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NÚMERO 201

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ECONOMIC AND POLITICAL IMPLICATIONS OF NEW DEVELOPMENTS IN THIN FILM SOLAR TECHNOLOGY

Abstract

Recent developments suggest that solar panels that are expected to be in production by early 2002 will be able to compete with gas priced at \$2.50 to \$3.50 in the southern United States. If the cost of solar power continues to drop by a factor of two every five years, solar power will dominate gas for the production of electricity during the day within five years. Solar power produced hydrogen may be competitive with natural gas by 2010. The major uncertainty in the production of hydrogen is whether the cost of electrolyzers can be reduced.

Resumen

Desarrollos recientes sugieren que los paneles solares, que se estima estén en producción a principios del 2002, podrán competir con gas a precios de \$2.50 a \$3.50 dólares en el sur de Estados Unidos. Si el costo de la energía solar continúa cayendo en un factor de dos cada cinco años, la energía solar dominará al gas en la producción de electricidad (durante el día) dentro de cinco años. El hidrógeno producido por la energía solar podrá competir con el gas natural para el 2010. La principal incertidumbre en la producción del hidrógeno es si el costo de los electrolizadores puede ser reducido.

Introduction[*]

The recent reports in the literature about new developments in thin film solar technology suggests that this technology has reached the point where it can be competitive with hydrocarbons without any new scientific breakthroughs.[1] The problems that remain are mostly economic, engineering and political. Solar power is now competitive with natural gas at prices of $2.75 per 1000 cubic and at prices of $2 per 1000 cubic feet within 5 years.[2] The implications of such a development on the energy security of Japan, the development of China, the future of the oil industry and consequential implications on the distribution of wealth in the world and development of third world energy producers are important. Japan, China and other developing nations would be assured of a secure, inexpensive source of energy. Such technology would also have substantial implications on the global warming as solar power would be a substitute for sources of energy that produce carbon dioxide.[3] This technology, however, could have some adverse implications. The income of many third world countries would be reduced. It could also lead to a further disengagement between the developed nations and many developing nations similar to what has happened at the end of the Cold War.

The policy community has not paid much attention to the recent developments in solar cell technology. Solar technology has been the stepchild of energy research. The Federal research budget for photovoltaic research is around 60 million dollars in 2000. One reason is that such research is not as exciting as other technical problems such as fusion. Research is to some degree driven by the interest of scientists.

This study is going to compare the cost of electricity produced by solar panels with the cost of electricity produced by combined cycle gas generators. Industry experts tell us that a substantial fraction of the investment in electrical generation in the United States will also be combined cycle gas. Thus, at the margin, combined cycle gas generators are the alternative technology. The assumption that all electrical power comes from combined cycle gas generators is conservative as it implies that the utilization rate for the combined cycles plants is the average utilization rate. In a

[*] The research reported in this paper was supported by The Baker Institute at Rice University and Conacyt in a grant to the Centro de Investigacion y Docencia Economicas, A.C. We would like to thank Charles Harris at Enron, William Laney Littlejohn, Ken Zweibel, at the NREL, Greg Nelson at First Solar for their help and comments.

[1] Zweibel (1999).

[2] First Solar has recently achieve ten percent efficiency by using a coating that enables the panels to use more of the blue spectrum. They expect these panels to be in production by early 2002. See Apendix for cost data.

[3] The question of global warming is still controversial. This study argues that solar power is competitive without a carbon tax. Should a policy to reduce carbon dioxide be implemented, the case for this technology is much more compelling.

country like the United States where the base load is supplied in part by hydro-electric or coal fired plants, the utilization rate of the combined cycle generators is lower than the average utilization rate and as a result, the capital cost per KWH produced is higher.

Historical Cost of Solar Power

Figure 1 [4]

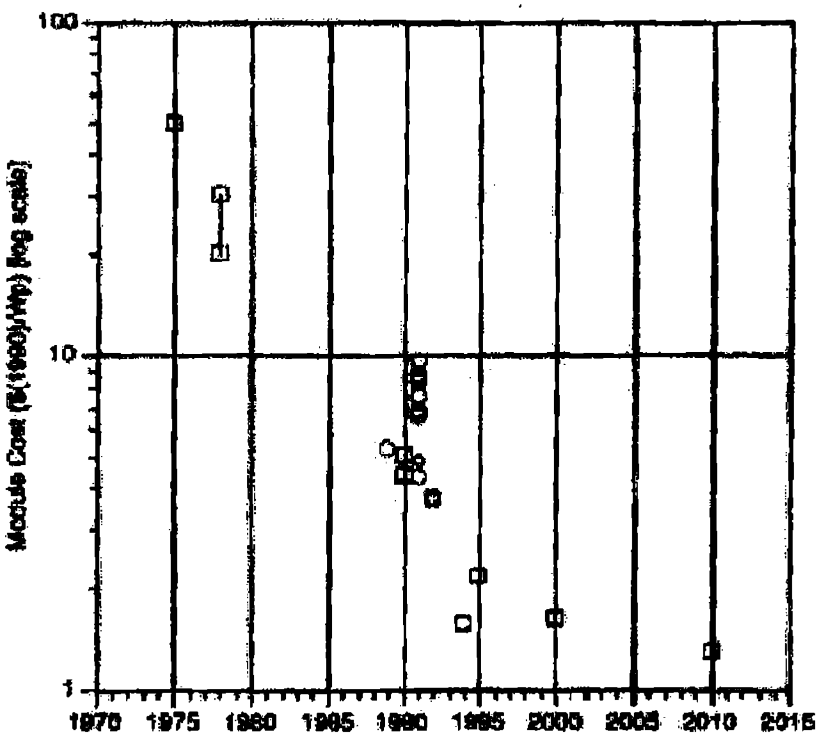


Figure 1 gives the cost of solar panels since 1970. The cost in 1975 was $50 per installed watt and by 1992 the reported costs had dropped $3 to $4 per peak watt. Costs of $2.75 per peak watt were reported for 1995. This suggest that in the period 1975 to 1995 the cost of solar cells dropped at 14.5 percent a year. The cost of solar power has dropped by a factor of two every five years.

[4] Figure 1 is from a 1994 study for the World Bank, Ahmed (1994). The cost of installed watt is the cost of a solar panel that produces one watt of electricity. At 15 percent efficiency, a square meter of solar panel produces 150 watts. Costs prior to 1992 are actual, The costs after 1992 are projected. The data includes thin film and crystalline silicon modules. Some of the numbers are actual prices and others may be manufacturing costs. See Cody and Tiedje (1996) for the 1995 costs.

Forecast of the Price of Gas

Figure 2

D.O.E. Forecast of Price of Gas

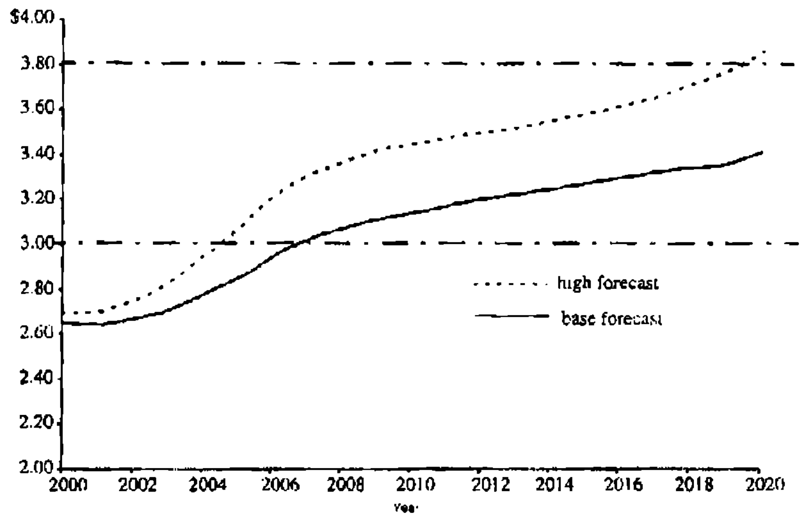


Figure 2 gives the 1998 Department of Energy forecast for the price of gas to electrical generators through the year 2020. The forecast is clearly wrong as the price of gas in the year 2000 is well above the forecast.[5] However, although such a forecast cannot be expected to be able to predict short run phenomena such as weather and short run economic activity, the DO.E. forecast reflects a scenario that is probably accurate. In the next few years, the source of gas to electrical generators will be from existing sources and the price will increase as demand grows. When the price of gas reaches the neighborhood of $3.00 per 1000 cubic feet, it becomes economical to market gas from the Alaska and North West Canada. These reserves are substantial, so at that price the supply curve of gas is very flat. For the purposes of this paper, we will assume that the price of gas will be between $3.00 to $4.00 per 1000 cubic feet. in the next ten years.

Thin Film Solar Cells

An important break-through in the production of efficient solar cells is thin films technology.[6] In 1995, the cost of these cells was roughly $400 per square meter.[7]

[5] Natural gas prices have reached levels around $5.00 per million BTU during October 2000.

[6] Thin films of exotic elements made of such as indium, gallium and selenium (SIGS) or cadmium and tellurium (CdTe) are deposited on glass. See Zweibel (1995).

[7] Zweibel (1995) p. 281. Converting cost per square meter to cost per kilowatt hour requires some assumptions about the rate of discount, the life of the solar cells, hours per year of sunlight, location

However, these cells have the potential of being very cheap to produce. The most expensive material in the production of solar cells is indium which costs about $200 per kilogram. However, it only takes 4 grams of indium to produce one square meter of solar panel. This would cost about 85 cents. The cost of materials to produce solar cells run may be under $10 a square meter.[8]

In the southern United States the sun delivers 2500 kilowatts per square meter per year. Thus, the present value of the revenue generated by a square meter solar panel is given by

$$V = \int_0^T e^{-rt} 2500\alpha p_s dt \tag{1}$$

where r is the discount rate, p_s is the price of solar electricity per kilowatt hour, α is the efficiency factor, and T is planning horizon. This expression can be written as

$$V = \frac{2500\alpha p_s \left[1 - e^{-rT}\right]}{r} \tag{2}$$

In equilibrium, the present value of the income stream has to be equal to the cost of the solar panel, C_s, plus the cost of the balance of systems, C_b.[9] Thus, the cost per installed square meter, C_M is given by

$$C_M = C_s + C_b = \frac{2500\alpha p_s \left[1 - e^{-rT}\right]}{r} \tag{3}$$

The correct discount rate is a subject of some controversy. Nordhaus (1994) reports a post tax rate of return of 5.7 on direct investment for all corporations and a 6.1 rate of return for large corporations. EPRI suggests 6.1 plus a .5 percent risk factor be used. To be conservative we are going to assume a discount rate of 7.5 percent

Efficiency values for thin films are now around 0.10. The life of solar panels is expected to be about 30 years. Assuming $r = 0.075$, $\alpha = 0.10$ and $T = 30$ we get

$$V = 2980 p_s \tag{4}$$

and efficiency. Roughly, a square meter in the southern United States and Northern Mexico receives approximately 2500 kwh per year

[8] Zweibel (1995) p. 286. See also Cody and Tiedje (1995). Recent developments suggestthat the cost of producing these panels is now between $45 to $75. a square meter.

[9] Balance of Systems are all the other costs necessary to install solar panel Ogden and Williams believed that in 1989 the cost was $33 per square meter, but that costs in the neighborhood of $20 could be achieved with economies of scale. This study will assume a balance of system cost of $35 per square meter. Note that the cost of land is trivial. An acre has 4047 square meters and the best location for solar installations would be unproductive desert. See Ogden and Williams (1989) p. 34.

The efficiency is expected to increase to 0.15 within the next five years without any technical breakthroughs. If these expectations are correct then

$$V = 4470 p_s \tag{5}$$

The relationship between the price of solar electricity and the value of the income stream is plotted in Figure 3 below.

Figure 3

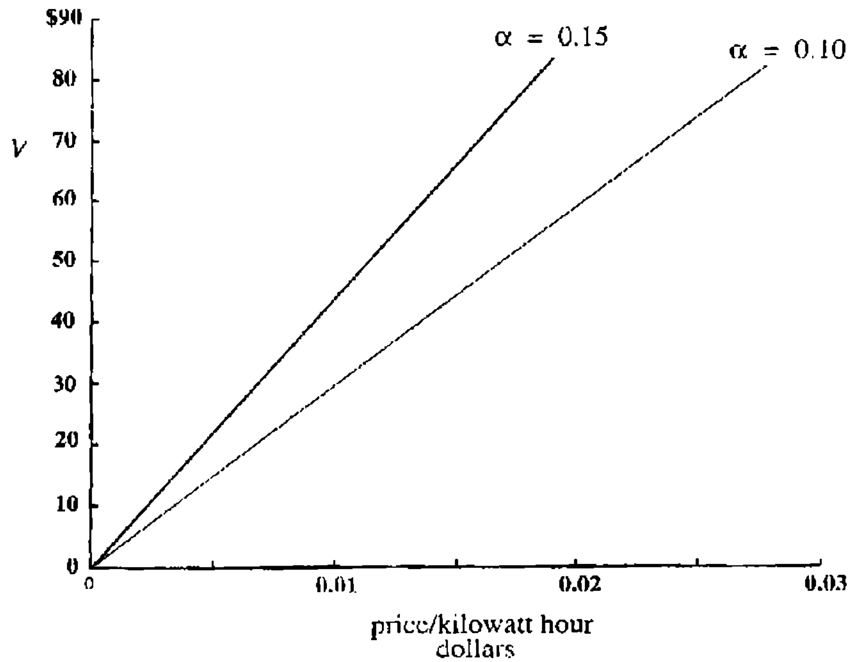


Figure 3 gives the present value of the power generated by a square meter solar as a function of the price of electricity for panels that are 10 and 15 percent efficient.

The cost of a kilowatt hour using a combined cycle gas generator is

$$P_E = \beta q + \frac{rk_0}{\left(1 - e^{-rT}\right)} \tag{6}$$

where q is the price of gas per 1000 cu. ft., β is the number of cubic feet necessary to produce one kilowatt and k_0 is the capital per kilowatt hour. If we assume that 1000 cubic feet produce one million BTU and a heat rate of 7200 BTU per kilowatt hour then $\beta = \frac{7200}{1000000} = 0.072$. If we assume that installed capacity is approximately \$800 per kilowatt hour and operates 75 percent of the time then $k_0 = \frac{800}{365 \times 24 \times .75} = 0.12$.

Figure 4

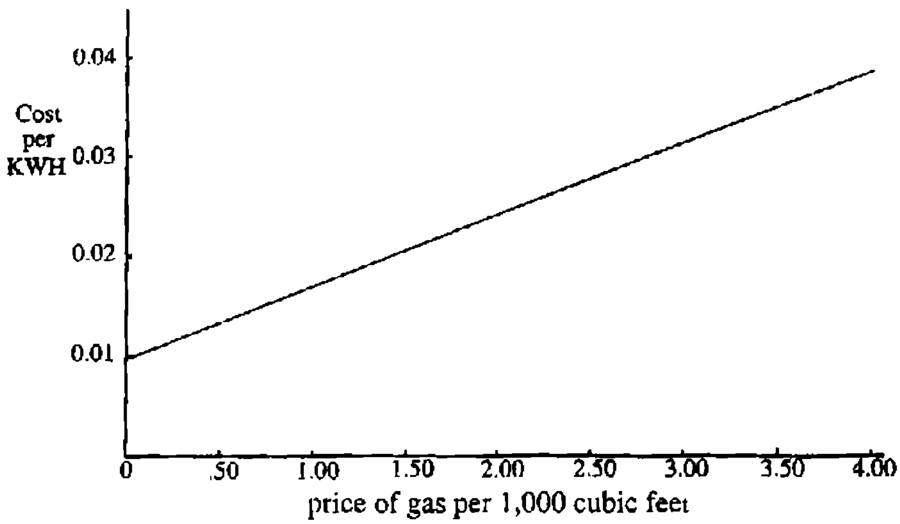


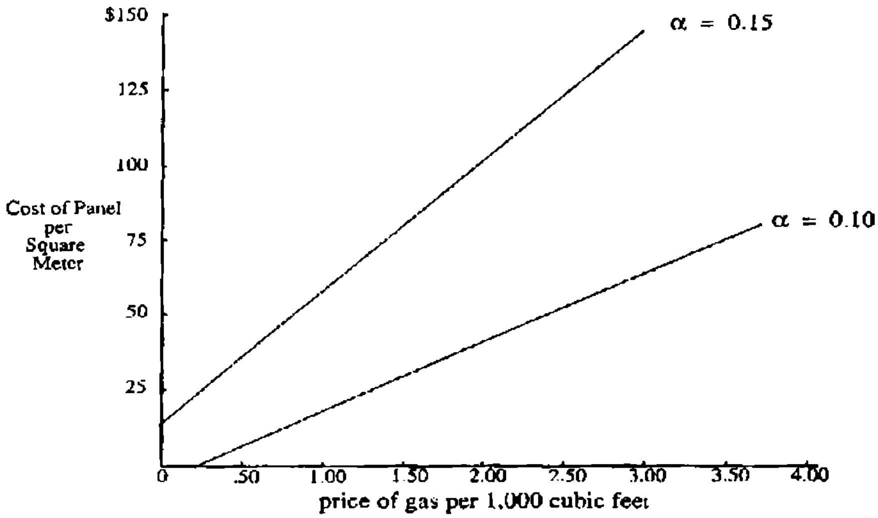
Figure 4 gives the relationship between the price of gas and the price of electricity generated by a combined cycle power plant.

If we solve (2) for p_s and set $p_s = p_g$, we can solve for the relationship between the price of gas, the discount rate and the present value of the electricity from solar cells. This is given by

$$V = \left[\beta q + \frac{rk_0}{\left(1 - e^{-rT}\right)}\right] \frac{2500\alpha\left[1 - e^{-rT}\right]}{r} \tag{7}$$

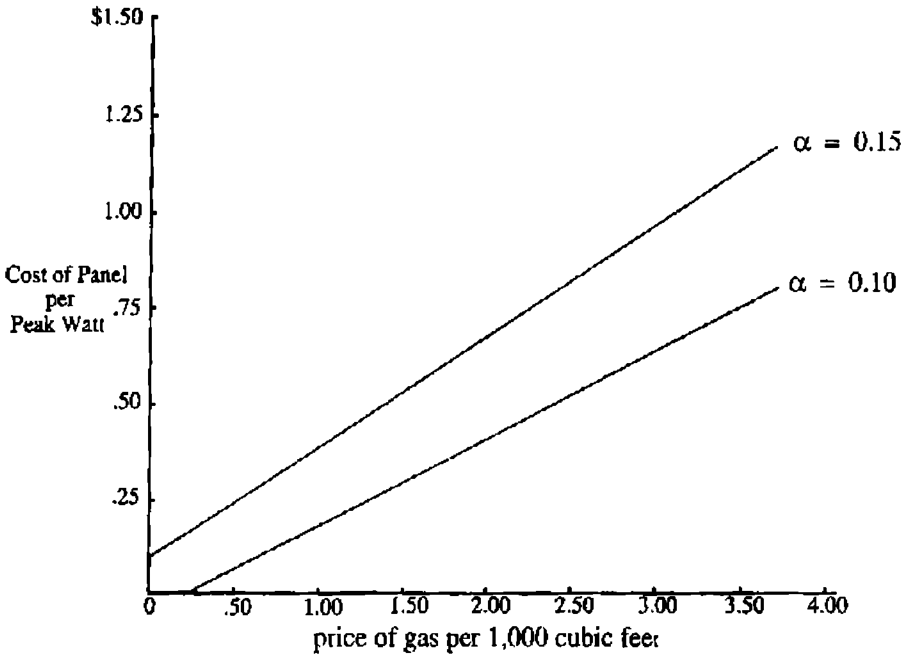
We can plot this relationship. If we examine Figure 5, we see that solar panels that are 10 percent efficient and cost between \$50 to \$75 per square meter are competitive with natural gas at prices between \$2.50 to \$3.50 per 1000 cubic feet.

Figure 5



Recall that this includes a balance of systems cost of 35 dollar per square meter Figure 6 below presents the same information in terms of the cost per peak watt.

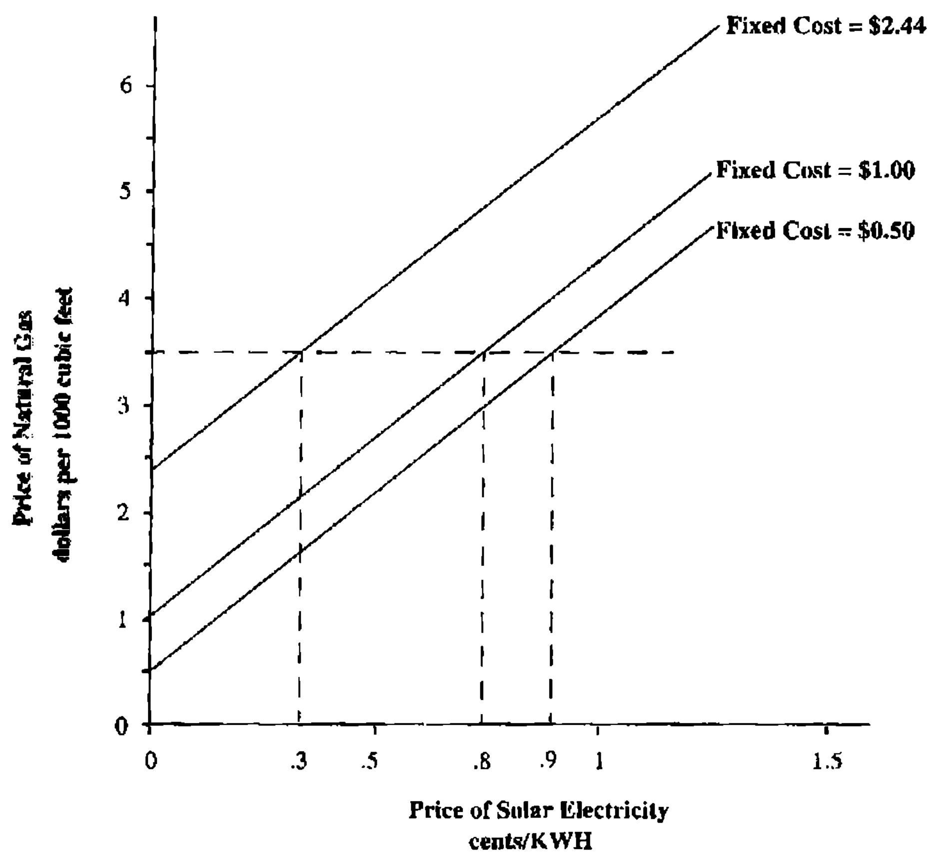
Figure 6



Solar Hydrogen

An important limitation with electricity produced by photovoltaic is that the sun does not always shine. One alternative that has been proposed is to use the electricity to convert water in to oxygen and hydrogen and then use the hydrogen as fuel.[10] It takes 331 KWH to produce one gigajoule which is roughly the energy in 1000 cubic feet of natural gas.[11] Thus, it is very easy to compute the variable cost of the cost of the hydrogen equivalent of 1000 cubic feet of natural gas as a function of the price of solar power.

Figure 7



[10] After we completed most of the work reported in this paper, Kenneth Zweibel brought to our attention Ogden and Williams (1989) as a source of data on the production of hydrogen from photovoltaic electricity. It is an excellent book that is unfortunately out of print. We wish to acknowledge that they have priority on many of the conclusions in this paper.

[11] 1000 cubic feet of natural gas is assumed to be 1,000,000 BTU which is 1.055 gigajoules. The parameters used to construct Figure 7 are derived from Table 7 on page 36 of Ogden and Williams (1989).

The cost of capital is a more difficult question. In the absence of cheap photovoltaic electrolyzer power, there has been no need to develop electrolyzer technology to produce hydrogen on a large photovoltaic scale. The current capital cost electrolyzer is reported to be $2.44 to produce one gigajoule of power. For such an electrolyzer to produce hydrogen that is competitive with natural gas priced at $3.50 per 1000 cubic feet development would require photovoltaic power that costs.3 cents per KWH. To achieve this cost would require a technical breakthrough. However, if the cost of electrolyzer can be reduced to the point where the capital cost is on the order of 50 cents to one dollar gigajoule, then photovoltaic hydrogen would be competitive with natural gas if the cost of photovoltaic power is .8 to .9 cents per kilowatt hour. At 15 percent efficiency, 1 cent per kilowatt hour electricity would translate into a cost of $45 per installed square meter. This can be achieved without any major technological breakthrough within the next five to ten years. The question is then if it is possible to design an electrolyzer that will produce hydrogen at the capital cost as under $1 per be gigajoule if there is high-volume production so that economics of scale can realized.[12]

Electrolyzers that can produce hydrogen at the capital cost as under $1 per be gigajoule together with PV power under one cent per kilowatt hour mark a transition in the energy economy analogous from the transition form hunting and gathering to agriculture.

Growth in Demand and the Cost of Photovoltaic Power

The cost of solar cells has roughly been dropping by a factor of 2 every 5 years. This has occurred in the environment where support for photovoltaic research has not been very aggressive and demand has been limited. Federal funding of photovoltaic research has been on the order of 60 million dollars a year. This significantly less than what has been spent on to a more exotic forms of power is such as fusion. The cost of photovoltaic power has been above $3 per peak watt so demand for solar cells has been limited to remote applications and other exotic uses.

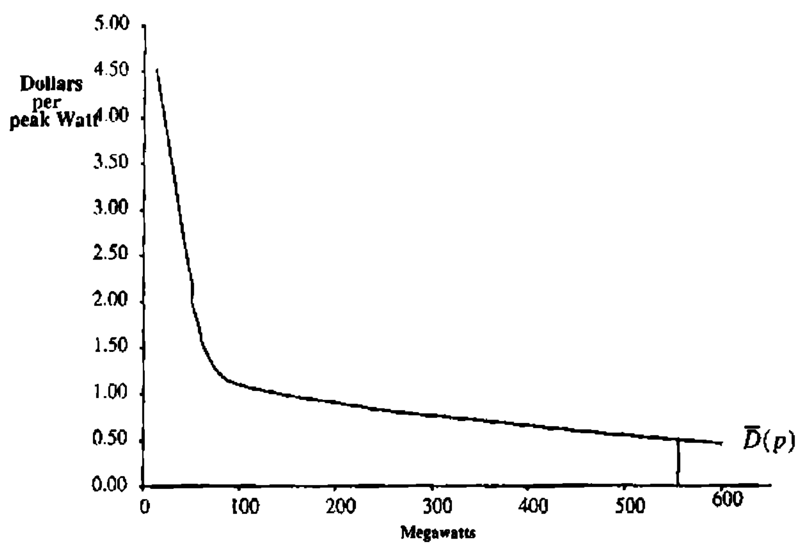
Figure 8 below is a schedule that gives the potential demand for photovoltaic electricity. It is not a demand curve in the traditional sense, but rather is a schedule of the demand for electricity in various applications and various prices based on Table 4 in Ogden and Williams. A pictorial representation of this table is very illustrative.

At very high prices the market is for exotic uses such as space satellites, buoys, corrosion protection. As the price drops below seven dollars a peak watt, the market

[12] Capital costs reported in the engineering literature are often accounting costs rather than economic costs which are the relevant costs in formulating economic policy. For example they frequently include sunk cost such as research and development and use a very high rate of discount. Further, there are usually large economies possible with large scale production. It may well be that it is possible to produce electrolyzers that can produce hydrogen at the capital cost that is under $1 per be gigajoule with existing technology.

for power in remote areas begins to open to photovoltaic power. Demand for such power sources is limited, so the potential market do not increase dramatically as price drops. A drop in the price from \$2.00 to \$1.50 increases potential demand by only 20 percent. However a drop from \$1.50 to \$1.00 increases potential demand by over 100 percent and a drop from \$1.00 to \$0.50 increases potential demand by over 400 percent.

Figure 8



The actual demand for solar cells will be a function of the cost of alternative technologies, the diffusion of information and policy. Let us assume as a rough approximation that a 400 increase in potential demand translates into a doubling of actual demand

Various experts have estimated the cost of producing the cost of silicon solar cells as a function of output. They have used a heuristic formula of the form

$$\frac{C_t}{C_0} = \left(\frac{Q_t}{Q_0}\right)^b \tag{8}$$

In that model the cost of producing solar cells, C_t depends on cumulative output, Q_t, base cost, C_0 and base cumulative output, Q_0. The assumption is that increased cumulative output results in learning which reduces costs.[13] An implication of this model is that doubling the growth rate of the demand for solar cells will decrease the time it take for the cost to half by a factor of two. These two factors are multiplied.[14] If this occurs, solar power at a price under one cent per kilowatt hour would be possible in five years.

Policy Issues

The economic consequences of solar energy on oil producers will begin to occur as soon as reasonably certain expectations about this technology are formed. If major oil producers are attempting to maximize long run profits, then this new technology should be reflected in their production plans before the new technology is fully implemented. The income of oil producing countries will remain constant or drop as the major producers increase their production. Major projects such as the development of the Caspian gas reserves or gas pipelines from Siberia to China may prove to the uneconomical. Inasmuch as many of the oil producing nations are developing nations, this is one more factor breaking the trade links between the developed world and the developing world.

A major foreign policy concern for the United States and the rest of the developed world is insuring secure sources of energy. There have been estimates that the military expenditures by the United States that can be imputed to each barrel of oil imported is as high as $60. Solar power that competes with natural gas at a price $3.50 per 1000 cubic foot gas would reduce the threat to the economies of developed countries from the disruption of oil supplies.

Solar power does not produce carbon dioxide so this is one way that the developed countries can increase their consumption of electrical power and still meet their commitments to reduce their carbon dioxide emissions. This is a classic case of the reduction of an externality and would justify a subsidy for solar technology. As the cost of solar cells drops because of learning and economies of scale, solar power may well replace hydrocarbon in uses such as fuel cells for automobiles. If the cost of installed solar panels drops to $45 a square meter and efficiency increases to about 15 percent, the problem of power storage could be solved using solar power to break water down into hydrogen and oxygen.

[13] Studies of the costs of producing silicon cells have found parameter values for b that range between -.51 to -.32. Cody and Tiedje (1996). They actually report values of $\lambda = 2^b$ that range for .7 to .8 which they call the progress ratio. These number correspond to values of b of -.51 to -.32.

[14] To illustrate this point, if the growth rate of demand is constant, α, then $\frac{dQ}{dt} = \alpha Q$ and $Q(t) = Q_0 e^{\alpha t}$. Since the increase is a function of the product αt, if the growth rate of demand doubles, the time it takes for cost to drop by a factor of two as a result of learning by doing is cut in half.

If China is to achieve a standard of living similar to the developed world, it is difficult to see that they could do so without a large increase in their consumption of energy. This will either require that they burn coal or else this will greatly increase the demand for oil and natural gas. If carbon dioxide emission is a problem because of global warming, making available solar technology to countries such as China, that have large coal deposits, but very little gas would be a simple way of eliminating what may soon be a very difficult political problem.

One of the potential problems is that producing solar cells may be a technology with decreasing average costs. Such technologies usually involve high fixed costs and low marginal costs. A classic example is the production of compact disks. There are high fixed costs, but the marginal cost of a compact disk is about a dime. The ratio of the sale price of a compact disk to its marginal cost is usually over a hundred. Another more important example is pharmaceuticals. Most of the cost of producing drugs is research and development. The cost of the pill is trivial. A recent example of this problem is the controversy between South Africa and the American drug companies about producing generic drugs for treating AIDS in South Africa. There is a clear dilemma. If the pharmaceutical companies are not allowed profits, they will not develop the drugs. On the other hand, if they are allowed to make a profit, drugs that are very inexpensive to produce will be denied to people that can not afford the market price. There could be similar problems with solar cells. Efforts to earn a profit by discriminatory pricing could delay the introduction of this technogoly. A question is whether the externalities are large enough so that some form government intervention is desirable.

Conclusions

The free market economy, with some support form government, has resulted in a development of photovoltaic technology where it is now at the point where it can compete with natural gas priced at $2.50 to $3.50 per million BTU in supplying power to the grid in latitudes where the sun can provides about 2500 kilowatt hours per square meter per year. Reasonable scenarios suggest that the price of gas will be in this range in the next five to ten years as the marginal supplier of gas become fields in Alaska and northwest Canada. Without any major technical breakthroughs, the price of photovoltaic power will reach the point where it clearly dominates gas at these price for producing power during the day. At that point, the price of photovoltaic power should be low enough so that it may be possible to produce hydrogen that is competitive with natural gas. The key bottleneck is the cost of electrolyzers.

For photovoltaic hydrogen to be competitive, the capital cost per gigajoule would have to drop from the present $2.44 per gigajoule produced to $.50 to $1.00 per gigajoule.

It is hard to say at this point whether this target can be reached through engineering and economics of scale or if there may need to be a substantial technical breakthrough. It is clear however, that even if we ignore global warming, the social and political implications of this technology are substantial enough that a good argument can be to accelerate development beyond what can be expected from market forces.

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Appendix

We are estimating the cost of solar panels using data from Zweibel (1999) and from information provided by First Solar. The First Solar process uses a fully automated plant that produces 3 square meters of solar panels per minute. The plant costs 35 million dollars. We use 10 percent cost of capital and 10 year live of equipment to compute the capital cost. We assumed the plant has a capacity 110 megawatts a year if the panels have an efficiency of 10 percent. Labor costs were based on eight skilled individuals to operate the plant (at $20.00 an hour) and 25 unskilled individuals (at $10.00 an hour) to box, and load the panels, janitorial services, etc. Material costs are from Zweibel.

This estimate of the cost does not include the return to the investment First Solar has made in developing the technology.

Cost of Solar Cells per Square meter	
Cost of capital per square meter at 75% rate of output	$5.50
Maintenance (3% of value of capital)	1.05
Direct labor cost ($320 per hour to run plant)	3.25
Materials	28.00
Total direct costs	$37.80
Overhead/other costs	10.00
Total cost per square meter	$47.80