FLYWHEEL STORAGE FOR PHOTOVOLTAICS:

An Economic Evaluation of Two Applications

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ABSTRACT

A worth analysis is made for an advanced flywheel storage concept for tandem operation with photovoltaics currently being developed at MIT/Lincoln Laboratories. The applications examined here are a single family residence and a multi-family load center, 8 kWp and 100 kWp, respectively. The objectives were to determine optimal flywheel sizing for the various operating environments and to determine the financial parameters that would affect market penetration. The operating modes included both utility interface and remote, stand-alone logics. All studies were performed by computer simulation.

The analysis concludes that flywheel systems are more attractive in residential applications, primarily because of differences in financing parameters and, in particular, the discount rate.

In all applications flywheel storage is seen to increase the optimum size of a photovoltaic system. For stand-alone environments, optimum configuration sizing is fairly insensitive to hardware cost of photovoltaics and flywheels for a given reliability when no diesel generator is included.

Overall, the worth analysis finds a high sensitivity in the areas of discount rate, PV capital cost, flywheel capital cost, and diesel fuel costs.

ACKNOWLEDGMENTS

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Also, a special thanks is extended to the Salt River Project, and specifically James Watkins and Marilyn George on their expedient handling of the institutional and technical barriers in supplying M.I.T. with the customer load profile data essential to the load center portion of this study.

Finally, many thanks to the members of the M.I.T. Energy Laboratory Photovoltaics Project, especially Dr. Richard Tabors, Project Manager, and Alan Cox. Where would the discount rate be without them?

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CONTENTS

CONTENTS (continued)

TABLE OF FIGURES

TABLE OF FIGURES (continued)

TABLE OF FIGURES (continued)

Chapter I. INTRODUCTION

This paper addresses economic issues that define the market environment for the advanced flywheel energy storage concept now being investigated by MIT/Lincoln Laboratories. The application is supplemental storage to photovoltaic energy conversion systems on the scale of 8 kWp and 100 kWp array sizes, as utilized by a residential and a multi-family load center, respectively.

Previous studies have indicated that total system energy capture by solar-electric conversion systems can be improved by 46-58 percent with the addition of a storage capacity roughly equivalent to an average one-day residence demand.[1] It has also been established that conventional flywheel energy storage is neither technically nor economically competitive with batteries.[2] However, for use in conjunction with photovoltaics in a residential configuration, it is suggested that flywheels can offer certain specific advantages over analogous battery functions. These advantages are obtainable only in a total system configuration, where the flywheel does not simply serve the single purpose of energy storage, but covers the function of power inversion and maximum power tracking as well. In addition, the new advanced concept incorporates magnetic bearing suspension, which cuts drag losses to levels previously unconsidered. Figure 1 illustrates where technical simplicity and cost savings find potential with this new concept in comparison with the battery/inverter and conventional flywheel/inverter systems. For a further account of design specifications, critical design areas, and development status, see [2].

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*This project was funded by the MIT Lincoln Laboratory under contract 87861.

SOLAR PV SYSTEM COMPARISON

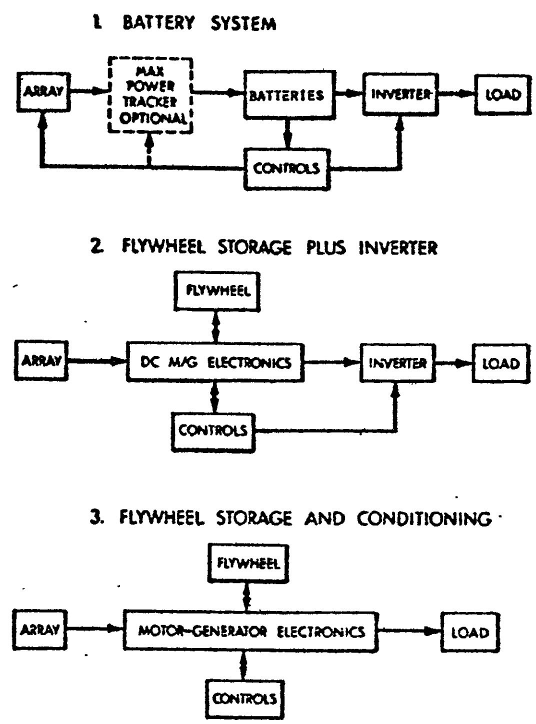

FIGURE 1

Chapter II. ORGANIZATION OF THE STUDY

II.1 Study Objectives

There were two objectives to this study. First, the appropriate sizing of a flywheel unit had to be determined for two application types: a single family residence utilizing a PV array of roughly 8 kWp capacity, and a multi-family load center utilizing an array size of roughly 100 kWp. The second objective was to simulate a range of technical and economic environments to determine sensitive market parameters.

II.2 Environments

Figure 2 shows an outline of the technical operating environments that provided the basis for testing market sensitivities. The utility interface studies were aimed primarily at determining the significance of various utility policies, including utility purchase prices for excess PV electricity and the utility rate structure, on the effect of flywheel storage on overall system worth.

The stand-alone studies included remote, non-grid-connect applications where all electricity demands, at a required reliability, were assumed to be supplied by the PV and flywheel (or PV, flywheel and diesel) system alone. The effort here was directed toward the issues of optimum configuration sizing, the cost of supply at a specified level of reliability, and the determination of distances from the distribution grid at which such a stand-alone system represented an economically viable alternative to grid-connection.

ENVIRONMENTS

- o UTILITY INTERFACE (FLAT RATE AND T·O·D)
  - PV FLYWHEEL
  - FLYWHEEL (T·O·D RATES)

- o STAND ALONE ANALYSIS
  - PV FLYWHEEL
  - PV FLYWHEEL DIESEL

FIGURE 2

II.3 Assumptions

Any study utilizing computer simulation with parametric variation is accompanied by a host of technical, logical, or economic modeling assumptions. The technical assumptions relate to the physical operational aspects of the hardware units employed; in this case, the flywheel and photovoltaics. Figure 3 summarizes these technical assumptions. Figure 4 lists methods for allocating and transferring watt-hours of energy within the simulation model, defined as program logic assumptions.

This study benefits from an economics routine with fairly broad capabilities for modeling the economic environment likely to exist over the operating life of the system. The assumptions defining this environment must be separated into several categories. First, the residence application must be separated from the larger load center application to reflect the difference in financing and construction characterizing these two types of projects (see Figures 5 and 6). Utility-interfaced operation requires assumptions as to the pricing environment for displaced utility electricity; these prices are listed in Figure 7. Finally, Figure 8 lists all hardware costs assumed in this study.

All figures in this paper are in 1980 dollars unless otherwise indicated.

Figure 3

Technical Assumptions

FLYWHEEL

- o Efficiencies

fixed loss:	200 watts
charge proportional:	.3 percent/hour
input electronics:	8 percent full load
	7 percent half load
output electronics:	8 percent full load
	7 percent half load
motor-generator:	4 percent full load
	2 percent half load

- o Maximum storage capacity set to vary.
- o Minimum storage capacity set to .25 * max.
- o Maximum input electronics charge capacity (in kW) set to vary as .14 times the area of the collector in m^2.
- o Maximum output electronics discharge capacity (in kW) set to vary as the peak demand divided by .9.

PV

Cell efficiency (at 28° C): .12
Cell efficiency temperature coefficient: .004
Average cell efficiency: .10
Tilt angle: latitude + 10°

DIESEL

Heat rate: 11,333 Btu/kWh

Figure 4

Logic Assumptions

Utility Interface

Distributed-dedicated storage logic modeled for operation of PV/flywheel system (flywheel is not charged by the utility)

Distributed-system storage logic modeled for operation of flywheel alone (with no PV, flywheel is charged by the utility).

Stand-Alone

Diesel generator rated to 2.33 times the average kWh demand level.

Diesel is not used to charge the flywheel but rather serves only as an instantaneous power backup.

Figure 5

Residence Application Initial Economic Assumptions

- 20-year system life
- 0 construction years
- 3 percent real discount rate
- Electricity price escalator: 3 percent/year
- Grid costs for single-phase line: $8,712/mile
- Diesel costs

  Diesel generator:
  Regression formula to fit current manufacturers costs

  Diesel fuel:
  Escalation rates vary given 55¢/gal wholesale, second quarter 1979 cost
  Escalation rate fixed at 6.6 percent/year after 1985

- Balance-of-system Costs

  -- High estimate:

  Array material and installation..........$14.3/m2
  Lightning protection....................$943.00
  Electrical equipment and installation....$522.00
  Operation and maintenance................$70/yr.

  Figures include 15 percent distribution and 15 percent contractor mark-up

  Source: G.E./SANDIA Executive Summary (vol. 1) January 1979 (ref. 3).

  -- Low estimate:

  PV array size proportional: $20.80/m2.

Figure 6

Multi-Family Load Center
Initial Economic Assumptions

- 20 year system life
- Balance of systems (BOS) costs of $20.80/m2
- 2 year construction period
- Sum-of-the-years digits depreciation

  No depreciation during construction
  40 percent debt/(debt + equity) ratio
- Investment tax credits of 10 percent
- Grid costs per mile:

  3 phase line $14,229/mile
- Diesel costs

  Diesel generator:

  Regression formula to fit current manufacturers costs

  Diesel fuel

  Escalation rates vary given 55¢/gal wholesale, second quarter 1979 start cost fixed at 6.6 percent/year thereafter

Figure 7

Utility Rate Structures

- o Electric Rate Structures (1980 $)

Phoenix

Flat Rate	$.066/kWh
TOD Rate	
TOD season:	April 1 - November 1
Peak period:	10 A.M. - 8 A.M.
Peak price:	$.071/kWh
Base price:	$.061/kWh

Boston

Flat Rate	$.0523/kWh
TOD Rate	
TOD season:	April 15 - August 15
Peak period:	Noon - 3 P.M.
Peak price:	$.125/kWh
Base price:	$.0498/kWh

- o Exogenous price inflation for electricity fixed at 3 percent/year.

FIGURE 8

COST ASSUMPTIONS

FLYWHEEL COSTS

ESTIMATED UNIT PRICE OF FLYWHEEL ENERGY STORAGE AND CONVERSION SYSTEM - 1985 (1980 $):

ITEM	LOW 1985 (LOW)	MEDIUM (1985 HIGH)	HIGH (CURRENT 197
ROTOR	$70/KWH	$140	$280
MOTOR-GENERATOR	105/KWAC	140	162
MAG. BEARING	14/KWH	28	105
VACUUM HOUSING	35/KWH	56	60
ELECTRONICS (GEN)	42/KWAC	140	140
ELECTRONICS (MOTOR)	42/KWAC	105	140
ENCLOSURE	34/KWH	45	45
SHAFT & HUB			34/KWH

PV COSTS

PV ARRAY ESTIMATES ARE DOE GOALS FOR 1985:

	1975 ($)	1980 ($)
LOW	$0.20/PK WATT	$0.28
MEDIUM	0.50	0.70
HIGH	0.65	0.91

II.4 Definitions

Breakeven Capital Cost

Throughout the analysis, the term Breakeven Capital Cost (BECC) is used in judging system or component worth. By standard definition, Breakeven Capital Cost is defined as:

$$BECC = \sum_{i=1}^{life} \frac{BENEFITS-COSTS}{(1 + r)^i}$$

where:

BENEFITS = total dollar equivalent of utility electricity displaced by the PV-flywheel system; plus, for stand-alone applications, distribution-line costs otherwise incurred.

COSTS = All costs of the system not to be included in the BECC figure.

LIFE = Assumed lifetime of the system is 20 years.

r = discount rate.

In calculating System Breakeven Capital Cost, the COSTS figure includes none of the costs associated with any component of the system. It thereby defines the total benefits that accrue to the system over its lifetime. Hence, the system BECC must account for all costs associated with: (1) the flywheel storage unit, (2) the PV modules, and (3) all balance of system. This includes all maintenance over the lifetime of the system.

The flywheel Breakeven Capital Cost maintains the original definition for BENEFITS, but defines COSTS as the balance of PV system costs plus PV module prices at an assumed module cost. Hence, it is important to note that when PV prices are attached to curves in the BECC graphs, they serve only as labels to describe the cost assumption made on the module component of the PV system, which is in addition to fixed BOS costs.

Flywheel Capacity

It is also necessary to define the term Flywheel Capacity. One characteristic of the flywheel is that its minimum state of charge be no less than 25 percent of its maximum charge capacity. The labels applied to the flywheel throughout specify this maximum charge capacity; hence, its real energy storage value is actually only 75 percent of this figure. Furthermore, losses are associated with the input and output electronics as well as the storage unit itself, the average storage capacity is reduced further. A rough approximation to the real storage capacity can be obtained by applying a factor of 0.62 to the labeled storage capacity figure (see [2]).

A Note on Analyzing System Value

One of the principle methods of worth analysis employed by this study is SYSTEM VALUE (or System BECC; see above). This has proven instrumental in comparing the effects of market parameters on total system operation. There are primarily two reasons why this has been important.

First, all studies to date have acknowledged that storage and photovoltaics are "competitive," in the sense that they each vie for displacing the first (and generally, most valuable) watt-hours of alternatively obtained electricity (either from the utility or from a diesel generator). The component that is capable of supplying energy coincident in time with a highly valued, closest alternative will render the greatest increment in system benefits in return. However, there are obvious functional and logical contingencies in a dual flywheel and PV application that restrict their system performance below the additive value of each,efined if each were to operate (and be valued) independently of the other. Hence, whereas it is certainly useful to investigate the effect of one component technology upon the economics of another, the entire story cannot be told here. System operation is fundamentally different from the summation of component operation.

This leads directly to the second reason for analyzing system value. Worth provides a rather safe comparative tool when examining the effects of sizing and market parameter trade-offs. This is because system hardware costs, at this point, can only be described in terms of goals, and the system BECC definition maximizes information content about a system with minimum reliance on market uncertainties. In addition, when system value is defined in terms of the worth of conventional electricity displaced, it takes on a special significance as energy policy becomes directed away from reliance on conventional fuels.

II.5 The SOLIPS Model and Data Base

This analysis was performed on the basis of computer simulation studies performed with the Solar Interactive Photovoltaic Simulator (SOLIPS)*. This model was designed to provide full kilowatt-hour energy consumption accounting for use in photovoltaic applications analysis. An economics package is attached and is capable of translating energy transfer summations into net present worth and breakeven capital cost

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*The SOLIPS model was developed by the author and the economics package was developed by Mr. Alan Cox, both of the M.I.T. Energy Laboratory.

figures, subject to specification of pertinent pricing, construction, and investment parameters. The model requires hourly energy demand profiles and solar weather data for the specific cases. Solar data for this study is provided by SOLMET. Load profile data was obtained by two means: The multi-family load center was represented by an actual demand tape for a master-metered apartment complex in Phoenix, Arizona; and the residence demand tape was created by the use of an existing model for residential energy consumption.

Chapter III. RESULTS

III.1 Single-Family Residence

III.1.a Utility Interface

Flat Rate

Solar and load profile data were obtained for sites in Boston and Phoenix, and are considered characteristic of the northeast and southwest geographic regions. Figure 9 outlines the issues crucial to this study and lists the simulation parameters that were varied. Figure 10 presents two graphs, which lay the groundwork for the utility-interface analysis. The case shown is for a Phoenix residence purchasing electricity from the grid at a flat rate; the utility does not purchase excess PV electricity.

The upper graph examines the effect of varying both PV array size and flywheel capacityon system breakeven capital cost. Note that the labels associated with flywheel capacity represent maximum charge capacity and that the real storage value is, in fact, roughly 0.62 times the labeled value (see "Definitions"). For 0 percent utility buyback, each configuration would be expected to reach an asymptotic benefit value as array size increased. In the zero flywheel case, for example, increasing the array size can at best serve only the solar-hour portion of the load, with no benefits accruing to electricity generated in excess of each hour's residence demand. As flywheel capacity is increased above zero, the displacement of utility electricity is extended beyond the solar fraction of the day. However, system benefits are again limited to an asymptote, since fixing the flywheel capacity restricts the number of watt-hours displaced by the system in the nonsolar hours.

This figure also reveals the diminishing returns that accrue to an increase in flywheel capacity. The finite demand of the residence over

FIGURE 9

UTILITY INTERFACE

PV + FW

ISSUES

- EFFECT OF FW ON SYSTEM WORTH
- SIGNIFICANCE OF UTILITY BUY-BACK RATE
- SIGNIFICANCE OF UTILITY RATE STRUCTURE

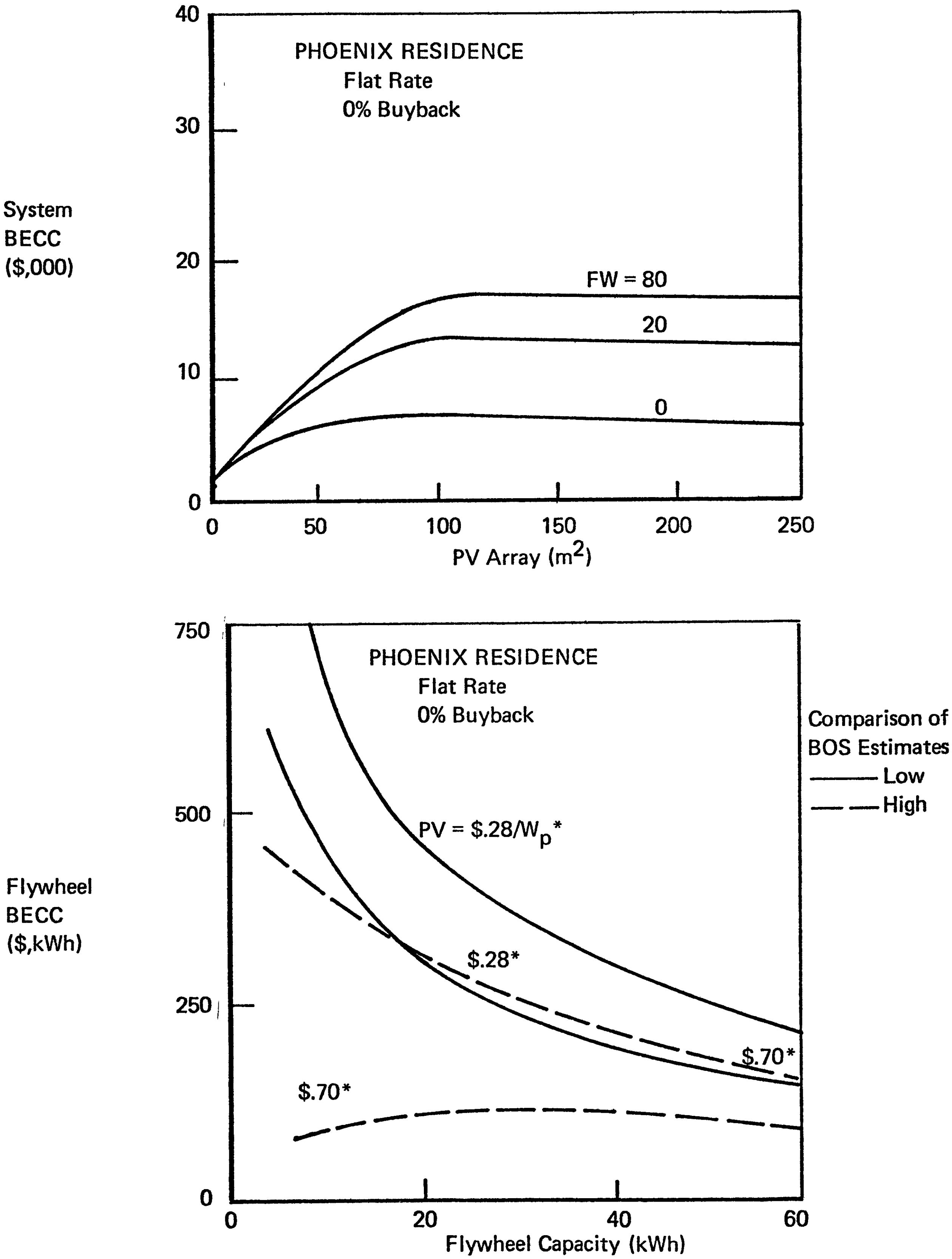
PARAMETERS VARIED

- UTILITY RATE STRUCTURE
- UTILITY BUY-BACK RATE
- COMPONENT SIZES

MEDIUM COST RANGE FOR HARDWARE COMPONENTS ASSUMED

FIGURE 10

UTILITY INTERFACE PV FLYWHEEL



* Costs = BOS + PV at Labeled Value

the year represents a maximum possible value for benefits when defined in terms of utility electricity displaced. Increasing flywheel capacity beyond what is necessary to service the nonsolar portions of the day leaves an increasing proportion of the storage capacity redundant and underutilized.

Accepting the shapes of the curves as reasonable, we can interpret the significance of the system dollar values. In this figure, any point along a given curve reveals the total dollar amount that could be afforded for the purchase of the correspondingly sized flywheel and PV array so the investor would break even in terms of total costs equaling total benefits. This sum includes all costs associated with all components of the alternative energy system, including operation and maintenance over an assumed 20-year the system lifetime. If the summation of all costs to the investor lies below this curve, then there would be sufficient financial incentive to invest in the PV and flywheel system.

Another important feature of the flywheel as revealed by this graph has been found to be true of storage in general. This is the shifting of optimum PV array size to the right as storage capacity is increased. This is true since more PV electricity is required to justify an incremental addition of energy storage capacity.

The lower curve of Figure 10 maps out the total cost to which only the flywheel component of the system would have to decline before net positive benefits began to accrue. This dollar sum includes all costs associated with the flywheel, again including operation and maintenance over the 20-year system lifetime. To establish this figure it was necessary to estimate a cost for all nonflywheel components, including the PV modules and balance of PV system. The estimates for Balance of System Costs were fixed at both the high and low values as defined in Figure 5. Flywheel breakeven costs are contrasted by the solid and dashed curves. For each BOS cost assumption, the cost of the PV module component was varied. Note again that the PV cost labels are merely indicative of the estimate used for the PV module component of the system. What follows directly from the figure is that the first kilowatt-hours of storage capacity are the most valuable to flywheel capacity, again revealing the phenomenon of diminishing returns. Taking the PV system costs as BOS + $ .70Wp, it is seen that a 40-kWh flywheel would have to sell for roughly $200/kWh total cost before adding any net value to the system when BOS costs are low, and just under $100/kWh for high cost BOS components.*

Figure 11 examines the case where the utility agrees upon a purchase price for excess PV electricity of 50 percent of its current (instantaneous) price to the customer. Under these conditions, benefits continue to accrue to the system for all electricity generated beyond that demanded by the residence. However, the incremental value of adding storage is seen to diminish over the no-buyback case.

For the lower set of curves involving flywheel BECC, it is necessary to label, in addition to module cost assumptions, the PV-array sizes, since the optimum configuration match (in terms of maximizing flywheel BECC) to any flywheel capacity always involves the addition of more PV. This is because the return on the PV investment, even when valued at 50

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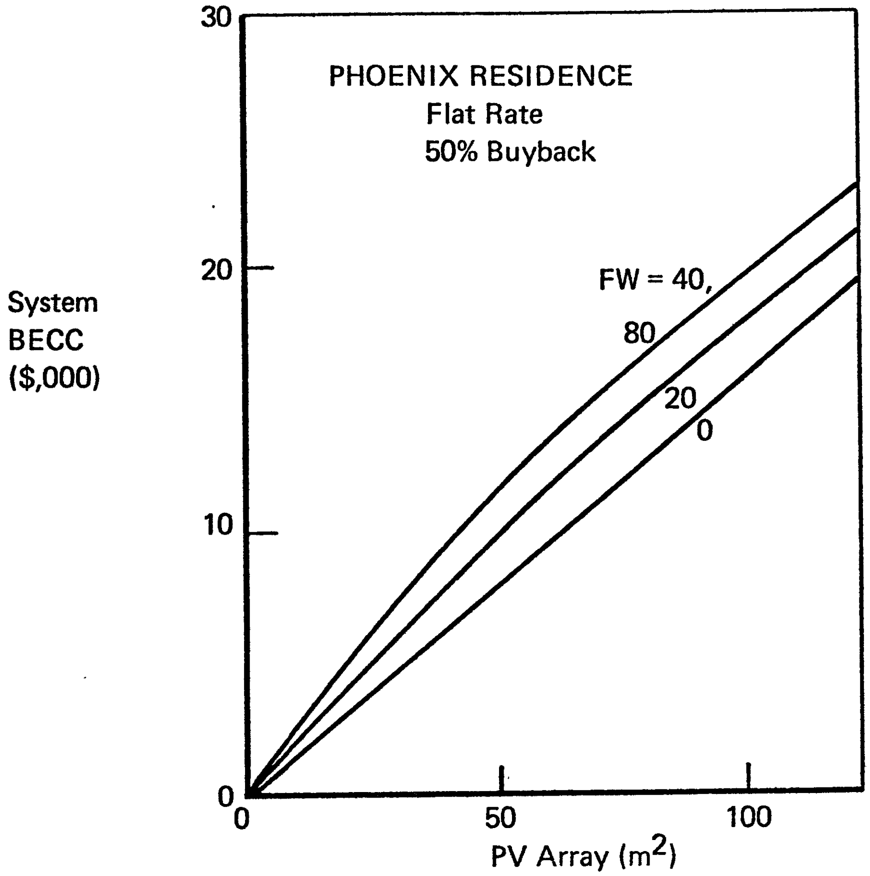
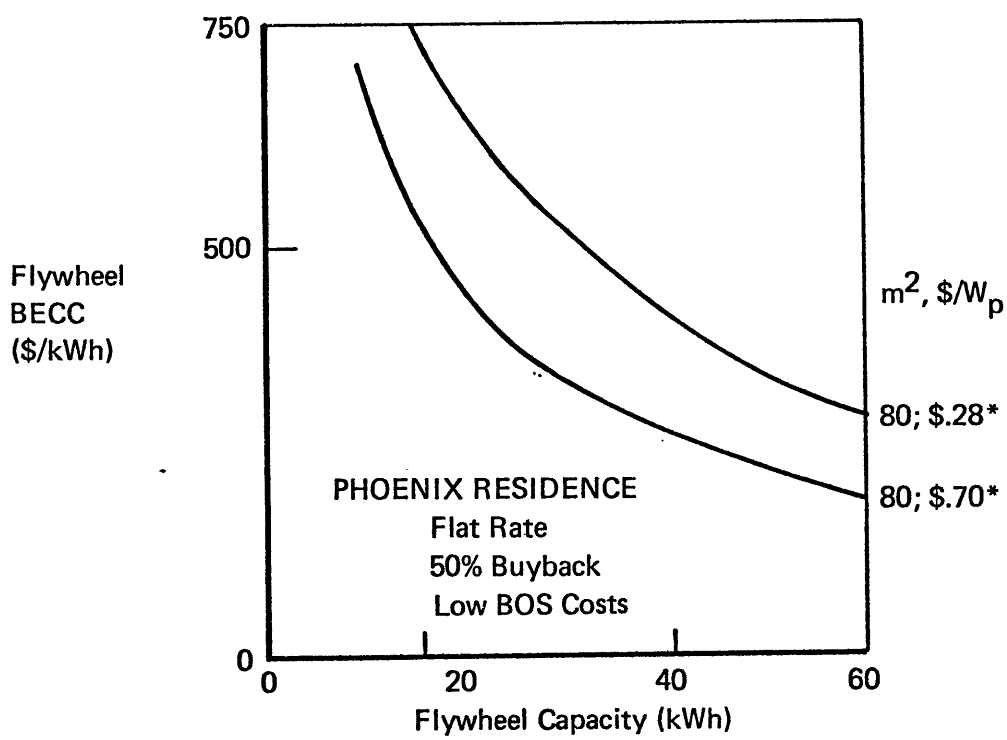
*The cost figures in the lower graph of Figure 10 are optimum in the sense that they result from finding the maximum flywheel BECC figure at each flywheel capacity over the range of PV array sizes. Hence this figure is established for optimum component (flywheel and PV) matches.

FIGURE 11

UTILITY INTERFACE PV AND FLYWHEEL SYSTEM





* Costs = BOS + PV at Labeled Value

percent of the price of utility electricity, totals a figure larger than the projected cost of the investment. These positive net benefits can then be applied to the purchase of a flywheel unit to yield the investment indifference values shown. Figure 12 depicts this relationship of PV array size to flywheel BECC.

By not fixing the PV cost assumption, but rather by assuming that PV costs are set at their non-storage-supplemented breakeven value at each buyback rate, the true relationship of just storage benefits (not "system" benefits) to buyback rate is exposed. This is shown in Figure 14. Two issues are readily apparent from this figure: First, storage looks best at the low buyback rates, and second, returns per kWh of flywheel capacity decrease as storage capacity is increased.

Time-of-Day-Rates

Figures 15 and 16 repeat the conditions of Figures 10 and 11 but assume that the utility adopts a time-of-day pricing scheme (outlined under "Cost Assumptions"). Comparison of Figures 15 and 16 indicates that a negligible increase in benefits accrues as a result of switching to the assumed time-of-day price structure. This cannot be regarded as revealing, however, since the differential rate structure used lasted for only a single season (summer), with only a 1.16/1 peak-to-base price ratio.

The sensitivity of cost figures to variations in time-of-day rates is explored in the Boston residential time-of-day study. Figure 17 presents the 50 percent buyback case for the rate structure described in Figure 19a, whereas Figure 18 presents the same case for the rate structure outlined in Figure 19b. Both sets of rates are within the range of reasonable utility policies. By extending the time-of-day

FIGURE 12

UTILITY INTERFACE:

EFFECT OF PV ARRAY SIZE ON

FLYWHEEL BREAKEVEN CAPITAL COST

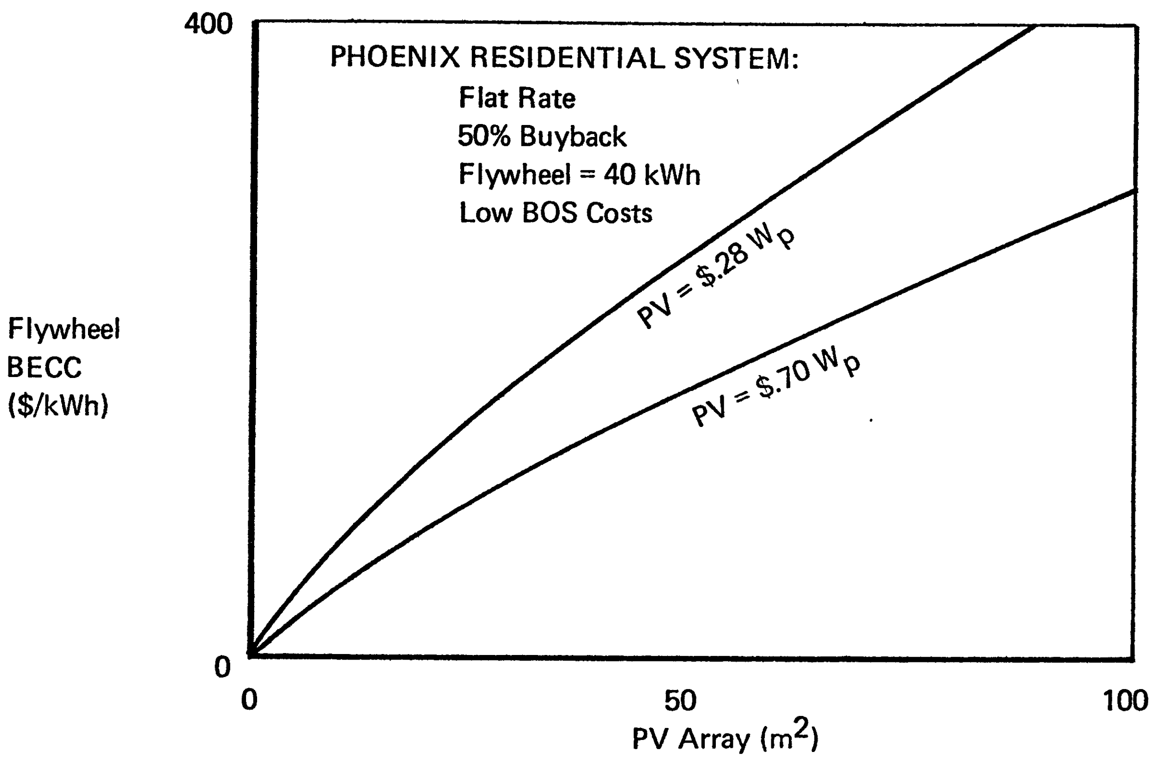
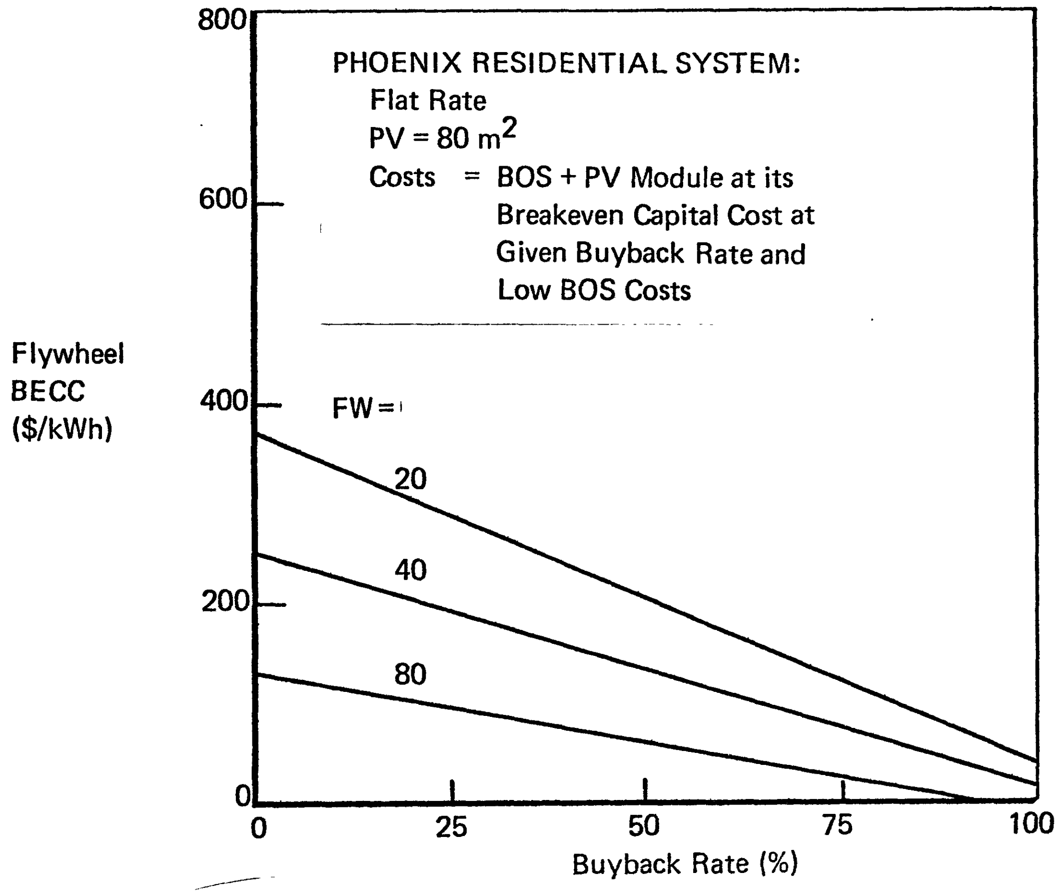


FIGURE 14

INFLUENCE OF UTILITY BUYBACK RATE ON FLYWHEEL WORTH



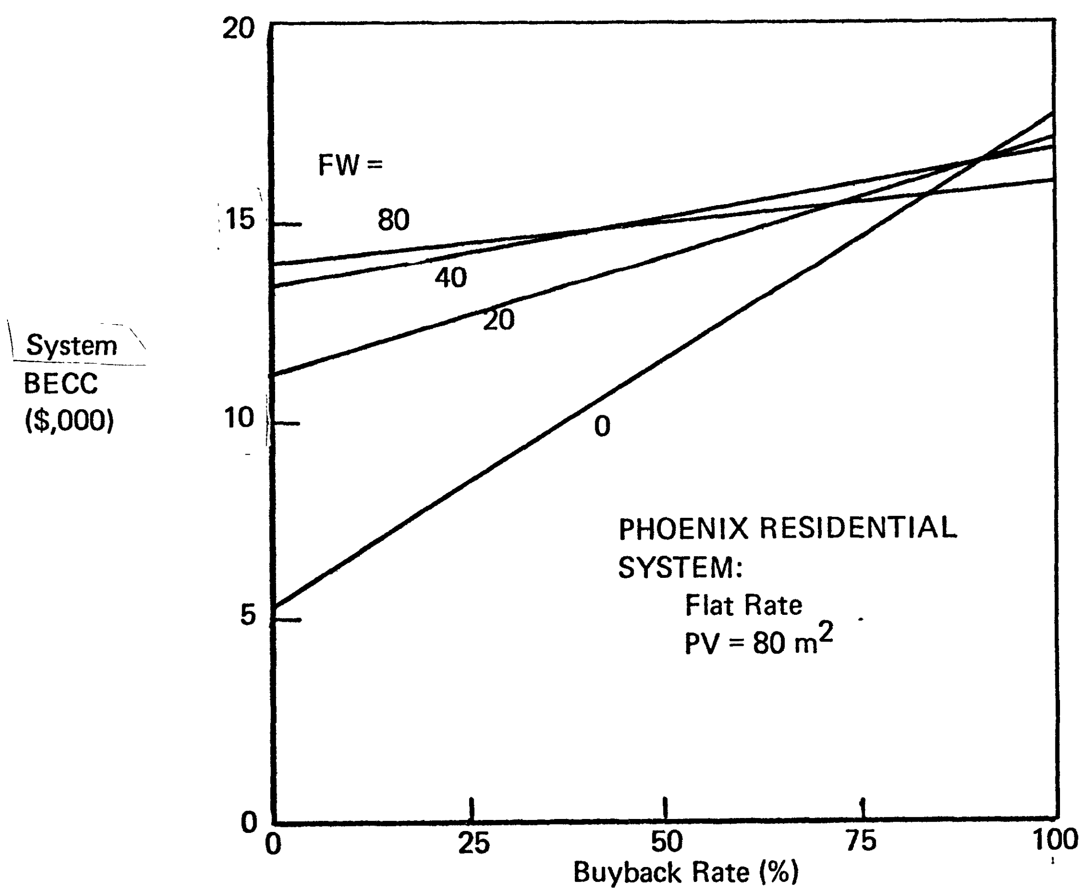
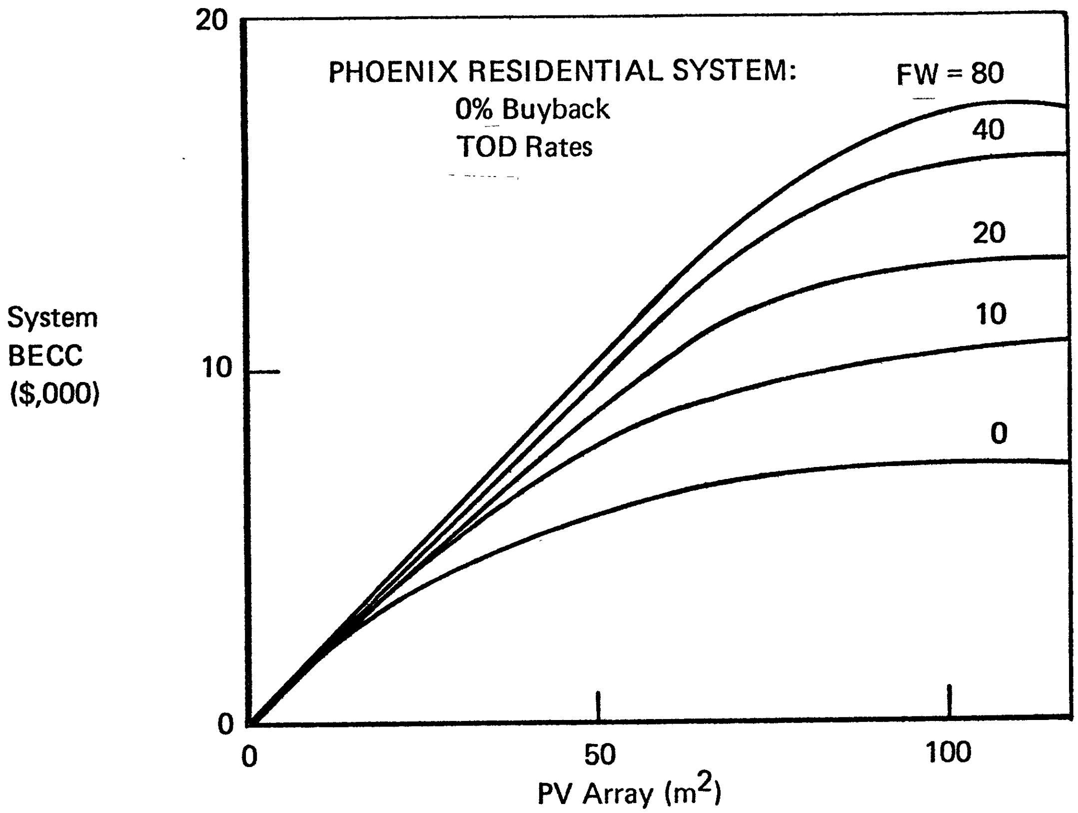


FIGURE 15

UTILITY INTERFACE/PV AND FLYWHEEL SYSTEM



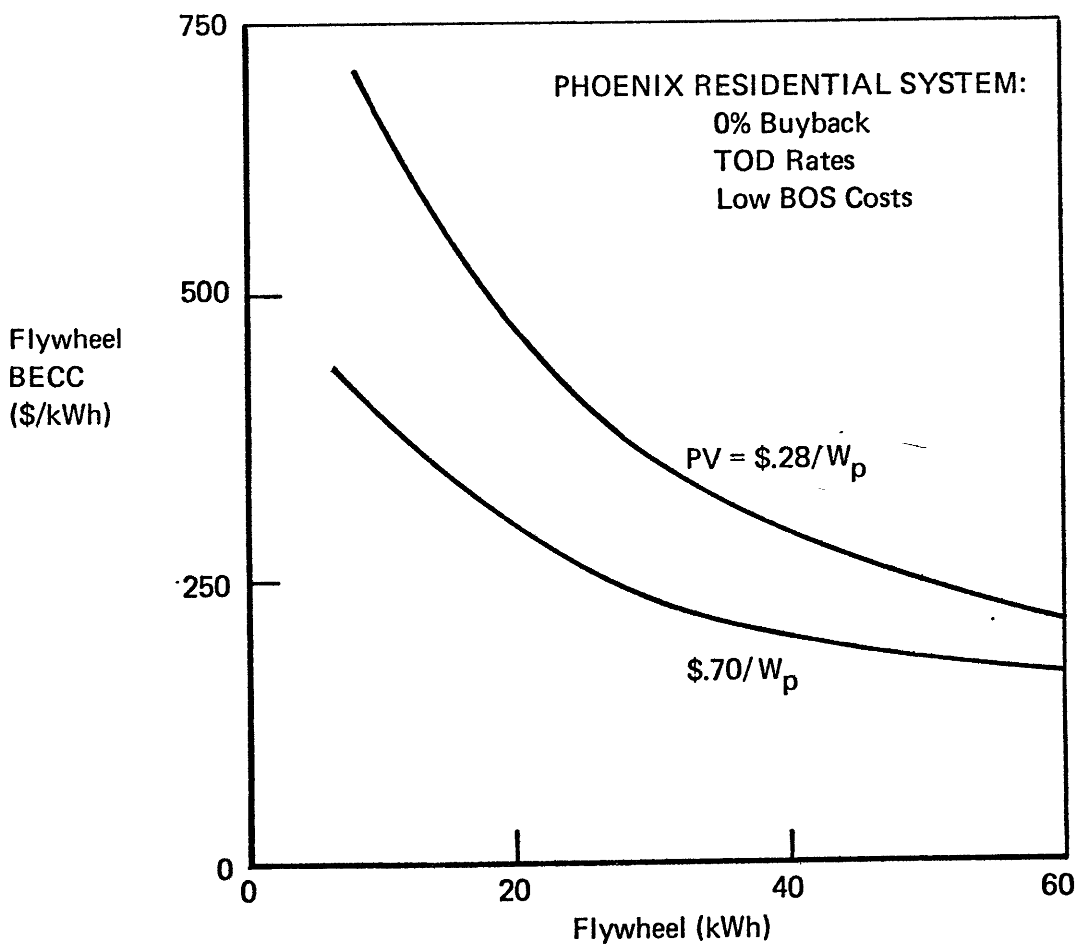


FIGURE 16

UTILITY INTERFACE/PV AND FLYWHEEL SYSTEM

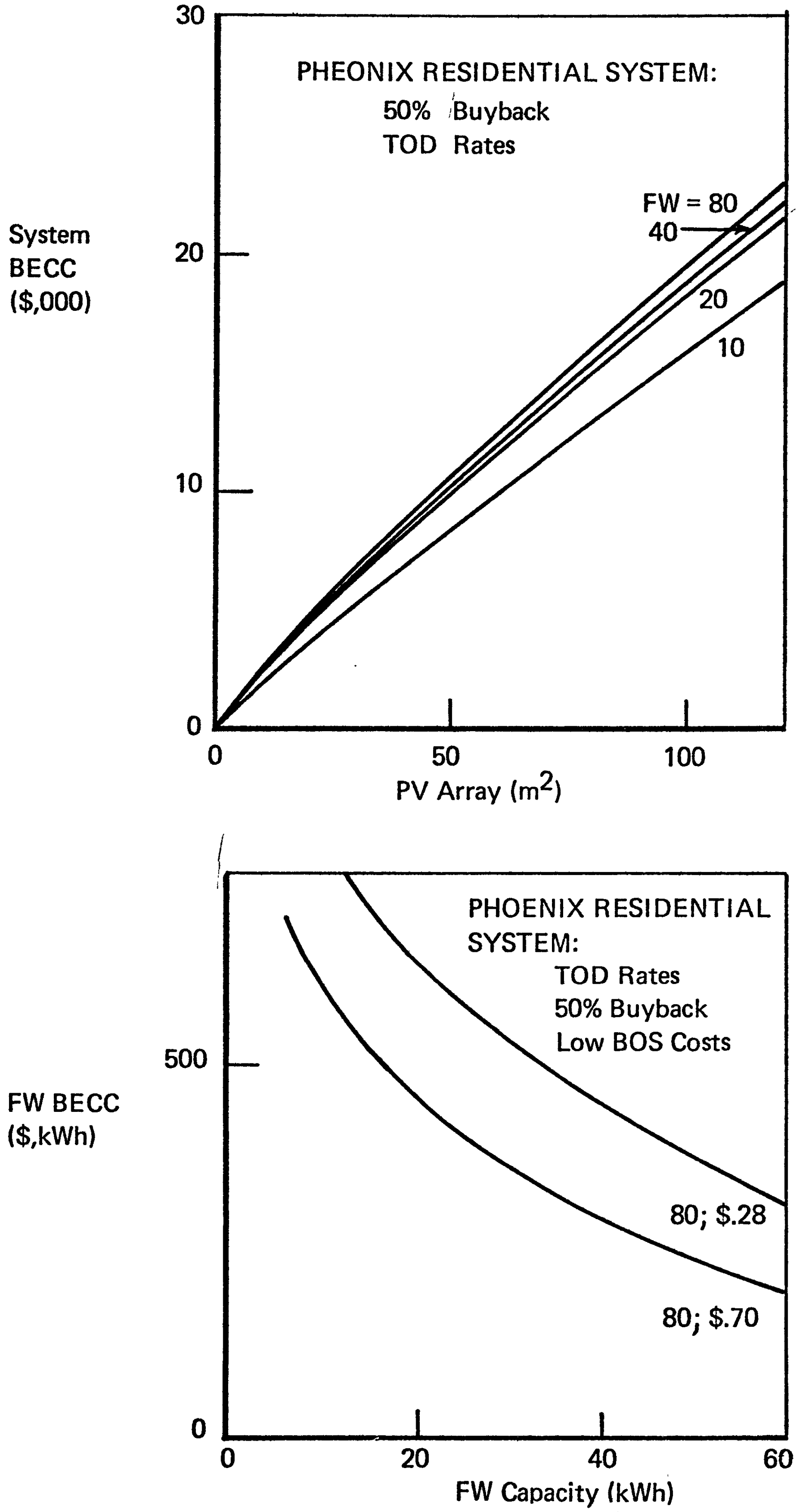


FIGURE 17

UTILITY INTERFACE/PV AND FLYWHEEL SYSTEM

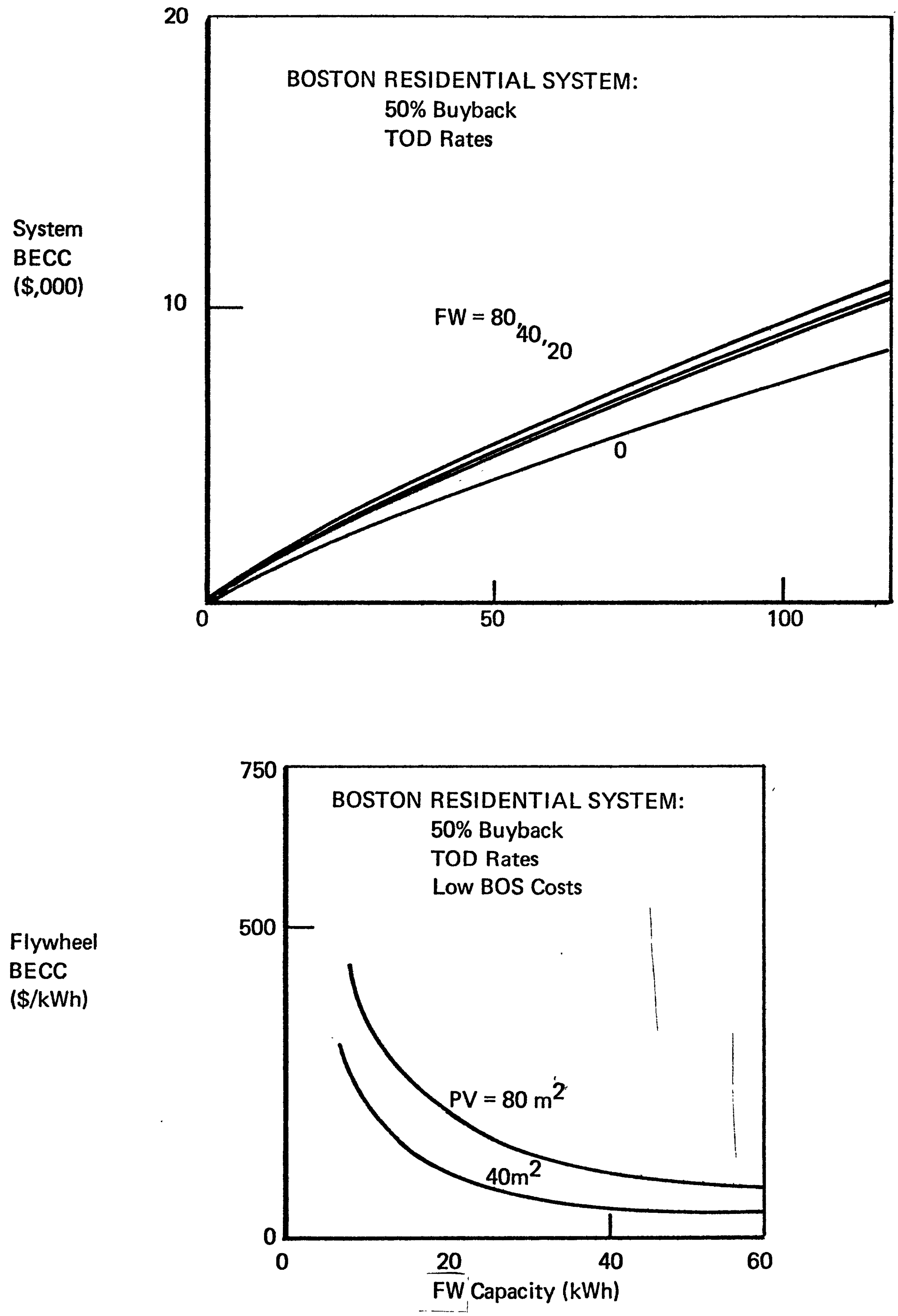


FIGURE 18

UTILITY INTERFACE/PV AND FLYWHEEL SYSTEM

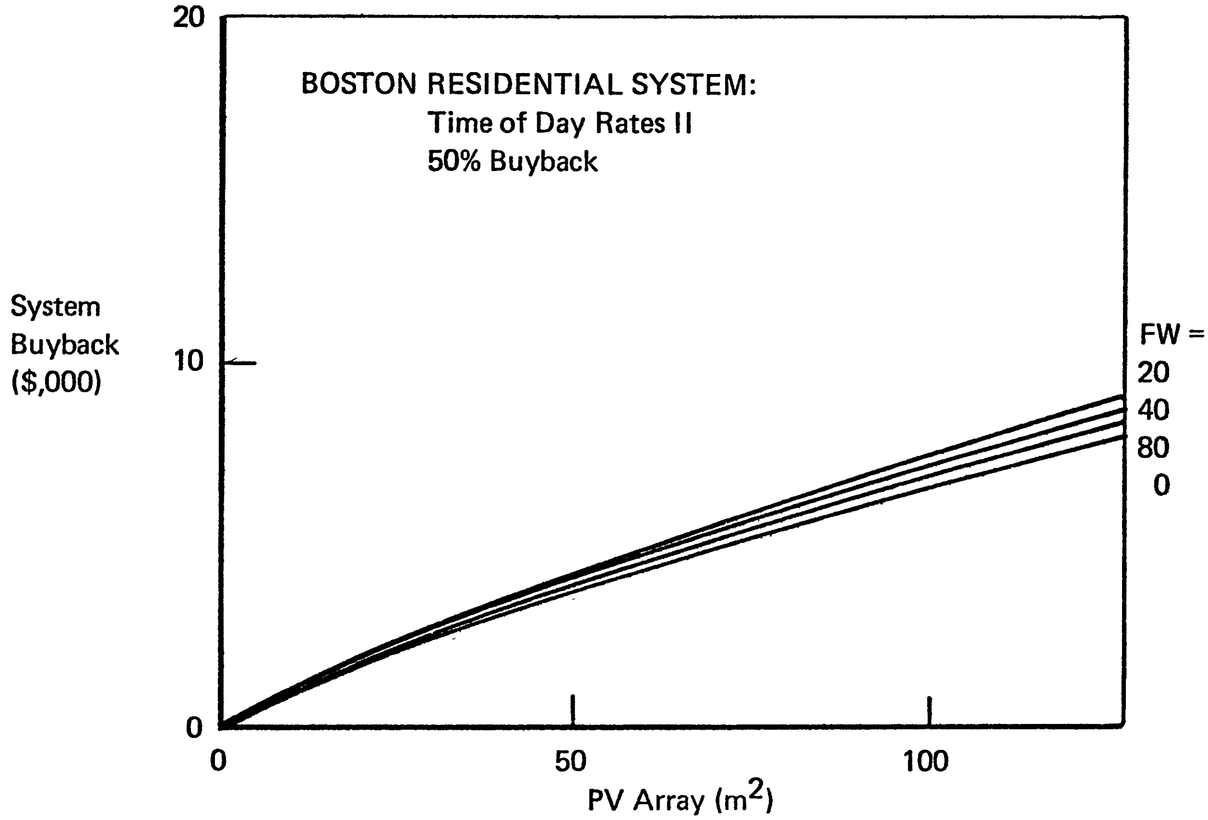


FIGURE 19

BOSTON T.O.D. RATES

(A)

RATE STRUCTURE I:

(1980 $)	AUG 15 - APRIL 15	APRIL 15 - AUG 15
PEAK HOURS	NONE	NOON - 3:00
PEAK PRICE		12.5¢/KWH
BASE PRICE	4.98¢/KWH	4.98¢/KWH

(B)

RATE STRUCTURE II:

(1980 $)	8 MOS WINTER PERIOD NOVEMBER - JUNE	4 MOS SUMMER PERIOD JULY - OCTOBER
PEAK HOURS	8:00 AM - 9:00 PM	8:00 AM - 9:00 PM
PEAK	6.175¢/KWH	6.977¢/KWH
BASE	1.264¢/KWH	1.264¢/KWH

season to include the full year and by broadening the price differentials between periods of the day, the effect of breakeven cost values is insignificant. In fact, for the pricing structures shown, the effects decrease system worth.

Comparing Boston and Phoenix

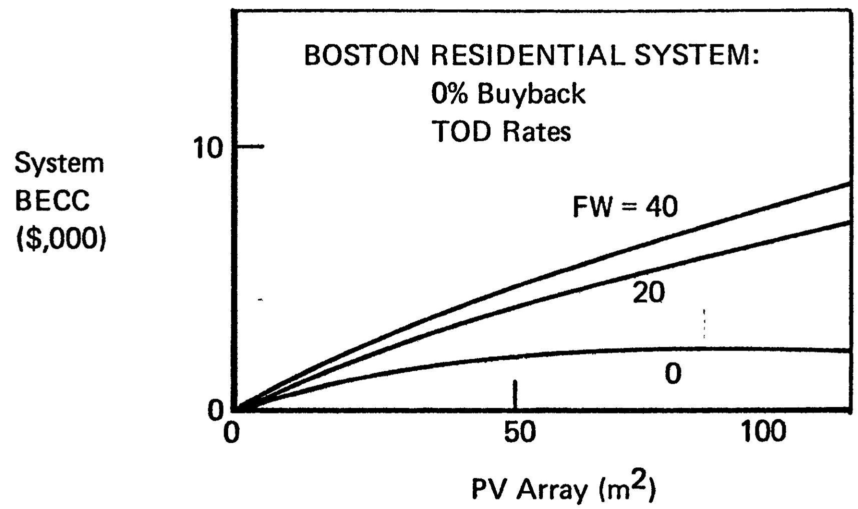
Figures 20, 21, and 22 repeat the analysis of Figures 15, 10, and 11, respectively, although with Boston data and parameters. The issues that prescribe curve shapes are the same for both geographic regions. However, taken in total, the different regions are defined by significantly contrasting results. All results for the Phoenix region are associated with consistently higher dollar breakeven values above the Boston cases. There are two primary reasons for this. First, both the flat rate and average time-of-day price figures for Boston are lower than the corresponding Phoenix prices. This yields a lesser total system value when the benefit is valued at utility-displaced electricity. Second, the sun shines brighter and longer in Phoenix than in Boston. This means not only that more electricity is supplied by the PV array, but also that with greater insolation intensities, PV generation is more likely beyond the instantaneous demand. This latter point is illustrated by the slightly lower optimum array sizes for given flywheel capacities in all Phoenix runs.

Sensitivity to the Cost of Electricity

An obvious question arises as to the sensitivity of investment indifference values to the cost of utility electricity, and to the role the latter plays as an incentive toward a PV-flywheel investment. Figure 23 explores these relationships for the Phoenix residential case. With no electricity buyback and with a flat-rate price structure, hardware

FIGURE 20

UTILITY INTERFACE/PV AND FLYWHEEL SYSTEM



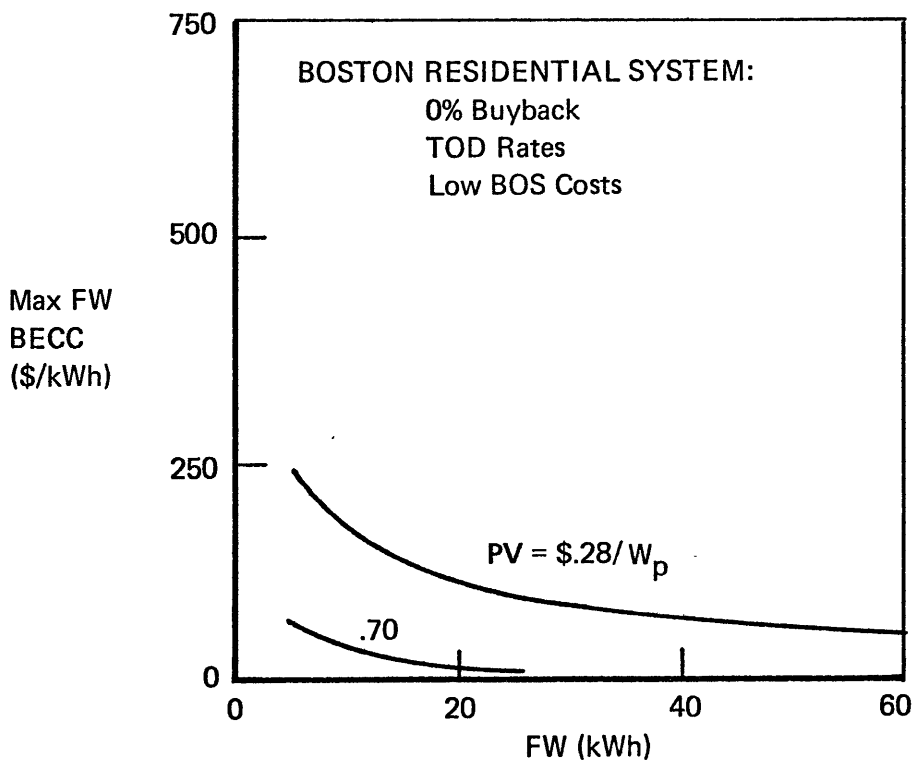
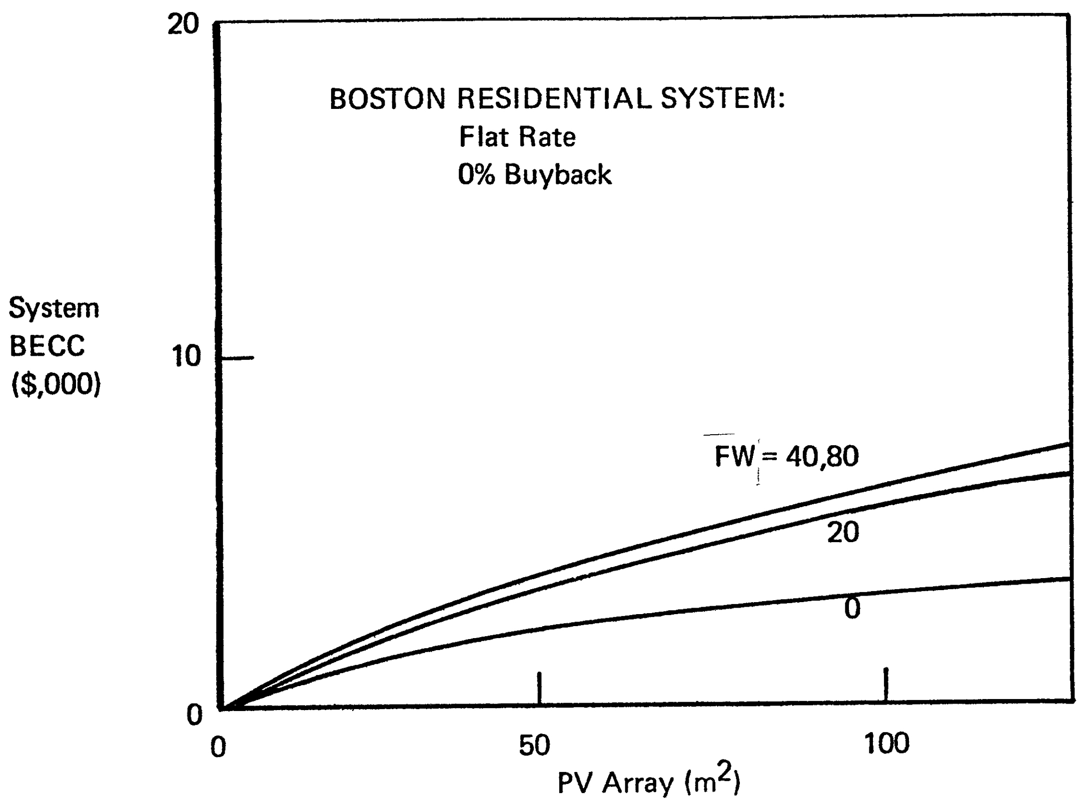
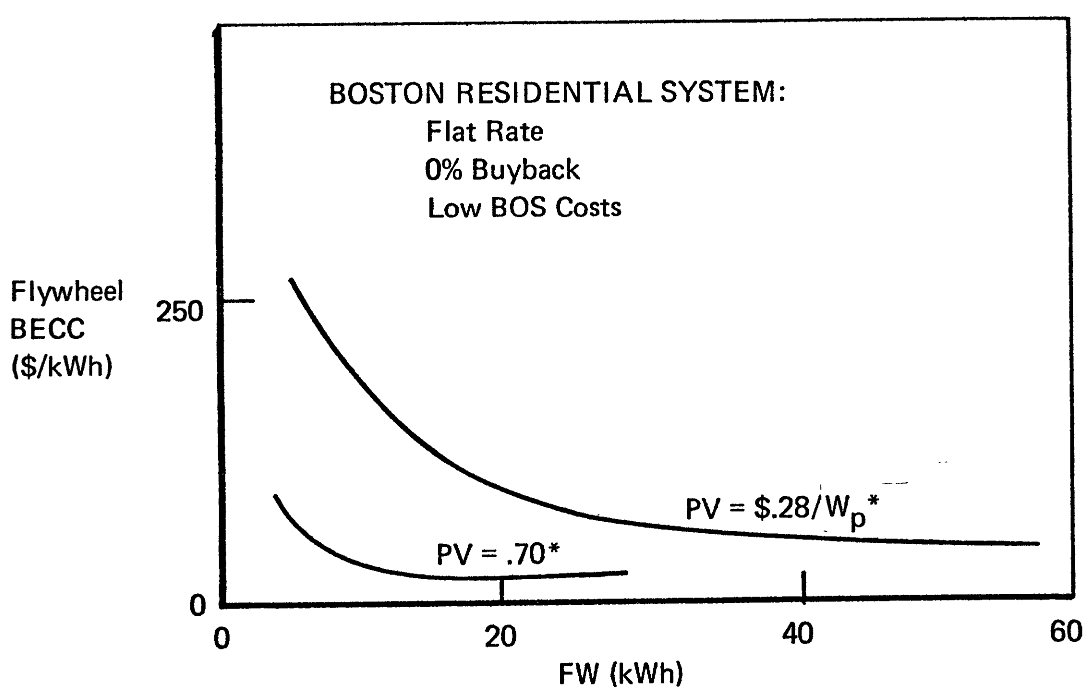


FIGURE 21

UTILITY INTERFACE/PV AND FLYWHEEL SYSTEM

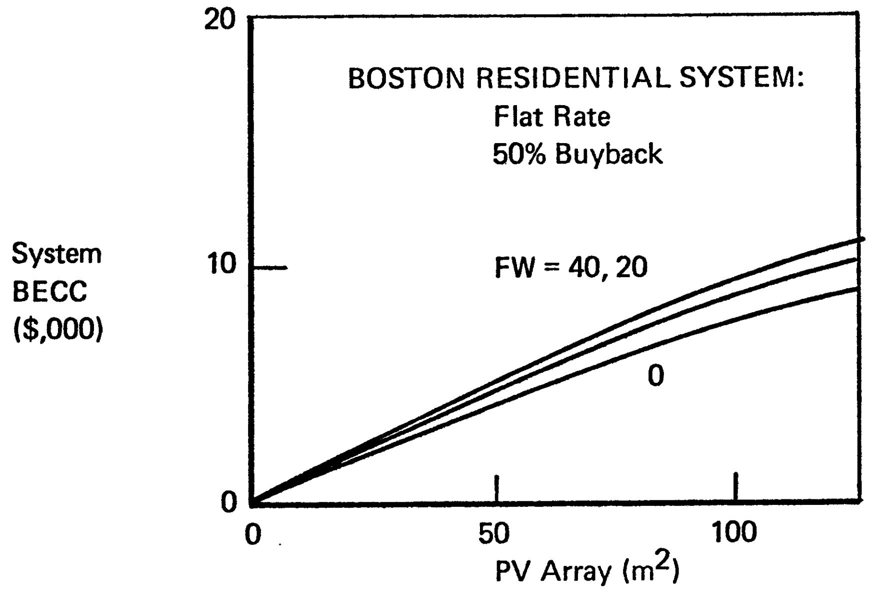


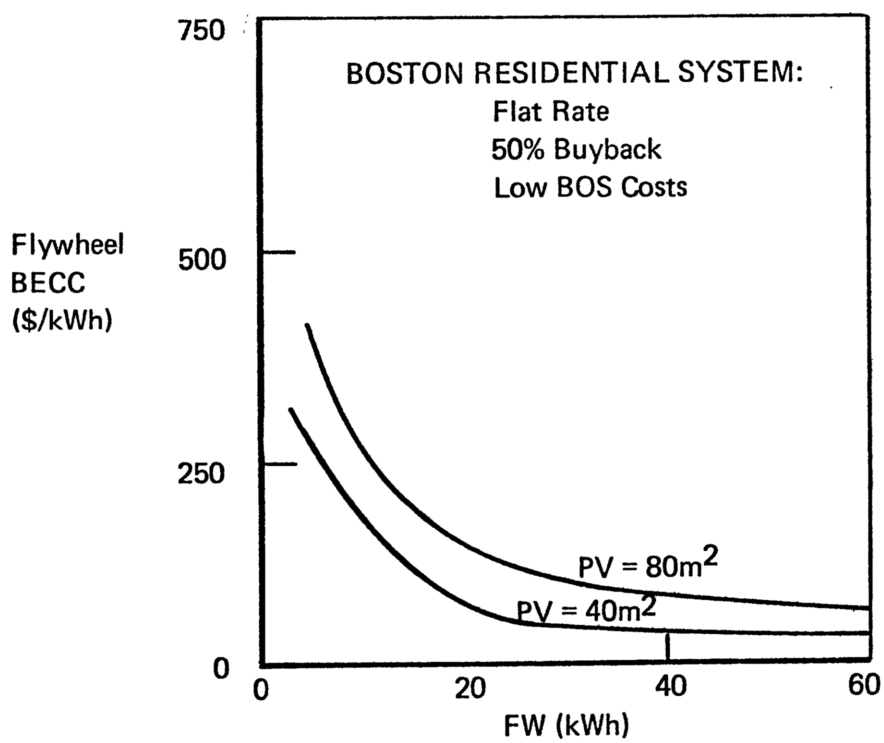


*Costs = BOS + PV at Labeled Value

FIGURE 22

UTILITY INTERFACE/PV AND FLYWHEEL SYSTEM





costs have been varied for the fixed configuration of 80 m^2 array with a 40-kWh flywheel to determine the relation of net benefits to cost of utility electricity at the start of the 20-year life of the system. The low, medium, and high cost assumptions are again defined in Figure 24. Breakeven costs, defined by zero net benefits, are the indifference points for investment decisions. It is seen that a $.10/kWh differential in assumed start cost of electricity is required to absorb the uncertainty in configuration cost projections. The steepness of the curves indicates the rate at which net benefits accumulate for the investment once beyond the breakeven value.

As an additional exercise, the discount rate was varied from 1 percent to 5 percent for the assumed Medium Costs case. The results are indicated by the dashed lines in the figure. A mere 4 percent difference changes the breakeven start cost of electricity by roughly 4 cents per kWh. This result is explored later in the analysis as finance explanations are given for the difference in investment outlook for the residential over the load center scale of application. Figure 25 then goes on to relate the same criteria under a 50 percent buyback scheme.

Utility and Flywheel Alone--No PV

Under the assumption that future utility policy may include the option for residences to serve as distributed energy storage centers, a logic was formulated to handle flywheel kWh transfers (no PV) in a grid-connected environment. This logic seeks to maximize benefits given the high- and low-cost purchasing opportunities of a time-of-day rate structure. Figure 26 presents the results of this study. Shown here is the flywheel BECC subject to implementation of the price structures of Figures 19a and 19b. The low curve (rate I) is a result of flywheel

FIGURE 23

NET BENEFITS VS. COST OF ELECTRICITY

Phoenix Residence: 0% Buyback; Flat Rate

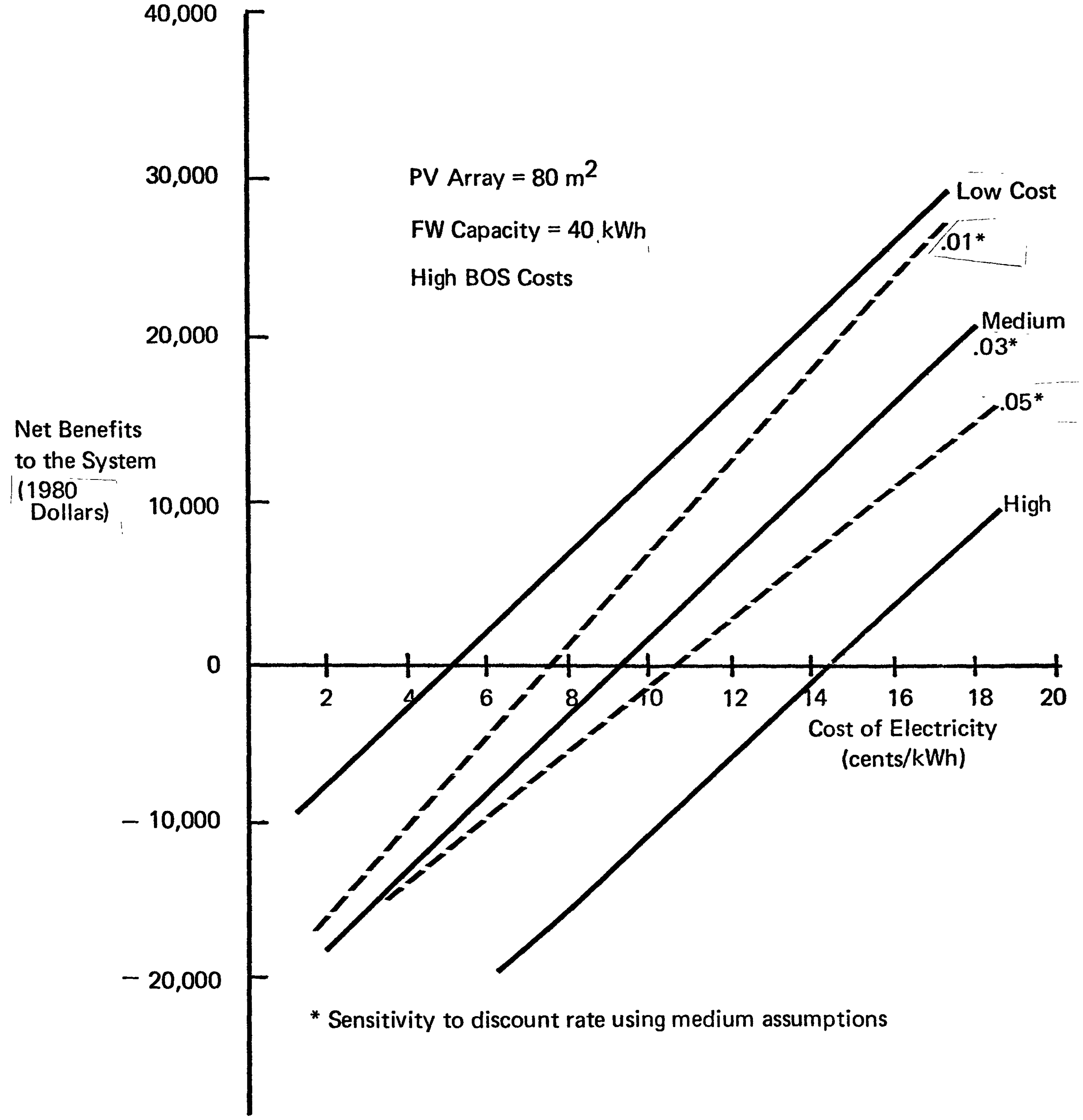


FIGURE 24

NET BENEFITS VS: COST OF ELECTRICITY

ASSUMPTIONS

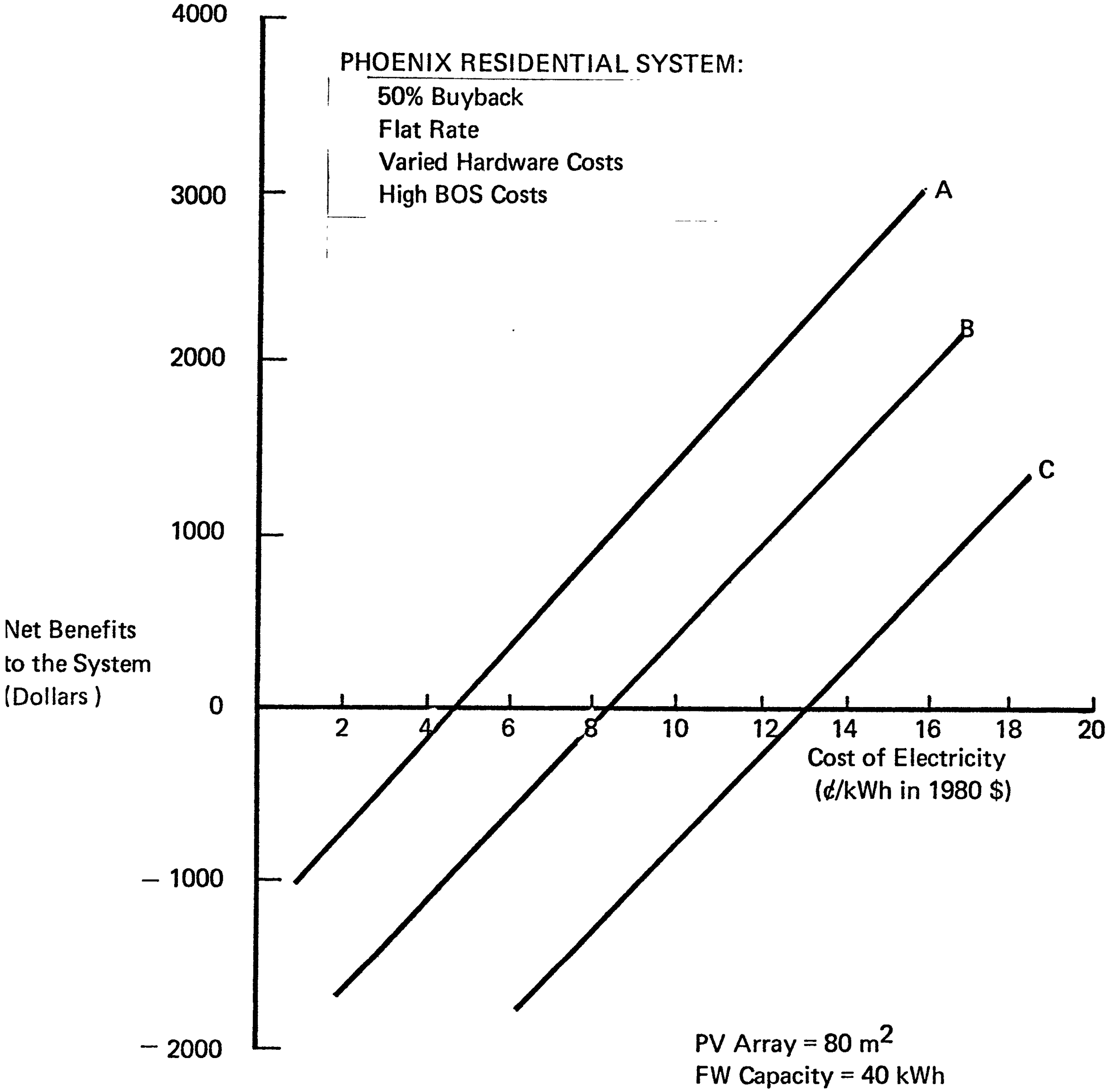
PV ARRAY = 80 M^2

FW CAPACITY = 40 KWH

HARDWARE COSTS			DISCOUNT RATE
LOW:	$.28/W_P$	PV	.01
	LOW	FW	.02
MED:	$.70/W_P$	PV	.03
	MEDIUM	FW	
HIGH:	$.91/W_P$	PV	
	HIGH	FW	

FIGURE 25

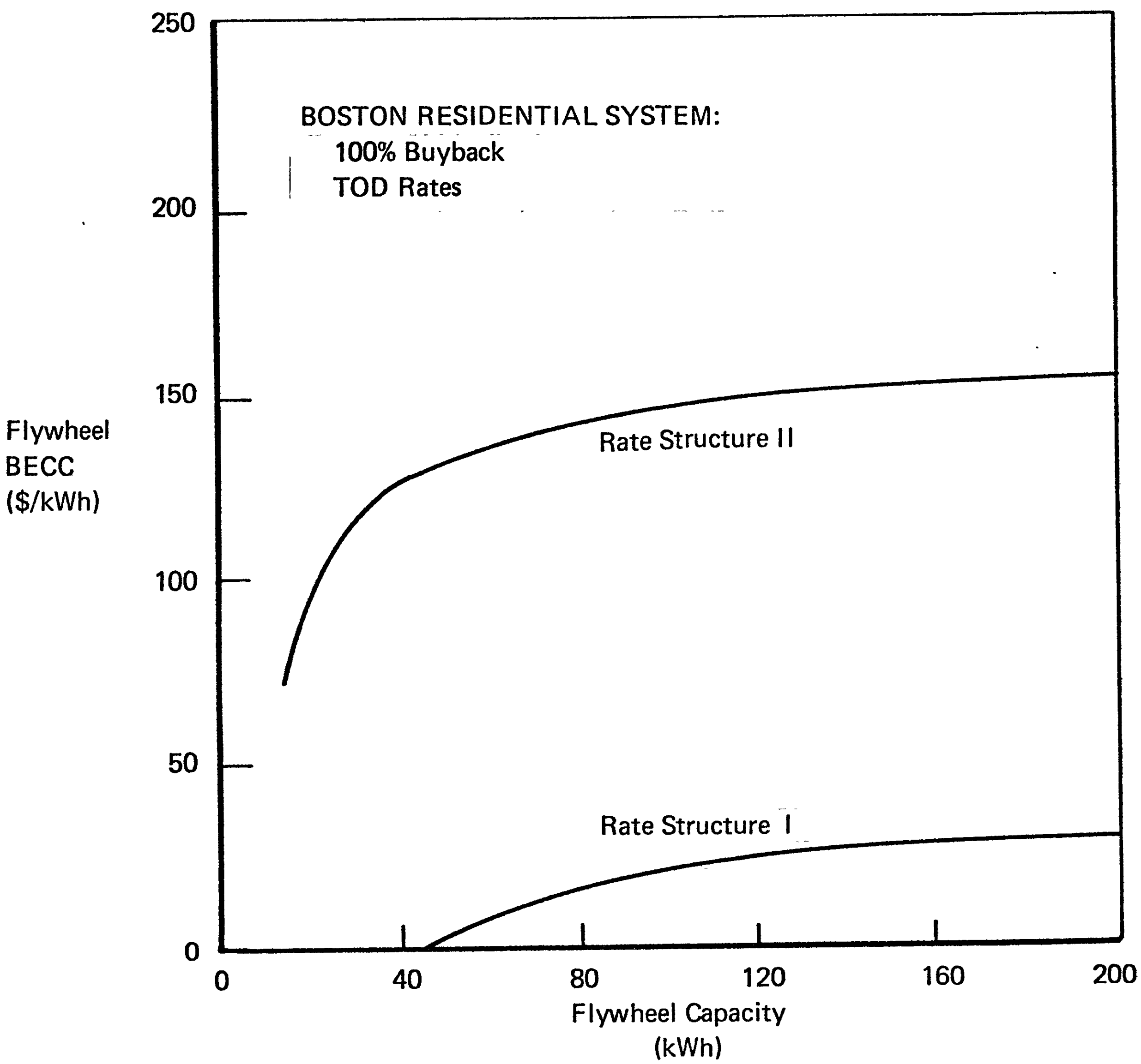
UTILITY INTERFACE PV AND FLYWHEEL SYSTEM
NET BENEFITS VERSUS COST OF ELECTRICITY



Hardware Costs
A: PV = $.28/Wp
FW = Low
B: PV = .70
FW = Medium
C: PV = .91
FW = High

FIGURE 26

UTILITY INTERFACE/FLYWHEEL ALONE



charging maintenance over that portion of the year where no time-of-day price differential exists. Conclusions drawn from this graph support the contention that storage cost economics are highly affected by differences in time-of-day rate-setting policy. Additional studies of storage utility interface in general will reflect more completely the worth of distributed storage used with time-variant rates.

III.1.b. Residential Stand-Alone Analysis

A remote applications analysis was performed for a single family residence with a benefit analysis now including, in addition to utility-displaced electricity, the cost of a distribution line as a function of distance from the grid. Figure 27 outlines the issues that are pertinent here as well as parameters varied to effect the analysis. The "cost of reliability" issue applies principally to the first part of the stand-alone study, which is a comparison of a flywheel and PV system with the economics of a grid connect. The second part assumes that a utility-equivalent reliability is attained with the addition of a diesel generator backup unit; the issues of configuration sizing of the tri-component system become prevalent.

PV and the Flywheel Alone--The Issue of Reliability

In any energy demand scenario, coordination of energy supply requires some assumptions regarding basic resource inputs. For conventional electricity production these assumptions include a readily available marketplace for conventional fossil or nuclear fuels. In the U.S., this marketplace has reached a level of sophistication where resource supply reliability is virtually no longer an issue. However, it appears a revival of energy systems based on weather-dependent technologies is in the offing and thus the issue of supply reliability becomes of paramount concern.

FIGURE 27

STAND ALONE ANALYSIS
PV + FW
VS.
UTILITY GRID CONNECT

ISSUES

- CONFIGURATION SIZING
- COST OF RELIABILITY
- DISTANCE FROM GRID AS BENEFIT

PARAMETERS VARIED

- FW CAPACITY (KWH)
- PV ARRAY SIZE (M^2)
- HARDWARE COSTS
- DISTANCE FROM GRID

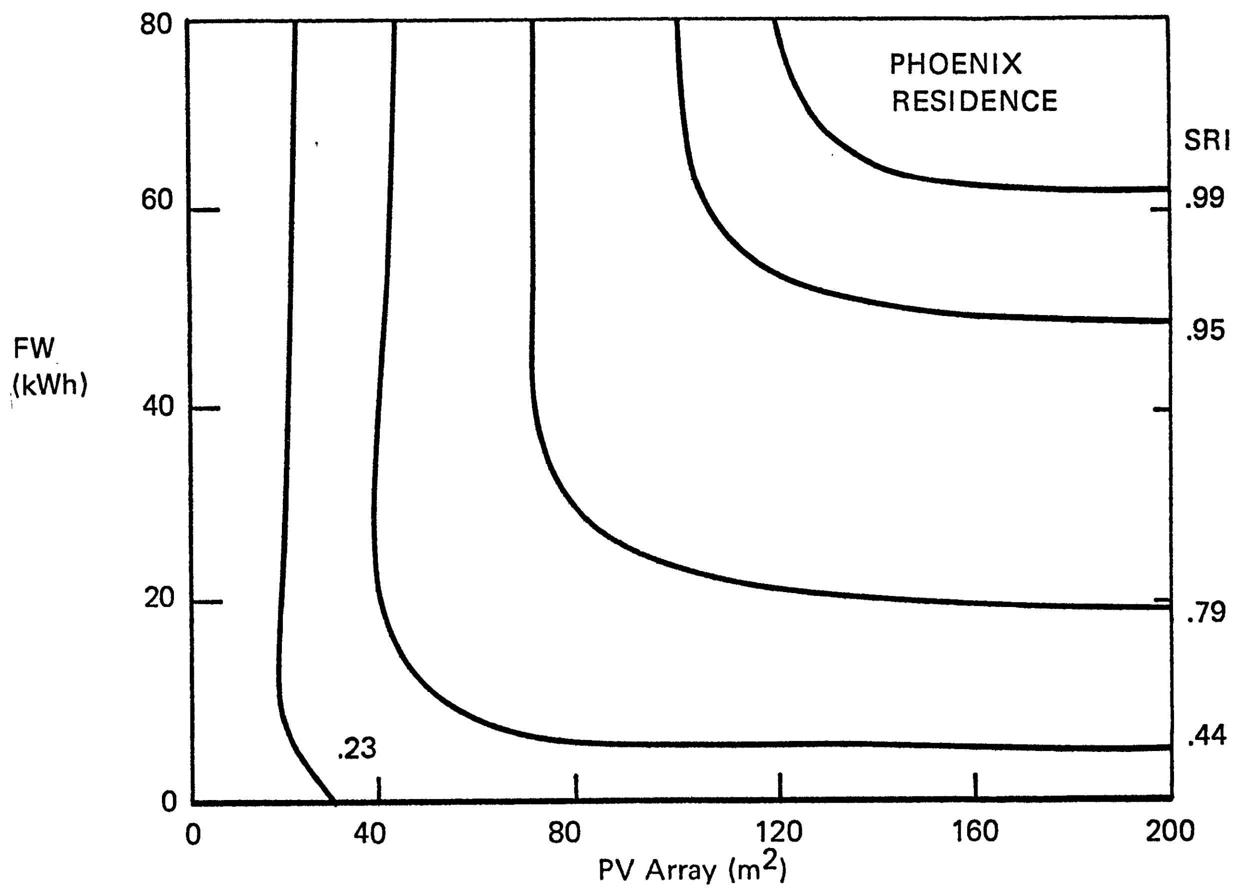
For a stand-alone configuration comprised of photovoltaics and a flywheel alone, it was necessary to analyze the issue of supply reliability and its implications for configuration sizing and system costs. Figure 28 begins this analysis. Here, iso-reliability lines are drawn over a range of component size combinations. Reliability in this case is defined as the Service Reliability Index (SRI), or the number of customer hours served over the number of customer hours demanded. The important difference here is that the utility definition of reliability applies to failure due to hardware outages, whereas the definition that applies to Figure 28 relates to interruptions resulting from insufficient array or storage sizing.

Figure 29 reveals the relationship between the SRI and Total Energy Not Met (TENM) for the first year of the simulated run life. As configuration size increases upward and to the right in the diagram, total energy not met by the system goes to zero. It is seen that the curve slopes in the two figures are nearly identical, indicating a high correlation and hence substitutability of the two measures.

The reason for the backWard-bending vertical portions of the curves is inherent in the flywheel operating specifications. Each of the functional components of the flywheel has an associated loss; one of these is directly proportional to the flywheel's state of charge. The operating logic for the flywheel dictates that it shall never be drained below one quarter of its total kWh capacity and hence larger flywheels, requiring a higher minimum state of charge, will necessarily have higher proportional losses. Thus, as flywheel capacity is increased for any fixed array size, total usable kWh will decline since total kilowatt-hours captured does not change.

FIGURE 28

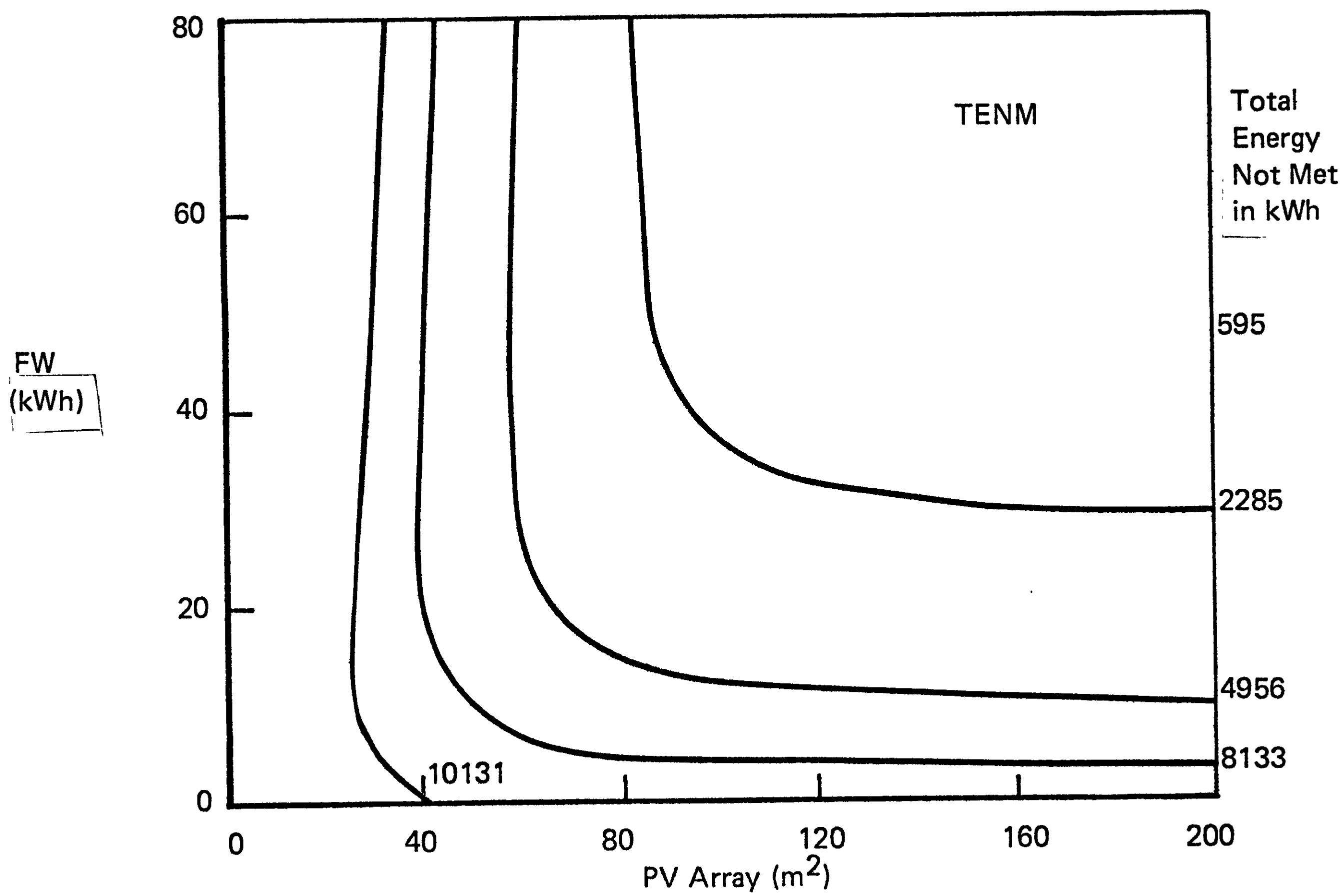
REMOTE STAND ALONE RESIDENTIAL SYSTEM: PV AND FLYWHEEL ONLY



ISO - RELIABILITY CURVES
BY SERVICE RELIABILITY INDEX (SRI)
(Hours Served/Hours Demanded)

FIGURE 29

REMOTE STAND ALONE RESIDENTIAL SYSTEM: PV AND FLYWHEEL ONLY



ISO -Total - Energy - Not - Met Curves

Fixing the PV module and balance-of-system costs, the flywheel cost projection is varied from its lowest to highest value to arrive at iso-total cost lines, as shown in Figures 30 and 31. As expected, those iso-cost lines with the lower flywheel cost assumption show a vertical shift toward greater flywheel dependence. What is most significant is revealed by the overlay of these lines on the iso-reliability curves. The sharp knee at each fixed reliability rules that optimum configuration sizing is quite insensitve to component costs. Note that sizing in the lower ranges of reliability requires a flywheel-(kWh) to-PV-array (kWp) ratio of roughly 2.5, whereas in the higher reliability ranges a ratio of 4 applies.

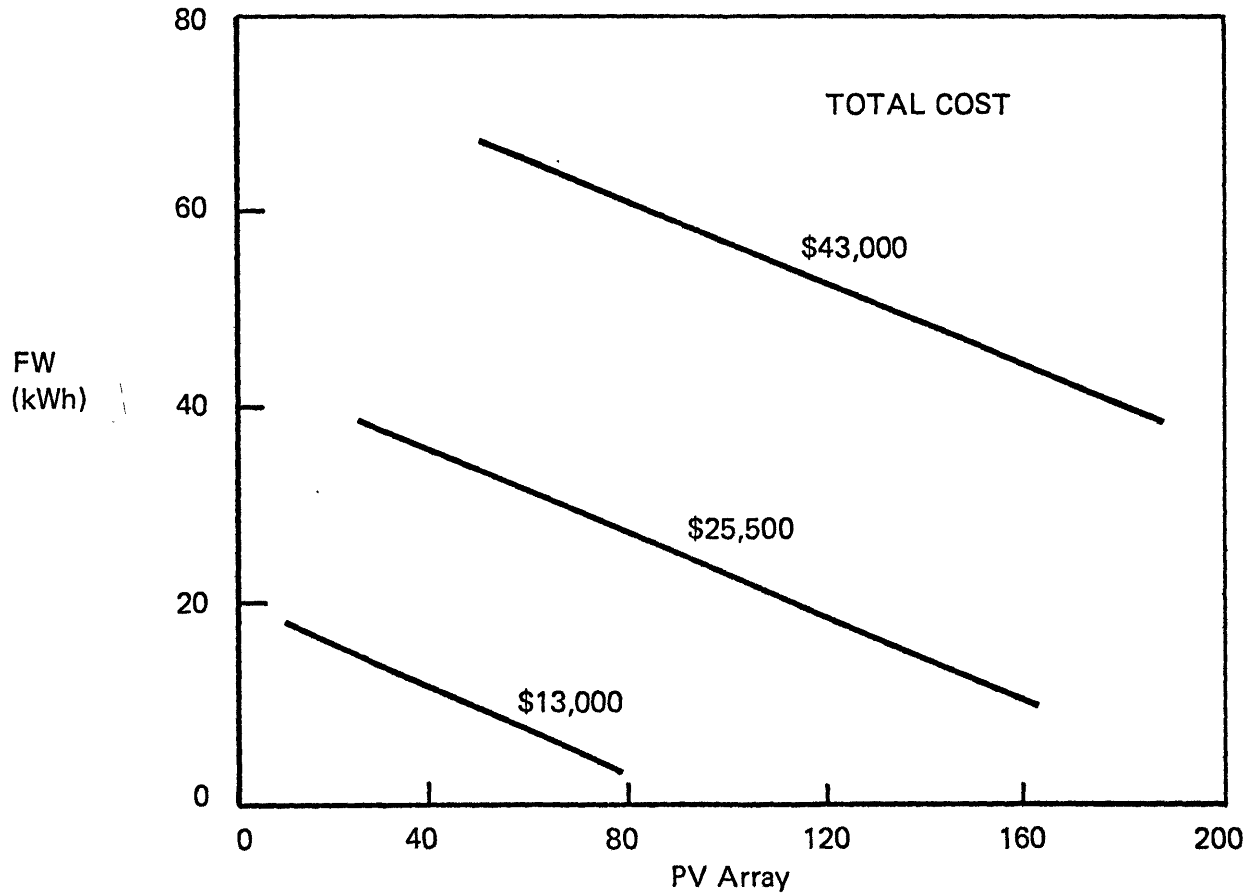
PV and Flywheel with Diesel Backup

When a diesel generator is added to the PV and flywheel system, the issue of supply reliability is eliminated, under the assumption of a ready means for obtaining the diesel fuel. Again, the issues of component reliability remain intact but were not modeled in this study. Figure 32 presents the directions for analysis under these conditions as well as the parameters varied to achieve these goals. The market parameters deemed important were the cost projections made for the system hardware as well as for the cost of diesel fuel.

Figure 33 represents a summary of the analysis for a remote residence application utilizing PV, a flywheel, and a diesel generator. With component size ranges set on each of the axes, and the TENM curves representing kilowatt hours of diesel energy, any point in the plane deterministically represents satisfaction of 100 percent of the total yearly application demand.

FIGURE 30

REMOTE STAND ALONE RESIDENTIAL SYSTEM: PV AND FLYWHEEL ONLY

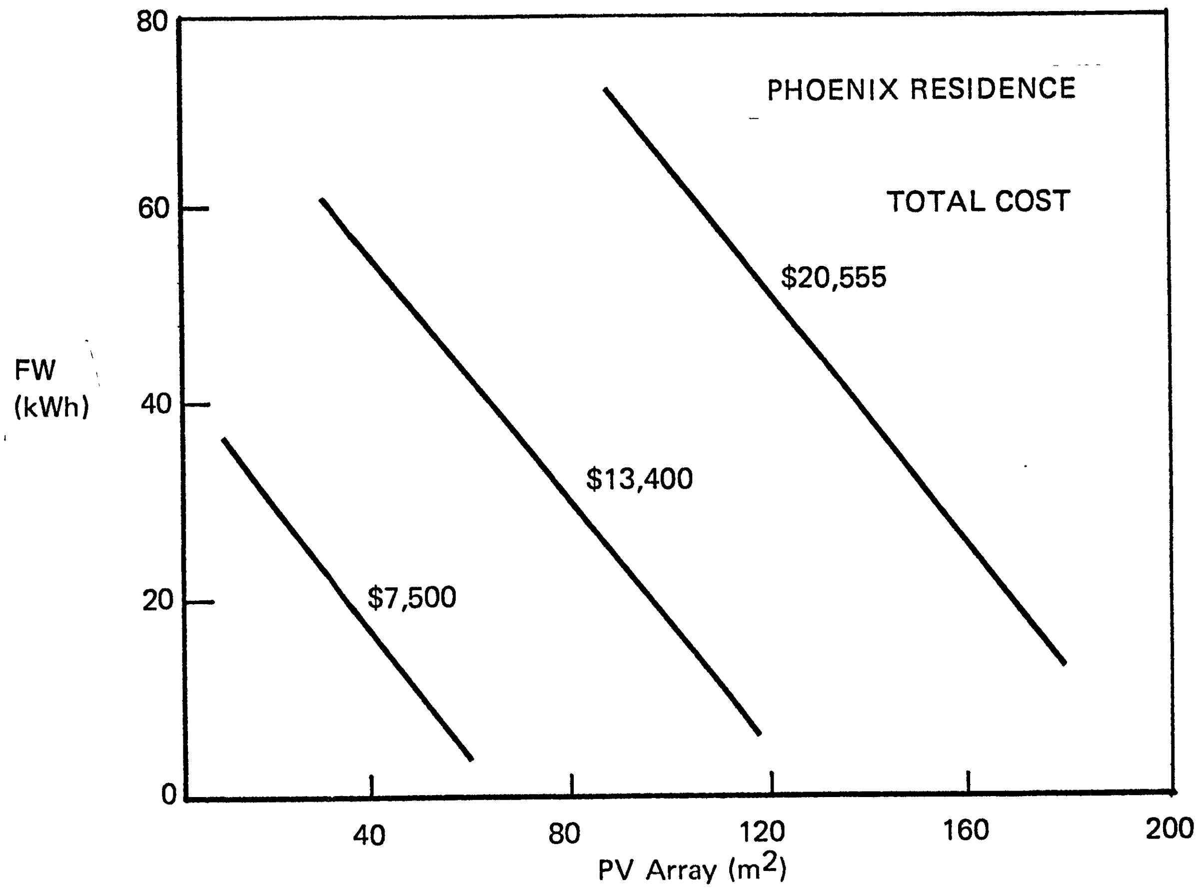


ISO – COST LINES

PV: $.70/PK WATT
FW: High Costs
Low BOS Costs

FIGURE 31

REMOTE STAND ALONE RESIDENTIAL SYSTEM: PV AND FLYWHEEL ONLY



ISO Cost Lines
PV: $.70/pk Watt
FW: Low Costs
Low BOS Costs

FIGURE 32

STAND - ALONE ANALYSIS
PV + FW + DSL
VS:
UTILITY GRID CONNECT

ISSUES

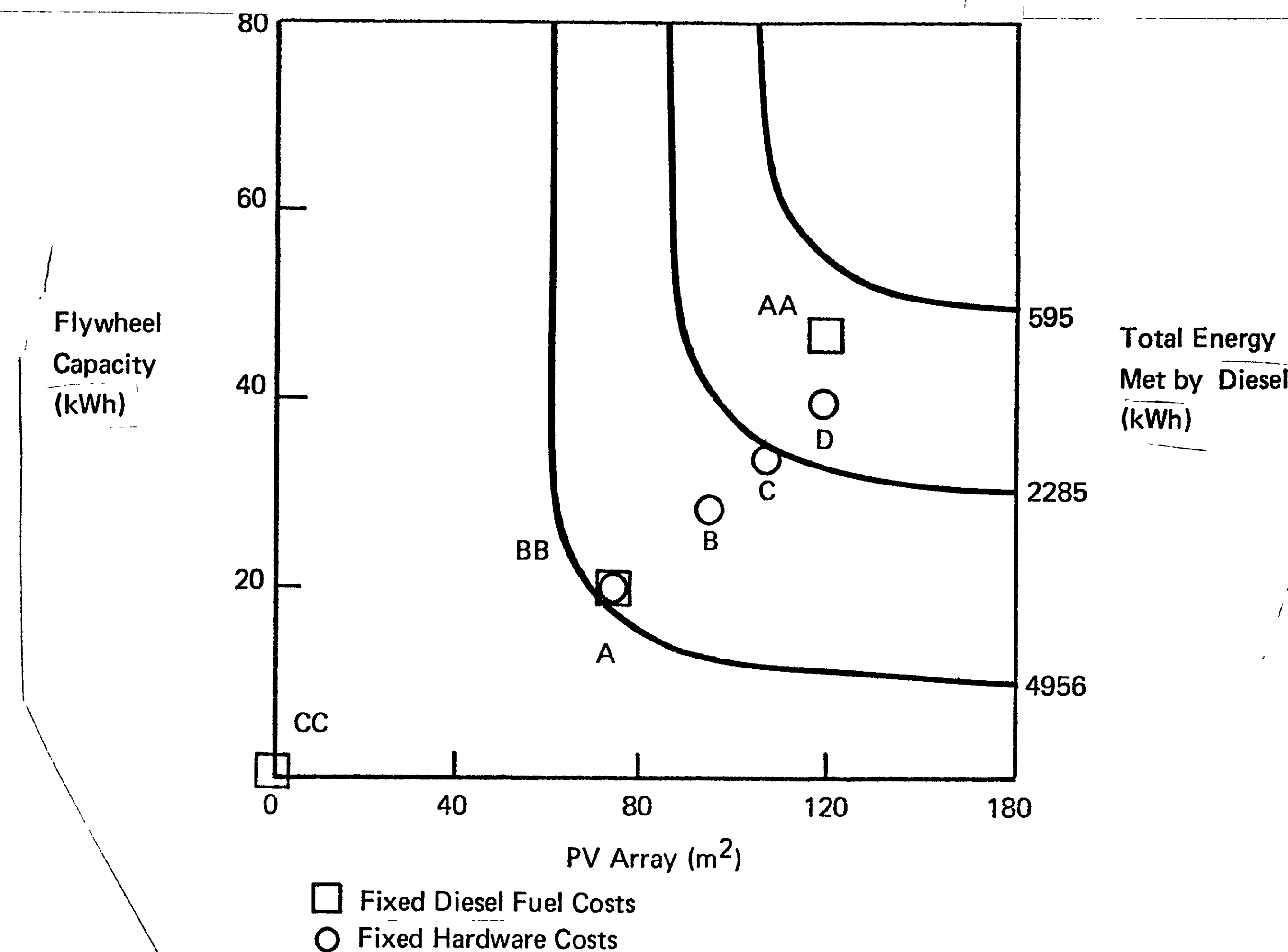
- OPTIMUM CONFIGURATION SIZING
- SENSITIVITY TO MARKET PARAMETERS

PARAMETERS VARIED

- HARDWARE COSTS
- DIESEL FUEL START COSTS
- COMPONENT HARDWARE CAPACITIES

FIGURE 33
REMOTE STAND ALONE PV FLYWHEEL/DIESEL RESIDENTIAL SYSTEM

Sensitivity of Optimum Configuration Sizing to
- Diesel Start Costs in 1985
- Hardware Costs
- Low BOS Costs



ASSUMPTIONS

Utility Tie in Costs as Benefits	Diesel Fuel Costs Fixed at $ .07/kWh in 1985; Hardware Costs Varied	Hardware Costs Fixed at PV = $.07/pk Watt FW = Middle; Diesel Fuel Costs in 1986
• $ .066/kWh 3%/Year Real Price Escalator	AA PV = .28 FW = Low	A $ .07/kWh
		B .097
	BB PV = .70 FW = Medium	C .133
• 30 Miles from Grid $8712/Mile	CC PV = .91 FW = High	D .169 After 1986 Escalate at 6.6%/Annum

The boxes and squares represent economically optimal solutions. The boxes are a result of fixing diesel fuel costs at $.07/kWh in 1980, applying a fixed 6.6 percent/year fuel price escalation factor for the years thereafter, and examining the effects of varying component cost assumptions on the configuration sizing solution. The range of solutions here is dramatic, revealing that a low-cost assumption for the PV and flywheel dictates that fully 92 percent of the energy demand be satisfied by these components alone, whereas assuming the high cost range optimally yields an all-diesel system.

On the other hand, fixing hardware costs at the medium projection and varying diesel fuel start costs for 1985 over a broad range yields a relatively minor, although significant, change in optimum system sizing. Figures 35-38 summarize the maximum net benefit analysis used to arrive at the configuration optimums of Figure 33.

Taking the most likely configuration solution (i.e., reasonable diesel fuel and hardware cost assumptions shown by the boxed circle (BB-A) of Figure 33), the net benefits as a function of distance from the grid are charted in Figure 39, where miles of distribution line not built now serve the benefits side of the equation. At just over one mile from the utility line, benefits rapidly begin to accrue to such isolated, total energy configurations.

III.1.c Summary of Residential Results

The significant findings of the foregoing results are listed below:

Utility Interface

- o Additional storage increases the optimum capacity of installed PV when hardware costs are in the low range.
- o Storage has the greatest value at low buyback rates.

FIGURE 35

OPTIMUM CONFIGURATION SIZING APPROACH

$$\text{MIN. COST} = A \cdot KW_D + B \cdot KW_{PV} + C \cdot KW_F$$
$$+ D \cdot KWH_D + E \cdot KWH_{PV} + F \cdot KWH_F$$

S.T. $\qquad \sum KWH \geq$ ANNUAL DEMAND

$$KW_D \cdot 8760 \geq KWH_D$$
$$KW_{PV} \cdot 8760 \geq KWH_{PV}$$
$$KW_T \cdot 8760 \geq KWH_F$$

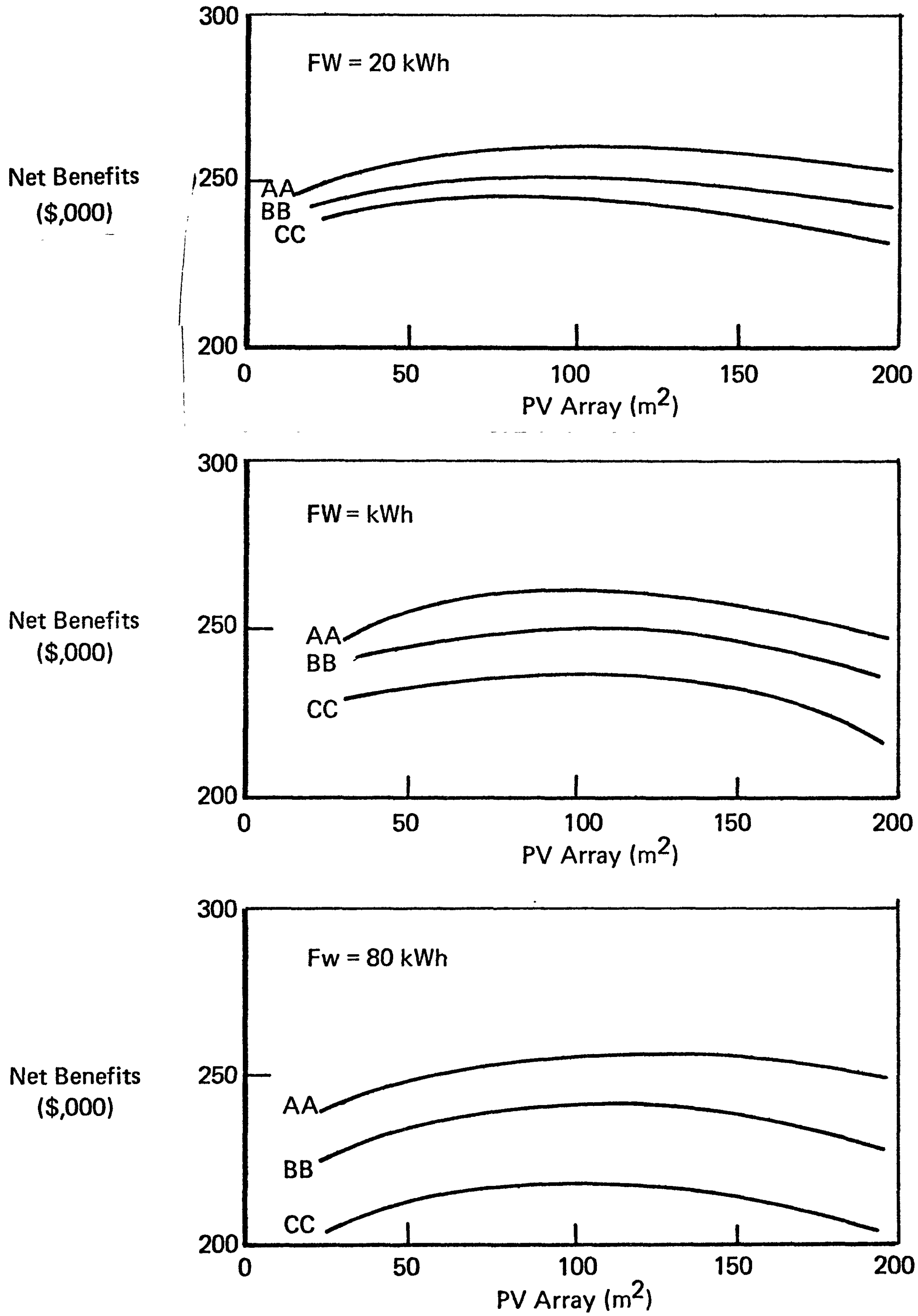
WHERE:

$A = \$/KW_D/YR$	$D = \$/KWH_D$
$B = \$/KW_{PV}/YR$	$E = \$/KWH_{PV}$
$C = \$/KW_{FW}/YR$	$F = \$/KWH_{FW}$
(CAPITAL COSTS)	(FUEL COSTS)

FIGURE 36

STAND-ALONE/PV FLYWHEEL DIESEL

SYSTEM NET BENEFITS VERSUS: ARRAY SIZE AND FLYWHEEL CAPACITY DIESEL FUEL COST OF $.07/kWh ASSUMED HARDWARE COSTS* VARIED



*Hardware Costs (1980):

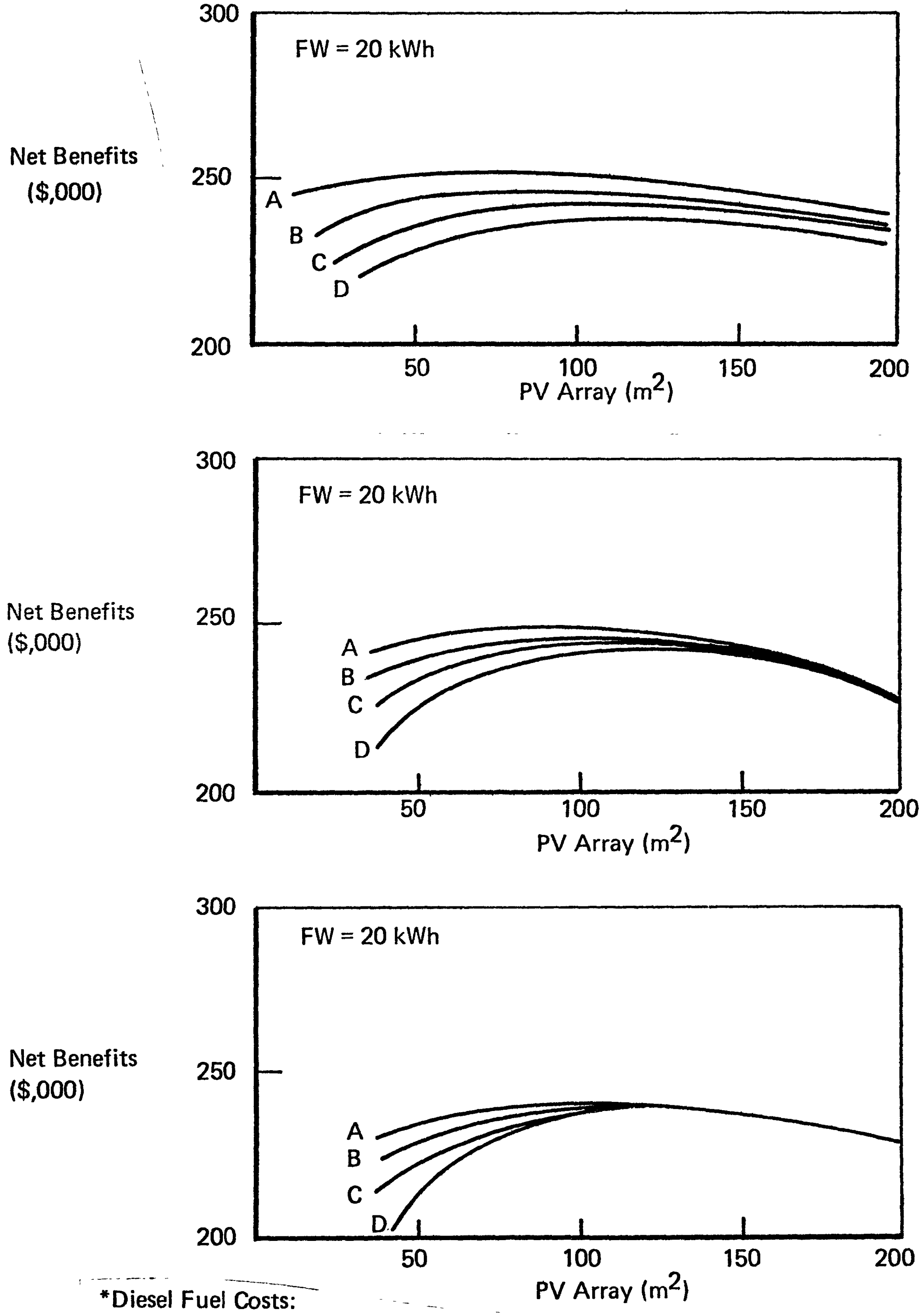
AA: PV = $.28 FW = Low

BB: PV = $.70 FW = Middle

CC: PV = $.91 FW = High

FIGURE 37

STAND-ALONE PV FLYWHEEL DIESEL
SYSTEM NET BENEFITS VS ARRAY SIZE AND FLYWHEEL CAPACITY
MIDDLE HARDWARE COSTS ASSUMED
DIESEL FUEL START COSTS* IN 1985 VARIED
COST COMPARISON TO UTILITY TIE-IN 30 MILES FROM GRID



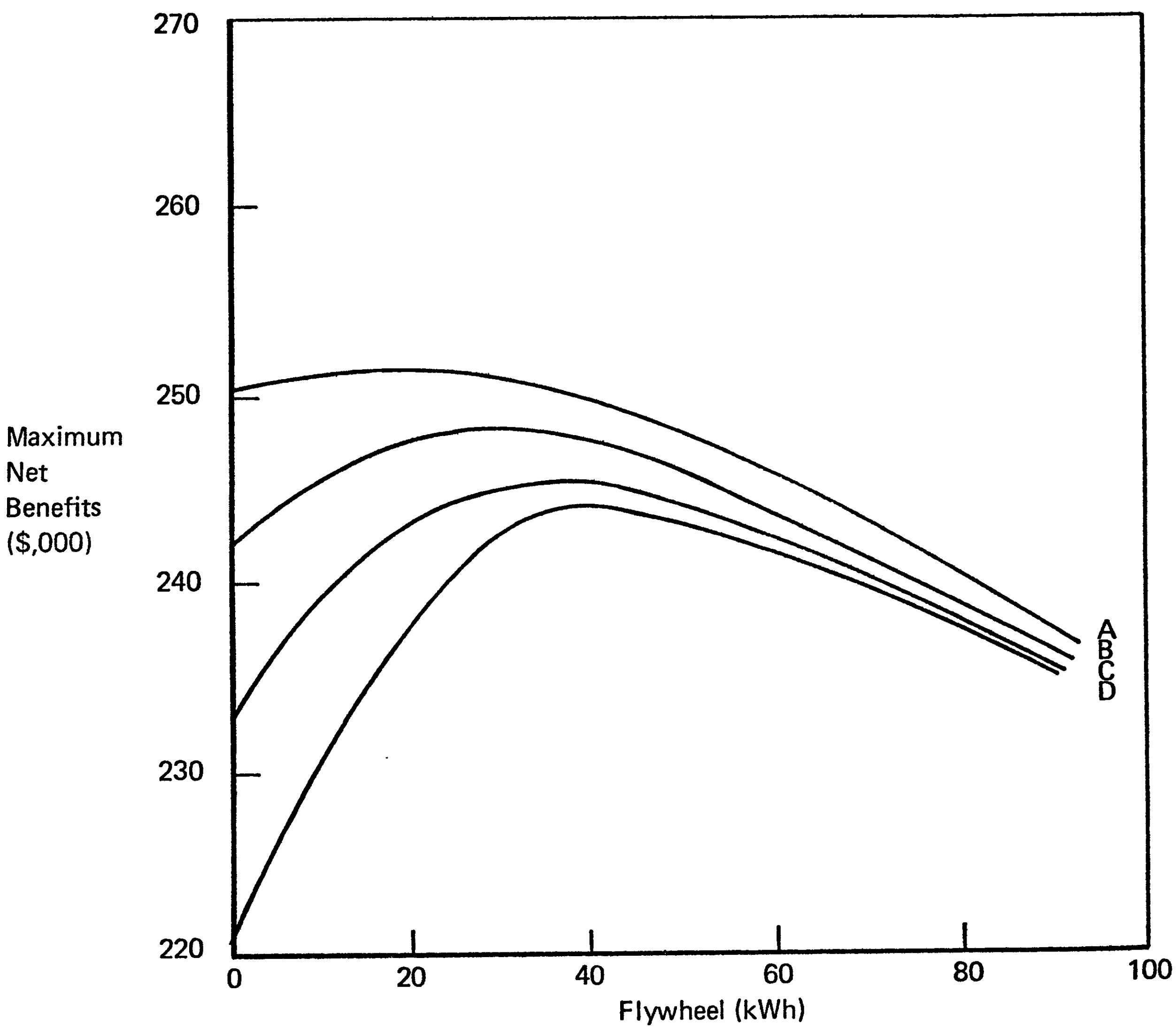
*Diesel Fuel Costs:
A = $.07/kWh; B = $.097/kWh; C = $.133/kWh; D = $.169/kWh

FIGURE 38A

STAND-ALONE PV FLYWHEEL DIESEL

MAXIMUM SYSTEM NET BENEFITS AT GIVEN FLYWHEEL CAPACITY

- Cost Compared to Utility Tie-In
  $.066/kWh
  30 Miles from Grid:
- Middle Hardware Costs Assumed
- Diesel Fuel Start Costs in 1985 Varied



Diesel Fuel Start Costs in 1985

A = $.07/kWh
B = $.097/kWh
C = $.133/kWh
D = $.169/kWh

Hardware Costs Assumed

PV = $.70 W_p
FW = Middle

Benefits

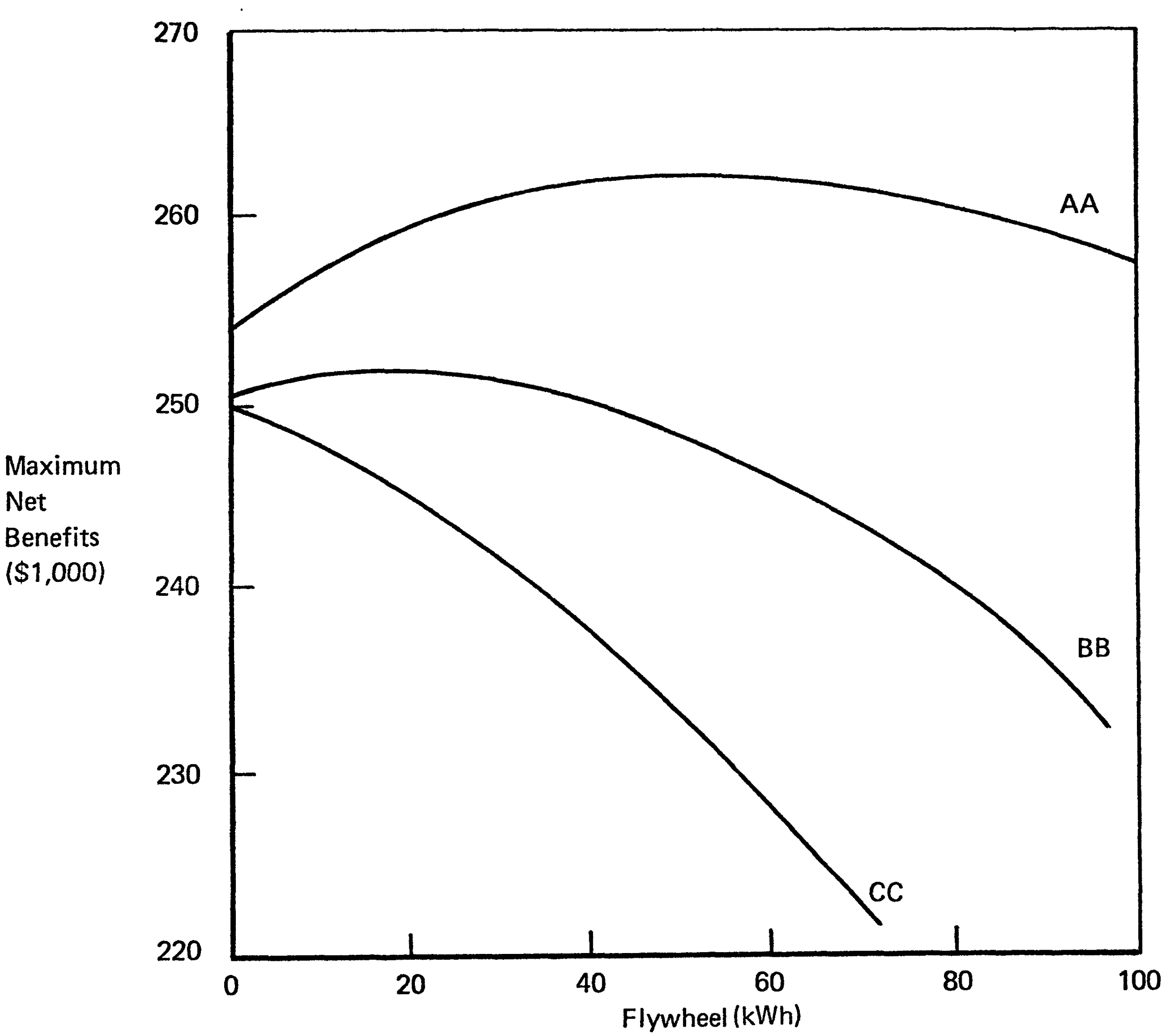
$.066/kWh

FIGURE 38B

STAND-ALONE/PV FLYWHEEL DIESEL

Maximum System Net Benefits at Given Flywheel Capacity

Cost Compared to Utility Tie-In
$.066/kWh
30 Miles from grid at $8,712/mile
Hardware Costs Varied
Diesel Fuel Start Cost in 1955 Set at $.07/kWh

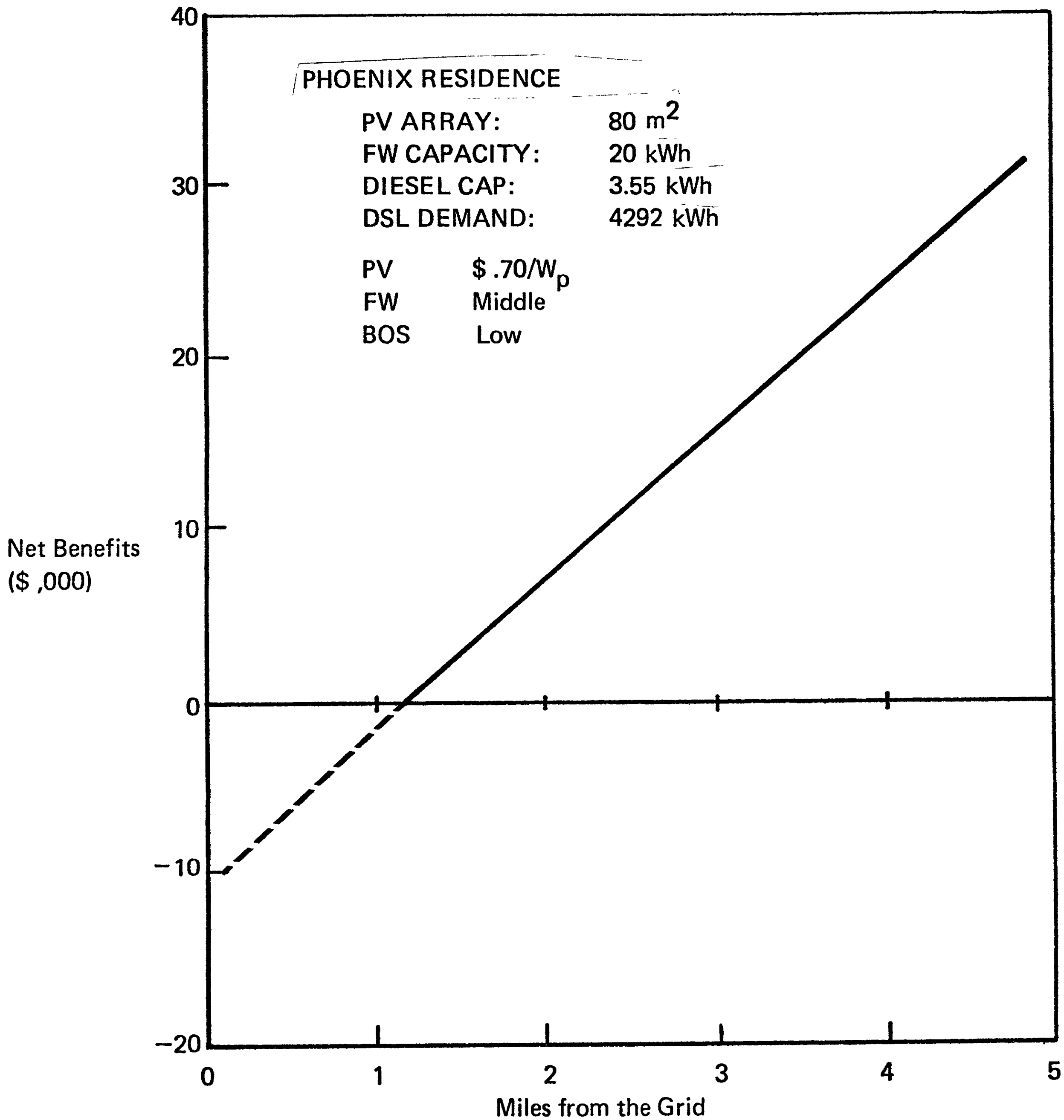


Hardware Costs

AA = PV : $.28/$W_p$ (1980)
FW : Low
BB = PV : $.70/$W_p$ (1980)
FW : Medium
CC = PV : $.91/$W_p$ (1980)
FW : High

FIGURE 39

PV + FW + DIESEL STAND ALONE COMPARED AGAINST UTILITY GRID CONNECT



- For a fixed storage capacity and PV array size, increasing utility buyback rates increases system worth when hardware costs are low. This is true since the marginal increase in benefits due to PV exceed the marginal decrease in benefits for the flywheel when buyback rate is increased.
- There are diminishing returns to increasing flywheel capacity at a given array size.
- Variations over the range of reasonable time of day rate structures have an insignificant impact on flywheel and system economics.
- Ten cents per kilowatt hour differential in assumed start cost for electricity is required to absorb the uncertainty in configuration cost projections.
- Using the most reasonable set of cost and financing projections for 1985, a PV-flywheel system will begin to look economically attractive when the cost of electricity exceeds 9¢/kWh (1980 $).
- The discount rate applied to residential investments is significant in determining when penetration of PV systems is likely to occur.
- Flywheel-Grid Connect (no PV) cost economics is highly affected by differences in time-of-day rate setting.

Remote/Stand-Alone

- Optimum configuration sizing for PV and flywheel (no diesel) is quite sensitive to component costs, requiring that flywheel capacity (in kWh) be roughly 2.5 - 4.0 times the array size (in kWp).
- Optimum size of a flywheel + PV system is highly sensitive to desired reliability.

- For a flywheel, PV, and diesel generator system, there is high sensitivity of optimum configuration size to the range of hardware cost projections when diesel fuel start costs are held fixed.
- For the same system, there is a medium sensitivity of optimum configuration size to diesel fuel costs when hardware costs are fixed.
- At just over one mile from the utility grid, positive net benefits begin to accrue to the operation of isolated total energy systems comprised of photovoltaics, a flywheel, and a diesel generator.

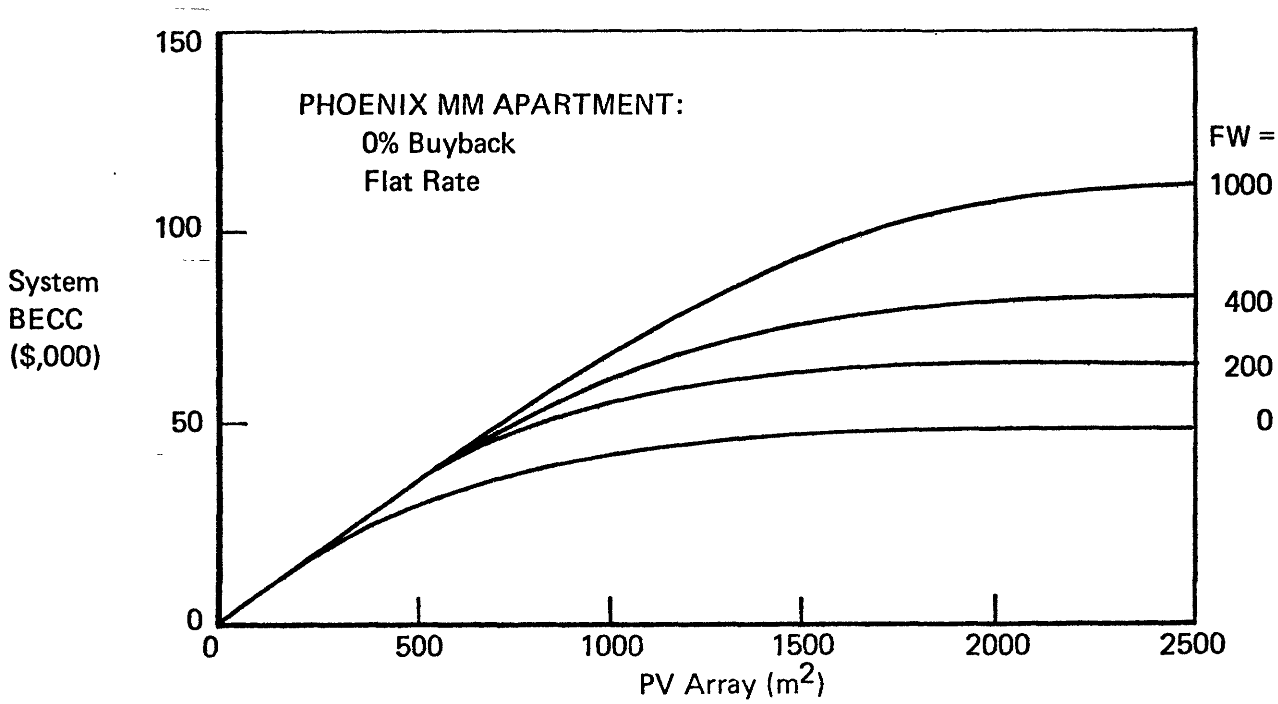
III.2 100 kWp Load Center

III.2.a. Utility Interface

Load profile data for a master-metered apartment complex in Phoenix were obtained from the Salt River Project and used as a representative of a large load center application for flywheels. The load tape shows a 36 kW average demand from September 1976 to August 1977, and an 84 kW peak demand. The studies performed are directly analogous to those of the residential analysis. Figures 40 and 41 reproduce the analytic environment of Figures 10 and 11 for the load center. All of the characteristics of the residential analysis are enforced, including diminishing returns to increasing storage capacity and the effects of storage in shifting optimum PV array capacity to the right. The most marked differences between the small-scale and large-scale applications to be noted here are the substantial reductions in flywheel breakeven capital cost over the range of flywheel capacities for the load center.

FIGURE 40

100 KW LOAD CENTER UTILITY INTERFACE



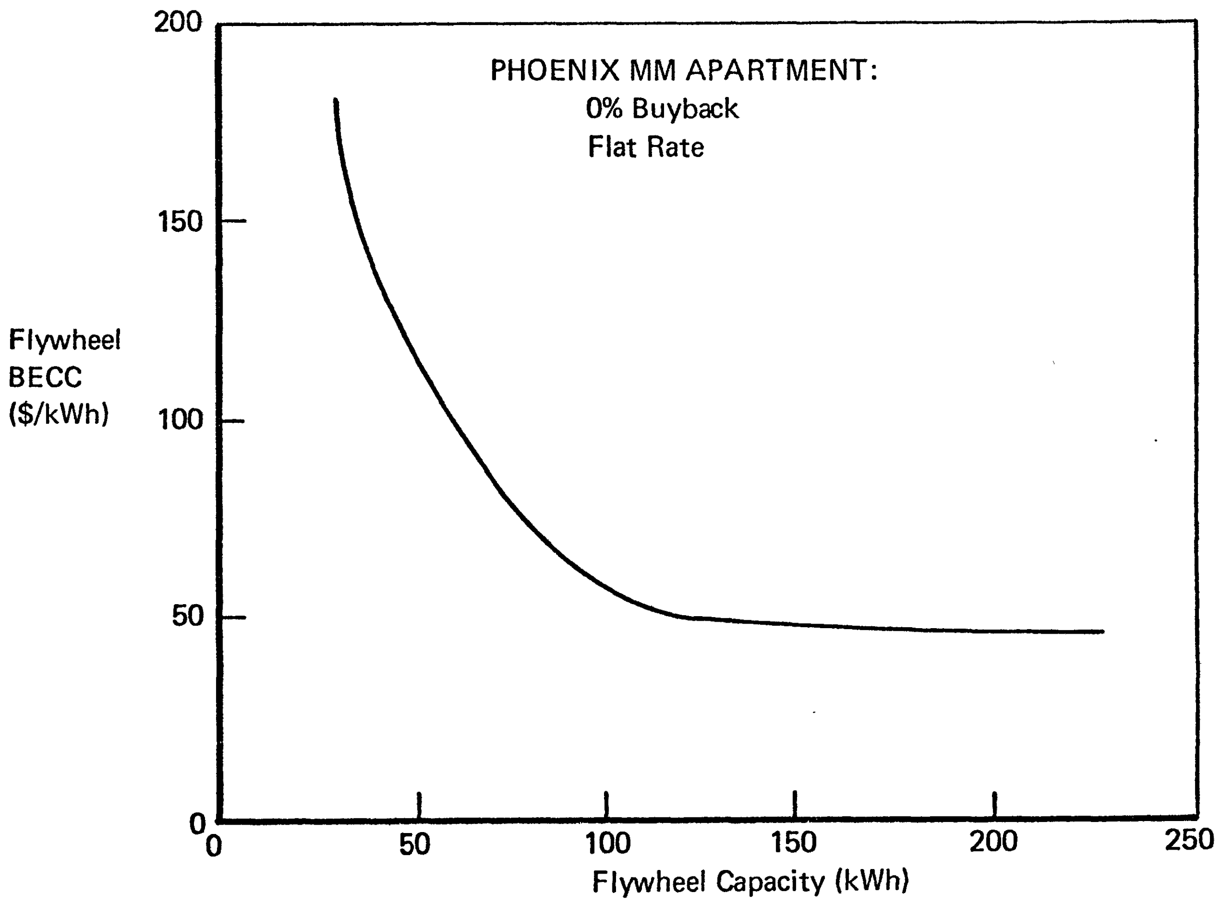
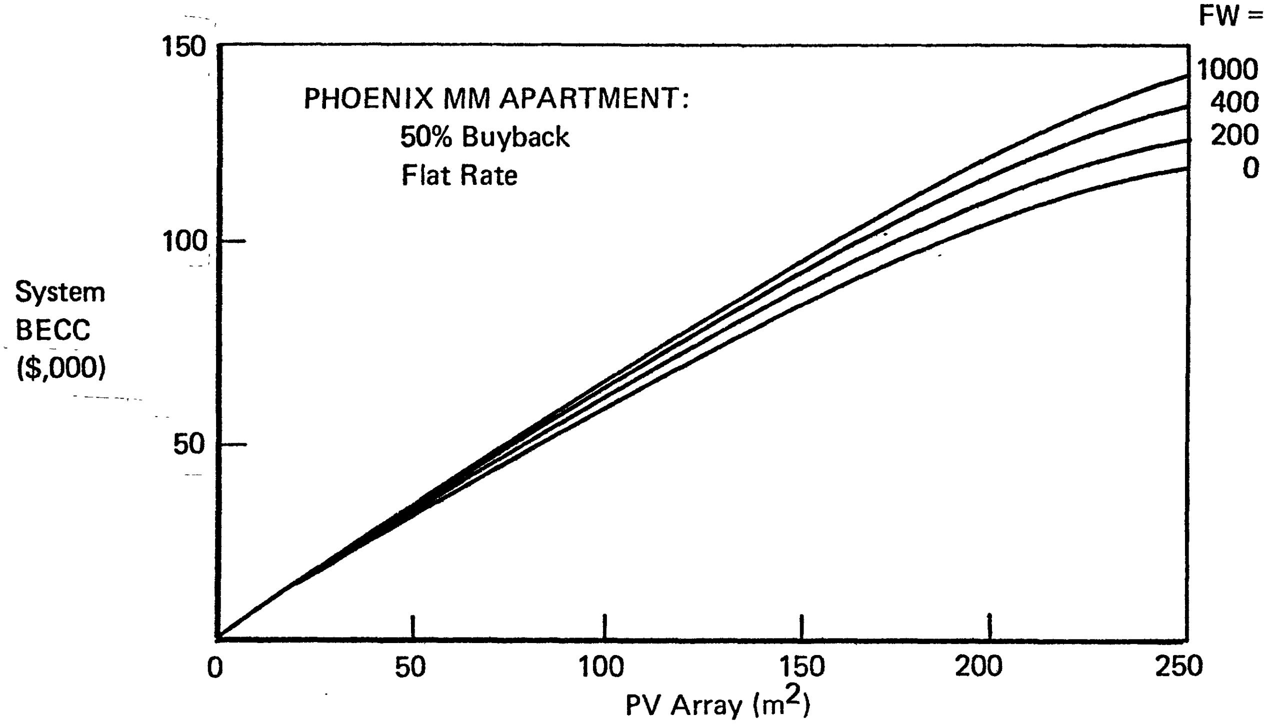
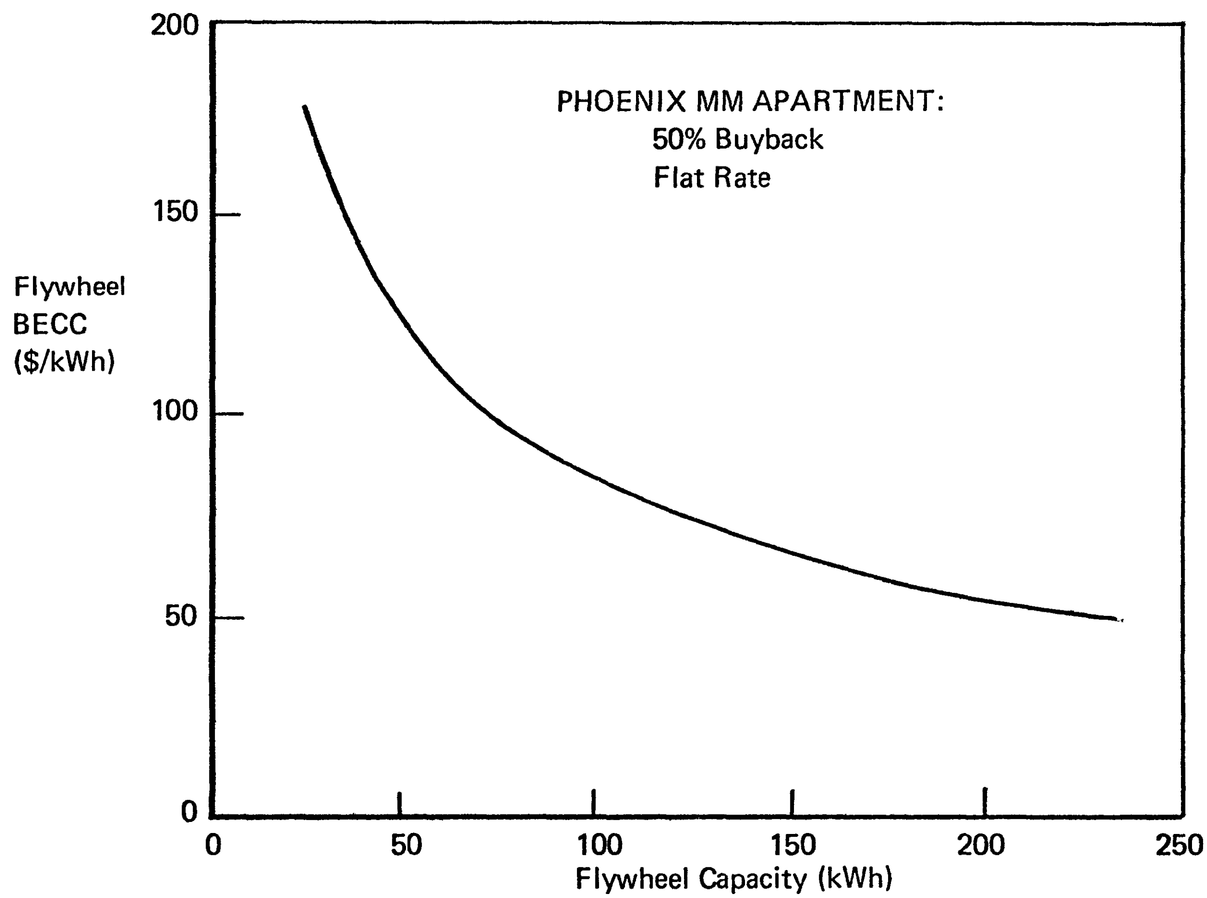


FIGURE 41

100 KW LOAD CENTER UTILITY INTERFACE





The parameter found to affect this difference most significantly is the discount rate, being set at 10 percent for the load center and 3 percent for the residence case.

III.2.b Remote Stand-Alone

PV and Flywheels/No Diesel

The studies conducted for the remote stand-alone residence were repeated for the 100 kWp load center. Figures 42 and 43 repeat the iso-reliability and iso-cost mappings, respectively, and again indicate the insensitivity of flywheel/array sizing to component hardware costs. Roughly the same rule applies as described in the single-residence analysis--that the optimum ratio of flywheel capacity (in kWh) to array size (in kWp) is roughly 2.5 in the lower ranges of reliability, rising to 4.0 in the higher ranges.

Figure 44 examines the total costs and benefits of such a system as a function of reliability. Reliability is defined here only in terms of resource sufficiency in meeting demand, not in terms of hardware outage. The total costs curve was established by assuming the hardware costs as shown; the total benefits are again defined in terms of the cost of kilowatt-hours of utility electricity not purchased. In a sense, the net benefits curve then maps out the cost of service reliability, however, it should be noted that the alternative electrical source against which the PV system is valued--the utility--generally provides power at 100 percent reliability (as reliability is defined here).

Figure 45 is a reflection of the previous figure with total benefits now including the advantage of not constructing a distribution line from distances of 10 and 20 miles from the grid. Net benefits under these conditions become positive, and intersection with the zero dollar line

FIGURE 42

ISO - RELIABILITY

(HOURS SERVED/HOURS DEMANDED)

100 KW LOAD CENTER

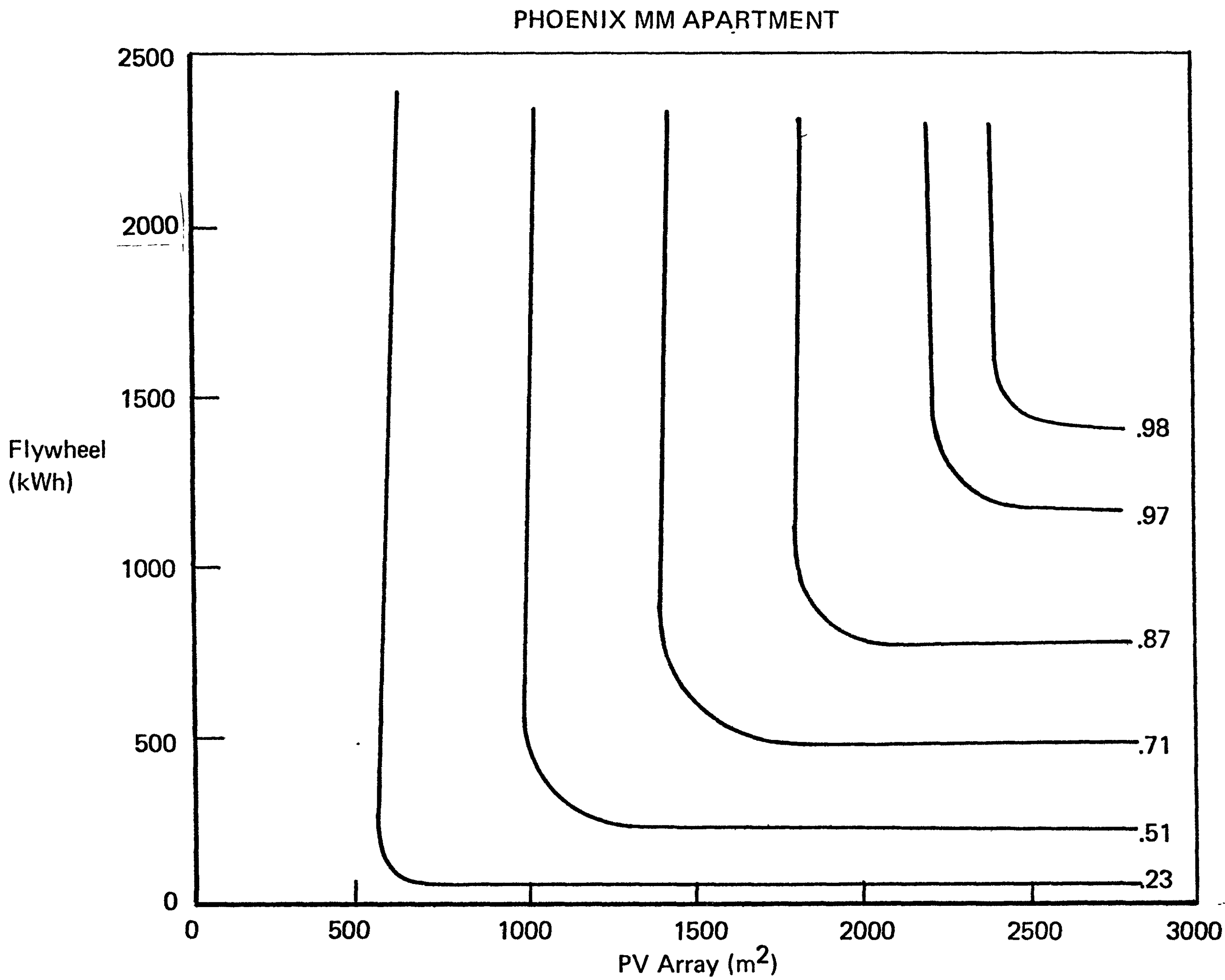


FIGURE 43

ISO - TOTAL COSTS

100 KW LOAD CENTER

PHOENIX MM APARTMENT

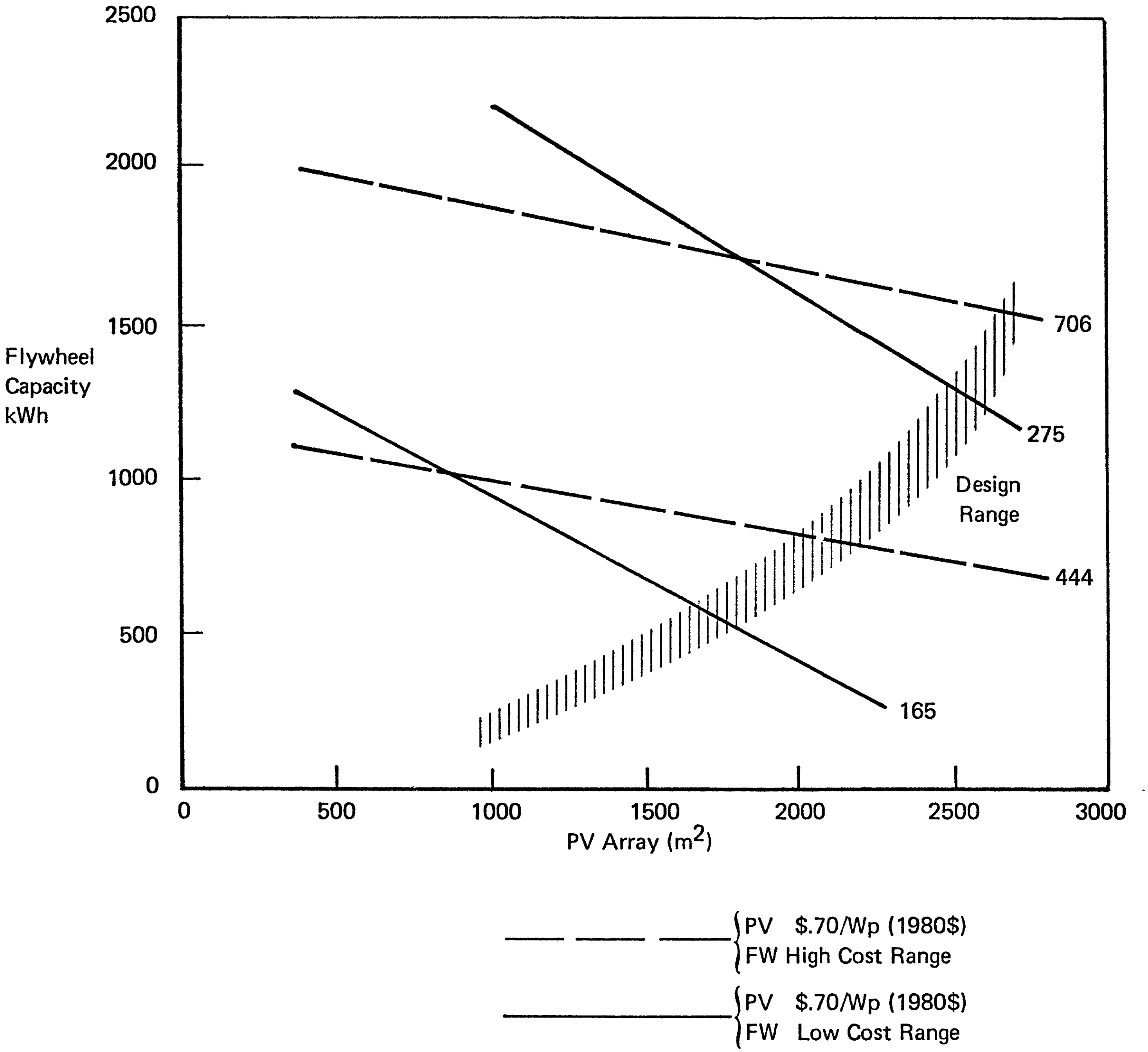


FIGURE 44

THE COSTS AND BENEFITS OF SERVICE RELIABILITY

(Benefits Equal Utility Electricity Displaced
Where Utility Supplies at 100% Reliability)

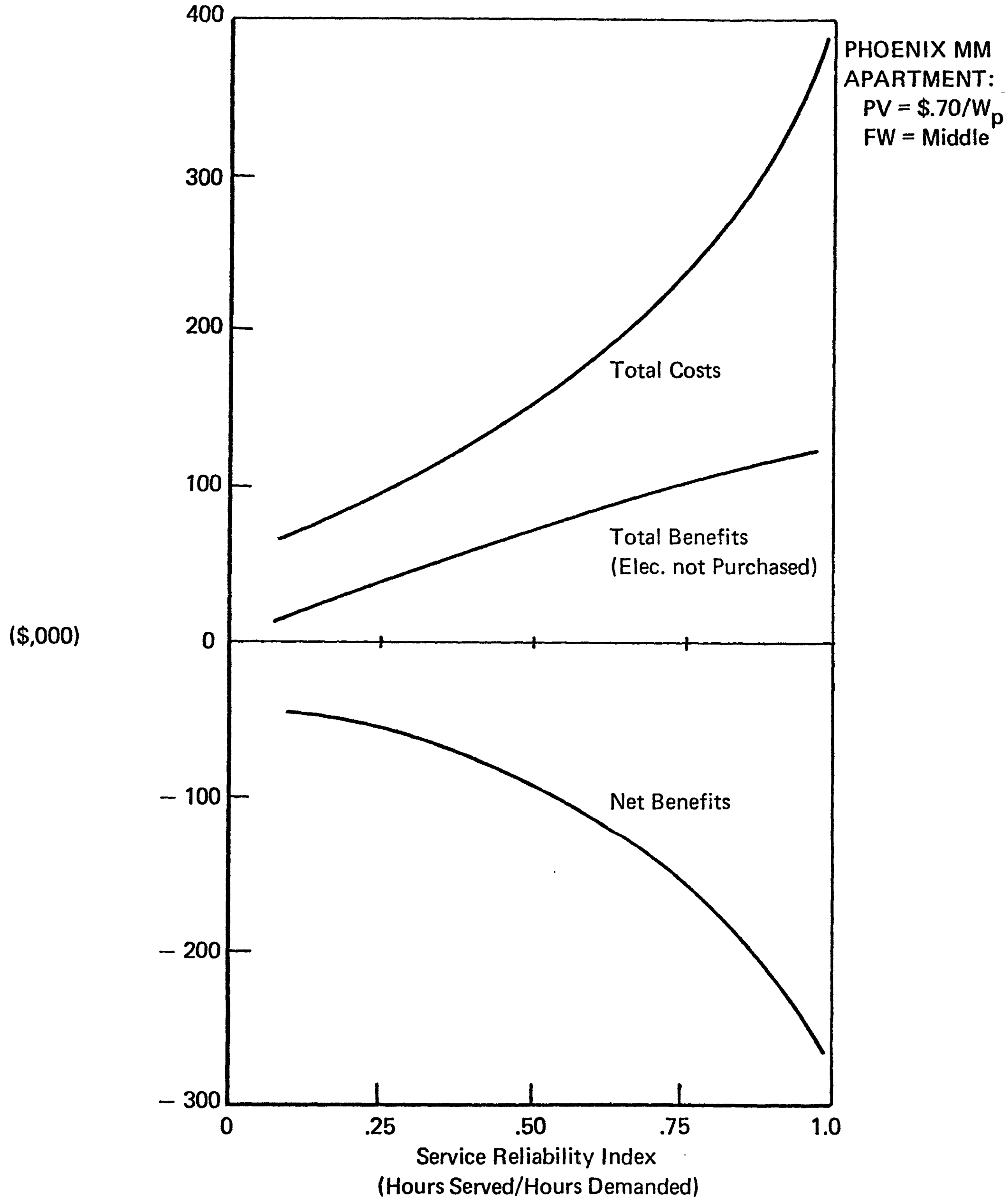
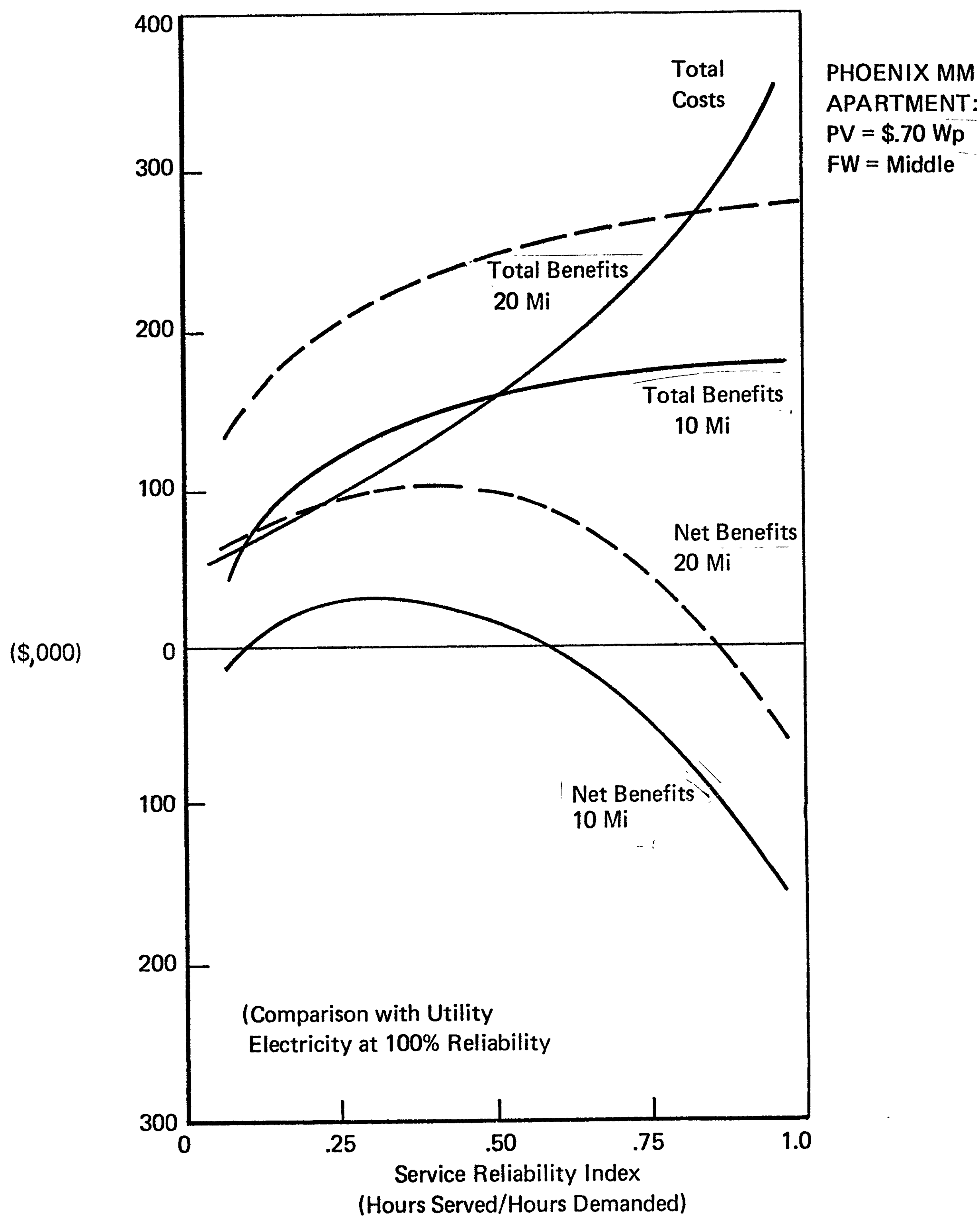


FIGURE 45

THE COSTS AND BENEFITS OF SERVICE RELIABILITY
(Benefits Equal Utility Electricity Displaced Plus Distribution Line Benefit at 10 and 20 Miles from Grid)



(vertical axis) discloses the reliability at which an investor would be indifferent toward a grid connect over constructing the PV/flywheel total (electric) energy system.

PV and Flywheel/Diesel Backup

The effect of large-project financing is perhaps revealed most strikingly by comparing Figures 46 and 33. Here the optimum configuration mix of flywheel, photovoltaics, and a diesel generator is sought. Whereas Figure 33 of the single-family residence study revealed large contributions by the flywheel and photovoltaics, the load center application finds that an all-diesel system is most practical under most economic conditions. Only when diesel fuel is expensive and hardware costs are at their lowest estimate do the new energy technologies enter the picture. These technologies represent large initial investments, and the high discount rate of 10 percent applied to such large-scale projects virtually eliminates all economic viability.

Figure 47 establishes the relationship of investment worth in terms of net benefits versus distance from the grid under the set of market conditions that prescribed the PV/flywheel/diesel system of box AA of Figure 46. Net positive benefits accrue to the system at a distance of only 10 miles from the distribution grid.

III.2.c Results of the 100 kWp Load Center Study

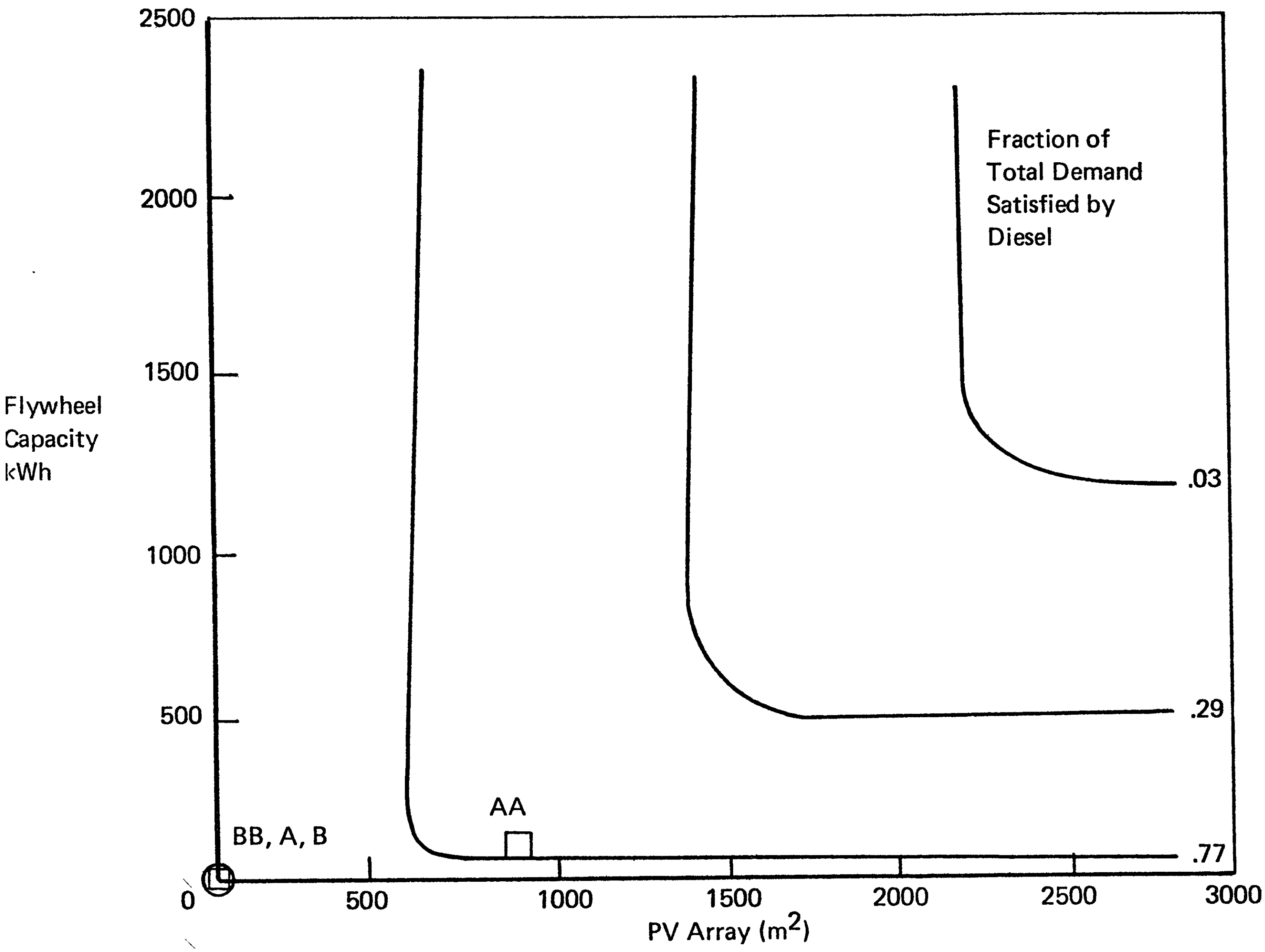
Utility Interface

- The addition of storage increases the optimum capacity of PV installed when hardware costs are in the low range.
- Storage serves the greatest increment in system value at the lower buyback rates.

FIGURE 46

OPTIMUM CONFIGURATION SIZING
REMOTE STAND ALONE 100 KW LOAD CENTER

PV FLYWHEEL DIESEL



Summary:
Phoenix Master Metered Apartment
Avg. Load: 36Kw
Pk Load: 84Kw
Diesel Capacity: 84Kw

□ Fixed Diesel Fuel Start Cost
AA Low Hardware Cost
BB High Hardware Cost

○ Fixed (Medium) Hardware Cost
A High Diesel Fuel Start Cost
B Low Diesel Fuel Start Cost

- o Diminishing returns accrue to increased flywheel capacity.

Stand-Alone

- o Optimum configuration sizing for PV and flywheel with no diesel is quite insensitive to component costs, but is very sensitive to desired reliability.
- o Sizing of a PV, flywheel, and diesel system tends toward high diesel contribution due to effects of the discount rate applied to high capital outlays for the PV and flywheel.
- o Positive net benefits accrue to the larger total energy applications at about 10 miles from the distribution grid.

III.3 Additional Studies

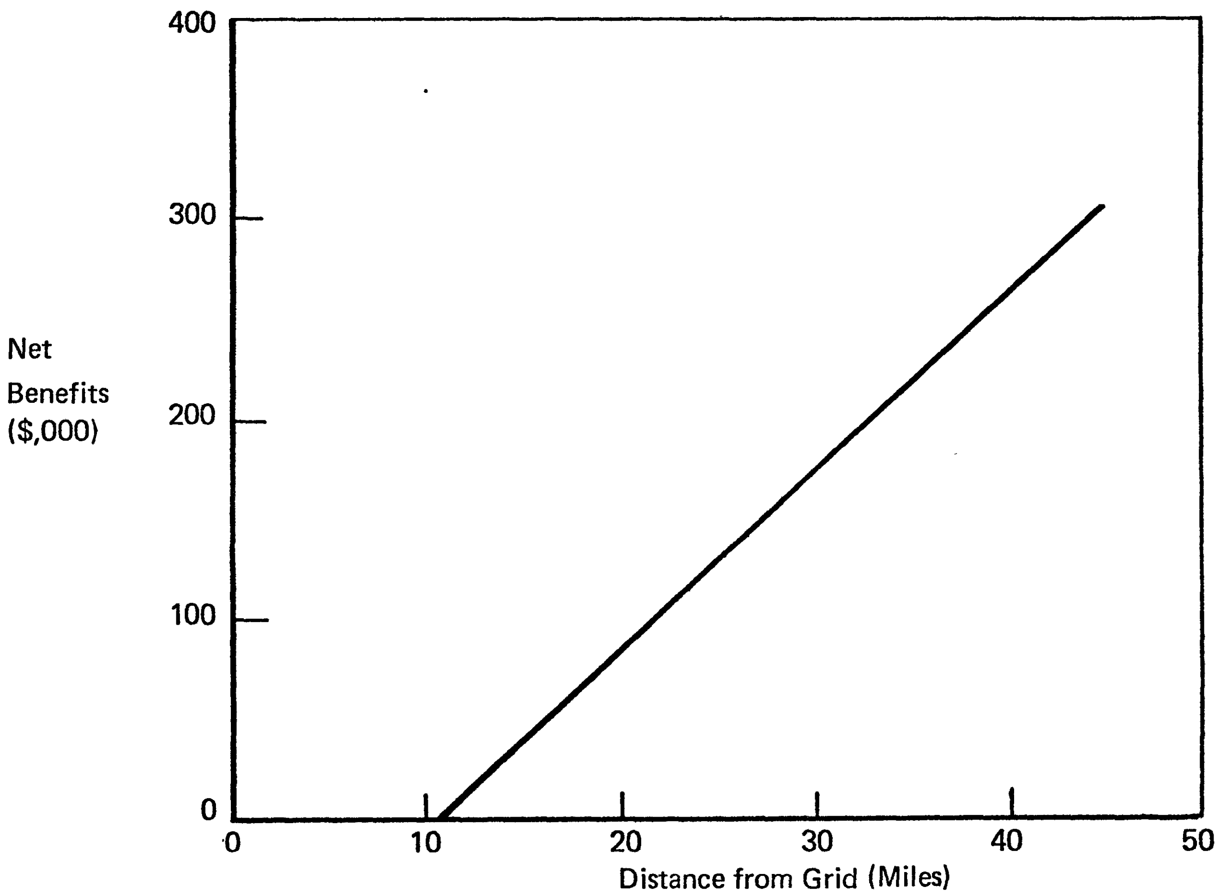
III.3.a Sensitivity to Flywheel Component Efficiencies

A full-scale prototype of the advanced flywheel concept has not yet been constructed at Lincoln Laboratories. This has necessitated the use of "best estimates" for component operating efficiencies. The assumed loss rates were summarized under Technical Assumptions in Figure 3. By fixing all components at these efficiencies, it was then possible to vary component efficiencies one by one to effect an overall parametric sensitivity analysis. Figure 48 presents the results of this analysis; Figure 49 describes the manner in which component losses were varied from the base case. All input, output, motor, and generator losses were varied by 2 percent in either direction, whereas a somewhat arbitrary variation was placed on other components. The double set of efficiencies given for the electronics components in Figure 49 describes rate of charge/discharge proportional loss figures. The left figure represents losses from 0 to 0.5 the maximum rate of charge/discharge and the right figure is the loss for higher charge/discharge rates.

FIGURE 47

STAND-ALONE VERSUS GRID CONNECT

WHEN DISPLACED DISTRIBUTION LINE COSTS ARE ACCOUNTED FOR



PV + FW + DSL Versus Grid-Connect

FIGURE 48

SENSITIVITY TO FLYWHEEL COMPONENT EFFICIENCIES

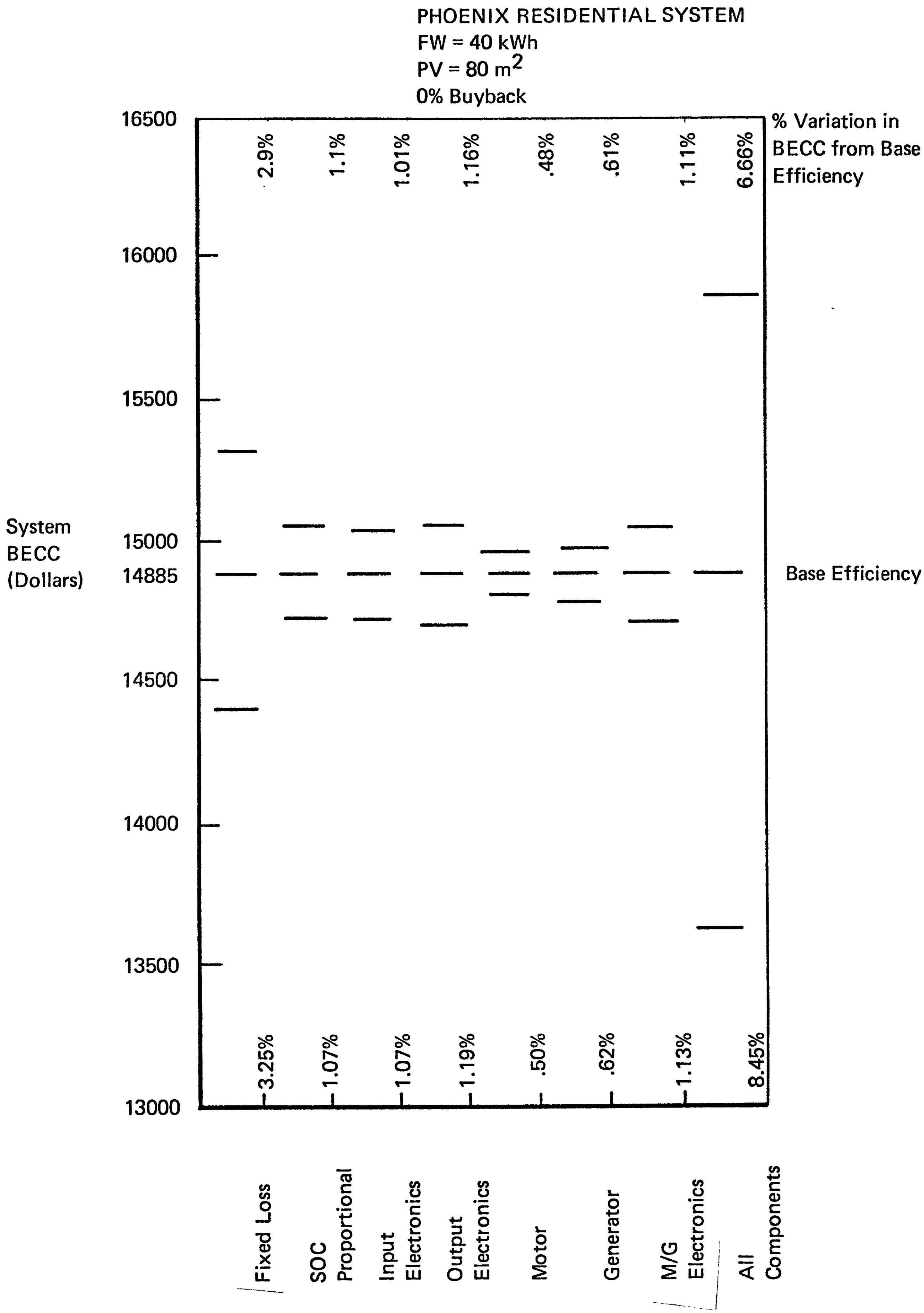


FIGURE 49

SENSITIVITY TO COMPONENT EFFICIENCIES

VARIATIONS PLACED ON EFFICIENCIES

PHOENIX RESIDENCE

PV = $80M^2$ FLYWHEEL = 40 KWH

0% UTILITY BUYBACK

COMPONENT		EFFICIENCY	
	BASE	HIGH	LOW
FIXED LOSS	200 WATTS	300 WATTS	100 WATTS
STATE-OF-CHARGE PROPORTIONAL	.003	.005	.001
INPUT ELECTRONICS	7%/8%	9%/10%	5%/6%
OUTPUT ELECTRONICS	7%/8%	9%/10%	5%/6%
GENERATOR ELECTRONICS	2%/4%	4%/6%	0%/2%
MOTOR ELECTRONICS	2%/4%	4%/6%	0%/2%
MOTOR/GENERATOR ELECTRONICS	PREVIOUS TWO	PREVIOUS TWO	PREVIOUS TWO
ALL COMPONENTS	ALL PREVIOUS	ALL PREVIOUS	ALL PREVIOUS

It is seen that input, output, and combined motor/generator electronics all yield roughly equivalent varations in system value for like changes in efficiency rating. That value is also similar to that produced by the shown change in state-of-charge proportional loss, and roughly one-third of the loss due to varying the fixed loss rate.

III.3.b. Comparison to Battery Storage

Conceptually, both batteries and flywheels can be described in terms of a generalized storage function, including all component loss characteristics as listed in Figure 3. In actuality, however, this is far too simple. For example, the battery loss estimates are hindered by the imprecision with which estimates can be made of the battery state-of-charge. In fact, no standard means has yet been developed for making such estimates on actual batteries in operation. Millner [2] has already placed estimates of the overall flywheel operating efficiency at 73.3 percent, and has summarized the battery-based storage efficiency (including max power tracker and inverter) at 65.4 percent.

To maintain this overall efficiency advantage over batteries, one needs to look again at the sensitivity of component efficiencies of Figure 48. For example, if a large change were expected in fixed-loss rate, this would have fairly significant impact on overall flywheel efficiency, whereas an unexpected difference in merely the motor electronics component would have minimal impact on overall flywheel efficiency.

III.4 Comparison of Single-Family Residence with the 100 kWp Multi-Family Load Center

From the previous analysis, the following conclusions can be drawn in comparing the two application types of this study:

- o Breakeven cost figures for flywheels are lower for the load center application due to:
  - o higher discount rates
  - o delay of benefits due to longer construction lags
- o As a result, the issues most affected are:
- o flywheel breakeven cost curves
- o optimum component sizing
- o distance from the grid at which positive net benefits accrue to the system (stand-alone analysis)

Chapter IV. DISCUSSION

IV.I Investment Decision Making

The question that must be answered in the flywheel worth analysis is whether the addition of energy storage to a photovoltaic system enhances the economic stature of that system. It has been shown that, looking at system benefits as whole, storage increase system value. However, this is only one side of the equation. The complete equation takes into account the costs of that system, and tests whether or not system benefits exceed these costs. The question with regard to flywheel storage is thus whether or not the expected cost of an increment in energy storage is greater or less than its marginal improvement upon system value. In other words, taking into account the expected cost of energy storage, do net benefits accrue as a result of its addition to system operation? Formulated in this manner, a criterion of maximizing net benefits explains under what conditions an investment would be made in energy storage as supplementing photovoltaics.

Evaluation of this figure is not so straightforward, however, for a number of reasons. First, the exact costs of all components and maintenance are unknown. We have, at best, estimates, usually in terms of manufacturers' prices and DOE price goals. In the flywheel study, a best estimate is assumed for costs, which are then varied in either direction to determine cost sensitivity. Second, there are various ways to value the benefits of any one project, depending upon the perspective of the investor. Here it is necessary to distinguish between a private investor's decision process versus that of a public decision-making body, or possibly, a public-minded consumer. Public investment decisions are likely to involve issues of social cost in producing electricity, such as relative environmental hazards, as well as reliability, security, and psychological concerns. These issues are inherently controversial and therefore not subject to discussion here. Private investment decisions deal almost exclusively with normal market conditions and prices. These conditions are more easily dealt with.

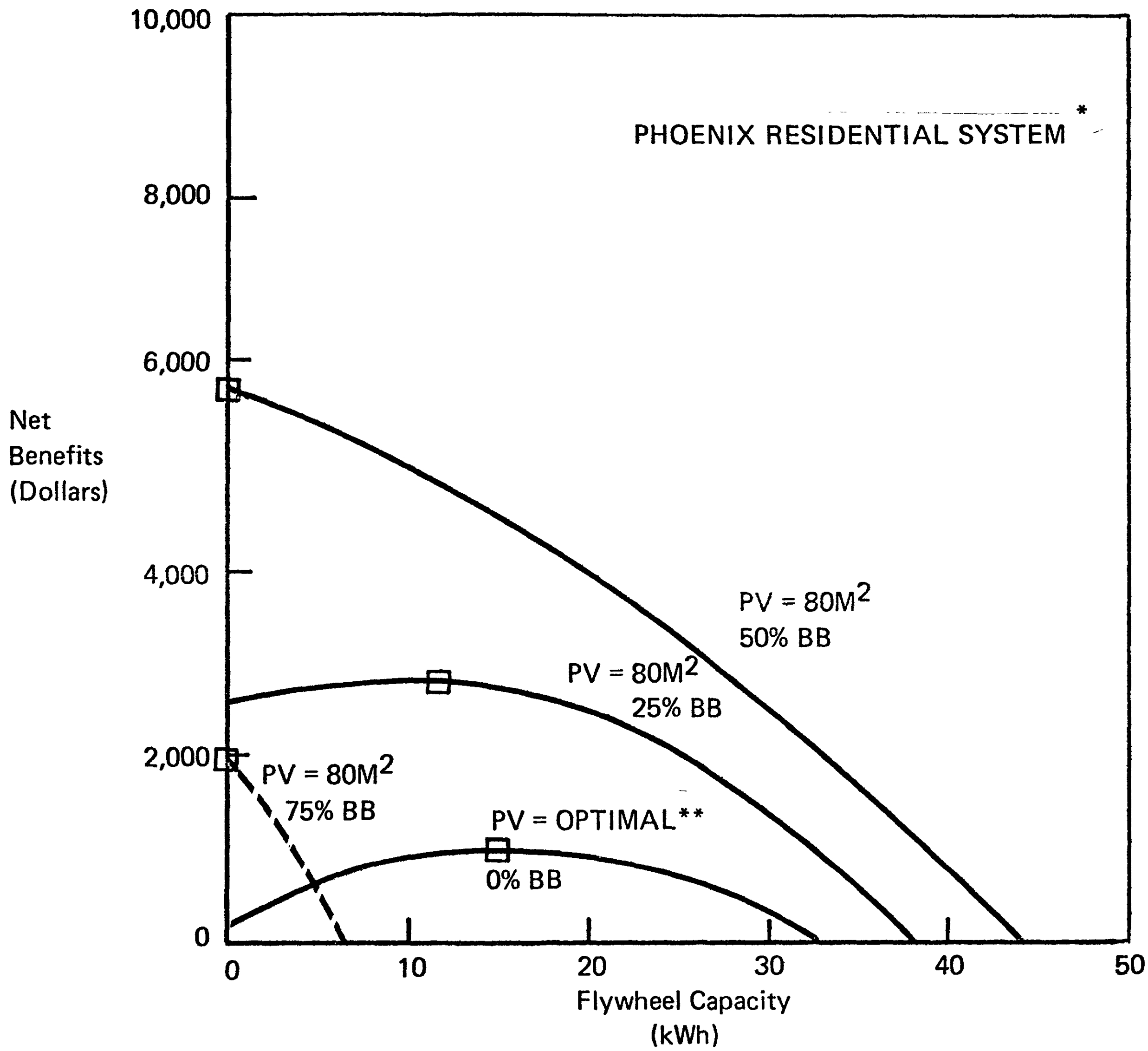
The Private Investor

It is assumed that the private investor always seeks to maximize profits. Any homeowner with a fixed dollar budget will make the decision to invest based solely on issues of relative return and relative risk. To satisfy his energy demand, an investor will go with the option that offers the potential for maximum return on investment when compared against the most likely alternative. This should include the full range of investment opportunities, including the option to reduce demand through conservation. However, in this study benefits have been strictly defined as the total dollars otherwise spent on utility-supplied electricity, priced at the expected cost of electricity in that year.

Under these conditions, a net benefit study was performed for the Phoenix residence case utilizing an 8 kWp PV array with a varying flywheel storage capacity. For the medium-cost assumption (dashed line of Figure 3) net benefits would never accrue unless the utility were purchasing electricity at, minimally, a 60 percent buyback rate, in which case an investor would invest in PV alone with no storage (Figure 50). So except for the very low buyback rates, over the full range of flywheel capacities the costs assumed would always exceed the benefits as defined above.

FIGURE 50

NET BENEFITS STUDY OF OPTIMAL FLYWHEEL CAPACITY



Medium Costs Assumed

Low Costs Assumed

□ Indicates Economic Flywheel Sizing Choice

** PV Array Size Corresponds to Optimal at Given Flywheel Capacity

* High BOS Assumptions

For purposes of carrying the description further, the low-costs assumption was used for system components. Figure 50 reveals that under these conditions storage does enhance system economics to the point where incentive for the investment would actually exist. For the 0 percent buyback case shown, little net benefits accure to PV alone, whereas adding of 20 kilowatt hours of storage capacity forces a peak in net benefits accumulated over the 20 year life of the system. The reason for this is as follows. The initial (infrastructure) costs of a photovoltaic system are significant, so substantial benefits must accrue before net benefits become positive. With a fixed household demand and low utility buyback, there are diminishing returns to increasing PV array size beyond roughly 35 m^2 with no storage. Energy storage captures excess PV electricity and so has the effect of "smoothing" the array output to precisely match the load, thus stalling the effect of diminishing returns to increasing array size. As the buyback rate increases, the utility purchase of excess PV serves the same purpose of storage in smoothing array output, and hence energy storage (and its associated cost) is merely redundant.

IV.2 The Need for Flywheel Research

Further research into the advanced flywheel storage concept is needed in many areas, most of which apply to storage systems in general. However, given that the flywheel concept does offer certain specific advantages over any other means of energy storage tested to date, and given the need to ensure a diversified competitive future market in energy storage devices, the reasons outlined here apply to flywheels in particular.

Alan Cox of the MIT Energy Laboratory has quantified some of the implications of storage availability based on the results of this study. A summary of his work is provided below, and his methodology is included as Appendix A.

- REMOTE LOCATIONS
  - Savings of $8,712/mi in transmission costs for residential standalone systems.
  - Storage economically preferable at locations 1-20 miles from grid (residential).
  - Present-valued savings in diesel-fuel backup are $4,165 at remote residence (3 percent discount rate, 20-year life).

- PEAK SHAVING
  - 50 kWh shifted per day will result in $5,000 in BOE savings (discounted)

- DECREASED UNCERTAINTY in electricity supply from PV decreases discount rate applied to PV investment decisions.

- DEMAND FOR STORAGE AS PV PRICES FALL
  - For users with PV BECC greater than future PV prices, optimal array size will increase (until MC = MB) with storage.
  - With storage at residence, optimum array size increases from 60 m^2 to 110 m^2. Electricity savings will be 15/BOE/year at residence.
  - Increased penetration. If Phoenix residential penetration is 5 percent without storage, increased optimum array size will result in 840,820/BOE/year savings.

- NEED FOR DIVERSIFIED RESEARCH EFFORT to ensure a competitive future market in storage devices.

Chapter V. CONCLUSIONS

The following conclusions can be drawn from this study:

- Flywheel systems are more attractive in smaller distributed applications that have small construction period lags and where low discount rates are applicable. These include residential applications as well as applications in developing countries.
- For low expected costs for PV and flywheels, the flywheel increases the size of an optimal photovoltaic system.
- Flywheel storage serves the greatest increment in system value at the lower buyback rates.
- Variations over the range of reasonable time-of-day rate structures have an insignificant impact on flywheel economics unless the flywheel is allowed to serve in a dispersed/system storage mode (as opposed to dispersed-dedicated).
- PV/flywheel/diesel total energy systems are competitive with a utility grid connect at distances starting one mile from the utility grid.
- For PV and flywheel remote stand-alone applications utilizing no diesel, optimum component sizing is insensitive to hardware cost.

APPENDIX A

THE NEED FOR FLYWHEELS

Alan J. Cox

MIT Energy Laboratory

This memo represents a brief attempt to set down a concise rationale for a well-funded flywheel storage and power conditioning project. The list of points is by no means complete.

The first point to be made is that flywheels should be evaluated on their capacity for penetrating the future market for electricity storage, in the same manner and order as PV arrays themselves are being evaluated.

The PV marketing plan is to introduce this technology in remote locations, and in developing countries, allowing the industry to build up production in anticipation of the market opening up for such low discount-rate users as government installations and electric utilities, or users who are experiencing high electricity costs, such as those already found in the Northeast residential-commercial rate classes. As the industry continues to enjoy the benefits of economies of scale and to develop new lower-cost technologies, the PV systems should penetrate deeply into the remaining residential market and enjoy considerable use in the industrial sector.

This study shows that there are clear advantages to using flywheels as backup storage in remote locations over diesel fuel use or construction of electricity transmission facilities. The benefits arising from investment savings in 69 kV transmission lines are $8,712/mile (1980 $). For an Arizona location, using reasonable estimates of 1985 flywheel costs, this makes flywheel storage an economically preferable option (over transmission line construction) at distances greater than 1 to 20 miles, depending on whether the load is residential or commercial and depending on other economic assumptions. The benefits in terms of diesel fuel saved would be $4,200 in 1985, over 20 years, discounted at 3 percent and assuming a 1985 diesel fuel price of $0.97/gallon. These figures, supplemented with the more extensive analysis of such factors as reliability, clearly indicate an early market for storage devices.

Another relatively short-term market at which the flywheel technology should be aimed is that arising out of attempts to shave peaking electricity requirements. Assuming heat rates of 8.5 mBtu/kWh for a base oil, coal, or synfuel plant, 10.0 mBtu/kWh for nuclear plant and 14.0 mBtu/kWh for a peaking gas turbine, 50 kWh shifted each day from peak to base plants will result in savings of 12.2 barrels of oil equivalent per year shifting to a nuclear base and 16.7 bbl/year for shifting to oil-synfuel base. Assuming a $20.00/bbl for oil, a 20-year life for the project, no operating and maintenance costs, no inflation and a 3 percent discount rate, the shift to oil-coal-synfuel base would have a discounted present value of almost $5,000. That figure is what could be afforded for a suitable flywheel within the reasonable future if required rates of return can be brought down through reduced interest loans and other incentives.

It may be worthwhile to note that anything which increases the reliability of the supply of electricity from a new technology is certain to reduce the discount rate that individuals and firms apply to it. The uncertainty and risk associated with PV will be reduced, to some extent, bringing individual discount rates with it.

As PV arrays continue to fall in price, users in situations that had experienced high breakeven capital costs will find themselves able to buy PV systems that will provide them larger savings in their electricity bills, provided, of course, a suitable storage system can be bought. For instance, in situations in which the original BECC peaked at $1.00/Wp, a PV user will experience considerable savings when array costs fall to $0.50/Wp. A PV consumer would be willing to expand his/her PV investment until the marginal benefit of increasing that investment reaches $0.50/Wp. The resulting savings could offset the cost of a flywheel since only with a storage device will the expanded electricity production be useful, once all desired load-shifting has taken place.

With such a system, and with falling array costs, more and more electricity consumers will correctly ascertain that their optimal PV array size is larger than that with no storage. Again, this is a clear result of the current study. These results indicate that, for a buyback rate equal to 0 percent, the optimum array size shifts from 60 m^2 to 110 m^2 for a Phoenix residence. This difference converts to annual electricity production of 10,624 kWh at the residence, or barrel of oil equivalent savings of 15.0 bbl/year, assuming the oil baseload heat rates. At a 5 percent penetration within the Phoenix synthetic utility, without storage, the increase in optimal sizing would increase the installed PV with storage from 400 MW to 733 MW. The increase in energy savings would be 840,820 barrels of oil equivalent per year.

A final argument to be made in favor of a strong flywheel-power-conditioning research program is to develop alternative storage devices which may maintain some competition in the future storage devices market, and which will have certain features that will make it a more appropriate storage device for some uses.

FOOTNOTES

1. General Electric Space Division, Applied Research on Energy Storage and Conversion for Photovoltaic and Wind Energy Systems, Final Report, Volume I: Study Summary and Concept Screening and Volume II: Photovoltaic Systems with Energy Storage, January 1978.

2. Ibid.

3. Alan R. Millner, "A Flywheel Energy Storage and Conversion System for Photovoltaic Applications," M.I.T./Lincoln Laboratory, paper presented at the international Assembly on Energy Storage, Dubrovnik, May 28-June 1.

4. From Alan J. Cox, "The Need for Flywheels," internal M.I.T. Energy Laboratory Memorandum, August 15, 1979. This memorandum is based on calculations using the results of this report and is enclosed as Appendix A.

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2. Millner, Alan R. A Flywheel Energy Storage and Conversion System for Photovoltaic Applications, M.I.T./Lincoln Laboratory, paper presented at the International Assembly on Energy Storage, Dubrovnik, May 28-June 1, 1979.

3. General Electric Space Division, Regional Conceptual Design and Analysis Studies for Residential Photovoltaic Systems, Volume I: Executive Summary, January 1979.