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A PHOTOVOLTAIC ASSISTED RESIDENCE WITH SUPPLEMENTAL BATTERY STORAGE: SEARCHING FOR A COMPLEMENTARITY

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OUTLINE

ABSTRACT

A significant mismatch may exist between residential load characteristics and array output from photovoltaic energy conversion systems. This has warranted a closer look at incorporating energy storage as a supplement device. Storage enhances total system energy capture although its weighted benefit is highly sensitive to the particular operating scheme. For utility interfaced systems which include a schedule for utility purchase of excess PV output, the advantage of the additional capture becomes a fairly complex function of the rated price structure, utility buy-back, and the system control logic. The problem arises since photovoltaics and storage each stand as independent investment opportunities for grid interconnected users, thus offering the potential for competition between them. This competition is characterized by a total system value somewhere below their additive stand-alone values.

This study includes a search for a system control logic, along with the economic and location-specific conditions, which maximize total system (PV and storage) value. The latter is defined in terms of the breakeven capital costs at which a user-owner would be economically indifferent toward purchase, given the utility as the sole competitor. Numerous customer-utility relationships are possible in addition to a variety of system configurations. Here, a utility interfaced storage operation without photovoltaics is examined against a tandem (PV-battery) arrangement with a range of utility buy-back policies. No studies were made to assess the value of only photovoltaics or only storage to the utility, though analysis on photovoltaics can be found in both Tatum (8) and Carpenter and Taylor (3).

The residence hardware and behavioral simulation were accomplished with the use of models previously developed by members of the MIT Energy Laboratory.

I. BATTERIES FOR RESIDENTIAL STORAGE -- An Overview

There frequently exists a significant mismatch between residential load characteristics and output from solar-electric energy conversion systems. Terrestrial solar energy has no flexibility in time and is unavailable for a significant portion of the demand period. This suggests an attractiveness of incorporating an energy storage facility. Previous studies[1] have shown that total system energy capture can be improved by 46-58% with the addition of a storage capacity roughly equivalent to an average one day's residence demand.* For utility interfaced systems which include a scheme for utility purchase of excess PV output, the advantage of storage becomes a fairly complex function of time-of-day price structure, rate differentials, utility buy-back rate, and the system control logic.

With substantial market penetration the utilities themselves would stand to gain with dispersed storage. Solar-electricity is generated during typical peak demand periods, but is not wholly coincident with these periods. By supplementing supply during the evening hours and during periods of reduced insolation, storage can, in the long term, help obviate the installation by the utility of increased generating capacity.

Lead-acid Batteries

At present, lead-acid batteries are the only real candidates for near term use in conjunction with photovoltaics. They are available in an extremely wide variety of sizes and can be tailored to a wide range of

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*Around 20 kwh. in the U.S.

specifications. Alternatives to the lead-acid cell are numerous, but their consideration to date has been precluded by economics of scale and cost. The more significant of these (for the residential market) include: inertial (flywheel), pneumatic, and various advanced storage concepts.[2] Discussion of these concepts can be found in references 2 and 4 as well as the specific storage literature.

Some of the more significant advantages which conventional lead acid batteries show over other current concepts include:

- relatively efficient operation at room temperature
- acceptable lifetime charge and discharge characteristics
- manufacture from relatively abundant and inexpensive materials
- acceptable mass/kwh capacity
- inexpensive due to existing economies of mass production

Environmental and Safety Hazards

There exist important obstacles to the widespread use and increased manufacture of lead acid batteries. Exact figures showing composition and amount of toxic chemicals resulting from manufacture are difficult to obtain due to lack of EPA guidelines in this area. It is known, for example, that significant amounts of lead are contained in the industrial waste water and that certain toxic metals are released into the air of the working environment. Also, stibine and arsine gassing occur as a result of battery charging, resulting in toxic gas concentration problems which must be translated into foolproof ventilation design criteria.

In addition to the problem with gas toxicity, hydrogen gas concentrations pose a signficant explosive hazard. For this reason designs would have to provide a ventilation system to account for all conceivable catastrophes. Sulfuric acid spillage is also a major problem in the event of catastrophe, and the battery system is certainly an electrical hazard, as there is no "turning off" a battery unless full discharge has been achieved.

For in-depth reviews of work in this area see references (2), (4), (5), (6).

Battery Maintenance

Battery performance is sensitive to the surrounding temperature conditions. Low temperatures effect electrolyte viscosity so as to reduce battery capacity due to an exaggeration of normal voltage drops under load. Higher temperatures have an opposite effect.[3] Recommended operating temperature for most common battery types is 77°F, with an acceptable operating range between 60-80°F. Normal home heating systems would need to be extended to the battery room, which, given the air circulation requirements, would present additional cost.

The only active maintenance requirement is periodic addition of water to the electrolyte. If desired, this could be done without user attention by use of mechanical equipment.

II. GENERAL MODEL DESCRIPTION

Three models were employed to complete the full analysis. First, a photovoltaic array/battery storage model provided simulation of the systems watt-hour generation characteristics where specific system parameters were made part of the program input file. Location was set by the specification of latitude and by the use of local hourly weather data for insolation, temperature, and wind conditions.

A load schedule model was set up to simulate appliance energy consumption and use patterns for a typical residence. These two models taken together form the residential simulation and yield bottom line figures which include watt-hour totals of utility displaced electricity specific to their respective price purchase periods. The third model, the economic valuation, applies fuel escalation, system degradation, and the rated price structure to these displaced utility energy figures to determine the net present value of accumulated energy savings over a 20 year period. With this, it determines a break-even purchase value by subtracting out all relevant system costs.

Credits

The PV simulation model (SOLOPS) as well as the load model were developed by Jesse Tatum while at the MIT Energy Lab (10). Work related to the economic valuation was completed by Paul Carpenter and Gerald Taylor at the MIT Energy Lab (3). Carpenter and Taylor are also responsible for developing the rate structure schemes. The selection of sites was based on regional analysis of Paul Carpenter and Dr. Richard Tabors (6).

II.1 System Components

The arrangement of the physical system is illustrated in figure 2.1.

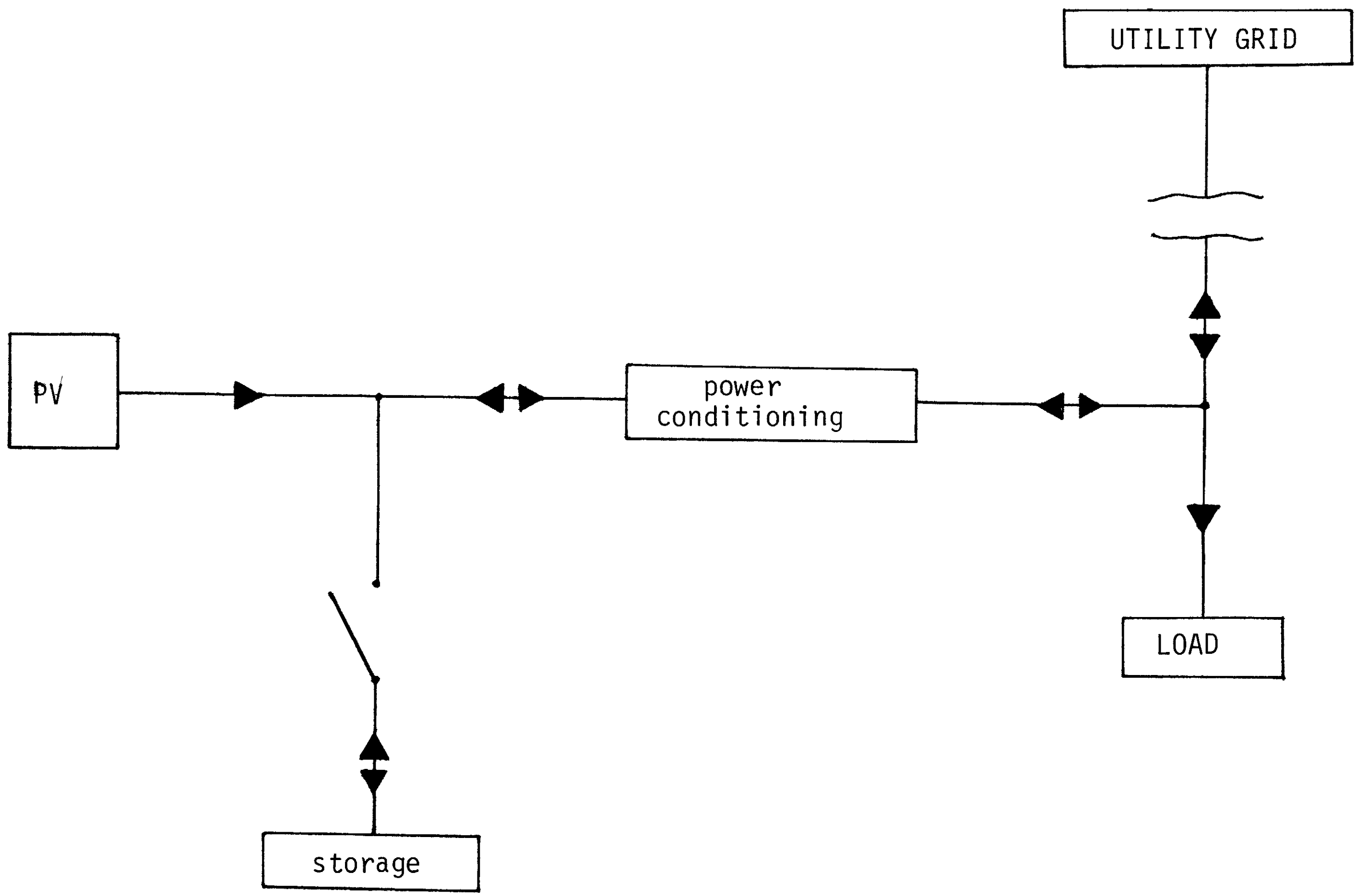

FIGURE 2.1

Photovoltaic Array

The major parameters of interest for the basic energy conversion system are given in Table 2.1. The insolation levels are determined by the hourly direct and diffuse components as retrieved from the weather tape. The array temperature, and hence efficiency, is a function of the ambient temperature and wind conditions, which are hourly weather (tape) data as well.

Table 2.1

array size	35 m^2
cell efficiency	.12
wiring and mismatch n	.95
packing factor	.80
tilt angle	latitude

Power Conditioning

Power conditioning is required to accomodate a utility interface in addition to typical residential AC loads. It consists of a versatile inverter circuit (inverter/regulator) to transform the direct current input into a 60 Hertz utility quality AC output as well as allowing for input voltage variations from the PV array. The latter would be particularly important in controlling battery charge rates.[4] This unit would also provide matching for maximum power transfer and could be designed to operate in reverse as a rectifier for a utility-to-storage

Table 2.2

dc/ac efficiency	.88
ac/dc efficiency	.98
inverter	60 Hertz
shunt regulator	

logic. The significant parameters for such a unit are given in table 2.2. The efficiencies are state-of-the-art and it is expected that there would be no problem in developing, for production purposes, a power conditioning device of this sort.

Lead-Acid Battery Storage

The simulation model included a storage capability with characteristics determined by currently available lead-acid batteries. The economic valuation used estimates of both current and advanced (Na-S) technology cost figures. Thus, the advanced battery estimates were made using a physical model based on current, lead-acid technology specifications. This is not unreasonable since the most sensitive system parameters are those related to costing (battery lifetime, battery and battery-related costs). Na-S storage cells were chosen since cost estimates of this battery were available and because it was considered a fair estimate for 1985 technology.

Performance features for the lead-acid battery are summarized in table 2.3. Battery storage efficiencies as reported in the literature range from 60-85%. For the model, an eight hour charge-discharge cycle between 10 and 90% of capacity yields a typical voltage efficiency of .84 *[5]. Using an amperage efficiency of .92 yields an overall battery efficiency of .77. When including the inverter and rectifier (for utility to storage) efficiencies of .88 and .98, respectively, the overall storage figure becomes roughly .68.

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*Based on the battery system for which the equation characteristics were obtained (by footnote reference 5)

As for cycle life, current lead acid batteries (e.g. those used in motive power service) reach upwards of 2000-2500 cycles, which for our purposes is roughly equivalent to 10 years service. As can be expected, cycle life is proportionately related to depth of discharge, with deeper discharges shortening the estimated life. Work on advanced batteries seeks to minimize this problem.

Table 2.3

number of cells in series	63	voltage efficiency = .85
ampere hours per cell	variable	coulombic soc = .95
		cutoff = .1
		ampeff = .92

II.2 Simulation Logic

Storage Control

All storage-related logic as developed in this model is included in the flow charts of figures 2.2 and 2.3. Figure 2.2 is a very non-specific account of how storage electricity is manipulated within the main control routine. Figure 2.3 describes in somewhat more detail the program electrical switching logic, the understanding of which requires familiarity with the program itself. In essence, the logic includes:

1) Charge by the utility -- charge the batteries subject to the appropriate conditions.
2) Charge by excess solar -- if there is excess solar electricity (after satisfying the load requirement) compare the value of storing vs: selling to the utility vs: dissipating to a thermal load, and allocate.

3) Drain to load -- if there is insufficient solar to meet load demands, and if the pricing constraints are appropriate, utilize stored electricity.

4) Drain to utility -- once all loads are met, then if 1) the logical control flags call for the sale of stored electricity, and 2) the price structure warrants a net return, sell stored electricity to the utility.

5) Adjust the state-of-charge on the batteries -- after considering all of the above, determine the final storage state of charge.

Storage Evaluation

An attempt was made to define a value logic which sets the constraints governing the first four conditions above. This determines, in essence, the battery control logic. The constraints are as follows:

1) Charge by the utility -- (logic occurs in subroutine BATLOG) electricity enters storage from the utilities subject to the following conditions:

   a) state of charge is less than SOCBUY (a set parameter) -- it becomes inefficient to charge beyond a certain fraction of storage capacity. (Efficiencies change at .8 SOC in STORE.)

   b) current price is a base price -- it is not economical to purchase in anything other than a base period

   c) the true cost of stored electricity is less than the peak price -- the true cost is the base cost divided by the storage and inversion efficiencies (i.e. for cities where there is little price differential between base and peak, you may never wish to purchase from the utility)

   d) next day must not be a weekend or holiday -- since base rates apply during these periods.

   e) tomorrows weather forcast shows low insolation (optional) -- if the weather looks good for tomorrow, the assumption is that storage today is unnecessary.

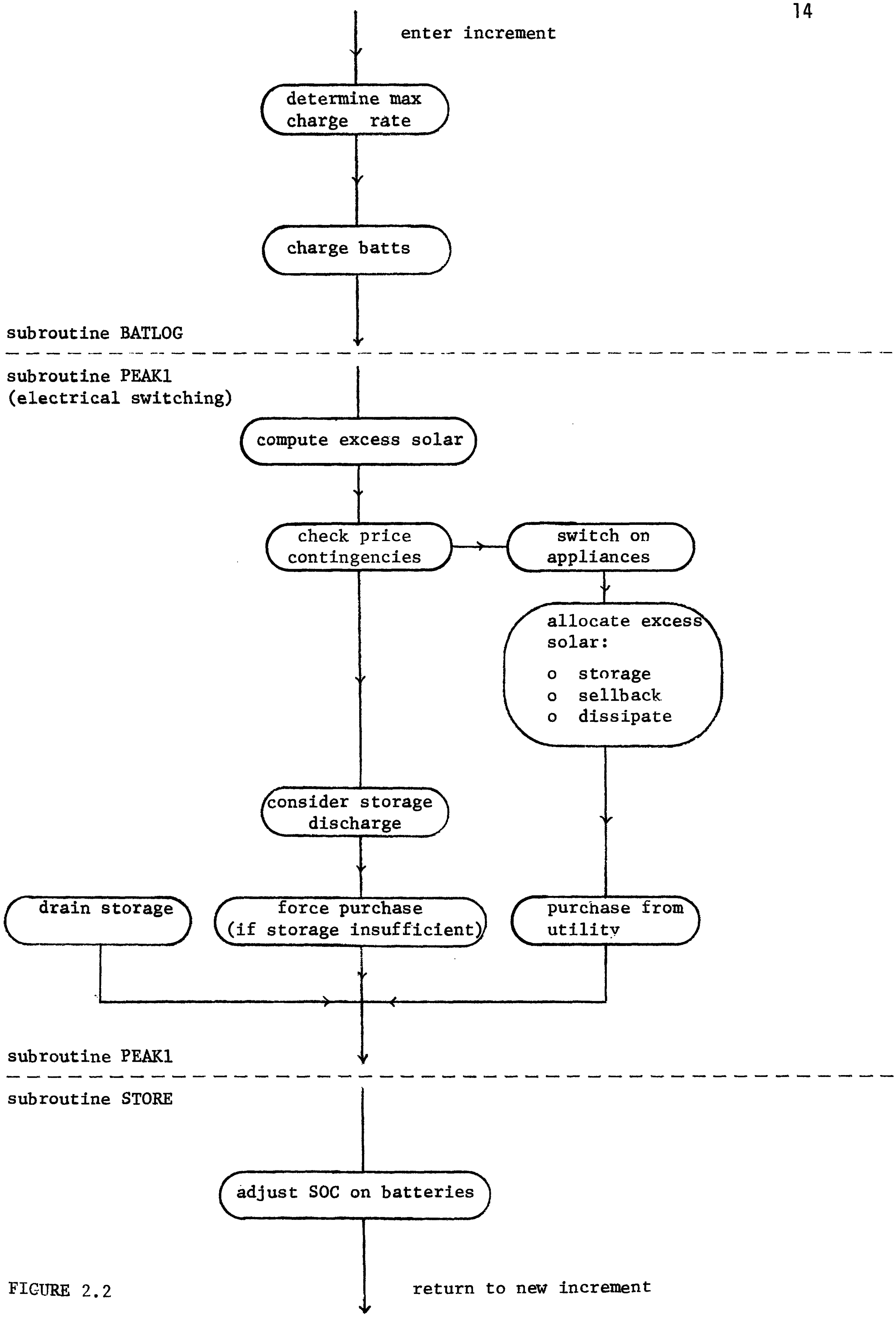
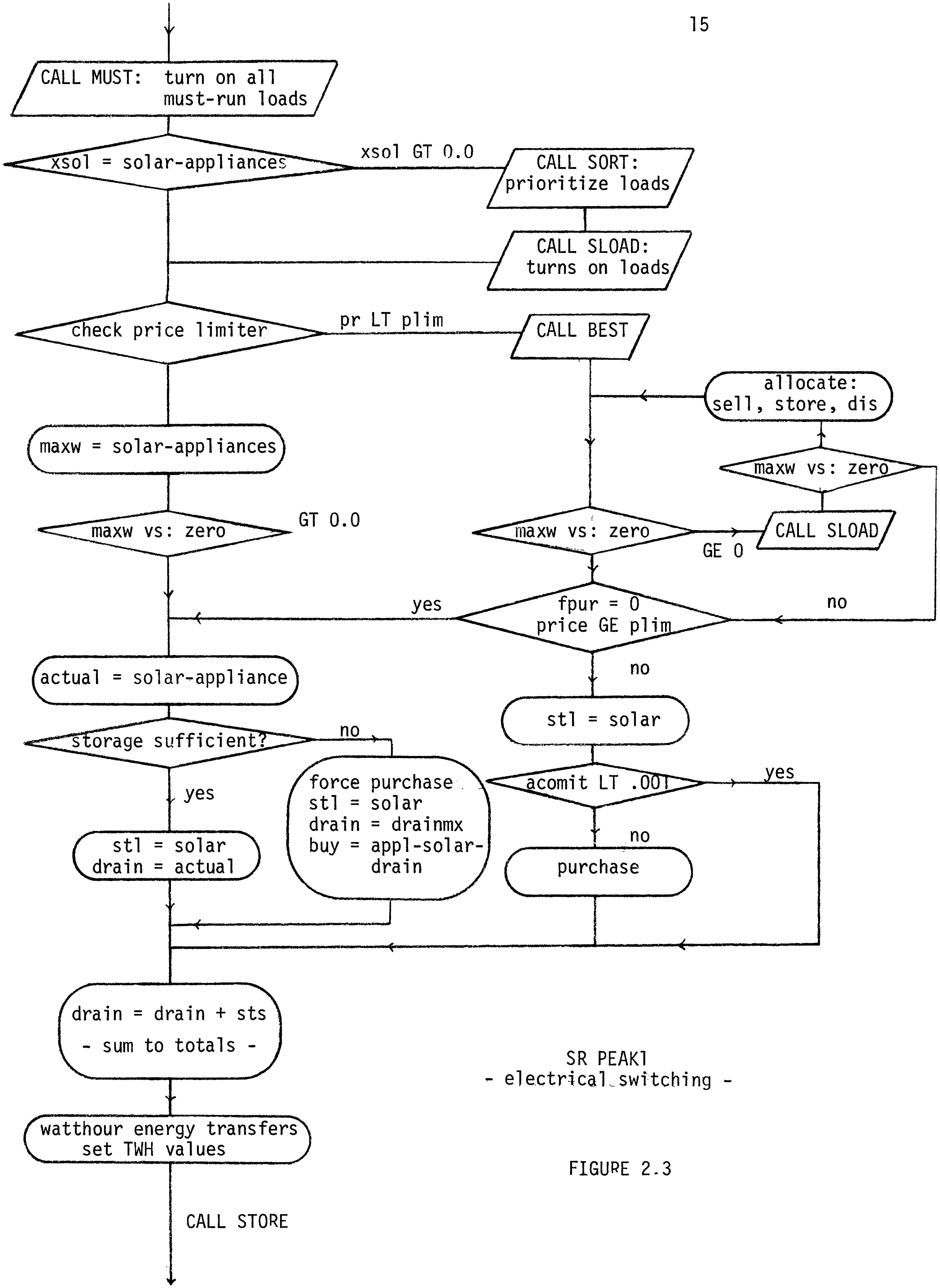

enter increment
determine max charge rate
charge batts
subroutine BATLOG
subroutine PEAK1
(electrical switching)
compute excess solar
check price contingencies
switch on appliances
allocate excess solar:
o storage
o sellback
o dissipate
consider storage discharge
drain storage
force purchase (if storage insufficient)
purchase from utility
subroutine PEAK1
subroutine STORE
adjust SOC on batteries
return to new increment

FIGURE 2.2



SR PEAK1
- electrical switching -

FIGURE 2.3

2) Charge by Photovoltaic array -- there exist three value functions to deal with alternative decisions in treating excess solar:

VSS	value of storing solar
SB	value of sellback to the utility
VD	value of dissipating to a thermal load (hot water heater, space heater, or the ground)

For comparison purposes, there are four choices for setting their relative values:*

OPTION =	0	VSS = T.0*PR SB = 0.9*PR VD = 0.0
	1	VSS = .1 (or .085 if SOC .GE. SOCBUY or PR .GE. PRICEP) SB = .09 VD = .08
	2	VSS = SOC and 4CAST dependent SB = BUYBK rate and PR dependent VD = 0.0
	3	(optimal model to date) VSS = PRICEP*EFF5*DCAC VD = PR*BUYBK*DCAC

where:

PR = current price of electricity from the utility
PRICEP = utility peak price
BUYBK = utility buy-back efficiency
EFF5 = overall storage efficiency
DCAC = inverter efficiency

Notes on Option 2

The value of sellback is straightforward -- it computes the value of the electricity that could be sold now:

SB = BUYBK*PR*DCAC

It takes into account the buy-back rate, the current price, and the inversion loss. This yields ¢/watt-hr which the owner could make during the current increment with excess solar.

VSS is more complicated. We wish to find a reasonable value of electricity now for comparison purposes. However, since we are storing for future use, we essentially must find a present worth from an expected use period. This present worth is a function of many things, primary of which are the following:

1) tomorrow's weather -- since storage capacity is assumed to be set up for a full one day capacity, considering tomorrow's weather with the current SOC should determine the likelihood of full use.

2) current SOC -- lessen the value for higher states of charge due to charging inefficiencies and the decreased likelihood of full use.

3) price at which electricity is likely to be used -- this is probably the peak price period, but special logic might be developed to determine that the current cost of the stored electricity is less than the peak rate. This would be fairly simple to implement but its effect would probably be insignificant. We assume here that all storage-to-load is at peak rate.

Based on this, the following logic was set up:

1) if SOC is low and the forecast shows low insolation, set

   VSS = PRICEP*EFF5*DCAC

   Thus, the value of storage is based on tomorrows usage times the peak price times the storage and inversion inefficiencies. If the stored electricity is used tomorrow -- this is its value to the owner.

2) if SOC is low and forecast shows high insolation, set

   VSS = .5*PRICEP*EFF5*DCAC

   since environmental dissipatation losses on the battery are insignificant for up to a week, lessen the value of storing to below the value of sellback (at a 50% buy-back rate) during peak, but above the base price.

3) if SOC is high and the forecast shows high insolation, set

   VSS = PRICEB*EFF5*DCAC

   The value of storage is most likely above sellback during base price at 50% buy-back.

4) if SOC is high and the forecast shows low insolation, set

   VSS = .8*PRICEP*EFF5*DCAC

   Since storage will most likely be used tomorrow, then if peak price is high, insure that there is sufficient storage.

The values for <u>high</u> and <u>low</u> SOC were determined by making a number of runs and finding the optimum.

Note on the Forecasting Model:
A routine was developed to take the next day's noon-hour insolation values and set a flag (I4CAST) to (0) if insufficient solar or (1) if sufficient solar is expected. A random integer generator is used to reverse the forecast decision with a specified probability, and the insolation breaking point (for solar sufficiency) was set by examining insolation values vs: PV sufficiency for previous runs. The values of HDIR and HDIF (direct and diffuse insolation) rather than SOLAR (PV electricity available) were used since the electricity figure says nothing regarding adequacy in meeting load demand. If one assumes correct system sizing, the insolation values will determine adequacy without reference to load characteristics.

3) Electricity exiting storage to load -- SOLOPS declares the priority of storage to load by the setting of the PLIM parameter in combination with computation of FPUR in the function FP. Together, they regulate the conditions under which purchases are made. Storage to load is made a priority (purchases minimized) whenever the current purchase price is greater than or equal to the value specified for PLIM. This logic is further described under PLIM in Tatum's <u>Input Parameter Definitions</u>. (8)

4) Electricity exiting storage to utility -- if the current price is above PLIM, and if I5FLG1 is set to include the sale of stored electricity to the utility, then any portion of the maximum dischargeable electricity (DRAINM) which does not go to load will be sold back to the utility.
   Further development would compare the current value of stored electricity with the value of selling back.

<u>Storage Handling</u>

<u>Charge/Discharge</u>

As stated, primary electrical switching logic is contained within the main control routine. The maximum charge and discharge rates are handled by separate calling functions, CMX and DMX, respectively. These functions use the current battery state of charge to estimate an allowable watts charged or drained for the given increment (for this study, one-half hr). A two-level constant current technique is used for both cases. For charge, a large fixed current is passed at a predetermined state-of-charge, at which point a smaller, also steady current is used to complete the charge. The break point is .8 SOC, above which charge occurs at one sixth the rate of that below this value. Charging uses a linear approximation to arrive at a projected SOC which is used to determine the average figure and the maximum charging rate for that increment. For discharge, below .2 SOC the current declines at about three times the rate for that above, and a two level approximation again is used.

The charge rate sets the battery charger load requirement as well as becoming an upper limit to the amount of excess solar to be allowed for that increment. When a logical flag calls for storage sellback to the utilities, discharge will be full for those increments under the appropriate pricing conditions (storage satisfies all loads before considering sale to the utility).

After passing through all storage switching logic, a STORE routine is called to approximate the new state of charge on the battery given the actual watts drained or charged.

Battery Voltage

The battery voltage varies with the state of charge, rate of charge/discharge relative to storage capacity, and to a small extent, on battery temperature. The equation selected gives a close approximation to the Standard Handbook for Electrical Engineers for voltage across a lead-acid cell, and is expressed by:[6]

(1) $$V = 1.965 + .045\ (I/I_8) + .075\ F + .17S + \max(0, F.\ \max(S-.8, 0)) + .5\ \min(0, F\ .\max(.2-S, 0))$$

V = cell potential
I = current in amperes (+ charge, - discharge)
I_8 = charging current at 8 hour rate ($C_8/8$)

S = level of charge/capacity
F = flat +1 charge
-1 discharge

Here 1.965 is the basic cell voltage, and the second term represents cell resistance. Although the resistance increases as the cell nears complete charge or discharge, this effect is ignored. The coefficient of F in the third term is half of the polarization potential. The coefficient of S in the fourth term reflects the effect of concentration changes. The last two terms correct for the higher/lower cell potential as complete charge/discharge is reached.[7]

State of Charge

It is difficult to identify a good indicator of battery state of charge. Voltage, current, and temperature, the most familiar parameters, do not give accurate measurements by themselves. Specific gravity is probably the best indicator since it depends on the extent of electrolyte mixing. The state of charge in the present model is determined by solving the quadratic equation for the current resulting from the energy flow (VI) for each increment. The new SOC is thus

$$SOC = SOC + I * \left(\frac{\text{time increment}}{\text{batt capacity (a-h)}}\right).$$

Final Note

Environmental dissipation is not taken into account as a battery loss. Assuming capacity sizing for day to day storage, such losses would be considered negligible since real loss rates are estimated to be no more than 10%/month for fully charged batteries.

II.3 Economic Valuation

The SOLOPS model generates as output summations of all PV generated electricity. This includes the total watt-hours supply to house load, as well as watt-hours sold back to the utility. These form the requisite base figures for the economic valuation. Here, the value of the energy conversion system to the user-owner is determined by calculating the costs of the (otherwise) purchased electricity which it replaced. Thus the only factors contributing to the value determination are the systems initial and operating costs played against the amount otherwise spent for electricity.

The valuation becomes only slightly more complicated when storage enters the picture. It is a simple matter to keep track of excess solar electricity being used to charge the batteries. However, within the battery this electricity becomes mixed with the utility charge and it becomes difficult to assess its final value due to the various drain options and the variable (SOC-dependent) battery inefficiencies. It therefore becomes necessary to include in the analysis the electricity purchased for battery charging. This admits a straightforward valuation of all electricity exiting the battery. The situation is depicted in figure 2.4.

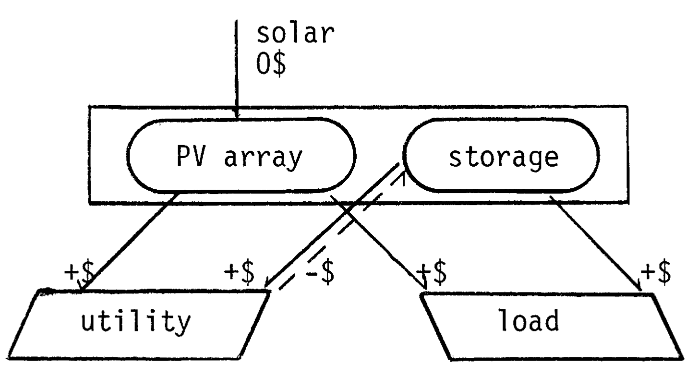


Fig 2.4

There are two components to the economic valuation model. The first applies system degradation and fuel escalation factors to the single-year SOLOPS data to arrive at a 20-year consumption replacement value. Second, a net present value calculation is performed by applying a discount rate to the yearly energy savings. This results in a gross market breakeven value. It should be emphasized that this represents a user-owner economic indifference value. An indifference to purchase given the utility as sole competitor under a scheme that includes a rated price structure and utility willingness to purchase from the array/storage system. The 'quality' of photovoltaic energy, proven by its availability during peak load hours, is reflected via application of time-of-day rates which were determined on the basis of marginal costs for each of the utility systems studied. For a more complete description of rate schedules, price escalation and cell degradation calculations, discount rate and subsystem costs, see Carpenter and Taylor (3).

Storage Costs

The breakeven capital cost computation sets 20 year system value against initial and operating expenditures as shown in the following equation:[8]

$$\text{B.E. VALUE} = \frac{(\text{NPV/ACOL}) - ((\text{FIXED COSTS/ACOL}) + \text{VAR COST})}{\text{Eff} * 1000}$$

fixed cost = \$500

var cost = \$11

NPV = \$/m^2 of array

1000 = (watts/m^2)

ACOL = 35 m^2 area of collector

EFF = .096 (system efficiency) (kw/m^2)

The breakeven value has units of dollars per peak watt of system output. The addition of battery storage to the configuration requires merely the inclusion of the additional fixed and variable costs. The determination of these costs was based largely on a recently published study by General Electric.[9] This report looks at two components, I_p and I_s combined as

$$I_c = I_p + I_s \cdot t.$$

Here, I_p is the cost associated with a storage system of a given power rating ($/kw) and I_s relates the energy storage capacity of the system, ($/kwh). With t being the maximum time discharge capability at the battery's rated power, I_c gives, in kwh, the total capital investment required.* I_p includes all power-related components (power conversion equipment, interface units, etc., i.e. anything there because the battery is there). I_s represents the storage cost i.e. battery plus balance of plant costs. Balance of plant would include beefed up foundation (sized to battery size), battery room, maintenance equipment, and so forth.

Lead-Acid Cost Figures

The G.E. estimates placed total system capital cost for lead acid batteries in a residential storage application at $200/kwh.[10] Here an 8-10 hour/day cycle was assumed over a nominal expected life of 10 years. The breakdown of this figure includes:[11]

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* Battery manufacturers price batteries both on kwh power and amp-hour at rated hour capacities.

I_p = \$130/kw

I_s = \$184/kwh (= \$138 batt costs*

\$46 balance of plant)

(1976 dollars)

For the purpose of this study, it was not necessary to include the power-related component since power conversion equipment already existed for the PV array interface.** Excluding I_p then, nominal ten-year battery costs are set at \$184 (1976 dollars). Projecting for a renewed purchase after 10 years, the 20 year fixed costs using a 3%*** real discount yields \$304/kwh (1978 dollars). This translates into a cost assumption of \$33.50/a-h.**** Operation and maintenance presents a negligible burden relative to this figure and hence was omitted. The modified valuation equation becomes, simply

$$\text{B.E. VALUE} = \frac{\dfrac{(\text{fixed Cost} + ((\text{A-h capacity}) . (\text{A-h costs})) + \text{var cost})}{(\text{NPV/ACOL}) - \text{ACOL}}}{\text{Eff} * 1000}$$

Advanced Batteries

An effort was made to derive a set of comparable figures for a DOE "best estimate" on a 1985 advanced battery. To begin with, a selection

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* A check with local manufacturers confirmed battery figures within this range when adjusted to current prices.

** Here, inverters present by far the most substantial cost component.

*** This reflects a 7% inflation rate and assumes a 10% investment opportunity.

****G.E. performed these calculations as follows: $I_c(\text{kwh}) = \dfrac{(I_s + I_p . t)}{t}$

For a renewed purchase after 10 years (only batteries are assumed replaced), the computation looks like: $184(1.03)^2 + 138\ (1.03)^{-8}$ based on design for a nominal 110 volt system) had to be made amongst the set of currently studied battery concepts. The sodium-sulphur (Na/S) battery was selected as the advanced battery system analyzed in this study based on its performance to date and the interest it has generated amongst some of the major research firms.* A detailed discussion of this battery can be found in reference (4) or by consulting the specific battery literature.

G.E. estimated total system capital costs for Na/S batteries in residential application at $92/kwh (1976 dollars). Storage related prices were set at $30 per kwh, the same figure used for utility application (this figure included balance of plant costs).[12] This would be a nonconservative figure given a residential application, but was used anyway as a "best estimate" within a state-of-the-art report. With this assumption, an Na/S advanced battery on a two-time installation (10 year life) would be $6.11/ampere-hour (a-h).

The $30/kwh figure, however, does not agree with the recent EPRI study which sets the 1985 projection at $50/kwh for battery costs alone. Added to the balance of plant costs used for the lead-acid estimates, this figure translates to $15/a-h fixed storage costs. Both of these figures ($6.11/a-h and $15/a-h) were used for comparison purposes in this study.

Battery System Without Photovoltaics

Runs were made to determine the breakeven cost of a battery facility used solely for the purpose of load leveling with no interconnections with a PV array. The valuation proceeded along lines strictly analogous to the photovoltaic model:

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* Ford Motor Company, Dow Chemical, General Electric, etc.

$$B.E. = \frac{(NPV/BATT\ CAPACITY) - (FIXED\ COSTS)}{Eff}$$

Again, breakeven units are in dollars per a-h capacity. Efficiency for the overall system (including inverter) was taken as .68. A zero degradation rate was used as an approximation in the net present value calculation since battery capacity is known to increase with initial use, tapering off to slightly below its original value towards the end of its useful life.[13]

Battery fixed costs for a stand-alone system are computed slightly differently from the previous case. Since no array exists, we must account for inverter costs by including power related (I_p) figures. Manipulation of the G.E. prices result in a fixed cost computation as follows:

I_p = \$130/kw (inverter)

I_s = \$138/kwh batteries

\$46/kwh bal of plant

Neglecting the \$138/kwh battery figure and assuming an 8-hour discharge cycle yields overall system costs of \$62.25 or unit costs of \$6.85/a-h. Since these are 1976 dollars, a 3% real discount rate is used to arrive at \$7.26/a-h. This figure applies to those components which will last the entire 20 years, and thus the final breakeven value should be interpreted in terms of a 20 year battery.

III. RESULTS AND ANALYSIS

Two studies were performed. The first was an experiment with the valuing of excess solar electricity which sought to determine that logic which most enhanced PV/Storage operation and economics. The second utilized this "best logic" in a regional analysis of the effects of storage capacity and battery costs on the total system breakeven value. An examination of breakeven costs for batteries as a stand-alone, on-site storage facility (no PV) is also included.

III.1 Search for a Best Logic

Description

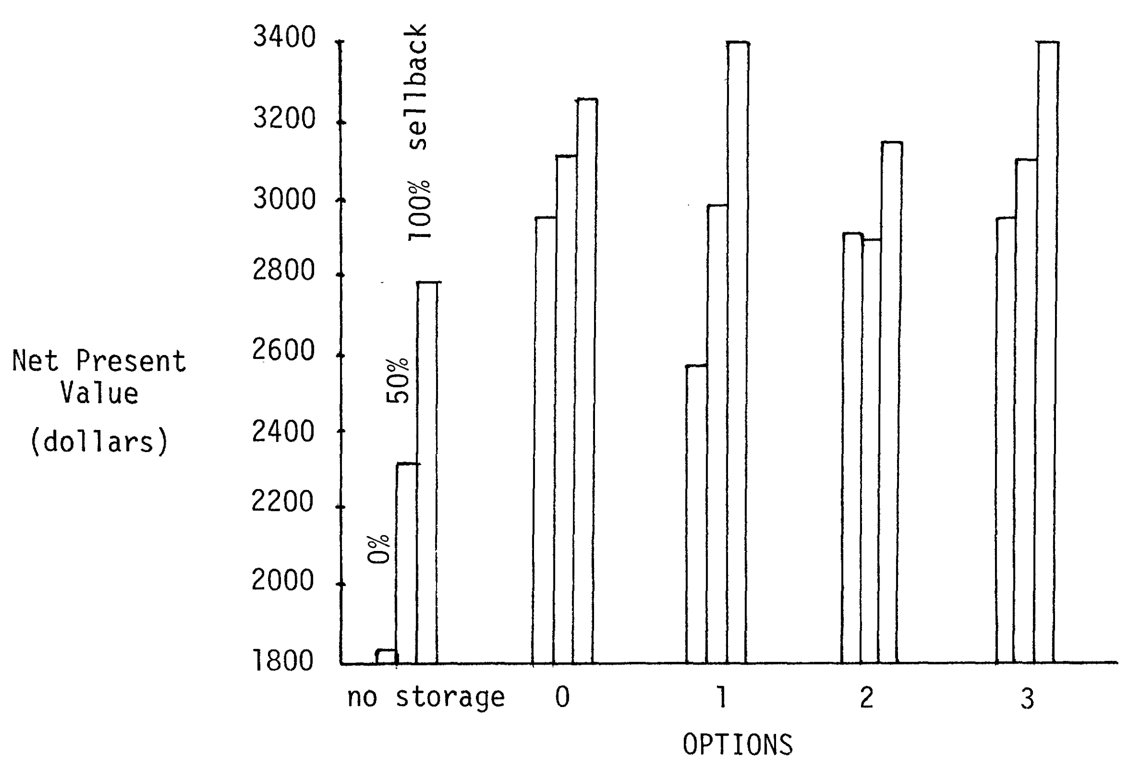
The addition of storage to a photovoltaic energy conversion system introduces the value optimization question of when to purchase and sell to the grid. Since both photovoltaics and storage offer themselves as independent investment opportunities for grid-interconnected devices, there exists the potential for competition between them in a dual application. Storage is meant to supplement the photovoltaic array by offering maximum use of its output, but in so doing, suffers from less than maximal use of its own contribution capacity. Hence, their combination will necessarily yield a figure less than their additive overall values.

Various storage logics were developed in attempt to maximize this value. These were described in section II.2 and the results are summarized in figure 4.1 with a listing of net present value for operation over a 20 year period. In this figure, each option designation in the far left column offers a brief explanation of the logic used in valuing (and hence allocating) excess solar electricity. Here, VSS is the value of storing, SS, selling to the utility, and VD, that of dissipating to thermal loads. As mentioned previously, dissipation valuing (VD) requires further work and hence was set below the others in

FIGURE 3.1

location and weather data:	Miami 1975
module efficiency	9.6%
area of collector	35 m^2
battery capacity	100 A-h

	NPV	BUYBK
No Storage	2800	100%
	2318	50%
	1837	0%
option 0: storage with	3255	100%
VSS.GT.SB.GT.VD	3101	50%
no forecasting	2947	0%
option 1: storage with	3398	100%
VSS=f(pr,SOC)	2987	50%
no forecasting	2576	0%
option 2: storage with	3142	100%
forecast-dependent battery	2882	50%
charge and VSS	2906	0%
option 3: BEST LOGIC	3419	100%
Storage priority except	3101	50%
during 100% buyback	2950	0%
VSS = PRICEP*DCAC*EFF5		
SB = PR*BUYBK*DCAC		



all cases. The breakeven value is not listed here since this requires computation of battery fixed cost, a parameter which was set to vary in the second part of this study.

Explanation

Numerous attempts were made at getting the forecast logic to prove itself. Runs were made changing the values of the various assumptions (insolation breakeven, forecast probability, etc. (see section II.2)), all of which had a marginal effect on the outcome. The factors which stand out as being significant are the buy-back rate, the peak/base-price differential, and the current price period. This is reflected in BEST LOGIC above.

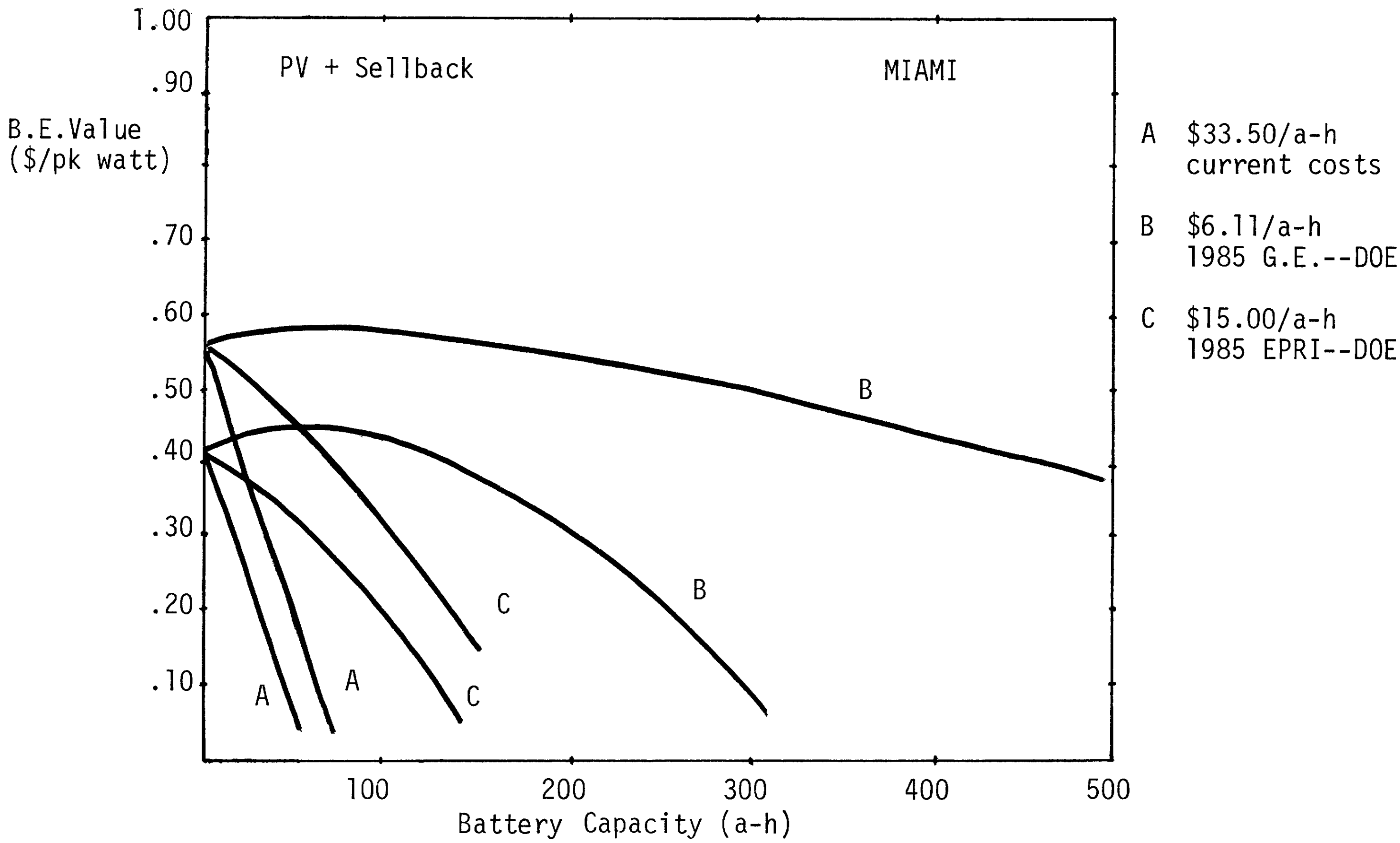
An efficient forecast model would yield improved breakeven cost figures over the nonforecasting techniques of assessing excess solar. Obviously the optimization scheme here is lacking. Examination of the incremental output reveals 1) that the forecast and value functions do what they are told to do, and thus 2) either the initial logic assumptions are invalid, or the values being toyed with are more complex functions than presumed. In the latter case, it is thought that interparameter sensitivity blurs individual parameter sensitivity to program output. The equations depicting component operation are not always linear, and thus neither are the relationships among specific variables. Additional sophistication might be added to this model by incorporating an objective function to model these relationships in an optimization format. It is doubtful even then, however, that the figures would offer a significant improvement over the 'best logic' shown here. The reason for this is inherent in the competition/complementarity question which should be made clear after presenting the second part of this study.

II.2 A Geographic Analysis Using Best Logic

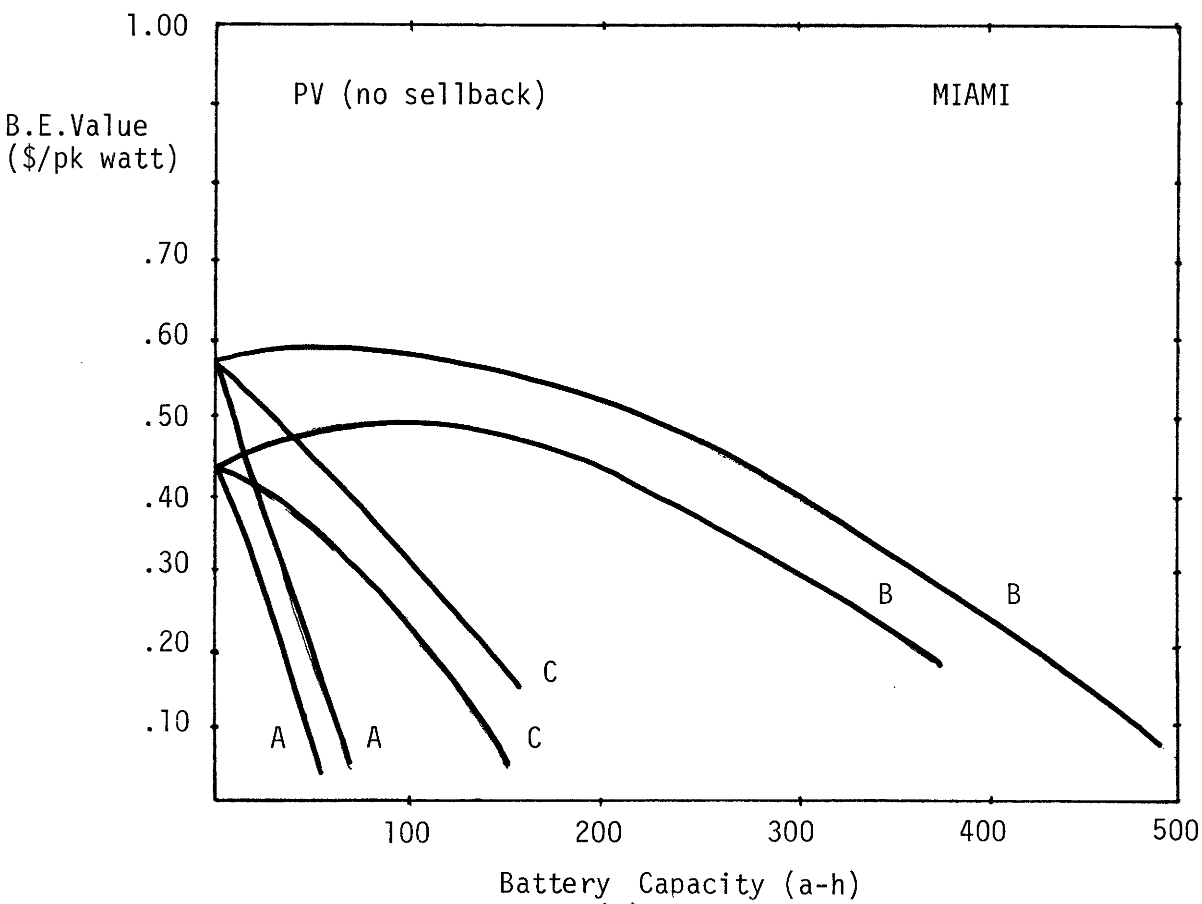
Three sites were selected to determine the effects of weather characteristics and utility rate structure on the advantage of adding a storage capability to a PV residence. Results are graphed in figures 3.2- 3.4 with total B.E. value set against capacity for various battery costs and buy-back schemes. Definition of B.E. value as it applies here is given under section II.3 (Economic Valuation; Storage Costs). The upper (a) graphs on each page illustrate the case whereby a storage facility would be adopted to satisfy load demand when array output was insufficient, and subsequently sell any remaining stored electricity to the utility. The lower (b) graphs represent a storage arrangement used solely to supplement the PV system in handling house load. Under this scheme, only excess PV electricity was sold back to the utility. Each graph portrays 3 curves, labeled A, B, and C. All 'A' curves are representative of current battery system costs at $33.50/a-h. The 'B' curves are for DOE'S best estimate for a 1985 storage cell based on a G.E. study. This figure is roughly $6.10/a-h. The EPRI 'best estimate' for 1985 was significantly different at $15.00/a-h, shown by the 'C' curve, and is considered the more realistic figure.

In no cases do current battery costs, nor the EPRI-DOE 1985 projections, effect an increase in photovoltaic economics. Only for the G.E. 1985 estimates do we see an improvement in PV-breakeven costs.

FIGURE 3.2

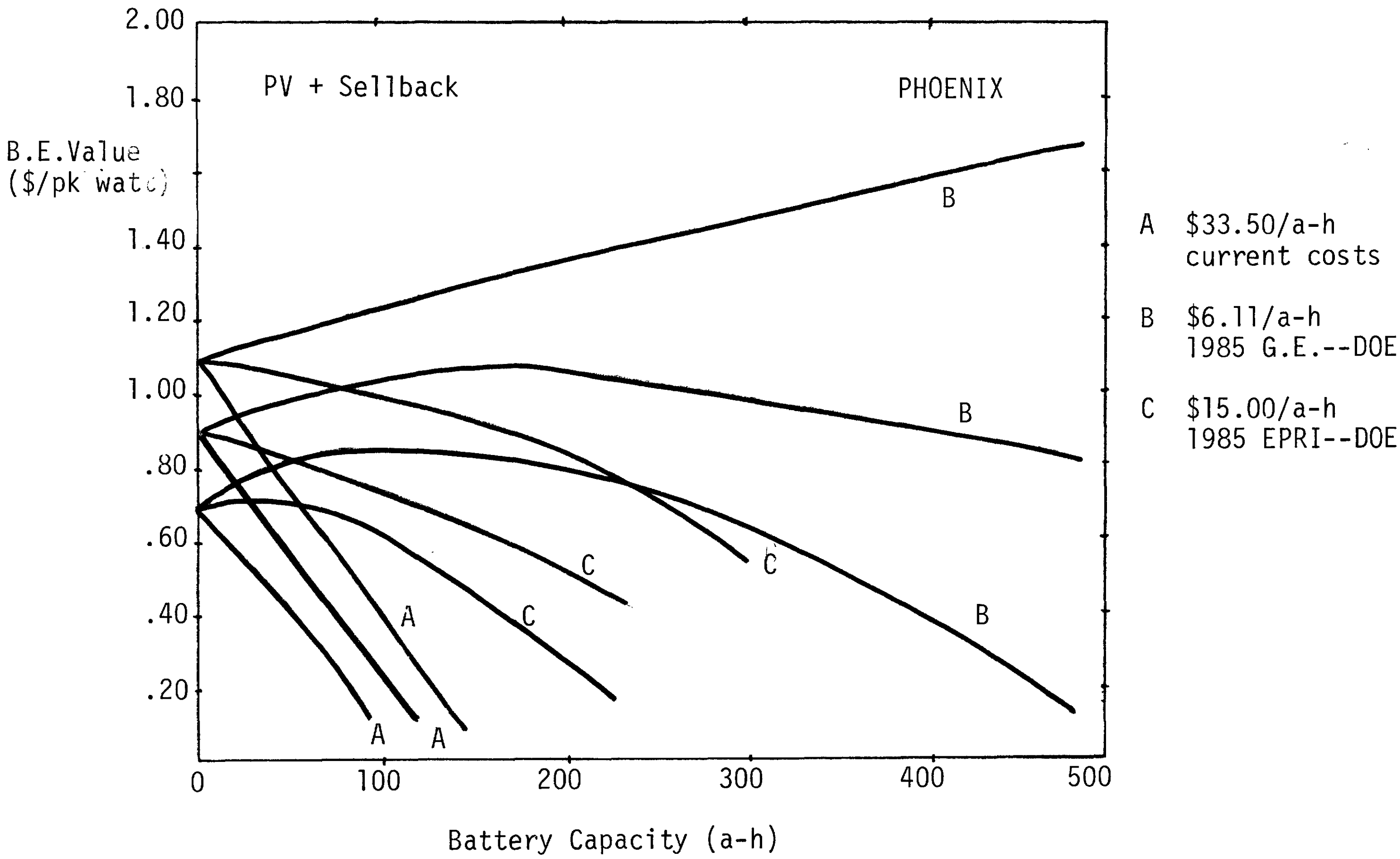

PV + Sellback
MIAMI
B.E.Value
($/pk watt)
1.00
.90
.70
.60
.50
.40
.30
.20
.10
A
A
B
B
C
C
100
200
300
400
500
Battery Capacity (a-h)
A $33.50/a-h
current costs
B $6.11/a-h
1985 G.E.--DOE
C $15.00/a-h
1985 EPRI--DOE

(a)

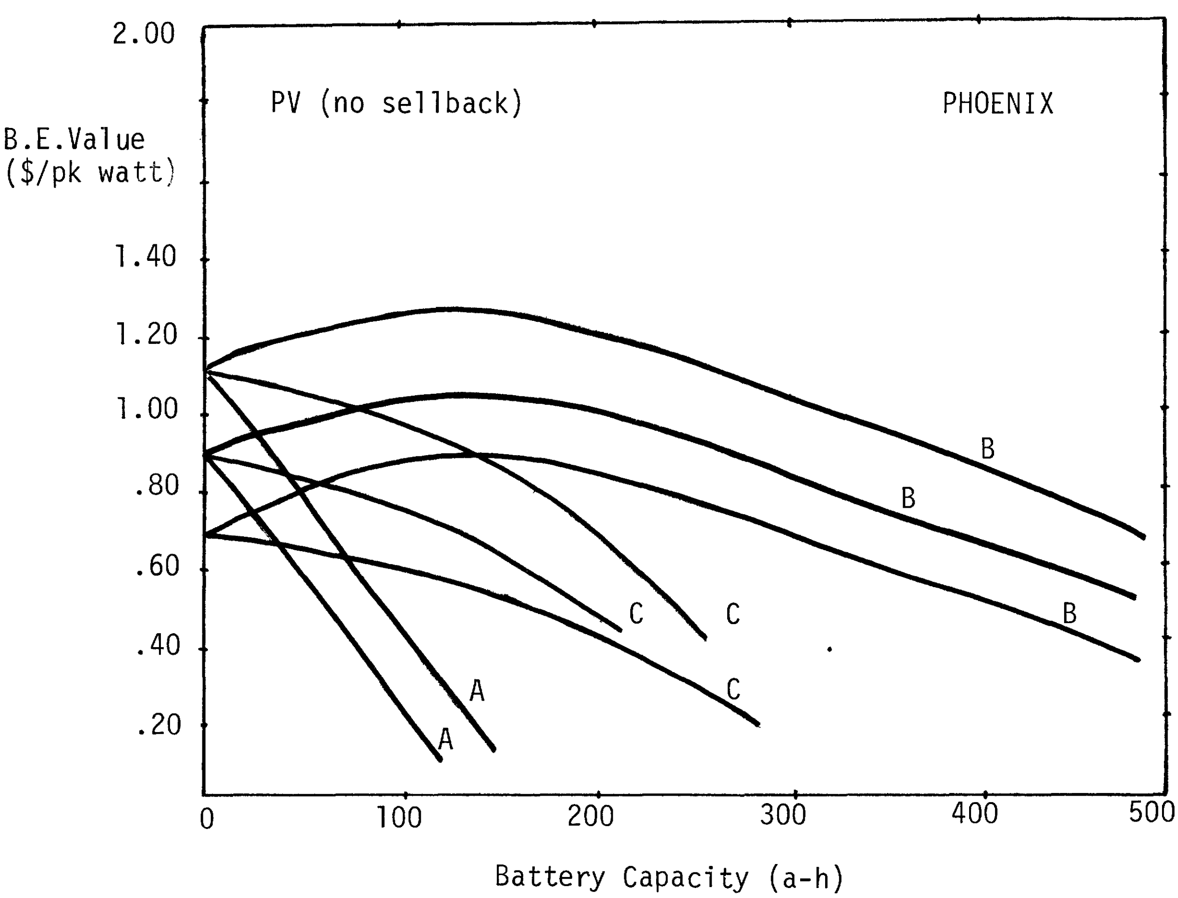

PV (no sellback)
MIAMI
B.E.Value
($/pk watt)
1.00
.70
.60
.50
.40
.30
.20
.10
A
A
B
B
C
C
100
200
300
400
500
Battery Capacity (a-h)

(b)

FIGURE 3.3

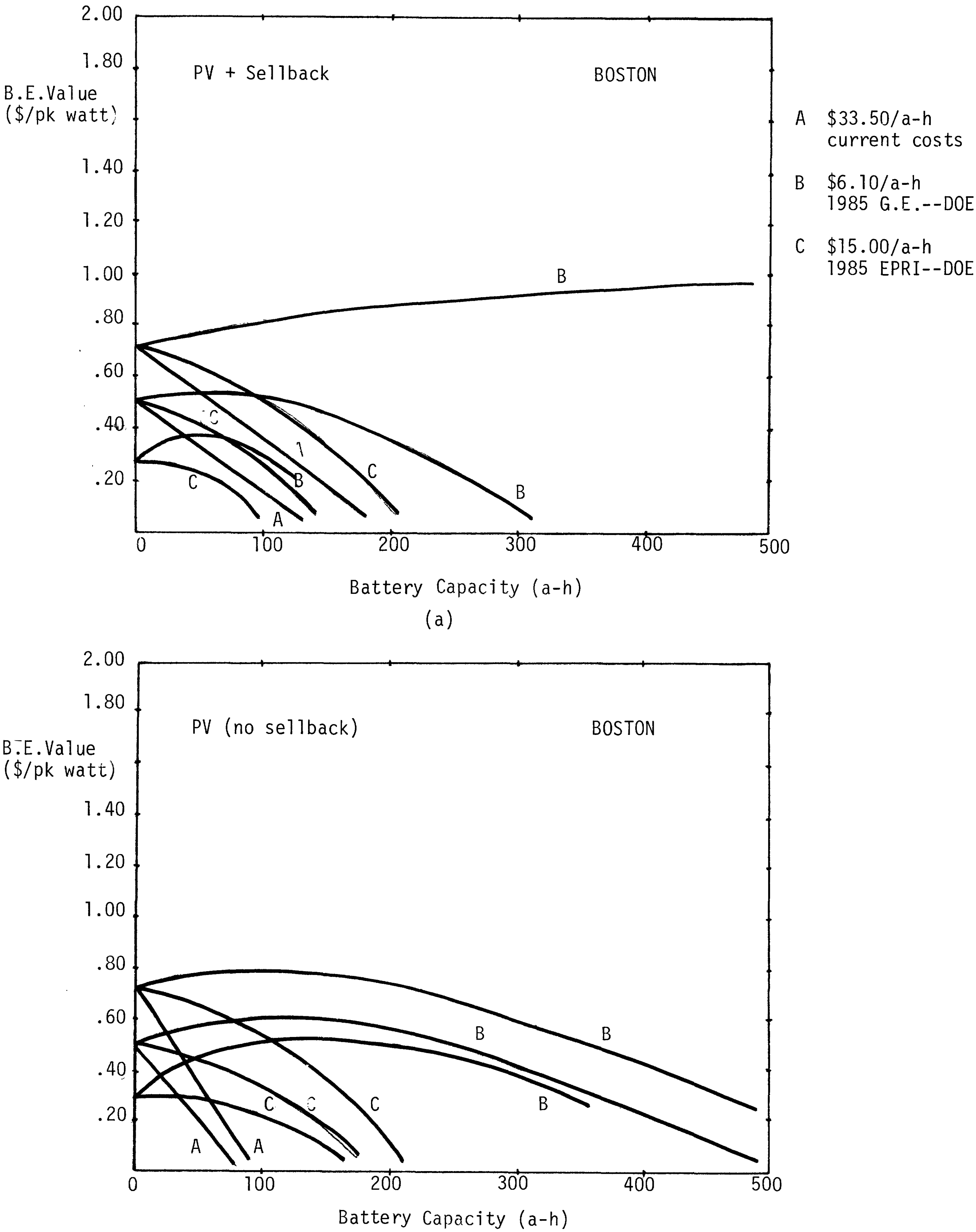

PV + Sellback
PHOENIX
B.E.Value
($/pk watt)
2.00
1.80
1.40
1.20
1.00
.80
.60
.40
.20
0
100
200
300
400
500
Battery Capacity (a-h)
A
B
C
A $33.50/a-h current costs
B $6.11/a-h 1985 G.E.--DOE
C $15.00/a-h 1985 EPRI--DOE

(a)


PV (no sellback)
PHOENIX
B.E.Value
($/pk watt)
2.00
1.40
1.20
1.00
.80
.60
.40
.20
0
100
200
300
400
500
Battery Capacity (a-h)
A
B
C

(b)

FIGURE 3.4


2.00
1.80
B.E.Value
($/pk watt)
1.40
1.20
1.00
.80
.60
.40
.20
PV + Sellback
BOSTON
A $33.50/a-h
current costs
B $6.10/a-h
1985 G.E.--DOE
C $15.00/a-h
1985 EPRI--DOE
B
C
B
C
B
C
A
0
100
200
300
400
500
Battery Capacity (a-h)
(a)
2.00
1.80
B.E.Value
($/pk watt)
1.40
1.20
1.00
.80
.60
.40
.20
PV (no sellback)
BOSTON
B
B
B
C
C
C
A
A
0
100
200
300
400
500
Battery Capacity (a-h)

Selling Storage vs: Not selling

For a storage sellback opportunity, the value of adding a storage facility can virtually increase without bound (within the capacity ranges of interest) given a favorable tradeoff between peak/base price differential and battery prices. Raising the utility buy-back rate increases the impact of the former and hence the runaway curves in the (a) graphs for Boston and Phoenix. The storage unit comes to serve the grid itself, a virtual purchasing sink, and the residential storage behaves more and more as an independent dispersed storage device.

Table 3.1 shows an increase in value differential (over the no-store case) resulting from a lowering of the buy-back rate. Doing so forces a more effective complementarity (excepting those nonpeaking cases). The reason for this is as follows: the lower the buy-back rate, the lower the value of a stand-alone storage facility, while the PV system becomes more in need of storage lest its excess solar is (or be essentially) discarded. Therefore total system capture of energy becomes more important as the utilities are less willing to purchase system excess. This point also came out of a previous G.E. study (4). It should be pointed out however, that if a value was assigned to dissipate electricity (to a thermal load for instance) the system value increases would not be as sharp for the lower buy-back rates. The option would be created to dissipate electricity at a real value possibly greater than a utility purchase price.

For no storage sale to the utility, the previous discussion holds without the confusion of a rising capacity/value relationship at the higher buy-back rates. Here, stand-alone storage would exist only to serve the immediate house load, forcing an optimum capacity to fall out. For a tandem operation, this condition becomes pronounced, as storage is more severely limited due to photovoltaic contribution to the load.

Optimum Storage Capacity

For the least expensive battery (B curve) it is seen that the storage no-sell option shows optimal battery capacities in the range of 100-200 A-h. This converts to 11-22 kwh, approximating a typical full day residence demand. With no storage sale opportunity, the residence load restricts the battery function to what it can satisfy in the limited time period of reduced insolation.

Breakeven Battery Costs

Figure 3.5 presents the results of an attempt to determine by region the breakeven battery prices as a function of battery capacity and associated fixed costs in a stand-alone operation.*

The Miami characteristics were such that batteries could not even prove their worth in paying back the fixed, storage-related costs, let alone the batteries themselves. The great disparity between regions is a strong display of the influence that time-of-day price structure has on battery economics. It should be noted that battery costs are shown in an expected 20-year life. (Cost computations are given in section II.3).

---

*Values become insignificant near zero battery capacity owing to the limits on the modeling equations used (particular equations are discontinous at a zero battery capacity). Also, battery capacity was used as a logical flag which inactivated certain switching logic and turned off entire routines when a zero capacity was specified.

TABLE 3.1

Breakeven Value Differentials over the no-storage case after addition of storage at $6.11/a-h and $15/a-h (as willingness by the utility to purchase excess solar goes down, the value of supplementing PV with storage increases by proportion):

	Buyback	Percent Increase in B.E. Value	
		$6.11 A-h	$15.00/A-h
BOSTON			
No Storage Sold	100% BB	11% increase	none
(only excess PV)	50% BB	22% increase	none
sold to the utility	0% BB	86% increase	
Storage Sold	100% BB	22% increase*	none
(in addition to	50% BB	14% increase	none
PV) to the utility	0% BB	36% increase	
PHOENIX			
No Storage Sold	100% BB	15% increase	none
	50% BB	14% increase	none
	0% BB	31% increase	
Storage Sold	100% BB	26% increase*	none
	50% BB	19% increase*	none
	0%	30% increase	

*For breakeven values estimated at 200 A-h capacity since residential units greater than this would entail unreasonable capital outlays in addition to requiring more sophisticated control and maintenance.

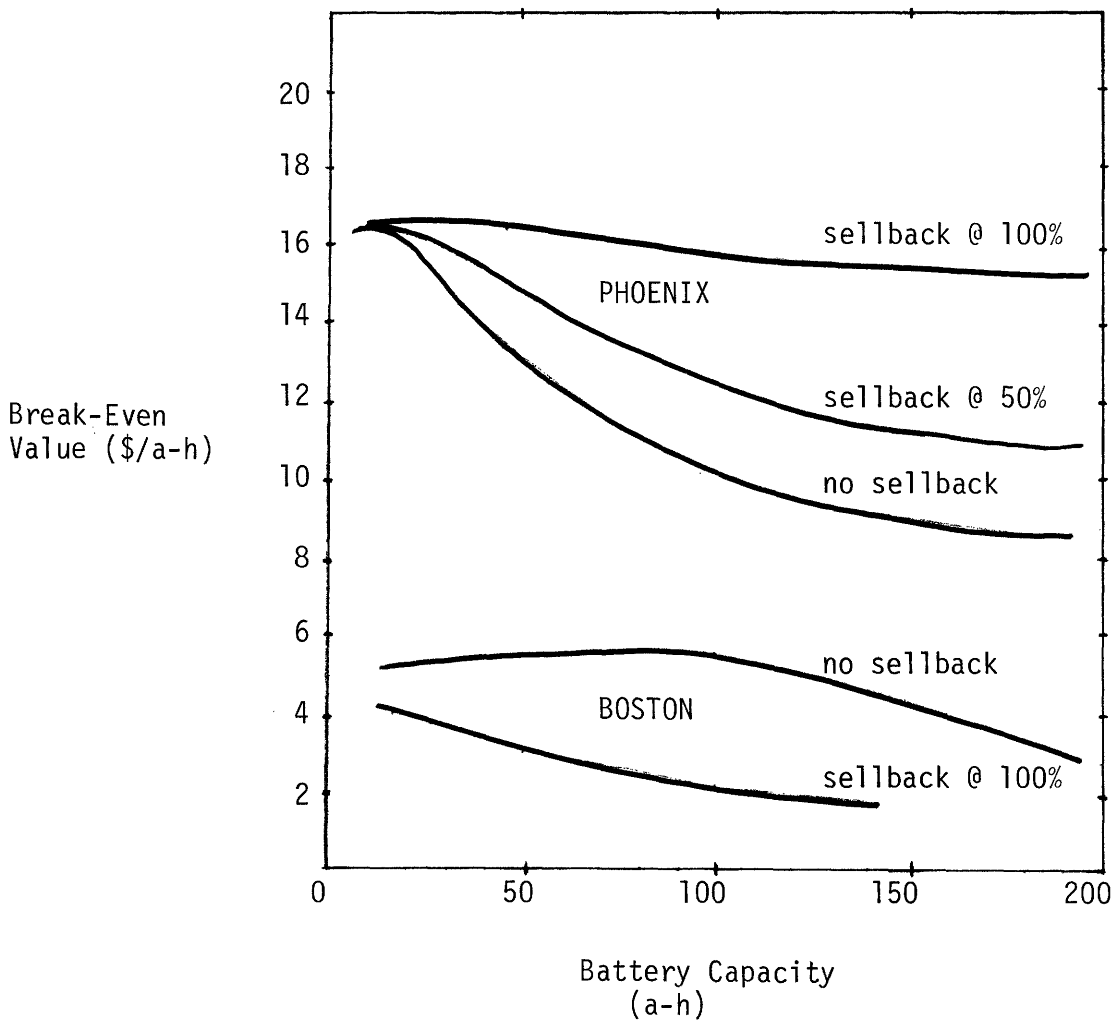
The inversion of the sellback curves for Phoenix over the other regions displays primarily the relative importance of battery efficiency and rated price structure:

- For low peak/base price differentials, battery efficiency becomes a significant parameter. The sale of storage results in greater discharge depths, a condition which, as discussed in section II, costs in terms of efficiency.
- Greater price differentials (from peak to base) obscure this relationship as a greater value is assigned to the ability to manipulate high quality electricity. In other words, the ability to store low-cost electricity for use during relatively high cost periods is a dominant criterion in establishing battery economics.

This would help to explain why some of the breakeven curves (B curves in figures 3.3 and 3.4) did not reach a maximum in the range considered. A storage-sell logic coupled with higher buy-back rates results in an increase in system value which approaches being linear with storage capacity. In this case (B curves), the battery cost projection is below the breakeven value of batteries in a standalone (battery plus utility, no PV) configuration, and the regional price structures showed sufficiently wide peak-to-base price differentials.

In figure 3.5, breakeven value is seen to peak well below a full day storage capacity. Explanation for this is shown by the trade-off between fixed costs and quality of electricity. Photovoltaics allowed storage of free power, whereas in a stand-alone configuration the higher cost energy restricts the desirability of capacities in excess of the daily peak period demand.

Break-Even Battery Costs
(no photovoltaics)



voltage = 110
fixed costs are
1985 projections

figure 3-5

III.3 SUMMARY

- Increased sophistication of the forecast model would probably show at best a marginal improvement in the modeling for an optimum battery-PV system complementarity.

- Storage and photovoltaics are competetive in the sense that they each vie for the residential load demand at the highest price purchase period. There are necessary functional and logical contingencies resulting from their dual application which restrict their dual system performance below the additive value of each in a stand-alone operation.

- In none of the cases considered do current battery costs prove that storage can improve PV economics. DOE's best estimate on advanced batteries for 1985 does show enhanced economics for a restricted set of operations and policy schemes, however this is using lower limit (highly improbable) cost figures.

- With the willingness on the part of the utilities to purchase residential stored electricity, a large peak/base price differential coupled with low battery costs results in a total-system value which improves with increasing battery capacity. Under these circumstances alone do storage batteries improve the economics of photovoltaics.

- The less the utilities are willing to pay for excess PV output, the more important storage becomes as a complementary unit. It increases total system energy capture.

- Optimal battery capacity is approximately around a typical full day residential load requirement, with capacity decreasing as costs rise.

Work suggested for further development on this model, or areas of interest for further analysis include:

- attempt an improvement over the valuing logic.

- develop a dissipation value logic to value the allocation of excess solar to thermal loads.

- run a sensitivity analysis on battery efficiency in the breakeven value computations.

- develop a degradation curve which models battery capacity over its rated life. Net present value is fairly sensitive to this parameter, particularly for the storage stand alone runs.

- vary the array size. Previous studies revealed an optimal array sizing of 35 m^2. This is represented by a peak in the per unit net breakeven value, and it is expected that storage will effect this value.

FOOTNOTES

1. Reference 4, Vol I, pg. 2-7.
2. Ibid, pg. 5-17.
3. Reference 2, pg. 4-9.
4. Reference 9.
5. Reference 5, pg. 4-76.
6. Ibid.
7. Ibid.
8. Reference 3.
9. Op cit, G.E., Vol. 1.
10. Ibid, pg. 5-17.
11. Telephone conversation with Mr. A.W. Johnson. Mr Johnson was project manager for the G.E. Study (ref. 4), August 24, 1978.
12. Ibid.
13. Telephone conversation with Mr. Bruce Migell of Atlantic Battery, Watertown, Mass., August, 1978.
14. Opcit, G.E., Vol. 1, pg. 5-16.

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1) Aerospace Corporations, Characterization and Applications Analysis of Gregg Storage Systems, prepared for the National Science Foundation, December 1977.

2) Bechtel Corporation, Energy Storage and Power Conditioning Aspects of Photovoltaic Solar Power Systems, First Quarterly Report Vol I, San Francisco, California, October 1975.

3) Paul Carpenter and Gerald Taylor, The Economic and Policy Implications of Grid - Connected Residential Solar Photovoltaic Power Systems, Masters Thesis submitted at MIT., June 1978.

4) Electric Power Research Institute, "Storage Batteries, the Case and the Candidates," EPRI Journal, October 1976.

5) Feduska, W. et al., Energy Storage for Photovoltaic Conversion: Task I, System Analysis--Utility Systems, Preliminary Task Report, Westinghouse Electric Corporation, January 1977.

6) General Electric, Applied Research on Energy Storage and Conversion for Photovoltaic and Wind Energy Systems, Final Report.

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    Volume II. Photovoltaic Systems with Energy Storage

    Volume III. Wind Energy Systems with Energy Storage

   G.E. Space Division for the National Foundation and U.S. Department of Energy, January 1978.

7) Spectrolab Incorporated, Photovoltaic Systems Concept Study, Final Report, Volume II. April 1977.

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9) Richard Tabors, Susan Finger, et al., SERI Photovoltaic Venture Analysis: Long-Term Demand Estimation, MIT Energy Lab, July 1978.

10) Jesse Tatum, A Parametric Characterization of the Interface Between Dispersed Solar Energy systems and the Utility Network, Masters Thesis submitted at MIT, September 1978.

11) Westinghouse Electric Corporation, Conceptual Design and System Analysis of Photovoltaic Power Systems, Final Report, Vol. II, March 1977.

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