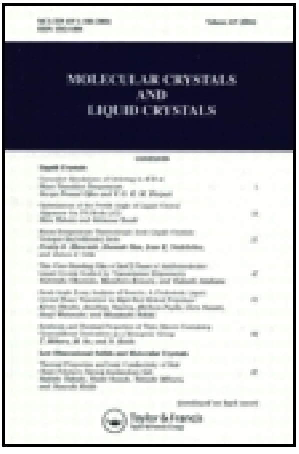

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World Energy Supply and Greenhouse Effect

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World Energy Supply and Greenhouse Effect

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Let me cite the conclusion of this paper at the outset. The conclusion is that there is a unique solution to the world energy supply and that solution is solar voltaic energy. I will return to this conclusion shortly. At first I want to give the reason for relating the "world energy supply" to the "greenhouse effect."

The major source of the greenhouse effect is the large concentration of CO_2 in the atmosphere. It is obvious that the major source of CO_2 comes from the burning of fossil fuels: oil, and coal. In brief, we need to replace coal and oil by another source of energy that does not produce CO_2. I believe that solar voltaic energy will be the unique answer to this other source of energy. Hence, solar voltaic cells are the solar solution to those two separate problems. If we were depending on the coming energy crisis to promote the use of solar voltaic energy the time scale would be in the order of 100 years. With that time scale it would be difficult to stir up public interest at this time. I say this even though an energy crisis 100 years hence still demands that we search for a solution now. The reason is that it traditionally takes at least 50 years to make a major transition in the source of energy, e.g. from wood to coal or from coal to oil. The general public does not get stirred up until the crisis is at our doorstep. In the case of the greenhouse effect the crisis (global warning) is at our door step now. Hence, the solution of the greenhouse effect will also solve the problem of an alternate source of world energy. In this sense, the greenhouse effect will be looked upon in retrospect as a very fortunate coincidence. Whether or not this last summer was due to the greenhouse effect is not necessarily important. We do know that the greenhouse effect will become obvious well within the next decade.

So much for the greenhouse effect. It is a lucky accident that it alerts us to seriously consider a change in the world energy supply.

The world energy supply must satisfy several more or less obvious constraints. It must have a permanent life, it must be ample to supply the world's energy budget, it must be benign and it must be economically viable. It is no exaggeration to say that the survival of the world as we know it depends on finding such a new energy source.

Let us examine the possible sources for this world energy supply. We can immediately discard coal and oil and gas because the supply of these nonrenewable fuels is finite. Whether the supply will last 100 or 200 years is unimportant when we are considering the long term survival of the world.

The sources of hydroelectric, wind and forest have an effectively infinite life but are totally inadequate to satisfy our energy budget. And finally, nuclear energy scarcely qualifies as being benign.

The above outline leaves only a single choice—that of solar voltaic energy that converts solar radiation directly into electrical energy.

Solar voltaic energy is available throughout the world—especially and fortunately in third world countries. Solar voltaic energy has an effectively infinite life and is clearly benign. The amount of land required in the U.S., for example—the most energy intensive country in the world—to supply all of its energy needs (outside of food) is only 1% of the area of the U.S. and the land can be desert or rocky soil.

That leaves the question of economic viability which is a major subject of this discussion.

To get an overall sense of proportion about the energy problem I would like to interpose several tabular summaries.† For simplicity I introduce the concept of energy measured in solar units. One solar unit is equal to the total solar energy incident on the earth averaged through the day and throughout the year. This concept can be applied to the whole earth or to any part of it as, for example, the U.S.

In Table I, I consider a range of energy of a million solar units in six steps of a factor of ten each. Because my arguments are, with few exceptions insensitive to factors of two variation in the assignment of energies, I replace mathematical precision by a factor-of-two validity. The long term solutions will be guided by these factors of two approximations even though immediate economic choices are often sensitive to cost differences of only a few per cent.

According to Table I, if the world's populace generated and consumed an amount of power equal to the solar power incident on the earth (that is, one solar unit) the mean temperature of the earth would rise to about 80°C. It is utterly clear that this rate of energy consumption is ruled out when that energy is supplied by oil, coal, gas, nuclear and geothermal sources because they all add heat to the earth. In order for the additional heat to be radiated into space the earth's temperature must rise. Note that the present mean temperature of the earth, about 20°C, is the temperature the earth needs to reradiate the one unit of solar energy normally incident on it. If we add a second unit, owing to world energy consumption of one solar unit, the temperature of the earth must rise to near that of boiling water in order to radiate the excess heat.

Consumption of 10^{-1} solar units leads to a "tropical climate", a convenient label for the 8°C rise in temperature incurred when the world's generation of power equals one-tenth of the solar power incident on it. This temperature rise also is

†These tabular summaries are taken from an earlier paper, A. Rose, "Solar Energy: A Global View," *Chem. Tech.*, **11**, 566. (1981).

TABLE I.

Overall view of energy consumption in solar units

Energy consumption (solar units)	Remarks
1.	"Boiling water" (global temperature rise to 80°C)
10^{-1}	"Tropical climate" (global temperature rise to 28°C)
10^{-2}	Absolute upper limit (1°C rise in temperature)
10^{-3}	U.S. level of power generation
10^{-4}	World level of power generation
10^{-5}	"Food" (crops) (fraction of incident solar energy used to feed 4×10^9 people)
10^{-6}	"Meat" (fraction of incident solar energy used in meat production)

Note: One solar unit equals the solar power striking the earth averaged throughout the day and throughout the year.

intolerable. It would, at least, lead to the melting of the ice caps and the consequent inundation of vast shorelines throughout the world.

Note that these levels of power consumption are not entirely academic. Power consumption in the major metropolitan areas, owing to the congestion of people and industry, is already between 0.1 and 1.0 solar units referred to those metropolitan areas. There is, of course, already a significant temperature rise of a few degrees within these areas but not a catastrophic rise. These areas are "air cooled" by convection currents and prevailing winds and are able to dump their heat load on the surrounding countryside. If the same levels of power consumption were world wide there would be no place to dump the heat except into outer space. In this case the temperature of the earth would increase to the levels of "tropical climate" or "boiling water" cited in Table I.

The third entry in Column 2 of Table I is labeled "absolute upper limit." This level of worldwide power consumption corresponds to 1°C rise in temperature. At this point experts may disagree on whether such a temperature rise would have major effects on the ice caps, the cloud cover, the weather patterns, or the distribution of plant and animal life. Whatever the arguments may be, pro or con, it is not the type of experiment the world should choose to explore. It is in this spirit that I have chosen the label "absolute upper limit." The fourth entry in column 2 of Table I reads "U.S. level." It means, of course, that the total power now generated in the United States is already equal to 10^{-3} of the total solar radiation on the U.S.[2] The reason for the "already" will become clear shortly.

The total power now generated in the world is equal to 10^{-4} of the total solar power of the world. (If we use only the land area for the "world", the power consumption is 1.5×10^{-4}; if we use the total area, land and sea, power consumption is 0.5×10^{-4}.)

GROWTH LIMIT IMPOSED BY ENERGY CONSUMPTION

We can thus draw a major conclusion about the world wide limit to growth imposed by the "absolute upper limit" of 10^{-2} solar unit: We are committed to come within a factor of two of the "absolute upper limit" of power consumption. This conclusion is based on three premises:

1. A stable world is likely to approximate the U.S. standard of living. There is clear evidence that the material standard of living is approximately proportional to power consumption.[3]
2. World population will increase by a factor of two before it levels off. If anything, this is an optimistic premise.[3] The world will be fortunate if the increase can be constrained to a factor of two.
3. The U.S. standard of living will increase by a factor of two before it levels off. Again, the prognostication is on the modest side. Departures from this premise are likely to be on the high side of a factor of two.[3]

We can combine these three premises to predict a world consumption of power of 0.5×10^{-2} solar unit. World power consumption, if it were at the present U.S. level, would be 10^{-3} solar unit. Allowing for a factor-of-two increase in population and a factor-of-two increase in standard of living yields the 0.5×10^{-2} solar unit. This is a scant factor of two under the "absolute upper limit," a barely respectable factor of safety. Again, let me emphasize that departures from this estimate are likely to be on the high side.

The factor of 100 that we have been discussing, between the present world power consumption of 10^{-4} solar unit and the "absolute upper limit" of 10^{-2} solar unit, is the same factor of 100 that allowed Weinberg and Hammond[4] to estimate that the world could support four times the present world population at twice the current U.S. standard of living. It is the same factor of 100 that allowed the Club of Rome[5] unerringly to forecast disaster no matter what elaborate model was inserted into their computer. It is also the same factor of 100 that appears in Kahn's[6] estimate of the increase in the world's GNP in the next 200 years.

The obvious corollaries to this major conclusion are that world planning must be aimed at confining the increase in world population to no more than a factor of two and that the U.S. and other highly developed countries have a pragmatic as well as a moral obligation not to exceed their share of the ultimate world power consumption. The limitation to growth imposed by the upper limit of 10^{-2} solar unit is clearly a long-term problem—measured in centuries. Moreover, other environmental constraints are likely to intervene before the absolute limit is reached.

POWER CONSUMPTION VIA FOOD

We return to the last two entries in Table I. The item labeled "food (crops)" has the following meaning. We take the present world population of 4×10^9 people and assign a food power consumption per person of 0.1kW. This value is based on the commonly recognized normal diet of 2500 kcal/d. The total food power computed in this way is 10^{-5} of the total solar power incident on the land area of the earth or 10^{-5} solar power unit. We assign the 0.1kW to food energy derived from "crops," since that derived from meat is only one-tenth of this value.

The last item in Table I, labeled "meat," means that the total food energy derived from meat is only 10^{-6} of the total energy incident on the earth.

GROWTH LIMITS IMPOSED BY FOOD

The food consumption in Table I is 10^{-5} solar unit. To supply this power, about 10^{-1} (10%) of the earth's surface[3] is utilized in agriculture, or, in other words, the input energy is 10^{-1} solar unit. The ratio of output to input power then gives an efficiency factor of 10^{-4} for world agriculture.

An optimistic estimate[3] of the potentially arable land is only a factor or two larger than the 10% now in use. In the absence of significant increases in agricultural efficiency, the limit to world population growth is only a factor of two, the same factor arrived at by the independent limitation imposed by total energy consumption.

Doubling of agricultural land in the time constraint of some decades needed to double the world population is a formidable task, particularly since the second 10% is far less fertile than the 10% now in use.

The possible relief from this severe constraint on population growth that is offered by improved solar efficiency of agriculture must be treated cautiously. The increased efficiency of the total spectrum of agricultural crops is far less than the dramatic increases achieved for selected crops such as corn.

COSTS

My purpose here is to explore the ultimate cost of solar energy in terms that are more or less familiar to everyone. I do so by comparing a solar energy farm consisting of photovoltaic solar cells with several solar energy farms that have served human beings throughout most of their existence.

The phrase "ultimate cost of solar energy" distinguishes that cost from the estimates that are frequently made in terms of the present "state of the art" or modest extrapolations of the "state of the art." Our society has barely begun to tap the imagination of its scientists and the expertise of its industry for the design of a low-cost solar energy system.

Energy to support our society has two major uses. First, it must provide power for heating, lighting, transportation, and industry—in brief, all of the applications outside of nutrition. This energy constitutes 99% of U.S power consumption (Table II).[2] Second, it must provide food, for which we use only 1% of the total energy budget. I will treat these two systems separately and then together.

A convenient set of conversions to keep in mind is given in Table III. Here one sees that the consumption of a pound of meat or of crops delivers an amount of energy to the body equal to about 1 kWh. The unit of a kWh is not important, since it is only the relative value that I wish to stress. At the same time, a kWh is a universally appreciated unit in almost every household when it comes time to pay the monthly electric bill. If we burn a pound of wood or dried vegetation, we

TABLE II.

Power consumption per person in the U.S.

	kW/person
Total power consumption	10
Food power consumption	0.1

can expect some three times as much energy as the body extracts on the average from crops per pound. Finally, burning a pound of oil yields twice the energy derived from burning a pound of wood. These are convenient conversions for comparing the costs of energy from different sources, as we are about to do.

In passing, let it be noted that the 10 kW per person is what makes modern highly developed society possible and is what fuels the so-called "good life". Since only 0.1 kW is needed to feed the human machine, our society has in a very real sense the equivalent of at least 100 servants for each citizen.[7] Flipping on a 100-W bulb is the energy equivalent of adding another servant. Stepping on the accelerator in anticipation of a green light calls forth the energy equivalent of over 1000 servants pushing on the rear end of our car and would have been the envy of any pharaoh. I am not extolling the "good life"; I am trying to give it a sense of proportion in terms of energy.

GENERAL PURPOSE SOLAR ENERGY SYSTEMS

Table IV lists three solar energy farms that might be considered for supplying the total power needs of the U.S., namely, 10^{-3} solar unit. They are forests, biomass, and solar (photovoltaic) cells. The solar efficiencies are 10^{-3}, 10^{-2}, and 10^{-1}, respectively. Solar efficiency, here, is the ratio of the heat produced, for example, per unit area of forest by burning the annual yield of wood to the solar energy incident on that area. It is immediately clear that to supply the total U.S. power using a solar farm of trees having an efficiency of 10^{-3} would require a solar power input of one solar unit. At the same time, a solar input of one unit means that the entire landscape of the U.S. must be covered by forest. Clearly, this is not feasible. Currently, forests cover some 30% of the U.S. as well as of the world land area. I am not proposing forests as a significant solar power system. I bring in the forest

TABLE III.

Some useful energy yields.

Energy Source	Energy yield (kWh/1b)
Meat crops	1
Wood Biomass	3
Oil	6

TABLE IV.

General-purpose solar energy systems

Systems	Efficiency factor	Input solar power[a]	Output power (solar units)
Forest	10^{-3}[b]	1	10^{-3}
Biomass	10^{-2}	10^{-1}	10^{-3}
Solar cells	10^{-1}	10^{-2}	10^{-3}

[a]Fractional land use to supply U.S. level of power consumption.
[b]Based on American Almanac data on the total weight of forest products and on the area of continuously harvested forests.

as one example of a highly inefficient and, in consequence, a highly dispersed solar system that can and does supply cheap energy—cheap by today's standards.

A second solar energy farm might consist of certain grasses or vegetation having an estimated solar efficiency[8] close to 1%, or 10^{-2} according to the scale we are using. Such a farm would need to occupy 10^{-1} of the land area in order to supply the U.S. level of 10^{-3} solar unit of power.

A third solar farm might consist of photovoltaic cells having an efficiency factor of 10^{-1}. The efficiencies of available solar cells are 5–20%. The fraction of land needed for this farm is then only 10^{-2} or 1% of the total area of the U.S. One percent of the U.S. is a parcel of land about 200 miles on a side. It is comparable to the land area covered by highways.

SOLAR ENERGY SYSTEMS FOR FOOD

Table V lists the two major solar systems and their efficiencies for supplying food energy. A wheat field that annualy yields a ton of wheat per acre (a good average yield[9]) has a solar efficiency a little over 10^{-4}. We have used 10^{-4} to take into account the fruit and vegetable components of our diet whose solar efficiencies are well below 10^{-4}. To supply the food power of 10^{-5} solar unit (Table I), some 10% of the land area must go to agriculture. The population density of the U.S. is close to that of the world, but the actual land area used for agriculture in the U.S. is closer to 20%. These factors account for our large exports of food as well as the assignment of part of the agricultural land to feed for livestock. The fraction of the world land area in crops is close to 10%.[3,9]

Finally, meat consumption in the world[9] is only one-tenth that of crops, by weight or by food energy, but still requires the same 10% of the land area as does crop agriculture owing to the lower solar efficiency for producing meat.

With the data of these tables we are in a good position to examine the economic viability of solar voltaic energy.

I begin with the fact that the party line on solar energy, namely, that the efficiency of the solar voltaic cells must be at least 10% in order to be competitive with the existing energy sources of coal and oil. If one goes to Washington to get support for research on solar cells and if the proposal involves an efficiency of appreciably less than 10% it is dismissed out of hand. If the proposal involved an efficiency of, say, 1% or less, the funding agency would likely recommend the nearest insane asylum.

The energy experts rely on their analysis of the solar voltaic systems and not on available data on other actual operating solar systems. In fact, what I am about to cite are the performances of a couple of well known solar farms and performances that are not dependant on any sophisticated theoretical analyses. Let me begin with what I think is the most impressive example, namely, a Kansas wheat farm.

The efficiency of the wheat farm is measured as the ratio of the food energy harvested each year to the total solar radiation energy incident on the wheat field during the entire year. This efficiency is not the 10% required by the energy experts—it is not even 1%. It is actually 0.01% or 1,000 times less efficient than a farm of solar cells (see Table V and Figure 1). The energy output of the wheat field is easily measured since the eating of one pound of wheat contributes one kilowatt-hour of energy to your body system. (If the wheat were burned the energy would be even more than one kilowatt hour). This means that we need 1,000 acres of wheat to match the energy output of one acre of solar cells. In spite of this enormous disparity in efficiency we can go into a supermarket and buy a pound of wheat, that is one kilowatt-hour of energy, for about ten cents. But ten cents a kilowatt hour is what many of us pay for electrical power from the Public Service Co. Let me reemphasize that we are not talking about a difference of a few percent that would depend on a very careful and sophisticated analysis. We are talking about a solar energy farm whose efficiency is 1,000 times smaller than that required by the experts for a solar voltaic farm to be economically viable.

Let me cite a second well known solar farm—that is, a forest of trees. The efficiency of this farm is 100 times smaller than the efficiency of a solar voltaic cell. Nevertheless, if we go out and buy a cord of wood for our wood burning stove we find that we have paid only one cent per kilowatt hour for the heat energy delivered by burning the wood. It is, of course, for this reason that many people during the energy shortage in the early 70's chose to heat their houses by wood burning stoves and fire places.

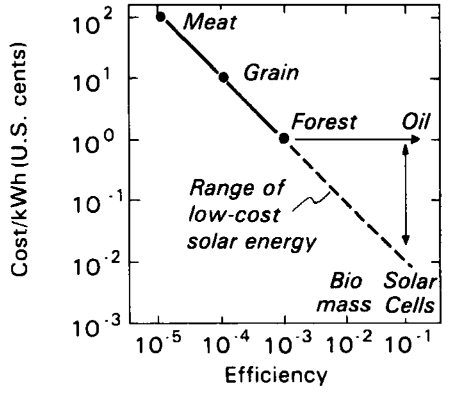

TABLE V.

Solar systems for food

Systems	Efficiency factor	Input solar power[a]	Output power (solar units)
Crops	10^{-4}	10^{-1}	10^{-5}
Meat	10^{-5}	10^{-1}	10^{-6}

[a]Fractional land use to supply world level of consumption.

I have just cited two examples of solar energy farms that radically violate the efficiency criteria set by the energy experts for solar voltaic cells and both examples supply and have supplied us with low cost energy.

I am *not* recommending that we use wheat fields or forests to supply our energy budget—the reason is very simple. To supply our total energy budget from forests we would have to cover the entire U.S. with trees. To supply our total energy budget by energy derived from solar voltaic cells we need only 1% of our land area. Already we are accustomed to using 10% of our land area to supply our food energy budget and that budget is only 1% of our total energy budget.

I have cited these examples to demonstrate in simple terms that we are already supplying low cost energy by solar farms that are 100 to 1,000 times less efficient than solar voltaic cells.

The crucial element in this argument has to do with the capital cost of these cells. I can only cite that since the early 1950's when intensive work on solar cells was begun, the price of these cells has come down by a factor of a thousand. They are now close to competitive with other sources of energy, namely, coal and oil. And the cost of these solar cells is still going down.

A crucial contribution to this long decline in costs is due to the landmark paper of Carlson and Wronski[10] in which they demonstrated that a low cost thin film of amorphous silicon could replace the expensive single crystals previously used.

What I have presented is a simple and I think a cogent argument that the future energy needs of the world can confidently and uniquely be satisfied by solar voltaic cells.

TABLE VI.

Comparative energy costs from various solar farms

Solar systems	Efficiency factor	Energy cost[a] per kWh equivalent (cents)
Meat	10^{-5}	100
Crops	10^{-4}	10
Forest	10^{-3}	1
Biomass	10^{-2}	?
Solar cells	10^{-1}	?

[a]The kWh costs of meat, crops, and wood are based on World Almanac data on cash receipts in 1973 of the primary producers of these products in the U.S.

In the face of what I said it is ludicrous and almost criminal that the federal support for research on solar cells has been reduced by over a factor of five in the last decade. That support should have been increased, not decreased, by more than a factor of five.

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