Energy Devices – Solar Energy (Lecture 8)

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Lecture outline:

- The sun's energy; what reaches us?
- The basics of a thermal generator.
- A simplified model of photovoltaics; implementation in semiconductors.
- Fundamental limits on conversion efficiency.

Resources:

- *The Physics of Solar Cells* – J. Nelson.
- *Physics Of Solar Cells: From Basic Principles To Advanced Concepts* – P. Würfel.
- *Fundamentals of Renewable Energy Processes* – A. V. da Rosa.
- "Solar collector basics" – J. Richter in J. Ren. Sus. Energy (043112, 2009).
- "Renewable Energy Annual 2007" – EIA/DOE.

"I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that." – Thomas Edison to Henry Ford and Harvey Firestone.[1]

[1] `http://www.nytimes.com/2007/06/03/magazine/03wwln-essay-t.html`

Image sources:

Fig. 1 (left)	Extended from discussion in `http://en.wikipedia.org/wiki/Proton-proton_chain`.
Fig. 1 (right)	Data from `http://rredc.nrel.gov/solar/spectra/`.
Fig. 2 (left)	Derived from `http://en.wikipedia.org/wiki/Parabolic_trough`.
Fig. 6	Following *Third generation photovoltaics: advanced solar energy conversion*, M. A. Green.

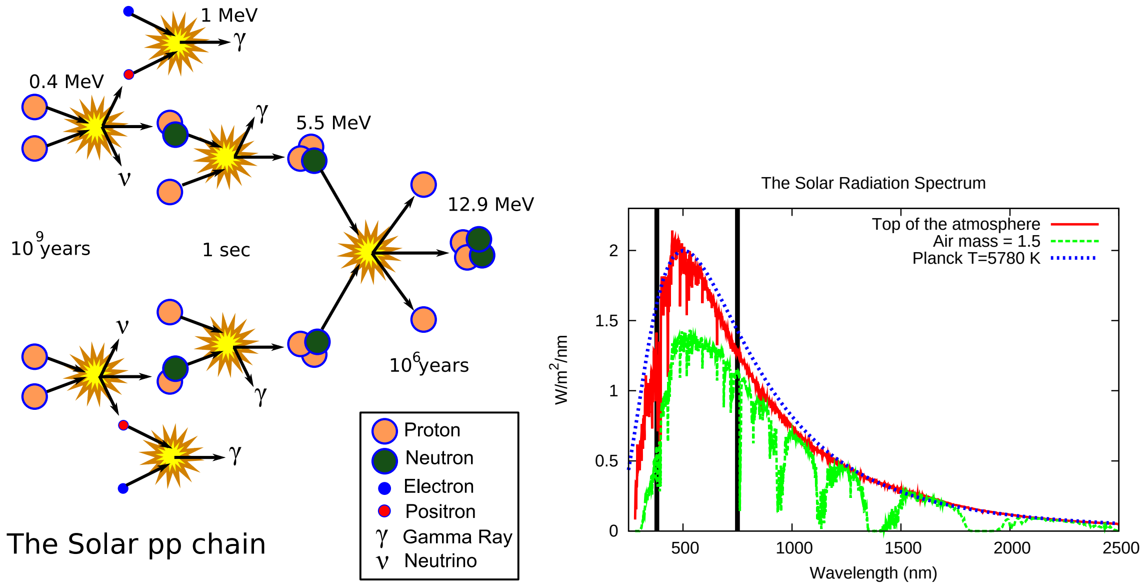

Figure 1: **Left: The origin of solar energy.** Last week's lecture described fission, so it is informative to compare fusion in the sun. Here, protons in the dense (~ 100 times water), hot (14×10^6 K) core of the sun fuse into deuterons. This step is very slow, allowing the sun to burn for billions of years. These fuse to helium-three, and those fuse to helium-four, emitting ~ 27 MeV. (See Lec. 7 notes for discussion of these energy units; compare this with the ~ 200 MeV in energy liberated in $^{235}\mathrm{U}$ fission.) The fusion energy is transported to the sun's surface, where the photosphere is visible to us at a temperature of ~ 5780 K. At this temperature, the sun emits 3.8×10^{26} W of radiant power. Where we are in space relative to the sun, we receive $1366\ \mathrm{W/m^2}$, of which, $\sim 1000\ \mathrm{W/m^2}$ can pass through the atmosphere (the opacity of the atmosphere $\sim 48°$ off Zenith, airmass 1.5, or AM1.5 for short). **Right: The spectrum of solar radiation on the Earth.** (Data from NREL AM0 and AM1.5 standards.) The red curve is the spectrum of solar radiation at the top of the atmosphere, roughly consistent with a black-body radiator at the sun's temperature (blue dotted line). The green line gives the spectrum of radiation reaching the earth. The lines mark off the visible spectrum, where ultraviolet (UV) is to the left and infrared (IR) is to the right. In the UV, there is significant attenuation by ozone, and in the IR there are a large number of oxygen, water, and carbon dioxide molecular resonances that strongly absorb radiation. The integrated power reaching the surface is $121,000$ TW (da Rosa). On the Earth's surface, if we put a collector tilted up by the latitude to roughly optimize over the sun's arc through the sky, the average annual power incident on that panel will span $150\ \mathrm{W/m^2}$ in northern US climates to $285\ \mathrm{W/m^2}$ in the southwest US (data: NREL).

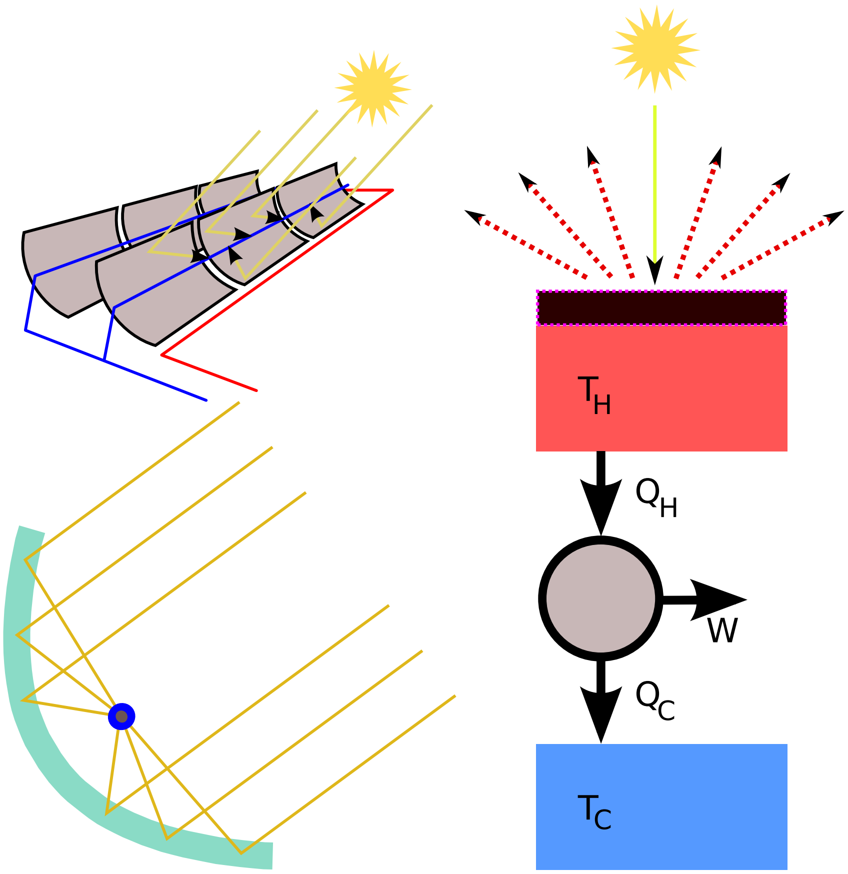

Figure 2: **Left: A parabolic trough collector**. Here, the sun's light is focused onto receiver tubes (an absorber surrounded by an evacuated cylinder), producing temperatures $\sim 400 - 600$ K. That heat can be transferred out and exploited in a heat engine, such as a steam turbine of Lec. 3 and 6. **Right: The general scheme of a solar thermal heat engine.** The efficiency of a heat engine between some T_H and T_C is limited by the Carnot efficiency (Lec. 6), $\eta = 1 - T_C/T_H$. (Here, the coldest T_C that we can practically achieve is the ambient air temperature of 300 K.) From this point of view, the hotter we can make the absorber, the better. Yet, the Stefan-Boltzmann law tells us that the energy radiated by such an absorber is proportional to T^4! For practical temperatures, only part of this may be radiated as visible light (like a red glow), but it represents a significant amount of energy in the IR. An important difference between the sun's light and this re-radiated light is that the re-radiated heat can go in any direction while the sun only subtends a small area of the sky. Thus, even if a radiator is not as hot as the sun, it can still radiate a significant amount of its power. One can combat this by limiting the IR radiation that is re-emitted and by increasing the size of the sun subtended on the sky as seen by the absorber with a concentrator (how a magnifying glass would make the sun look bigger). Based on these considerations, the maximum efficiency achievable for a black absorber is $\sim 85\%$ (Würfel). The main families of solar thermal are tough systems (like the parabolic trough; having a linear receiver), dish systems (like a large, steerable satellite dish), and power tower systems (with a field of heliostats to direct the sun's light at an absorber in a tower). In practice, peak solar-to-electric efficiencies have been found to be 20%, 23% and 29% for troughs, towers, and dishes respectively (Smil, *Energy at the crossroads.*)

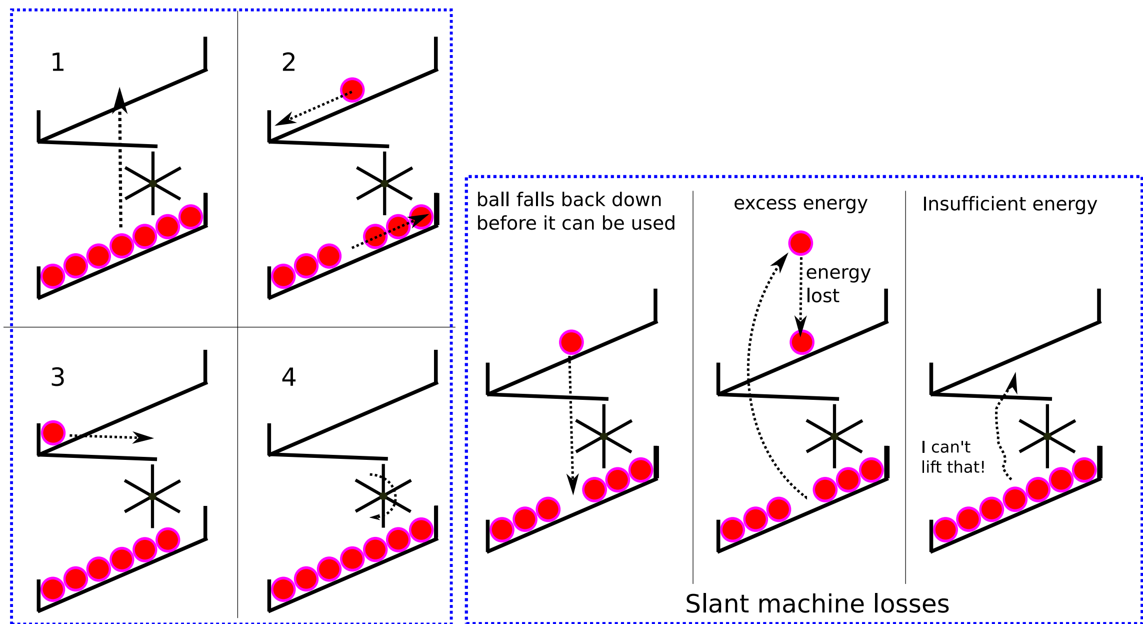

Figure 3: **Left: a mechanical model of photovoltaics.** In frame 1, 7 balls rest on the bottom tilted shelf. Because they are packed in, they are not able to roll. In frame 2, we lift a ball to the top shelf. It is now free to roll down to the bottom of the shelf. The remaining balls on the bottom fall into the hole left behind. Another way to imagine this, though, is that the hole bubbles up to the top of the shelf. In frame 3, the ball rolls down toward a rotor, and in frame 4 induces rotation before it falls back into the hole on the lower shelf. Any ball you choose to lift will go through the same trajectory and allow energy to be extracted. **Right: some limits of the slanted machine.** Case 1: if the ball falls back down (by rolling off the shelf) before it can be used, that energy is lost. Case 2: if we lift the ball too high (so that it is well above the top shelf), the energy will be lost. Case 3: if an “operator” is unable to lift one of the balls to the top shelf, their effort was for naught.

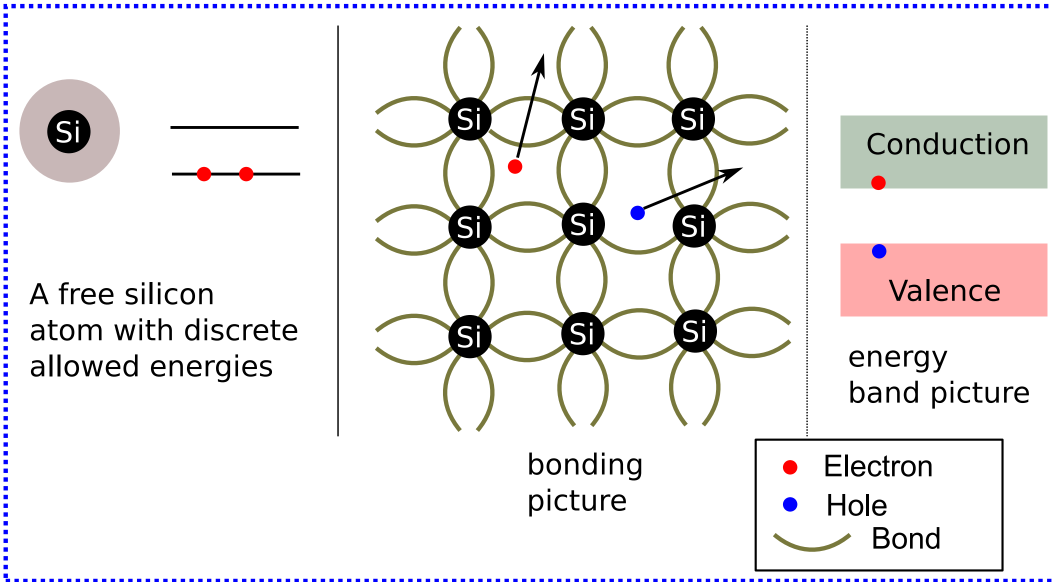

Figure 4: The photovoltaic is similar in operation to the slant machine, Fig. 3. Here we identify the rolling balls and the shelf. **Discrete states and bands:** From the spectra of radiation emitted by atoms, we know that their electrons occupy discrete energy levels allowed by quantum mechanics. (The atom can absorb and emit radiation of discrete frequencies associated with transitions of the electron between these levels.) This description applies to free atoms, but when atoms are packed into a solid, these discrete energies can broaden into bands. **Electrons in the solid:** Some of these energy bands are associated with the electrons that hold the solid together. Silicon has 14 electrons and keeps its inner 10 electrons ($1s^2 2s^2 2p^6$), but the four outer electrons ($3s^2$ and $3p^2$) form four covalent bonds with other silicons. The bonding electrons here are in the so-called "valence band". **The conduction band:** If you put a voltage across the silicon, the electrons in the valence band can't budge, and so the resistivity is very high. This is analogous to the lower row of balls in the slant machine. If one ball is moved to the empty shelf, it is free to roll down, and the hole it leaves behind is free to roll up. In the same way that a photon can excite the discrete levels of an atom, a photon with sufficient energy can excite an electron from the valence band to the next band up, which is empty. There, the electron is free to move around, and so the band is called the conduction band. (Likewise, the hole that it left behind is free to move around.) The energy necessary to drive this transition is called the *bandgap energy*.

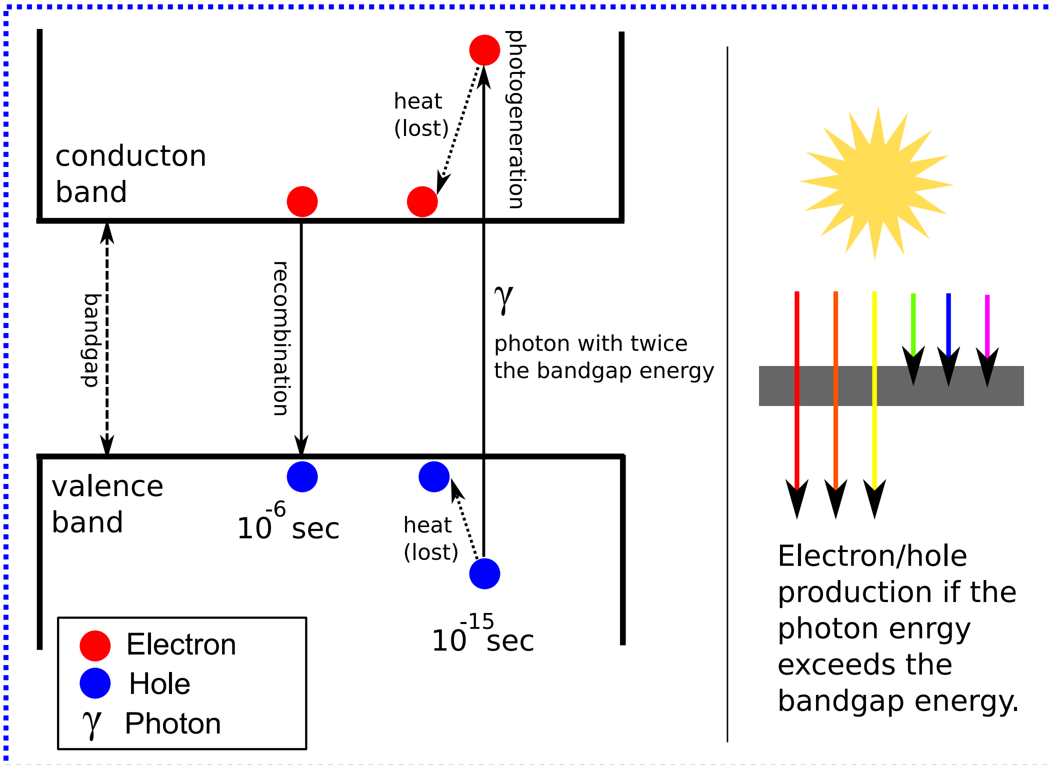

Figure 5: **Excitation across a bandgap.** Here a photon excites an electron up to the conduction band in a process called "photogeneration". Sunlight has photons of a wide range of energies (see the spectrum in Fig. 2). The rainbow on the right shows the rough sense of this absorption. If photon has insufficient energy to excite the electron (the red, orange and yellow lines), it will not be absorbed in the semiconductor. In this figure, photons blueward of green have enough energy to excite the electron across the bandgap, and so are absorbed in the semiconductor. Many of the solar photons have energy well in excess of the band gap, and so may excite an electron from low in the valence band to high in the conduction band. Because the electron is so energetic compared to other particles in the solid, it will tend to bump into the lattice of the solid and give up its energy as heat. Similarly, the hole left by the electron will bubble up to the top of the valence band (another way to conceptualize this is that the other electrons in the valence band fall into the hole left by the missing electron). The process of bumping into the lattice can only take away tiny amounts of energy away from the electron, so when it reaches the bottom of the conduction band, it is extraordinarily unlikely that a *single* bump will take away enough energy for it to fall back to the valence band. Thus, the electron takes about 10^{-15} seconds to give up its newfound energy as heat, but it takes microseconds for it to fall from the bottom of the conduction band back to the valence band. The electron sitting at the bottom of the conduction band still embodies some of the energy of the incident photon. In a solar collector, our goal is to convert that energy into electrical energy. As soon as the electron falls back into a hole in the valence band (a process called "recombination"), that energy is lost, so one has to find a way to quickly exploit the electron's energy. One way to do this is to herd the electrons one way and the holes another way before they can recombine. In standard cells, this is done with a junction of dis-similar semiconductors. Fig. 6 shows a schematic of this process.

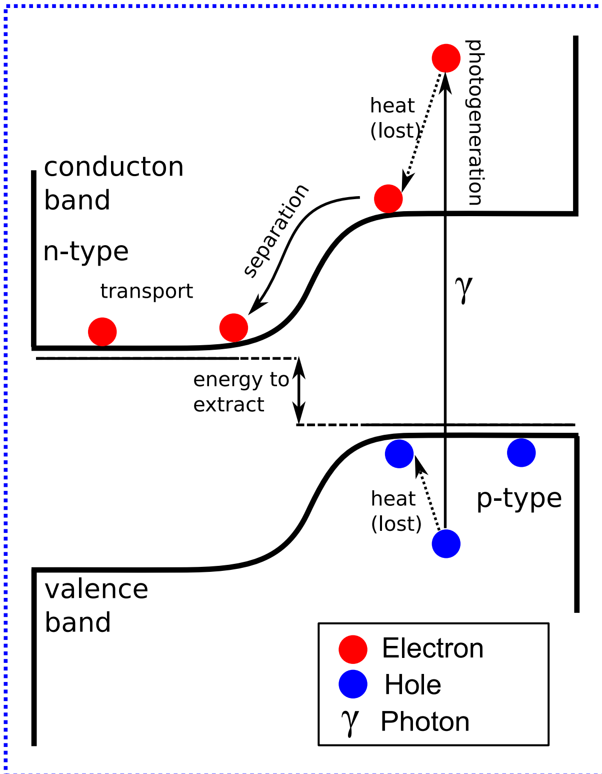

Figure 6: In Fig. 5, we saw that a photon with sufficient energy could excite an electron to the conduction band. On its own, it will recombine to the valence band, so that the energy gained from the photon could not be exploited electrically. There are a wide variety of photovoltaic cell designs, but what they have in common is that to extract electrical energy, they separate the electrons and holes through some type of "semi-permeable" interface. The silicon junction above uses the same idea as a diode to achieve this. (A diode is a circuit component that behaves like a one-way valve for current.) Here, one joins two slabs of dis-similar semiconductors (here, strictly the same silicon semiconductor but doped differently). In Fig. 5, the conduction band and valence band were at the same energies moving from left to right, but by joining the two different types of semiconductor, these bands "bend" so that the bottom of the conduction band on the left side is at a lower energy than on the right. (In this schematic, electron energy increases along the vertical axis.) Here, the electrons are carried to the left across a gradient (rolling down the hill) and holes are carried to the right (bubbling up). This is similar in spirit to the slanted ball machine in Fig. 3. The difference in potential between the electron and hole can be extracted as electrical energy through attached electrodes.

1 Efficiency

1.1 Summary of photovoltaic loss

Let's break down the efficiency of a practical single-gap cell (Würfel). Only photons in the solar spectrum that are not reflected and have an energy exceeding the bandgap will be absorbed. For silicon's bandgap, these are photons more blue than 1130 nm (1.1 eV), and absorption here takes place with 74% efficiency. Next, whatever energy the photon has *in excess of the bandgap* is lost as heat. This thermalization step has 67% efficiency. Yet now, we can not extract the full bandgap energy because of thermodynamic losses (the other way of saying this is that the open-circuit voltage is less than the electron-hole pair energy). This thermodynamic term has efficiency 64%. The final factor is related to how we extract power from the cell. The factors so far describe the efficiency that energy in solar photons is converted into the potential energy of electron-hole pairs in the cell. To extract power, we want a *current* of such electrons, recalling that $P = IV$ (power is current times voltage). Yet, when we draw a current, the voltage available drops. At maximum power, this leads to an electrical recovery efficiency of 89% (this is sometimes called the fill factor). The cumulative efficiency is then 28%. In addition to the device efficiency, there is also the power density of incoming solar radiation. At peak, this is about $1000\ \mathrm{W/m^2}$, but because of weather, and the arc of the sun through the sky, the annual average power density will be lower. Annual insolation in the best areas of the world for fixed (tilt equals latitude) arrays is $285\ \mathrm{W/m^2}$, or $\sim 30\%$ of peak AM1.5 insolation.

Almost all of these terms are fundamental and irreducible (for this single junction, single-exciton type of cell we are considering). We might be able to improve the absorption by minimizing reflected light, but one still only exploits part of the spectrum because the photons must have energy greater than the bandgap. One may then try to move to a lower bandgap energy so that lower photons can excite the cell; then, though, each photon produces less energy, so the more energetic photons buy you less (the rest of its energy is lost to thermalization). There is therefore an optimum bandgap for solar radiation around 1.4 eV. At the 1.1 eV of our silicon, we are still close to this maximum. In this simple "single exciton" scheme, the photon can produce only one electron-hole pair and the rest is lost to heat. Therefore the thermalization loss is irreducible. Next, consider thermodynamic and electrical recovery losses. Here, a loss term is that some recombination must occur in the cell, and that this must be associated with the emission of some radiation. Thus, in all of these one reaches a fundamental efficiency floor of around 33% (Nelson). For the geometrical factors, one can gain by having cells track the sun, but this introduces significant cost. In 2007, the average single crystal cell that shipped had 17% efficiency. Most growth in the industry has been in thin films ($\sim 40\%$ market share), whose shipments now exceed crystalline silicon cells ($\sim 60\%$ market share). Thin films have $8 - 12\%$ efficiency, but lower cost. (data: EIA)