NPG NEGATIVE POPULATION GROWTH

THE NPG FORUM

# Balancing Humans in the Biosphere:

## Escaping the Overpopulation Trap

**by Robert Costanza**

*This is the eighth in a series of NPG FORUM papers exploring the idea of optimum population—what would be a desirable population size for the United States? Without any consensus even as to whether the population should be larger or smaller, the country presently creates its demographic future by inadvertence as it makes decisions on other issues that influence population change.*

*The approach we have adopted is the "foresight" process. We have asked specialists in various fields to examine the connection between alternative population futures and national or social objectives in their fields of interest. In this issue of the FORUM, Dr. Costanza looks at the "population trap" and suggests approaches to bring population into balance with the ecosystems that support us.*

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*— Lindsey Grant, Editor.*

Cultural evolution has allowed humans to change their behaviors and adapt to new conditions much faster than biological evolution. It has also removed the inherently long run bias of biological evolution and made us susceptible to several social traps. The most critical of these is the overpopulation trap, caused by the imbalance between the short term incentives to have children and the long term social and ecological costs of having too many. But the severe and very real uncertainty about the long run costs of too many humans has hindered debate and action on this issue. We cannot wait for the uncertainty to be resolved, because by then it will be too late. What we must do is deal with the uncertainty in a more appropriate way. We should tentatively assume the worst and then allow ourselves to be pleasantly surprised if we are wrong, rather than assuming the best and facing disaster if we are wrong. A crude worst case estimate of optimal US population based solely on renewable resources and current consumption levels yields about 85 million people. An average resource consumption level of one half current levels combined with a more equitable distribution of resources would yield a high quality lifestyle for 170 million.

Human beings, like all other animals, make decisions based on responses to local, immediate reinforcements. They follow their noses, with some mediation by *genetic* (and in the case of humans and some other species *cultural*) programming. To understand the human population problem, one needs to understand how this complex of local reinforcements and programmed responses interact over several different time scales with the ecosystem within which humans are embedded.

Biological evolution has a built-in bias towards the long run. Changing the genetic structure of a species requires that characteristics (phenotypes) be selected and accumulated by differential reproductive success. Characteristics learned or acquired during the lifetime of an individual cannot be passed on genetically. Biological evolution is therefore an inherently slow process requiring many many generations to significantly alter a species' physical characteristics or behavior.

Cultural evolution is much faster, and in recent years it has accelerated to hyperspeed. Learned behaviors that are successful can be almost immediately spread to other members of the culture and passed on in the oral, written, or video record. The increased speed of adaptation that this process allows has been largely responsible for *homo sapiens'* amazing success at controlling the resources of the planet[1]. But there is a significant downside. Like a car that has picked up speed, we are in much more danger of running off the road or over a cliff. We have lost the built-in long-run bias of biological evolution and are susceptible to being led by our hyper-efficient short run adaptability over a cliff into the abyss.

## The Overpopulation Trap

This process of short-run incentives getting out of sync with long-term goals has been well studied in the last decade under several rubrics[2], but the one I like best is John Platt's notion of 'social traps'[3]. In all such cases the decision-maker may be said to be 'trapped' by the local conditions into making what turns out to be a bad decision viewed from a longer or wider perspective. We go through life making decisions about which path to take based largely on 'road signs,' the short-run, local reinforcements that we perceive most directly. These short-run reinforcements can include monetary incentives, social acceptance or admonishment, and physical pleasure or pain. In general, this strategy of following the road signs is quite effective, unless the road signs are inaccurate or misleading. In these cases we can be trapped into following a path that is ultimately detrimental because of our reliance on the road signs. For example, cigarette smoking has been a social trap because by following the short-run road signs of the pleasure and social status[4] associated with smoking, we embark on the road to an increased risk of earlier death from smoking-induced cancer. More important, once this road has been taken it is very difficult to change to another (as most people who have tried to quite smoking can attest).

The problem of overpopulation is a classic social trap, as has been pointed out by Garrett Hardin, Paul Ehrlich and many others[5]. The biological and cultural incentives to procreate that are incumbent on individuals in the short run, combined with rapid reductions in mortality that have changed the long run ecological cost structure, have led us into the jaws of this most serious of traps. Cultural evolution has so far changed only the short-run half of the equation (lower mortality) and has put us on the path to unsustainable population growth. It is time for cultural evolution to change the other half of the equation to bring us back into balance.

## Short-Term Benefits and Long-Term Costs of Human Population Growth

What are the major costs and benefits of human population growth? We can divide them into three broad groups, individual, cultural, and ecological.

Individuals make decisions about family size, so ultimately it is the costs and benefits individuals *perceive* that will make a difference. Culture's role is to translate long term ecological costs and benefits into individual behavior. The major benefits to parents of additional children are as (1) workers; (2) care givers in old age; and (3) genetic carriers. The major costs are rearing to a productive, independent age. In most of the world the benefits of children as workers and care givers are still significant, and the costs to raise children to a productive age are low, since levels of education are low and children can start working productively at a very early age. In many countries children begin to 'pay for themselves' by age 10 or so. In the US and other 'developed' countries the situation is quite different. Children have little or no direct benefit to parents as workers and the prevalence of social security systems means they are not absolutely necessary as care givers in old age (although they are still desirable in this role). Meanwhile their costs to raise to 'productive age' are enormous. In highly industrialized countries 'productive age' means after at least 4 years of college and the costs to the parents are daunting. It is little wonder that family sizes in industrialized countries have fallen so dramatically.

But it is the long term ecological costs of more humans that are now becoming critically important. These long term costs are caused by our speeded up cultural evolution and must ultimately be solved by the next wave of cultural evolution.

Cultural evolution also has an interesting effect on human impacts on the environment. By changing the learned behavior of humans and incorporating tools and artifacts, it allows individual human resource requirements and their impacts on their resident ecosystems to vary over several orders of magnitude. Thus it does not make sense to talk about the 'carrying capacity' of humans in the the same way as the 'carrying capacity' of other species since, in terms of their carrying capacity, humans are many subspecies. Each subspecies would have to be culturally defined to determine levels of resource use and carrying capacity. For example, the global carrying capacity for *homo americanus* would be much lower than the carrying capacity for *homo indus*, because each American consumes much more than each Indian does. And the speed of cultural adaptation makes thinking of species (which are inherently slow changing) misleading anyway. *Homo americanus* could change its resource consumption patterns drastically in only a few years, while *homo sapiens* remains relatively unchanged. I think it best to follow the lead of Herman Daly[6] in this and speak of the product of population and per capita resource use as the *total impact* of the human population. It is this total impact that the earth has a capacity to carry, and it is up to us to decide how to divide it between numbers of people and per capita resource use. This complicates population policy enormously, since one cannot simply state an optimal *population*, but rather must state an optimal number of *impact units*. How many impact units the earth can sustain and how to distribute these impact units over the population is a very dicey problem indeed, but one that must also be included in our next round of cultural evolution.

## The Importance of Uncertainty and How to Deal With It

One key element that has frustrated population policy is the enormous degree of uncertainty about long term human impacts on the biosphere. The argument can be summarized as differing opinions about the degree to which technological progress can eliminate resource constraints. Current economic world views (capitalist, socialist, and the various mixtures) are all based on the underlying assumption of continuing and unlimited economic growth. This assumption allows a whole host of very sticky problems, including population growth, equity, and sustainability to be ignored (or at least postponed), since they are seen to be most easily solved by additional economic growth. Indeed, most conventional economists define 'health' in an economy as a stable and high *rate of growth*. Energy and resource limits to growth, according to these world views, will be eliminated as they arise by clever development and deployment of new technology. This line of thinking is often called 'technological optimism.'

An opposing line of thought (often called 'technological pessimism') assumes that technology will *not* be able to circumvent fundamental energy and resource constraints and that eventually economic growth will stop. It has usually been ecologists or other life scientists that take this point of view[7] largely because they study natural systems that *invariably do* stop growing when they reach fundamental resource constraints. A healthy ecosystem is one that maintains a stable level. Unlimited growth is cancerous, not healthy, under this view.

The technological optimists argue that human systems are fundamentally different from other natural systems because of human intelligence. History has shown that resource constraints can be circumvented by new ideas. Technological optimists claim that Malthus' dire predictions about population pressures have not come to pass and the 'energy crisis' of the late 70's is behind us.

The technological pessimists argue that many natural systems also have 'intelligence' in that they can evolve new behaviors and organisms (including humans themselves). Humans are therefore a part of nature, not apart from it. Just because we have circumvented local and artificial resource constraints in the past does not mean we can circumvent the fundamental ones that we will eventually face. Malthus' predictions have not come to pass *yet* for the entire world, the pessimists would argue, but many parts of the world are in a Malthusian trap now, and other parts may well fall into it.

This debate has gone on for several decades now. It began with Barnett and Morse's 'Scarcity and growth' and really got into high gear with the publication of 'The limits to growth' by Meadows et al.[8] and the Arab oil embargo in 1973. There have been thousands of studies over the last 15 years on various aspects of our energy and resource future and different points of view have waxed and waned. But the bottom line is that there is still an enormous amount of uncertainty about the impacts of energy and resource constraints, and I doubt that the argument will ever be decided on scientific grounds.

In the next 20-30 years we may begin to hit *real* fossil fuel supply limits as well as constraints on production due to global warming. Will fusion energy or solar energy or conservation or some as yet unthought of energy source step in to save the day and keep economies growing? The technological optimists say yes and the technological pessimists say no. Ultimately, no one knows. Both sides argue as if they were certain, but the worst form of ignorance is misplaced certainty.

The optimists argue that unless we *believe* that the optimistic future is possible and behave accordingly it will never come to pass. The pessimists argue that the optimists will bring on the inevitable leveling and decline sooner by consuming resources faster and that to sustain our system we should begin to conserve resources immediately. How do we proceed in the face of this overwhelming uncertainty?

We can cast this optimist/pessimist choice in a classic (and admittedly oversimplified) game theoretic format using the 'payoff matrix' shown in figure 1. Here the alternative policies that we can pursue today (technologically optimistic or pessimistic) are listed on the left and the real states of the world are listed on the top. The intersections are labeled with the results of the combinations of policies and states of the world. For example, if we pursue the optimistic policy and the world really does turn out to conform to the optimistic assumptions then the payoffs would be high. This high potential payoff is very tempting and this strategy has paid off in the past. It is not surprising that so many would like to believe that the world conforms to the optimist's assumptions. If, however, we pursue the optimistic policy and the world turns out to conform more closely to the pessisimistic technological assumptions then the result would be 'Disaster'. The disaster would come because irreversible damage to ecosystems would have occured and technological fixes would no longer be possible.

If we pursue the pessimistic policy and the optimists are right then the results are only 'Moderate.' But if the pessimists are right and we have pursued the pessimistic policy then the results are 'Tolerable'.

| Current Policy | Real State of the World: Optimists Right | Real State of the World: Pessimists Right |
|---|---|---|
| Technological Optimist Policy | **High** | **Disaster** |
| Technological Pessimist Policy | **Moderate** | **Tolerable** |

**Figure 1.**
**Payoff matrix for technological optimism vs. pessimism**

Within the framework of game theory, this simplified game has a fairly simple 'optimal' strategy. If we *really* do not know the state of the world then we should choose the policy that is the maximum of the minimum outcomes (i.e. the MaxiMin strategy in game theory jargon). In other words, we analyze each policy in turn, look for the worst thing (minimum) that could happen if we pursue that policy, and pick the policy with the largest (maximum) minimum. In the case stated above we should pursue the pessimist policy because the worst possible result under that policy ('Tolerable') is a preferable outcome to the worst outcome under the optimist policy ('Disaster').

Given this analysis, what can one recommend for population policy? Because of the large uncertainty about the long term impacts of population growth on ecological sustainability, we should *at least provisionally assume the worst*. We must *assume* that the dire predictions of the Ehrlichs and Pimentels[9] are correct and plan accordingly. If they are right we will still survive. If they are wrong we will be pleasantly surprised. This is a much different scenario than the consequences of provisionally assuming the best about the impacts of population growth, as Julian Simon[10] would have us do. If we assume Simon is right and he is not, we will have irreversibly degraded the planet's capacity to support life. We cannot rationally take that risk.

## Escaping the Overpopulation Trap

How then do we communicate this conclusion to the people who make the decisions - the potential parents - and escape the overpopulation trap? The elimination of social traps requires intervention - the modification of the reinforcement system. Indeed, it can be argued that the proper role of a democratic government is to eliminate social traps (no more and no less) while maintaining as much individual freedom as possible. Cross and Guyer list four broad methods by which traps can be avoided or escaped from. These are education (about the long-term, distributed impacts); insurance; superordinate authority (i.e., legal systems, government, religion); and converting the trap to a trade-off , i.e. correcting the road signs.

Education can be used to warn people of long-term impacts that cannot be seen from the road. Examples are the warning labels now required on cigarette packages and the warnings of environmentalists about future hazardous waste problems. People can ignore warnings, however, particularly if the path seems otherwise enticing. For example, warning labels on cigarette packages have had little effect on the number of smokers.

The main problem with education as a general method of avoiding and escaping from traps is that it requires a significant time commitment on the part of individuals to learn the details of each situation. Our current society is so large and complex that we cannot expect even professionals, much less the general public, to know the details of all the extant traps. In addition, for education to be effective in avoiding traps involving many individuals, *all* the participants must be educated.

Governments can, of course, forbid or regulate certain actions that have been deemed socially inappropriate. The problem with this approach is that it must be rigidly monitored and enforced, and the strong short-term incentive for individuals to try to ignore or avoid the regulations remains. A police force and legal system are very expensive to maintain, and increasing their chances of catching violators increases their costs exponentially (both the costs of maintaining a larger, better-equipped force and the cost of the loss of individual privacy and freedom).

Religion and social customs can be seen as much less expensive ways to avoid certain social traps. If a moral code of action and belief in an ultimate payment for transgressions can be deeply instilled in a person, the probability of that person's falling into the 'sins' (traps) covered by the code will be greatly reduced, and with very little enforcement cost. On the other hand, the problems with religion and social customs as means to avoid social traps are: the moral code must be relatively static to allow beliefs learned early in life to remain in force later, and it requires a relatively homogeneous community of like-minded individuals to be truly effective. This system works well in culturally homogeneous societies that are changing very slowly. In modern, heterogeneous, rapidly changing societies, religion and social customs cannot handle all the newly evolving situations, nor the conflict between radically different cultures and belief systems.

Many trap theorists believe that the most effective method for avoiding and escaping from social traps is to turn the trap into a trade-off. This method does not run counter to our normal tendency to follow the road signs; it merely corrects the signs' inaccuracies by adding compensatory positive or negative reinforcements. A simple example illustrates how effective this method can be. Playing slot machines is a social trap because the long-term costs and benefits are inconsistent with the short-term costs and benefits. People play the machines because they expect a large short-term jackpot, while the machines are in fact programmed to pay off, say, $0.80 on the dollar in the long term. People may 'win' hundreds of dollars playing the slots (in the short run), but if they play long enough they will certainly lose $0.20 for every dollar played. To change this trap to a trade-off, one could simply reprogram the machines so that every time a dollar was put in $0.80 would come out. This way the short-term reinforcements ($0.80 on the dollar) are made consistent with the long-term reinforcements ($0.80 on the dollar), and only the dedicated aficionados of spinning wheels with fruit painted on them would continue to play.

## Balancing the Human Species in the Ecosystem

Balancing the human species in the ecosystem is therefore *in principle* a simple problem. Simply make the long-run, distributed, whole-system, *worst case* costs and benefits of human population growth (and all other human activities) incumbent on all individuals in the short-run and locally, at least provisionally until the worst case impacts can be lowered. If your next child will be a net cost to the planet of $x$, you should be required to pay $x$ , up front, for the right to have it, at least until it can be proven to have a lower impact. In a sense, this is an extension of the 'polluter pays principle' to the polluter pays (at least provisionally) for uncertainty too. If and only if this whole system cost accounting (including uncertainty) is in place can we expect individual decisions about population growth to have any meaning for the planet as a whole.

Of course, *in principle* is very far from *in practice* in this particular case. The problems of devising cultural mechanisms to effectively communicate that cost to the individual parents are daunting. But no one said it was going to be easy. The next stage of our cultural evolution has got to be the development of just this capacity to put back in the long run constraints that the initial phase of cultural evolution appeared to release us from. We need to develop and use cultural 'road maps' and 'scouts' to counter our dependence on 'road signs' in the tricky terrain we now find ourselves. I offer the following summary suggestions, and challenge the anthropologists and sociologists to put their research to practical use in devising cultural mechanisms to implement them.

1. Establish a *hierarchy* of goals for national and global ecological economic planning and management. Sustainability should be the primary long term goal, replacing the current GNP growth mania. Issues of justice, equity, and population are ultimately tied in with sustainability as preconditions. Only sustainable levels of human population are desirable. Economic growth in this hierarchy is a valid goal only when it is consistent with sustainability. The goals can be put into operation by having them accepted as part of the political debate, and implemented in the decision making structure of institutions that affect the global economy and ecology (like the World Bank).
2. Develop *better global ecological economic* modeling capabilities to allow us to see the range of possible outcomes of our current activities, especially the interrelated impacts of population, per capita resource use, and wealth distribution.
3. Adjust current incentives to reflect long run, global costs, *including uncertainty*. To paraphrase the popular slogan, we should: model globally, adjust local incentives accordingly. In addition to traditional education, regulation, and user fee approaches, a flexible assurance bonding system has been proposed to deal specifically with uncertainty[11]. Curbing population growth requires that long term worst case ecological costs be made apparent to potential parents in a culturally acceptable way.
4. Allow no further decline in the stock of *natural capital* by taxing natural capital consumption. This policy will encourage the technological innovation that optimists are counting on while conserving resources in case the optimists are wrong. Revenues can be used to mitigate problems (like counteracting the economic forces for unwise population growth) and easing up on income taxes especially for the lower end of the income scale.

## Optimal US Population Under Prudently Pessimistic Assumptions

Given all this, what can be said about the 'optimal' size of the US (or any other country's) population? Obviously, it depends on the level of per capita resource consumption, the ability of technology to overcome resource constraints, and the long term impacts of humans on the biosphere. These last two involve enormous uncertainties. But I have argued that in the face of this uncertainty we should be prudent until it can be proven otherwise. We should assume the worst. Then if cold fusion or some other technology comes in to save the day we can be pleasantly surprised. But we should not *bank on* cold fusion, hot fusion, or anything else since the costs of being wrong are disaster. 'Don't count your solutions before they hatch' applies to fusion technology, population policy, and all other uncertain endeavors.

So if we make some prudently pessimistic assumptions where do we end up? First we should assume that technology will be no more effective at removing resource constraints than it is now, and that per capita resource consumption will remain at current levels. Actually for a true 'worst case' analysis we could assume consumption per capita would continue to rise, but we'll leave a little optimism in the assumptions. Assuming the worst as regards the long term impacts of humans on the biosphere leads us to conclude there are already far too many humans. Many authors have documented the potential adverse impacts of our current population on soil erosion, forest depletion, water and air pollution, and a host of other impacts. How many people could we sustain at current technology and consumption patterns if the worst of these impacts were true and unremediated? Certainly no more than we now have, but how many less?

I fall back on a rough energy calculation. In the worst case we must stop burning fossil fuels, both because we are running out and because the greenhouse effect is causing adverse climate changes. Assume also that in the worst case nuclear energy is too unsafe to use. So the question comes down to how many people could we sustain at current technology and consumption patterns on renewable energy alone. This level is also consistent with the earlier recommendation to maintain the stock of natural capital at current levels to insure sustainability. Remember that the worst case means no significant improvements in energy efficiency as some technological optimists are predicting, but to balance this I will allow that all the renewable energy currently incumbent on the US can ultimately be used.

The fossil and nuclear energy consumption in the US in 1986 was $74 \times 10^{15}$ BTU. The US population in 1986 was about 240 million. This gives an annual per capita fossil and nuclear energy consumption of about 300 million BTU per capita per year, which I'll use to represent total current resource use[12]. The total solar energy captured by the US environment (including nearshore waters) is about $100 \times 10^{18}$ BTU per year[13]. But solar energy is much more dispersed and lower quality than fossil fuel. It has been estimated to take about 2000 BTU of solar energy to do the equivalent amount of *useful* work as 1 BTU of fossil fuel[14]. So the solar energy captured is equivalent to about $5 \times 10^{16}$ BTU of fossil fuel. Assume that no more than half of this is available to drive human society directly, with the rest necessary for the ecological life support system. Dividing this remainder of $2.5 \times 10^{16}$ BTU by the $3 \times 10^{8}$ BTU/person/yr energy needs of current US citizens yields about 85 million people, or about 35% of the current population. But current US per capita resource consumption is arguably more than what is required for a high quality lifestyle, and is not distributed very equitably over the population. Let us assume that with a more equitable distribution and a more 'European' level of consumption per capita we could support about twice the above estimate or 170 million at a high quality lifestyle on renewable energy alone. This is admittedly a very rough calculation, and it is not the most pessimistic one possible. But I think its a good general benchmark. 170 million people might be supportable on a sustainable basis at something approaching our current quality of life, but 240 million probably cannot unless some major technical breakthroughs happen or we all reduce our standard of living significantly. Prudence requires that we target 170 million or less until the technical breakthroughs happen (if they happen). Otherwise our standard of living may go down to disastrous levels due to ecological deterioration from which we could never recover.

**FOOTNOTES:**

[1] Vitusek, P., P. R. Ehrlich A. H. Ehrlich, and P. A. Matson. 1986. Human appropriation of the products of photosynthesis. *BioScience* 36:368-373. They estimate that humans now directly control from 25 to 40 percent of the total primary production of the planet's biosphere. Human activity is also beginning to have an effect on global climate and the planet's protective ozone shield.

[2] Including, but not limited to, the 'tragedy of the commons' (cf. Hardin, G. 1968. "The Tragedy of the Commons." *Science*. 162:1243-1248), and the 'prisoner's dilemma' (cf. Axelrod, R. 1984. *The Evolution of Cooperation*. Basic Books, New York.)

[3] Platt, J. 1973. "Social traps." *American Psychologist*. 28:642-651.;
Cross, J. G., and M. J. Guyer. 1980. *Social Traps*. (University of Michigan Press, Ann Arbor); Teger, A. I. 1980. *Too Much Invested to Quit*. (Pergamon, New York); Brockner, J. and J. Z. Rubin. 1985. *Entrapment in Escalating Conflicts: A Social Psychological Analysis*. (Springer-Verlag, New York. 275 pp.); Costanza, R. 1987. "Social Traps and Environmental Policy." *BioScience*. 37:407-412.

[4] This particular positive reinforcement has in the last few years begun to turn into a negative one. As smoking becomes less socially acceptable we should expect the number of new smokers to fall and many old smokers to escape the trap. But the process of escape is much more difficult than the process of avoidance.

[5] Hardin, G. 1986. "Cultural Carrying Capacity: a Biological Approach". *BioScience* 36:599-606. Ehrlich, P. R. and J. P. Holdren. 1971. "The Impact of Population Growth." *Science* 171:1212-1217. Ehrlich, P. R. and A. H. Ehrlich. 1990. *The Population Explosion*. (Simon and Schuster, New York. 320 pp.)

[6] Daly, H. E. 1977. *Steady State Economics*. (W. H. Freeman, San Francisco. 185 pp.)

[7] Notable examples are Paul Ehrlich and Garrett Hardin. Herman Daly is a rare economist who shares this view.

[8] Barnett, H. J. and C. Morse. 1963. *Scarcity and Growth: The Economics of Natural Resource Availability*. (Johns Hopkins, Baltimore.) Meadows, D. H., D. L. Meadows, J. Randers, and W. W. Behrens. 1972. *The Limits to Growth*. (Universe, New York.)

[9] Pimentel, D. and M. Pimentel. 1990. "Land, Energy and Water: The Constraints Governing Ideal U. S. Population Size." The NPG FORUM.

[10] Simon, J. L. and H. Kahn (eds). 1984. *The Resourceful Earth: A Response to Global 2000*. (Basil Blackwell, New York.) 585 pp.

[11] Costanza, R. and C. H. Perrings. 1990. "A Flexible Assurance Bonding System for Improved Environmental Management." *Ecological Economics*. 2:57-76.

[12] Although this is still an underestimate because we are currently using at least 5% renewable fuels in the form of wood and hydropower, and solar energy runs the ecosystems that provide life support functions.

[13] Costanza, R. 1980. "Embodied Energy and Economic Valuation." *Science*. 210:1219-1224.

[14] All BTU's (British Thermal Units) are equal in their ability to raise the temperature of water. A BTU is defined as the amount of heat energy required to raise one pound of water one degree Farenheit. A BTU is equal to .252 kcal, 1054 J, or 0.0002929 kWh. But in terms of ability to do useful work, the concentration or quality of the energy is important. Because sunlight is very dispersed relative to fossil fuel, it takes about 2000 BTU of sunlight to grow enough trees to produce as much electricity as 1 BTU of oil (Odum, H. T. and E. C. Odum. 1976. *Energy Basis for Man and Nature*. McGraw Hill, New York. 296 pp.)


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