The impact on space and terrestrial sectors of a sudden rise in solar cell efficiency.

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September 11, 2007

Abstract

In this paper, we examine what will happen if this breakthrough occurs in the form of a sudden sharp increase in solar cell efficiency, assuming an unchanged mass and cost per area of solar array. We first focus on the small space sector, then the larger and more uncertain market for terrestrial energy production.

1 Introduction

When asked what energy source will be the most important in a world 15 years from now, most respondents (27%) in a recent survey named solar energy[3]. This is not surprising. The sun is by far the most abundant source of power in the solar system. Nearly all energy forms used on Earth are, either directly or indirectly, based on solar energy, the most prominent being fossil fuels, biomass, wind, hydro energy, tidal, and solar energy. The latter can be directly converted into electricity in several ways. So it would appear that direct harnessing of solar power should be one of the biggest hopes as an alternative energy source. However, extrapolating from current growth estimates, one arrives at a much more modest role for solar energy in the future – probably still in single-digit percentiles in 20 years. It appears the only way that solar power can live up to its expectations is through some dramatic break-through that will dramatically increase its growth rate. In this paper, we assume that this breakthrough happens by some break-through in research. A break-through appears rather likely – several approaches are currently underway to dramatically increase the solar capture efficiency, most notably concentrators, semiconductor heterostructures, and quantum wires and quantum dots for multiple exciton generation to capture a larger fraction of the solar spectrum. In this paper, we focus on photovoltaic (PV) power generation (although century-old thermal power generation is seeing remarkable revival in recent years).

If light is incident on such a PV cell, some of the photons are absorbed. If enough energy is transferred, the electron can pass into the conduction band, leaving a hole (absence of an electron in the lattice) behind. Such electron-hole pairs that capture a fraction of the incident photon's energy (the exact amount is given by the property of the semiconductor – in the most common material, silicon, about 1 electon-volt is captured, equivalent to about half the energy in of a green photon at the solar spectrum's maximum). In a PV cell with a single PN junction, each photon with enough energy creates exactly one electron/hole pair. (Higher efficiency PV cells often have more than one pn junction to create more electron/hole from photons in the a larger region of the spectrum.) Both electrons and holes are mobile and can carry current.

The simplest PV cell is made from two layers, the P- and N- type semiconductors. The resulting PN junction creates an electric field from the P-type to the N-type semiconductor. This electric field causes electrons and holes freed by light absorption to flow in different directions (the electrons to the N-type side, and the holes to the P-type side). If an external current path is connected to the junction, electrons will flow through it to their original (P-type) side to unite with holes. Thus, a current I is set up across a voltage V, producing power IV[2]. This is illustrated in Fig.1.

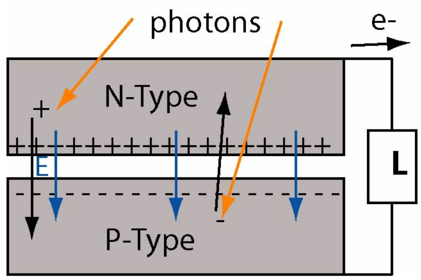

Figure 1: Principle of the photovoltaic cell. If a current I flows across the voltage V corresponding to the electric field E, a power IV is delivered to the load L.

One of the most important properties of a photovoltaic cell is its conversion efficiency η. This is defined to be the ratio of the maximum electric power $P_{max} = \mathrm{Max}(IV)$ produced by the cell to the total incident light power $P_{incident}$, $\eta = \frac{P_{max}}{P_{incident}}$.

In their special role as direct converters of electromagnetic to electric power, PV cells have become an important source of power in many uses. In space applications, they are especially attractive. We first concentrate on the space sector in Section 2 since it is much smaller and easier to analyze, and is probably more sensitive to innovation because of higher requirements on performance.

Firstly, for the vast majority of satellites, any other power source would have to be carried up to space, which is expensive. Secondly, the solar light intensity outside Earth's atmosphere is high—about 1370 $\mathrm{W/m^2}$. For these reasons, photovoltaic solar generators have been the most common choice for satellites in the inner solar system since the beginning of the space era. (For deep-space probes to the outer planets and beyond, solar power has been less attractive since the solar intensity drops with quadratically with separation from the sun.)

In terrestrial applications, photovoltaic generators have also proved very important. They have been adopted for off-the-grid applications in remote areas, solar-powered small devices, and for powering homes. In 1999, global sales of the PV industry broke the $1 Billion barrier, having enjoyed an average 20% increase over the 90's. The annual production of solar cell capacity has increased even faster, as shown in Fig. 2. We analyze the effect of a major efficiency breakthrough on the terrestrial sector in Sect. 3.

The main driver for this development has been the increasing solar cell efficiency and diminishing cost. Currently, the efficiency for commercial Si solar cells is about 17%. Higher efficiencies are

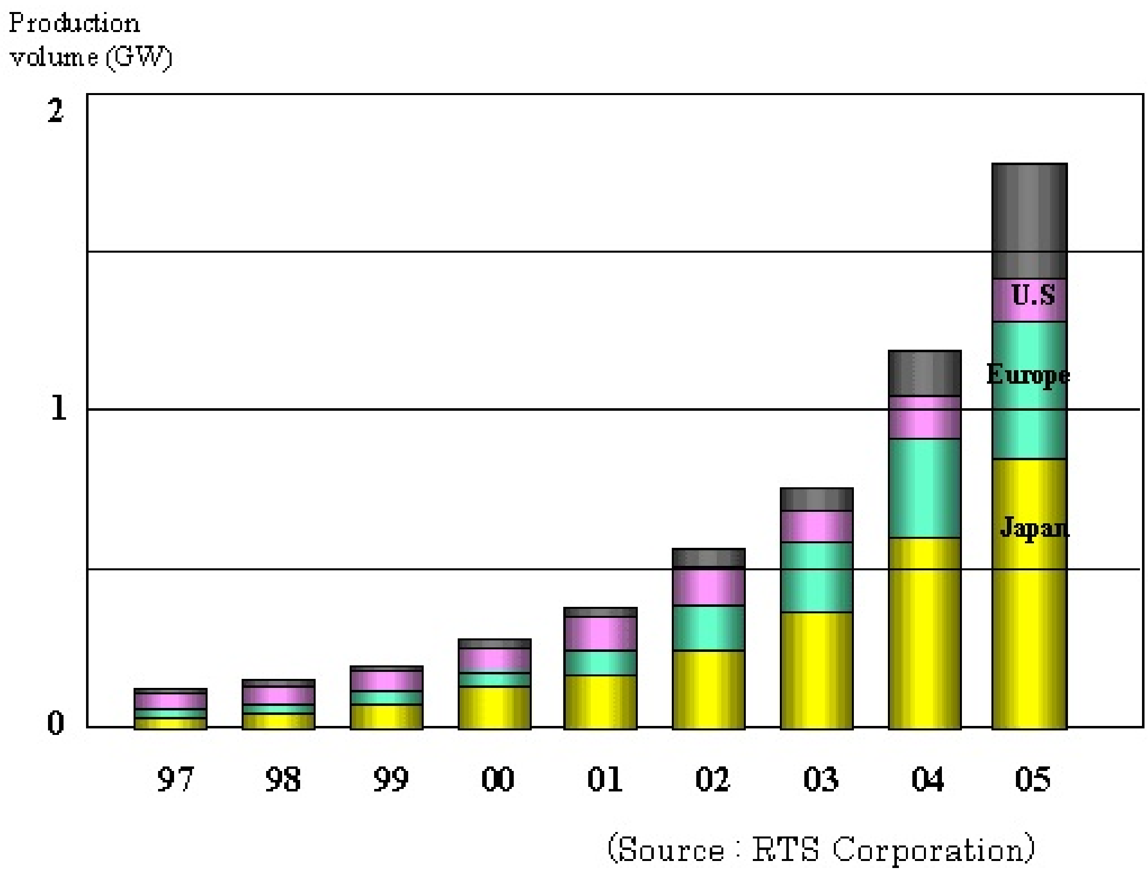

Figure 2: World Photovoltaic Shipments to 2005 (Source: RTS Corporation; for prior years, see [10])

possible by use of multiple junctions, concentrators, and other materials such as GaAs.

1.1 Scenario: Sudden Rise in Efficiency

Given the rapid progress in the efficiency of solar cells over the past decade, it lies near to ask: **Scenario Statement:** *"What impact will a sudden sharp rise in solar cell efficiency have on the space and terrestrial sectors?"* To define the problem further, we impose the following constraint: *Assume that the cost and mass per solar cell area are unchanged.* [1]

The remainder of this paper seeks to answer this question. Solar cells are commonly used in very complex systems, such as satellites. So how can we predict the effect of increased efficiency of PV generators–only one of many subsystems—on the overall system configuration? It would be prohibitively difficult to re-optimize the system's configuration. So instead we approach the problem from a broad view-point. We scale the relevant parameters to determine the 1st order approximation of the system's new configuration. The most important parameters are the size/mass, power,

[1]The scenario is not far-fetched. A consortium that includes the University of Delaware, where the technology was pioneered, and E.I. du Pont de Nemours and Company (DuPont) recently demonstrated a hetero-junction PV cell reaching 43%, and plans to soon reach 50% conversion efficiency while keeping cost fixed[5].)

performance, and cost. Thus, keeping one of these constant, we can estimate how the other three change. For example, for system X, we ask: "If the power requirement is unchanged, how will the increase in solar cell efficiency affect the mass and cost, and performance of X?" By keeping one of the parameters of the system constant, we do not explore the whole parameter space, so our prediction to the Scenario Statement is only a first-order approximation. But it will be good enough to understand the fundamental relationships between the solar cell efficiency and the whole system and make rough numerical estimates.

We will restrict the analysis to the most relevant applications in space and on Earth. The first includes predictions on mass, cost, and performance, for satellites; atmospheric drag of satellites (or the ISS) in low-earth-orbit; solar ion propulsion technology; and solar-powered deep-space probes. The second discusses effects on off-the-grid as well as commercial, on-the-grid, power production.

2 Space Sector

In this section, we consider how the change in η affects space systems with earth-orbiting spacecraft (Sec. 2.1) and interplanetary satellites (Sec. 2.2). We suppose that the solar cell efficiency changes by a factor k, so the new efficiency is $\eta' = k\eta$, where η is the previous efficiency.

2.1 Earth-Orbiting Spacecraft

We first consider earth-orbiting satellites because they all receive the same light intensity throughout their lifetime. This group includes the majority of spacecraft: communications, remote sensing and GNSS satellites; space stations; etc.

2.1.1 Unchanged Power

First, consider the implications of unchanged power.

A. Mass Reduction. In this case, the the solar array's area and mass change according to

$$A'_{SA} = A_{SA}\frac{\eta}{\eta'} = A_{SA}/k \tag{1}$$

$$M'_{SA} = M_{SA}\frac{\eta}{\eta'} = M_{SA}/k \tag{2}$$

This results in a mass saving of

$$\Delta M_{SA} = M_{SA}(1 - \frac{1}{k}) \tag{3}$$

This light spacecraft would require less propellant mass, scaled by the ration of the new to previous total mass:

$$m'_{prop} = m_{prop}\frac{M'}{M} = m_{prop}\frac{M - \Delta M_{SA}}{M} \tag{4}$$

The total first-order approximation to the mass reduction is thus

$$\Delta M_{tot} = M_{SA}(1 - 1/k)(1 + \frac{m_{prop}}{M}) \tag{5}$$

B. Example: Envisat. As an example of the mass savings, consider Envisat, Europe's climate satellite. With a mass of 8211 kg, propellent mass of 319 kg, and an approximate solar array mass of 280 kg,[2] the mass savings amount to $\Delta M_{tot} \sim 300(1 - 1/k)$ kg. For a doubling in solar cell efficiency, Eq. 5 gives $\Delta M_{tot} \sim 150$ kg. At current launch costs to GEO, this corresponds to a considerable cost savings of $150\text{kg} \cdot \frac{\text{EUR}20000}{\text{kg}} = 3$ M EUR.

C. Atmospheric Drag Reduction. Drag is proportional to the spacecraft's cross section A_{CS} perpendicular to the line of motion. Since the solar array area is decreased, the this cross-section is diminished by

$$\Delta A_{CS} = \alpha A_{SA}(1 - 1/k) \tag{6}$$

where $0 < \alpha < 1$ accounts for the orientation of the solar array with respect to the line of motion.

Thus, the ratio of the deceleration of the spacecraft due to drag is given by

$$\begin{aligned} \frac{a'}{a} &= \frac{D'}{M'}\frac{M}{D} \\ &= \frac{A'_{CS}}{M'}\frac{M}{A_{CS}} \\ &= \frac{1 - \alpha\frac{A_{SA}}{A_{CS}}(1 - 1/k)}{1 - \frac{M_{SA}}{M}(1 - 1/k)(1 + m_{prop}/M)} \end{aligned} \tag{7}$$

where $A'_{CS} = A_{CS} - \alpha\Delta A_{SA}$.

To understand what happens qualitatively, this equation can be simplified by making the (generally true) assumptions that (*i*) $M_{SA} \ll 1$ and (*ii*) $m_{prop}/M \ll 1$. Then, using Eq. 7, we obtain

$$\frac{\Delta a}{a} \approx -\frac{\alpha A_{SA}}{A_{CS}}(1 - 1/k) \tag{8}$$

where $\Delta a = a' - a$.

D. Example: International Space Station (ISS). Because of drag, the ISS must be reboosted regularly to maintain its orbit. Each year, about 6 Progress rockets and 1 ATV reboost the station. Per day, it looses roughly 200m in altitude [8]. Using the fact that its orbital velocity at distance r from the center of the Earth is given by $v = \sqrt{\frac{GM}{r}}$, this drop in altitude (Δr) corresponds to a velocity change $\Delta v = -\frac{1}{2}v\frac{\Delta r}{r} \approx -0.11$ m/s. Thus, the station looses about 40 m/s per year. To reboost the station (mass ~ 200 tons) using chemical propellant with ISP ~ 5000 s, conservation of momentum gives that roughly 16 tons of propellant are needed.

For the ISS, the approximations required for Eqs. 8 are justified. Thus, with $A_{SA}/A_{CS} \sim 1$, $\alpha \sim 1/2$, and $k = 2$ (solar cell efficiency doubles), we obtain $\frac{\Delta a}{a} \sim -1/4$. Thus, 25% less propellant

[2] The satellite has a peak power of 7kW. The solar array mass was calculated using the standard value of 25 W/kg [4].

is required to keep the station in orbit. This corresponds to about 4 tons, or about $80 M USD (assuming $20,000 / kg). Again, this is just a rough estimate, but it gives a ballpark idea of the amount of money involved—and that amount is impressive!

E. Space Debris and Micrometeorites. Atmospheric drag results from the bombardment of an object with small particles. But bombardment with larger particles—space debris and micrometeorites—scales the same way as drag in a dilute atmosphere. Thus, the risk R of being struck by such particles is diminished to

$$R' = R\frac{A'_{CS}}{A_{CS}} = R(1 - \frac{A_{SA}}{A_{CS}}(1 - 1/k) \qquad (9)$$

2.1.2 Unchanged Mass

If the mass of the spacecraft is unchanged, then the solar panel area is increased. But the extra power requires further mass in electronics, thermal control systems, batteries, and so forth. The mass of these systems is not necessarily linear with power, so the analysis becomes more difficult. However, we can still obtain first-order approximations for the case where $k \sim 1$. Specifically, assume that the masses of each of the subsystems are given by the functions $f_i(P)$, where P is the power of the spacecraft. Then for a small power increase P_0 to $P_0 + \Delta P$, the combined mass of these N subsystems changes by

$$\delta M = \sum_{i}^{N} \frac{\partial f_i}{\partial P}(P_0)\Delta P \equiv \chi \Delta P. \qquad (10)$$

From here, it's easy to show that the total power would increase by $M_{SA}(1-1/k)/\chi$. I am not aware if there are approximations to the functions $f_i(P)$, but it seems that they may be approximated for given classes of spacecraft. But since we don't know them, and therefore don't know χ, it is impossible at this point to make numerical predictions for the result of a change in solar cell efficiency. Instead, we can make a few qualitative statements:

- the spacecraft power will increase since χ is positive.
- possible increased data transmission rate (proportional to P) and/or error resistance
- possible decreased antenna size on the ground
- possible performance increase in active remote sensing

2.2 Interplanetary Satellites

Moving away from Earth, we consider interplanetary satellites.

2.2.1 Unchanged Power

If the power for interplanetary satellites is unchanged, then its mass decreases by ΔM_{tot} given by Eq. 5. Alternatively, the mass could decrease by the lesser amount of ΔM_{SA} and the acceleration due to its thrusters would be increased by a factor

$$\frac{a'}{a} = \frac{1}{1 - \frac{M_{SA}}{M}(1 - 1/k)} \tag{11}$$

Example: SMART-1. As an example, consider SMART-1, ESA's solar ion-drive powered mission to the Moon. The transfer from GEO took about 16 months, but if the solar array size is decreased due to increased efficiency, Eq. 11 with $M_{SA} = 80$ kg and $M = 350$ kg gives that the trip length decreases by 10% for $k = 2$ to only 14 months.[3]

2.2.2 Unchanged Mass

In the case of unchanged mass, solar ion drives would have more power. Assuming the same propellant and flux is used, the energy expended on each ion would increase to $E' = kE$. The ion's momentum p is related to its total energy and ionization energy $E_{ion}$by $E - E_{ion} = \frac{p^2}{2m}$, where m is its mass. Thus, since ion drive's thrust $T \propto p$, the new-to-old thrust ratio is given by

$$\frac{T'}{T} = \sqrt{\frac{k - E_{ion}/E}{1 - E_{ion}/E}} \approx \sqrt{k} \tag{12}$$

$$\tag{13}$$

using the fact that $E_{ion}/E \ll 1$.

Thus, for $k = 2$, SMART-1 would accelerate $\sqrt{2}$ times faster, shortening the trip to only 11 months. In this analysis, it was assumed that the ion engine could produce k times higher voltages without a mass increase. In reality, some mass increase would be required, and the trip would actually be shortened to a time somewhere between the 11 months of this example and the 14 months calculated for the case of unchanged power.

2.2.3 Deep Space Probes

The range of solar-powered deep space probes would also rise after an efficiency increase. Today, it's feasible to use solar power as far as 3AU's from the sun: NASA's Dawn mission, planned for 2006, uses a solar powered spacecraft to explore Vesta and Ceres of the asteroid belt [12]. The solar power produced by a solar array, P is related to the distance from the sun, R, by

$$P \propto \frac{1}{R^2} \tag{14}$$

[3] M_{SA} approximated assuming 25W/kg and total power = 2kW

So, if it's feasible today to use solar power at a distance R, then it will be feasible to use it at

$$R' = R\sqrt{\frac{\eta'}{\eta}} = R\sqrt{k} \tag{15}$$

Therefore, a doubling in PV efficiency will enable solar-powered missions to distances of at least 4AU's—possibly close enough to Jupiter (5AU's).

3 Terrestrial Sector

Solar power may not play as central a role on the ground as it does in space, where it covers most of electricity needs, but because of the sheer size of the terrestrial market, solar power in that sector is nevertheless a much larger industry. Global sales reached roughly \$7 billions in 2007 and are expected to reach nearly \$40 billion in 2010[6]. In the case of an increase in solar cell efficiency, an area of solar cell produces k times more, so that the specific cost[4] per unit energy decreases as

$$C' = C/k. \tag{16}$$

Consider the demand $D(P)$ and supply $S(P)$ curves for a quantity Q at price P of solar energy. Initially, the equilibrium point is at $S(P_0) = D(P_0)$. After the efficiency changes by k, the supply changes to $S'(P) = kS(P)$. The new equilibrium point is at

$$S'(P_0 + \Delta P) = kS(P_0 + \Delta P) = D(P_0 + \Delta P) \tag{17}$$

In the limit where $k \sim 1$, so where $\Delta P/P \ll 1$, Eq. 17 can be approximated to

$$\left(\frac{\partial D}{\partial P}\right)_{P_0} = (k-1)\frac{S(P_0)}{\Delta P} + \left(\frac{\partial S}{\partial P}\right)_{P_0} \tag{18}$$

This can be simplified to

$$\frac{\Delta Q}{Q} = \frac{k-1}{\frac{D_0}{S_0} + \frac{\epsilon_S}{\epsilon_D}} \tag{19}$$

using the definitions for the price elasticity of demand, $\epsilon_D = -\frac{\partial \ln D}{\partial \ln P} = -\frac{\partial D/D_0}{\partial P/P_0}$ and price elasticity of supply $\epsilon_S = \frac{\partial \ln S}{\partial \ln P}$. Note that both elasticities are positive for typical markets.

We must consider two cases of solar power, on-the-grid and off-the-grid electricity.

3.1 On-the-Grid Electricity

In Eq. 19, we see that ΔQ must be positive for $k > 1$, as expected. Furthermore, $\Delta Q \propto k - 1$. Since solar electricity on the grid has many substitutes, the price elasticity of demand is rather

[4] Total cost of the solar array, including structural support, installation, etc.

high. Thus, for $k \sim 1$, the quantity of solar electricity bought would be increased. For the case where k is not necessarily close to unity, we must have better knowledge of the supply and demand curves to solve Eq. 17 directly.

Solar power is rapidly becoming economically viable compared to the market price of electricity. Whereas five years ago $C \sim 0.25 - 0.50$ USD / kWh [11], it is currently about 0.11 USD/kWh by some estimates [2], if averaged over the first ten years of ownership of a home installation in a high-insulation area such as California (it is more expensive in less sunny places)[5] . This drop in cost makes solar power competitive with grid electricity cost $C_m \approx 0.10$ USD/ kWh [7], which is largely derived from non-renewable energy sources. It should be noted, however, that C_m does not take externalities into account. If it did, solar power may actually be cheaper since some experts put the externalities for the current mix of power sources at $\sim 0.10 - 0.15$ USD/kWh [9]. In addition, fossil-fuel-based electricity is becoming more expensive rapidly, growing by about 7% annually[7], while solar power is dropping in price. A sudden considerably increase in solar cell efficiency would tip the balance.

One of the problems with home installations is that labor cost and cost of ancillary equipment amounts to about the price of the PV cells themselves (USD 5000 vs. USD 8000 to cover the average home's electricity needs). Indeed, it is questionable that solar power installations for homes make any sense at all since large installations can dramatically reduce labor and ancillary equipment cost. Furthermore, if a high-insulation region such as a California desert can be chosen, the economics are further improved. Companies are only now beginning to realize this, and several large-scale power plants are in planning and under construction (e.g., an 80-MW plant being build by Cleantech LLC near Fresno, California). In this case, with additional fixed labor and ancillary equipment cost taking a smaller fraction of the full price, an increase in solar cell efficiency would become even more effective. Of course, remote power production entails some loss in power lines, but currently much of California's electricities already comes from other states.

3.2 Off-the-Grid Electricity

In the case of off-the-grid electricity, such as is used in remote areas, solar electricity has fewer substitutes, and so the demand is less elastic (i.e., ϵ_D is smaller than for on-the-grid use). The price elasticity of supply, meanwhile, should be less dependent on being on the grid or off it. Therefore, Eq. 19 shows that with ϵ_D smaller, ΔQ is smaller.

4 Conclusions

We estimated the effect of increased PV efficiency on the relevant space and terrestrial systems. The analysis was limited to first-order approximations based on scaling power, mass, and cost. Though simple, this analysis goes a long way in elucidating the relationships between these properties and the performance of the systems.

[5] It is assumed here that the house can store its daylight energy surplus; realistically, it might have to buy grid power at night, raising the 0.11USD/kWh estimate somewhat to ~ 0.15 USD/kWh

In the space sector, we found that the PV efficiency rise would result in cheaper satellites (incl. space stations) due to lower launch mass and lower atmospheric drag (less orbital maintenance). Furthermore, the performance of satellites would increase. We also showed that cheaper, faster, and further science missions would become possible. In particular, we showed that the feasible operating distance for solar-powered deep-space missions will increase, and that higher acceleration for electric ion propulsion will result.

In the terrestrial sector, we found that solar power is on a tipping point where it becomes economically competitive with traditional power sources in high-insulation areas such as California. If solar power production is pushed in large-scale installations where fixed labor and ancillary costs are fractionally lower, then its commercial viability is even more sensitive to solar cell efficiency, and a sudden rise may make it competitive in a large fraction of the world's climates.

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