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Solar Energy and Electric Utilities: Should They Be Interfaced?

In many applications adapting solar energy to electric utilities limits its economic potential.

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Solar energy technologies and their applications constitute a broad and diverse array of energy supply options. Solar systems are currently under development for applications in the generation of electric energy, production of industrial process heat, and heating and cooling of buildings. The identification of promising solar applications and the elimination of unpromising ones are necessary for the efficient development and use of the solar resource. In applications where solar systems are interfaced with conventional supply systems, it is important that the solar systems be evaluated in context with the cost and performance characteristics of the conventional systems that they are designed to supplement or replace.

A number of investigators have proposed solar energy systems that interface with conventional electric utility supply systems. Whether considering solar thermal conversion systems to produce electric utility power or solar systems for thermal applications in buildings, the systems' designers have generally concluded that solar energy can reduce electric utility fuel and capital requirements. In both utility power system and utility customer end-use applications, solar energy saves fuel directly by substituting for utility fossil and nuclear fuels. Utility capital and indirect fuel savings occur as a result of the ability of the storage system, always included in the solar system design, to displace the solar system's auxiliary energy requirements to off-peak hours. The effect is to reduce the utility's peak-period loads from those which would otherwise occur, thereby allowing the substitution of base-load plant and fuels for peak- and intermediate-load plant and fuels.

Recent investigations of certain solar heating and cooling systems have emphasized that solar insolation outage can be covered entirely with inexpensive off-peak electric power (*1*). All that is required is the incorporation of a thermal storage system with capacity adequate to meet the design-day building load. What these studies have failed to point out is that the inclusion of thermal storage effectively reduces the function of the solar collector component of the solar energy system to the displacement of off-peak electric energy. This fact greatly diminishes the economic benefits that can be attributed to solar energy systems.

It is the purpose of this article to reevaluate the economics of solar energy systems that interface with conventional electric utility supply networks. The reevaluation proceeds along two paths. First, adopting the implicit assumption of many solar system designers that there are abundant supplies of low-cost off-peak electricity, we undertake systems studies of several of the more important solar energy applications. Second, adopting a standard economic approach to the periodic load problem, we examine the general problem of interfacing solar energy and electric utility supply systems.

A central theme of the systems studies is that solar energy systems are most logically compared with the storage-augmented versions of the conventional systems that they are designed to supplement or replace. Adopting this approach, we estimate solar collector break-even costs for solar/electric-resistance and solar/heat pump systems for space heating and solar thermal conversion systems for electric power generation. For solar/electric-resistance heating, the upper bound on solar collector break-even costs is found to be approximately \$30 per square meter (≈ \$3 per square foot) if auxiliary energy is from coal-fired utility generating plants and \$75 per square meter if auxiliary energy is from oil-fired utility plants. For all the solar/heat pump configurations examined, the collector break-even costs are found to be substantially lower than for the comparable solar/electric-resistance heating systems.

The general problem of interfacing solar energy and electric utilities is treated by analyzing the economics of solar collection in terms of two alternative scenarios. In the first scenario, off-peak electricity, even if priced at variable cost (utility fuel cost), remains available for the indefinite future. (This corresponds to the economists' firm-peak case.) In the second scenario, through the introduction of either simple off-peak price discounts or time-of-use pricing, the utility's load curve becomes flat (shifting-peak case). For the first scenario, it is shown that solar collection systems generally will be economical only if they can deliver solar energy at a cost lower than the variable (fuel) cost component of off-peak electricity. In regions of the country where the utility off-peak fuel is coal or nuclear fuel, this implies very low solar collector break-even costs. In regions of the country where the cost of off-peak electricity is higher than that of other auxiliary energy forms—the utility

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fuel is oil—the most economical and energy-conserving solar systems will not interface with the electric utility. For the second scenario, the economic benefits of solar collection in most applications are found to be approximately equal to the value of the displaced utility fuel, indicating break-even points for solar collectors that are roughly equal to those under the first scenario.

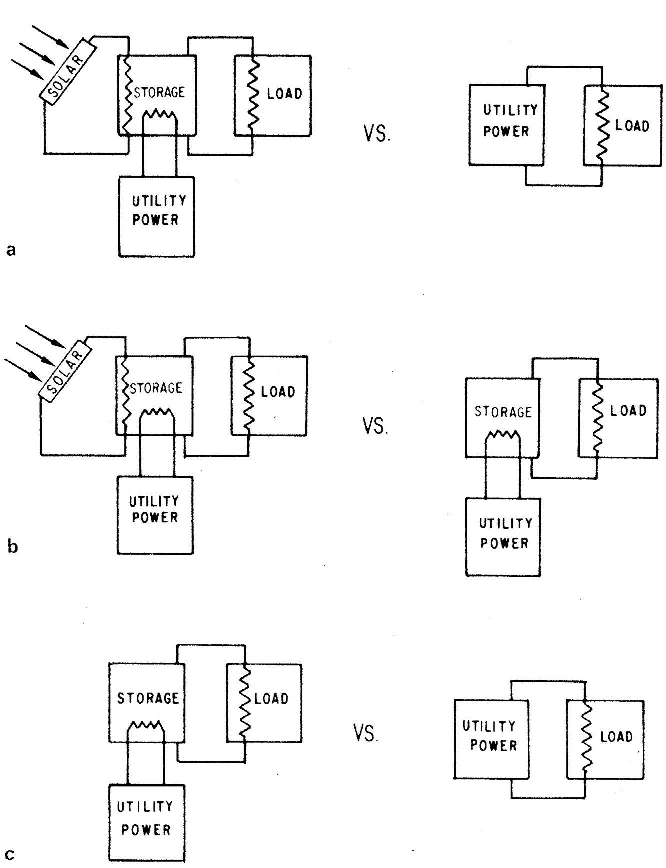
The general conclusion of this article is that solar energy systems and conventional electric utility systems represent a poor technological match. The basic problem is that both technologies are very capital intensive. The electric utility, because of the high fixed costs of generation, transmission, and distribution capacity, represents a poor backup for solar energy systems. On the other hand, the solar collection system, because it represents pure, high-cost capital and because of the periodic nature of its output, should not be considered as a part-load source of auxiliary energy for the electric utility. Viewed in this context, the low break-even costs established for solar collector systems that interface with electric utilities are merely symptomatic of the problem of matching two technologies that in important respects may be incompatible.

Because of our extensive use in this article of the concept of solar collection break-even cost, it is important from the beginning to point out that (i) these costs are always calculated by directly comparing the capital and fuel requirements of conventional systems with those of solar systems providing services of comparable quality, and therefore (ii) break-even cost values, where presented here, are dependent on the costs assumed for the conventional technologies, but (iii) the qualitative conclusions reached are essentially independent of the exact break-even cost values. We do not explicitly examine passive solar building concepts that modify and reduce normal thermal load requirements, nor do we analyze intermittent solar concepts (for example, air-conditioning systems without adequate backup to cover solar outages) for which there are no conventional counterparts. As shown below, the upper-bound break-even costs of solar collection are effectively "pinned" to the value of off-peak utility fuel. By stating break-even costs in terms of current prices of off-peak utility fuel, we effectively neglect: any price-distorting effects of government development or subsidy programs, the many environmental spillover benefits that are commonly associated with solar energy, fuel conservation benefits beyond those reflected in current prices of utility fuel, and the possibility of fuel price escalation beyond the general inflation rate over the lifetime of the solar system (*2*). However, none of these factors are likely to significantly affect the economics of solar systems that interface with electric utilities relative to the economics of solar systems that do not.

Solar/Electric-Resistance Heating

The reconceptualization necessary to properly assess solar heating systems that interface with conventional electric supply systems is shown in Fig. 1. Instead of comparing the cost of the solar heating system including storage with the cost of the conventional heating system (as in Fig. 1a), the solar system designer should compare the cost of the solar-supplemented storage heating system against the cost of the simple storage heating system (Fig. 1b). In practice, the latter comparison will proceed only after the benefits of storage heating relative to direct heating have been determined (Fig. 1c). It is our contention that most of the electricity supply savings claimed for solar energy systems stem from the storage, rather than the solar, component of the systems.

That storage heating systems are cost-effective in service areas supplied by winter-peaking utilities is well established (*3*). A recent study indicates that the utility savings, mostly capital savings, exceed the thermal energy storage



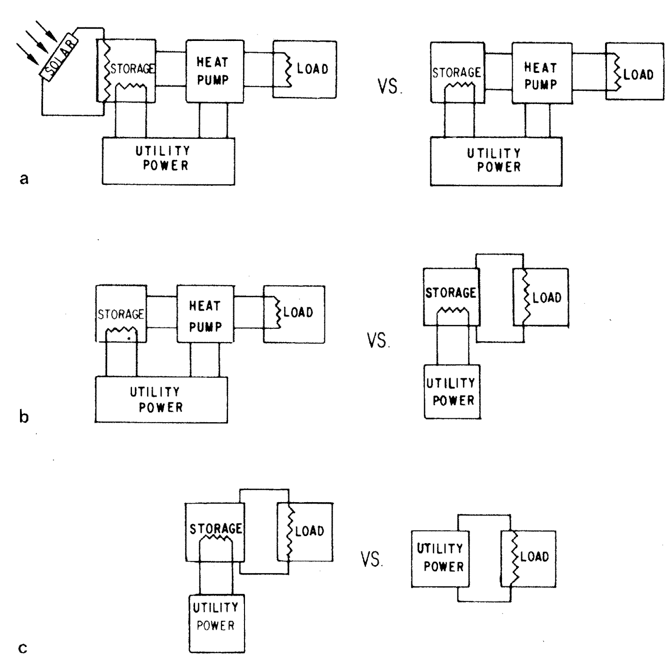


Fig. 1 (left). Comparisons among solar, storage, and conventional space heating systems. Fig. 2 (right). Comparisons among solar-assisted heat pump, storage, and conventional space heating systems.

costs by a factor ranging from 2 to 4 (*4*). The important consideration for the design of solar systems is that, given a storage capacity adequate to meet the design-day heating load, it makes economic sense to add a solar collector system only to the extent that it is cost-effective to substitute solar energy for off-peak electric energy. This consideration establishes an upper bound on acceptable solar collection costs:

$$C < S \cdot E$$

Here C is the annualized cost (dollars per square meter per year) of the installed collector system (including the costs of piping, pumps, controls, heat exchanger, and the collector itself), S is an upper limit on the amount of solar energy collected (kilowatt-hours thermal per square meter per year), and E is the cost of supplying off-peak electricity (dollars per kilowatt-hour electric). For many regions of the country, a representative value for the cost of supplying off-peak energy is 10 mills per kilowatt-hour (= \$0.01/kwh), which covers base-load fuel costs ($\approx$ \$1 per 10^6 Btu) and base-load operating and maintenance costs. Under efficient cost allocation rules, all utility capital expansion costs should be charged against energy use during other time periods (*5*). An optimistic level of solar collection over the space heating season is 300 kwh m^{-2} $year^{-1}$ (= 100,000 Btu per square foot per year). Because, for a fixed storage capacity, annual collection efficiency decreases with collector area, this figure represents an upper limit on solar collection. Inserting these values for electricity cost and solar energy collection into the relation above, we obtain an upper bound on the break-even cost of the solar collection system of \$3 m^{-2} $year^{-1}$. If the real capital recovery rate is 10 percent per year, this corresponds to an upper bound on collector system costs of \$30/m^2 ($\approx$ \$3 per square foot). This is a very low break-even value compared with estimates based on either the average or the peak-period cost of electricity supply. The upper bound on the break-even cost is \$75/m^2 if the auxiliary energy cost is 25 mills/kwh.

In service areas supplied by summer peaking utilities, storage space heating generally is not cost-effective. In such service areas, the displacement of daily winter peak loads into nighttime valleys does not reduce the utility's annual peak capacity requirements. That the addition of a solar collector system could be cost-effective in this situation appears highly improbable. Having to support a sizable portion of the investment in the storage system, the return on the investment in the collector system will have to be higher than for the winter-peaking service area. The break-even cost of the solar collector will be correspondingly lower and may even be negative.

Solar-assisted electric hot water heating may justify a higher collector cost than solar space heating. Solar hot water systems enjoy a better duty cycle, displacing off-peak electricity on a year-round basis. On the other hand, solar hot water systems suffer a disadvantage relative to simple storage systems. This stems from the small additional cost of storage hot water heaters over conventional systems. Usually all that is required is a somewhat larger tank with improved insulation. The addition of a solar collection system, however, usually involves the addition of a separate preheat storage tank. A similar cost burden occurs in solar space heating applications when, in order to improve solar collection efficiency, separate storage systems are incorporated in both the solar supply loop and the backup electric supply system.

Solar Energy/Heat Pump Systems

Solar heating systems more complex than the ones described above have been proposed. In particular, the solar-assisted heat pump has received considerable attention (*6*). In one version of this system, the output of the solar collector is first input to a storage reservoir on the cold side of the heat pump (*7*). The solar energy is removed from the reservoir by the compressor action of the heat pump and is delivered to the building load.

The principal advantages of the solar-assisted heat pump are the lower temperature required for the output of the solar collector and the improved heat pump performance because of the solar warming of the input reservoir. According to the system's advocates, this allows the use of a much lower cost solar collector, thus improving the break-even economics of solar heating. However, as shown below, another effect of incorporating a heat pump in the solar system design is to drive down the break-even cost for the solar collection system.

The same techniques used in evaluating solar systems that interface with resistance heating can be used to analyze the solar-assisted heat pump design. Figure 2 presents a set of system comparisons building from direct resistance heating to the solar-assisted heat pump system. One of the steps in the system evolution in Fig. 2 represents an inferior progression and has been included only to facilitate the analysis. The system incorporating a heat pump in Fig. 2b is inferior to the system without a heat pump.

The heat pump operating solely off the electrically augmented storage on the input side is deficient on a number of counts. Because the heat pump can extract no more energy from the storage than is input, supplemental off-peak electricity is more efficiently stored and recovered in the system on the right side of Fig. 2b, where no work of compression is involved. The heat pump system is also more capital intensive, requiring a higher initial customer investment and greater utility capacity to meet the heat pump's contribution to the utility's daily peak load. As will become clear below, the inclusion of the heat pump with an electrically augmented input reservoir in Fig. 2 is simply part of a gedanken experiment to determine the overall cost-effectiveness of the solar-assisted heat pump system.

The system comparison in Fig. 2a lends itself to a particularly simple interpretation of the role of the solar collector subsystem. The system on the right side can be conceived as operating in almost the same way as its solar counterpart, the only difference being that the electrical energy is input to the right-hand storage reservoir during off-peak nighttime hours, while the solar energy is input to the left-hand reservoir during daytime hours. Although, as described above, this use of electricity is extremely inefficient, it amounts to no more than a simulation of the use of the solar energy that is input to the solar system.

Viewed in this context, the gross benefit from the addition of the solar collector to the heat pump system is no greater than the benefit realized when a solar collector is added to a solar-resistance heating system, namely the displacement of off-peak electric energy. However, now the gross benefit must also cover (relative to the solar-resistance system): the added capital cost of the heat pump over the resistance system, the utility capital costs associated with the supply of electricity to the heat pump during on-peak hours, and the cost of utility energy to run the heat pump. For the fraction of time when solar energy is not available, the heat pump can run off ambient air. This does not alter the relative economics of the solar-assisted heat pump and the storage heat pump in the comparison in Fig. 2a, because both systems would benefit equally from this option. However, it would reduce the heat pump cost burden slightly by the amount of the additional off-peak electricity displacement credit.

The additional capital cost of the heat pump system relative to the resistance system, after an air conditioner capital cost credit, is approximately \$1000 (*8, 9*). For a nominal collector area of 50 m^2, this corresponds to a reduction relative to the break-even point for the collector subsystem in the solar-resistance system of \$20/m^2. In service areas supplied by winter-peaking utilities, a more significant cost penalty is the utility capital cost of meeting the design-day compressor load (*10*). This cost, covering utility demand-related capital expansion costs at the generation, transmission, and distribution levels, amounts to approximately \$500 per peak kilowatt, corresponding to \$2000 for the heat pump and \$40/m^2 for the 50-m^2 collector. The break-even point is then −\$30/m^2 if auxiliary energy costs are 10 mills/kwh and \$15/m^2 if auxiliary energy costs are 25 mills/kwh.

In a service area supplied by a summer-peaking utility, utility winter peak-day capacity costs are considerably lower, depending on such considerations as reserve margin under scheduled maintenance outage. However, even if utility power costs are assumed to be negligible, the break-even point for the solar collector component of the solar-assisted heat pump system will be lower than that of the solar/electric-resistance heating system by the amount of the added capital cost of the heat pump.

Another solar energy/heat pump design concept is illustrated in Fig. 3. Here, the storage reservoir is on the "hot" side of the heat pump and both the solar collector and the heat pump deliver energy directly to the reservoir. We shall not analyze this system in any detail here (*11*); however, it can readily be shown that this system is always inferior to the solar-assisted heat pump analyzed above. The basic problem with the system design in Fig. 3 is that it quite literally forces two capital-intensive subsystems, the solar collector and the heat pump, to compete rather than supplement one another in supplying the heating load.

The conclusions reached regarding these two generic types of solar energy/heat pump systems appear to be applicable to all solar/heat pump configurations. Our analyses of other heat pump concepts indicate that they can always be evaluated by decomposition into some combination of the solar/resistance-heating and the two solar/heat pump concepts described above. All the solar/heat pump concepts that we have identified have break-even solar collection costs considerably lower than the break-even solar collection costs of the solar/resistance-heating system in Fig. 1.

Solar Electric Power Generation

Many of the same kinds of trade-offs affecting the economics of solar energy applications in buildings affect the economics of solar electric power generation. Figure 4 presents the solar electric analogs of the heating system comparisons presented in Fig. 1.

The usual procedure for determining the cost-effectiveness of a solar electric generating system is the comparison indicated in Fig. 4a. The cost of the solar electric system, including any necessary backup to cover solar outage, is compared with the cost of the conventional generating system. In Fig. 4a the comparison is presumed to be between the solar system including its backup boiler and a conventional intermediate generating plant. (To facilitate later analysis, a base-load generating plant has been included on both sides of Fig. 4a. This facility cancels out in the comparison.) Although the comparison in Fig. 4a is the standard method of evaluating solar electric systems, a more meaningful comparison is that shown in Fig. 4b.

That a solar electric system can survive comparison with a storage-augmented base-load generating plant is very doubtful. Given low-cost storage, a storage-augmented base-load plant can replace a combination of base and intermediate (or peaking) plants (see Fig. 4c). In a recent study, the Public Service Electric and Gas Company (*12*) calculated break-even costs for thermal storage in this application at \$570/kw (10-hour storage device) and \$320/kw (5-hour storage device) (*13*). On the other hand, in a Fig. 4a–type evaluation of the economics of solar electric power systems, the Aerospace Corporation (*14*) assumed solar storage device costs several times lower than the PSE&G storage break-even costs. For the most attractive solar electric application examined in the Aerospace study (a central station receiver plus 6-hour storage compared to an intermediate generating plant), the heliostat effective break-even cost was about \$30/m^2. Already a difficult cost objective to achieve, the break-even cost would have been considerably lower if the solar electric system had been compared against a storage-augmented base-load generating plant.

Generalization

The preceding analysis was limited to the types of solar systems that interface with electricity supply systems. In considering such systems, we stressed the low break-even costs of solar collection systems whose only effect is to substitute solar energy for low-cost off-peak electricity. The question naturally arises as to how the break-even economics would be affected by the absence of low-cost off-peak electricity.

In an important sense, off-peak electric power is merely a by-product of on-peak electricity. However, its future availability might very well diminish as utilities and regulators begin to price it at cost and customers respond by purchasing it in increasing quantity. The European experience indicates that, given adequate customer price incentives, the time required for complete "valley filling" for a winter-peaking utility system can be as short as 10 to 15 years (*2*). Therefore, to complete our analysis of solar energy systems that interface with electric utility systems, we will generalize our results by considering two alternative scenarios. In the first scenario, off-peak electricity, even if priced at variable cost (utility fuel cost), remains available for the indefinite future; in the second scenario, as a result of the introduction of a new technology or the implementation of some form of peak-load pricing, the utility's load curve becomes flat. The first scenario corresponds to the economists' firm-peak case; the second scenario to the shifting-peak case.

In the first scenario, in most parts of the country off-peak electricity will remain the lowest-cost auxiliary energy available for solar energy systems. Systems that use this form of auxiliary energy will represent the economically (and socially) most efficient solar energy systems. Thus, to be economical, solar collection systems will have to be low enough in cost to supply solar energy that is cost-competitive with off-peak electricity.

Even in the first scenario, there may remain many utility service areas where off-peak electricity is not the lowest-cost source of auxiliary energy. Today, many utilities use oil in base-load generating plants, with the cost of the oil approximately \$87 per metric ton (\$13 a barrel). After correction for transmission and distribution losses, this gives a cost of approximately 25 mills/kwh (\$8.40 per 10^6 Btu). On the other hand, the price of home heating oil is currently about 11¢

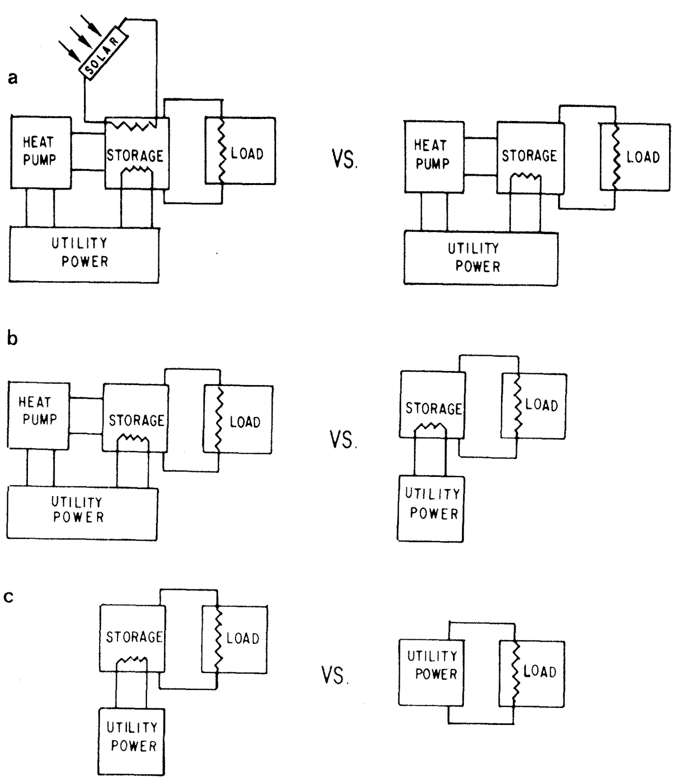
per liter (42¢ per gallon), which after correction for furnace conversion efficiency is equivalent to approximately 15 mills/kwh ($5 per 10^6 Btu). Thus, in service areas supplied by utilities using oil-fired base-load plants, home heating oil represents a lower-cost auxiliary energy form. Although natural gas can also be used to supplement solar systems, its price (marginal cost) under national deregulation is likely to be somewhat higher than the price of oil.

To summarize, the findings for the scenario involving indefinitely available low-cost off-peak electricity are as follows. In service areas supplied with electricity from coal or nuclear generating plants, the most economical solar energy systems will be those that use off-peak electricity as the auxiliary energy source. Accordingly, solar collection systems generally will be economical only if they can deliver solar energy at a cost lower than the cost of off-peak electricity. As we have already seen, the upper limit on break-even costs is about $30 per square meter of collector area. In service areas supplied with off-peak electricity produced from expensive fuels, such as oil or natural gas, the most economical solar energy systems will be those that utilize auxiliary fuels other than off-peak electricity. In these service areas the most economical solar systems will not interface with the utility supply system.

Probably a more meaningful test of the interfacing of solar systems and electric utility systems occurs in the second scenario, when the utility load curve is flat. This can occur if the utility, through the application of a judicious pricing strategy (higher prices during high-demand hours than during low-demand hours), manages to equalize the rates of consumption during all the subperiods of its demand cycle. In this case, the demanders during each subperiod press against the utility's capacity and are responsible, in varying measure, for the utility's long-run expenditures for capacity expansion (*15*).

In this situation, the effect of a solar heating system on the utility's load curve and on its unit cost of supply can be conceived as occurring in the following way. Let us assume that the utility takes into account the effect of solar outages by setting its high-demand and low-demand subperiod prices such that consumption during the low-demand period, including consumption required to cover worst-case solar outage, is equal to consumption during the high-demand period. It follows, in this case, that utility capacity is underutilized during the demand cycles when solar insolation is available for home heating. Solar energy still serves to displace utility fuel; however, the underutilization of utility capital relative to its rate of utilization in supplying a simple electric storage heating system raises the unit cost of electricity supply. This added cost, which represents a real increase in the capital component of electricity cost, must be incorporated, ex ante, into the higher unit price charged solar heating customers than charged storage heating customers. From the solar heating customer's perspective, the increase in unit price is exactly offset by the zero variable-cost component of energy from the customer's solar collection system. (The utility's capital investment and the total energy consumed by the customer are unchanged.) Thus, just as for the firm-peak case, the net benefit of solar collection for the customer, and for society as a whole, is equal to the value of the displaced electric utility fuel. [This result can be shown to follow from a general analysis of the periodic load problem (*11*).]

Although in the preceding discussion of the shifting-peak case we have implicitly assumed the existence of only one type of utility plant, this is not a serious limitation for most solar applications. In home heating applications, for example, the fraction of the load for which solar substitutes for electric supply will not be sufficient, of itself, to allow the utility to substitute intermediate-load for base-load plants. In central station electric power applications, solar must compete directly against base-load plants, the only plant type in use under the uniform load, shifting-peak case.



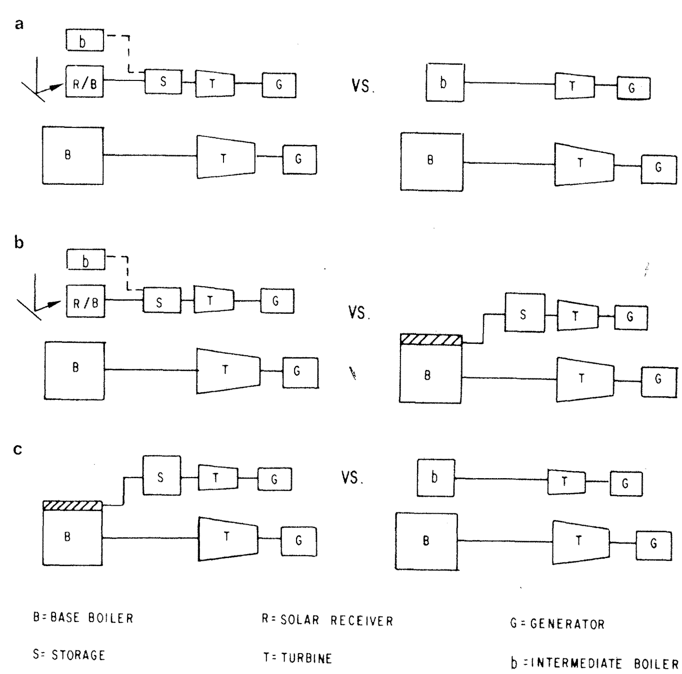


Fig. 3 (left). Comparisons among solar/heat pump, storage, and conventional space heating systems. Fig. 4 (right). Comparisons among utility solar thermal conversion, thermal storage, and conventional power generation.

Summary

Analyses of the economics of solar collection in the firm- and shifting-peak cases (that is, with off-peak electricity indefinitely available or with a flat load curve) indicate that, for many important applications, solar energy systems that interface with electric utilities can be justified only in terms of the value of the off-peak utility fuels that they displace. In regions where off-peak electricity costs are low, the most economically efficient solar energy systems will be those that use electricity as the auxiliary energy source. This implies extremely low break-even costs for a number of important solar energy applications. In regions where the cost of off-peak electricity is higher than that of competing energy forms, the most economical solar energy systems will utilize auxiliary fuels other than electricity.

The general conclusion is that conventional electric utility systems and most solar energy systems represent a poor technological match. The basic problem is that both technologies are very capital intensive. The electric utility, because of the high fixed costs of generation, transmission, and distribution capacity, represents a poor backup for solar energy systems. On the other hand, the solar collection system, because it represents pure, high-cost capital and because of its outage problems, cannot be considered as a part-load source of auxiliary energy for the electric utility system.

References and Notes

1. See, for example, P. J. Hughes, W. A. Beckman, J. A. Duffie, paper presented at the Sharing the Sun Conference, Winnipeg, Canada, August 1976. See also *Solar Engineering Magazine* (August 1976), p. 24.
2. Basing the break-even cost for the solar collection system on the current price of base-load fuel is equivalent to assuming that the real rate of increase of the price of base-load fuel less the real time rate of discount of money is zero. This appears to be a reasonable assumption. See, for example; Staff Report, Executive Office of the President, Council on Wage and Price Stability, *A Study of Coal Prices* (Washington, D.C., March 1976); J. G. Asbury and K. Costello, *ASME Publ. No. 76-IPC-PWR-7* (May 1976).
3. J. G. Asbury and A. Kouvalis, *Argonne Natl. Lab. Publ. No. ANL/ES-50* (April 1976). Although the storage components on either side in Fig. 1b are drawn the same, the storage devices used in electric storage heating systems are generally of higher quality or lower cost than the storage devices used in solar systems. Under worst practice, the same storage device used in the solar system can be incorporated in the storage heating system. The principal advantage of storage in electric storage heating is the high temperature, up to 1200°F, that can be achieved in magnesite bricks or other materials.
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6. S. F. Gilman, Ed., *Solar Energy Heat Pump Systems for Heating and Cooling Buildings–Workshop Proceedings* (Pennsylvania State Univ. Press, University Park, and ERDA Technical Information Center, Oak Ridge, Tenn., 1975).
7. See, for example, V. D. Karman, T. L. Freeman, J. W. Mitchell, "Simulation study of solar heat systems," paper presented at the Sharing the Sun Conference, Winnipeg, Canada, August 1976.
8. Gordian Associates Incorporated, "Evaluation of the air-to-air heat pump for residential space conditioning," report prepared for the Federal Energy Agency under contract FEA-CO-04-50171-00, April 1976.
9. As shown in (*8*), the cost of a heat pump sized to meet the cooling load is approximately $1000 greater than the cost of an air conditioner. This cost difference holds approximately for most regions of the country. Although the heat pump is less efficient in the air-conditioning mode than the standard air conditioner, this charge against the heat pump is ignored here. None of the solar-assisted heat pump concepts considered here use solar energy when the heat pump is operating as an air conditioner.
10. We ignore the resistance component of the heat pump's design-day power demand. For the system design concept examined here, energy can in principle be input to the storage reservoirs during nighttime hours to eliminate the following day's on-peak resistance power requirement.
11. For a detailed analysis see J. G. Asbury and R. O. Mueller, *Argonne Natl. Lab. Publ. No. ANL/ES-52* (August 1976).
12. Public Service Electric & Gas Co., "An assessment of energy storage systems suitable for use by electric utilities," report prepared for the Energy Research and Development Administration under contract E(11-1)-2501 and the Electric Power Research Institute under research project 225, July 1976.
13. These break-even storage costs correspond to PSE&G's "typical values" for generating plant capital and fuel costs. The PSE&G also calculated break-even cost ranges corresponding to variations in input costs. The PSE&G typical value conventional-plant generating costs are similar to those used in the Aerospace study cited below.
14. Aerospace Corp., "Solar thermal conversion mission analysis—Southwestern United States," report prepared for the National Science Foundation under contract NSF-C797, January 1975.
15. For the efficient-price solution, see O. Williamson, *Am. Econ. Rev.* **56**, 810 (1966); M. Crew and P. Kleindorfer, *J. Polit. Econ.* **79**, 1369 (1971).
16. We thank E. Croke for a very helpful suggestion and R. Giese, S. Nelson, and V. Rabl for a number of useful comments. Supported by the Chemical and Thermal Energy Storage Branch, Division of Energy Storage Systems, Office of the Assistant Administrator for Conservation, Energy Research and Development Administration.

Ruminant Livestock Research and Development

Six vital areas of ruminant R & D need increased support to help meet year 2000 productivity needs.

T. C. Byerly

Ruminant livestock (cattle, sheep, goats, water buffalo, camels) represent one of man's most valuable renewable resources. They provide edible protein of exceptional value, fiber, leather, and a wide variety of useful by-products and even, in some countries, motive power and fuel. How to maintain an adequate supply of ruminant products—in the face of rising human population—is one of the more serious research problems facing agricultural scientists today. An obvious solution would be to increase the ruminant inventory by increasing the rates of calving and weaning. But to do this would require a corresponding increase in the quantity and quality of the feed base. Instead, by placing more research emphasis on increasing the efficiency of ruminant production, we could boost world production of ruminant meat and milk protein by 50 percent without adding to the current land area used to support ruminant livestock, and without increasing the present world inventory of ruminant livestock. In reality, an intermediate course is most likely to develop, with a moderate increase in numbers occurring along with an increased efficiency of production.

A brief survey of pertinent data shows the need for this projected 50 percent increase in production and the extent of the resources required to attain the goal.

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