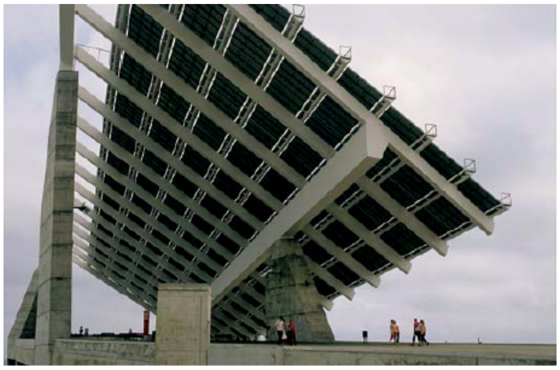
Solar PV on Earth and in Space: A New Perspective for Energy

by Marty Hoffert, Physics Dept., New York University



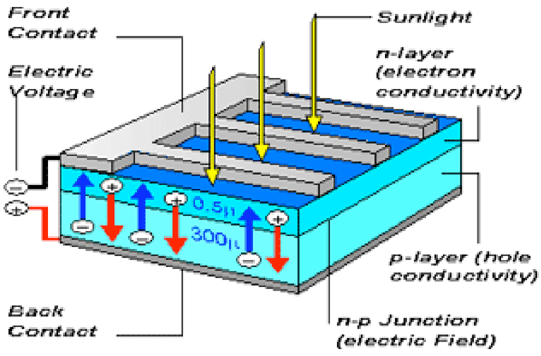
Introduction. Solar Photovoltaic (PV) cells could power the US and the world if one considers them limited only by solar flux (Turner, 1999). A vastly greater amount of solar energy is available in space which could in principle run a civilization much more advanced than ours (Dyson, 1960, Kardashev, 1964). But so far renewable energy sources (excluding hydro and wood burning by pre-industrial societies) are less than 1% (< 0.1 TW) of human primary energy consumption. Physics and economics are reviewed here bearing on a goal of increasing the power input from solar PV to 1 terawatt electrical (1 TWe = 10^{12} watts electrical), or more, by the mid 21st century, roughly equivalent to 3 TW from chemical or nuclear energy, or 2.3 billion tonnes of carbon emissions per year from coal avoided. My focus on PV, whose moving parts are "excitons" -- bound states of electrons and "holes" -- in no way implies that solar thermal-dynamic systems or other energy technologies aren't important.

The reality is that utility executives in the US, China and India clearly believe conventional coal-fired power plants are the most cost-effective electricity sources now. They're planning to build 850 of them shortly, enough to overwhelm Kyoto carbon emission reductions by a factor of five (Clayton, 2004). These investments will be "sunk" some 50 years. Can PV be competitive for baseload electricity as envisioned by the PV Roadmap of the National Renewable Energy Laboratory (http://www.nrel.gov/ncpv/vision.html)? The answer, I will argue here, is yes, provided we act boldly with innovative technology and systems, and in some cases against conventional wisdom. My personal views inform this review. I and colleagues find that at present energy costs there are no existing technologies, individually or in combination, that could simultaneously power our growing economy & stabilize global warming below, say, 2 degrees Celsius (Caldeira et al., 2003). There could be. But each path has branches with technology cost hurdles to overcome.

An alternate view is that technologies "already exist" to solve the climate/energy problem for fifty years (Pacala and Socolow, 2004). I've discussed it with these authors, and believe there's less difference between us than might appear. To paraphrase Bill Clinton, the issue is what the definition of "exist" is. There are promising paths and some components at "industrial scale." But it will take major R & D to make them cost-effective at the needed global scale. That doesn't imply doing nothing to reduce emissions now. Prompt action and accelerated research are not competing ideas. The earlier & the more emissions are limited, the more likely to avoid the worst impacts of fossil fuel burning: hurricanes in some locations, droughts in others, coastal flooding, acidification of the oceans, biodiversity loss & eventual breakup of polar ice sheets (Knutson and Tuleya, 2004; Caldeira and Wickett, 2003; Hansen et al, 2004). All non-fossil energy options look expensive, particularly if future damage costs are highly discounted. I emphasize here that technology costs are moving targets. Moore's-Law-like reductions have occurred in many technology classes from learning-by-doing and research. And innovation can change the game entirely. There's a real danger that overly conservative approaches based on extrapolated economics, as opposed to inventions & system based on physics, will miss potential solutions (Hoffert et al., 2002). A potentially fatal failure for any high-tech civilization faced with existential threats is "failure of imagination" (Clarke, 1982, Kean and Hamiliton, 2004). Good reasons to revisit solar PV from a fresh perspective.

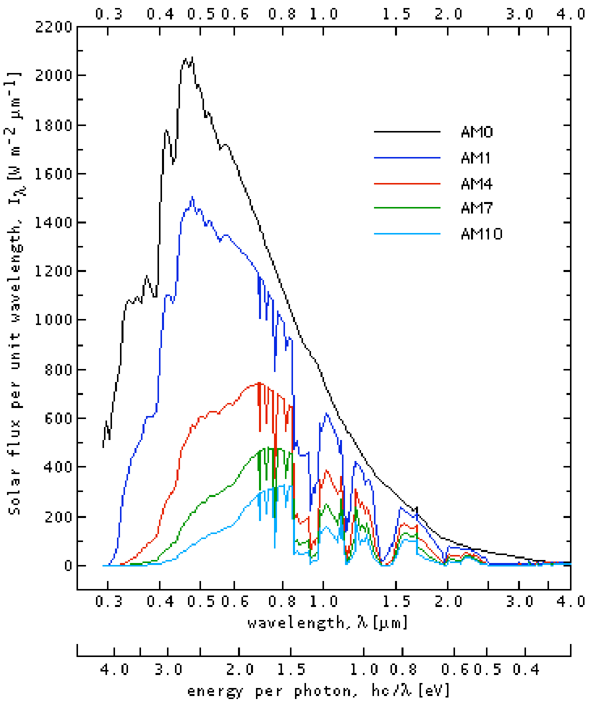
Energy efficiency. Solar cells convert incident solar flux to electric currents. They all have at least one photoactive layer that is itself a sandwiched layer of two semiconductors -- materials that are insulators at absolute zero but become electrically conducting under certain conditions. A semiconductor has a band of fully occupied electron states (a *valance band*) and a band where electrons can flow (a *conduction band*). The conduction band is empty at zero kelvins. At room temperature some electrons exist in the conduction band from random thermal motion -- hence the term *semiconductor*. The energy in photons of light incident on PV cells is what produces electric currents. The energy difference between valance and conduction bands is the *bandgap energy* $\varepsilon_0 = h\nu_0$, where h is Planck's constant $\approx 6.63 \times 10^{-34}$ J-s $\approx 4.14 \times 10^{-15}$ eV-s and ν_0 the bandgap frequency. Each semiconductor has a characteristic bandgap typically of the order of magnitude of an electron-volt (eV).

Quantum mechanics mandates that incident photons with energy $< \varepsilon_0$ dissipate their energy as heat, and are thus wasted. Only photons with energy $\geq \varepsilon_0$ can raise electrons to the conduction band. Even photons with $h\nu > \varepsilon_0$ only contribute a fraction of their energy, $\varepsilon_0/h\nu$, to raising electrons to the conduction band. The excess above ε_0 is also dissipated. Electrons energized to the conduction band leave positively charged "holes" in the semiconductor matrix. This is crucial to PV cell operation. Semiconductor layers are "doped" with impurities during manufacture to produce either an abundance of carrier electrons (n-layers) or an abundance of holes (p-layers), and the dissimilar layers are sandwiched together to produce a permanent electric field near the p-n junction, as shown in the inset for crystalline-Si cells. Electrons liberated close enough to the junction to not recombine (with holes) are swept across the boundary by the electric field. This creates a charge imbalance that can't be neutralized inside the cell because the electric field prevents electrons from recrossing the boundary. Electricity is only produced when electrons recombine with holes after traveling



through an external circuit. If there's no external load and the sun is shining an open-circuit voltage exists at the contacts. When a load is connected, current flows. To the outside world the cell looks like at battery. Unlike batteries, power available drops whenever photons stop making electron-hole pairs (at night, or when clouds roll by).

The efficiency with which PV cells convert energy in photon fluxes to direct current is limited by the fact that sunlight is distributed over a spectrum of frequencies ν; or, equivalently, over a spectrum of wavelengths $\lambda = c/\nu$, $c = 3.0 \times 10^8$ m/s being the speed of light; whereas semiconductor bandgaps absorb light of specific wavelength. The inset shows solar intensity per unit wavelength, I_λ (W/m^2-μm) distributions in space above the atmosphere and at the surface for various "air masses" as functions of wavelength in microns, and energy per photon in electron volts (data from Kreith and Krieger, 1978). Here AM0 denotes the solar spectrum in above the atmosphere. The other curves are the spectrum after atmospheric absorption for an overhead sun of zero zenith angle (AM1) and after sunlight has passed through slant paths of increasing zenith angle: four (AM4), seven (AM7) and ten (AM10) times as thick as an air mass one directly overhead. The wavelength integrated intensity $I = \int I_\lambda d\lambda$ of these curves declines as progressively thicker layers of atmosphere absorb more sunlight: $I_0 = 1370$, $I_1 = 890$, $I_4 = 440$, $I_7 = 255$, and $I_{10} = 153$ W/m^2, respectively. $I_0 = 1370$ W/m^2 is the solar constant at Earth's orbital distance. Averaged over diurnal cycle and cloudiness effects, solar intensity at the surface is in the range 150-200 W/m^2, perhaps 250 W/m^2 in clear-sky deserts. Higher, and constant in time at unshadowed orbits, solar fluxes in space are major advantage of space solar power.



A limiting efficiency of PV cells can be derived for single bandgap semiconductors as follows. From the above discussion the monochromatic absorption efficiency is

$$\eta(\nu,\nu_o) = \left\{ \begin{matrix} (\nu_o/\nu); & \nu \ge \nu_o \\ 0 \;\; ; & \nu < \nu_o \end{matrix} \right\} \qquad [1]$$

To get the peak efficiency possible when exposed to sunlight we need to weight this by the distribution of photon energy versus frequency in sunlight. The intensity distribution per unit frequency $I_\nu(\nu)$ is related to the wavelength distributions by $I_\nu \equiv \; I_\lambda d\lambda/d\nu$. Note that $d\lambda/d\nu = -(c/\nu^2)$ and $I_\lambda(\lambda) = -\,(\nu^2/c)I_\nu(\nu)$. The same total intensity is thus obtained regardless of whether one integrates over wavelength or frequency:

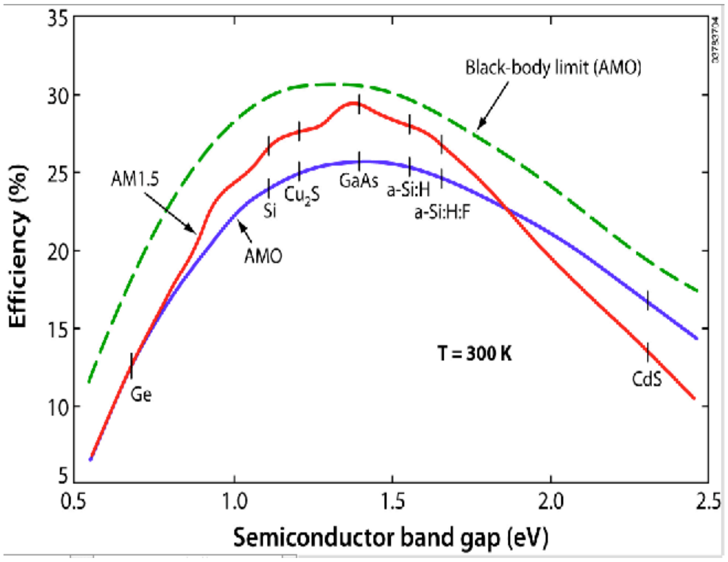
$$I = \int_0^\infty I_\lambda(\lambda)d\lambda = \int_0^\infty -(\nu^2/c)I_\nu(\nu)\bullet -(c/\nu^2)d\nu = \int_0^\infty I_\nu(\nu)d\nu\,. \qquad [2]$$

The upper-bound efficiency for any sunlight distribution $I_\nu(\nu)$ is calculable as a function of the single-bandgap frequency (or bandgap energy $\varepsilon_o = h\nu_o$):

$$\eta(\nu_o) = \frac{\int_0^\infty \eta(\nu,\nu_o)I_\nu(\nu)d\nu}{\int_0^\infty I_\nu(\nu)d\nu} = \frac{\int_0^\infty \eta(\nu,\nu_o)I_\nu(\nu)d\nu}{I} \qquad [3]$$

This limit was first derived by Schockley and Queisser (1961) at Bell Labs.

Numerical integrations of [3] shown in the inset below indicate Schockley-Queisser (SQ) efficiencies peak in the 20-30% range for semiconductors with bandgaps in of 1-2 eV, depending on spectral details. Remarkably, PV cells, and even fabricated PV modules with spaces between cells, have achieved close to this limiting efficiency with silicon and gallium arsenide crystals, and continue to improve for thin film technologies. Confirmed module efficiencies calibrated at $I_p = 1$ kW/m^2 intensity are 25.1% for gallium arsenide/gallium antimony (GaAs/GaSb; with a solar concentrator), 22.3% for crystalline silicon (Si), 13.9% for copper indium diselinide ($CuInSe_2$), 12% for amorphous silicon (a-Si) and 10.5% for cadmium telluride (CdTe) (Kazmerski, 1997, table 10). The SQ single bandgap limit has been already been surpassed with innovative (not cheap) cells. Efficiencies > 40% have been attained, often with concentrators requiring two-axis suntracking and active cooling.



Key technologies for raising η are: (1) *hetrojuction* cells, single bi-layer sandwiches (as in crystalline silicon PV cells), but with top and bottom layers made of different semiconductors with different bandgaps, not just different p- or n-doping; (2) *multijunction* cells; multiple stacked semiconductor layers of different bandgap capturing otherwise wasted photons; (3) *quantum* dot cells, incorporating nanocrystals producing as many as three electrons per absorbed photon, instead of the usual one. The problem to be overcome is the broad solar spectrum -- a typical stellar photosphere. But laser beams produce spectrally narrow light beams. These are convertible to electricity by PV cells at high efficiency when their wavelength is tuned to the PV bandgap. The record so far is 59% for an AlGaAs PV cell powered by an infrared laser beam at ~ 0.8 μm (Dickinson, 2002).

Highly efficient cells are important, but the main factor holding back solar PV is cost. However impressive, breaking the SQ limit is more a scientific than a commercial achievement. Even a hundred percent efficient PV cell wouldn't be cost-effective with today's costs. Polycrystalline thin films are driven today by the prospect of dramatic cost reductions despite their lower than single crystal silicon efficiency. These films are of order 1 μm thick compared to 300 μm thick for crystalline Si. A recent US Department of Energy workshop on solar research identified a as major priority "harvesting of solar energy with 20 percent power efficiency and 100 times lower cost (http://www.sc.doe.gov/bes/reports/abstracts.html)." We're already beyond 20%. The challenge is cost. As the priority shifts to baseload terawatts storing and transmitting electricity from intermittent low power density sources could increasingly become the cost pacers. That's why transmission & storage should be pursued with aggressive R & D and demonstrations now in parallel with aggressive efforts to reduce module cost.

Costs. A wholesale "cost of electricity" (CoE, in ¢/kWe-hr) from any electricity-generating device can be defined as the cost per unit electric energy output including financing, operating costs and effects of outages amortized over the plant lifetime, fuel costs, and carbon taxes, if any; but excluding transmission and storage costs & profit. It is calculable from (Hoffert and Potter, 1997)

$$\text{CoE} = C_P \bullet \frac{\text{FCR} + \text{OMR}}{\text{DUTY}} + \frac{C_F + C_{TAX}}{\eta} . \qquad [4]$$

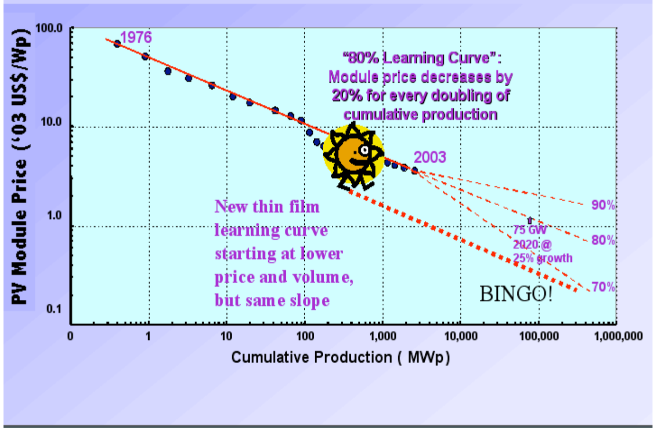
Here C_P is initial capital cost per installed power in cents per kilowatt ($/kWe x 100 ¢/$), FCR is the fixed charge financing rate, OMR the operation and maintenance rate (% of C_P /yr), DUTY the % time operational x 8760 hr/yr, C_F the cost of fuel and C_{TAX} the carbon tax (both in ¢/kWe-hr) and η the average energy generation efficiency = (electrical energy out)/(solar or wind or chemical or nuclear energy in). It's important to distinguish between average, peak, or other reference power that the C_P is based on, If, for example, a fossil fuel plant has C_P = $1000/kWe based on mean or baseload kilowatts, FCR =15%/yr, OMR = 3%/yr, and operates 82% of the time, it's cost of electricity is

$$\text{CoE} = \frac{1000\ \$/\text{kWe} \times 100\ ¢/\$ \times 18\%/\text{yr}}{82\% \times 8760\ \text{hr/yr}} = 2.5\ ¢/\text{kWe-hr},$$

even with zero fuel & tax costs. Fuel costs and thermodynamic inefficiencies roughly double this to five cents per kWe-hr typical of coal plants today. The CoE of fossil-fueled power plants with CO_2 up the stack would increase, making emission-free alternatives like PV more competitive, if carbon emission taxes were imposed, i.e., by "cap and trade" regimes.

Crystalline silicon has the largest PV market share today. But thin films of copper indium diselinide ($CuInSe_2$), cadmium telluride (CdTe), gallium arsenide (GaAs) & amorphous silicon (a-Si) appear more promising costwise (Zweibel, 1990). Costs of many (but not all) technologies decline over time from accumulation of manufacturing knowledge and economies of scale. Historical declines in PV capital cost per peak watt, C_P (in $\$/W_p$), as a function of cumulative installed capacity, P_T (in MW_p), can be fit by power laws of the form (IEA, 2000): $C_P = C_{Po}(P_T/P_{To})^{-b}$, where $C_{Po} = \$10/W_p$ at $P_{To} = 100\ MW_p$ are typical reference conditions. On log-log plots, the learning index, b, is the slope of linear segments over which a particular power law applies. Declining capital costs are alternately expressible as *progress ratios*, PR $\equiv 2^{-b}$; i.e., fractional cost declines for each doubling of installed capacity [$b \equiv -\ln(PR)/\ln(2)$].

PV Module Cost Versus Cumulative Production in peak megawatts: History & projected "Learning by Doing" & by accelerated R & D curve for thin films (from Ken Zweibel, NREL)



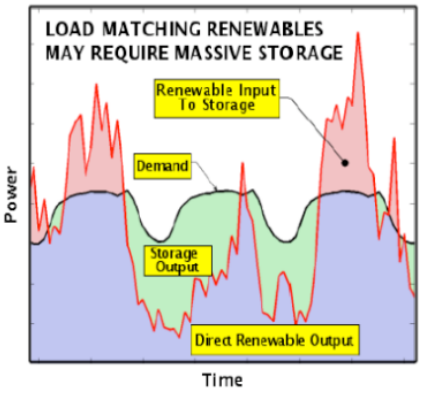
Learning curves are empirical curve fits employed to extrapolate future technology costs subsuming many factors (Grübler, 1998). Numbers differ because of different interpretations of costs, but history suggests progress ratios for PV of 82% (PR = 0.82, b = 0.286). For cumulative installed PV capacity of 1800 MW_p at the end of 2003 (IEA, 2004) this corresponds to capital costs today of $10 \times (1800/100)^{-0.286} \approx 4.4\ \$/W_p$. Cost scenarios developed at NREL by Ken Zweibel in the inset have thin film technology pursued aggressively in response to the terawatt challenge, resulting in near-term C_P step-accelerated declines followed by historical learning curve trends. Because PV modules are rated at solar intensities of $I_p \equiv 1\ kW/m^2$ corrections are needed to get site-specific CoEs. A typical long-term average midlatitude solar flux at Earth's surface including diurnal cycle and clouds effects is $I_E \approx 0.2\ kW/m^2$, perhaps $0.25\ W/m^2$ in Nevada or North African deserts. The sun is much brighter in space, $I_s \approx 1.37\ kW/m^2$ being the solar constant. Average solar intensities different from I_p can be subsumed in DUTY $\equiv (I_m/I_p) \times$ % time operational x 8760 hr/yr.

From the foregoing analysis a typical capital cost for PV modules today is $C_P \approx \$4400/kW_p$ ($\$4.4/W_p$). Even assuming this drops to $C_P = \$2500/kW_p$ ($\$2.5/W_p$), with FCR + OMR = 18%,

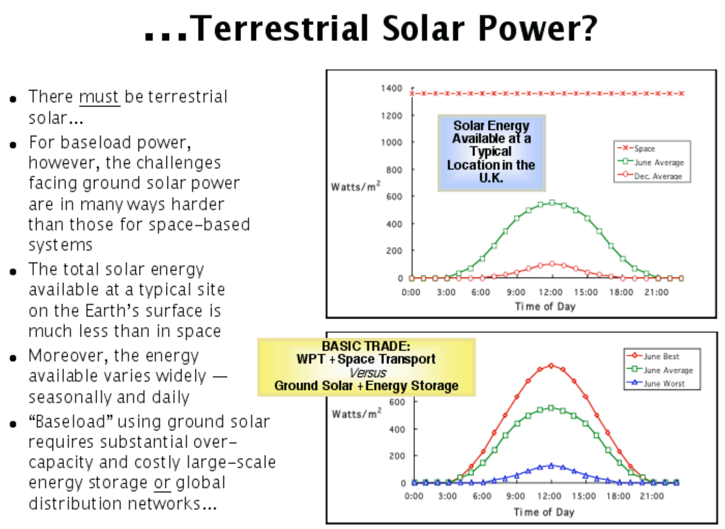
I_m = 250 W/m^2 (clear-sky desert conditions) and an 82 % duty cycle the busbar cost of electricity is still

$$\mathrm{CoE} \approx \frac{2500\ \$/\mathrm{kW_p} \times 100\ ¢/\$\ \times 18\ \%/\mathrm{yr}}{(250/1000)\ \times\ 82\ \% \times 8760\ \mathrm{hr/yr}} \approx 25\ ¢/\mathrm{kWe\text{-}hr}$$

This is five times more expensive than fossil fuel plants today, not counting storage. Since the CoE of renewables is roughly proportional to their capital cost, dropping the busbar CoE for PV to 5 ¢/kWe-hr implies C_P dropping to \$500/kW_p (50 ¢/W_p), perhaps \$400/kWp (40 ¢/Wp) for mid-latitude rooftops. This is the region of Zweibel's graph labeled "BINGO." Arguably, accelerated technology development could rapidly drop capital costs after which historical rate declines continue.



When that happens transmission and storage "user friendly" to PV sources will be needed. Selling surplus power to utility grids by running electric meters backward ("net metering") is feasible only if fluctuating sources generate a small fraction of baseload. But at some point the ability of grids to serve as a backup must saturate. Some European grids absorbing massive input of subsidized wind power may already have reached that point. Storage batteries employed by early adopters "off the grid" today cost > 25 ¢/kWe-hr based on amortized capital cost and 400 charge-discharge cycles (Zweibel, p. 256). Other energy storage technologies (pumped water, compressed air, flywheels, reversible hydrogen fuel cells and superconducting-inductive) are less technically mature, require often unavailable geographic features & are generally more expensive today (Berry and Lamont, 2002). For baseload, storage comparable in magnitude to fluctuating renewable inputs is needed (Strickland, 1996; Love et al., 2003; & inset above). Attaining 5 ¢/kWe-hr or less CoE at PV module busbars, however important, would basically shift the baseload system cost-pacer to storage systems. Even for today's pricey rooftop PV, "balance of system" costs are nontrivial.



...Terrestrial Solar Power?

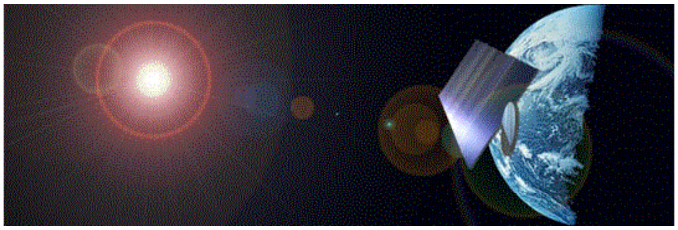
- There must be terrestrial solar...
- For baseload power, however, the challenges facing ground solar power are in many ways harder than those for space-based systems
- The total solar energy available at a typical site on the Earth's surface is much less than in space
- Moreover, the energy available varies widely — seasonally and daily
- "Baseload" using ground solar requires substantial over-capacity and costly large-scale energy storage or global distribution networks...

Solar Energy Available at a Typical Location in the U.K.

BASIC TRADE:
WPT + Space Transport
Versus
Ground Solar + Energy Storage

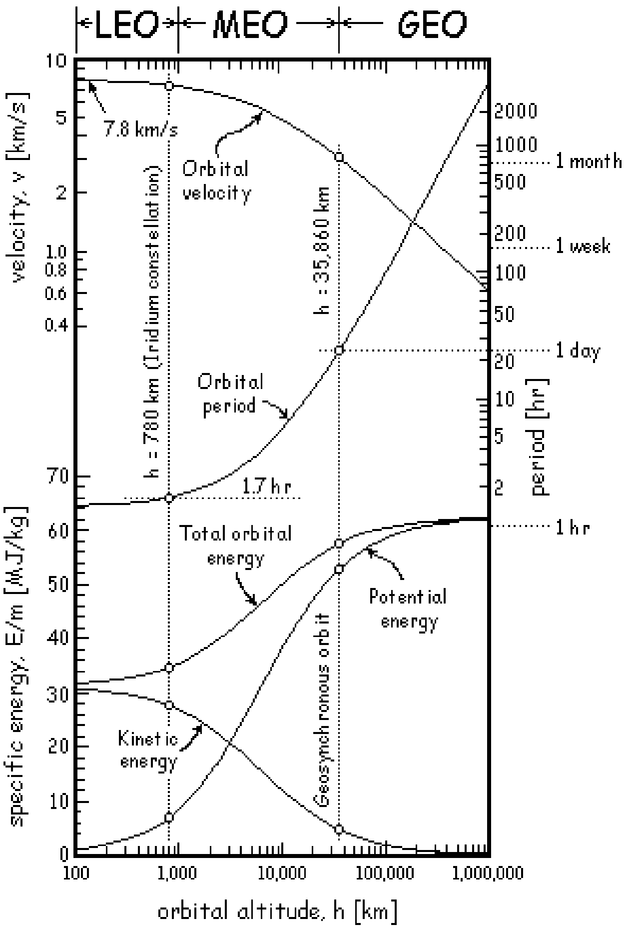
Space. The space solar power (SSP) system proposed by Peter Glaser (1968) & studied by NASA & DoE during the "energy crisis"

70s (Koomanoff and Bloomquist, 1993) has been revisited lately; in most cases assessed as technically promising for global baseload electricity (Erb, 1997; Mankins, 1997; NRC, 2001, Lior, 2001, McSpadden and Mankins, 2002, Seboldt, 2004). There are also new ideas, new technologies, and new business plans -- e.g., Hyde et al. (2003), who boldly target high-value consumers with pinpoint accuracy with sun-energized diode lasers in GEO firing at PV collectors on the surface. But there is no serious funding. Indeed, SSP is often left off the list of energy options to fossil fuel burning, despite the evident fact that it's one of the few technologies capable in principle of powering civilization emission-free as long as the sun shines. SSP can generate multi-terawatt levels in geosynchronous orbit (GEO; 36,000 km above the equator) where sunlight is bright and constant and the satellite remains a fixed distance from any point on the rotating Earth, effectively eliminating the need for baseload storage at the cost of space transportation & wireless power transmission (Erb, 1997).

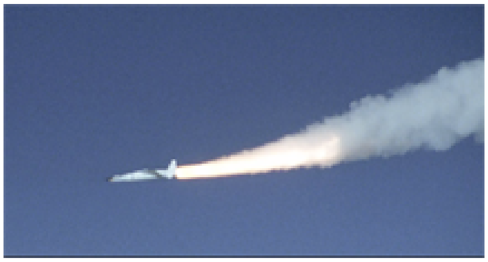


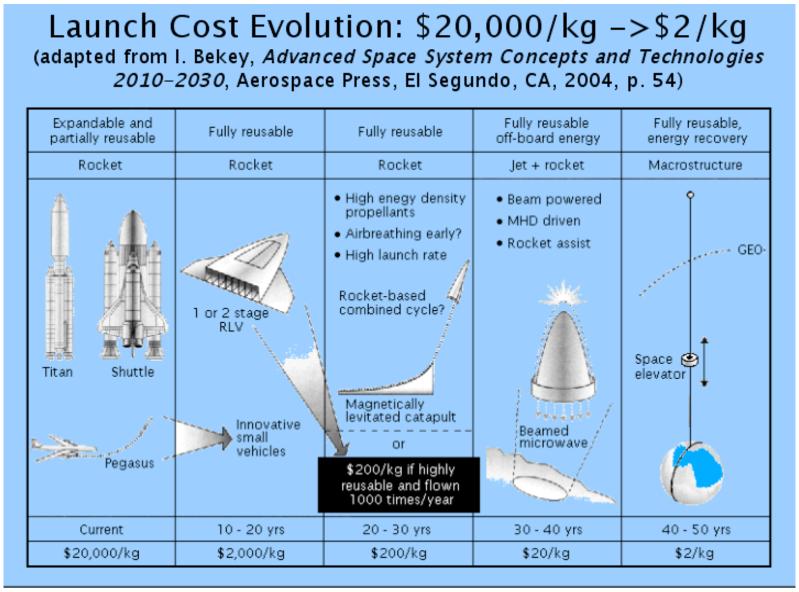
Wireless power transmission (WPT) was the dream of Nikola Tesla -- the brilliant, eccentric early 20th century innovator most responsible for the alternating current (AC) three-phase high voltage transmission lines dominating electric grids today. His Wardenclyffe plant near Shoreham, Long Island, was intended as a major milestone. Tesla wrote in "The Future of the Wireless Art," which appeared in *Wireless Telegraphy & Telephony*, 1908, that Wardenclyffe would make possible " . . . the transmission of power, without wires, . . .on a scale large enough to carry conviction." Tesla was unable to complete Wardenclyffe, and is unlikely to have been successful if he did, because technology didn't exist at the time to generate electromagnetic waves in tight beams with low propagation power losses. (He planned a kind of waveguide between the ground and the entire atmosphere within which users would tap power). Diffraction losses would have been a killer. Tesla had a powerful WPT vision, but no magnetrons, rectennas, lasers or photocells to realize it. These came later in the 20th century along with solid-state power electronics like the thyristor enabling high voltage direct current (HVDC) transmission lines. Semiconductors, electronics, radar and photonics make Tesla's dream possible today along lines-of-sight, including for SSP at microwave and optical frequencies where the atmosphere is transparent. Feasible end-to-end efficiency ranges with aggressive research & development are 40-60% (microwaves) and 20-40% (lasers) (Brown, 1996; Dickinson, 2002; Hoffert et al., 2004; Totani, 2005).

A frequent objection is that space transportation is too expensive. But what drives these costs? Can innovative technologies drop them significantly? Surprisingly, the energy per kilogram to insert a mass in orbit is same order of magnitude as the energy needed to fly that mass across the US on a commercial airliner. That launch costs with the Space Shuttle ($20,000/kg) are >> air freight stems partly from inefficient rocket propulsion, partly from markets too small to justify developing less expensive vehicles, partly from maintaining an army of scientists and engineers for maintenance and checkout, and partly from the low duty cycle of the Space Shuttle. The inset shows, from standard Newtonian mechanics, orbital velocity, period and total energy per unit mass (relative to Earth's surface) of an object inserted in circular orbit as a function of its altitude from a hundred to a million kilometers up. A huge potential for access-to-space cost reductions is implicit in the fact that total energy per unit mass to reach orbit (excluding drag) in the range 32-64 MJ/kg (~ 9-18 kW-hr/kg, since 1 kW-hr = 3.6 MJ). At 5¢/kWe-hr electricity the implied energy cost per kilogram is fifty cents to a dollar!



Were launch costs to drop to within factor of ten of energy costs (as they are for cars, trains and planes) order of magnitude space access cost reductions would follow. One point of attack is the huge liftoff-mass-to-payload ratios of today's chemical rockets. These stem mainly from lifting the oxidizer, liquid oxygen, before it's burned & expelled. Lifting oxygen (8/9 of fuel-oxidizer mass of the Space Shuttle) through the atmosphere has been likened to a fish swimming in the ocean carrying a bottle of water; a shortcoming underscored by the successful test flight by NASA last year of the airbreathing hypersonic X-43A research supersonic combustion ramjet (scramjet) vehicle, which attained 7000 mph (3.12 km/s) at 110,000 ft (34 km) altitude (inset). The excitement and innovation in the launch business today involves private entrepreneurs. Burt Rutan's Scaled Composites SpaceShipOne also rocketed into history, winning the "X Prize" as the first private manned spacecraft to exceed an altitude of 367,400 ft (112 km). There's a way to go from straight up to the threshold of space to orbital velocity and the searing heat of reentry. But there are promising paths. Scramjets, for example. (I worked in the 60s for scramjet pioneer Antonio Ferri at what is now ATK GASL, Ronkonkoma, NY, who built the X-43A scramjet just tested.) Orbit-capable scramjet/rocket hybrids appear feasible at launch costs of 200-400 $/kg (Bekey, 2003).





Launch Cost Evolution: $20,000/kg ->$2/kg

(adapted from I. Bekey, *Advanced Space System Concepts and Technologies 2010-2030*, Aerospace Press, El Segundo, CA, 2004, p. 54)

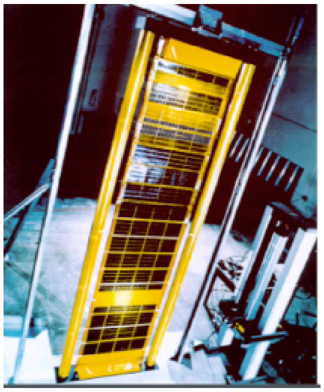
Expandable and partially reusable	Fully reusable	Fully reusable	Fully reusable off-board energy	Fully reusable, energy recovery
Rocket	Rocket	Rocket	Jet + rocket	Macrostructure
Current	10 - 20 yrs	20 - 30 yrs	30 - 40 yrs	40 - 50 yrs
$20,000/kg	$2,000/kg	$200/kg	$20/kg	$2/kg

Scramjets aren't the only technology that can make space affordable. The progression of promising launch technologies summarized by Bekey (inset above) evokes Moore's law and learning curves describing historical cost reductions in other technology classes. At the end of this rainbow are space elevators. Long the domain of science fiction, riding 36,000 kilometers up to geostationary orbit in an elevator along an ultra-strong cable has entered the realm of the possible with the discovery of carbon nanotubes with strength-to-weight ratios 200 times higher than steel (Yacobson and Smalley, 1997; Edwards & Westling, 2002). Nanotube cables could be the breakthrough enabling "skyhooks," as steel cables enabled suspension bridges, but they will remain unobtainium until we can fabricate arbitrary long cables or ribbons in bulk. Work is in progress as the payoff is immense in many applications.

Table 1. ISS Solar Array

Property	Units	Value	Comments
Incident Solar Flux	W/m2	1,370	Solar constant outside Earth's shadow cone
Solar Array Peak Power	We	250,000	Total of all 8 wings typical values
Solar Array Mean Power	We	125,000	Total of all 8 wings typical values
Area of PV Wings	m2	2560	Each wing is ~ 32 m x 10 m = 320 m2 per panel, ~ 2560 m2 total
Thickness of PV Wings	m	0.00033	Solar cell assembly thickness = 0.33 mm including cover glass
Mass of PV Wings	kg	1,600	Total of all 8 wings typical values
Density of PV Wings	Kg/m3	1,900	(Wing mass)/[(Area x Thickness)
Solar Array Efficiency	%	7.1	[(Peak Power)/(Area x Solar Constant)] x 100%
Specific Power	kWe/kg	0.16	[(Peak Power)/(Mass of PV Wings)] x 0.001 kWe/We

A nearer-term opportunity to reduce launch costs is reducing the mass of solar collectors. The present specific power (P/M, power per unit mass) of single-crystal silicon solar panels on the International Space Station (ISS) is < 0.1 kWe/kg (breakdown is in the inset, but it doesn't include support structure that roughly halves P/M). Note that crystalline-Si cells are ~ 300 μm thick, whereas thin films under development for Earth and space applications are ~ 1 μm. Moreover, ultralight support structures made of inflatable-rigidizable structures are possible for space PV. Thin-film PV on "gossamer structures" could raise P/M to the 1-10 kWe/kg range (Hyde et al., 2003). Deployable lighweight solar arrays are near-term technologies being tested now (Adler et al., 2004). The inset, for example, shows a PV panel deployable in space from an inflatable structure under development by the L'Garde Company of Tustin, CA.



Global warming has decades of inertia invested in the carbon cycle, climatic response and coal power plants. To transform the energy system to one in which PV provides terawatts of electric baseload as Earth gets demonstrably warmer, and perception grows that we have to do something about fossil fuel emissions, a parallel electricity infrastructure may be needed alongside the existing one, much as passenger airlines coexisted with passenger railroads and ships. Investments of multinational corporations, entrepreneurs and venture capitalists; along with sustained, targeted and intense public sector research; are crucial. For these to succeed, the potential of solar PV systems to provide global baseload electricity has to be understood and appreciated.

Critiques & Responses. Technology is rife with examples of Arthur C. Clarke's First Law: "When a distinguished but elderly scientist states that something is possible he is almost certainly right. When he states that something is impossible, he is very probably wrong (Clarke, 1982, p. 29)." Polls indicate most Americans are pro-solar and don't understand why it's not here. But some critics claim that not only are Earth-based (Hayden, 2001) and space-based (Zubrin, 1999; Fetter, 2004) PV not cost-effective now, they *never* will be.

Hayden holds that solar power in general is a hoax because costs haven't dropped as predicted by advocates in the 70s. Nor, I would add, have they dropped for nuclear plants, which have become *more* expensive. Coal gasification integrated combined cycle plants, precursors to DoE "FutureGen" power plants making electricity and hydrogen with CO_2 sequestered, aren't being built either in significant numbers, because *they're* too expensive. Hydropower is saturated and natural gas costs at all-time highs. *No* electricity- generating technology is cost-effective today versus coal plants with CO_2 up the stack. Adverse economics of alternate energy technologies is the stated reason for the US not ratifying Kyoto. In opposition to SSP Zubrin too invokes present costs, which, as analyzed above, can decrease orders of magnitude thereby changing the game entirely. Fetter (2004) doesn't argue against terrestrial PV but claims space PV will never be cheaper than Earth PV. Were these critics all right we should give up on PV. Bad advice. They are in fact making unsupported intuitive guesses about future technology costs (Hoffert et al., 2002; Smith, 2004).

Consider for example how Fetter's critique is affected by the present assessment. He compared Earth-based with Space-based PV capital costs (including launch costs in SSP case) normalized by their respective solar intensities and transmission-storage efficiencies. His criteria for space PV to compete economically with Earth PV (Fetter, 2004) can be expressed

$$\frac{C_{Ps} + (M/P)C_L}{\eta_{trans} I_s} \le \frac{C_{PE}}{\left[1 - f(1 - \eta_{store})\right] I_e}, \qquad [5]$$

where C_{Ps} and C_{PE} are installed unit costs of photovoltaic arrays in space and on Earth ($/kW$_p$), C_L is the unit cost of placing mass in orbit ($/kg), (M/P) is the mass per unit power produced [\$/kg; the inverse of the specific power (P/M) in kg/\$], I_s and I_E are mean solar intensities in space and on Earth (W/m^2), η_{trans} end-to-end WPT transmission efficiency, η_{store} end-to-end transmission (or round-trip storage) efficiency for Earth PV, and f the fraction of energy transmitted over long distances or stored. The terrestrial transmission efficiency term in square brackets equals η_{store} for the terawatt baseload application (f = 1). Near-term values achievable with modest R &D from the present assessment are: P/M = 1.5 kW$_e$/kg, η_{trans} = 40%, η_{store} = 60%, I_s = 1.4 kW/m^2, I_e = 0.2 kW/m^2, C_{PE} = \$4,400 \$/kW$_p$ & C_{Ps} = 8,800 \$/kW$_p$; for which the launch costs at which space and Earth solar PV compete on capital cost is

$$C_L \le (P/M)\left\{\left(\frac{\eta_{trans} I_s}{\eta_{store} I_E}\right) C_{PE} - C_{Ps}\right\} \le 17{,}600\ \$/\mathrm{kg}. \qquad [6]$$

Even present-day costs of 15,000 \$/kg to GEO for Russian & Chinese launches with geosynchronous transfer capacity (Futron, 2002) are low enough to collapse the case that space PV will never be cheaper than Earth PV. One can argue specific numbers, but the potential for cost reductions on all fronts is huge. The claim that ground-based PV will always be cheaper than space-based, even excluding launch costs, also makes no sense in light of well-known storage and grid-connectivity problems of surface PV. Transmission & storage costs can in principle be subsumed in PV capital costs but Fetter's numbers suggest that they haven't been. Energy storage for Earth PV is hardly negligible for baseload applications; particularly if PV costs drop as projected by NREL's roadmap. If C_P declines by factors of 10-100, it will for *both* Earth and space. In that case comparable cost reductions will be needed in WPT and launch costs (for SSP) and storage (for terrestrial) to reach the canonical 5 ¢/kWe-hr price pointfor baseload. Whether Earth or space PV is better is in any case the wrong question for reasons developed shortly.

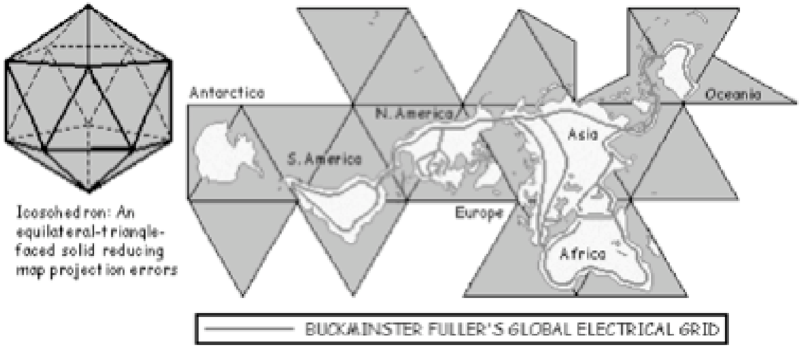
On Earth, dramatic declines in thin film PV costs accompanied by low cost storage could transform PV from "conspicuous conservation" (inset) to electric power for the masses. In space, many exciting technologies could make a difference including electro-optic power transmission with solid-state diode lasers (laser power beams are also an enabling technology of space elevators). Lasers have much less diffractive beam spreading than microwaves permitting smaller units and lower initial capital investment (Hyde et al, 2003). Recent breakthroughs at Intel in silicon lasers may have major implications for laser cost reductions (Rong et al., 2005). In the longer term is the potential of sun-pumped lasers that combine the functionality of PV collectors and laser power beamers in a single unit (Cougnet et al., 2004). The issue isn't whether Earth or space solar PV are cost-effective now -- neither

is -- but that technology opportunities exist to generate cost-effective baseload terawatts by midcentury. We don't know what systems will be winners. My message to the critics is that the case for solar PV is as good as it is for any other multiterawatt source. But we have work hard reduce costs on all PV solar enabling fronts. The stakes are too high not to.

Visions. The remarkable ongoing electrification of planet Earth in the 20th century (Ausubel and Marchetti, 1997) is energized increasingly by coal, whose oxidation releases stored solar energy and carbon accumulated over hundreds of millions of years as CO_2. I focused here on next-generation technologies that could shift the energy source of much of world's electric power grids to solar PV. But it will likely not be enough. Massive efforts in energy conservation, carbon sequestration and nuclear power are needed in parallel. There are also different visions of how solar PV can, and should, evolve in the long run. These need to be explored up front because each path has its own issues, technologies and policy implications.

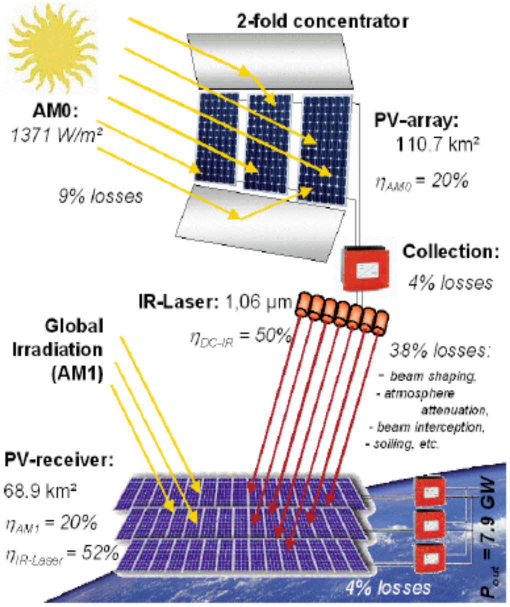
Peter Glaser's vision, and more recently that of John Mankins in the NASA "Fresh Look Study," leads to a ring of multigigawatt satellites 36,000 kilometers above the equator. A fleet of one hundred solar power satellites, each with PV arrays the size of Manhattan, could generate 1 TWe on Earth. These might be constructed initially by heavy lift vehicles ferrying materials to GEO from Earth's surface, perhaps transitioning to space elevators by midcentury (inset, left). The powersats would be large enough to appear as a ring of bright objects in the night sky -- evoking a Promethean image from Yeats (1956), "The Golden Apples of the Sun." Big job. But solar arrays 8 times larger in area & costly energy storage is needed to generate 1 TWe from Earthbound PV.

Dramatic high-tech visions have been advanced for Earth-based solar PV too, including massive arrays in clear-sky deserts connected across continents by low-loss HVDC lines (Klimke, 1997); and perhaps eventually across the world by global grids of liquid nitrogen-cooled copper oxide or nanotube superconducting wires linking daytime & nighttime hemispheres. The "worldgrid" vision depicted in the inset occurred to the brilliant & quirky US innovator, R. Buckminster "Bucky" Fuller in the 1970s.

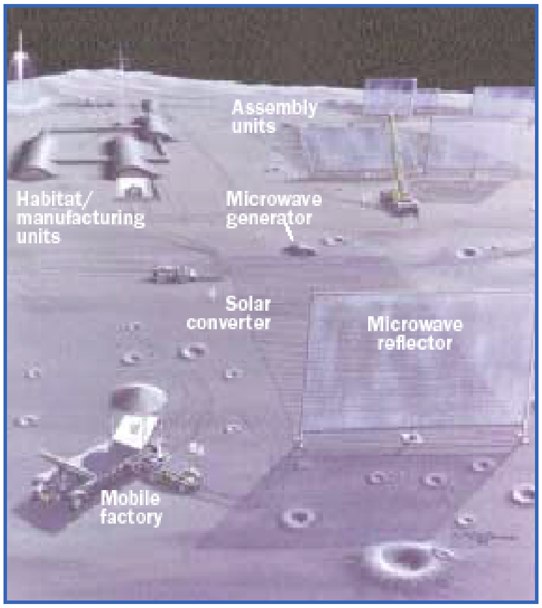


Remarkably, Bucky went public with his idea even before high-temperature superconductors were discovered that could enable it, much as the space elevator idea was imagined by the Russian visionary V. Artsutanov (1960) decades before the discovery of carbon nanotubes rendered them a possibility, at least in principle.

It is misleading to argue that that Earth and space PV necessarily compete with each other as some critics do. They can be natural allies in systems that exploit their complementary attributes. Multiple power sources provide enhanced stability in an ecological sense. One ingenious vision has PV panels in a halo orbit at the L-2 Earth-sun Lagrange point 1.5 million kilometers above the midnight longitude beaming power to the nighttime hemisphere as Earth rotates beneath it, thereby supplementing daytime electricity from surface solar PV (Landis, 1997). More recently, Geuder et al. (2004) explored whether both Earth and space solar PV could provide all of Europe's electricity demand by 2030 cost-effectively. Depicted in the inset, their assumed system is energized by ~110 km^2 PV arrays in GEO beaming power with infrared lasers to ~70 km^2 PV arrays on the surface to inject ~ 8 GWe to the grid; the surface arrays are also powered by sunlight reaching Earth's surface. Together with terrestrial input buffered over diurnal cycles by pumped hydro the system shown delivers 10 GWe baseload. Increasing to three the number of satellites beaming to the same ground arrays provides 25 GWe. Surface PV receivers are sited in clear-sky North African deserts to avoid clouds and land use conflicts & electricity transmitted to Europe via HVDC lines. Several power options were considered, including surface PV only, the latter meeting baseload with even more pumped storage. Results of this study indicate that terrestrial solar systems in North Africa could meet the load curve of Europe with levelized electricity generation costs of ~ 5 ¢/kWe-hr at load levels ≥ 0.1 TWe. For SSP, loads ≥ 1 TWe were needed to make the price point. These findings, of course, contradict assertions that SSP will never be cost-effective. As usual in systems analyses, the devil is in the details. Among other things, Geuder et al. (2004) conclude SSP is destined for the global-scale because of its ability to easily change the location of ground receivers -- a point also made by Hyde et al. (2003).



Space transportation costs are clearly a factor in SSP economics. I discussed earlier several ways to make access-to-space from Earth's surface affordable. However, an alternative approach to lifting SSP materials to orbit against Earth's gravitational field is using extraterrestrial resources. For example, electromagnetic mass-drivers can lift lunar materials and components fabricated on the Moon, which has a far shallower gravitational potential well to climb from, and requires far less energy to reach GEO, than Earth's surface (Clarke, 1950). This idea was further developed in connection with artificial space colonies and resources available on the Moon and asteroids (Maryniak and O'Neill, 1993; Lewis et al., 1993; O'Neill, 2000). O'Neill's seminal vision was that construction of solar power satellites could serve as an economic driver for artificial space colony ecosystems at Lagrangian points of the earth-Moon system, alternatives for colonization to inhospitable planetary surfaces of Venus and the outer planet moons & even Mars.



But Criswell (2002) argues persuasively & with many technical details worked out that if one is going to build PV modules from lunar materials it could be more cost-effective to construct the entire solar power system on the Moon -- most of the raw materials needed exist in the lunar regolith, as does abundant solar radiation -- and beam the power to Earth (inset). Why not skip the Earth-orbiting part? -- with the possible exception of reflecting satellites to focus microwaves beams to rectennas on Earth's surface. Recently, as we have seen, laser power beaming has become an active research area, with application to SSP, space-to-space power beaming and space elevators. The entire constellation enabling technologies is very dynamic, with major implications for alternate electrical energy systems for Earth. What's lacking is appreciation of the potential, and funding to pursue it.

Conclusions. However desirable terawatt-scale PV might be now, it isn't an option for prompt emission reductions. Don't blame Jimmy Carter. The US was on that path until Ronald Reagan after assuming the office of President had the solar panels put there by Carter ripped from the roof of the White House, simultaneously slashing Carter's funding for alternate energy R & D. It never recovered. R & D programs of the energy crisis 70s are still criticized by some as boondoggles. This misses the point. Many research projects fail. But an innovation like the transistor justifies all of Bell Labs. Imagine if renewable and other energy R & D had continued full bore over past 30 years. We might have options "on the shelf" now when we need them. For example, a coal/synfuel plant developed as a demonstration project with Federal funding in the 70s is now profitable in the private sector as the Dakota Gasification Co. (Fairley, 2005). Ironically this plant is now a poster child demonstrating the feasibility of coal gasification for this administration's coal-based FutureGen 10-year R & D program. This is no partisan critique. Neither US political party has lately had the insight or nerve to seriously invest in new energy ideas, even as fewer students in this country study the science and engineering needed to solve the problem. On the positive side, a realization is dawning that innovation matters, even by corporations not identified with concern about global warming. But major investment is needed now, the example explored here, solar PV, profusely demonstrates, including promising unconventional ideas and enabling technologies. This is the best hope for bringing emission-free terawatt-scale & cost-effective power on line by midcentury.

Specifically, solar PV can provide emission-free baseload electricity at multi-terawatt levels with targeted investment in thin-films, user-friendly transmission grids, storage systems, and other enabling technologies, comparable to investments needed to derive similar power levels from nuclear and coal with combined cycle plants with sequestered CO_2 online. Parallel investment in space-based solar PV and its enabling technologies including wireless power transmission and low cost launch systems is likewise urged. The National Research Council in its recent assessment of SSP did not sufficiently explore the potential for cost-reductions. The issue is not whether to develop advanced solar PV on Earth *or* in space, but what strategic technologies can dramatically change the cost picture of both? WPT as a contemporary realization of Tesla's dream can exploit explosive developments in solid-state electronics and communications. Power beaming between Earth and space at microwave and laser frequencies is feasible today & should be pursued as a logical next step to SSP (Hoffert et al., 2004). Governments, universities and private sector laboratories are not pursuing this yet at levels that matter. They should.

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of the country, and most residential and commercial buildings could generate their own energy on-site. Wind energy could be the lowest-cost option for electricity generation in favorable wind areas for grid power, and offshore systems could become prevalent in many countries by achieving a commercially viable cost by using floating platforms technologies. Geothermal systems could be a major source of base-load electricity for large regions. Biorefineries could be providing a wide range of cost-effective products as rural areas embrace the economic advantages of widespread demand for energy crops. Vehicle fuels could be powered by a combination of hydrogen fuel cells, with some bioethanol and biodiesel in significant markets.

5.3.3 Current Portfolio

The current Federal portfolio of renewable energy supply technologies encompasses 11areas, described below:

- **Wind Energy**. Generating electricity from wind energy focuses on using aerodynamically designed blades to drive generators that produce electric power in proportion to wind speed. Utility-scale turbines can be several megawatts and produce energy at between 4-6¢/kWh depending on the wind resource. Smaller turbines (under 100 kilowatts) serve a range of distributed, remote, and stand-alone power applications, producing energy between 13-19¢/kWh. Research activities include wind characteristics and forecasting, aerodynamics, structural dynamics and fatigue, control systems, design and testing of new onshore and offshore prototypes, component and system testing, power systems integration, and standards development.

  Research program goals in this area vary by application. For distributed wind turbines under 100 kw, the goal is to achieve a power production cost of 10-15¢/kWh in Class 3 winds by 2007. For larger systems greater than 100 kw, the goal is to achieve a power production cost of 3¢/kWh for onshore at sites with average wind speeds of 13 mph (wind Class 4), and 5¢/kWh at offshore sites with average wind speeds of 13 mph (wind Class 4) by 2012. See Section 2.3.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-231.pdf

- **Solar Photovoltaic Power**. Generating electricity from solar energy focuses on using semiconductor devices to convert sunlight directly to electricity. A variety of semiconductor materials can be used, varying in conversion efficiency and cost. Today's commercial modules are 13 percent to 18 percent efficient, and grid-tied photovoltaic (PV) systems generate electricity for about 17-22¢/kWh. Efficiencies of experimental cells range from 12 percent to 19 percent for low-cost thin-film amorphous and polycrystalline materials, and 25 percent to 37 percent for higher-cost III-V multijunction cells. Research activities, conducted with strong partnerships between the Federal laboratories and the private sector, include the fundamental understanding and optimization of photovoltaic materials, process, and devices; module validation and testing; process research to lower costs and scale up production; and technical issues with inverters and batteries. The photovoltaics industry is growing rapidly, with 1,200 MW produced worldwide in 2004.

  Research program goals in this area focus on scaling up laboratory-sized PV cells to much larger sizes suitable for product markets; validation of new module technologies for outdoors use to achieve 30-year outdoor warrantable lifetimes; and addressing of substantial technical issues associated with high-yield, first-time, and large-scale (greater than 100 MW/yr) manufacturing for advanced technologies. The long-term cost goal for electricity from PV cells for residential PV applications is

$0.06/kWh, compared to costs ranging from $0.18 to $0.23/kWh in 2004. The interim cost goal is to reduce the 30-year user cost for PV electric energy to a range of $0.14 to $0.19/kWh by 2010. See Section 2.3.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-232.pdf

- **Solar Heating and Lighting**. Solar heating and lighting technologies being developed for buildings applications include solar water heating and hybrid solar lighting. The near-term solar water heating research goal is to use polymer materials and manufacturing enhancements to reduce the cost of solar water heating systems to 4.5¢/kWh from their current cost of 8¢/kWh. Near-term solar lighting research goals are to demonstrate the second generation of the lighting system, coupled with an enhanced control system, and determine the market potential of the technology. See Section 2.3.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-233.pdf

- **Concentrating Solar Power**. Concentrating solar power (CSP) technology involves concentrating solar energy 50 to 5,000 times to produce high-temperature thermal energy, which is then used to produce electricity. Parabolic trough systems (1-100 MWe) that can generate electricity for a power cost of 12 to 14¢/kWh have been demonstrated commercially. Large-scale systems employing power towers (30-200 MWe) have been demonstrated. Prototype dish/Stirling engine systems (2 kWe-10 MWe) are operating in several states.

The program goals in this area are focused on CSP. The long-term goal is to achieve a power cost of between $0.035/kWh and $0.062/kWh, compared to the cost of between $0.12-$0.14/kWh in 2004. The interim goal is to reduce the cost of large-scale CSP power plants in the U.S. Southwest, where solar conditions are most favorable, to $0.09-$0.11/kWh by 2010.. See Section 2.3.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-234.pdf

- **Biochemical Conversion of Biomass**. Biochemical technology can be used to convert the cellulose and hemicellulose polymers in biomass (agricultural crops and residues, wood residues, trees and forest residues, grasses, and municipal waste) to their building blocks, such as sugars and glycerides. Using either acid hydrolysis (well-established) or enzymatic hydrolysis (being developed), sugars can then be converted to liquid fuels, such as ethanol, chemical intermediates and other products, such as lactic acid and hydrogen. Glycerides can be converted to a bio-based alternative for diesel fuel and other products. Producing multiple products from biomass feedstocks in a biorefinery could ultimately resemble today's oil refinery.

  Program goals in this area focus on the research and design of biorefinery processes that convert biomass feedstocks into valuable bio-based chemicals and fuels. By 2010, the goal is to finalize a process flow diagram with material and energy balances for an integrated biorefinery with the potential for three bio-based chemicals or materials. By 2012, the goal is to complete a system-level demonstration with corn kernels' fiber and recalcitrant starch aiming at 5 percent to 20 percent increase in ethanol yield from ethanol plants. Also by 2012, the goal is to reduce the estimated cost for producing a mixed, dilute sugar stream suitable for fermentation to ethanol to $0.10/lb, compared to the cost of $0.15/lb in 2003. If successful, this cost goal would correspond to $1.75 per gallon of ethanol, assuming a cost of $45 per dry ton of corn stover. See Section 2.3.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-235.pdf

- **Thermochemical Conversion of Biomass.** Thermochemical technology uses heat to convert biomass into a wide variety of products. Pyrolysis or gasification of biomass produces an oil-rich vapor or synthesis gas, which can be used to generate heat, electricity, liquid fuels, and chemicals. Combustion of biomass (or combinations of biomass and coal) generates steam for electricity production and/or space, water, or process heat, occurring today in the wood products industry and biomass power plants. Analogous to an oil refinery, a biorefinery can use one or more of these methods to convert a variety of biomass feedstocks into multiple products. See Section 2.3.6 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-236.pdf

- **Biomass Residues**. Biomass residues include agricultural residues, wood residues, trees and forest residues, animal wastes, pulp, and paper waste. These must be harvested, stored, and transported on a large scale to be used in a biorefinery. Research activities include improving and adapting the existing harvest collection, densification, storage, transportation, and information technologies to bioenergy supply systems—and developing robust machines for multiple applications.

  The long-term research program goal in this area is to develop fully integrated crop and residue harvesting, storage, and transportation systems for food, feed, energy, and industrial applications by 2020. Interim goals toward this end include, by 2006, measurable cost reductions in corn-stover supply systems with modifications of current technology. By 2007, the goal is to develop whole-crop harvest systems for supplying biorefineries of multiple products and, by 2010, enhancements to the whole-crop harvest systems that include fractionation for maximum economic return, including returns to soil for maximum productivity and conservation practices. By 2015, the goal is to develop an integrated system for pretreatment of residues near harvest locations and a means of collecting and transporting partially treated substrates to a central processing operation. See Section 2.3.7 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-237.pdf

- **Energy Crops**. Energy crops are fast-growing, often genetically improved trees and grasses grown under sustainable conditions to provide feedstocks that can be converted to heat, electricity, fuels such as ethanol, and chemicals and intermediates. Research activities include genetic improvement, pest and disease management, and harvest equipment development to maximize yields and sustainability.

  The overall research goal of this program is to advance the concept of energy crops contributing strongly to meet biomass power and biofuels production goals by 2020. Interim goals include, by 2006, to develop feedstock crops with experimentally demonstrated yield potential of 6-8 dry ton/acre/year and accompanying cost-effective, energy-efficient, environmentally sound harvest methods. By 2010, the goal is to identify genes that control growth and characteristics important to conversion processes in few model energy crops and achieve low-cost, "no-touch" harvest/ processing/transport of biomass to process facility. By 2020, the goal is to increase yield of useful biomass per acre by a factor of 2 or more compared with year 2000 yields. See Section 2.3.8 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-238.pdf

- **Photoconversion**. Photoconversion processes use solar photons to drive a variety of quantum conversion processes other than solid-state photovoltaics. These processes can produce electrical power or fuels, materials, and chemicals directly from simple renewable substrates such as water, carbon dioxide, and nitrogen. Photoconversion processes that mimic nature (termed "bio-inspired") can also convert CO_2 into liquid and gaseous fuels. Most of these technologies are at early stages of research where technical feasibility must be demonstrated, but a few (such as dye-sensitized solar cells) are at the developmental level.

The research program in this area is still in an exploratory stage. In the near term, research will focus on applications related to electrical power and high-value fuels and chemicals, where commercial potential may be expected during the next 5 to 10 years. If successful, larger-scale applications of photoconversion technologies may follow in the period from 2010 to 2015, with materials and fuels production beginning in the period 2015 to 2020, and commodity chemicals production in the period from 2020 to 2030. See Section 2.3.9 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-239.pdf

- **Advanced Hydropower**. The goal of advanced hydropower technology is to maximize the use of water for generation of electricity, while eliminating harmful environmental side effects. Representative technologies include new turbine designs that improve survivability of fish passing through the power plant and increase dissolved oxygen in downstream discharges, new assessment methods to optimize operation of reservoir system, and advanced instrumentation and control systems that modify turbine operation to maximize environmental benefits and energy production.

  The research program goals in this area include, by 2006, the completion of testing of hydroelectric turbine technology capable of reducing the rate of fish mortality to 2 percent, which would equal or better other methods of fish passage (e.g., spillways or fishways). Also in the near term, the goal is to complete the development of the Advanced Hydro Turbine Technology in support of maintaining hydroelectric-generation capacity due for relicensing between 2010 and 2020. See Section 2.3.10 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-2310.pdf

- **Geothermal Energy**. Geothermal sources of energy include hot rock masses, highly pressured hot fluids, hot hydrothermal systems, and shallow warm groundwater. Exploration techniques locate resources to drill; well fields and distribution systems allow the hot fluids to move to the point of use; and utilization systems apply the heat directly or convert it to electricity. Geothermal heat pumps use the shallow earth as a heat source and heat sink for heating and cooling applications. The U.S.-installed capacity for geothermal electrical generation is currently about 2 gigawatts; but, with improved technology, the U.S. geothermal resource could be capable of producing up to 100 gigawatts of electricity at an estimated cost of less than 5¢/kWh.

  The research program goals in this area focus on reducing the cost of geothermal energy. For "flash" power systems, the goal is to reduce the levelized cost of power generated by conventional (hydrothermal) geothermal resources from 6.1 cents per kWh in 2000 to 4.3 cents per kWh by 2010. For "binary" power systems, the goal is to reduce this cost from 8.7 cents per kWh in 2000, to 6.1 cents per kWh by 2010. See Section 2.3.11 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-2311.pdf

5.3.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- **Wind Energy**. Research challenges include developing wind technology that will be economically competitive at low-wind-speed sites without a production tax credit, developing offshore wind technology to take advantage of the immense wind resources in U.S. coastal areas and the Great Lakes, and exploring the role of wind turbines in emerging applications such as electrolytic hydrogen production, water purification, and irrigation.

- **Solar Photovoltaic Power**. Research would be required to lower the cost of solar electricity further. This can occur through developing "third-generation" materials such as quantum dots and nanostructures for ultra-high efficiencies or lower-cost organic or polymer materials; solving complex integrated processing problems to lower the cost of large-scale production of thin-film polycrystalline devices; optimizing cells and optical systems using concentrated sunlight; and improving the reliability and lowering the cost of inverters and batteries.

- **Solar Buildings**. Future research could include reducing cost and improving reliability of components and systems, optimizing energy efficiency and renewable energy combinations, integrating solar technologies into building designs, and incorporating solar technologies into building codes and standards.

- **Concentrating Solar Power**. Future challenges requiring RD&D include reducing cost and improving reliability; demonstrating Stirling engine performance in the field; and developing technology to produce hydrogen from concentrated sunlight and water.

- **Biochemical Conversion of Biomass**. Research is required to gain a better understanding of genomes, proteins, and their functions; the enzymes used for hydrolyzing pretreated biomass into fermentable sugars; the micro-organisms used in fermentation; and new tools of discovery such as bio-informatics, high-throughput screening of biodiversity, directed enzyme development and evolution, and gene shuffling. Research must focus on improving the cost, yield, and equipment reliability for harvesting, collecting, and transporting biomass; pretreating biomass before conversion; lowering the cost of the genetically engineered cellulose enzymes needed to hydrolyze biomass; developing and improving fermentation organisms; and developing integrated processing applicable to a large, continuous-production commercial facility.

- **Thermochemical Conversion of Biomass**. Research is needed to improve the production, preparation, and handling of biomass; improve the operational reliability of thermochemical biorefineries; remove contaminants from synthesis gas and develop cost-competitive catalysts and processes for converting synthesis gases to chemicals, fuels, or electricity. All the processes in the entire conversion system must be integrated to maximize efficiency and reduce costs.

- **Biomass Residues**. Research challenges include developing sustainable agriculture and forest-management systems that provide biomass residues; developing cost-effective drying, densification, and transportation techniques to create more standard feedstock from various residues; developing whole-crop harvest and fractionation systems; and developing methods for pretreatment of residues at harvest locations.

- **Energy Crops**. Future crop research needs include identifying genes that control growth and characteristics important to conversion processes, developing gene maps, understanding functional genomics in model crops, and applying advanced management systems and enhanced cultural practices to optimize sustainable energy crop production.

- **Photoconversion**. Photoconversion research requires developing the fundamental scientific understanding of photolytic processes through multidisciplinary approaches involving theory, mechanisms, kinetics, biological pathways and molecular genetics, natural photosynthesis, materials science, catalysts, and catalytic cycles.

- **Geothermal Energy**. Future research needs include developing improved methodologies for predicting reservoir performance and lifetime; finding and characterizing underground fracture permeability; developing low-cost innovative drilling technologies; reducing the cost and improving the efficiency of conversion systems; and developing engineered geothermal systems that will allow the use of geothermal areas that are deeper, less permeable, or drier than those currently considered as reserves.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

5.4 Nuclear Fission

Currently, there are 440 nuclear power plants operating in 31 nations that generate 17 percent of the world's electricity (see Figure 5-1) and provide nearly 7 percent of total world energy (see Figure 5-2). Because they emit no GHGs, today's nuclear power plants avoid the CO_2 emissions associated with combustion of coal or other fossil fuels.

During the past 30 years, operators of U.S. nuclear power plants have steadily improved economic performance through reduced costs for maintenance and operations and improved power plant availability, while operating reliably and safely. In addition, science and technology for the safe storage and ultimate disposal of nuclear waste have been advanced. Waste from nuclear energy must be isolated from the environment. High-level nuclear wastes from fission reactors (used fuel assemblies) are stored in contained, reinforced concrete steel-lined pools or in robust dry casks at limited-access reactor sites, until a deep geologic repository is ready to accept and isolate the spent fuel from the environment. Used nuclear fuel contains a substantial quantity of fissionable materials, and advanced technologies may be able to recover energy from this spent fuel and reduce required repository space and the radiotoxicity of the disposed waste.