Basic Choices and Constraints on Long–Term Energy Supplies

Population growth and energy demand are exhausting the world's fossil energy supplies, some on the timescale of a single human lifespan. Increasingly, sharing natural resources will require close international cooperation, peace, and security.

Paul B. Weisz

Human society, like any system composed of dynamic processes, depends on an external energy source. Historically, that source was the Sun, which provides heat, light, and photosynthesis for food to support work energy by man and animal, and affects wind and water motion. Since the early 19th century, though, the discovery of and access to a vast supply of fossil fuels within Earth has enabled the industrial revolution, near–exponential growth of population,[1] technologies, and wealth. That period could well be renamed the energy revolution (see figure 1).

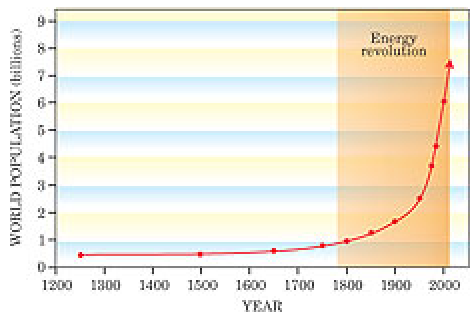

Figure 1

As we enter a new millennium, we are growing increasingly concerned about the limits of our fossil fuels that are driving the world's economies. Many journal articles, committee reports, and books have addressed this "energy problem"; they contain opinions, ideas, and suggestions from experts within their various subdisciplines on possible ways to improve our practices or innovate technologically. But a complex interdependence exists among the technological, social, and environmental aspects of energy use (see the articles in Physics Today, April 2002). Furthermore, many of the ideas researchers propose cannot significantly impact the real magnitude of the energy problem or may provide only short–term relief.

Our basic choices are limited. Nature's energy resources are confined to two categories: Earth–stored fossil residues and nuclear isotopes, whose economic utility is limited by the finite amounts that exist on Earth, and the radiation flux of solar energy, whose economic utility is limited by the finite rate at which we can capture the Sun's energy and by the land areas that societies can dedicate to harness it.

The longevity of the fossil energy supply and the net rate of solar energy availability are both reduced by the energy consumed through their conversion to a suitable energy form and the technologies that accompany that conversion: storage, delivery, maintenance, and repair of environmental damage. Solar–derived consumer energy, whether as electricity, biomass, or wind, represents a clean, alternative energy form. It is important to understand a basic law of nature: Energy, once used, is not regenerable. So the public term "renewable energy" is misleading.

The following analysis examines the magnitudes of the world's energy supplies and the basic constraints on our ability to support in the long term society's demands using those finite supplies. To put those magnitudes into a human context for policymakers and the public, the longevity of our resources will be expressed on the scale of a human lifespan (where 1 human lifespan is approximately 75 years).

Energy demands

In viewing overall societal energy issues, it is useful to express energy magnitudes in units of the quad (Q), where 1 Q = 10^{15} BTU, roughly equal to 2.5 × 10^{14} kcal or 1.06 × 10^{18} joule. Current US energy consumption is about 100 Q/year, roughly a quarter of the world's total demand.[2]

Energy demand by humanity continues to rise. An increase of about 1.5% per year is projected in the US and world demand is expected to increase by 1–2% per year for many decades, mainly due to continued population growth. While total demand is, of course, influenced by personal demand, even unusually large (20%, say) conservation efforts would be nullified by population growth in less than 20 years.

Earth–stored resources

- **Petroleum.** In 1956, petroleum geologist M. King Hubbert correctly predicted that a peak and subsequent drop in US production would occur around 1970.[3] In fact, foreign imports have since risen to 60% of current consumption. US dependence on foreign petroleum is certain to increase.

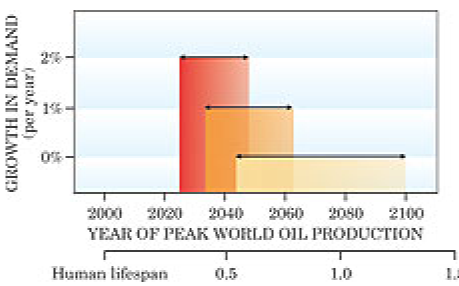

Figure 2

In 2000, Jay Hakes of the Energy Information Administration presented a similar and extensive US Department of Energy assessment of the likely trend and peak in the world petroleum supply.[4] Figure 2 shows the predicted range of years when the peak is likely to occur for demand whose growth rate may be between 0–2%. Because growth rates due to population alone are anticipated to be at least 1% per year for many decades to come, the pivotal event is expected to occur well within a human lifespan. Moreover, the analysis was based on an optimistic estimate of the world oil resource of approximately 2200–3900 billion barrels, nearly twice the proven reserve.[5] That would place the anticipated time to reach the peak well within a few decades.

- **Natural gas.** A natural gas shortage exists now in the US. Yet the current growth rate of US demand is approaching 3% per year.[2,6] As seen in figure 3, the proven US natural gas reserve would last very few years, even at constant (year 2000) demand.

Estimated gas reserves worldwide are relatively large. Geologists have good reasons to believe the sum of our reserves and still undiscovered (but likely to exist) natural gas could last roughly for another 45–60 years (see figure 3).[2,6] However, those reserves are widely scattered around the world: 58% are reported to be located in Russia, Iran, and Qatar, with small contributions in numerous other countries.[2] Clearly, their use will depend on vast international and intercontinental transportation by pipelines, transoceanic shipment as liquefied natural gas (LNG), or advance conversion to liquid fuels. Energy sacrifice by basic thermodynamic requirements plus process efficiency loss will accompany advance conversion to liquid fuels. Geopolitical cooperation will be essential.

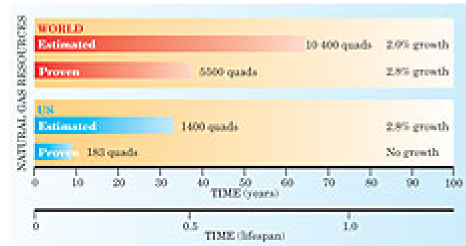

Figure 3

- **Coal.** The largest fossil fuel resource available in the US is coal. The energy content of the current US reserve is about 5667 Q. If demand remains frozen at the current rate of consumption, the coal reserve will indeed last roughly 250 years.[2] That prediction assumes equal use of all grades of coal, from anthracite to lignite. Population growth alone reduces the calculated lifetime to some 90–120 years (see figure 4).

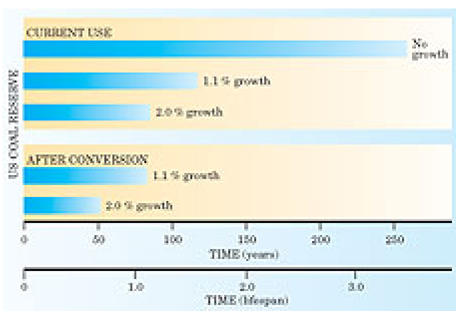

Figure 4

Any new uses of coal would further reduce the supply. The Fischer–Tropsch process has been used to convert coal to gasoline motor fuel in South Africa for decades, for example. The process requires that one carbon atom of coal be sacrificed to generate at least two hydrogen atoms, and it takes energy to decompose water to make that hydrogen. As a result, the process consumes 2 Q of coal to generate 1 Q of motor fuel. Hydrogen production would require an even greater consumption of coal. The use of coal for conversion to other fuels would quickly reduce the lifetime of the US coal base to less than a human lifespan (see figure 4).

High carbon dioxide emissions also accompany the conversion of coal to any motor fuel. For more details on how CO_2 complicates the energy problem, see the box on page 50.

- **Dilute fossil residues.** Oil shale, or bitumen, is sedimentary rock containing dilute amounts of "heavy oil" or near–solid carbonaceous residues. The US has negligible amounts of that resource. Worldwide estimates of the total energy contents are large but highly speculative.[2,7]

To harvest the dilute solid carbonaceous contents requires drastic measures: Either underground combustion, heating, steam, or air to drive the carbonaceous solids toward the surface, or the mining of huge volumes of solids using heat, solvents, and steam to extract the resource. The extracts must be further processed to yield usable hydrocarbon fuels, a process that requires further energy sacrifices. Compared to petroleum, these heavy oils present additional refining and environmental problems because of the abundance of nitrogen, oxygen, and metal compounds found in them. Also, the amount of CO_2 released during processing and use greatly exceeds that released by the current use of petroleum fuels.

- **Nuclear energy.** Uranium fission plants in the US are presently supplying less than 8% of our total energy demand. Were the current nuclear technology expanded to provide the electricity now supplied by coal (about 23 Q), the estimated US uranium resources[2] would be exhausted in about 35–58 years—less than a human lifespan.

Constraints on solar energy use

The amount of solar energy received across US latitudes is approximately 22 Q per year per 4000 km^2 (about a million acres) on average.[8] Technologies based on this resource have the potential to become major contributors to our energy supplies (see Sam Baldwin's article in Physics Today, April 2002, page 62.)

Photovoltaic solar cells convert 10–20% of incident radiation directly to electricity. Figure 5 illustrates how large a surface area of cells would be required to generate a particular amount of electricity. The yellow region indicates electricity produced directly at the cell. The blue region is a more realistic mapping and indicates the larger cell areas needed to cover the energy losses in transformers, transmission, power–equalization over time, and efficiency losses that occur for any conversion to gaseous or liquid fuels. Thus about 40–80 thousand km^2 of area—roughly 2–4 times the size of Massachusetts—could supply about 20 Q, or 20–25%, of today's US total energy requirements.

That amount and more of available land can probably be found in the US. But the size illustrates the magnitude of the technological and social impact. It is instructive to compare what fraction of other nations' total areas would be required to supply their current energy demand. The percentage ranges from as low as 0.2% for Australia to as much as 24% of the land occupied by Belgium (see the table on page 51). The data assume a 15% solar–cell efficiency, and 50% efficiency at the site of consumption.

Biomass energy production requires photosynthesis exclusively on fertile land, but it is another much discussed alternative energy. The US has about 1.6 million km^2 (400 million acres) of arable land that provides food for the current US population, with about 20% of the food left for export. The US is likely to progressively need that 20% in the next few decades as its population increases. Moreover, the current agricultural productivity depends on fossil fuels to provide the reactive nitrogen required to make fertilizer. Otherwise, about three to four times that 1.6 million km² of arable land will be needed to provide photosynthetic nitrogen fixation to generate the current food supplies.

Quite apart from fertile land requirements, the solar–to–biomass conversion efficiency is very much smaller than for the conversion of solar to electrical energy. Modern agriculture can generate about 1–1.5 million kg of biomass vegetation per square kilometer of land with about 16 000 BTU per kg, for a total of about 0.06–0.09 Q on 4000 km² of land. However, after accounting for external energy consumed through the agricultural process and the conversion of biomass to a useful fuel, the net energy production, if any, is less than 0.02 Q on 4000 km²—two orders of magnitude smaller than that of photovoltaic cell conversion. That is, biomass conversion would require some 100–fold more area of fertile land.

Wind energy is another secondary product of solar radiation. Although few studies have assessed its ultimate technological promise, researchers estimate that the technology could potentially generate a maximum of 3–22 Q of electricity in the US.[9] Energy losses due to transmission, supply, and demand fluctuation or conversion to other energies will reduce the actual contribution, but wind energy provides a significant potential resource contribution.

Hydrogen fuel from solar–cell electricity would be free of CO_2 emissions, but the "hydrogen economy" would depend on vast land areas as illustrated by the yellow band in figure 5. In addition to energy losses during conversion to hydrogen, energy losses will occur in the creation and operation of a vast new infrastructure designed to store, ship, distribute, and handle huge amounts of hydrogen at all levels, from manufacture to uses. In a recent analysis, Reuel Shinnar[10] of the City College of New York noted that the enormous effort to alter our infrastructure to create a hydrogen economy argues strongly for the direct automotive use of electricity itself, for which much of the infrastructure and potential technology are at hand.

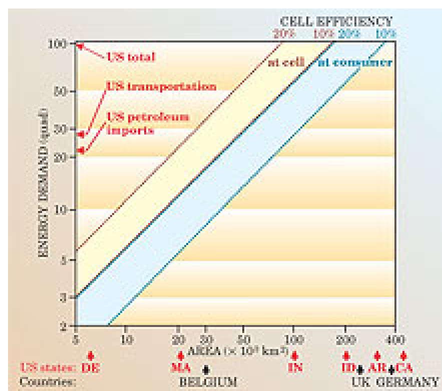

Figure 5

Energy science

Energy availability determines, drives, limits, and shapes the working capability of all processes of society.[11] The silent and plentiful gift of energy has fundamentally influenced the application of economic theory as well as the teachings of most other disciplines in the educational system.

- **Economics.** In the 1970s, Nicholas Georgescu–Roegen[12] tried to demonstrate the actual relationship between economics and thermodynamics, the basic physics of energy. He observed that most economists believe that "the economic process can go on, even grow, without being continuously fed low entropy," which in a thermodynamics context means "without receiving new energy." As we approach the limits of our easy access to energy, the defining economic currency will be dominated by availability of energy units rather than by an artificial currency, be that gold or dollars.

This change in economic theory is well illustrated by the silicon photovoltaic cells that brilliantly accomplished their mission in space flight in 1972 at an affordable economic cost. Yet, if they had to provide us with indispensable alternative energy, they would have had to operate continuously for at least 20 years just to replace the energy invested (or consumed) in their production. By 1999, photovoltaic cells were reported to produce their investment energy in about 3–7 years.[13]

That history illustrates the profound economic importance of the concept of net energy. The economic value of an alternative energy technology depends on the net rate of energy Q_{NE} it will deliver after the rate of energy production Q_{PR} is debited by the energy consumed for its operation Q_{OP} and the energy invested in its creation E during its lifetime T:

$$Q_{NE} = Q_{PR} - (Q_{OP} + E/T).$$

For example, ethanol production from biomass, which involves a complex agricultural and industrial processing system that requires large and diverse external energy inputs Q_{OP}, easily results in a negative Q_{NE}, yet government subsidies can make the production profitable to producers.

- **Education.** The educational system has become focused on how to manage, produce, distribute, and enjoy the objects, services, and pleasures that plentiful energy makes possible. That system has grown into ever more disciplines and subdisciplines that serve ever more specialized skills. Dedication to basic science—that is, to the laws of nature that allow, control, and constrain all abilities and potentials—is no longer emphasized. Basic science remains limited largely to recitation of formalisms that are gladly forgotten after examination time because little effort is made to relate their basic and universal relevance to specialties, the totality of life, and society.

More than ever since the beginning of the energy revolution, knowledge of the basic nature and limits of energy is needed to realistically determine and carry out effective policy designed to guarantee reliable energies in the future. That could well help ensure the survival of civilization. As H. G. Wells once remarked, "Human history more and more becomes a race between education and catastrophe."

A knife–edge issue

The major source of the world's energy supply, the fossil fuels, will decline in availability within several decades. It is of paramount importance that the public and policymakers recognize the ensuing shortages and the urgent need for policies that will address them. In particular, an urgent commitment to solar and nuclear energy technologies appears to be mandatory for the long term.

Solar energy technology offers the most promising capabilities for the future because photovoltaic cells can generate potentially large quantities of electricity for nations with sufficient land area. Worldwide use, though, will depend on international peace and cooperation.

Current uranium fission technologies could provide enough energy for a few decades.[14] Advanced fission technologies that involve breeder methodologies and the use of thorium, as envisioned by Edward Teller,[15] could extend that timeline to many hundreds of years. Controlled nuclear fusion remains a unique energy alternative of vast magnitude. Moreover, nuclear technologies are not dependent on location and land area. At the moment, public concern over potential risks has virtually stopped the pursuit of this energy source.

Peaceful cooperation among nations will be increasingly and vitally important for accessing and sharing our remaining resources. Human society faces no greater risk, however, than ignorance of the basic laws of nature, the role and finite magnitudes of energy sources, the arithmetic of population growth (see Albert A. Bartlett's article in this issue on page 53), and their consequences on the survival of humanity. As Shirley Ann Jackson, president of the American Association for the Advancement of Science, points out (see *APS News*, October 2003, page 8), "The public policy arena needs the voice of science itself . . . weighing in on knife–edge issues with the voice of reason."

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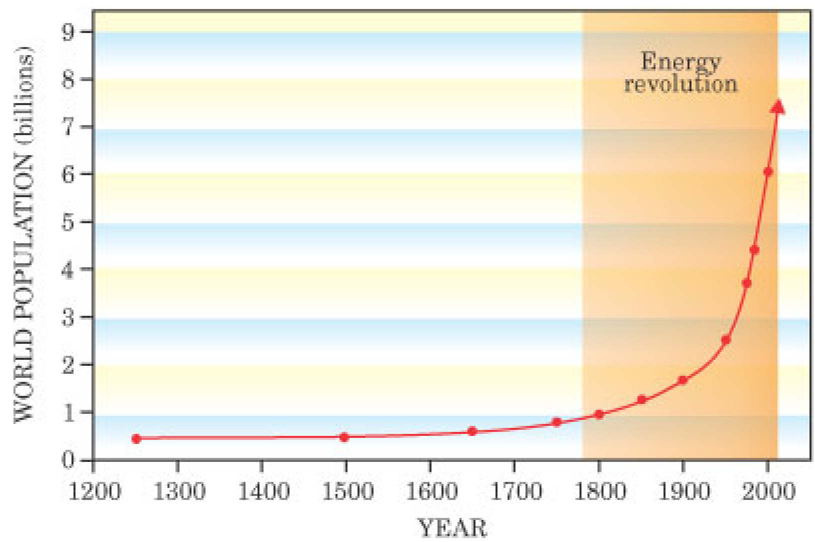

Figure 1. World population growth since the 13th century.

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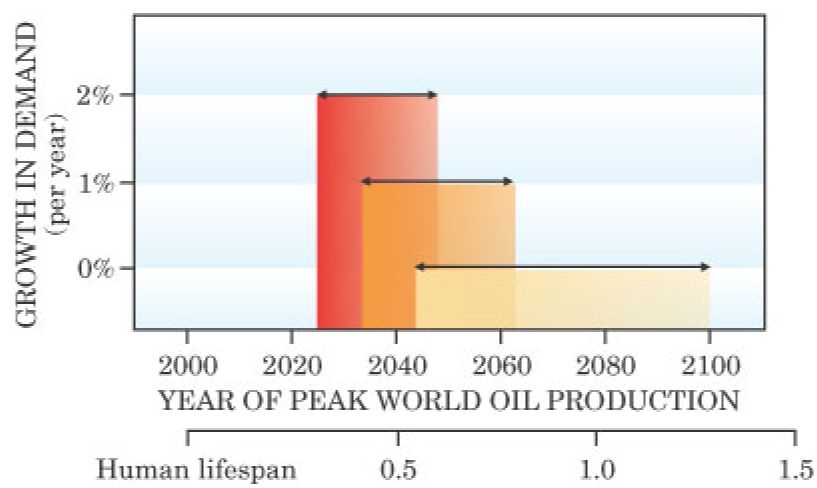

Figure 2. Predictions indicate that the peak and subsequent decline in world oil production will probably occur within the next few decades. The data here are based on optimistic estimates that place the oil reserve at 2248–3896 billion barrels. Just how soon the peak will occur depends on annual population growth rates and increases in demand. The given ranges account for uncertainty in predicting the future: For each estimate of projected growth in demand for petroleum—0, 1%, or 2%—there exists a 95% chance that the peak will occur by

the year on the left–hand end of the range and a 5% chance that it may occur as late as the year on the right–hand end. (Data from ref. 4.)

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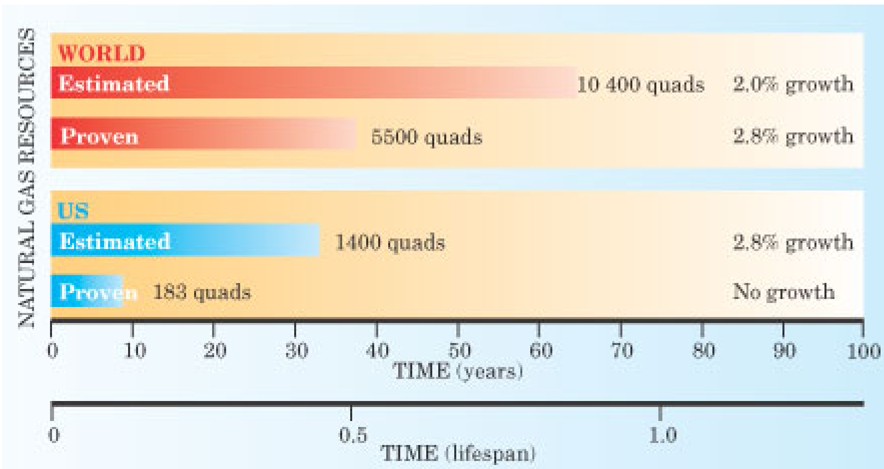

Figure 3. Outlook for world and US natural gas capacity, based on current proven gas reserves and on currently estimated resources (including unproven and nonproduceable amounts). The energy content is given to the right of each bar, the length of which indicates the amount of time that the natural gas supply is likely to last. That longevity depends on the annual growth in usage (shown on the far right) that may occur over the next few decades. (Based on data from ref. 6, and ref. 2, Energy Information Administration *International Energy Outlook 2004*.)

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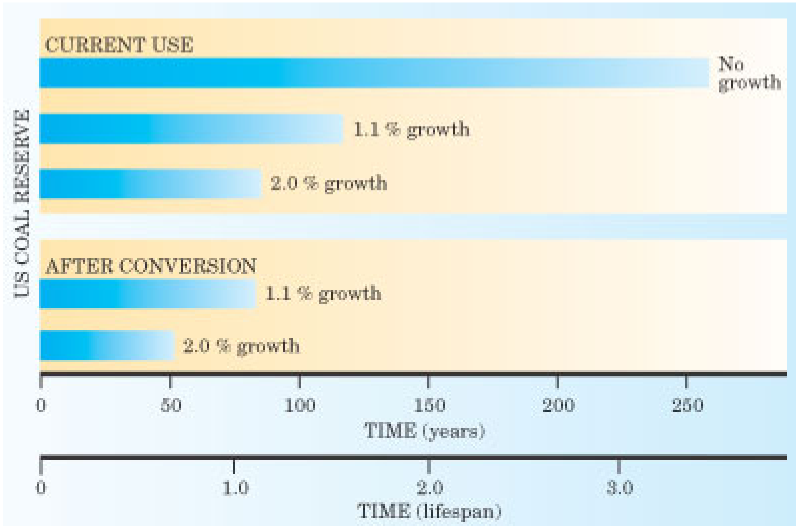

Figure 4. Outlook for the longevity of the US coal supply, based on the current consumption rate and a range of anticipated annual growth rates—up to a 2% increase in demand per year. The two lowest bars indicate the longevity of the coal supply if coal is converted to other fuels. Experts estimate that roughly 54% of the reserve underground—comprising anthracite, bituminous, subbituminous, and lignite rock—is recoverable. (Data from ref. 2, *Annual Energy Review 1999*.)

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Box1: Basic Problems Associated with Carbon Dioxide Emissions

The massive quantities of carbon dioxide currently generated during fossil fuel consumption are responsible for progressive global warming. This problem has become a matter of global concern and has led to large efforts and expenditures for research in technologies designed to sequester CO_2.[16]

Unfortunately, permanent immobilization confronts fundamental problems. Like H_2O, CO_2 is a chemically inert molecule. Its only potential reaction partners possibly available in sufficient magnitudes may be mineral oxides—for example, calcium– and magnesium–silicates. They exist in dense geological formations. However, no useful reaction rate is achievable in such locations. Their use would require mining, shipping, grinding, special activation processing,[17] and disposal of gigatons of the solids.

Most prominent research projects are directed toward massive physical storage of CO_2 by injection into those geological formations or within the deep oceans (see Jorge L. Sarmiento and Nicolas Gruber's article in Physics Today, August 2002, page 30). It is difficult to accurately predict the integrity of such physical storage over long periods[16] because many variables in complex environments are involved. Attempts to manipulate marine or terrestrial ecosystems and increase the amounts of CO_2 these sinks naturally hold are fraught with great complexities that involve multiple and interactive processes.[18]

Any conversion of a carbonaceous fossil fuel to a fuel of lower carbon content—including the conversion all the way to hydrogen—will eject the excess carbon as CO_2. The problem of its emission to the atmosphere is simply transferred from the points of consumption to the location where the conversion process takes place. Therefore, the CO_2 problem is not eliminated by a "hydrogen economy" if the hydrogen is created by the conversion of coal, petroleum, or natural gas.

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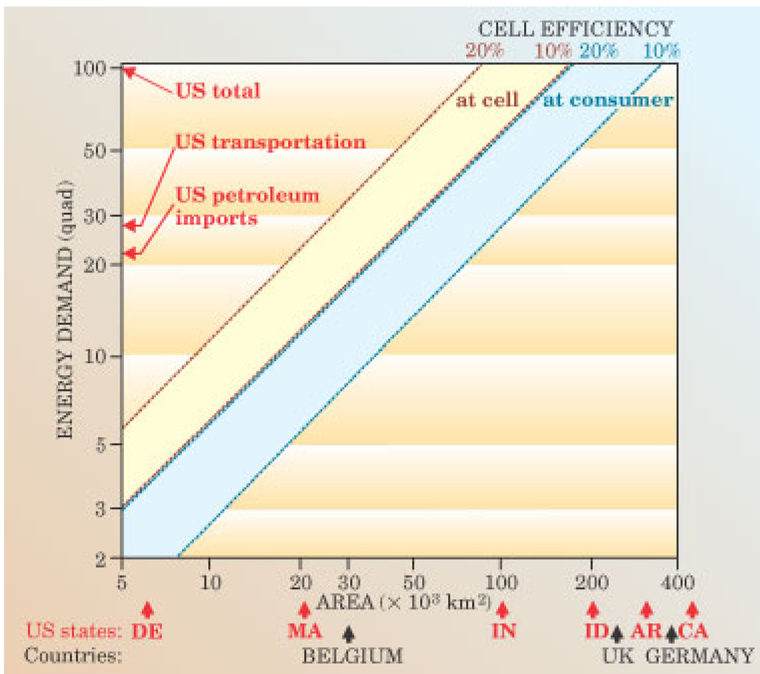

Figure 5. Photovoltaic cell areas required to generate electrical energy that could supply a sizable fraction of the US economy. The yellow area plots the electrical energy produced at the solar cell surface for efficiencies between 10 and 20%. The blue area plots the energy at the consumer side and accounts for losses in transmission, storage, and so forth, in addition to efficiency losses. Some US states (Delaware, Massachusetts, Indiana, Idaho, Arkansas, and California) and world nations provide the scale of the enormous land areas that would be required.

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Solar Cell Area Requirements to Meet Energy Demand in Select Countries

	Energy consumed per year*		Land area	Approximate solar cell area needed	
	Quads per 10^6 people	Total quads	10^3 km^2	10^3 km^2	% of land
US	0.36	100	9 591	263	2.7
Belgium	0.27	2.7	30	7	24.0
Australia	0.19	4.8	7 580	13	0.2
Russia	0.17	26	16 981	69	0.4
Japan	0.17	21.8	372	58	15.4
Germany	0.17	14	356	37	10.3
UK	0.17	10	243	26	10.8
France	0.17	10	546	26	5.0
Brazil	0.05	8.6	8 466	23	0.3
China	0.03	32	9 377	84	0.9
Egypt	0.03	2.0	996	5	0.5

*Data from Department of Energy/Energy Information Administration *International Energy Annual 1999*.

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