FINANCIAL ANALYSIS OF SOLAR ENERGY APPLICATIONS WITH ENDOGENOUS SYSTEM SIZING

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Abstract

This paper is concerned with analysis of economic feasibility of solar energy systems. Methodology for estimating energy output from different sized systems is briefly presented, and this is used to determine technical coefficients for a mixed integer model which optimizes the size of the solar heating unit for a particular use. An empirical example of hot water heating on a Georgia dairy is presented. Cost curves are provided for the dairy example to illustrate the effect of sizing on the economic feasibility of solar heating and to elucidate the structure of the optimal sizing decision.

Key words: solar energy, economics, solar water heating, dairy water heating.

Analyzing the economic feasibility of solar technology presents researchers with an interesting set of analytical problems. The relatively small amount of solar literature for agricultural applications has produced mixed results regarding feasibility of this technology (Heid; Kwon; Hartman; and Hardy et al.). Some of the special characteristics of solar investment decisions, which lead to differences in these results, are discussed in this paper.

Economic feasibility of solar technology is affected by several parameters. Clearly, different uses of solar technology will influence feasibility because each use will be associated with a specific type of solar equipment and supply capability, and with a particular pattern and level of energy demand. Subjective differences in assumptions required for financial analysis of a solar investment, such as the proper discount rate, tax environment, and projected conventional energy prices, could lead to different conclusions about the viability of similar investments. Also, location of the solar unit influences the analysis due to climatic effects, and the time period of the study is important due to changes in costs and technology.

Differences in these parameters hamper generalizations about feasibility of solar technology. However, some general characteristics and cost relationships for different uses of solar energy can be identified. These relationships are related to the sizing of the solar equipment for different uses, and the effects of different sized systems on energy production and costs. This paper focuses on a specific solar application, water heating on dairies, but the analysis emphasizes the effect of solar equipment sizing on costs and production. Since the rejection of an investment in a specific solar technology can be viewed as an optimal sizing decision, an understanding of the sizing effects is useful in explaining why some solar investments are economically feasible while others are not.

This paper proceeds from a brief literature review to the financial analysis of a solar water heating system that was installed on a Georgia dairy. Primary data from the solar installation are then used to estimate energy availability from larger solar units, and these estimates are included in an optimal sizing model which is presented and discussed.

RELATED LITERATURE

Solar technology has been applied and studied for diverse agricultural uses. Katzman and Matlin (1978) concluded that solar photovoltaic energy systems for irrigation may become economically feasible in the middle to late 1980's. Hayden and Thompson analyzed a dairy application and stated that current solar technology can significantly reduce energy demand from conventional sources in the milking parlor, but they did not present a detailed economic analysis. Heid concluded that solar drying of corn may be economically feasible under certain assumptions and with several caveats related to corn quality deterioration and possible insect problems. Kwon concluded that on-farm solar grain drying is economically feasible. Hartman tied the feasibility of solar heat for brooding to assumptions about solar equipment costs and future energy prices. Hardy et al. clearly rejected the solar alternative for poultry house heating.

SOLAR WATER HEATING ON DAIRIES

The solar application analyzed is a water heating system that was installed and monitored on

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a Georgia dairy farm. Current production practices on dairies require large amounts of hot water to maintain sanitary conditions. A dairy's water demand depends upon the parlor and equipment design, the number of head milked and the number of daily milkings. Traditionally, hot water demands are met with either propane or electric water heaters. The large price increases in electricity and propane have led to interest in alternative forms of water heating. One alternative is a solar based technology which supplements conventional methods by preheating water. Several studies have reported solar and waste heat scavenger applications on dairies (Copeland; Copeland and Miller; Vaughn and Vaigneur; Jarrell; and *Progressive Farmer*).

The Georgia Piedmont region farm, which cooperated in this project, milked 225 cows and used approximately 600 gallons of 160 degree fahrenheit water per day. The dairy's water is drawn from a well, stored in a 120-gallon preheat tank connected with the solar unit, moved through two inline propane water heaters and is then available for use in the milking parlor.

The monitored solar unit was a 7.24 square meter four-panel, flat plate collector with a 5 square meter Mylar reflector. Silicon based fluid is mechanically exchanged between the solar collector and the coils within the water preheat storage tank. Sensors regulate the silicon flow between the collector and the storage tank with exchange occurring if the temperature of the fluid returning from the water storage tank is less than that of the fluid in the collector.

Data on system performance were collected periodically from September 3, 1980 through September 2, 1981. Jarrell reported the primary data used in this study. The thermal value of the total system was determined by BTU computer sensors located in the plumbing to monitor the water after it leaves the well and again after it leaves the propane heaters. A second BTU computer with sensors in the plumbing measured the solar BTU's generated before the water entered and after the water exited the solar unit.

FINANCIAL ANALYSIS OF THE FOUR PANEL SOLAR UNIT

The BTU and propane consumption data provided the information needed to calculate the net present value of the solar heating system under different assumptions about future propane prices. The analysis assumed that the solar heating equipment would be used to supplement the propane heaters, and that existing propane heating capacity would remain intact. Standard net present value analysis of after tax cash flows (Penson and Lins) can be used to analyze the solar investment. Net present value calculations, assuming internal financing of the solar investment, are presented below.

The value of propane savings in any year, n, is:

$$(1)\quad VS_n = PS_O(1-t)(1+ip)^n,$$

where VS_n is the value of propane savings in year n, PS_O is the value of propane savings in the first year, t is the marginal tax rate, and ip is the annual growth rate assumed for propane prices.

The after tax operating and maintenance cost for the solar unit, assuming this cost in the initial year is equal to 1 percent of the initial equipment cost (Beckman et al., p. 114), is equal to:

$$(2)\quad OM_n = CS(1-t)(.01)(1+i)^n,$$

where OM_n is the operating and maintenance cost of the solar unit in year n, CS is the initial cost of the solar equipment, and i is the annual rate of increase in operating and maintenance costs.

The present value of the net change in cash flow from installing the solar unit is equal to:

$$(3)\quad PV_{CF} = \sum_{n=1}^{N} (VS_n - OM_n)/(1+k)^n,$$

where k is the discount rate and N is the life of the solar unit.

The after tax net present value of the solar equipment, assuming 5-year ACRS depreciation (U.S. Dept. of Treasury, p. 16), a 10 percent investment tax credit and a 15 percent special tax credit for solar investments (U.S. Dept. of Treasury, p. 20) is:

$$(4)\quad NPV = PV_{CF} - [(CS - .25CS/(1+k)) - \sum_{n=1}^{5} DEP_n(t)/(1+k)^n - SV/(1+k)^N],$$

where DEP_n is the depreciation on the investment claimed in year n and SV is the salvage value of the solar equipment at the end of N years.

The analysis assumes a 15-year life for the solar equipment with a salvage value of zero at the end of that time. A 12 percent discount rate and 25 percent marginal tax rate were used. Operating and maintenance costs for the solar equipment were assumed to be 1 percent of the initial cost for the solar equipment, and they were assumed to increase at an annual rate of 8 percent. The 1982 installed cost of the solar equipment was $3,571.

An initial price of $.93 per gallon of propane was used, with three annual rates of propane price increases being examined: 8, 12, and 16 percent, in nominal dollars. The net present values for the four panel collector using these assumptions were: −$874, −$373, and $326 for the propane price increases of 8, 12, and 16 percent, respectively. Given these assumptions, the solar investment should be rejected if propane prices are expected to rise by 12 percent or less annually, and accepted if price increases of 16 percent or greater are expected.

OPTIMAL SIZING OF THE SOLAR HEATING SYSTEM

In the dairy heating study, data were collected for only one size solar heating system due to budgetary constraints. This approach permits an accept or reject decision to be made on the installed solar unit, but does not permit an accept or reject decision on solar applications in general because the system that was installed may not be the most cost effective alternative. After the solar performance data were collected, the analysis was extended to optimize the size of the solar heating system and to account for abnormalities in weather during the data collection period.

Installed costs estimated for alternative solar units were obtained from the manufacturer of the four-panel solar unit used on the dairy. There are two basic size units available from this manufacturer, a four-panel and a six-panel unit. The manufacturer indicated that larger units would be a simple combination of these two sizes. Heat storage capacity and Mylar reflectors were assumed to increase proportionally with collector area.

Estimating BTU Availability From Different Sized Solar Units

An important step in optimization of size of the solar unit for a specific use is estimation of energy availability from different sized systems. Estimation is difficult because the BTU availability increases less than proportionately with the size of the solar unit (Beckman et al., vii). This decrease in efficiency occurs even with increasing storage capacity because of the decline in the efficiency of heat transfer at the higher temperatures attained as the total heat demand level is approached.

Beckman et al. describe a method of estimating BTU availability from different sized solar systems that is well accepted in solar literature (Hollands et al.; Brandemuehl and Beckman). This method, called the f chart method, is based on computer simulations (Beckman et al.) which estimate the relationship between collector characteristics, weather conditions, heat demand, and the expected solar contribution to meeting the heat demand. A brief description of this method is presented, and the reader is referred to Beckman et al. for further detail. The description of the f chart method is followed by a discussion of modifications that were made in applying the method to the data available for this study.

The f Chart Method

The f chart method is based on the estimated relationship between the percentage contribution of a solar heating system to the total heat demand and several variables describing collector characteristics, heat demand and climatic conditions. The basic equation for estimating the BTU contribution is (Beckman et al., p. 60):

$$(5)\ f = 1.029Y - .065X - .245Y^2 + .0018X^2 + .0215Y^3 \quad \text{for } 0 < Y < 3 \text{ and } 0 < X < 18,$$

where:

- f is the fraction of the total heat load provided by the solar system in a month,
- X is a factor related to the ratio of a reference collector energy loss to the total heating load during the month, and
- Y is a factor related to the ratio of the total energy absorbed on the collector plate surface to the total heating load during the month.

The variables X and Y are calculated from the solar system characteristics and average monthly climatic conditions as:

$$(6)\ X = F_R U_L\ (F_R'/F_R)\ (T_{ref} - \bar{T}_a)\ (\Delta t)\ (A/L)$$

and

$$(7)\ Y = F_R\ (ta)_n\ (F_R'/F_R)\ (\overline{ta}/(ta)_n)\ (\bar{H}_t NA/L),$$

where:

F_R, U_L, (F_R'/F_R), $(ta)_n$, and $(\overline{ta}/(ta)_n)$ are efficiency factors specific to the collector and correction factors for these (Beckman et al., pp. 10-24), and:

- T_{ref} is a reference temperature determined to be 100°C,
- $\bar{T}_a$ is the monthly average ambient temperature for the geographical location of the collector,
- Δt is the total number of seconds in the month,
- A is the area of the solar collector (m^2),
- L is the monthly total heating load (J),
- $\bar{H}_t$ is the monthly average daily radiation incident on the collector surface per unit area (J/m^2), and
- N is the number of days in the month.

For hot water heating systems, an additional correction factor is needed to calculate X to reflect the base temperature of the water to be heated, the target temperature of the water, and the average ambient temperature each month (Beckman et al., p. 87). This factor is:

$$(8)\ (X_c/X) = (11.6 + 1.18\,T_w + 3.86\,T_m - 2.32\,\bar{T}_a)/(100 - \bar{T}_a),$$

where:

T_w is the water supply temperature,
T_m is the target temperature to which the water will be heated, and
$\bar{T}_a$ is the monthly average ambient temperature.

The correction factor (X_c/X) is multiplied times the right-hand-side of equation (6) to calculate the adjusted value of X to be used in equation five.

In order to use the f chart method, the collector efficiency parameters are estimated using procedures recommended by the National Bureau of Standards. Monthly heat load is estimated based on past data or accepted engineering principles and characteristics of the specific heating situation. Average monthly ambient temperatures and solar radiation data are available for several locations in the U.S. and are reprinted in Beckman et al. The decrease in efficiency related to larger solar units is captured by parameterizing the size of the solar unit (A) in equations (6) and (7) to obtain different values of X and Y for different sized units. These values of X and Y are used in equation (5) to estimate BTU output for different sized solar units.

Application of the f Chart Method to the Dairy Solar Heating System

The most difficult step in applying the f chart method outlined is obtaining the collector efficiency parameters required for the equations. The procedure for obtaining these parameters is complex and requires specialized equipment and a controlled test environment (Kreider and Kreith, p. 187). This testing procedure was not conducted for the collector used on the dairy, but an alternate procedure, based on data that were gathered and the f chart method, was used and is discussed.

Data on total BTU demand and the solar BTU contributions were collected at thirteen unequal time intervals during the test year. These data were used to calculate the observed value of f in each period. This approach provided performance data from the actual operation of the equipment in its intended use over a wide variety of operating conditions. Daily temperature data for the test year were obtained from the National Weather Service. Daily solar insolation data for the test year were obtained from researchers at the Georgia Institute of Technology (Benson).

Observed weather data for the test period were substituted into equations (6), (7), and (8) in place of the average weather variables. Equations (6) and (7) were respecified as:

$$(9)\ X = F_R U_L\,(F_R'/F_R)\,\delta, \text{ and}$$

$$(10)\ Y = F_R(\tau\alpha)_n(F_R'/F_R)\,(\overline{\tau\alpha}/(\tau\alpha)_n)\mu,$$

where:

$$\delta = (T_{ref} - \bar{T}_a^*)(\Delta t)(A/L)(X_c/X)^*,$$
$$\mu = \bar{H}_t^* N\,A/L, \text{ and}$$

$\bar{T}_a^*$ and $(X_c/X)^*$ reflect the substitution of observed values of $\bar{T}_a^*$ and $\bar{H}_t^*$ for their average monthly values in the equations.

Letting $F_R(\tau\alpha)_n\ (F_R'/F_R)\ (\overline{\tau\alpha}/(\tau\alpha)_n) = \beta_1$ and $F_R U_L\ (F_R'/F_R) = \beta_2$, and substituting equations (9) and (10) into (5) yields:

$$(11)\ f = \beta_1(1.029)\mu - \beta_2(.065)\delta - \beta_1^2(.245)\mu^2 + \beta_2^2(.0018)\delta^2 + \beta_1^3(.0215)\mu^3.$$

Equation (11) was estimated with the Gauss-Newton method, and the thirteen observed values of f, δ, and μ were used to estimate the combined efficiency and correction factors β_1 and β_2. This estimation yielded a value of .3027 for β_1 and .6862 for β_2, with asymptotic standard errors of .032 and 1.05 for β_1 and β_2, respectively. The goodness of fit statistic, equal to the square of the predicted and observed values of f (Kennedy, p. 25) was .945.

Given these estimates of the efficiency parameters of the installed collector, the calculation of BTU availability from different sized solar units under average weather conditions was straightforward. Average weather data were interpolated to coincide with the thirteen measurement periods. These data and the efficiency parameter estimates were used in equations (5) through (8) to calculate the per period BTU contribution of different sized solar units. These BTU estimates were used as the technical coefficients for the solar activities in the mixed integer programming model described in the next section.

The Sizing Model

A mixed integer programming (MIP) model (McCarl et al.) was constructed to optimize the size of the solar heating system as a possible supplement to the propane heaters already in place. A schematic of the initial tableau, assuming a 12 percent annual increase in propane prices, is presented as Table 1. The model was constructed to allow the purchase of varying

TABLE 1. SCHEMATIC FOR OPTIMAL SOLAR SIZING TABLEAU WITH 12 PERCENT ANNUAL INCREASE IN PROPANE PRICES

	Solar integer activities - area (m²)					Continuous propane activities					RHS
Activities	A7.24	A10.86	......	A61.54	A65.16	P1	P2	....	P12	P13	
Cost	1,976.8	2,618.9		16,026.7	16,718.7	10.46	10.46		10.46	10.46	
BTU 1	491.0	724.6		3,243.5	3,375.2	48.3					≥ 4,188
BTU 2	936.7	1,388.7		6,659.1	6,765.2		48.3				≥ 11,178
.											.
BTU 12	1,136.2	1,651.5		5,884.1	6,022.0				48.3		≥ 5,088
BTU 13	620.3	905.6		3,445.2	3,542.3					48.3	≥ 3,209
MAXS	1	1	......	1	1						≤ 1
MIN PROP 1						1					≥ 8.67
MIN PROP 2							1				≥ 25.52
.											.
MIN PROP 12									1		≥ 11.52
MIN PROP 13										1	≥ 7.33

size solar units and/or propane to satisfy the BTU demand for heating water in each of the thirteen periods.

The right-hand-side (RHS) of the model represents the total BTU demands for each of these periods and a restriction that at least 10 percent of each period's BTU requirement must be met by propane. The BTU demand in each period is different due to seasonal differences in the operation of the dairy and because the periods are of unequal length. The 10 percent propane requirement was used to ensure BTU availability in the event of a number of cloudy days and represents a conservative bias in the model.

Technical coefficients for the solar activities represent the BTU's available each period for the various sized solar units. These were estimated from the measurements for the four-panel unit in place at the dairy with the f chart method, as discussed earlier. Since the solar integer activities represent successively larger four- and six-panel solar collector combinations, a restriction (MAXS SI) was made to permit only one solar activity to enter the solution. The propane technical coefficients were derived from the data collected at the dairy. Each propane activity in the model is defined to represent the purchase of 1 gallon of propane in one of the thirteen measurement periods.

The body of the tableau represents the heat demand and BTU availability for a single typical year's operation of the dairy. Since the life of the solar equipment is anticipated to be 15 years, however, the cost values in the model represent the present value of all costs incurred over the entire 15 years.

The installed costs of the base four-panel and six-panel units were \$3,571 and \$4,731, respectively. The cost coefficients for each solar activity in the model were:

$$(12)\quad CS - .25\,CS/(1+k) - \sum_{n=1}^{5} DEP_n(t)/(1+k)^n + \sum_{n=1}^{15} CS\,(1-t)\,(.01)\,(1+i)^n/(1+k)^n,$$

where all terms are as previously defined.

The cost of each propane activity represents the after tax present value of purchasing 1 gallon of propane in each respective period over the 15-year horizon. Each propane cost coefficient is equal to:

$$(13)\quad \sum_{n=1}^{15} P_o(1-t)\,(1+ip)^n/(1+k)^n,$$

where:

P_0 is the base cost of 1 gallon of propane, \$.93, and all other terms are as defined previously.

The value of the objective function, therefore, is the discounted after tax minimum cost of meeting the dairy's hot water heat demand over a 15-year period.

RESULTS FROM THE SIZING MODEL

The basic model, Table 1, was solved under three different propane price assumptions representing annual increases in propane prices of 8, 12, and 16 percent. Under each price assumption, two solutions were obtained, a propane only solution and a mixed propane and solar solution, Table 2.

Under the 8 percent propane price increase assumption, 2,823 gallons of propane were needed per year at a present value cost of \$22,358. The solar heating unit did not enter the optimal solution under this assumption.

Twelve percent annual propane price increases resulted in a solar unit entering the optimal mixed integer solution. Two six-panel units totaling 21.72 square meters were optimal, with a net present value savings of \$984. With this solar unit, 711 gallons of propane

TABLE 2. RESULTS OF MIXED INTEGER OPTIMAL SOLAR SIZING MODEL FOR THREE PROPANE PRICE ASSUMPTIONS, GEORGIA, 1980-81

	Propane Amount	Propane Cost	Size of solar units	Cost of solar units	Total cost	Net present value[a]
	gallons	dollars		dollars	dollars	dollars
8 pct. increase in propane prices:						
Propane only	2,823	22,358	0	0	22,358	—
Propane-solar	2,823	22,358	0[b]	0	22,358	—[b]
12 pct. increase in propane prices:						
Propane only	2,823	29,529	0	0	29,529	—
Propane-solar	2,112	22,095	two six panels	6,450	28,545	984
16 pct. increase in propane prices:						
Propane only	2,823	39,550	0	0	39,550	—
Propane-solar	1,544	21,636	four six panels	12,900	34,536	5,014

[a]The net present value of the solar contribution is by definition the difference between total cost of propane only and the total cost of the propane-solar solution.
[b]No solar activity entered the optimal solution for the 8 percent increase in propane prices.

were saved annually over the propane only solution.

Under the 16 percent annual propane price increase assumption, four six-panel units were optimal with a net present value of $5,014. In this solution, the solar equipment replaced the equivalent of 1,279 gallons of propane per year.

ANALYSIS OF COST RELATIONSHIPS

Although the MIP sizing model provides an optimal solution for the solar investment decision, a better understanding of the solution can be obtained by analyzing the underlying cost relationships. Cost relationships for solar applications display several distinctive properties. Discontinuities in costs occur due to indivisibilities of the solar equipment because solar panels can only be purchased in discrete sizes. For a given demand, solar costs rise in a non-linear manner due to decreases in efficiency as successively larger units are added, and the presence of excess capacity for larger units.

Excess capacity of solar units can be attributed to seasonality of BTU demand and the seasonal nature of the availability of solar insolation. For any given size of solar unit, it is possible to have excess solar capacity during some time periods and deficient solar capacity, relative to total BTU demand, in other time periods. The occurrence of excess capacity increases with larger solar units, leading to steeper increases in solar marginal costs as the size of the solar unit increases.

Propane and solar marginal cost curves for the dairy example are presented in Figure 1. All costs in Figure 1 are expressed as after tax net present values. The horizontal axis represents the possible sizes of the solar units from the MIP model and the usable BTU's available annually from each size unit. The vertical axis measures the present value cost of generating 1,000 BTU's per year over the 15-year horizon.

The stepped solar marginal cost curve represents the marginal cost per thousand BTU's associated with adding each successive increment of 3.62 square meters (two panels) of solar collector area. Marginal cost in this context is not the traditional cost, dCOST/dX, associated with continuously divisible inputs, but rather is $\Delta COST/\Delta X$ (Baumol, p. 190). In this example, ΔX represents the change in BTU output associated with a discrete addition of 3.62 square meters of collector area.

Peaks and troughs of the solar cost curve arise directly from the relative costs and BTU production of the four- and six-panel units. Based on the cost data provided by the manufacturer, the four-panel units are always more expensive per BTU generated. Peaks of the marginal cost curve represent a heavier concentration of four-panel units.

The decline in efficiency from larger units can be seen in the narrowing of the horizontal segments of the solar cost curve as total size increases. This narrowing is exacerbated for large units by existence of excess capacity in some time periods. In the MIP model, the smallest size unit where excess capacity occurred was the 39.82 square meter unit, which had excess capacity in period twelve. The largest unit, 65.16 square meters, had excess capacity in periods 10 through 13. Presence of excess capacity in this example is partly due to the requirement that 10 percent of each period's BTU demand be met with propane. Narrowing of the horizontal segments of the solar cost curve can thus be explained by: (1) decreases in efficiency for larger units which reduces the number of available BTU's from each expansion and (2) increases in excess capacity for larger units which reduces the number of usable BTU's for each expansion. The total annual BTU demand for the dairy is represented by the vertical line drawn at 136,352 thousand BTU's.

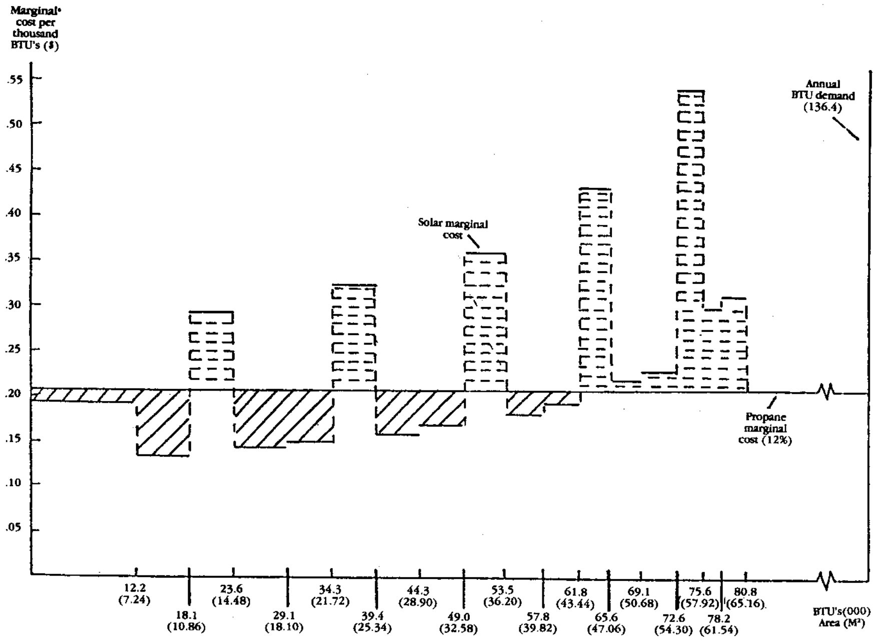

Figure 1. Solar and Propane Marginal Cost Curves for MIP Model Showing Two Panel Solar Size Increments and 12 Percent Annual Propane Price Increases, Georgia, 1980-81.

[a] All costs are after tax net present values.

Total cost of meeting any level of BTU demand by the use of propane is represented graphically as the area under the propane cost curve and to the left of the BTU level, Figure 1. The total cost of meeting any level of BTU demand with solar energy is represented graphically as the area under the discontinuous solar marginal cost curve and to the left of the BTU level. For each BTU level, the net present value (NPV) of solar energy is equal to the hatched area minus the dashed area to the left of that BTU level. This area is maximized, for the 12 percent propane price assumption, with a solar collector area of 21.72 square meters and an NPV of $984. Since this size of solar collector generates 34,326 thousand usable BTU's annually, 102,026 thousand BTU's must be provided by propane.

Further analysis of the 12 percent propane price increase case indicates that the NPV of the 32.58 square meters units is $935, only $49 less than the NPV for the optimal sized system. This larger system consists of three six-panel units, and saves an additional 304 gallons of propane per year, compared to the optimal unit. The third highest NPV is $704 for the 28.96 square meter system.

The graphical representation of the sizing problem in Figure 1 is complicated by the choice between alternative combinations of four- and six-panel units. Figure 2 shows a marginal cost curve for only the more cost effective six-panel units which dominated the MIP solution. This marginal cost curve shows less variability and facilitates immediate recognition of the optimal solar size solution for any propane price scenario. Propane cost curves representing the 8 percent, 12 percent and 16 percent annual price increases used in the MIP model are labeled P8, P12, and P16, respectively. The optimal solution is found where each propane price line crosses the discontinuous portion of the solar marginal cost curve. The vertical portion of the solar cost curve represents the range of propane costs over which a particular sizing solution is optimal (Kottke). The solar NPV is the area below the propane cost line and above the solar marginal cost curve.

SUMMARY AND CONCLUSIONS

Rejection of a solar investment occurs when the present value marginal cost of energy generation with solar equipment exceeds the present value marginal cost of energy generation from conventional sources, for all sizes of solar systems considered. Differences in the feasibility of solar technology in specific uses result from differences in the assumptions about the subjective parameters of the decision and from differences in the specific solar equipment and the application which is being considered.

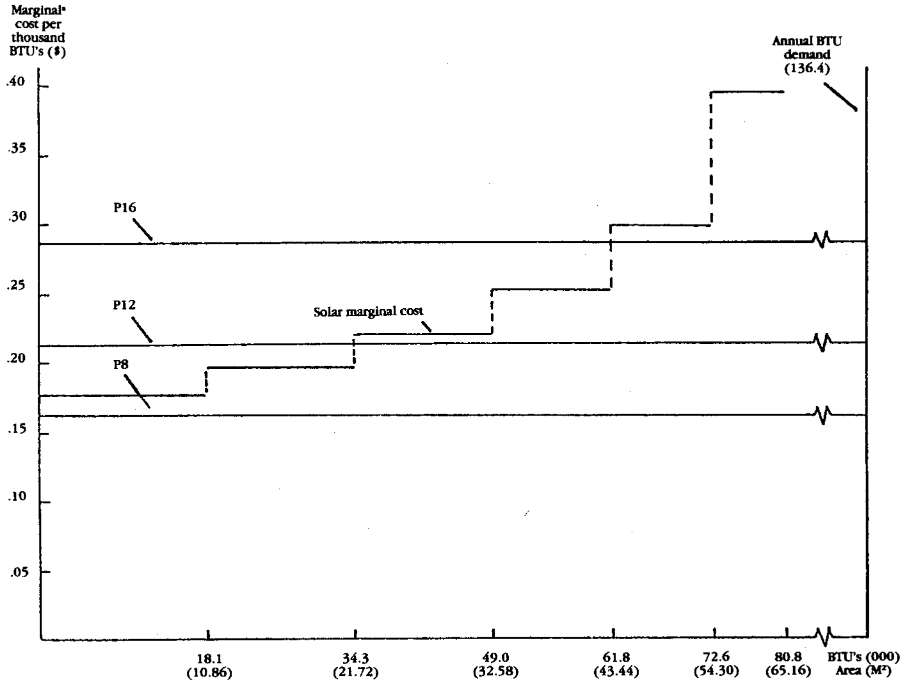

Figure 2. Solar and Propane Marginal Cost Curves for MIP Model Showing Six Panel Increments in Solar Units, Georgia, 1980-81.

[a]All costs are after tax net present values.

Care must be taken in the analysis of any solar heating application to explicitly consider the effects of equipment sizing and abnormal weather on the investment decision. The effect of these factors on the decision is clearly illustrated in this paper by comparing the simple financial analysis of the solar unit installed in the dairy to the results of the optimal sizing model. Under the 12 percent propane price increase assumption, the initial financial analysis resulted in a −$373 net present value and a reject decision for solar equipment in the dairy. The generalized MIP solution for the same price assumption showed a larger system to be optimal with a net present value of $984.

The MIP model is a flexible and computationally efficient technique for analyzing solar investment decisions under alternative price and technological conditions. The structure is general enough to be useful in evaluating many different types of solar applications. The model could be readily extended to optimize the sizing of the propane system simultaneously with the solar equipment, rather than viewing the solar equipment as a supplement as was done here.

Sizing analysis requires estimates of solar output data for each solar size option considered. The f chart method is a heuristic technique for generating these estimates which is considerably less expensive than installing and monitoring several sized systems. Validation of f chart estimates through installation of larger experimental units is recommended, however, since the cost effectiveness of larger systems in dairy use appears promising.

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