Solar

Solar Energy

- Concentrated Solar (Solar Thermal)
  - Use solar radiation to generate steam for turbine to generate electricity
- Photovoltaics (from Chapter 8)
  - directly convert photons into electricity
- Solar Fuels
  - Generate H_2 (maybe CH_3OH) by splitting water with solar photons
- Positives
  - no shortage of energy (mind-boggling large amount of E!)
  - carbon neutral
- Negatives
  - sun doesn't shine all the time
  - transmission losses
  - land usage issues
  - energy cost of implementation

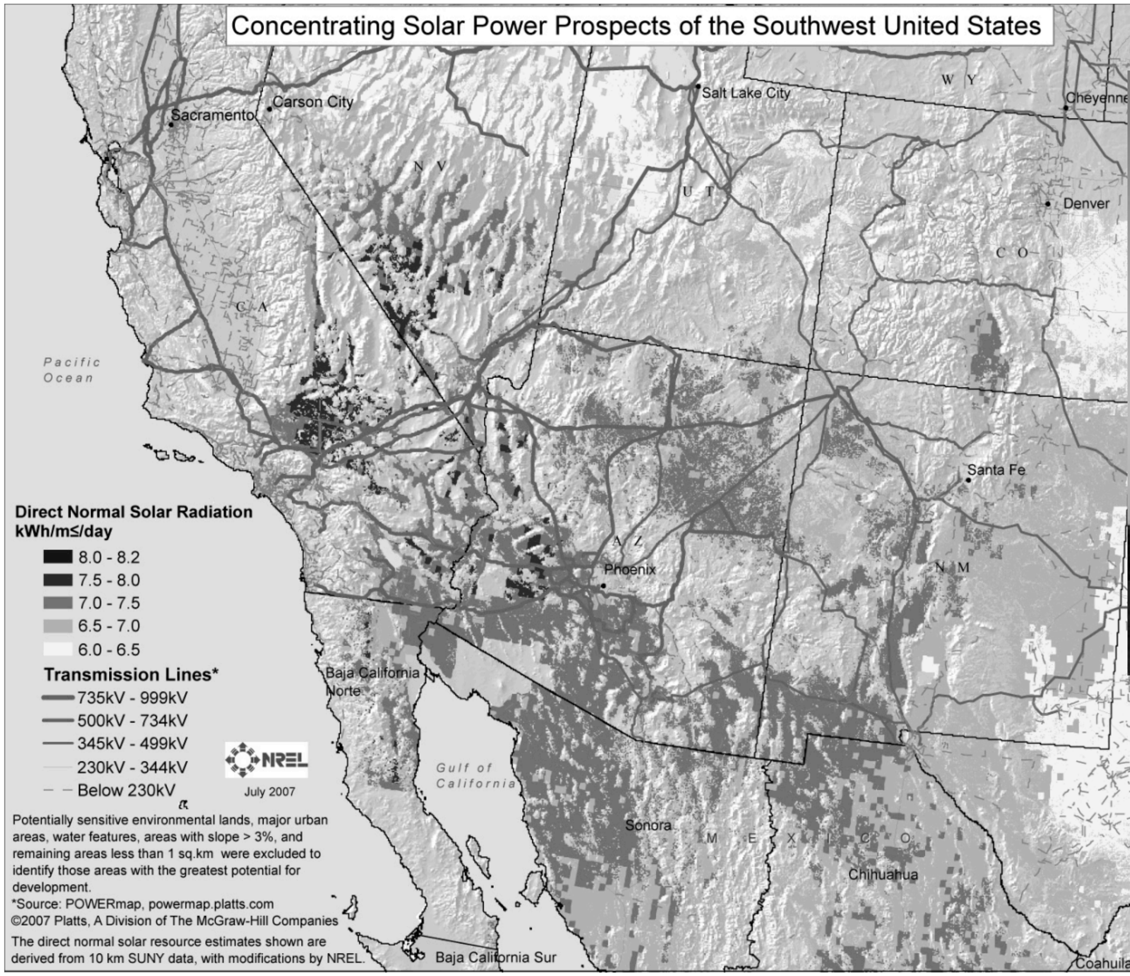
Alamosa SunEdison 8.22 MW PV solar plant (activated Dec 17, 2007)

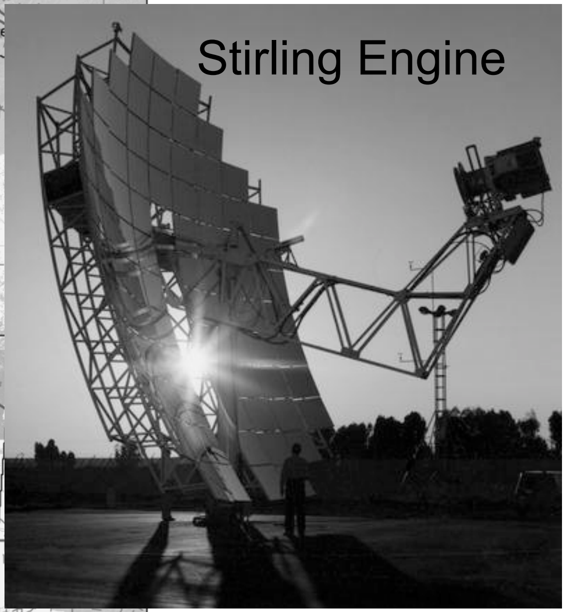
Seasonally adjusted fixed-axis photovoltaic panels at the SunEdison photovoltaic power plant near Alamosa, Colorado. Steve Wilcox Source: National Renewable Energy Laboratory, Photographic Information Exchange.

Stretched-membrane heliostats with silvered polymer reflectors surround the Solar Two power tower in Daggett, California. *Credit: Sandia National Laboratories / PIX 00036*

Solar Thermal

Need direct (not angled) sunlight & power lines for transmission





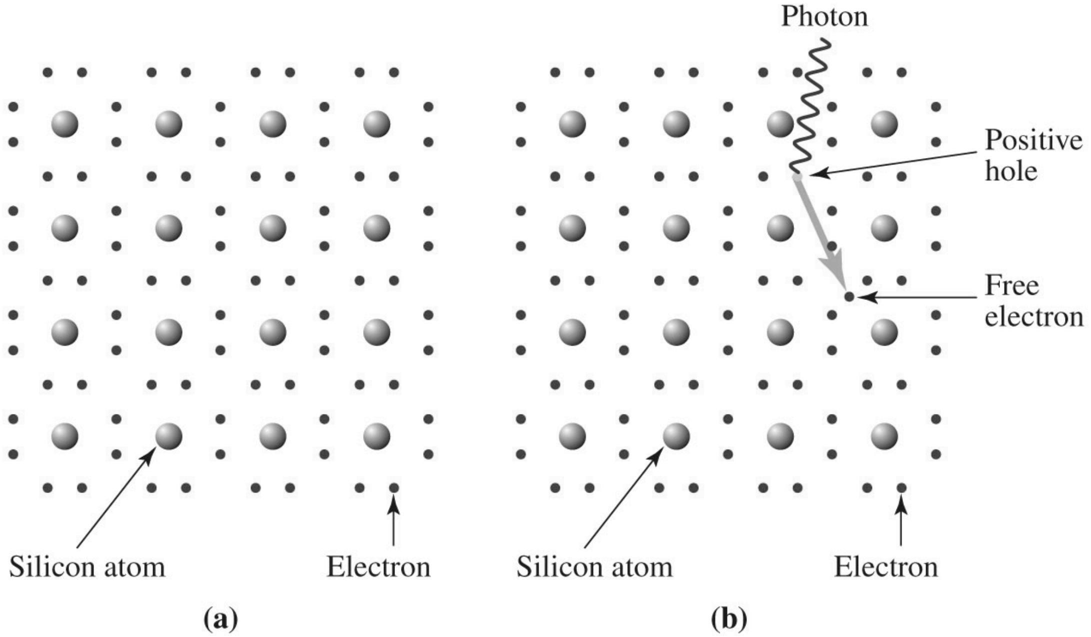
Stirling Energy Systems, Inc. (SES)/Boeing, 25 kW Dish Stirling system at sunset. Source: National Renewable Energy Laboratory, Photographic Information Exchange.

Since solar thermal schemes drive heat (steam) engines, they are limited by Carnot efficiency considerations; also an issue of storage

Solar Photovoltaics (Ch. 8.9)

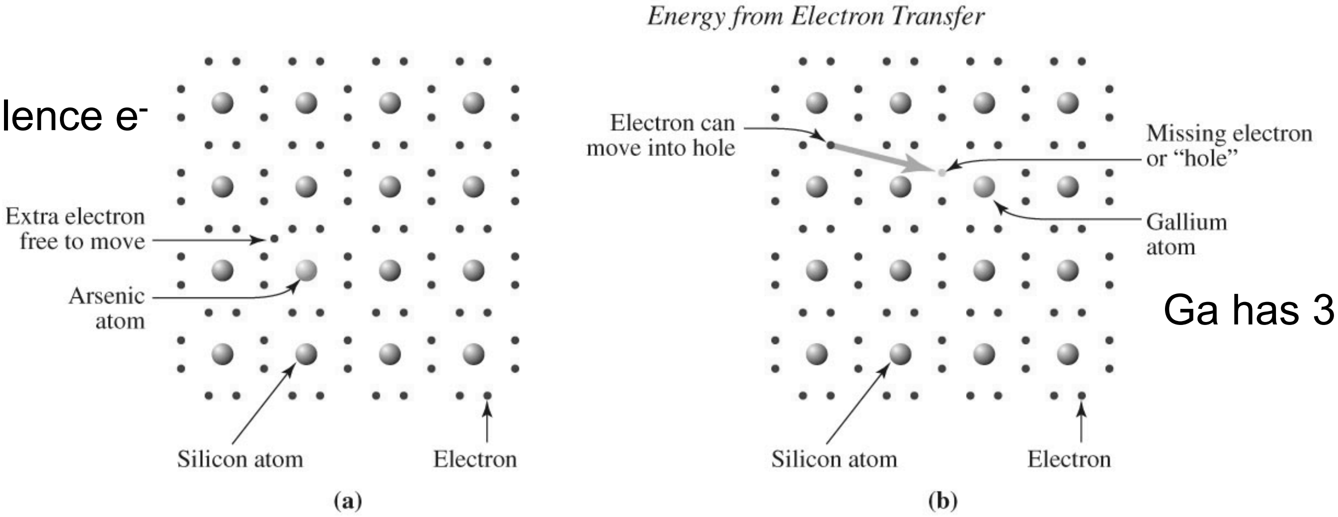
Pure:

Si has 4 valence e^-



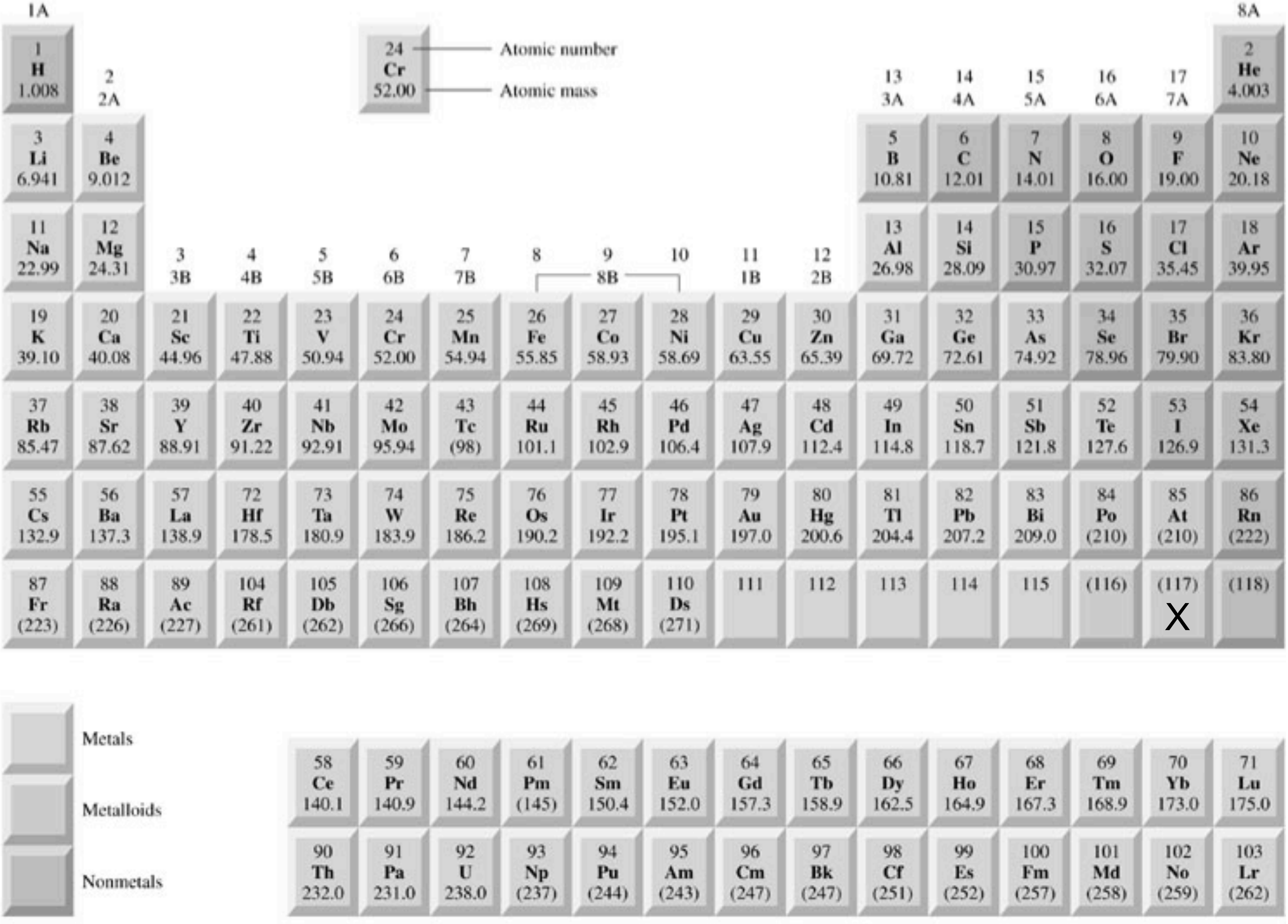
Doped:

As has 5 valence e^-



Ga has 3 valence e^-

The Periodic Table



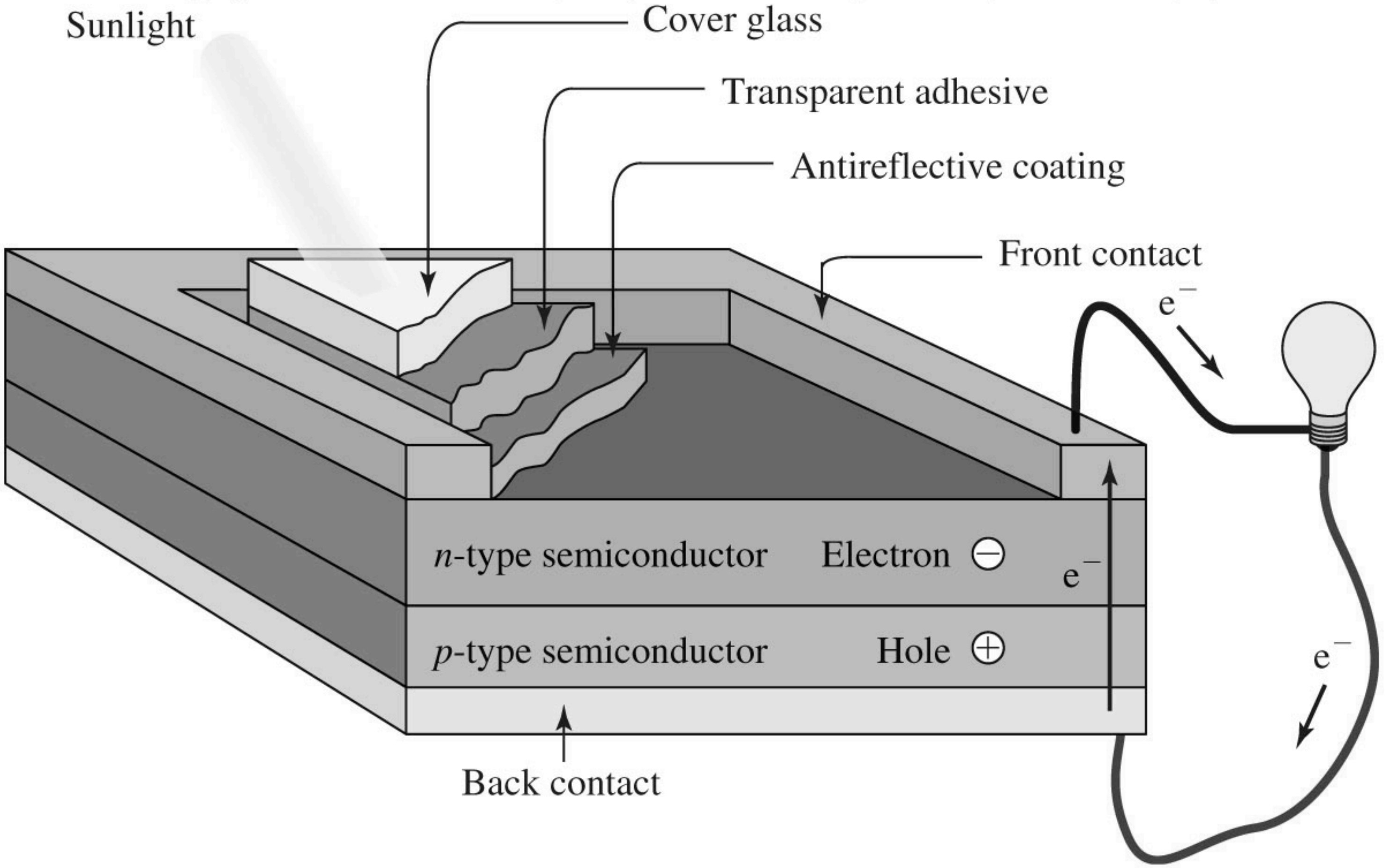
24 Cr 52.00
Atomic number
Atomic mass

1A	2 2A	3 3B	4 4B	5 5B	6 6B	7 7B	8	9 8B	10	11 1B	12 2B	13 3A	14 4A	15 5A	16 6A	17 7A	8A
1 **H** 1.008																	2 **He** 4.003
3 **Li** 6.941	4 **Be** 9.012											5 **B** 10.81	6 **C** 12.01	7 **N** 14.01	8 **O** 16.00	9 **F** 19.00	10 **Ne** 20.18
11 **Na** 22.99	12 **Mg** 24.31											13 **Al** 26.98	14 **Si** 28.09	15 **P** 30.97	16 **S** 32.07	17 **Cl** 35.45	18 **Ar** 39.95
19 **K** 39.10	20 **Ca** 40.08	21 **Sc** 44.96	22 **Ti** 47.88	23 **V** 50.94	24 **Cr** 52.00	25 **Mn** 54.94	26 **Fe** 55.85	27 **Co** 58.93	28 **Ni** 58.69	29 **Cu** 63.55	30 **Zn** 65.39	31 **Ga** 69.72	32 **Ge** 72.61	33 **As** 74.92	34 **Se** 78.96	35 **Br** 79.90	36 **Kr** 83.80
37 **Rb** 85.47	38 **Sr** 87.62	39 **Y** 88.91	40 **Zr** 91.22	41 **Nb** 92.91	42 **Mo** 95.94	43 **Tc** (98)	44 **Ru** 101.1	45 **Rh** 102.9	46 **Pd** 106.4	47 **Ag** 107.9	48 **Cd** 112.4	49 **In** 114.8	50 **Sn** 118.7	51 **Sb** 121.8	52 **Te** 127.6	53 **I** 126.9	54 **Xe** 131.3
55 **Cs** 132.9	56 **Ba** 137.3	57 **La** 138.9	72 **Hf** 178.5	73 **Ta** 180.9	74 **W** 183.9	75 **Re** 186.2	76 **Os** 190.2	77 **Ir** 192.2	78 **Pt** 195.1	79 **Au** 197.0	80 **Hg** 200.6	81 **Tl** 204.4	82 **Pb** 207.2	83 **Bi** 209.0	84 **Po** (210)	85 **At** (210)	86 **Rn** (222)
87 **Fr** (223)	88 **Ra** (226)	89 **Ac** (227)	104 **Rf** (261)	105 **Db** (262)	106 **Sg** (266)	107 **Bh** (264)	108 **Hs** (269)	109 **Mt** (268)	110 **Ds** (271)	111	112	113	114	115	(116)	(117) X	(118)

58 **Ce** 140.1	59 **Pr** 140.9	60 **Nd** 144.2	61 **Pm** (145)	62 **Sm** 150.4	63 **Eu** 152.0	64 **Gd** 157.3	65 **Tb** 158.9	66 **Dy** 162.5	67 **Ho** 164.9	68 **Er** 167.3	69 **Tm** 168.9	70 **Yb** 173.0	71 **Lu** 175.0
90 **Th** 232.0	91 **Pa** 231.0	92 **U** 238.0	93 **Np** (237)	94 **Pu** (244)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (247)	98 **Cf** (251)	99 **Es** (252)	100 **Fm** (257)	101 **Md** (258)	102 **No** (259)	103 **Lr** (262)

Metals
Metalloids
Nonmetals

A Photovoltaic Cell

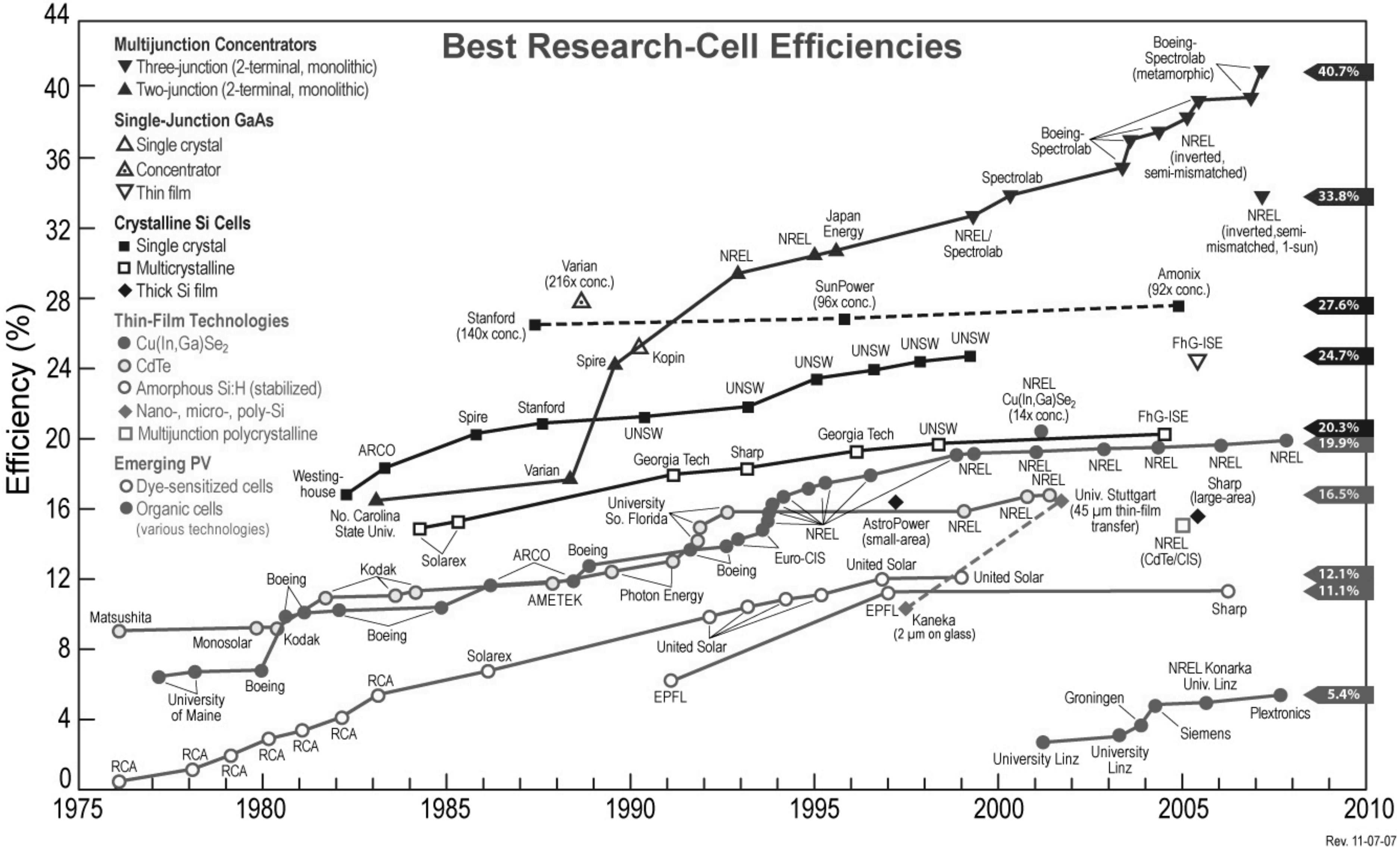


$$\text{Solar cell efficiency(\%)} = \frac{\text{Power out (W) x 100\%}}{\text{Area(m}^2\text{)x1000W/m}^2}$$

(10% efficiency=100W/m^2 or 10W/ft^2)

Energy content of incoming sun light

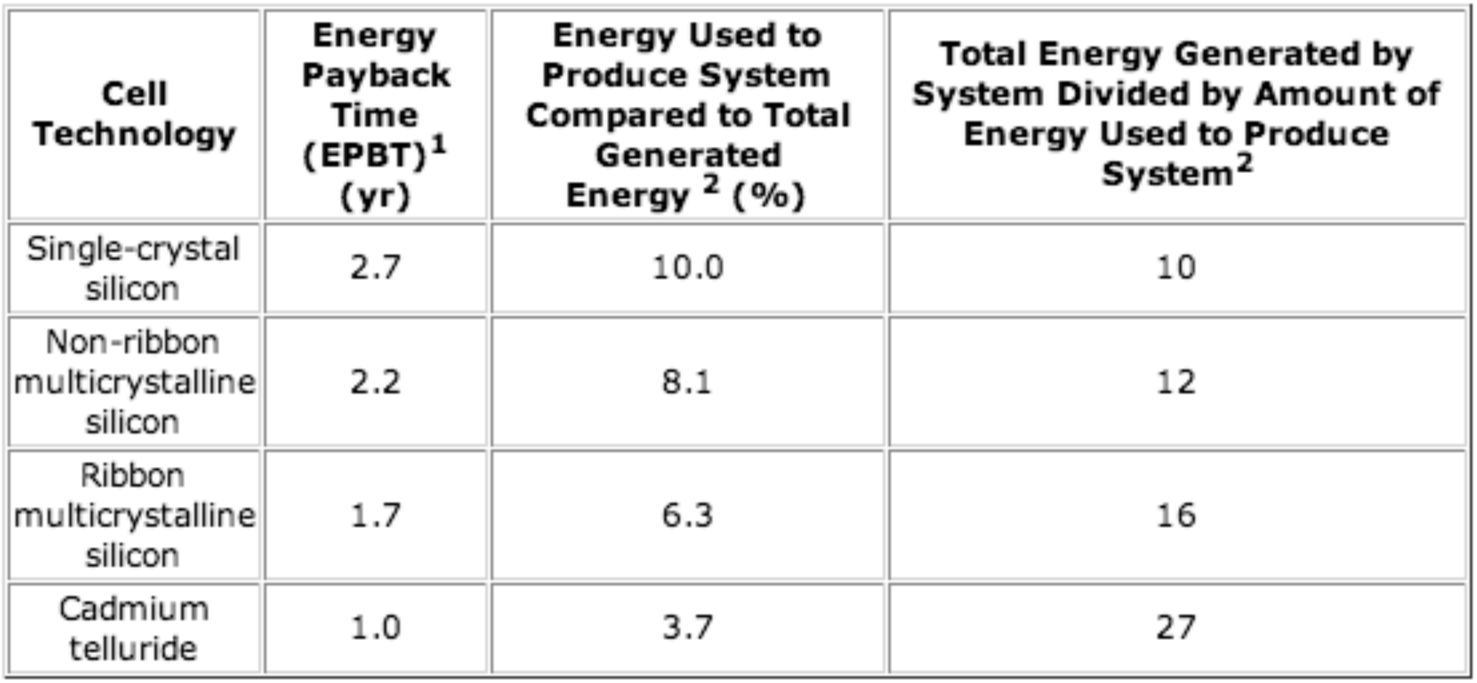
PV Cell Efficiencies Since 1975



Lawrence Kazmerski, Don Gwinner, Al Hicks, 11/11/07, NREL

Solar PV Energy Balance Calculations

System Energy Payback Times for Several Different Photovoltaic Module Technologies



Cell Technology	Energy Payback Time (EPBT)[1] (yr)	Energy Used to Produce System Compared to Total Generated Energy [2] (%)	Total Energy Generated by System Divided by Amount of Energy Used to Produce System[2]
Single-crystal silicon	2.7	10.0	10
Non-ribbon multicrystalline silicon	2.2	8.1	12
Ribbon multicrystalline silicon	1.7	6.3	16
Cadmium telluride	1.0	3.7	27

1. V. Fthenakis and E. Alsema, "Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004-early 2005 status," *Progress in Photovoltaics, vol. 14, no. 3, pp. 275-280, 2006.*

2. Assumes 30-year period of performance and 80% maximum rated power at end of lifetime.

Solar Panels

Typical solar panel is 1 m x 2 m & produces 75-350 Watts of power

$$\text{Solar cell efficiency(\%)}=\frac{\text{Power out (W) x 100\%}}{\text{Area(m}^2\text{)x1000W/m}^2} \qquad (10\%\ \text{efficiency}=100\text{W/m}^2\ \text{or}\ 10\text{W/ft}^2)$$

Energy content of incoming sun light

$$\frac{75\text{ W}}{1\text{ m}\times 2\text{ m}\times 1000\text{W/m}^2}\times 100\% = 3.7\%$$

$$\frac{350\text{ W}}{1\text{ m}\times 2\text{ m}\times 1000\text{W/m}^2}\times 100\% = 17.5\%$$

It is dark at night so panel only produces electricity ~ 1/3 of the time, so 117 W/panel

$$117\text{ W}=\frac{117\text{ J}}{\text{sec}}\times\frac{60\text{ sec}}{1\text{ min}}\times\frac{60\text{ min}}{1\text{ hr}}\times\frac{24\text{ hr}}{1\text{ day}}\times\frac{365\text{ days}}{1\text{ year}}=3.7\times 10^9\ \text{J=3.7 GJ}$$

US uses 13.3 EJ electricity/year, so

$$13.3\times 10^{18}\,\text{J}\times\frac{\text{panel}}{3.7\times 10^9\ \text{J}}=3.6\times 10^9\ \text{panels}\Rightarrow 7.2\times 10^9\ \text{m}^2=7{,}200\text{km}^2$$

Context:

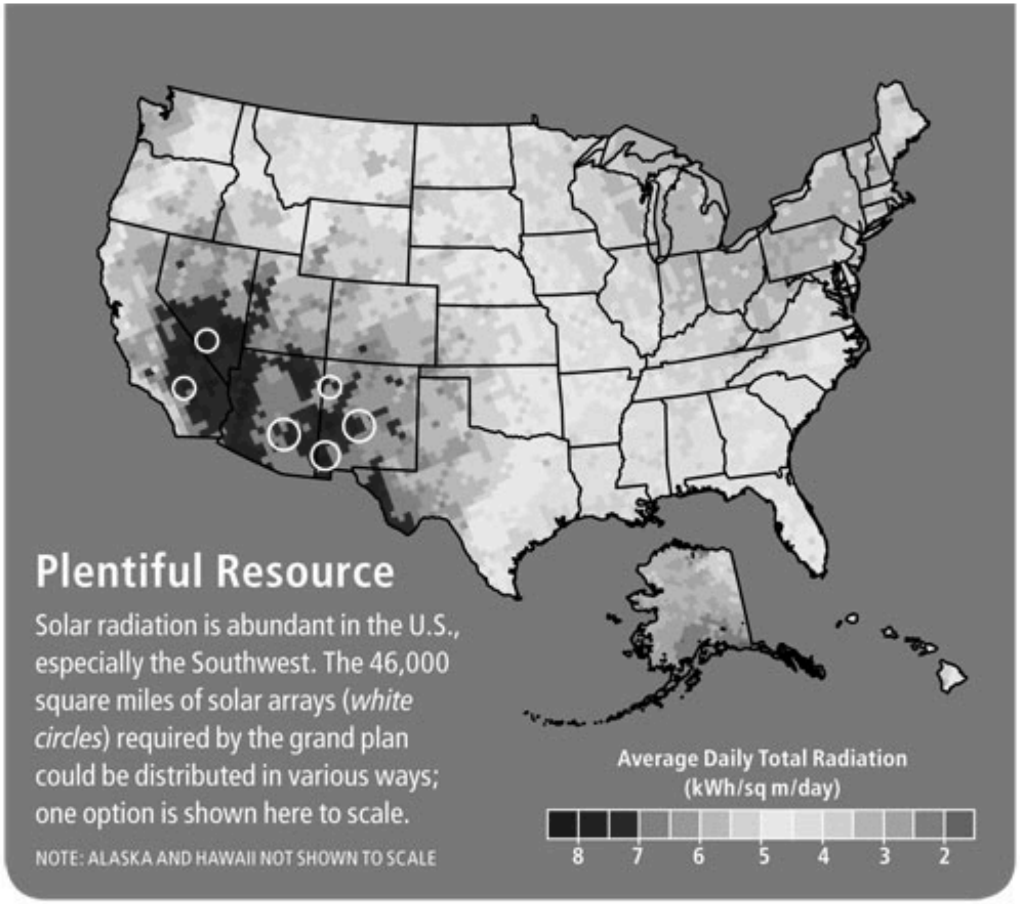
100 million homes in US, putting 12 panels on each would give 1/3 of needed power

US Interstate highway system is 3,500 km^2

A Grand Solar Plan Indeed

Zweibel, K.; Mason, J. Fthenakis, V. “A Solar Grand Plan”, Scientific American, *298* #1 64-73 **2008**.

Goal for 2050	(2007)
PV:	
30,000 sq miles land	(10 sq miles)
14% module efficiency	(10%)
Installed cost: $1.2/W	($4/W)
Electricity price: $0.05/kWh	($0.16/kWh)
Total capacity: 2,940 GW	(0.5 GW)
Compressed Air storage:	
535 billion cu ft	(0)
Installed cost: $3.9/W	($5.80/W)
Electricity price: $0.09/kWh	($0.20/kWh)
Total capacity: 558 GW	(0.1 GW)
Solar Thermal:	
16,000 sq miles land	(10 sq miles)
17% module efficiency	(13%)
Installed cost: $3.7/W	($5.30/W)
Electricity price: $0.09/kWh	($0.18kWh)
Total capacity: 558 GW	(0.5 GW)



Plentiful Resource

Solar radiation is abundant in the U.S., especially the Southwest. The 46,000 square miles of solar arrays (*white circles*) required by the grand plan could be distributed in various ways; one option is shown here to scale.

NOTE: ALASKA AND HAWAII NOT SHOWN TO SCALE

- Goal: to provide 69% of our electricity
- Goal: to provide 35% of our total energy
- 46,000 square miles of land will be required (size of New York state)
- $420 Billion investment (2007 Federal budget for Defense was $700B)

Assuming 2 year energy payback:

$$2\text{ years}\times 4056\text{GW}\times\frac{24\text{ hrs}}{1\text{ day}}\times\underset{\substack{\text{fraction sunny}\\\text{hours in a day}}}{0.35}\times\frac{365\text{ days}}{1\text{ year}}\times\underset{\substack{\text{fraction sunny}\\\text{days in a year}}}{0.85}\times\frac{1\text{x}10^{6}\text{kW}}{1\text{GW}}\times\frac{3.6\text{x}10^{6}\text{J}}{1\text{kWh}}=38.0\text{x}10^{18}\text{J}=\boxed{38\text{ EJ}}$$

Energy Summary

World Reserves	
Coal	20,200 EJ
Natural Gas	7,170 EJ
Oil	10,200 EJ
US use:	
Coal	20.8 EJ
Natural Gas	26.3 EJ
Oil	37.2 EJ
Nuclear	8.7 EJ
Biofuels	16.7 EJ
Wind	36 EJ
Solar	38 EJ

Cost of Electricity from Alternative Energy Sources

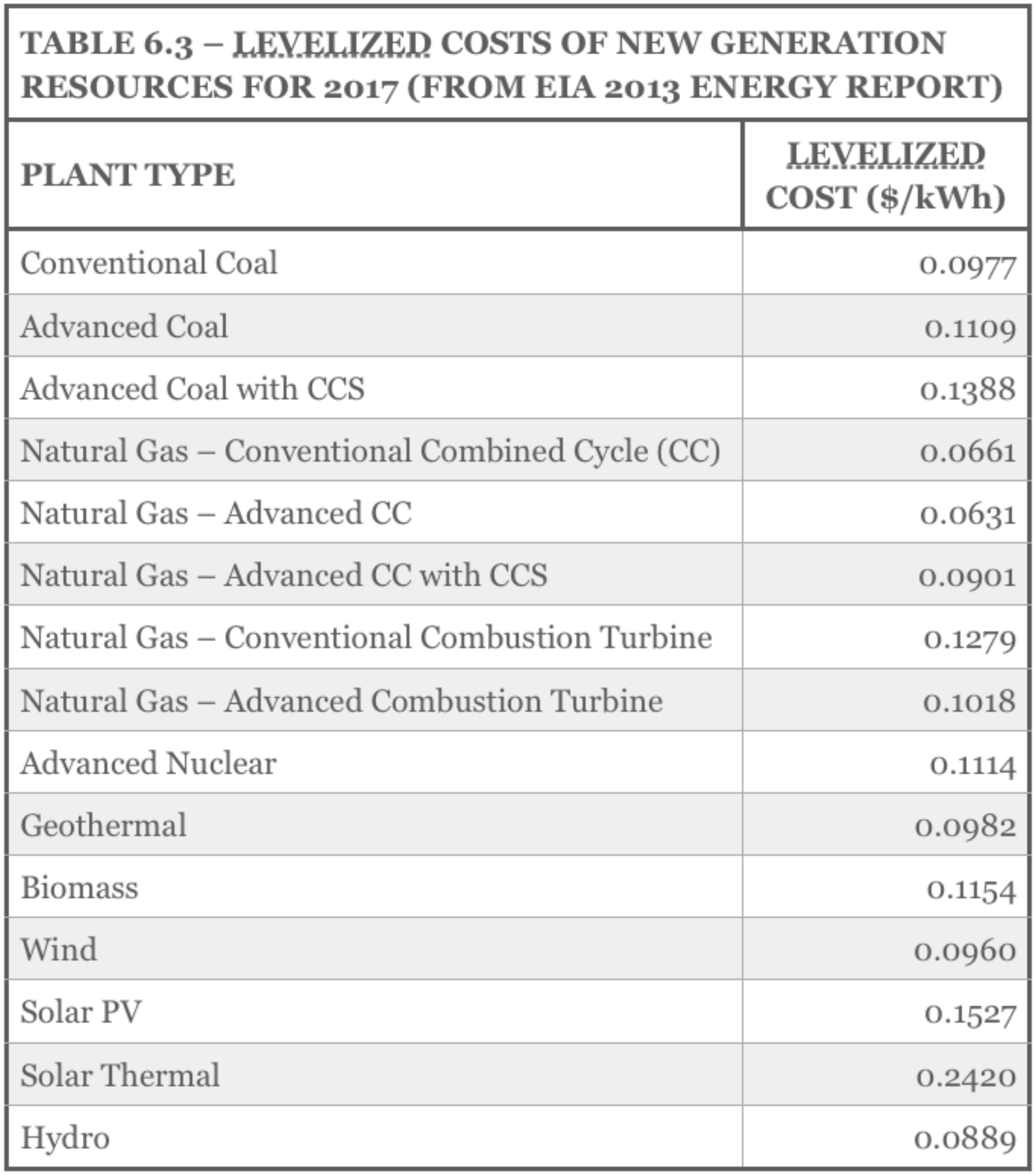


TABLE 6.3 – LEVELIZED COSTS OF NEW GENERATION RESOURCES FOR 2017 (FROM EIA 2013 ENERGY REPORT)

PLANT TYPE	LEVELIZED COST ($/kWh)
Conventional Coal	0.0977
Advanced Coal	0.1109
Advanced Coal with CCS	0.1388
Natural Gas – Conventional Combined Cycle (CC)	0.0661
Natural Gas – Advanced CC	0.0631
Natural Gas – Advanced CC with CCS	0.0901
Natural Gas – Conventional Combustion Turbine	0.1279
Natural Gas – Advanced Combustion Turbine	0.1018
Advanced Nuclear	0.1114
Geothermal	0.0982
Biomass	0.1154
Wind	0.0960
Solar PV	0.1527
Solar Thermal	0.2420
Hydro	0.0889