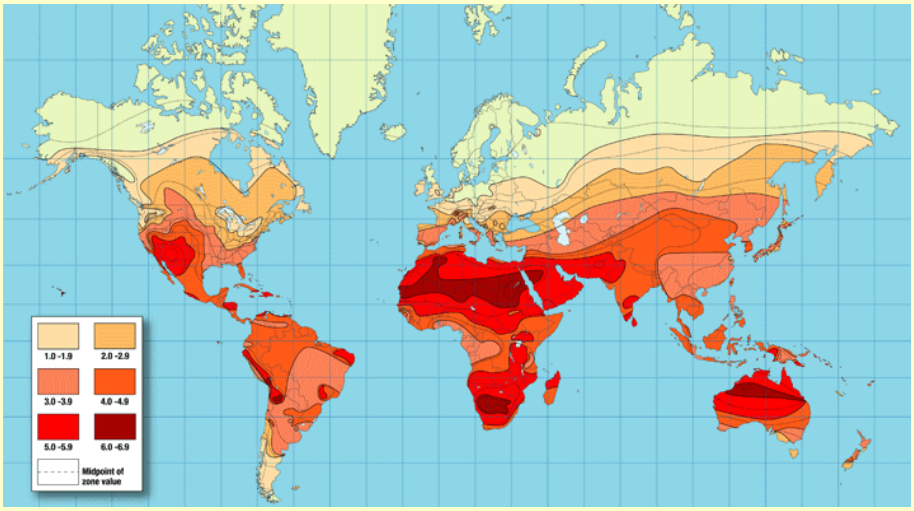



The Climate Change Problem
Surface Air Warming (°F)
2×CO₂
4×CO₂
−5 0 5 10 15 20 25
Source: GFDL R15 Climate Model; CO₂ transient experiments, years 401−500.

Energy Balance of the Earth



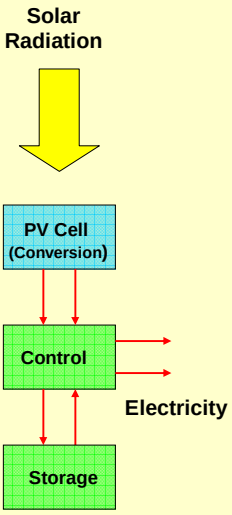
Solar Insolation: kWh per sq.m per day
Power, AM1.5: 1 kW/sq.m (max.)



Direct Solar Power

- **Photosynthesis:** *Wood; Biofuels.*
- **Heat:** *Passive buildings; Water heating.*
- **Solar Thermal:** *Electricity.*
- **Photovoltaics:** *Electricity.*

PV Generation of Electricity



Efficiency!

Processes

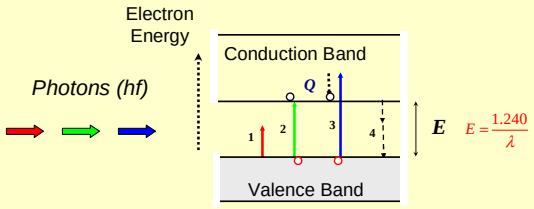
- Absorption of Energy
- Creating free charges
- Separating free charges
- Collecting current

PV Cell Materials

- High absorption
- Correct Energy Gap
- p-n Junction
- Large carrier Lifetime
- Stable
- Abundant resources
- Economical

Absorption of sunlight

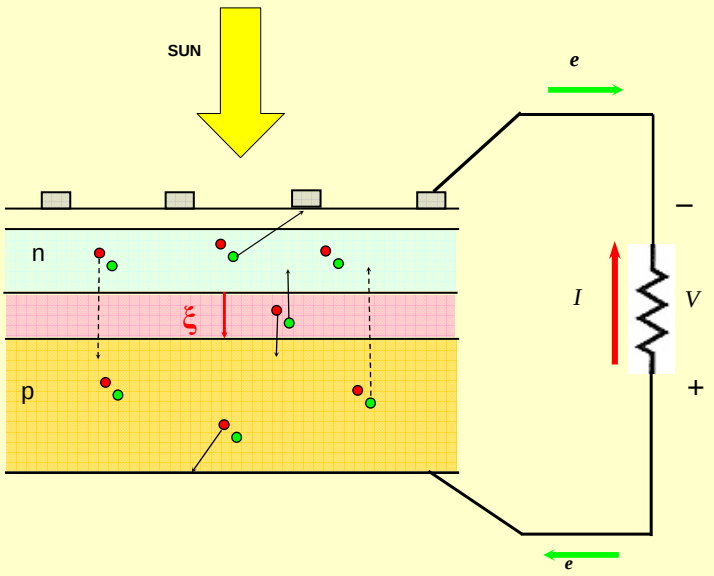
Creating excited free carriers (current)



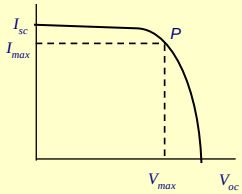
$E < E_g$: Transparent; no absorption.
$E = E_g$: 100% absorption; Free carriers.
$E > E_g$: Less than100% absorption; Free carriers.

Optimum E_g: 1.45 eV Max Energy absorption: 48%

Silicon PV cell

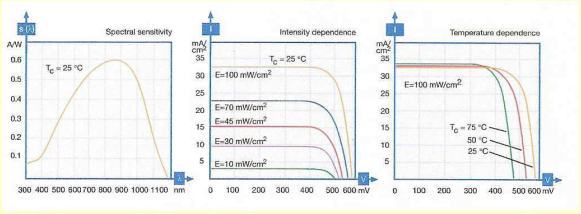


Characteristics of a Si PV cell



$$FF = \frac{I_{max} V_{max}}{I_{sc} V_{oc}}$$

$$e = \frac{\text{Power In}}{} = \frac{I_{max} V_{max}}{P_{in}} = \frac{FF \times I_{sc} V_{oc}}{P_{in}}$$



For maximum efficiency the three quantities *FF*, I_{sc} and V_{oc} must all three be as large as possible.

A PV system thus has to be designed so that the cells always operate at its maximum power point.

PV Cell Technologies

Crystalline Technologies

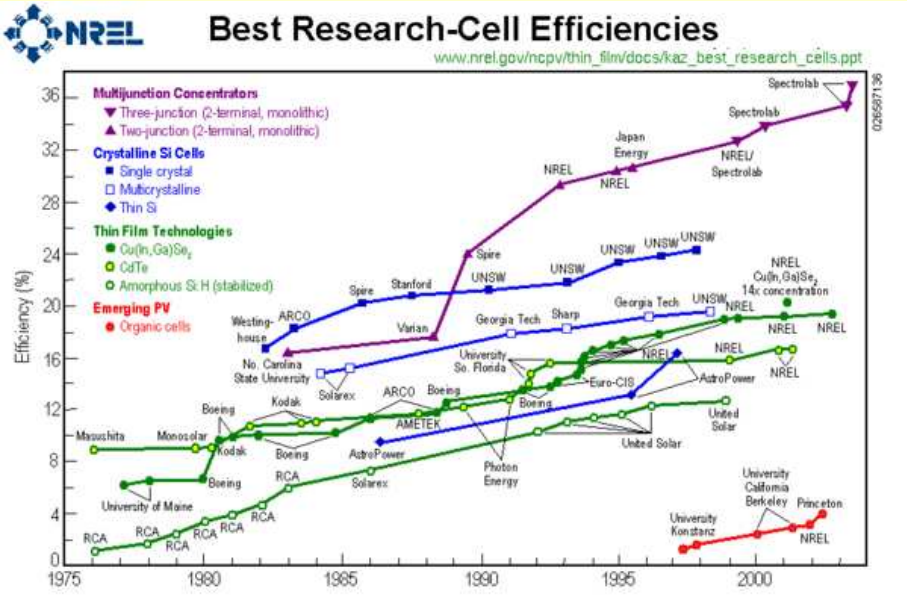
- III-V (Ga-P-As) -- Expensive: Space application.
- Single Crystal Silicon
- Polycrystalline Silicon
- Ribbon Silicon

Thin Film Technologies

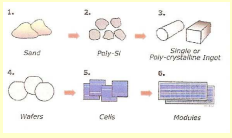
- Amorphous Silicon (a-Si)
- Cadmium Telluride (CdTe)
- Copper-Indium-diSelenide (CIGS)

Other Technologies

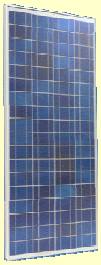
- Concentrators
- Polymer & Chemical cells

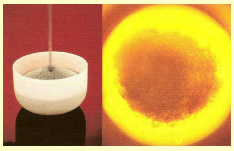


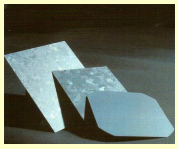
Silicon Solar Cell Technology



100 – 200 watt



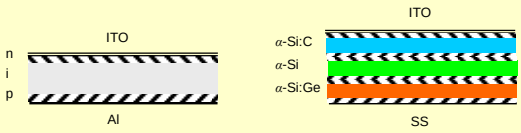




10 gm Si per watt

3 watt

Amorphous Silicon

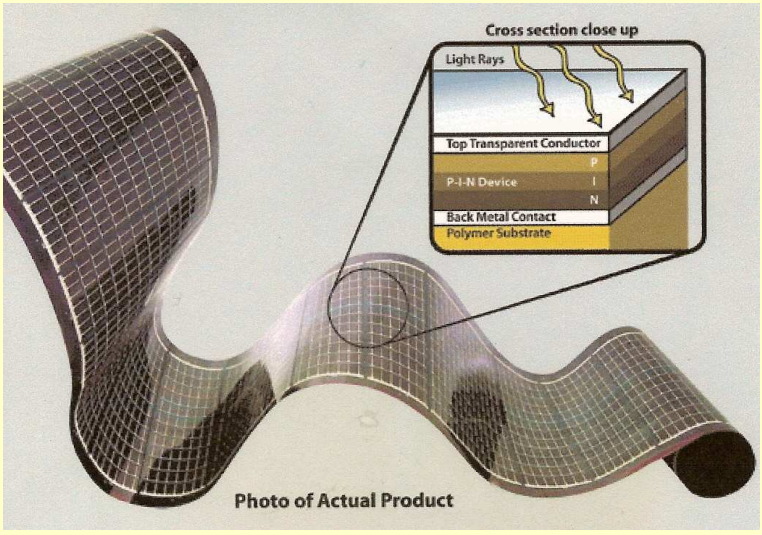


Production:
Gas discharge of Silane
Contains 5 – 10% Hydrogen
Films about 1 um
Low temp: 200 C
Glass or flexible substrates
Roll-to-Roll Process

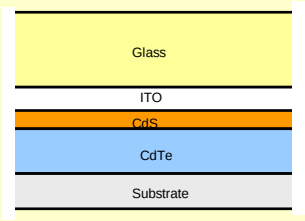
Properties:
Tuning of bandgap possible.
Initial degradation
Single layer: 4% efficient
Triple layer: 8% efficient
Non toxic materials

Abundant Resource material

Flexible a-Si on a polymer substrate



Cadmium Telluride - CdTe



Production:
Sublimation
Chemical deposition
Vacuum evaporation
Medium temp: 500 C
Easy to manufacture
Batch processing

Properties:
Stable
Fairly high efficiency: >10%
Contain toxic materials
Materials not quite abundant
Cadmium pollution

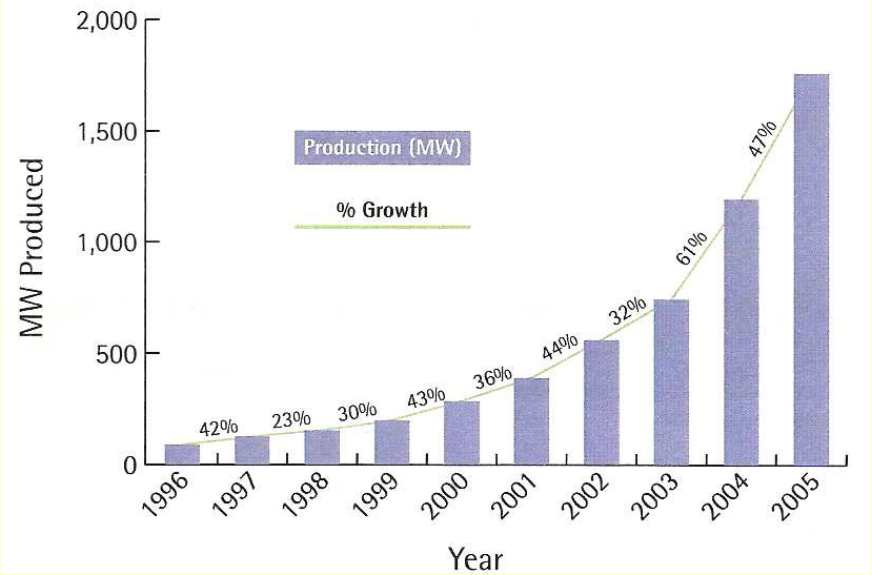
Copper-indium-diselenide - CIGS

Production:
Sputtering
Co-evaporation
Gas selenization
Vacuum evaporation
Medium temp: 600 C
Batch processing
Complicated to manufacture

Properties:
Fairly high efficiency: >10%
Needs protection against moisture
Contains toxic materials
Materials very scarce

Maximum of 20 GW production due to shortage of Indium

Figure 2.1 Cell Production (MW) and percentage growth rates 1996 to 2005



Cost of Silicon PV

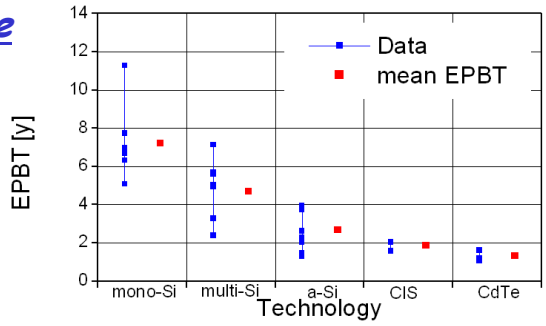
Present:
- Module: ≈ $2.50 per watt
- Roof installed: ≈ $6.50 per watt

500 MW automated plant:
- Module: < $1 per watt
- Roof installed: ≈ $3.50 per watt

SA coal:
- R70 billion 4200 MW
- R17 per watt (≈ $2.40)

Nuclear: ??

Energy Payback Time



Worldwide PV market

Figure 2.3 World PV Market by Application

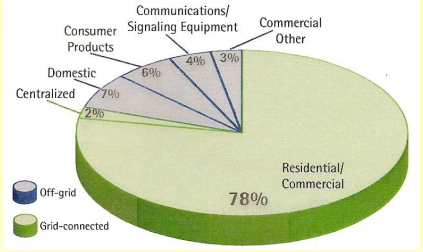
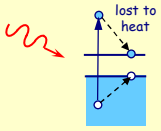


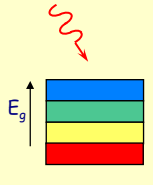
Figure 2.4 World PV Market 2005, by Country and Region

Region	Country	Installed (MW-DC)
Europe	Germany	700
	Spain	20
	Italy	5
	Rest of Europe	25
Europe Subtotal		750
Asia	Japan	320
	Southeast Asia	20
	India	20
	China	5
Asia Subtotal		365
US/Canada	United States	108
	Canada	5
US/Canada Subtotal		113
RoW	Australia & Region	50
	Middle East	25
	Latin America	21
	Africa	20
	Other	20
RoW Subtotal		136
Total		**1,364**

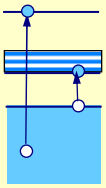
Future PV Concepts

present technology: 32% limit for
- single junction
- one exciton per photon
- relaxation to band edge

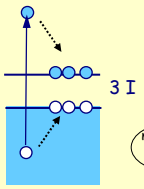




multiple junctions

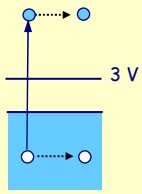


multiple gaps



multiple excitons per photon

nanoscale formats



hot carriers

rich variety of new physical phenomena
challenge: understand and implement

10%/20%/30% target

Can it be achieved?

2050: energy required = 946 EJ

"50%" = 473 EJ $\rightarrow$ 15 TW

$P = E / t \rightarrow 473 \times 10^{18}$ J / (365 day x (24 x 3600) s/day)

$P = 1.4998 \times 10^{13}$ W ≈ 15 TW

At 10% efficiency an area that receives 150 TW is required

1.2×10^5 TW reaches the earth's surface.

$\therefore$150 TW ÷ 1.2×10^5 TW = fraction of earth's surface

= 0.13% $\rightarrow$ 1.5×10^{11} m^2.

Equivalent to 6 areas, 160 km x 160 km

Solar energy area requirement

- 6 areas of 2.5 TW each = 160 km x 160 km