The Energy Impacts of Solar Heating

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The attractions of solar energy are obvious: it is nondepletable, provides immunity to embargoes and fuel price increases, and is generally less damaging to the environment than conventional sources (1). Further, specific solar technologies (for example, water and space heating) have achieved or are approaching costs that are competitive with conventional sources in many regions of the country (2).

The purpose of this article is to examine the impact of a rapid implementation of active solar space heating and water heating on the U.S. energy supply. The findings are considerably different from those of the recent Domestic Policy Review of Solar Energy (DPR) (1), a multiagency analysis of the possible range of implementation of solar energy during the balance of the century. The difference is due to the fact that in calculating solar heating contributions, I include the energy required for construction of the solar facilities. When these energy inputs are considered, the energy saved by a rapidly expanding solar heating system becomes significantly less than if calculated without considering these factors. Offsetting this result is the very favorable effect of solar heating on the specific mix of fuels.

If solar heating is rapidly adopted, it will displace premium heating fuels (oil and gas). This conversion to solar heating will shift load from the residential and commercial sectors, in which the solar equipment will be used, to the industrial sector, and particularly to the steel and aluminum industries. Because this industrial demand is largely met with indigenous fuels—coal in the case of the steel industry, and coal, nuclear, and hydroelectrically produced electricity in the case of the aluminum industry—the effect of solar heating is both to substitute for depletable fuels and to cause a shift to domestic fuels. During the rest of the century, this shift may be more important than the net energy produced in helping the United States meet energy demand and reduce imports.

Summary. The energy required to build and install solar space- and water-heating equipment is compared to the energy it saves under two solar growth paths corresponding to high and low rates of implementation projected by the Domestic Policy Review of Solar Energy. For the rapid growth case, the cumulative energy invested to the year 2000 is calculated to be 1/2 to 1 1/2 times the amount saved. An impact of rapid solar heating implementation is to shift energy demand from premium heating fuels (natural gas and oil) to coal and nuclear power use in the industries that provide materials for solar equipment.

In discussing the impacts of solar heating I first consider the general case of net energy analysis for an expanding supply system. Second, I review several estimates of the energy requirements of solar heating equipment and adapt them to the needs of this study. Third, I select two solar heating integration paths to represent low and high growth rate scenarios. The paths chosen were selected to represent, as far as possible, an exponential fit to high and low cases in the DPR. I then combine these results to estimate the net contribution of solar space and water heating (as contrasted with the more prevalent gross energy projections), and discuss the projected impact of solar energy implementation on fuel mix.

The Dynamics of Net Energy

It is possible for an expanding energy system to act as a substantial energy drain, because the consumption of energy for the creation of new production facilities for the system can exceed the system's own energy production. The factors that increase the magnitude and duration of this drain are rapid growth rates of the energy systems, long times for single production units to achieve an energy payback, and long construction times. The interrelation between these system characteristics and their influence on net energy system outputs has been independently analyzed a number of times (3, 4). Further applications, usually to nuclear power systems, can be found for specific integration paths (5).

For solar heating technologies the net energy dynamics can be important because, relative to conventional energy sources, solar energy collectors and converters substitute an initial capital investment (frequently of energy-intensive materials) for a lifetime of fuel consumption. As such, the energy costs of solar facilities are front-end costs. As a contrast, the energy needed to provide coal and equipment for a coal-fired system is more evenly distributed over the operating life of the plant (6). An additional reason for examining the net energy dynamics of solar energy is the rapid rate of growth of solar energy use proposed for the remainder of the century.

As an illustration of the relative importance of net energy in a dynamic sense, the payback time (at which cumulative energy investments and outputs are equal) for a system expanding linearly in time is exactly twice the payback time for a single unit. For exponential growth paths, the system payback time is an increasing function of both the growth rate and single unit payback time.

For the analysis in this case, a number of simplifying assumptions have been made:

1) The time between solar heating equipment manufacture and operation is assumed to be zero. If this is not so, for example, because of slow inventory turnover in the industry, then this analysis overestimates the net energy output.

2) The energy requirements of the facilities required for solar equipment manufacture, or for associated industries, are not considered in either a static or dynamic sense, except to the extent that this energy has been amortized in the estimates of materials energy content. For example, if rapid expansion of glass manufacturing capacity accompanies the growth of solar collectors, the use of historically "average" energy intensity for glass will neglect the dynamics of its expanding system. Similarly,

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the dynamic effects that would occur in our energy system in lieu of solar heating use are not considered.

3) I did not consider the energy requirements for maintenance, repair, or replacement of solar heating equipment.

4) No attempt has been made to project reductions in the energy intensity of solar equipment. To the extent that the equipment cost correlates with its energy content, projections of falling prices for solar equipment implicitly suggest that the energy payback times will drop. However, if the anticipated price reductions are due in large part to expected reductions in installation and assembly cost, they will have little effect on the energy intensity of the equipment.

5) No projection has been made of the effects of conservation in the aluminum, steel, glass, or other industries on the energy intensiveness of the materials used by solar equipment manufacturers.

6) Alternatives to active solar energy production for reducing fuel consumption for heating (for example, passive solar, insulation) are not considered, either individually or in combination with active solar energy production.

Energy Inputs to Solar Heaters

Recent studies of the energy required to manufacture and install solar heating equipment reflect the lack of agreement concerning methods of energy accounting. For example, Baron (*7*) calculates energy payback time on the basis of the ratio of the fossil fuel equivalent energy used for manufacturing, transporting, installing, and operating (for 20 years) the solar device to the amount of energy that would be consumed annually if fossil fuels provided the same services. He also calculates payback based on the thermal value of the output alone. Other authors such as Payne and Doyle (*8*), and Lenchek (*9*) calculate payback times on the basis of the thermal contributions of the solar collectors; this neglects the inevitable losses associated with conventional heating and, according to Baron's method, overstates payback times by 60 percent. However, Baron treats the operation energy consumed over the lifetime of the device as part of the construction energy requirement; this approach is not suitable for a dynamic analysis because operation energy loads do not accrue before the system begins operation.

In addition to their analysis of three commercially available solar heating systems and review of several estimates of solar heating payback, Payne and Doyle discuss methods for reducing the energy requirement of the systems. Lenchek's calculation refers to an integrated solar space heating, water heating, and cooling system at Colorado State University; the analysis is separated into payback calculations for the system with and without cooling, and is followed by a description of modifications to provide a less energy-intensive design.

Despite different assumptions and methods, these three studies are generally in good agreement. For example, all find that the collector energy investment represents about 40 percent of the total energy required to produce the system. As shown in Table 1, the estimates of system payback time, when expressed as the ratio of the fossil fuel inputs to annual fossil fuel savings, range from about 3 to 9 years. The fossil fuel basis for calculation of payback times was selected because it is assumed that energy contributions from solar heating will ultimately be traceable to savings in fossil fuel consumption. This approach of rating solar output by fuel displacement was used in the DPR, so these payback estimates are compatible with the DPR growth projections. The payback period for solar water heating was estimated by Payne and Doyle to be roughly half that of space heating because of its year-round use. For solar heating in the South, their payback time estimate was further reduced, from 10.4 years to about 3 years (expressed on a thermal basis).

Table 1. Estimates of solar heating payback.

Reference	Estimated payback time (years)	Modified estimate (years)*
Baron (*7*)		
Washington, D.C.	7	5.2
Boston	11	8.4
Phoenix	5	3.8
Charleston	8	6.0
Payne and Doyle (*8*)	10.4	6.5
Lenchek (*9*)†		
Without cooling	7	4.4
With cooling	5.4	3.4

*Baron's results were modified to treat operation energy as a load against system output, rather than as a front-end energy investment. Estimates by Payne and Doyle (*8*) and Lenchek (*9*) were divided by 1.6 in accordance with Baron's estimate that 1.6 units of fossil fuel energy are required to provide 1 unit of heat. †Includes both space and water heating.

I have not attempted to resolve the residual differences between these studies for several reasons. First, as Baron's study indicates, performance and payback time vary geographically. In addition, the designs available have different energy input requirements and output performance. The actual payback period achieved in practice will also vary because of different habits among users, for example, in their rates of hot water consumption.

Although this analysis does not directly address the cost of solar heating, the estimates of the payback time for solar heating (3 to 9 years) suggest that a significant portion of solar equipment cost is the cost of the energy required for its manufacture. As the costs of fossil fuels increase, the costs of solar equipment are also likely to increase (barring offsetting cost reductions through technical improvements). Consequently, projections that do not consider this cost sensitivity will be overly optimistic in projecting solar heating costs.

Solar Growth Scenarios

Two estimates of future solar energy use from the DPR have been considered for this analysis. They are the base case (low solar growth) and option 3 (major national commitment to solar energy). These estimates are that, in the year 2000, active solar heating will contribute 0.9 quad (1 quad = 1.056 gigajoules) for the base case and 2.4 quads for option 3.

For comparison, a recent Harvard Business School study (*10*) projects that solar space and water heating, including passive as well as active systems, could contribute 6.4 quads in 2000. The Council on Environmental Quality's (CEQ) (*11*) maximum estimate is 2 to 4 quads from both active and passive solar heating and cooling in 2000. Because these studies provide a combined estimate from both active and passive solar heating systems, a direct comparison with the DPR estimates used in this analysis is not possible. When passive solar contributions are combined with the DPR active solar estimates, the option 3 projection is 4.8 quads, which is reasonably consistent with the CEQ and Harvard esimates.

The DPR provides estimates for only 1985 and 2000; it does not specify a year-by-year integration path for solar heating. But complete integration paths are needed for a dynamic analysis, and I have constructed these on the basis of the DPR estimates (see appendix). An exponential form was assumed for the integration paths, with parameters selected to be consistent with the DPR estimates for 2000. These integration paths are not consistent with the DPR's 1985 estimates for technical reasons explained in the appendix.

The Net Energy Impact

Both annual and cumulative fuel displacements that would result from the two solar integration scenarios are calculated for the period 1978 to 2000. These displacements are gross savings; net energy savings are calculated by subtracting the energy required to produce solar equipment from the gross savings for each year. The results of the calculation are presented in Table 2 and in Fig. 1. For these calculations, the input energy required to produce solar equipment is simply the product of the payback time with the capacity of installed solar heating equipment (or the annual additions to solar capacity).

Because of the range of uncertainty in calculating the payback periods for solar heaters, as well as the mix of space heating and water heating (not specified in the DPR), I have calculated net fuel savings for single unit paybacks of 3, 5, 7, and 9 years. It should be recalled that the payback time for solar water heating is shorter than that for space heating. As a result, the appropriate average payback time is likely to be smaller than the estimates for space heating given by Baron or by Payne and Doyle in Table 1. Lenchek's estimate of payback time is for an integrated space and water system.

As these results indicate, the energy required to manufacture solar equipment equals a sizable fraction of the energy savings provided by solar heating; in fact, through the end of the century input energy may actually exceed energy saved. Under the rapid growth case, the cumulative energy (Fig. 1a) delivered from 1978 through 2000 is roughly 7 to 21 quads ($30 billion to $100 billion at the current world oil price), less than would be expected if the energy input requirements were ignored. Under this same rapid case, the annual fuel savings (Fig. 1b) are, for a 3-year payback time, about half those of the gross estimates. The estimate of solar energy contribution is of course progressively less for longer payback times. As expected, the difference between gross and net energy is somewhat less for the slower integration rate, although this effect is less important than that due to variations in the estimate of individual unit payback time. Figure 1, c and d, illustrates, respectively, the cumulative and annual energy saved by solar heating for the slower growth case.

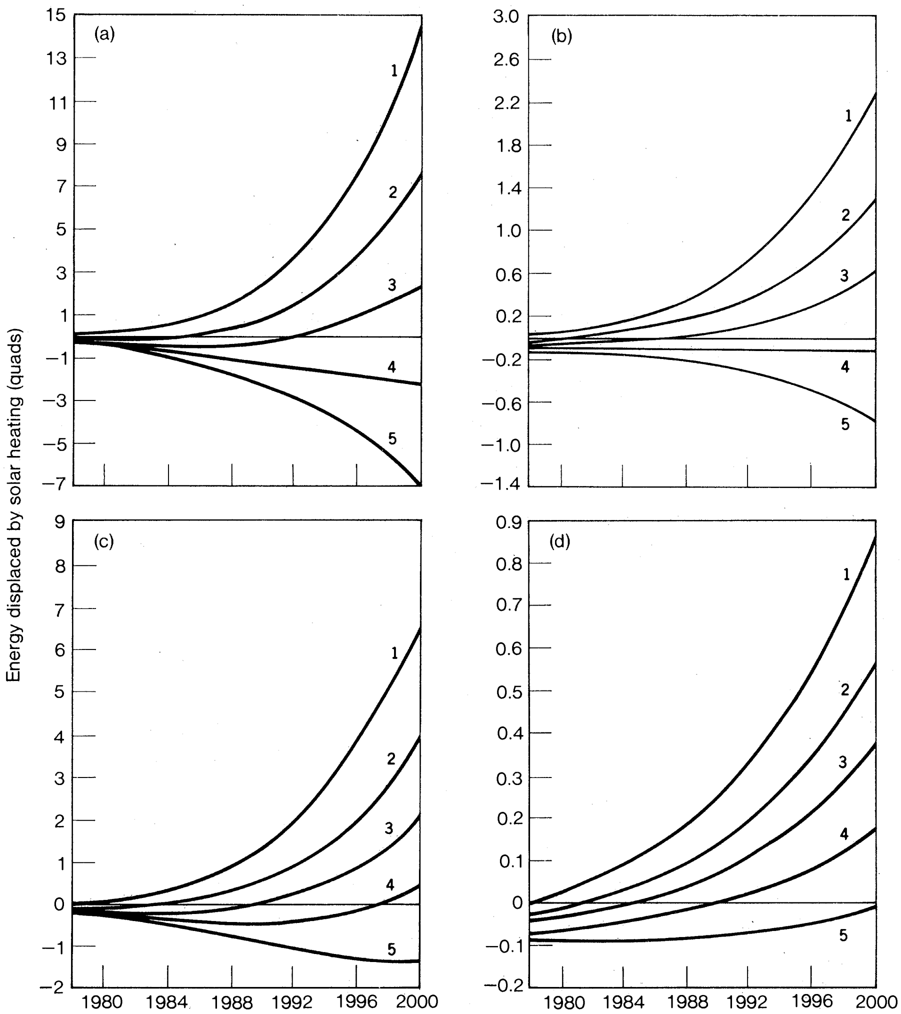

Fig. 1. (a) Cumulative energy displaced by solar heating and (b) annual energy displaced according to the rapid growth case (DPR option 3). (c) Cumulative energy displaced and (d) annual energy displaced according to the low growth case. Curve 1 is, in each figure, the gross solar energy displacement; curves 2, 3, 4, and 5 are the net energy displaced for solar unit energy paybacks of 3, 5, 7, and 9 years, respectively.

The Energy System Impacts

The difference between these gross and net energy estimates is the amount that will be consumed by the solar equipment industry and by the industries supplying its materials. Most of this energy will be used to produce materials: aluminum, steel, and glass. Lenchek's estimate is that 60 percent of the energy used to manufacture the system he analyzed went to produce iron and steel and 32 percent to produce aluminum. Payne and Doyle estimated a lower percentage (50 percent) for materials, of which aluminum was the largest component in two of the three designs they analyzed. Baron does not specify the energy input breakdown beyond the fact that materials account for about 84 percent of his system total when operation energy is excluded.

The effect on energy demand in these industries can be quite substantial. By the year 2000, under the rapid growth case, the annual investment in solar heating equipment is estimated at 1 to 3 quads, depending on the payback period selected. If 50 to 80 percent of this energy is used to provide aluminum and ferrous metals, the additional consumption by these industries will then be 0.5 to 2.5 quads. For comparison, 1975 energy consumption by the iron and steel industry was about 4.2 quads, and by the aluminum industry, 0.77 quad (*12*). Thus the dynamics of expansion of these industries, and of the energy systems to support them, are also likely to be important.

Fortunately, these two industries rely primarily on domestic fuels. The steel industry uses coal directly as its principal fuel, and the aluminum industry uses base load electricity. Much of this electricity comes currently from hydroelectric sources, but future expansion will probably be met with coal-fired and nuclear plants. It therefore appears that, in addition to its other benefits, a program to rapidly develop solar heating has the potential to shift 1 or 2 quads per year from premium fuels to coal and uranium by the end of the century, provided that the increased amounts of energy from these sources are available. This of course assumes that the materials for solar equipment are domestically produced. If these materials are imported, then the shift from imported to domestic energy will not occur.

Comments and Conclusions

Because of the many uncertainties in this analysis, I am unwilling to make a single numerical estimate of the effect of energy inputs on the net saving by solar heating. But the importance of this effect over both a wide range of system growth rates and single unit energy payback times makes it clear that during the balance of the century, the net contribution from solar heating is likely to be far less than gross estimates indicate.

Eventually the high solar heating growth rates assumed for this calculation will slow down. When this occurs the influence of the dynamic effect will be reduced.

This analysis is not meant to substitute for the economic evaluation of these technologies, nor to imply that long system payback times imply that individual decisions to use solar heating are counterproductive. Even if the upper estimate of the solar payback time (9 years) is correct, a solar heating system would still consume far less fossil fuel over its lifetime than would a conventional heating system. Rather, the point is to call attention to a situation analogous to that of a business with high initial costs and poor cash flow for the first few years.

The estimates of solar energy contributions can be misleading in supply planning if taken alone, so it is important that the influence of this effect be recognized. There are undoubtedly other energy technologies that can exhibit similarly large differences between gross and net energy produced, and to which this type of analysis should be applied. The characteristics that create a serious planning issue and invite analysis are long single-unit payback or construction times coupled with rapid system growth rates. The implications and conclusions drawn from these results are as follows.

1) Energy supply scenarios that are based on gross solar estimates underestimate conventional fuel demand.

2) During the balance of this century, the value of solar heating in shifting the mix of fuels may be as important as its impact on the quantity of fuels consumed. It appears that rapid growth of solar heating will increase demand for coal- and nuclear-produced energy, and reduce demand for oil and natural gas.

3) If, during a supply crisis, the United States attempts rapid implementation of solar heating (perhaps along the lines of the highest estimates of the DPR), the effort may be counterproductive. Demand for conventional energy would actually increase, although it would shift from the residential and commercial sector to the industrial sector.

4) The cost of solar heating and other energy technologies with long single-unit payback times will be sensitive to fossil fuel prices. Consequently, calculations of fuel prices at which solar energy will compete will be incorrect unless this sensitivity is understood.

5) Vigorous research and development directed toward the reduction of solar equipment energy intensiveness is indicated. As an example, a reduction by 2 years in the unit energy payback time would, in the rapid growth case, result in a cumulative savings of 4.8 quads through the year 2000, with annual savings of 0.16 quad in 1990, and 0.66 quad in 2000.

Appendix

The DPR gives only point estimates of future solar use (with many cautionary statements regarding uncertainty), but a dynamic net energy analysis requires the full integration path. The estimates of interest are shown in Table 3.

For defining integration scenarios consistent with the DPR estimates, an exponential integration rate was judged most representative of the path of new energy technologies in their initial years [see, for example (*13*)]. For the initial year of the DPR estimate, 1977, the contribution from active solar technologies was described only as "small," so it was assumed that this could be taken to be zero without misrepresentation. This condition leads to the selection of an integration form:

$$C(t) = a\{e^{\alpha(t - t_0)} - 1\} \qquad (1)$$

where C is installed capacity measured in quads per year, t is time in years, a and α are constants, and t_0 is 1977. However, to estimate the coefficients of this equation one requires two point estimates, which the DPR does not give. The DPR does indicate that 1985 energy is 0.2 quad greater in the option 3 than in the base case.

This condition, when coupled to the

Table 2. Calculated solar heating contributions (in quads).

Growth and payback	Cumulative through 1985	Cumulative through 2000	Annual production 1985	Annual production 2000
Rapid growth case				
Gross savings	0.65	14.68	0.18*	2.23*
Net savings				
3-year payback	0.05	7.48	0.06	1.24
5-year payback	−0.35	2.68	−0.02	0.57
7-year payback	−0.75	−2.12	−0.09	−0.09
9-year payback	−1.15	−6.92	−0.17	−0.75
Slow growth case				
Gross savings	0.41	6.62	0.11	0.85*
Net savings				
3-year payback	0.05	3.92	0.05	0.56
5-year payback	−0.18	2.12	0.00	0.37
7-year payback	−0.42	0.32	−0.04	0.17
9-year payback	−0.66	−1.48	−0.08	−0.02

*The gross annual production in 1985 and 2000 is slightly lower than the assumed capacity for these years because the capacity targets are for year end. The production estimates are derived from an integration of capacity throughout the year.

Table 3. Estimates from the DPR's tables 8 and 16. All estimates measure fossil fuel energy displaced, rather than delivered solar energy.

Energy use	Base case 1977	Base case 2000	Option 3 1985	Option 3 2000
Active residential and commercial	Small	0.9 quad		
Active residential			0.2 quad*	2.1 quads
Active commercial			†	0.3 quad

*Increment over base case (which is not given for 1985). †Less than 0.01 quad.

exponential form chosen above, leads to unreasonable results. For example, if the 1985 base case energy contribution is chosen to be 0.12 quad, then the option 3 estimate for 1985 is 0.32 quad. Using the year 2000 estimates and the 1985 estimates just mentioned to calculate the constants in Eq. 1, one obtains growth scenarios with identical exponential rates. That is, the growth rates for the two cases are identical and the estimates are fixed in a ratio of 8:3 for all years.

This result is unreasonable because of its implications for the early years of the period of interest (1978 to 1980, for example). Under option 3 the 1980 energy estimate according to this formulation exceeds 0.09 quad, implying roughly one million solar heating units. Further, because the growth rates are identical, the integration paths do not permit an examination of the sensitivity of the net energy effect to growth rate changes, and this does not satisfy an intuitive desire that the rapid integration growth rate be higher than that of the base case.

For these reasons, the base case path was taken as described above, with the 1985 energy assumed to be roughly 0.12 quad. But the option 3 path was altered to provide more realistic estimates in the initial years. The integration paths analyzed were

$$C(t) = 0.0941\{e^{0.1025(t - t_0)} - 1\} \quad (2)$$

for the base case, and

$$C(t) = 0.0941\{e^{0.1425(t - t_0)} - 1\} \quad (3)$$

for option 3. These paths satisfy capacity estimates for the year 2000, but for 1985 give 0.12 and 0.2 quad estimates for the base case and option 3, respectively.

While this is seemingly a great deal of discussion over an apparently minor point, the fact is that the importance of the invested energy relative to the output energy is fairly sensitive to the form and rate of the integration path selected.

References and Notes

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