HCP/T—22221—01/2

Hr. 2037

4-24-78

MASTER

APPLIED RESEARCH ON ENERGY STORAGE AND CONVERSION FOR PHOTOVOLTAIC AND WIND ENERGY SYSTEMS

FINAL REPORT

VOLUME II

PHOTOVOLTAIC SYSTEMS WITH ENERGY STORAGE

JANUARY 1978

PREPARED FOR

NATIONAL SCIENCE FOUNDATION
AND THE
U.S. DEPARTMENT OF ENERGY
ASSISTANT SECRETARY FOR ENERGY
TECHNOLOGY
DIVISION OF ENERGY STORAGE
SYSTEMS

UNDER CONTRACT NO. NSF C-75-22221-01

DISCLAIMER

DISCLAIMER

Available from:

National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

Price:	Printed copy:	$12.0C
	Microfiche:	$3.00

HCP/T-22221-01/2
UC-60, UC-63, UC-94b

APPLIED RESEARCH ON ENERGY STORAGE AND CONVERSION FOR PHOTOVOLTAIC AND WIND ENERGY SYSTEMS

FINAL REPORT

VOLUME II
PHOTOVOLTAIC SYSTEMS WITH ENERGY STORAGE

JANUARY 1978

Prepared By

General Electric
Space Division
Valley Forge Space Center
P.O. Box 8555
Philadelphia, Pennsylvania 19101

For The

National Science Foundation
and
U.S. DEPARTMENT OF ENERGY
Assistant Secretary for Energy Technology
Division of Energy Storage Systems
Washington, D.C. 20545

Under Contract No. NSF C-75-22221

Notice

FOREWORD

This report presents the results of a study of the use of energy storage in conjunction with photovoltaic and wind energy conversion systems. The program was conducted under National Science Foundation contract number NSF-C-75-22221 with direction from the Energy Research and Development Administration, through Dr. George C. Chang, ERDA Program Monitor. Dr. Richard Schoen of NSF provided initial program direction prior to September, 1976.

The report consists of three volumes. Volume I contains a Study Summary of the major results and conclusions. Volume II contains a description of the study methodology, procedures, analyses, and results associated with use of energy storage in conjunction with Photovoltaic Systems. Volume III contains information similar to that of Volume II, but directed toward use of energy storage with Wind Energy Conversion Systems.

The study was conducted by Advanced Energy Programs - General Electric Company, Space Division. Principal contributors included A.W. Johnson, Program Manager, E.J. Buerger, Dr. R. Fogaroli, A. Kirpich, R. Landes, R. McCarthy, N.F. Shepard, H. Thierfelder and S.M. Weinberger. In addition, the following organizations provided information, consultation and/or analyses pertinent to the study.

C&D Batteries Div., of Eltra Corp., Plymouth Meeting, Pa.
GE Corporate R&D Center, Schenectady, N.Y.
GE Direct Energy Conversion Programs, Boston, Mass.
GE Electric Utility Systems Engineering Dept., Schenectady, N.Y.
Public Service Electric and Gas Co. of Newark, N.J.
GE TEMPO, Santa Barbara, Calif.

Mr. W.R. Terrill, Manager, Solar Electric Power Programs, and Mr. R.J. Barchet, Manager, Photovoltaic Programs, provided overall guidance for the study within General Electric.

Additional contributions to the study report were received from the review team which included the following members:

Dr. Len Magid Dr. Doug Warschauer Dr. Mort Prince Dr. Hal Macomber Mr. Don Teague Dr. Bob Thresher	Division of Solar Energy, ERDA
Dr. George Chang Dr. Al Landgrebe Mr. Rufus Shivers Dr. Wayne Coffman	Division of Energy Storage Systems, ERDA
Mr. Larry Gordon	NASA-Lewis Research Center
Dr. Henry Dodd	Sandia Laboratories, Albuquerque, NM

VOLUME II

TABLE OF CONTENTS

VOLUME II

TABLE OF CONTENTS (CONT.)

VOLUME II

TABLE OF CONTENTS (CONT.)

VOLUME II

LIST OF TABLES

VOLUME II

LIST OF TABLES (CONT.)

VOLUME II

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONT.)

VOLUME II

LIST OF ILLUSTRATIONS (CONT.)

VOLUME II

LIST OF ILLUSTRATIONS (CONT.)

VOLUME II

LIST OF ILLUSTRATIONS (CONT.)

INTRODUCTION

The variability of energy output inherent in photovoltaic energy conversion systems (PVCS) has led to the investigation of energy storage as a means of managing the available energy when immediate, direct use is not possible or desirable. Several energy storage concepts have been successfully employed for many years in the United States and elsewhere. The most notable examples are hydro systems, representing an upper level of storage size or "capacity" and batteries and flywheels for important but smaller scale applications. In Germany, thermal storage has been used successfully as a means of utility load leveling. This portion of the General Electric study was directed at an evaluation of those energy storage technologies deemed best suited for use in conjunction with a photovoltaic energy conversion system in utility, residential and intermediate applications. Break-even cost goals are developed for several storage technologies in each application. These break-even costs are then compared with cost projections presented in Volume I of this report to show technologies and time frames of potential economic viability. The form of the presentation allows the reader to use more accurate storage system cost data as they become available. The report summarizes the investigations performed and presents the results, conclusions and recommendations pertaining to use of energy storage with photovoltaic energy conversion systems.

SECTION 1

SUMMARY AND CONCLUSIONS

1.1 STUDY OBJECTIVES AND SCOPE

The principal objectives of the study with respect to photovoltaic energy conversion systems and their use of energy storage were:

1. The assessment of selected candidate storage concepts.
2. Evaluation of the effects of selected parameters on the attractiveness and worth of energy storage.

The scope of the investigations included both utility and non-utility applications. In addition to establishing cost goals for storage, the impact of charging storage from multiple sources, as well as from photovoltaic systems alone, was included, along with the effects of insolation forecasting and transient smoothing of the PV system output.

Representative loads and average fuel costs were utilized. Generation mix per se was not included as a variable. Three basic photovoltaic system sizes were included: large photovoltaic arrays clustered to provide selected amounts of "penetration" of PV systems in terms of total utility system capacity, a 500 kW PV array for intermediate applications, singly or in multiples, and a 10 kW array for residential application. Results were based on climatic data from three widely separated locations which could be considered representative of conditions in coastal, mountain and plains areas of the contiguous United States.

1.2 STUDY APPROACH

The study was conducted using the following general procedural steps:

1. Review of current concepts for the use of eleven storage methods including mechanical, thermal, electrical and electrochemical types of storage devices.

2. Assessment of suitability of concepts for use with photovoltaic energy conversion.

3. Determination of present through the year 2000 cost goals for energy storage vs. storage capacity under different conditions relative to:

   a) Application
   b) Available photovoltaic energy/location
   c) PV system penetration (utility case)
   d) Storage efficiency
   e) Fuel price escalation rate
   f) Other cost/viability factors

1.3 OVERALL FINDINGS - ENERGY STORAGE WITH PHOTOVOLTAIC ENERGY CONVERSION SYSTEMS

This section of the study report presents the overall findings and general conclusions reached as a result of the study. These findings and conclusions are described below. More detailed findings related to the specific study baseline conditions and assumptions are presented in the sections immediately following and elsewhere throughout the body of the report. It is significant to note that because of the interaction of basic parameters involved in actually applying photovoltaic systems and energy storage, the overall study results provide general guidance which must be supplemented by detailed investigations for any specific system design proposed.

1. Energy storage improves both the energy utilization and the worth of photovoltaic energy over that of systems not using storage. This is illustrated in Figure 1.3-1 for the utility and residential cases, with the cross-hatched area indicating the increased savings due to storage over and above the basic PV system savings. Intermediate storage system savings followed a pattern similar to the residential savings. The range and implications of the storage improvements are discussed in more detail for each application level.

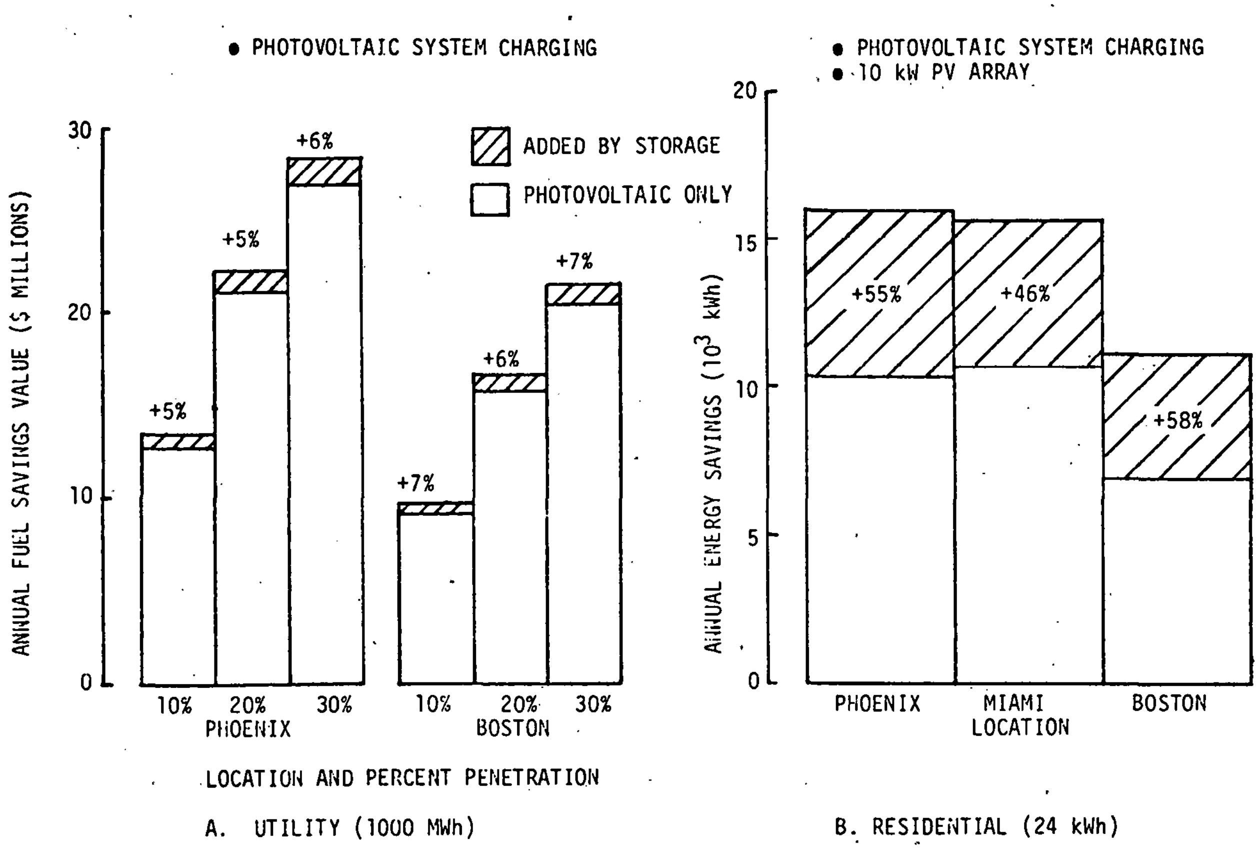


FIGURE 1.3-1. ANNUAL SAVINGS DUE TO STORAGE AT REPRESENTATIVE STORAGE CAPACITIES

2. On the utility level, energy storage provides a substantial additional benefit due to displacement of other generation equipment and, in some cases, transmission and distribution equipment.

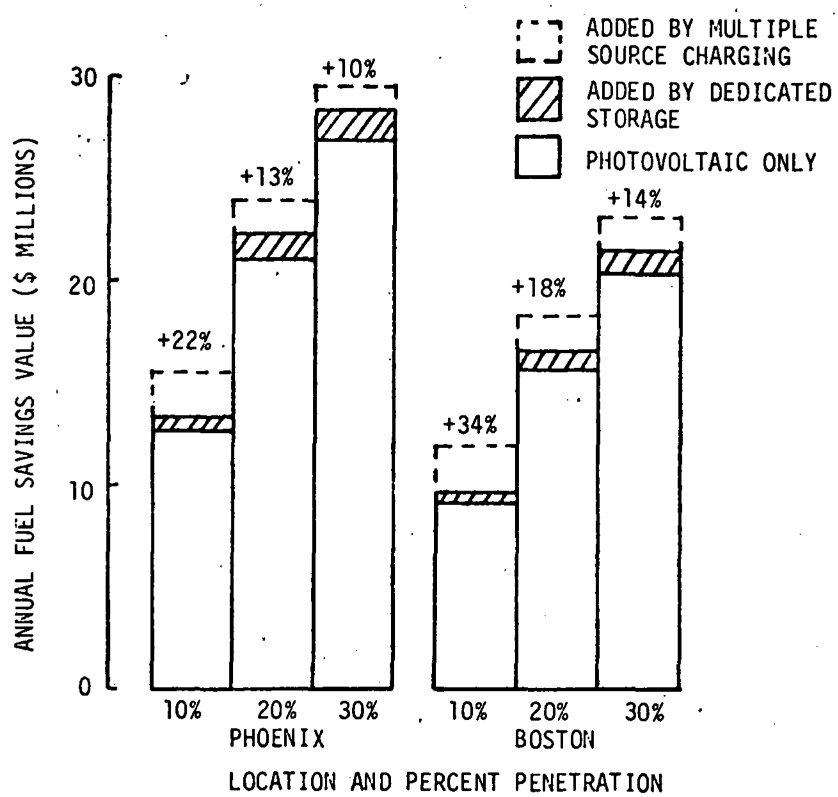
3. Of the eleven energy storage concepts considered in the study, none show economic viability at current storage costs and energy prices when dedicated to use with photovoltaic energy conversion systems (PV system-only charging).

4. Energy storage on the utility level is always significantly more useful and economically attractive if it is charged on a system-wide or multiple source basis rather than dedicated to photovoltaic system charging alone. This is shown in Figure 1.3-2 which shows the added multi-source charging value as a dashed area above the previously-presented dedicated charging savings.

5. A further advantage of multi-source charging is increased displacement of other generation equipment due to more reliable storage operation.

6. Pumped hydro storage systems offer the best storage economics for those applications (primarily utility system-wide charging) with proper scale and site characteristics. In addition, current pumped hydro storage costs represent cost goals for large scale storage systems, since they are presently economic on a system wide charging basis in many utility systems.

• MULTIPLE SOURCE CHARGING



INCREASED UTILITY SAVINGS DUE TO MULTI-SOURCE CHARGING OF STORAGE

FIGURE 1.3-2. INCREASED UTILITY FUEL SAVINGS DUE TO MULTI-SOURCE CHARGING OF STORAGE

7. Of the several relatively near term storage technologies, battery energy storage is the most universally attractive across the range of applications studies. An advanced battery at projected 1985 conditions was the only storage concept with wide applicability to show potential economic viability in the near term.

8. Energy storage systems other than pumped hydro will offer economic viability if increasingly severe economic conditions are postulated

between now and year 2000. Figure 1.3-3 presents break-even cost goals for utility and residential batteries at several electricity price escalation rates and start years of 1985 and 2000. Current costs of lead-acid batteries and the 1985 cost projection for advanced batteries are also shown. Battery life was assumed at 10 years. If a 20 year life battery becomes available the break-even cost goals would increase by over 30% in the residential application and by 7 to 14% in the utility application. The clear superiority of system wide or multi-source charging of storage is again shown.

9. Although the type of energy storage system should be selected on an individual application basis, the differences in storage system characteristics suggest that a mix of storage concepts may be desirable. For example, a utility network could employ pumped hydro storage for 10 hour discharge duty and advanced batteries for peaks of shorter duration where battery economics closely approach pumped hydro. The transmission and distribution facilities of a utility system may also make a mix of storage technologies desirable.

10. Insolation forecasting appears to offer only a modest improvement in storage value over what can be obtained using reasonably straightforward judgmental storage operational strategies.

11. Energy storage in residential and intermediate applications can achieve as high as a 45 to 70 percent increase in total system energy capture. When realistically achievable storage costs are considered, storage can, at best, increase the worth of the basic PV system by 25 to 40 percent.

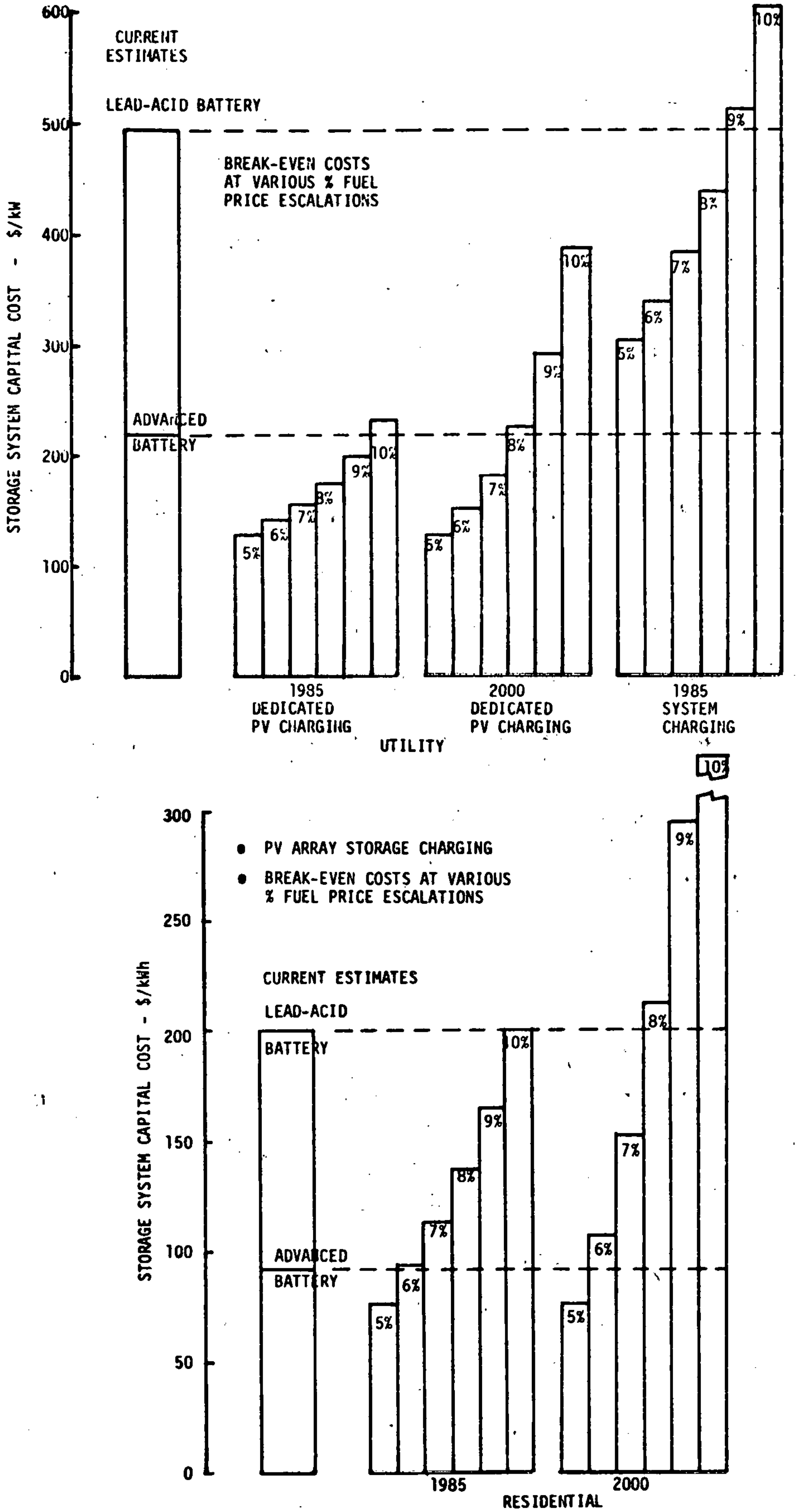


FIGURE 1.3-3. CONDITIONS LEADING TO ECONOMIC VIABILITY OF UTILITY AND RESIDENTIAL ENERGY STORAGE SYSTEMS - PHOTOVOLTAIC ENERGY CONVERSION

12. High electric rates combined with the non-tax-deductibility of energy costs makes the residential energy storage system generally much more economic than the intermediate, under present pricing and tax policy.

13. The special utility case studies performed by GE-EUSED, using a Monthly Production Simulation Program analysis, produced worth-of-storage results similar to other study findings. The results indicated that:

 (a) Operating storage in a dedicated manner with PVCS can lead to a significant (~2.7:1) economic penalty.

 (b) There is a potential (~16%) to improve the value of system storage in PVCS appplications by accurate weekly forecasting of PVCS output.

14. The smoothing of PVCS output with energy storage devices is a technical requirement for certain types of single generator - single load situations. For large scale or utility type operations, the requirements for stability of output are better met by other means. No economic value results from using storage for output smoothing except in the intermediate applications. Rate structures in these applications can make smoothing attractive in cases where lower level power demands can be achieved with a corresponding reduction in customer charges.

15. Over the range of parameters studied and at the baseline economic conditions of 1985 start and 6% fuel price escalation, cost goals (break-even costs) for energy storage fell in the following approximate ranges in 1976 dollars:

Utility	-	300-400 $/kW
Residential	-	80-100 $/kWh
Intermediate	-	15-25 $/kWh

Specific cost goals are both technology and application dependent. The methodology and results for each application will be discussed in the sections that follow, along with individual concept applicability for use with PVCS.

1.4 STORAGE WITH PHOTOVOLTAIC SYSTEMS - UTILITY APPLICATION

1.4.1 CANDIDATE STORAGE CONCEPTS

Candidate energy storage concepts selected, in conjunction with the concept reviews discussed in Volume I of this report, for further investigation for use with photovoltaic energy systems in utility applications included:

1. Pumped Hydro
   a. above ground
   b. underground
2. Underground Compressed Air
3. Batteries
   a. lead-acid
   b. advanced
4. Inertial (Flywheel)
5. Hydrogen

Note that thermal storage systems were not considered further in this portion of the study due to their lesser applicability to electrical output energy systems such as photovoltaic systems. This is discussed in Part B of Volume I. Similarly, superconducting magnetic energy storage was not considered further because of the present immaturity of the technology.

1.4.2 METHODOLOGY FOR UTILITY APPLICATION ANALYSIS

The available information and data on the candidate storage concepts, experience to date, and development status were reviewed in detail. Suggestions, advice and other inputs were obtained from several other organizations including other General Electric departments, a utility company (PSE&G) and a battery manufacturer (C&D Batteries). In addition, contacts were made with various other Government agencies and investigators. A summary description of the various general storage technologies was prepared for reference and is presented in Volume I of this report, along with projected costs for each concept.

A set of candidate storage evaluation criteria was prepared, selectively reduced to key criteria and subsequently used for preliminary ranking of the various storage concepts. Part B of Volume I of this report presents the results of this ranking for each application and for both wind and photovoltaic energy conversion systems.

In order to establish values for the "worth" of storage under various conditions, selected locations, loads and generating capacities were analyzed using computer routines. Present estimates of system life, O&M requirements and interest during construction (CCF) were used in the analysis (See Table 5.3-1 of Volume I). The analytical procedures are described in detail in Section 3 of this volume.

1.4.3 GENERAL RESULTS AND FINDINGS - UTILITY APPLICATION

Dedicated photovoltaic system storage in utility systems was found to be non-economic at current system cost estimates and nominal energy price escalation projections. Figure 1.4-1 displays economic viability tested against increasingly severe economic conditions for each of the seven utility storage concepts which survived the initial concept screening.

	START YEAR AND ENERGY PRICE ESCALATION RATE			
CONCEPT	1977 5%	1985 6%	1990 8%	2000 10%
Above ground pumped hydro	X	X		
Underground pumped hydro	X	X		
Underground compressed air	X	X	X	
Lead-acid batteries	X	X	X	X
Advanced batteries	X	X	X	
Inertial storage	X	X	X	X
Hydrogen	X	X	X	

X = Non-Economic; blank = Economic

FIGURE 1.4-1. ECONOMIC VIABILITY OF UTILITY ENERGY STORAGE CONCEPTS - PHOTOVOLTAIC DEDICATED CHARGING

The escalation rates shown range from 0 to 5% over the assumed general inflation level of 5%. Note that only the extreme year 2000, 10% escalation conditions result in viability for five storage concepts operating in a PV dedicated charging mode.

System wide, or multi-source, charging substantially improves storage economics as shown in Figure 1.4-2.

	START YEAR AND ENERGY PRICE ESCALATION RATE			
CONCEPT	1977 5%	1985 6%	1990 8%	2000 10%
Above ground pumped hydro				
Underground pumped hydro				
Underground compressed air	X			
Lead-acid batteries	X	X	X	
Advanced batteries	X			
Inertial storage	X	X	X	
Hydrogen	X	X	X	

X = Non-Economic; blank = Economic

FIGURE 1.4-2. ECONOMIC VIABILITY OF UTILITY ENERGY STORAGE CONCEPTS - MULTI-SOURCE CHARGING

Multi-source charging results in four storage concepts becoming viable at the baseline 1985 start, 6% price escalation condition. Both types of pumped hydro show present viability with 5% price escalation (zero differential escalation).

With regard to overall (non-economic) attractiveness of the various concepts for PV system use, the following was concluded for the utility case:

1. Although all seven concepts can be interfaced with a photovoltaic energy source, the hydro and compressed air systems present modularity problems due to the variability of the energy source. When specific system designs are attempted, the system costs for PV only charging would, therefore, tend to be increased over nominal projections for these technologies.

2. Inertial storage does not look particularly attractive in terms of drive systems and input-output conversion equipment requirements. In addition, the developing flywheel technology requires additional work to meet the energy density and operational requirements at the utility level.

3. Hydrogen systems appear to offer possibilities for reasonable modularization, but the variability of the PV source input could result in both an increase in modularity requirements and possible further reductions in system efficiency (already low) and reliability.

4. Battery systems, taken as a general class, possess the best overall characteristics for use directly with photovoltaic systems. There are significant differences between the so-called advanced battery systems now under development, and it is not clear which of these advanced systems might eventually emerge as the most technically successful.

Although there are design and/or developmental problems to be resolved, these are being pursued in a manner that will lead to a conclusive type of testing via the Battery Energy Storage Testing (BEST) program. The successful development of an "advanced" battery must be matched by achievement of low cost. Present lead-acid battery costs, for example, preclude showing viability with <u>dedicated</u> PV-utility equipment unless very extreme future economics are encountered even beyond those used as study parameters. For PV-only storage charging, even the present advanced battery cost predictions do not make an "advanced" battery attractive until economic pressures increase substantially.

An overall conclusion might be stated in summary, considering the foregoing, that: When both technical and economic characteristics are considered, the use of utility-level energy storage is more attractive and provides more options if it is approached on a multi-source charging basis. Under the latter condition, hydro, compressed air and possibly hydrogen systems could be used where siting conditions permit. Batteries and possibly flywheels, at some future point in time, could provide system peaking power at dispersed locations. Thus, a range of options is left open which may be tailored to specific utility company needs.

1.4.4 PARAMETRIC EFFECT ON WORTH OF STORAGE - UTILITY APPLICATION

The parameters examined for utility applications using photovoltaic energy systems are presented in Figure 1.4-3 and include the following:

1. Location/insolation characteristics
2. PV system penetration (as a percent of utility generation capacity)
3. Storage charge/discharge rate
4. Storage efficiency
5. Storage size
6. Fuel price escalation rate
7. Start year

Storage break-even cost computations resulting from computer data analyses were adjusted to account for the major differences in storage concept-peculiar parameters, such as efficiency, operation and maintenance and component replacement requirements. The adjusted break-even costs were then used as a basis for establishing the relative viability of the various concepts. Concepts of greatest promise/interest were then evaluated in further detail over a range of economic conditions through the year 2000.

The general effects of the above parameters on storage economics are as follows:

1. Over the range of sites, location showed an effect of about $\pm$ 11% on the mean energy savings and thus on the capitalized energy credit.

2. Photovoltaic system penetration proved to have a major effect as 20% penetration yielded about 55% more storage energy savings than 10% penetration, and 30% penetration about twice as much as 10%. These results were considerably different from those with wind energy systems.

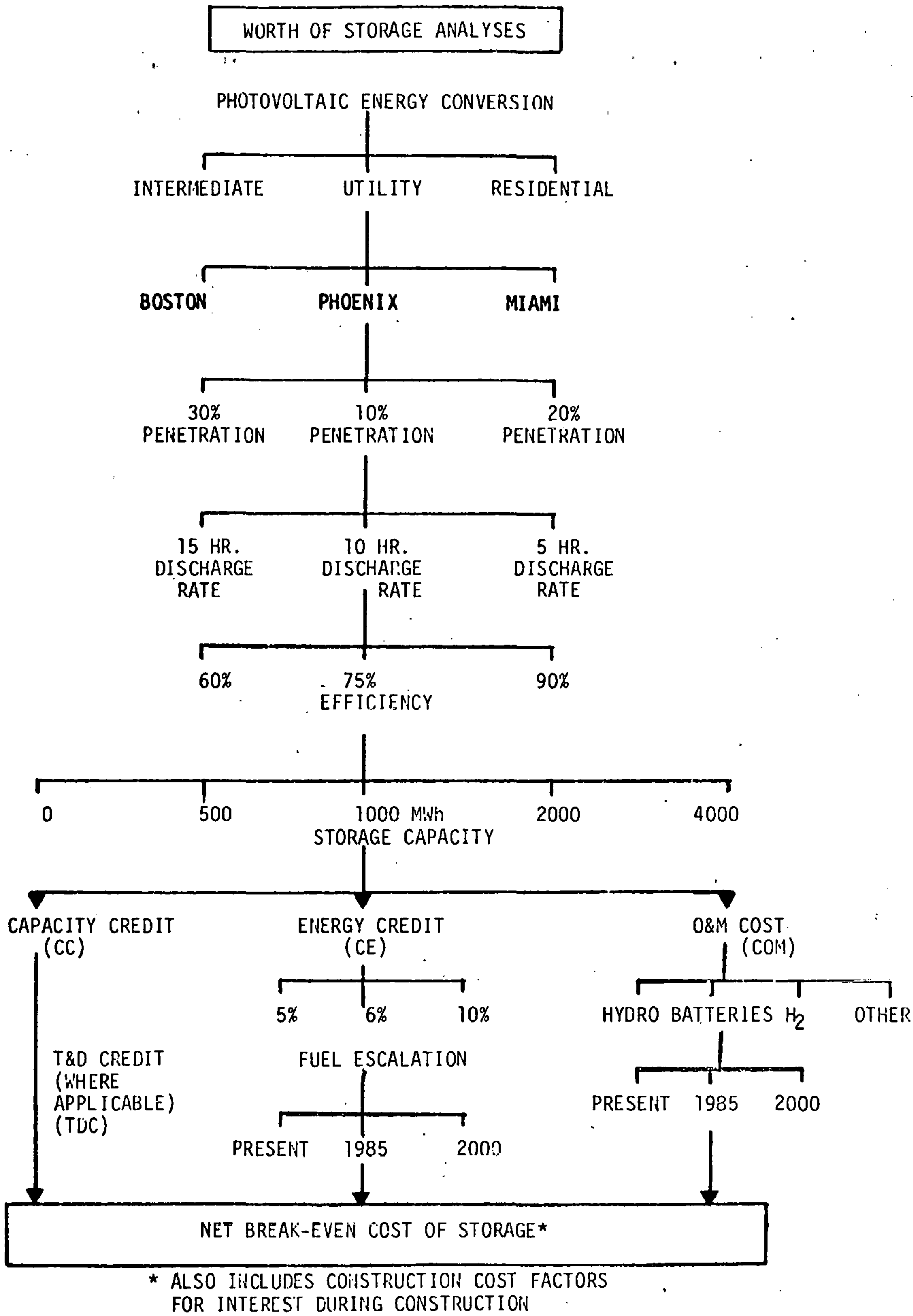


FIGURE 1.4-3. RANGE OF PARAMETERS - UTILITY APPLICATION

3. Use of a 5 hour versus a 10 hour discharge rate indicated a maximum energy credit improvement of about 15% at the same penetration level.

4. Storage system efficiency increasing over a range from 60% to 90% showed an overall 23% energy credit improvement.

5. Energy credit per unit of storage was seen to consistently decrease as system size was increased, although total energy credit increased.

Figure 1.4-4 presents the mean annual dollar savings resulting from storage versus storage capacity, and shows the effect of photovoltaic system penetration as well as the steadily decreasing savings per unit.

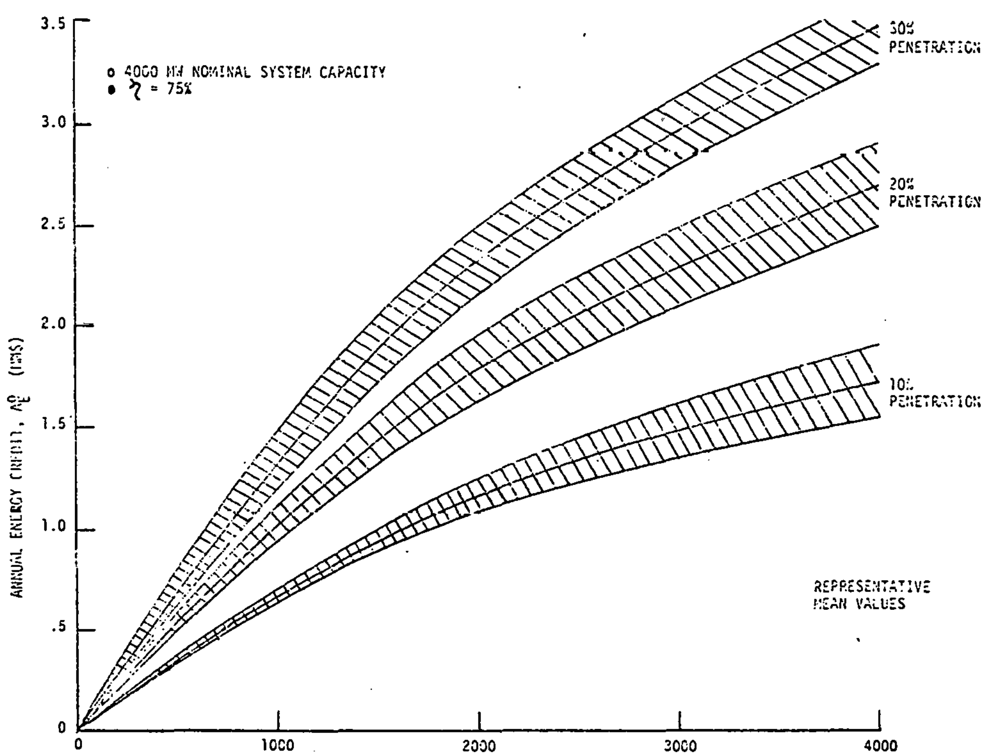


FIGURE 1.4-4. ANNUAL SAVINGS VERSUS STORAGE CAPACITY - UTILITY APPLICATION

6. Energy credit obviously increases as fuel price escalation rate increases.

7. For fuel price escalation rates greater than general inflation, assumed at 5% in the analysis, energy credit increases as start year is moved out in time.

Figure 1.4-5 presents the results of break-even cost computations for 1000 MWh of dedicated storage capacity, 5 and 10 hour discharge rates, and the extreme economic conditions of 10% fuel price escalation rate and a year 2000 start. Representative system cost estimates are also shown for comparison. Break-even costs higher than cost estimates indicate potential for economic viability.

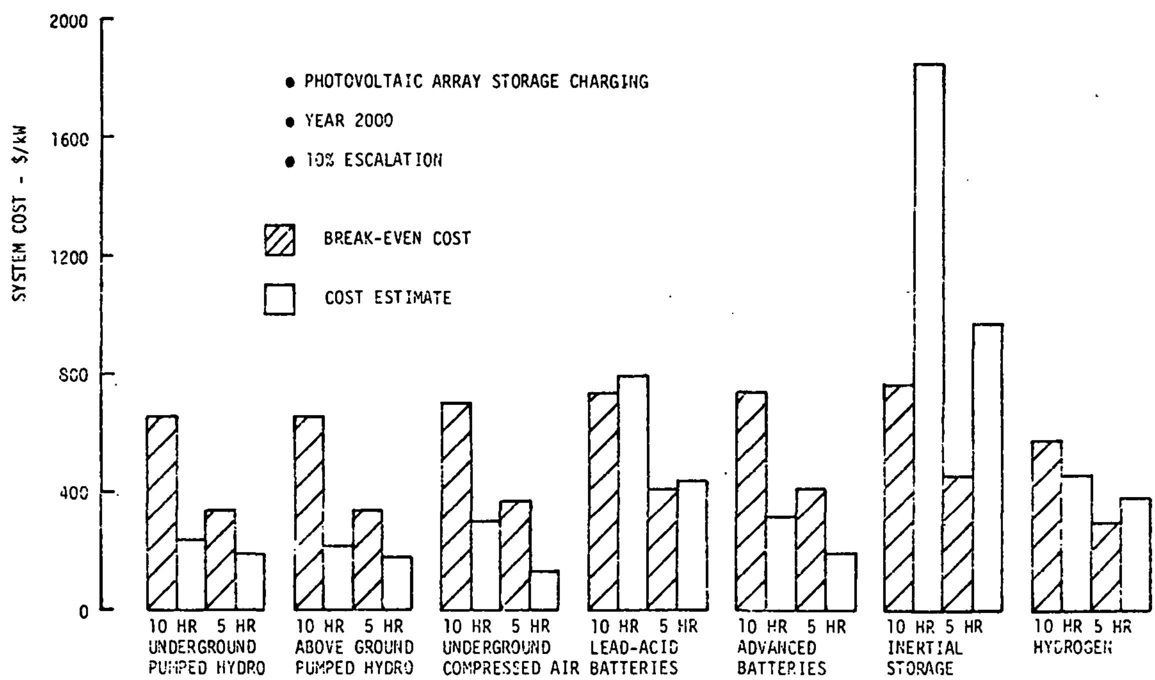


FIGURE 1.4-5. BREAK-EVEN COSTS COMPARED TO SYSTEM COST ESTIMATES, PHOTOVOLTAIC ENERGY CONVERSION - UTILITY APPLICATION

Capacity credit and transmission and distribution costs (where applicable) are included in the above data, which indicate five systems of potential viability - both types of hydro, compressed air, advanced batteries and hydrogen. The first four plus lead-acid batteries (due to widespread interest in this concept) were selected for more detailed economic analysis as presented in Section 3.3.6.

The above analysis at extreme economic conditions affords maximum opportunity for a storage concept to demonstrate economic potential. System cost estimates shown are taken from the year 2000 projected values as given in Volume I of this report. It should be noted that the concepts showing potential viability at the ten hour discharge rate do not change when a 5 hour discharge rate is assumed except in the case of hydrogen. Discharge rate also affected viability potential for multi-source charging as shown in Figure 1.4-6.

An important finding of the utility break-even analysis is that energy credit alone is not sufficient to achieve viability. There must be some form of benefit due to displacement of other equipment. Estimates of these benefits - capacity credits and transmission and distribution (T&D) credits, have been drawn from several sources and nominal values incorporated in the break-even results.

A major conclusion of the utility analysis as previously stated is that system wide storage, or multi-source charging, is much more attractive than dedicated photovoltaic system storage, with break-even costs increased by more than two to one. This is further evident in Figure 1.4-6 below, which indicates all of the seven storage concepts possessing some degree of economic potential at the 10% escalation year 2000 condition. Ten and five hour discharge rates are shown to point out clear differences in application potential. As can be seen, hydro and compressed air storage are much more attractive on a ten hour basis while battery systems and inertial storage are more cost effective at five hours.

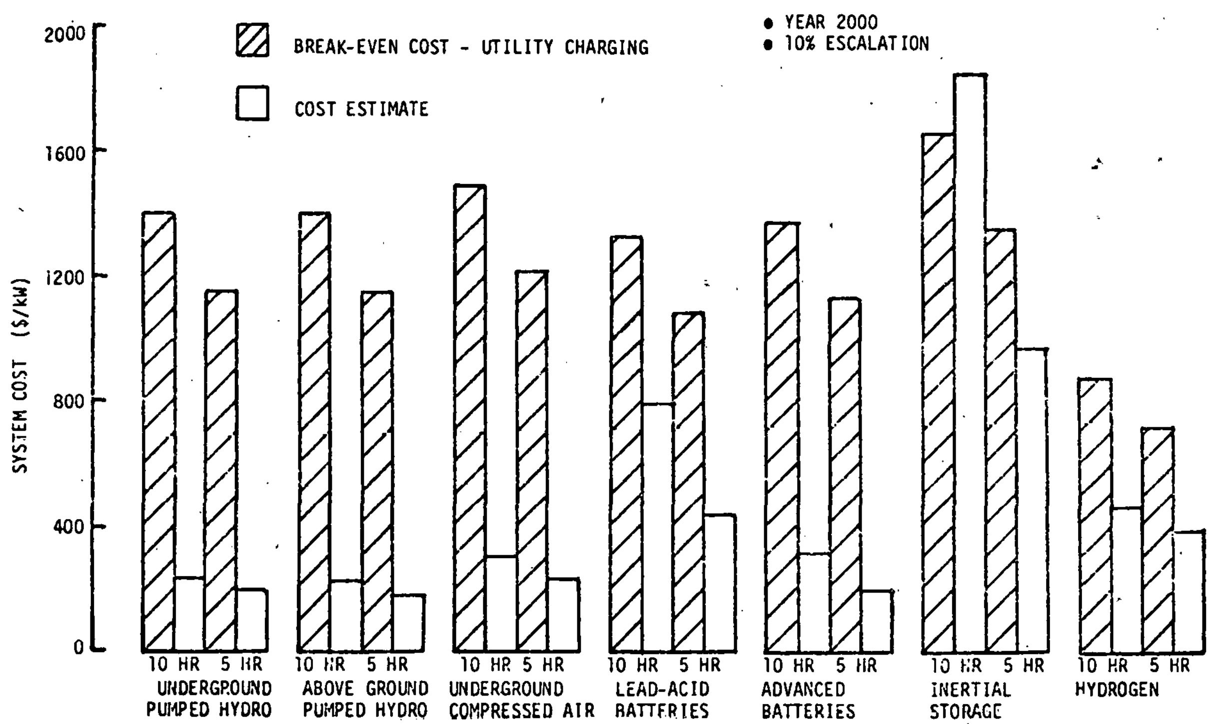


FIGURE 1.4-6. BREAK-EVEN COSTS COMPARED TO SYSTEM COST ESTIMATES - UTILITY APPLICATION

Insolation forecasting in conjunction with multi-source charging indicated only a slight improvement in energy credit for perfect forecasting over what could be achieved with simple storage operational strategies. Forecasting must necessarily involve not just photovoltaic output but load demands, to determine the net requirements on dispatchable generation equipment. Several judgmental storage operational strategies that could be easily implemented with only knowledge of load trends, gave energy credit within 10% of that achieved with perfect prior knowledge of daily net load.

1.5 STORAGE WITH RESIDENTIAL PHOTOVOLTAIC SYSTEMS

1.5.1 CANDIDATE STORAGE CONCEPTS

Candidate storage concepts for use with residential photovoltaic energy systems, selected in conjunction with the concept reviews presented in Volume I of this report include:

1. Compressed air/pneumatic storage
2. Batteries
   a. Lead-acid
   b. Advanced
3. Inertial (flywheel)

All of the above systems were deemed to be of sufficient interest to carry forward for more detailed economic comparison against break-even cost goals.

1.5.2 METHODOLOGY FOR RESIDENTIAL APPLICATION ANALYSIS

Evaluation of candidate storage technologies for the residential application followed the procedure described for the utility application (Section 1.4.2). Available information and data were reviewed, evaluation criteria examined and subsequently reduced to key criteria, and the four technologies cited in Section 1.5.1 were selected for more detailed investigation. Values for the worth of storage analyses were obtained by matching typical residential loads and photovoltaic system output for several locations and then employing energy storage to improve the match. Current estimates of system life and operation and maintenance requirements were used in the analysis (See Table 5.3-2 of Volume I). The analytical procedures are described in detail in Section 3 of this volume.

1.5.3 GENERAL RESULTS AND FINDINGS - RESIDENTIAL APPLICATIONS

The advanced battery is the only storage concept to demonstrate viability potential for residential photovoltaic systems under reasonable economic conditions. Figure 1.5-1 presents economic viability tested against increasingly severe economic conditions for each of the four residential storage concepts which survived the initial concept screening.

Inflation was assumed at 5%, thus the escalation rates shown range from zero differential to 5% over inflation. The advanced battery is the only storage concept which reaches economic viability at the 1985, 6% case.

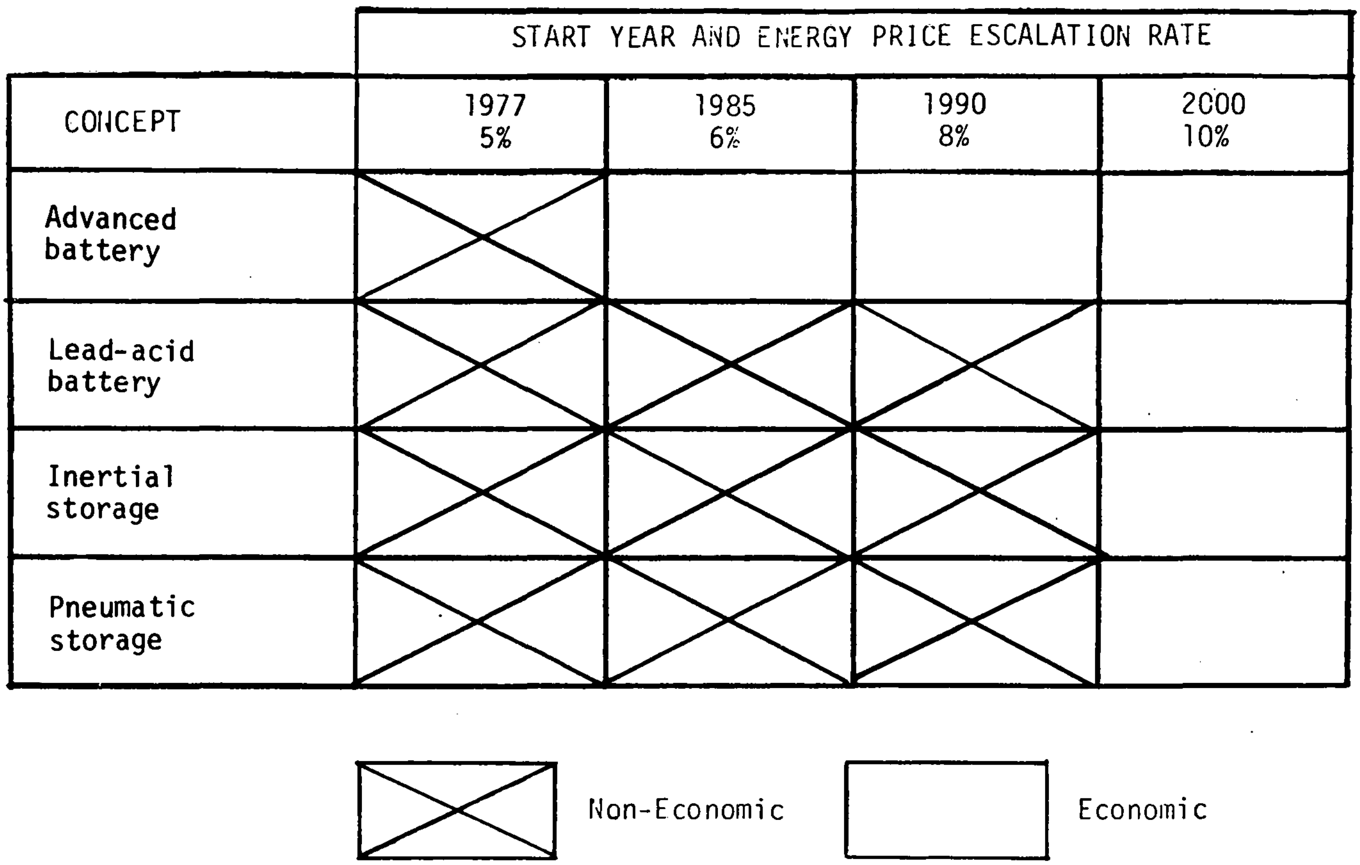


FIGURE 1.5-1. ECONOMIC VIABILITY OF RESIDENTIAL ENERGY STORAGE CONCEPTS

With regard to overall (non-economic) attractiveness of the storage concepts considered for PV system use, the following was concluded for the residential case:

1. The inertial and pneumatic storage systems both require equipment which would pose owner-operator difficulties. Excessive noise is probable in both cases and both have potential personnel hazards that would require special attention in storage system designs.

2. Battery systems offer the same advantageous load and input responsiveness as in the utility case. System design problems are present in that specifically designed control and switching systems are required but these do not appear to be insurmountable problems. A diversity of opinion seems to exist on the question of hazards in the residence due to use of dc voltages, acid or other chemical release, and (in the case of lead acid batteries) hydrogen release. In the final analysis, the subjective issues concerning the potential chemical and hydrogen hazards appear the most difficult to resolve.

3. Additional work on the details of control and interface of the residential PV conversion and storage system will be required for achievement of a significant future market.

1.5.4 PARAMETRIC EFFECTS ON WORTH OF STORAGE - RESIDENTIAL APPLICATION

The parameters investigated in the residential application of energy storage to photovoltaic energy systems include:

1. Location/insolation characteristics
2. Storage efficiency
3. Storagc size
4. Fuel price escalation rate and start year
5. Effect on PV system worth

Storage break-even cost computations were adjusted to account for concept peculiar differences in such factors as efficiency and operation, maintenance and replacement requirements. The general effects of the above parameters on storage economics are as follows:

1. Energy savings from storage increased with insolation and photovoltaic system output, ranging from a low in Boston to a high in Phoenix, as shown in Figure 1.5-2.

2. An increase in storage system efficiency from 60 to 90% increased energy savings by about 15%.

3. Energy savings per unit storage steadily decreased with storage capacity, as seen on Figure 1.5-2. A pronounced "knee" in the energy savings curve at 24 to 30 kilowatt hours storage capacity, results in this being the upper range on economic storage size.

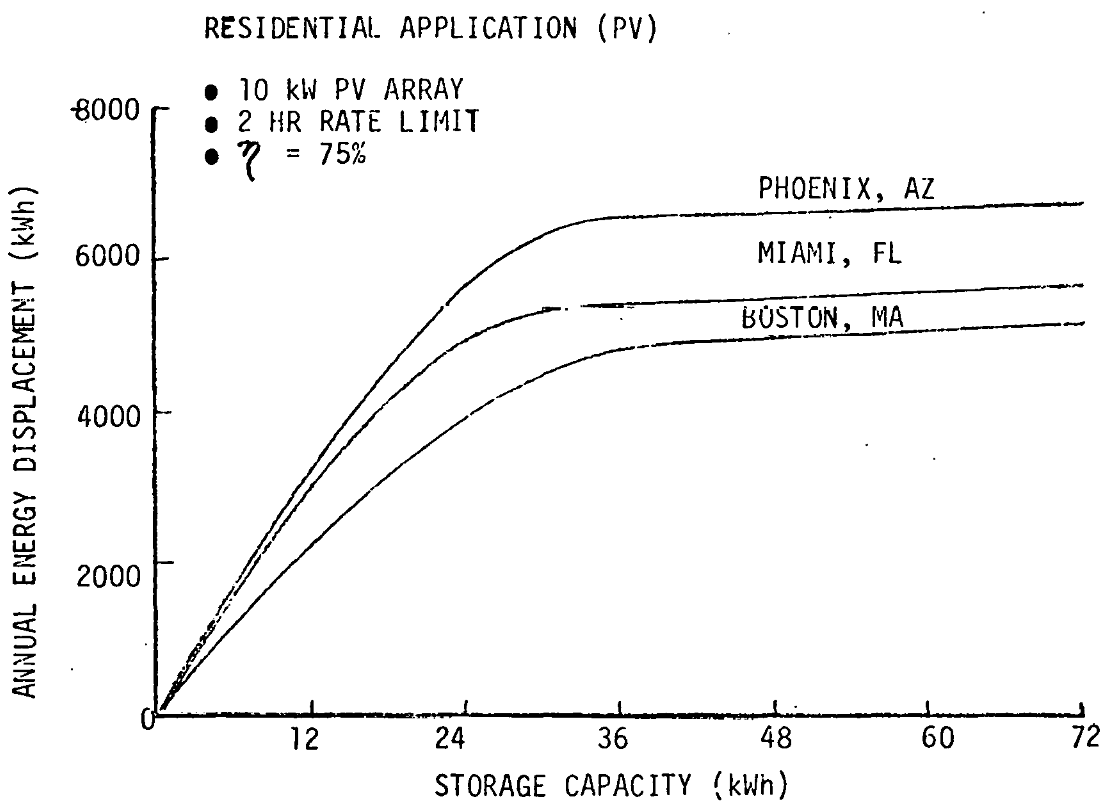


FIGURE 1.5-2. EFFECT OF LOCATION AND STORAGE CAPACITY ON STORAGE ENERGY SAVINGS

4. Storage break-even cost increases with energy price escalation rate and start year delay. The effect is shown in Figure 1.5-3 for both lead-acid and advanced batteries. The latter was the only concept studied which approached viability at a nominal 6% price escalation, 1985 start condition.

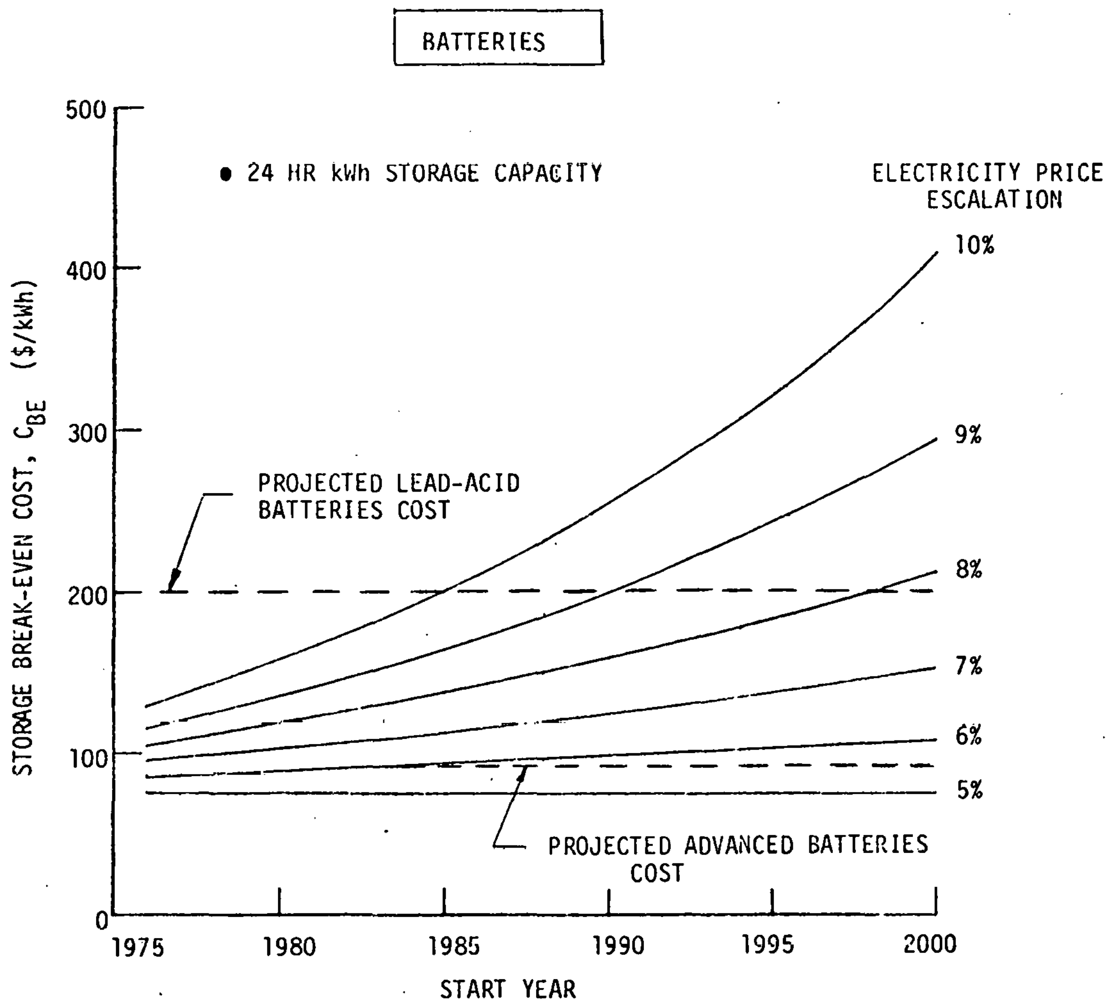


FIGURE 1.5-3. STORAGE BREAK-EVEN COST VERSUS START YEAR AND PRICE ESCALATION RATE FOR RESIDENTIAL BATTERY STORAGE SYSTEMS

5. Energy storage does have the potential to increase the value of the photovoltaic energy system. The effect is shown in Figure 1.5-4. Storage capacity in the 24 to 30 kWh range increases total energy capture by from 45 to 70 percent, which thus increases total system worth by the same amount. Energy storage priced below its break-even cost can permit some of the increased worth to be reflected in a higher allowable photovoltaic system cost. For example, 30 kWh of storage priced at 40 $/kWh increases the basic photovoltaic allowable cost by about 28% in the 1985, 6% escalation case and over 40% for the extreme year 2000, 10% escalation case.

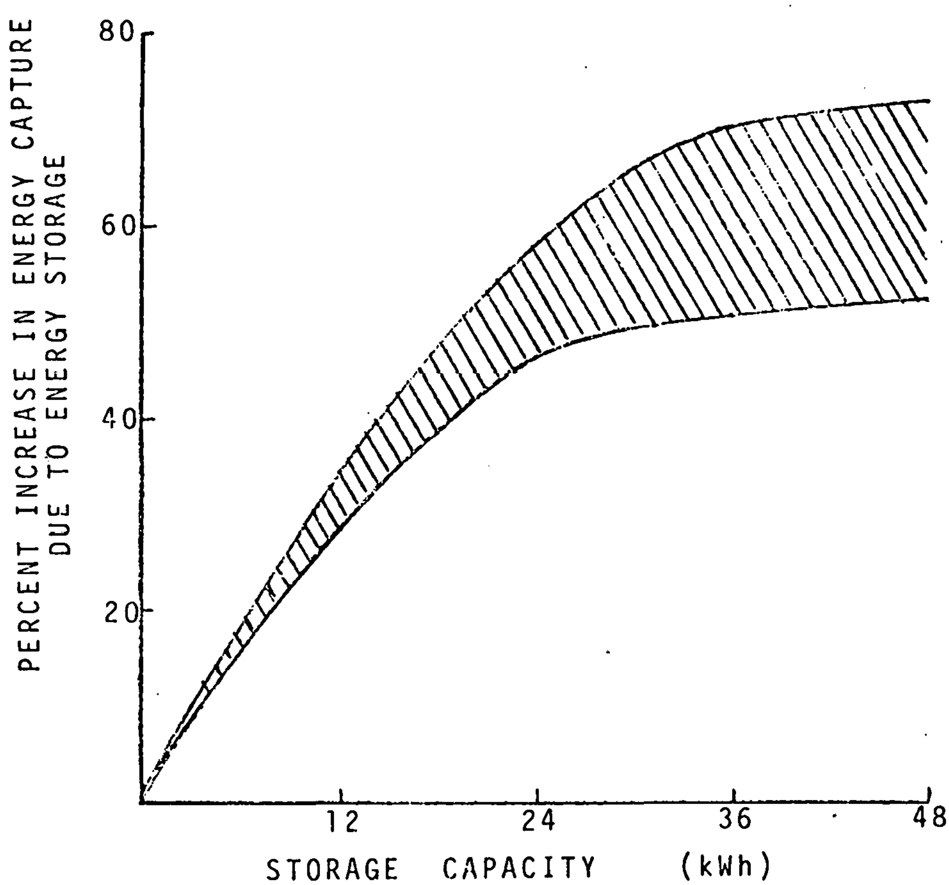


FIGURE 1.5-4. EFFECT OF ENERGY STORAGE ON TOTAL PHOTOVOLTAIC SYSTEM ENERGY CAPTURE

Figure 1.5-5 gives the results of break-even cost computations for 24 kWh capacity residential systems at the 10% energy price escalation rate and year 2000. The projected system costs shown, permit comparison between concepts under these favorable conditions. Break-even costs higher than system costs indicate viability potential for all four concepts, with an "advanced" battery by far the most attractive.

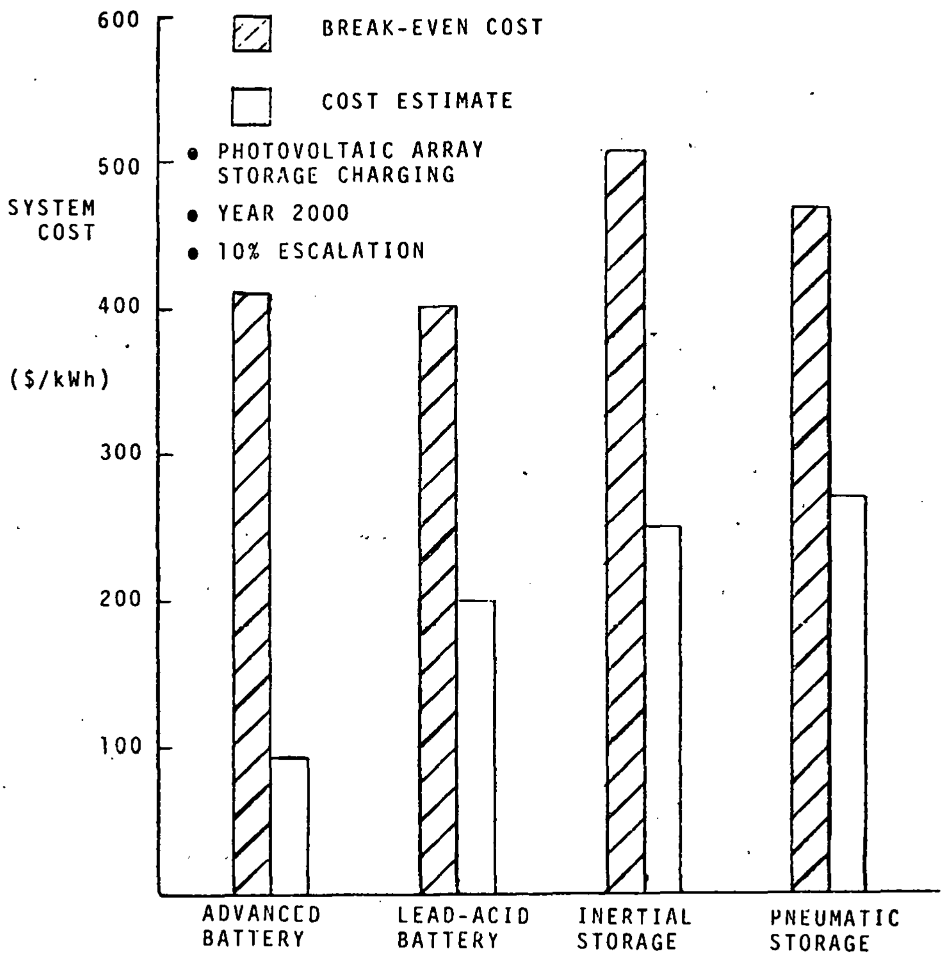


FIGURE 1.5-5. BREAK-EVEN COSTS COMPARED TO SYSTEM COST ESTIMATES - YEAR 2000, 10% ESCALATION - RESIDENTIAL APPLICATION

1.6 STORAGE WITH INTERMEDIATE PHOTOVOLTAIC SYSTEMS

1.6.1 CANDIDATE STORAGE CONCEPTS

Candidate energy storage concepts selected for further investigation for use with photovoltaic energy systems in intermediate applications included:

1. Pumped Hydro
   a. Above Ground
   b. Underground
2. Underground Compressed Air
3. Batteries
   a. Lead-Acid
   b. Advanced
4. Inertial (flywheel)
5. Hydrogen

Thermal systems were eliminated from further analysis in this portion of the study due to their general inapplicability to electrical output energy systems such as photovoltaic systems. (See Part B of Volume 1). Of the remaining concepts, several (particularly hydro and underground compressed air) would be applicable only to a very large scale intermediate applications.

1.6.2 METHODOLOGY FOR INTERMEDIATE APPLICATION ANALYSIS

Candidate storage technologies were selected for the intermediate application using the same techniques described previously for the utility and residential applications. Values for the worth of energy storage were obtained by matching photovoltaic system outputs for several locations to a load selected as typifying a shopping center operating routine. Current estimates of system life and operation and maintenance requirements are used in the analysis (See Table 5.3-1 of Volume I). The analytical procedures are detailed in Section 3 of this volume.

1.6.3 GENERAL RESULTS AND FINDINGS - INTERMEDIATE APPLICATION

Energy storage with intermediate photovoltaic systems proved to be economic only in extremely large scale applications with site characteristics adaptable to hydro or underground compressed air systems. Figure 1.6-1 presents economic viability tested against increasingly severe economic conditions for each of the seven storage concepts considered.

Inflation was assumed at 5%, thus the escalation rates shown range from zero differential to 5% over inflation. Note that not until the extreme 10% escalation, year 2000 conditions does a storage concept with a wide application range (advanced batteries) achieve economic viability.

CONCEPT	START YEAR AND ENERGY PRICE ESCALATION RATE 1977 5%	1985 6%	1990 8%	2000 10%
Above ground pumped hydro	X			
Underground pumped hydro	X			
Underground compressed air	X	X		
Lead-acid batteries	X	X	X	X
Advanced batteries	X	X	X	
Inertial storage	X	X	X	X
Hydrogen	X	X	X	

X = Non-Economic; blank = Economic

FIGURE 1.6-1. ECONOMIC VIABILITY OF INTERMEDIATE ENERGY STORAGE CONCEPTS

With regard to technical and operational attractiveness of these seven concepts, the following was concluded for the intermediate application:

1. Hydro and compressed air concepts below the utility scale could be utilized only for very special cases such as large relatively isolated industrial or commercial operations where both the siting and scale of operations were compatible.

2. The possible future use of flywheel or hydrogen systems is dependent upon further development and the evaluation of specific system designs.

3. Batteries offer a degree of attractiveness if available along with suitable interface hardware. The range of possible system sizes, specific designs, and requirements is so broad as to preclude meaningful generalizations. The level of owner-operator responsibility achievable, could range all the way from the residential situation to something approaching utility level skills.

4. The most meaningful way to attack the problem of energy storage implementation for intermediate applications would appear to be to select one or two high potential applications, assuming availability of the storage technology desired, and proceed from that point to develop a specific design. Other non-technical issues such as user acceptance and compliance with local regulations should also be considered at that time on a case basis. The drive to develop utility-level storage devices is a more likely forcing function in the development of advanced storage technology than fixed plant intermediate applications.

1.6.4 PARAMETRIC EFFECTS ON WORTH OF STORAGE - INTERMEDIATE APPLICATIONS

The parameters investigated for energy storage in conjunction with PV energy systems in intermediate applications include:

1. Location/insolation characteristics
2. Energy and power demand levels
3. Storage efficiency
4. Storage size
5. Fuel price escalation rate and start year.

Storage break-even costs were adjusted to include the effects of concept-particular factors such as efficiency, interest during construction (where applicable), and operation, maintenance and replacement requirements. The principal results and findings include:

1. For a given energy and power demand the energy savings resulting from use of energy storage varied directly with insolation level, being highest in Phoenix and lowest in Boston.

2. Energy savings from storage varied inversely with peak load as shown in Figure 1.6-2. Photovoltaic array peak output was set at 500 kW, thus the peaks shown are 40, 50 and 60% of photovoltaic peaks. Figure 1.6-2 can easily be extrapolated to higher loads by maintaining these ratios.

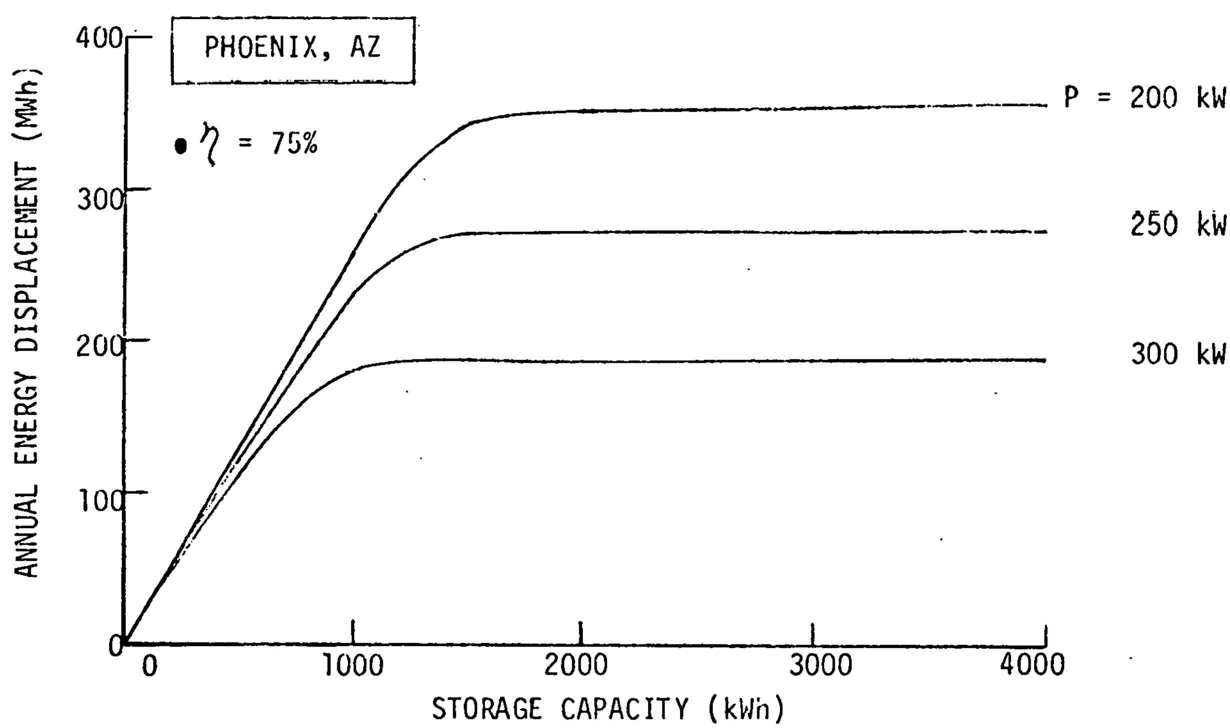


FIGURE 1.6-2. STORAGE ENERGY SAVINGS VERSUS STORAGE CAPACITY AND PEAK POWER DEMAND - INTERMEDIATE APPLICATION

3. Storage energy savings increased almost directly with storage system efficiency. Energy savings at 90% efficiency was about 26% higher than savings at 60% efficiency.

4. A very pronounced "knee" in the savings curve appeared at about 1000 to 1500 kWh storage capacity (2-3 kWh/PV kW_{RATED}) as can be clearly seen in Figure 1.6-2. This makes storage capacities beyond this range highly unlikely to be economically attractive.

5. Storage break-even cost increased with energy price escalation rate and start year delay.

Figure 1.6-3 presents adjusted break-even costs for 1000 kWh capacity intermediate storage systems at the 10% energy price escalation rate, year 2000 conditions. Peak load is assumed at 250 kW or 50% of PV rating. Figure 1.6-3 was used to screen potential storage concepts as the conditions provide maximum opportunity to show viability potential, indicated by break-even cost higher than system cost estimate.

Five concepts show viability potential - advanced batteries which will be widely applicable and the hydro and compressed air storage concepts which will find only rare application in intermediate systems due to the large scale requirements and siting requirements. Hydrogen is also marginally viable under the year 2000 conditions shown. The first four were carried forward for more detailed economic analysis along with lead acid batteries.

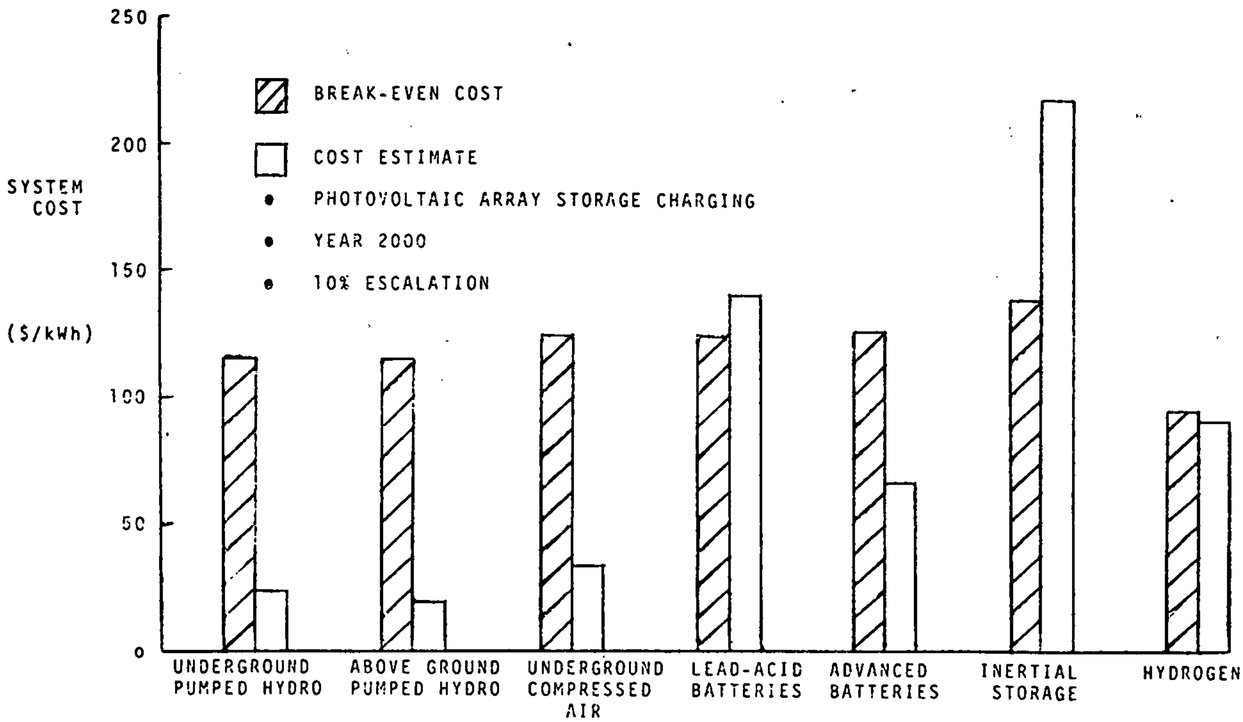


FIGURE 1.6-3. BREAK-EVEN COSTS COMPARED WITH SYSTEM COST ESTIMATES - INTERMEDIATE APPLICATION - YEAR 2000, 10% ESCALATION

1.7 SPECIAL UTILITY SYSTEM PLANNING ANALYSIS

The special case studies performed by GE-EUSED are described in detail in Section 3.3-7. The work performed consisted of establishing a baseline for realistic 1995 operating conditions in the Boston area/New England Power Pool and determining the results of adding both PVCS and energy storage to the system. These results were compared with the more generalized study analyses and found to have reasonable overall correlation. Figure 1.7-1 presents the findings of the special case studies along with related study data for comparison purposes.

The results indicate:

1. Break-even cost results for use of dedicated storage about 15-20% above generalized study results.

2. Improvement (~ 16%) of storage break-even cost performance (with perfect forecasting of PVCS output vs. no forecasting) but still about 17% less attractive than system storage with no PVCS contribution.

3. A significant reduction in storage break-even cost (~ 25%) with PVCS and storage as opposed to system storage with no PVCS contribution and no forecasting.

4. Superiority of system-wide storage by about 2.7:1 over dedicated storage.

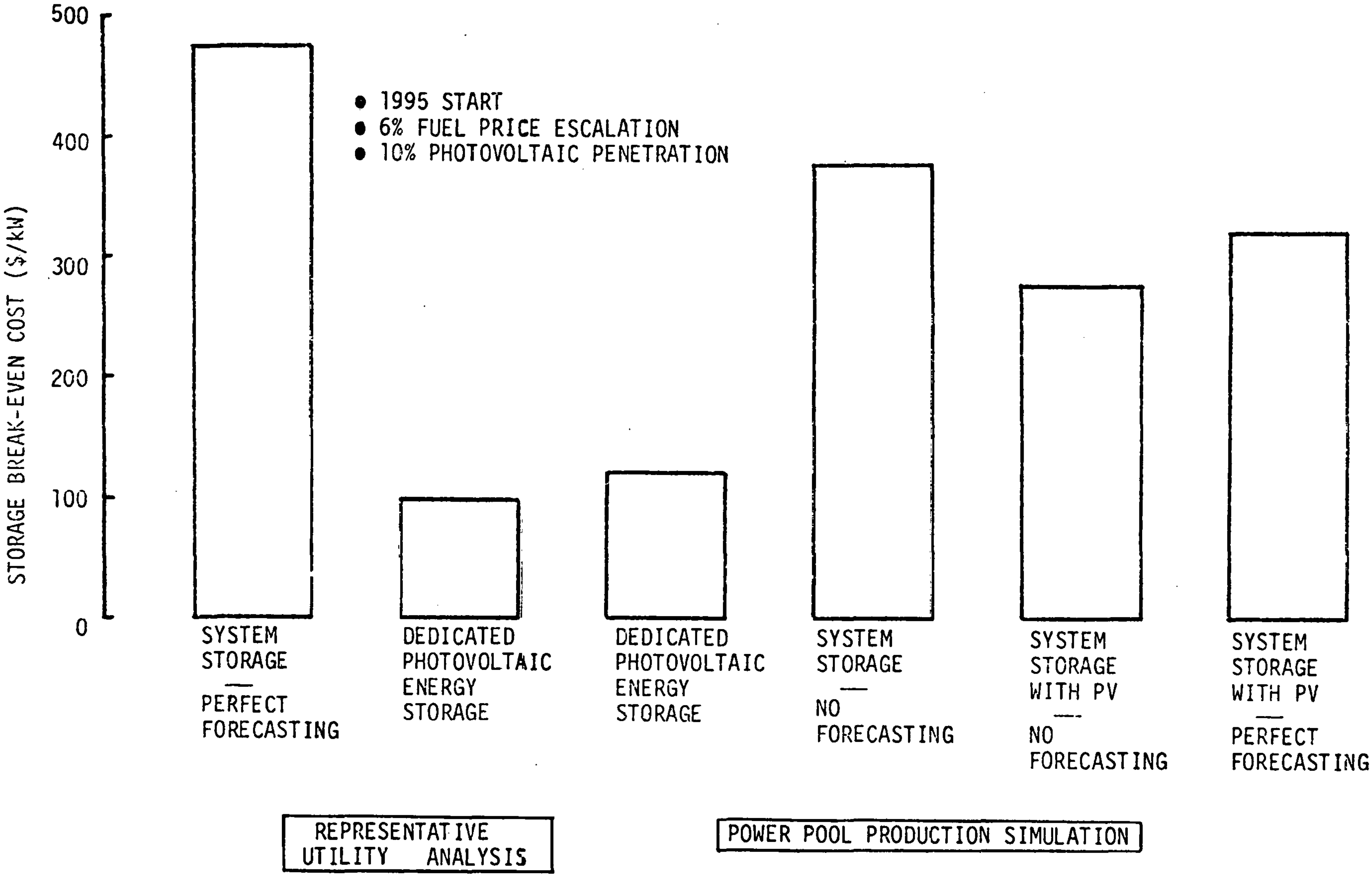


FIGURE 1.7-1. SPECIAL CASE STUDY FINDINGS AND RELATED STUDY RESULTS FOR PVCS WITH STORAGE

SECTION 2

BASELINE PHOTOVOLTAIC CONVERSION AND STORAGE
SYSTEM CONCEPTS

2.1 UTILITY SYSTEMS

2.1.1 BASIC SYSTEM ARRANGEMENT

The basic unit for a photovoltaic power plant is assumed to be a generation module rated at a nominal output of 30 MW, and is based on a prior conceptual design study.[1] These modules would be arranged to provide total PV system output ratings from approximated 375-1100 MW. This range incorporates penetrations of roughly 10%, 20%, and 30% of a nominal 4000 MW capacity, "representative" utility system. Figure 2.1-1 shows the overall block diagram of the photovoltaic power plant.

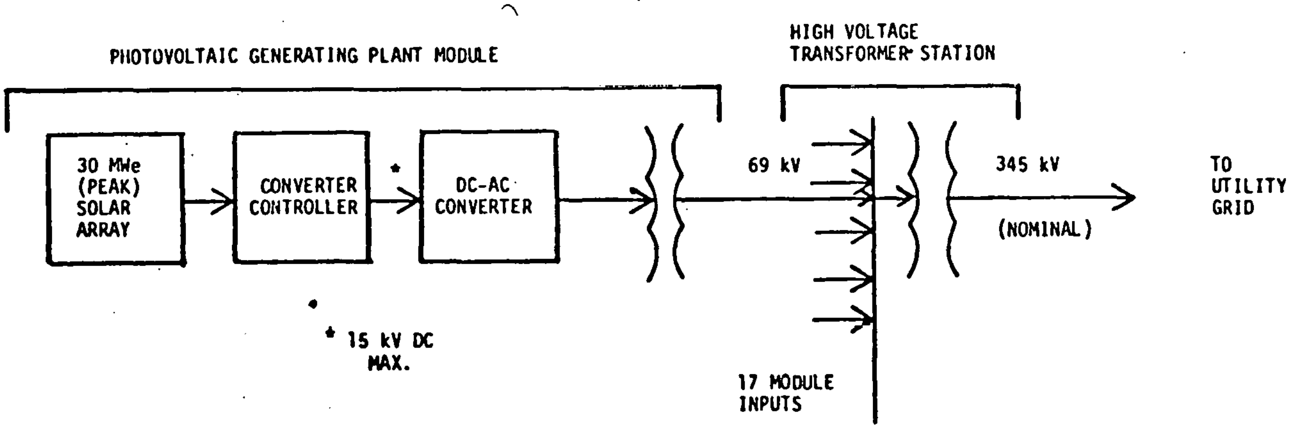


FIGURE 2.1-1. BASELINE PHOTOVOLTAIC POWER PLANT MODULE

The photovoltaic modules would require a sizeable amount of land area, depending upon the assumptions made concerning unit output. The latter are further dependent on the concentration ratios assumed as well as other design factors. These design considerations are not directly pertinent to this study. It is significant, however, to note that the use of sizeable land areas stimulates interest in the physical proximity of energy storage facilities that might be added. The further questions of distributed storage units and/or impact on transmission facilities also become important. These are discussed further in other portions of this report and should be key concerns in the design and layout of an actual plant. To relate the relative physical size of such a plant, Figure 2.1-2 shows the area involved for the case of a 375 MW installation and a relatively low concentration ratio.

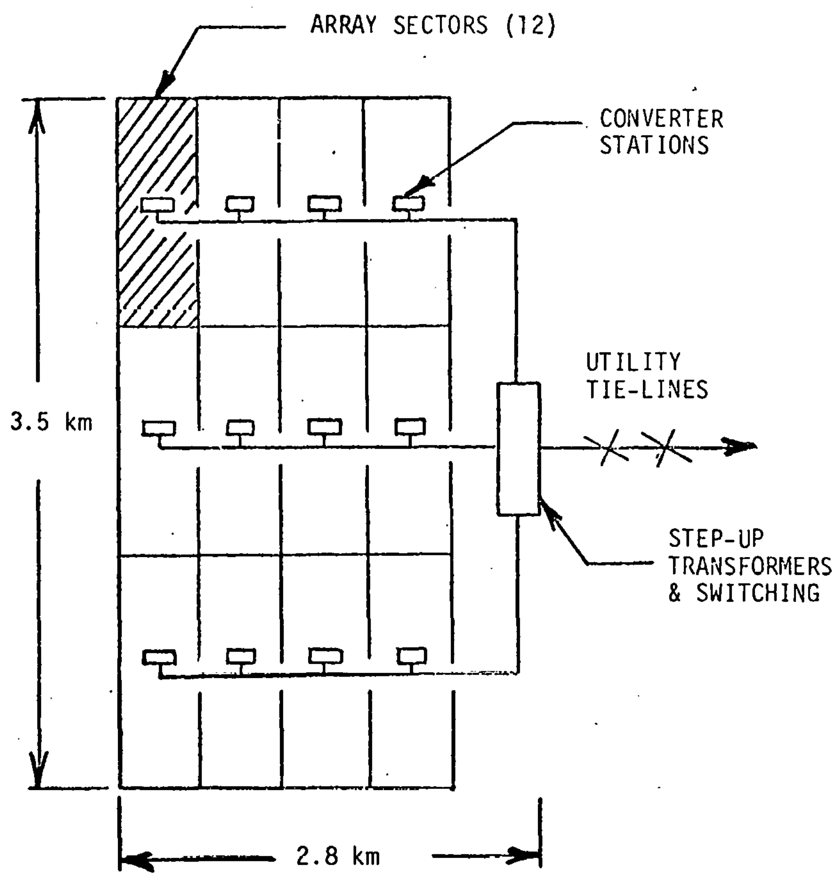


FIGURE 2.1-2. PHOTOVOLTAIC POWER PLANT CONFIGURATION FOR 375 MW AT LOW CONCENTRATION RATIO

A nominal cell efficiency of 13.4% is assumed throughout the study, and actual performance analyses include the effect of variation in local photovoltaic output with the available insolation levels. Additional land area would be allocated for energy storage systems as required by the specific storage method chosen. The detail parameters for generated outputs, load conditions and net system operating results are presented together in a later section since the different geographical areas studied have their own unique conditions.

2.1.2 OVERALL PHOTOVOLTAIC PLANT OPERATION

The dc electrical output of each solar array sector is brought to a centrally located converter station. The direct current is converted to three-phase alternating current at a nominal 69 kilovolts (kV) and 60 Hertz (Hz) for forwarding to the transformer station by underground cable. At the transformer station, the outputs of the converter stations are gathered, connected and transformed from 69 kV to a voltage suitable for transmission to the utility grid.

2.1.3 DC-AC CONVERTER STATION OPERATION

The dc-ac converter would typically consist of a "line-commutated" solid state, bridge-connected, thyristor valve configuration. Variations in solar cell temperature and incident light intensity cause attendant variations of input voltage and current to the dc-ac converter. These variations must be accommodated by the converter, while optimizing power output and providing an acceptable ac output voltage and frequency. The converter accepts a nominal input voltage range variation in the order of 15% and up to a ten to one variation in current. A converter transformer steps the voltage up to 69 kv utilizing a "Load Tap Changer" (LTC) which modifies the effective transformer turns ratio during loaded conditions. The LTC functions to accommodate changes in solar array output voltage and assures that the converter operates at its optimum "firing angle". DC circuit breakers are included to disconnect the inverter from the solar array in the event that the converter is disabled temporarily by an ac system fault. The dc circuit breakers also provide protection for the converter in the event of faults in the dc bus or thyristor valves.

DC smoothing reactors minimize ripple currents and maintain electro-magnetic radiation from the solar array circuits within acceptable limits. Filters connected to the ac bus absorb current harmonics generated in the converter. The ac wave shape is thereby kept within acceptable harmonic content limits for the utility grid and associated plant equipment. The ac harmonic filter equipment also serves as a power factor correction device and uses shunt capacitors as well as resistive and inductive elements. This approach counteracts the inherent lagging power factor characteristic of the converter valves and transformer.

Automatic converter station operation is anticipated based on use of a computerized control system. The control equipment automatically adjusts the power output to the maximum power point of the solar array.

2.1.4 TRANSFORMER STATION OPERATION

The converter station outputs are gathered and stepped up to transmission line voltage using standard mechanical and electrical equipment and station layout, including necessary switching.

2.1.5 STORAGE SYSTEM INTEGRATION AND INTERCONNECTION TO THE PHOTOVOLTAIC ENERGY CONVERSION SYSTEM

The principal objective of this area of study investigation was to identify and assess major limitations or consequences that could be expected as a result of applying various energy storage methods in conjunction with a PV energy conversion system. The energy storage system was assumed to serve the PV system exclusively; therefore, the power input to storage would be derived solely from that available from the photovoltaic system. Discharge of stored energy would occur as part of a combined PV-energy/storage system output to a utility network. The option of supplying a portion of the storage charging energy from the utility was also considered, but is treated later in this report in Section 3.6 on multiple-source charging. It may be noted that in general, this latter option tends to reduce the storage interface and integration problem, so that the storage system considerations discussed in this section are likely to be the most severe.

The situation to be considered is similar to other "process flow" problems in that the system components must work together compatibly to produce a desired output (in this case, electric power) without either damage to components or excessive efficiency losses.

The numerous criteria examined earlier in this study were re-considered by the study team in order to identify especially critical design or operational parameters. "Critical" in this case was defined as a condition resulting uniquely from the incorporation of energy storage with a PV system which might make the integrated concept unworkable or otherwise undesirable. The conditions of most concern were then investigated in more detail, considering representative sizing and input-output parameters. In addition, consultations were held with equipment designers to obtain the benefit of their experience on probable equipment limitations. The results of these investigations are described in the following sections for the various storage technologies. It should be recognized that due to the scope of investigations involved, only the more pressing concerns could be covered, and any future implementation of these storage methods should be predicated on more detailed investigation of specific designs.

Special concerns investigated were:

1. Consequences of photovoltaic system input interruption during storage charging.
2. Limitations imposed on basic system equipment.
3. Equipment rating problems
4. Possible sizes for modularization.
5. Potential impact of concept options on cost effectiveness and operational suitability.

2.1.5.1 Pumped Hydro Storage

Use of pumped hydro storage in conjunction with a photovoltaic power plant could be treated either as part of an existing hydro facility (or extension of such a facility) or as a completely new installation. The cost and technical requirements would be quite different for the two situations. For study purposes, since some utilities have little or no hydro capability in place, the impact of adding such storage was assumed to be that of adding a pure pumped storage (PPS) facility to an existing utility network, independent of any conventional hydro-electric generation. A system assessment of the use of pumped storage in conjunction with a photovoltaic array was made by: identifying critical design parameters; determining the existence of typical equipment; and evaluating the implications and impact of the variability and interruptibility of the PV-generated energy. No distinction need be made between above-ground and underground pumped hydro installations in this portion of the storage assessment, since the differences in pumping heads, costs, potential hazards, etc., have already been identified for both methods and discussed in Volume I of this report. The total photovoltaic energy output level of 375 MVA or about 10% PV system penetration has been used as a reference point in considering the application of pumped hydro and the other candidate concepts.

Integrated System Concept

A nominal pumped hydro system assessed for study purposes is shown in Figure 2.1-3. A reservoir having a maximum head of 1000 feet above the sump drives

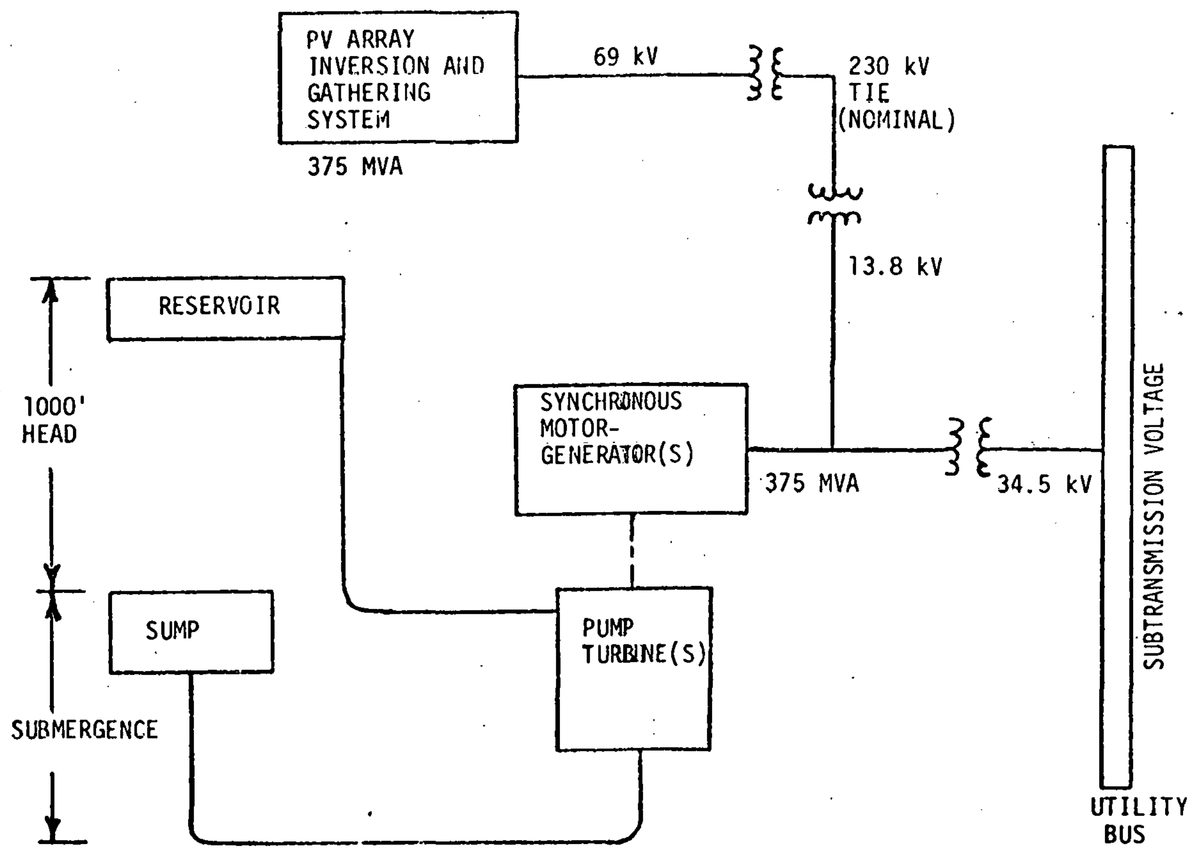


FIGURE 2.1-3. PHOTOVOLTAIC ENERGY CONVERSION WITH PUMPED HYDRO STORAGE-UTILITY APPLICATION

a reversible pump-turbine with a flow rate sufficient to obtain approximately 375 MVA output from the reversible motor-generator which is synchronous with the utility. The discharge to the reservoir is dependent on the variability and presence of the photovoltaic energy source. The pump-turbine is set somewhat below the sump to prevent pump-turbine cavitation.

This system is predicated on constant speed operation and operates in the following manner when charging from a PV energy conversion system. (Discharge per se is not directly affected by the energy source, although it is part of the overall system consideration with respect to operational modes).

When the reservoir head is low, the pump, driven by the constant speed motor with maximum horsepower input, pumps at its maximum flow rate. As the reservoir head rises but still with maximum horsepower input, the flow rate decreases. If the power input to the pump is reduced, due to the variability of the energy source, the flow rate also decreases.

<u>Functional Assessment</u>

Hydraulic generator/motors can be found in the 375,000 KVA rating size, with a speed range of 72 to 200 rpm, normal full-load efficiency of 97.6% at 0.9 PF, and an output of 13,800 volts.

The power required to drive this generator is:

$$\text{Power} = \frac{\text{KVA X PF X 1.341 (Hp/kW)}}{\text{Efficiency}}$$

$$= \frac{375{,}000 \text{ X } 0.9 \text{ X } 1.341}{0.976}$$

$$= 463{,}716 \text{ horsepower}$$

If this is taken to be the brake horsepower input to the pump, the flow rate in gallons per minute which is possible against a total head (static and dynamic) would be:

$$Q_1 = \frac{H_p \times \eta_p \times 3960}{H_T \times S.G.}$$

$$= \frac{463{,}716 \times 0.7 \times 3960}{1000 \times 1.0}$$

$$= 1{,}285{,}423 \text{ gpm} \approx 1.3 \times 10^6 \text{ gpm}$$

where

η_p = 0.7 (assumed)

S.G. = 1.0

H_T = Total Head

Hydraulic Turbines, Inc., HTI, was consulted to determine the practicality of obtaining a pump turbine operating in the 200-RPM speed range capable of this million gallon per minute flow rate. All pumped hydro systems are custom designed but it was determined that the system described is well within existing experience. The IEEE paper, "Survey of Pumped Storage Projects in the United States and Canada to 1975"* shows that for turbine heads in the 200-300 meter ranges (600 - 1000') 2 to 8 units are used, with individual generators rated at from 125 MVA to 333 MVA, with speeds from 200 to 360 RPM, and voltages of 13.8 to 17 kV. Eight methods for starting the pump (motor) are given and for the head of interest here, the "Pony Motor" start is the most prevalent choice.

* IEEE Transactions on Power Apparatus and Systems, Volume PAS-95, No. 3, May/June 1976.

On the question of energy source variability, HTI advised that pump manufacturers do not recommend operation of the pumps below 50% load because of efficiency, stability and possible cavitation. Below 50% load the efficiency of the system decreases significantly and without a proper flow rate, the turbine unit vibrates excessively and cavitation can occur which may damage the pump. Although the unit submergence should preclude cavitation, minimum unit submergence is desirable as it is a cost consideration which is very site dependent. Usually, model testing is performed to determine the minimum unit submergence required for a given installation.

It may be noted that in a conventional hydro storage operation, the on/off cycling amounts to perhaps 20-30 cycles/month. With photovoltaic system use, and assuming appropriate procedural constraints, it was decided the consequences of a much higher rate of cycling should be considered. On-off switching rates of up to 8-10/day pose no special problem for pumped hydro systems. In Europe these systems are reportedly turned on and off without concern many more than 8 times/day.

It is believed that existing or obtainable site insolation data could be used to establish, for a given location, the likelihood of achieving satisfactory hydro pumping operation within the cycle range indicated above. A more detailed investigation of the absolute limits for pump-turbine cycling under PV system operation should be performed in conjunction with any specific application designs.

With respect to the impact on the photovoltaic energy system itself due to loss of load, there is no new impact consequent to operation with a pumped hydro system.

The manufacturer's recommendation that the hydraulic pumps should not be operated below 50% load imposes some additional considerations on the photovoltaic energy system. Presumably the 50% pump load would be equated to the minimum desirable operating conditions for the energy source. If the system design requires that whatever photovoltaic power is available must be supplemented by utility power for pumping, then some means of proportioning the pump load between the utility and the PV system source would be required. The load proportioning must accurately determine the capability of contribution in order to achieve the most efficient utilization of energy. The choice of using integrated units as opposed to separate pumps, turbines, and motors would be a system design option, although Francis pump-turbines are predominantly used at the present time.

Conclusions

1. The choice of an above or underground hydro system is significant in terms of heads, equipment ratings, sizing, site availability and cost, but these are not necessarily significant limitations to the use of pumped hydro with photovoltaic energy systems.

2. Interruptibility and cycling of hydro pumping operations is a location-dependent design consideration, but is not an unsurmountable problem.

3. Where suitable sites are available, pumped hydro is a technically desirable method of energy storage, but may require modularity of the pumping configuration which would reduce cost effectivity of a dedicated storage system.

4. Use of auxiliary power (from the utility) for pumping during low insolation periods is a logical alternative. Integrated PV-utility pumping may also be desirable to reduce equipment module requirements. Other hybrid operating concepts are also possible.

2.1.5.2 Underground Compressed Air Storage

The possible use of compressed air in an underground cavern or enclosure as a method of storing PV-generated energy was considered in the light of current concepts for underground compressed air storage.

The assessment and discussion which follows describes photovoltaic system use of the compressed air storage concept in basic terms; identifies critical system design parameters; examines availability or existence of typical equipment; and evaluates the probable impact of the variable and interruptible nature of the PV energy source.

Integrated System Concept

The compressed air storage system operating with a photovoltaic energy source of electric power is diagrammed in Figure 2.1-4. The system shown is unfired (no fuel combustor) and various methods of improving the system by way of heat exchangers and auxiliary turbo machinery are not shown.[3] The compressor, motor generator, and expander are all on the same shaft which operates at constant speed both on charging and discharging the storage volume of compressed air. The discharge of the storage volume through the expander is the same, regardless of the manner in which the volume is charged,provided that proper consideration has been given to allotting sufficient photovoltaic capacity to supply the demand. To charge the system, the compressor running at

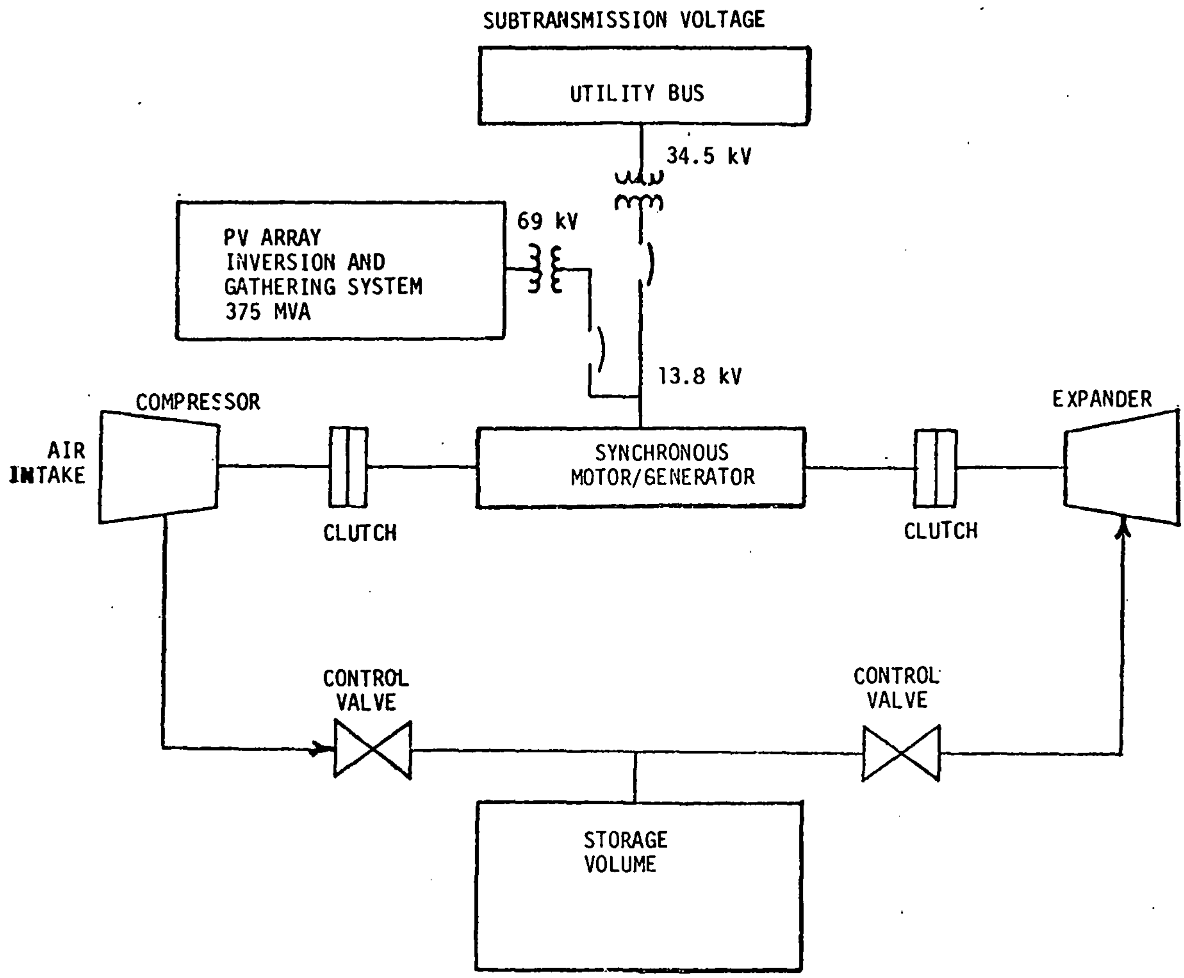


FIGURE 2.1-4. PHOTOVOLTAIC ENERGY CONVERSION WITH COMPRESSED AIR STORAGE-UTILITY APPLICATION

constant speed input provides a flow rate (lbs. of air/sec) dependent upon the pressure in the storage volume. The flow rate will decrease as the pressure in the storage volume increases to a pressure matching the power input. An increase in storage pressure will then require an increase of input power. The operation of the compressor is generally described in terms of the pressure ratio and the power input to the compressor.

A clutch is shown on both sides of the motor generator to indicate the desired versatility. The single shaft system can be operated independently of the storage volume (in case of failure) and the compressor or expander can be operated independently with the storage volume.

Functional Assessment

Table 2.1-1 below was taken from the ERDA report[2] of the GE Study on compressed air storage. From this table it can be seen that since the turbine expander speed is 3600 rpm (3000 rpm is European use) the motor-generator and compressor are also 3600 rpm and no gear boxes are required. Synchronous motor-generators of this size (375 MVA) and speed present no problems.

TABLE 2.1-1. CHARACTERISTICS OF COMBUSTION TURBINES FOR COMPRESSED AIR STORAGE

PRESSURE RATIO	INLET TEMP. (°F)	SPECIFIC TURBINE FLOW (LB-AIR/kWh)	SPEED (RPM)	OUTPUT (MW)	HEAT RATE BTU/kWh
10:1	1850	14	3600	168	6200
11:1	-	-	3600	169	4600
40:1	2000	11	3600	-	4000
43:1	1470	13	3000	220	4770
25:1	1650	13	3000	232	5370
4.5:1	1022	11.4	3000	290	5560

The power required to drive the expander is a function of the air flow (lb/sec) and the adiabatic head, L_{ad}. The adiabatic head is given by:

$$L_{ad} = \frac{1545\, T_1 \, (R_c^{\sigma} - 1)}{\bar{m}\, \sigma}$$

where:

R_c = ratio of compression (say 10.3)

T_1 = absolute temperature for an inlet temperature of 1985°F (T_1 = 2445°R)

$\bar{m}$ = molecular weight of air (28.96)

$$\sigma = \frac{k-1}{k} \quad \text{where } k = \frac{\text{spec. ht. @ const. press.}}{\text{spec. ht. @ const. vol.}}$$

for air k = 1.4 σ = 0.2857

$$L_{ad} = \frac{1545\ (2445)\ (10.3^{.2857} - 1)}{(28.96)\ (0.2857)}$$

= 432,363 feet

The power to drive the turbo machinery is given by:

$$P(bhp) = \frac{\text{Flow (lb/sec) X Head (ft)}}{\text{550 (ft -lb/sec) X Turbine Effic.}}$$

$$\text{or} \quad \text{Flow (lb./hr.)} = \frac{\text{P(bhp) X 550 X Effic. X sec /hr}}{\text{Head}}$$

= KVA X PF X Gen. Effic. X hp/kW X ft -lb /hp X sec/hr X Turbine Effic.

$$= \frac{(375{,}000)\ (.9)\ (.97)\ (1.341)\ (550)\ (3600)\ \text{X Turbine Effic.}}{(432{,}363)}$$

$\cong$ 2 X 10^6 lb/hr X Turbine Effic.

The GE Gas Turbine Division was contacted as to the availability of compressors capable of this flow rate, and provided the information shown in Table 2.1-3.

TABLE 2.1-2. GE COMPRESSOR DATA

MODEL	SPEED (RPM)	# OF SHAFTS	AIR FLOW (LB/HR)	PRESSURE RATIO
MS 3000	7100	2	500,000	7:1
MS 5000	5100	1 or 2	1,000,000	8:1
MS 7000	7600	1	2,200,000	10:1

Further consultations determined that a minimum pressure residual must be maintained: 12 atmospheres (407 ft. of water) was suggested. Initial startup is usually proposed as a "boot strapping" of the expander by using a motor rated at 10% of power output to spin up the turbine, after which the expander is operated as a gas turbine to accelerate the system to synchronous speed. At synchronous speed, the synchronous motor generator would be used to drive the compressor and the starting equipment turned off.

It was reported that all systems considered thus far have been constant speed-variable power systems and consideration of a variable speed, variable power energy source would require new study for a concept design. For a constant speed system, the system would stall once the power input to the compressor matched the pressure in the storage volume or when the power decreased below a matching pressure. It was suggested that a multiple compressor (say three) multiple shaft system could be considered. With this modular concept, as more photovoltaic power was available, a second and then a third compressor could be brought up to speed each independently feeding the storage volume. Alternatively, the compressor could be selected on the minimum power available from the photovoltaic system and when excess power is available, it could be pumped back into the utility. Of course, the compressor could be selected on some other proportion of power less than the maximum available and the utility power could be used to supplement the PV source. Present pumped air storage systems are primarily being considered as utility load levelers. Work conducted to date indicates that little treatment has been given to the control systems required, and this area is likely to be quite complicated. Not enough engineering has yet been applied to this problem.

With respect to stall power level, it seems likely a minimum pressure ratio of 5.1 should be maintained and if available power is insufficient to obtain this pressure ratio, the compressor(s) should be disconnected.

From the preceding it is clear that the fundamental pumped air system is considerably like a pumped hydro storage system so far as use with a photovoltaic energy system is concerned. Other observations on pumped hydro with respect to switching, interconnections and loss of load apply as well to pumped air.

Conclusions

1. An underground compressed air system can be designed to work in conjunction with a photovoltaic energy system.

2. The sizing, consequences of interruption, and site-related characteristics of compressed air storage for photovoltaic system use are very similar in nature to these same considerations for pumped hydro storage.

3. A hybrid operation in conjunction with other utility power generation storage charging sources is a more likely application approach. This method could avoid or reduce equipment modularity requirements that would otherwise be encountered in designing a PV-only system with efficient component sizes.

2.1.5.3 Battery Storage Systems

Both lead-acid batteries and a number of advanced batteries now under development [3,4] are potentially compatible with the concept of an integrated PV-energy storage and conversion system. Extensive studies have been done, and estimates made for lead-acid batteries.[5,6,7] Assessments of expected results for advanced batteries have also been made, and a major test program, the Battery Energy Storage Test Program,[8,9,10] has been organized. Since the above types of data are readily available, and battery operation in general is well understood, the purpose of this section is primarily to assess the major consequences of interfacing this type of storage with a photovoltaic conversion system. It will be assumed in this discussion that any successful advanced battery will meet or exceed the key performance characteristics of a lead-acid battery; therefore, attention will be directed at the operational results to be expected with lead-acid batteries as the storage system for PV energy conversion. Fundamental considerations such as placement of power conversion equipment and typical voltages and currents will be discussed.

Integrated Photovoltaic Conversion System Concept

A lead-acid battery storage system for utility use with a PV system is shown in Figure 2.1-5. The preliminary design shown for the photovoltaic energy

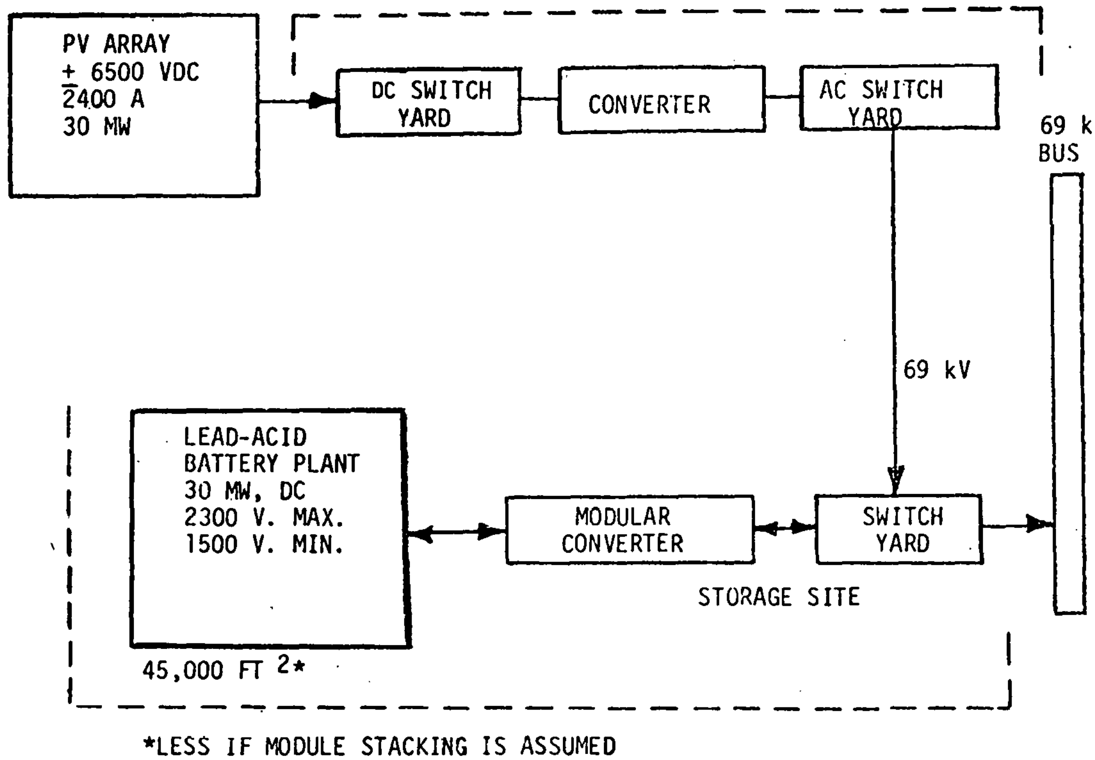


FIGURE 2.1-5. PHOTOVOLTAIC ENERGY CONVERSION WITH LEAD-ACID BATTERY STORAGE - UTILITY APPLICATION

system was taken from a recent GE-ERDA study.[1] The information shown for the lead-acid storage system was extracted from and/or based on the EPRI Workshop report on "Lead-Acid Batteries for Utility Applications".[3]

The discharging of the storage system per se is not directly affected by the PV energy source, and is not included in this portion of the discussion.

For the PV system as shown, no accounting of losses or effect of capacity factor is indicated. The power outputs indicated are maximums. If a capacity factor of 25% is assumed for the photovoltaic array, an average power output of 7.5 MVA can be relied upon to charge the batteries. Since the equipment for the storage system is selected on a power basis, several system alternatives should be considered for determining the equipment complement of the storage system, as described below.

Functional Assessment

Storage equipment can be selected so that the power ratings are correlated to the maximum power available from the energy source. The system would then have poor efficiency because the average power level is much less than rated. Electrical equipment is more efficient at rated conditions and the efficiency at rated conditions improves the higher the power and voltage ratings (i.e., with size). Also, for inverter units in the 30 MVA size, stable operation is not possible for low power (around 10%) input. Regardless of size, cooling of inverter/converter equipment must be varied as a function of load for improved efficiency. This condition may be improved by the alternative of modularizing the power conditioning equipment into, for example, three sets of 30% power capability each. Thus, depending upon the power output from the PV array, only 1/3 of the power conditioning equipment is operated at less than rated conditions. Each of the power conditioning modules would be less efficient at full load than a single unit but the system efficiency should be better than that of operating one large unit in the 20 to 50% efficiency range. An actual design trade-off would be required before the advantage of modularizing could be established. It must be kept in mind, however, that modularizing will impact reliability and will also severely affect cost effectiveness. A third alternative is to select a PV array power rating such that the average power output is correlated to the storage need. For this alternative, some other options must in turn be exercised when the source is providing maximum, and in this case, excess power. The power could be dissipated by inefficient operation of the PV system, pumped back into the utility system or, again, the storage system could be modularized. Modularization, as before, will increase complexity and decrease cost effectiveness.

In conjunction with the first alternative, an option for maintaining charging power for storage at a constant level is to supplement the photovoltaic power with utility power. For specific utility systems, this option may have merit, but the determination is strongly dependent on the particular utility operating situation.

Conclusions

It may be readily shown that the power ratings of the PV conversion system with respect to the power ratings of the storage system may be approached by one of three alternatives:

1. Modularization
2. Overrating
3. Supplemental energy supply

Firm conclusions regarding optimum configurations and equipment sizing could only be made after specific preliminary system designs were carried to the point where system performance could be traded-off against system cost effectiveness; however, certain observations can be made:

1. With regard to cost effectiveness, the unit cost of an inverter rises disproportionately as the size or power rating is decreased, but the cost of gathering interconnections may be a much larger percentage of system cost for multiple unit clusters than will the inverter equipment. Therefore, the cost effectiveness of the PV conversion and storage system will be drastically affected by the degree of modularization.

2. A PV conversion system with its power output variation will offer some design challenges in obtaining the best match of power ratings. Trade-offs with unit efficiencies must be expected.

3. Battery storage systems inherently offer the possibility for distributed unit location and are flexible in their physical arrangement. Interruption of the charging cycle merely exercises the switching devices and their associated instrumentation. Restart of the charging process does not involve the same problems of inertia associated with large rotating machinery. Thus, a significant aspect of energy storage being associated uniquely with a variable output source, such as PV, is reduced to a minimal problem. Conversely, the battery system can be expected to provide an instantaneous and variable-magnitude discharge response when called upon to meet a changing load demand.

2.1.5.4 Flywheel Energy Storage

Flywheel storage with PV energy conversion systems at the utility scale of usage is covered in this Section. Assessment is made by describing a representative system in fundamental terms, so that the critical system parameters can be identified. The impact and implications of charging the storage via a variable and interruptible PV energy conversion source are included in the discussion.

Integrated System Concept

The fundamental flywheel storage system is shown in Figure 2.1-6. The system consists of: a flywheel which stores kinetic energy, a constant speed motor/generator, and a variable speed coupling (or a variable frequency converter). Since the mass of the flywheel is fixed, the kinetic energy of the flywheel can only be charged or discharged by changing the flywheel speed. For utility use, a synchronous motor/generator would provide the most desirable interface to the utility bus. That is, it would be desirable to have the flywheel discharge via a constant speed generator synchronized to the utility bus. Conversely, for charging, the constant speed machine would be used as a motor to charge the flywheel. In order to accomplish this, it is necessary to interpose a variable speed coupling between the constant speed machine and the variable speed flywheel. This variable speed coupling (during charging) must accept power (torque X speed) from the constant speed machine, which is equivalent to the variable photovoltaic output and, in turn, raise the then

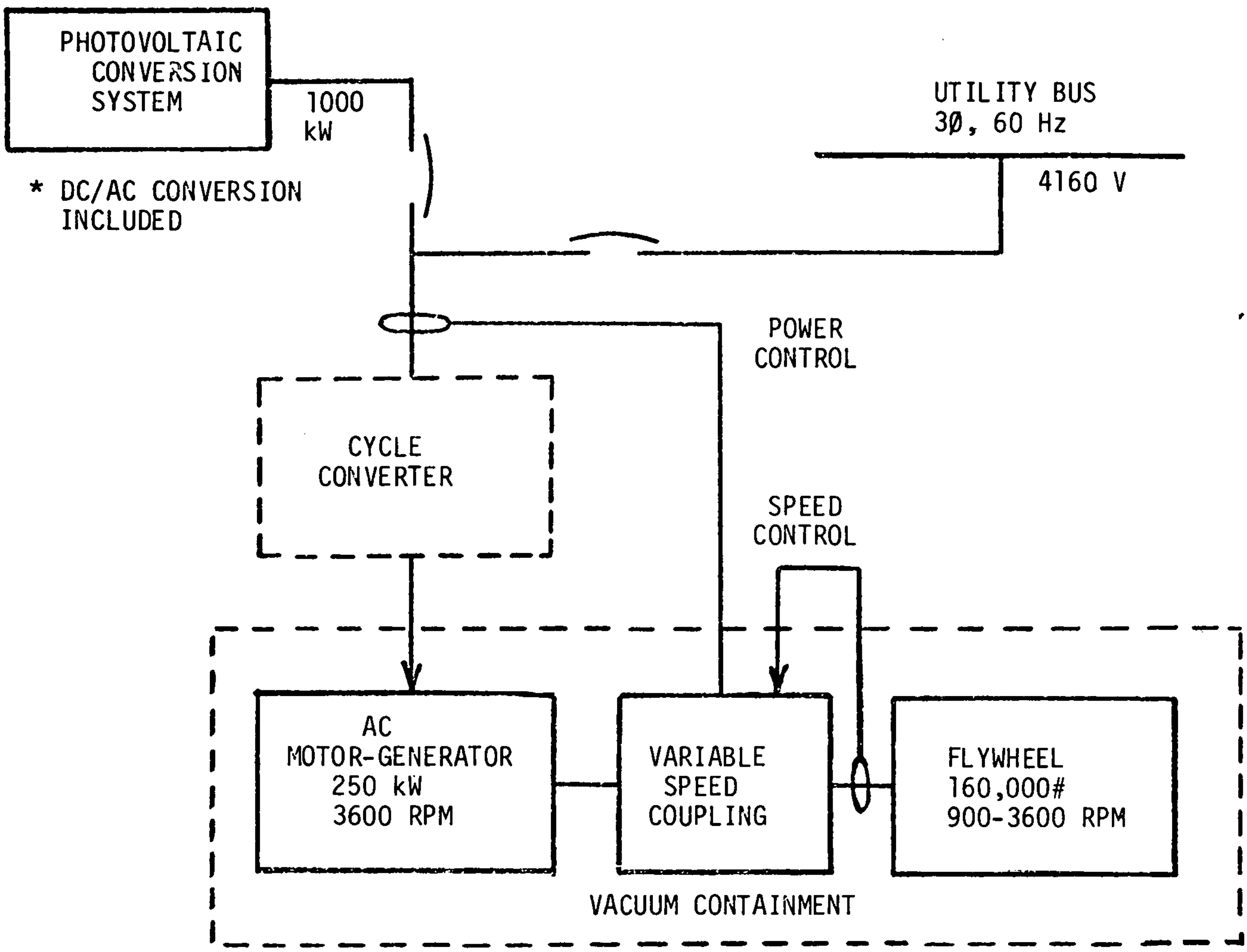


FIGURE 2.1-6. PHOTOVOLTAIC ENERGY CONVERSION WITH FLYWHEEL ENERGY STORAGE-UTILITY APPLICATION

existing speed of the flywheel to a still greater speed. In order to fully utilize the available energy source power, the coupling must be controlled on the basis of sensed power. In discharging into the utility grid, the source is open circuited and the coupling is controlled on the basis of scheduled power out of the synchronous generator. That is, the discharge power is a selected value and the variable speed coupling is controlled so as to maintain the selected output.

An alternative scheme using a cycle converter (shown dotted in Figure 2.1.6) may also be employed to modulate the input/output speed of the ac motor-generator to charge/discharge the flywheel. For this option, the frequency on the utility side of the converter must be constant and the frequency on the motor/generator side must be controlled for charge/discharge and power level. When charging from the variable power level photovoltaic source, the frequency out of the cycle converter must be increased until the speed of the motor is greater than the speed then existing on the flywheel. Conversely, when discharging, the power and frequency from the cycle converter to the utility must be maintained constant as the ac generator, being driven by the flywheel, is constantly slowing down.

In order to minimize idling or standby losses due to friction and windage losses of the flywheel, the high speed units are generally enclosed in a chamber evacuated of air or other gases and mounted on very efficient bearings.

As with other storage systems considered, the charging cycle is the key portion of the system operation which needs be considered to assess the hardware design impact of the PV conversion flywheel system interface. The discharge cycle is unaffected, provided proper energy balance has been allocated, since the storage system effectively isolates the load (during discharge) from the variations of the source. This observation, however, should not be interpreted as meaning that the system aspects of the discharge side can be ignored in the overall concept since, since the total system operational philosophy is involved.

Functional Assessment

An ERDA study[11] describes a basic flywheel rotor module for utility application. This flywheel is a 160,000 pound 185 inch rotor capable of delivering 2.5 MWh (10 hour discharge) and has a maximum speed of 3,600 RPM. When connected to a 3600 RPM synchronous generator, the variable speed transmission allows flywheel speeds from 3600 to 900 RPM. The configured systems as described in the above study (Section 5.3) assume constant (rated 250 kW) power during charge and discharge. For a photovoltaic energy conversion source with a capacity factor of about 25% assume a power rating of 1000 kW. With the variable speed coupling system, the operation of the motor-generator would be as for any normal application, and the generator efficiency would be close to 95% from 50% load to full load, dropping sharply below the 50% load point. The variable speed coupling, however; would have poor efficiency except at rated (or low slip) conditions.

To illustrate, consider the operation of some type of slip clutch while the system is charging and assume the flywheel is spinning at 900 RPM and 15% of the source power or 125 kW are available. The generator at 50% load will be turning at 3600 RPM and since the power output of the generator is a constant 125 kW there is a constant torque of:

$$Q = \frac{125\ \text{kW}}{3600\ \text{RPM}} \cdot 3413\ \frac{\text{Btu}}{\text{kWh}} \cdot 778\ \frac{\text{ft-lb}}{\text{Btu}} \cdot \frac{1\ \text{hr}}{60\ \text{min}} \cdot \frac{1}{2\pi}\ \frac{\text{Rev}}{\text{Rad}}$$

$$= 244.5\ \text{lb-ft}$$

applied at the input. Since there is no loss of torque through the clutch, the power into the flywheel is given as

$$P = 125 \times \left(\frac{900}{3600}\right) = 31.2\ \text{kW}$$

Therefore, about 95 kW must be dissipated in the variable coupling device as the flywheel is accelerated from 900 to 3600 RPM as illustrated in Figure 2.1-7. Ignoring the damping and shaft spring parameters of the system (which should be negligible), the time constant for the flywheel under constant torque from the motor is:

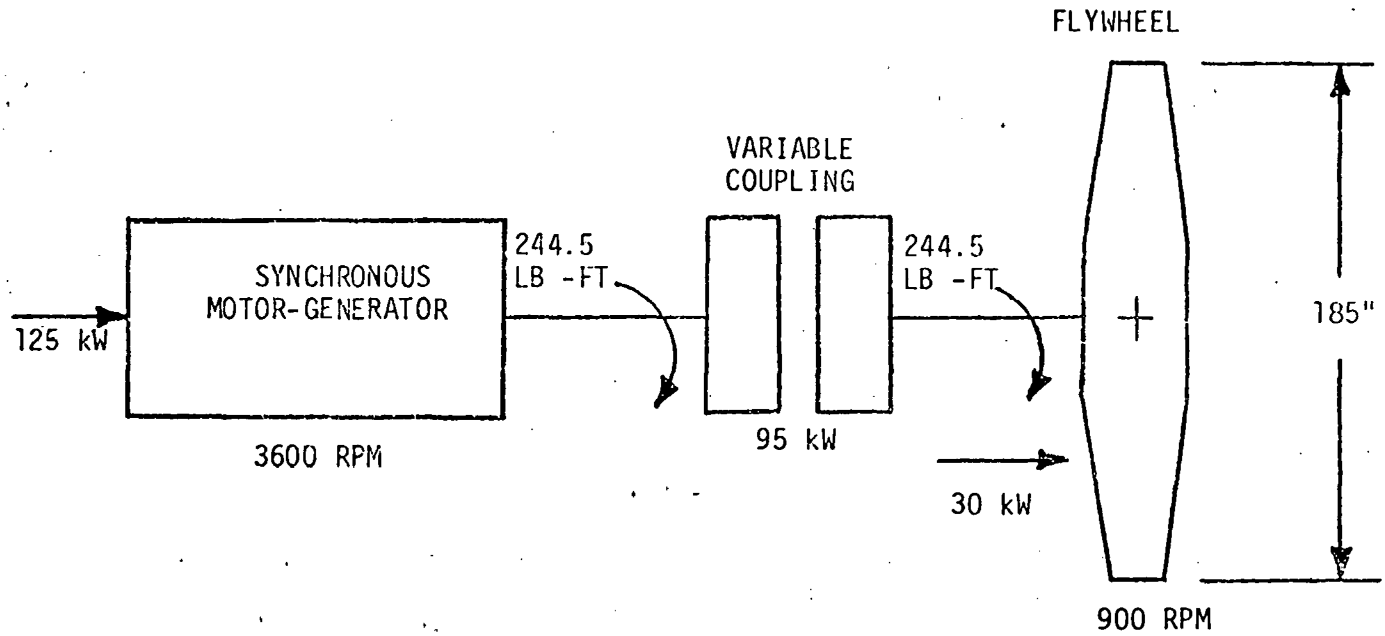


FIGURE 2.1-7. SLIP POWER DISSIPATION IN VARIABLE SPEED COUPLING

$$dt = J \frac{d\omega}{Q}$$

where

$$J = 1/2\ MR^2 \text{ (assumes right circular cylinder)}$$

$$= \left(\frac{1}{2}\right) \left(\frac{160,000}{32.2}\right) \left(\frac{185}{2 \cdot 12}\right)^2$$

$$= 1.47 \times 10^5 \text{ slug-ft}^2$$

$$d\omega = \frac{3600-900 \quad (2\pi)}{60}$$

$$= 282.7 \text{ Rad /Sec}$$

$$dt = \frac{(1.47 \times 10)^5 \quad (282.7)}{244.5}$$

$$= 169,993 \text{ sec}$$

$$= 47.2 \text{ hrs.}$$

$$= 1.97 \text{ days}$$

As the flywheel speeds up to the same speed as the motor, less power is dissipated in the coupling. The total energy lost in accelerating the flywheel is the integral of the slip characteristic of the coupling device over the period of acceleration.

It has been suggested in the previously-mentioned report, that this dissipative situation can be ameliorated considerably through the use of automotive type transmission systems, one such being the Trancor constant velocity transmission (CVT). Essentially, this CVT would continuously minimize the speed ratio between the constant speed motor and the variable speed flywheel. The result would be high accelerating torques applied to the discharged flywheel but little power being dissipated in the transmission. Units of 250 Hp (186 kW) have been built, but they are still developmental. For state-of-the-art, eddy-current clutches have been suggested for utility applications. Eddy-current clutches were also considered by GE Advanced Energy Programs personnel for use with the Mod-1 Wind Turbine Generator. The size of these clutches is about the same size as an 1800 RPM synchronous machine or slightly larger.

If the variable speed motor/generator option is considered, the variable speed coupling is replaced by a fixed coupling and the frequency range for the cycle converter is 3:1. Down conversion of frequency is simpler than the up conversion inferred by the arrangement shown in Figure 2.1-6. In any case, the cycle converter will be operated with variable power input, such that a single unit will not be very efficient. The efficiency of the cycle converter would be improved by modularizing units to a fraction of the total load then switching modules in and out such that all but one module was operated at full load. The system complexity will be increased in this case, and therefore the reliability of the system will decrease somewhat with modularization.

Conclusions

1. Flywheel storage systems can be interfaced with a variable power source such as a photovoltaic system. The degree of success, however, will be dependent upon the satisfactory development of the flywheel itself and also a large variable speed transmission system, capable of long life with a relatively large number of operating cycles. In addition, suitable bearings and enclosures must be available.

2. Alternative designs may introduce requirements for modularity which would increase the complexity and cost of the system. A design trade-off would be required to select a preferred system.

2.1.5.5 Hydrogen Gas Generation and Storage System

This section provides a practical assessment of a system using fuel cells to generate hydrogen for storage, with subsequent utilization of the stored energy by burning the hydrogen in a fuel cell to produce electricity. The system energy input requirements are supplied by a photovoltaic energy source and the generated electricity is supplied at utility level and scale. A candidate H_2 system will be described along with the identification of critical system parameters and evaluation of the probable results of interruption or variation in the photovoltaic input.

Integrated System Concept

A basic hydrogen generation and storage system is shown in Figure 2.1-8, based on information contained in a supporting study performed for this program by General Electric Direct Energy Conversion Programs (DECP).[12] In the figure, electrical lines are shown solid, and plumbing lines are shown dotted. In assessing this storage system for the impact of interfacing with a PV energy source, it is not necessary to consider the discharge of the storage system since it should be presumed that the storage system has been appropriately scaled to supply specific utility needs, and the storage device effectively isolates the utility demand from the variability of the source. The essentials of the hydrogen generation system which

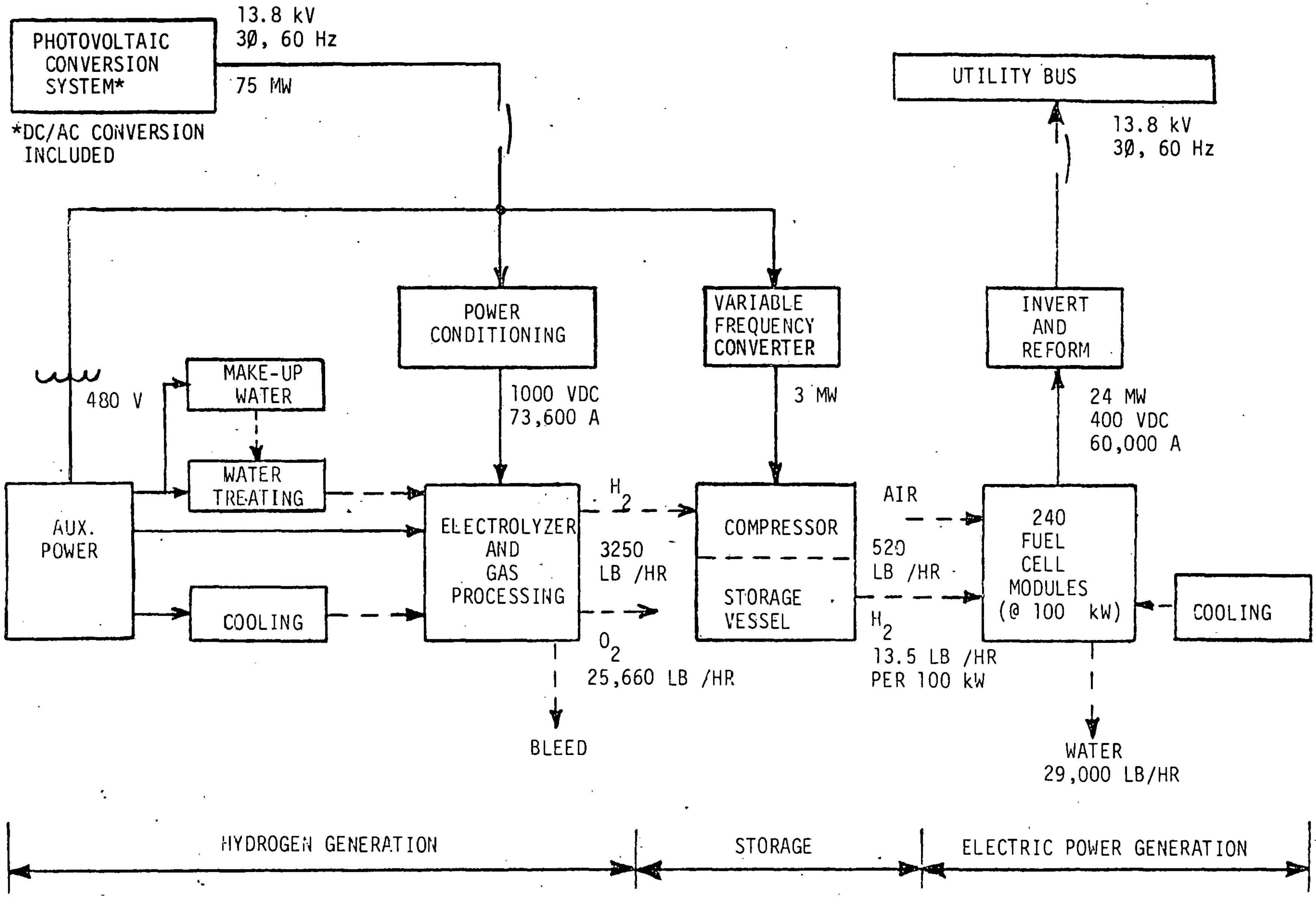


FIGURE 2.1-8. PHOTOVOLTAIC ENERGY CONVERSION WITH A HYDROGEN GENERATION AND STORAGE SYSTEM-UTILITY APPLICATION

charges the storage system are as follows: The Electrolyzer which provides the hydrogen (and incidental oxygen) must be provided with a constant voltage direct current source. The output flow rate of hydrogen is then proportional to the amount of current (power, in effect, since the voltage is constant) provided with a constant voltage direct current source. Treated water is fed into the electrolyzer in a recycle with continuous flow rate and at a controlled pressure and provides the "raw material" for the electrolysis. The gases formed by the electrolysis are then processed by separators, dryers and associated components which are not affected per se by the flow rate. However, heat exchangers required for the electrolysis and gas processing, are affected by flow rate, since the main reaction and other processing must be done at controlled temperatures. Therefore, the flow rate of cooling liquids must be varied as a function of the rate of hydrogen production which increases as the power provided by the photovoltaic array increases. Similarly, the flow rate of make up water must increase as power (dc current) increases, in order to supplant the water that has been decomposed by electrolysis.

The hydrogen generated by the electrolysis is generally stored under pressure and is available to generate electrical power via a fuel cell for either utility peaking requirements or base load requirements. Based on the DECP study, and an assumption that it is desirable to have as many fuel cells as the maximum hydrogen flow out of the electrolyzer will allow, it is noted that 75 MW of input power to the storage system from the photovoltaic array will provide approximately 25 MW of fuel cell output.

Functional Assessment

A fundamental consideration for the hydrogen storage system is the manner in which the hydrogen (once it has been generated) is stored. Of the three methods of storage discussed in the DECP report: compressed gas, liquid, or metal hydride, the compressed gas is assessed as the most near term (See Table 2.1-3). The metal hydride system of storage is promising, but is developmental and the liquid hydrogen storage method has high charge/discharge cost and only a fair intermittent operation capability. The assessment of

TABLE 2.1-3. COMPARISON OF HYDROGEN STORAGE METHODS

POINT OF COMPARISON	METAL HYDRIDE	LIQUID	COMPRESSED GAS
Equipment Cost, \$/1000 SCF	350-530	1000-1300	550-1200
Energy Expenditure, kWh/lb H_2/Storage Cycle	0.8-1	4-5	0.5-1
Intermittent Operation Capability	Good	Fair	Good
Hydrogen Volume per Container Volume	Medium	High	Low
Storage Vessel Cost as Percentage of Total Storage Cost	Medium	Low	High
Equipment Cost Required to Induct Hydrogen in or out of Storage as Percentage of Total Storage Cost	Medium	High	Low

the storage method and the system for use with photovoltaic input power was discussed further with DECP personnel. The basic compressed gas storage system requires: a pressure vessel, a reciprocating compressor, and a large ac powered motor drive of low synchronous speed. This system is shown in

Figure 2.1-9. The drive horsepower required for a three-stage compressor is 1.79 X 10^{-4} times the standard cubic feet per day of hydrogen processed, (V_b). For continuous 24 hour operation at rated output:

$$V_b = 3250 \text{ lb of } H_2/\text{hr} \times 1/.0052 \text{ ft}^3/\text{lb} \times 24 \text{ hr/day}$$
$$= 15 \times 10^6 \text{ ft}^3/\text{day}$$

then:

$$\text{Drive Power} = 1.791 \times 10^{-4} \; V_b = 2686.5 \text{ hp} \cong 2000 \text{ kW}$$

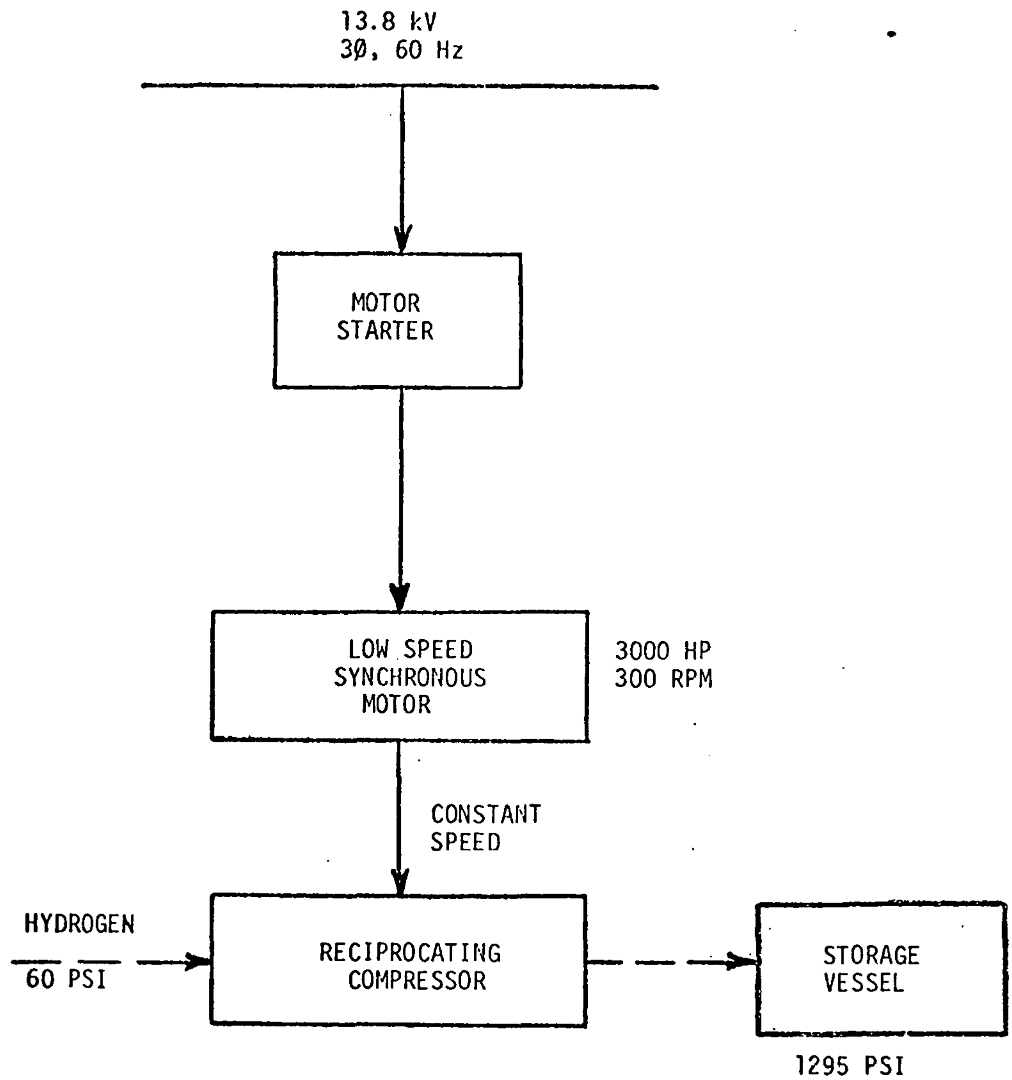


FIGURE 2.1-9. COMPRESSED GAS STORAGE SUBSYSTEM

The significance of this system configuration is that a constant speed motor is driving a reciprocating compressor. This combination has essentially the same output at any pressure within the capability of the driver and the compressor, but the capacity (flow rate) varies due to input energy variability, so this system cannot operate at constant speed. As shown in Figure 2.1-8, a variable frequency converter is required to drive the positive displacement compressor at a speed correlated to the hydrogen flow rate. DECP has suggested elimination of the compressor by operating the electrolyzer at higher water pressure since the recycled water can have a constant flow rate. This scheme, shown in Figure 2.1-10, transfers the variable speed requirement to the pump supplying the make-up water, and requires a heavier electrolyzer unit.

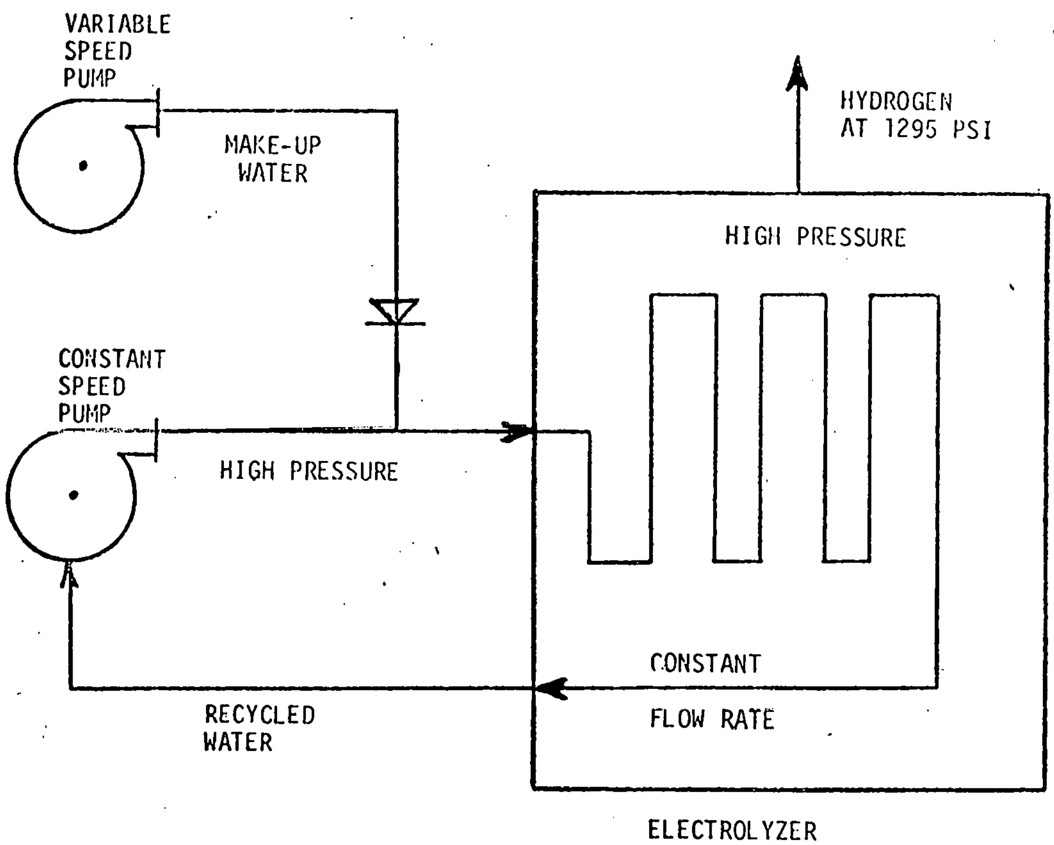


FIGURE 2.1-10. ELECTROLYZER CONFIGURATION WITH COMPRESSOR ELIMINATED

With regard to the interruptibility of the hydrogen generation process, there are no unusual design or process problems associated with periods of inoperation, except for the impact on cycle life of switching elements.

As for variability of energy source, the range of power variability will as previously stated, require variable speed drives to vary the cooling fluid flow rate as a function of the rate of hydrogen generation. It has also been suggested by DECP that cooling flow be stopped for power input to the electrolyzer below 10%.

The selection of variable speed pump(s) for the make-up feed water is a design problem not under consideration here, but a system is conceivable whereby the hydrogen generation can continue for very small (less than 10%) power into the electrolyzer.

Because of power conditioning requirements for the electrolyzer, it is doubtful that efficient operation can be obtained unless the power conditioner is modularized (e.g., 10 units each rated at 10% of maximum power). The power conditioners, as most electrical equipment, operate most efficiently at or near rated power. The efficiency decreases drastically below about 50% of rated load.

The hydrogen storage system is basically amenable to dedicated operation with photovoltaic systems but at severe cost to efficient operation. The definitive course for improvement of operation efficiency appears to be to completely modularize all aspects of hydrogen generation and power generation; but the consequences of the resultant complexity may seriously affect utility requirements for reliability and availability.

It is noted that the low voltage levels associated with the power input to the electrolyzer and also out of the fuel cells results in very high currents. Clearly, exceptional care must be taken in the design of all interconnecting conductors to minimize resistances and consequent power losses and cooling problems.

Conclusions

1. A hydrogen generation and storage system can be made to perform satisfactorily in conjunction with a photovoltaic conversion system for charging power, but penalties due to modularization may impact cost effectivity of a dedicated system.

2. The precise operating characteristics of such a system would require a design analysis for a specific system.

3. For the near term, a compressed gas storage system presents the least complications. Other storage methods may be introduced at a later time. Hydride storage appears to offer the most desirable possibility for the long term future.

2.2 RESIDENTIAL SYSTEMS

2.2.1 BASIC ENERGY CONVERSION SYSTEM

The basic energy producing unit assumed for the residential photovoltaic energy conversion application was an 84 square meter array rated at a nominal 10 kW output. Such a system would be located on the roof of the residence. The system output would normally be connected for residence use via additional control system and power cabling and the conventional residential load center. Additional terminal enclosures at the load center would be required. The array interconnection, and operational procedures would require conformance with the applicable codes. Specific designs for homeowner or architect selection would be necessary. Particular attention would be required with respect to standardization of equipment and implementation practices in order to accommodate large-scale use of such systems.

2.2.2 PHOTOVOLTAIC CONVERSION SYSTEM OPERATION

Table 2.2-1 gives the major parameters of interest. The output levels at the selected sites are matched to representative loads as discussed in Section 3.

TABLE 2.2-1. PHOTOVOLTAIC SYSTEM CHARACTERISTICS

Rated Power	7.2 kW	9.6 kW*	12.0 kW
Solar Array Area	63 m^2	84 m^2	105 m^2
Insolation Level	1. kW/m^2		
Array Temperature	60°C		

* Used in detailed investigations

2.2.3 STORAGE SYSTEM INTEGRATION AND INTERCONNECTION TO THE PHOTOVOLTAIC CONVERSION SYSTEM

The basic PV array with energy storage added was considered on a case-by-case basis with respect to the probable consequences of being inter-connected with various storage systems. By virtue of previous suitability screening as described in Volume I of this report, the use of systems other than batteries, flywheels, and small-scale pneumatic (compressed air) storage were ruled out for further consideration. However, the possible alternative of a conventional (hot water) thermal system at the residential level is discussed in this Section.

2.2.3.1 Battery System Storage

Most recently, the primary emphasis on battery storage development has been directed at utility applications and vehicular transportation needs. While advanced versions of present lead-acid batteries and also various other types of "advanced" batteries are actively being pursued [4,13], the prime utility interest cited above indicates why very little firm data exists upon which to base an assessment of residential-scale PV system battery storage hardware interface problems with advanced batteries. However, it is well known that alternative lead-acid battery sizes and scalings are possible. Modern residential battery storage systems could readily use the lead-acid technology of motive power batteries now available to industry. Residential use of advanced batteries must remain dependent on the current R&D efforts leading to a sound product and the subsequent resolution of issues relating to maintenance requirements, potential hazards, and the ownership responsibilities which are as yet unknown and/or undefined. The discussion which follows, therefore, is based on lead-acid battery technology and the assumption that eventually one or more so-called "advanced" batteries will be available with performance characteristics at least as favorable as those for lead-acid batteries.

Integrated System Concept

Figure 2.2-1 shows a concept for a photovoltaic system with lead-acid storage batteries, and identifies the principal components involved. The values given relate to a single battery size (43 kWh). Figure 2.2-2 shows the physical dimensions of such a battery as proposed by C&D Batteries, Div., of Eltra Corp., during the course of a supporting study for this energy storage investigation. Table 2.2-2 gives other proposed characteristics of such a battery.

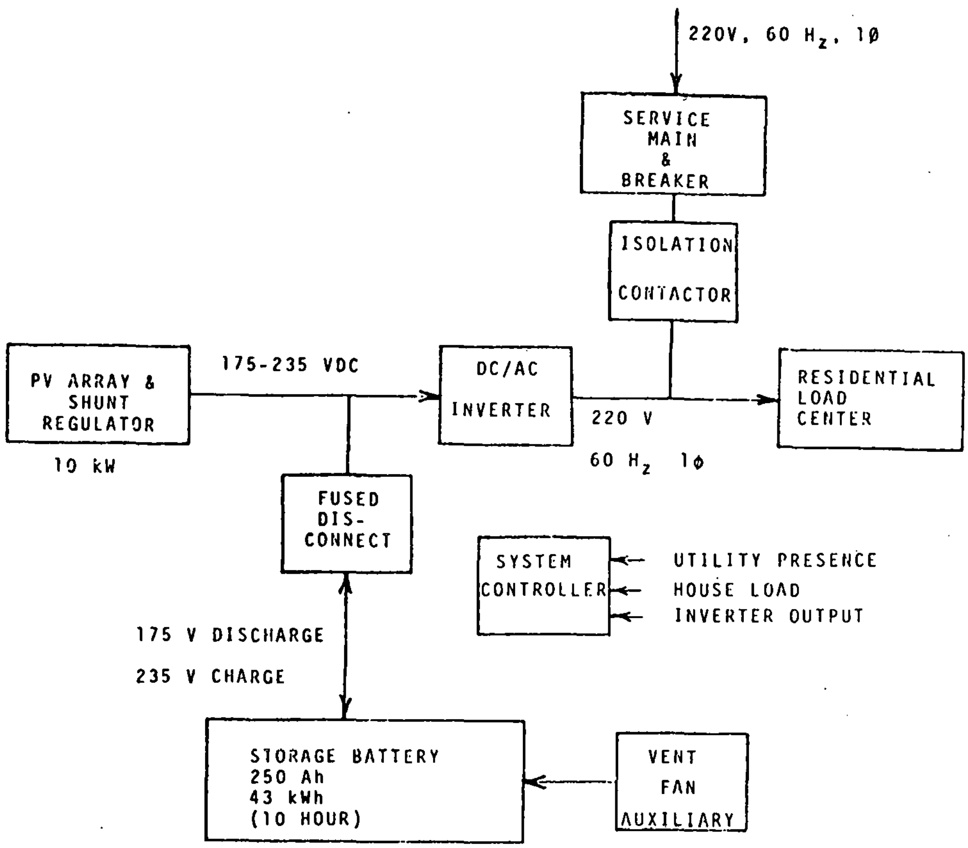


FIGURE 2.2-1. RESIDENTIAL BATTERY ENERGY STORAGE SYSTEM - PHOTOVOLTAIC ENERGY CONVERSION

TABLE 2.2-2. REPRESENTATIVE RESIDENTIAL LEAD-ACID BATTERY CHARACTERISTICS

Capability	4.3 kW Peak
10 HR System Power	43 kWh
Number of Cells	96 Series
Ampere Hours per Cell	225 AH (Derated 333 AH)
Physical Dimensions One of 4 Modules	22.5"L x 27"W x 23"H
Weight per Module	1410 Pounds
Hydrogen Evolution	0.145 Ft^3/Cell/Cycle (New Cell)
Recommended Charge Voltage	2.45 Volts per Cell
Discharge Voltage (End of Life)	1.83 Volts per Cell
Water Consumption Gal./Cycle/Cell	0.0008 Gal.

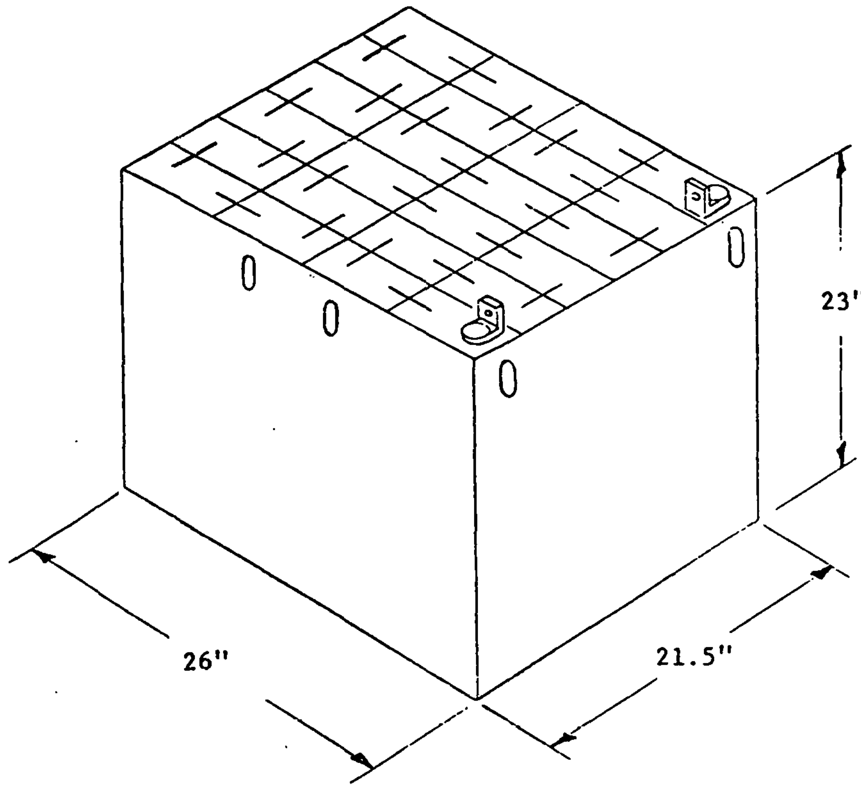


FIGURE 2.2-2. REPRESENTATIVE LEAD-ACID BATTERY MODULE FOR A RESIDENTIAL STORAGE SYSTEM

The concept shown provides for isolation of the utility, PV array, and storage system via contactor units. Normally, the house loads would be met first by the directly usable PV system output and supplemented as necessary by the utility power. During periods of low insolation, the battery, charged previously with excess energy, would provide load power, again, backed up by the utility. During times when more than one source is supplying the load, synchronism of the ac outputs must be assured by the control system. In event of a fault on the utility lines, isolation is required to prevent unwanted power feedback from the residential PV system to the utility.

Functional Assessment

The system components required for a residential PV energy conversion system with battery energy storage are not specifically available in the sense of "tailored" designs and sizes for this particular application. The technology required, however, including manufacturing facilities and processes is available. It would be possible to assemble such systems on an individual basis using existing equipment for power conversion and interconnection. The control system would require that specific engineering and design be accomplished. In most cases, local codes and utility regulations would require prior coordination and approval for connection and operation of such systems. The system engineering and design requirements would at present make individual installations very costly and only a degree of product-line standardization could alleviate this problem. At the residential level, particular attention would be required to avoid operational problems or hazards arising from carelessness with respect to battery water replenishment, prevention of hydrogen accumulation, and failure to properly secure the storage area. (The latter most likely would be within the residence structure). It should also be recognized that not only will present array concepts not be practical for many densely populated neighborhoods, but in addition, many existing residences would lack a suitable area for a battery storage system to be added without extensive modification. Nevertheless, the problems cited appear reconcilable provided a substantial commitment to a residential energy storage program were to be made by industry and government agencies.

Conclusions

1. There are no functional barriers of a technical nature that would prevent use of an integrated photovoltaic lead-acid battery storage system at the residential level.

2. The availability and acceptability of any type of "advanced" battery for residential use is hypothetical at the present time and judgment should be reserved until enough technical data is available to permit preliminary design of such a system.

3. A responsible homeowner attitude would be essential and maintenance support must be locally available.

2.2.3.2 Flywheel Storage Systems

Small flywheel storage systems presently exist for limited applications in the transportation and industrial fields. These applications are based on use of various shapes of steel flywheels. They have serious limitations to scale-up for advanced energy storage requirements due to need for higher energy density materials for the flywheel, and also need for improved bearings and enclosure systems. By-passing these considerations, however, the use of a flywheel system with a residential photovoltaic system may be examined to determine the functional compatibility of the combination.

Integrated System Concept

Figure 2.2-3 shows the principal components needed for a residential system. The operational mode would include having the PV system supply the house load directly whenever possible. When the PV system generates excess power, the storage contactor is closed to permit the flywheel to be charged. Any further input energy above these needs would be dissipated by other means. House loads may be met by storage discharge alone or in combination with PV output. The utility serves as backup and may be isolated by a contactor device. A system controller (not shown in the figure) is required to sense

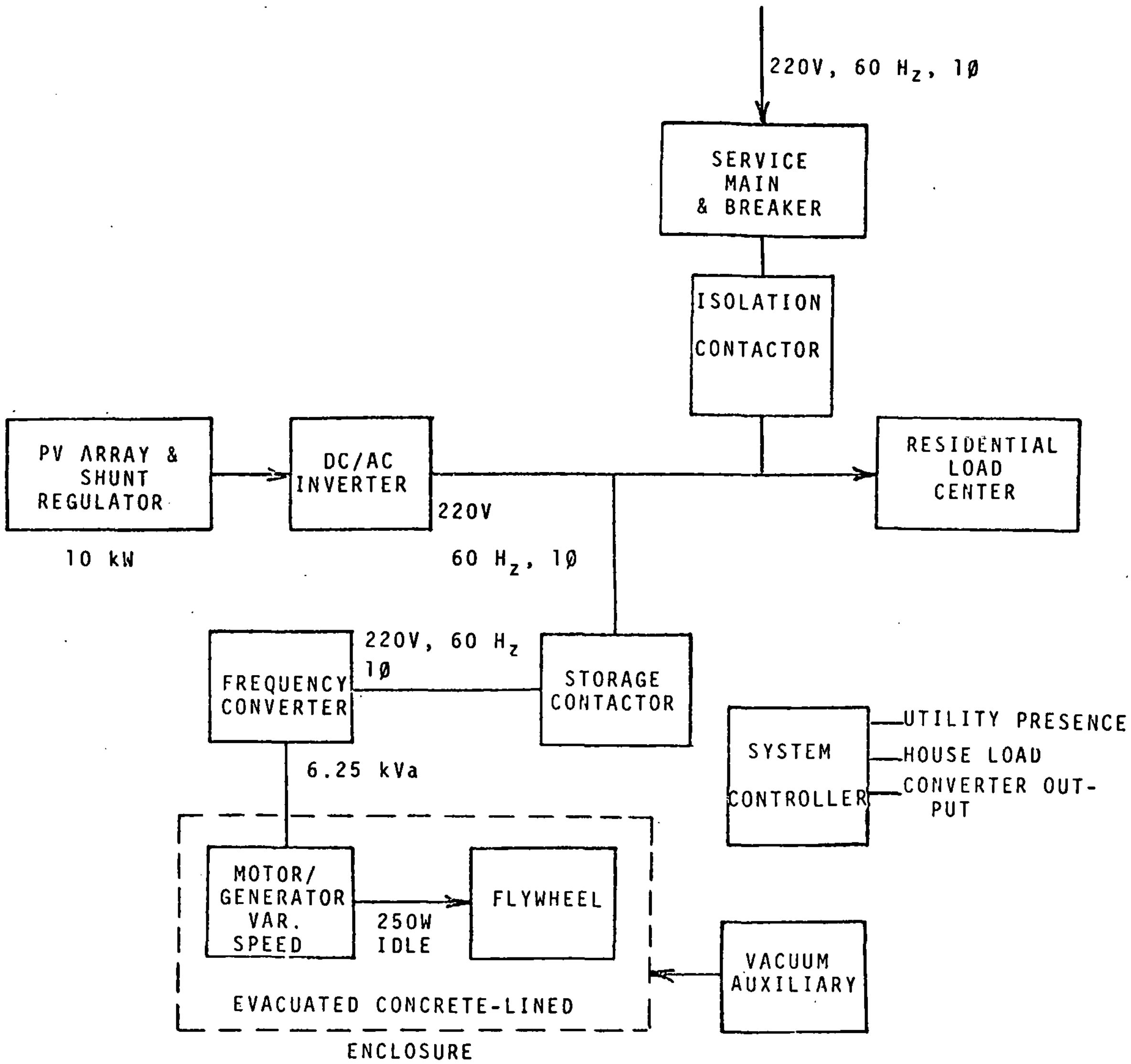


FIGURE 2.2-3. RESIDENTIAL FLYWHEEL ENERGY STORAGE SYSTEM-PHOTOVOLTAIC ENERGY CONVERSION

voltages and currents to assure proper operational sequence and the synchronous operation of the ac systems. The motor-generator and frequency converter are variable speed ac machines. For flywheel charging, the speed of the ac motor is determined by the frequency converter which changes a constant frequency power input to variable frequency power output. During discharge, the varying frequency power output of the generator is converted to a constant frequency by the frequency converter, making it compatible with the normal utility power which serves the residential loads. The necessary speed-frequency conversion can also be accomplished mechanically by a variable speed transmission interposed between the flywheel and motor generator.

Functional Assessment

The components required for flywheel system use are not readily available in the sizes and configurations that would be needed. The flywheel itself, along with bearings and enclosure system require further developmental work. Rockwell[11] reported on a 5 kWh flywheel as at the "forseeable" technology level using advanced flywheel technology. Such a system would have a composite rotor design with precision quality bearings, but short of the quality of those for space vehicle use. Early in this study, a residential design was projected on the basis of a conventional steel flywheel and up to 48 kWh storage capacity, but was found to have costs in excess of $250/kWh of storage capacity.

Conclusions

1. A residential flywheel system requires components that are either not available at the residential market level and/or require further advanced development.

2. From an operational standpoint, a system of this type has undesirably high standby or charge maintenance losses which must be considered.

3. The amount and complexity of equipment involved combines to cause expectation of high cost and in all probability owner maintenance difficulties.

4. There is no technical reason why a flywheel system cannot be functionally integrated with a photovoltaic conversion system at the residential level.

5. Noise generated by the system is a problem requiring design attention.

2.2.3.3 Pneumatic Energy Storage

This form of energy storage was of interest at the residential level as a counterpart to the large-scale underground compressed air storage for utility use. Significant work on this type of storage concept was not found in earlier literature searches and consequently a specific investigation of major requirements was undertaken. The system aspects are discussed in the succeeding paragraphs.

Integrated System Concept

Figure 2.2-4 shows the major elements which would be required for this type of energy storage. Air compression to about 700 psig was estimated as appropriate to the desired discharge level for a storage size of about 50 kWh. Compression would be accomplished by a multi-stage piston compressor driven by an ac motor. The discharge of the compressed air tank would be used to drive an air turbine and a small alternator. The connection to the residential load center is not shown, but would be similar to other residential systems in that controls and contactor devices would be required to isolate the utility

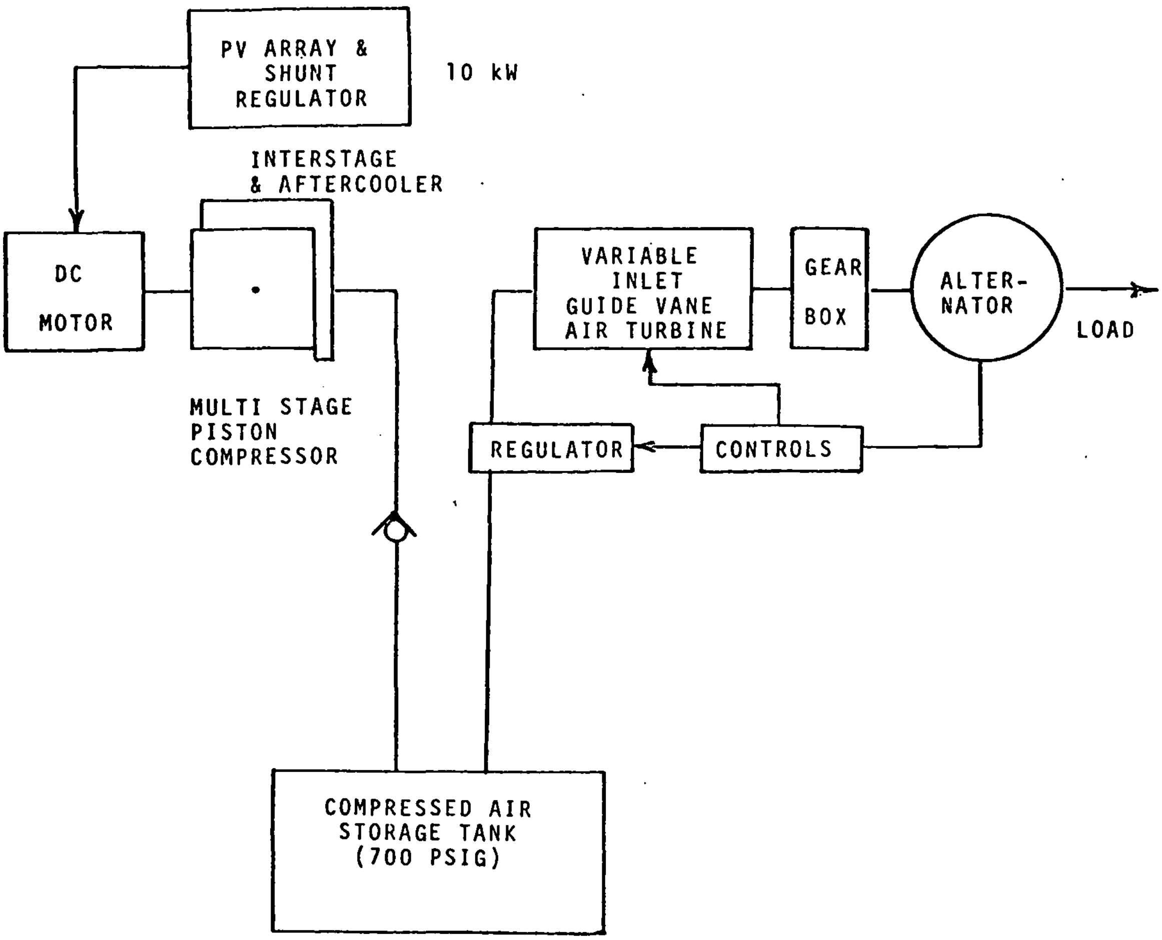


FIGURE 2.2-4. RESIDENTIAL PNEUMATIC ENERGY STORAGE SYSTEM - PHOTOVOLTAIC ENERGY CONVERSION

power, the storage system and the PV array under various operating conditions. The ac outputs from these sources would require synchronization as well.

Functional Assessment

As can be seen from the diagram, a considerable amount of equipment is required for this concept. Some items are not readily available at present, although the AiResearch Manufacturing Division of Garrett Corp. [14] is fabricating an air-turbine driven alternator system rated at 80 kW. This unit, however, is only intended for use as part of a Canadian proof-of concept experiment.[15] The efficiency of this concept was estimated to be in the order of 60% which is not particularly attractive. Another major problem with this concept is the weight and volume of the tankage. It is very conceivable that the 12 foot diameter, 15,000 lb tank estimated for the 50 kWh of storage could be placed outside the residence, underground. Also, selection of a small storage capacity would obviously help reduce this problem. The other major factors that detract from the residence use of such a system would include the obvious hazard of the high pressure air tank, noise from the mechanical components, and high temperature ($\sim$ 1000°F) at the compressor discharge. The concern about interruptibility that was identified with utility underground compressed air storage is reduced to small proportions at the scale of operation involved in the residence case. Proper design for motor disconnection under low PV output conditions should essentially resolve this item.

Conclusions

1. Off-the-shelf components are not presently available to produce pneumatic storage systems on a quantity basis, but could likely be made available within present technology. The air turbine performance results on the Canadian project would be a key item to monitor.

2. The pneumatic storage system as conceived can be integrated technically with a photovoltaic system but has a number of very negative features. At the present time these do not appear readily resolvable in the context of a residential scale system.

2.2.3.4 Thermal System Storage

Although thermal-oil and thermal-steam types of energy storage were not found attractive for integrated use with PV systems, additional consideration is offered here with respect to conventional hot water systems for residential scale use. A major reason for discussion of the residential thermal storage possibilities is that the major portion of the residential loads are thermal in nature, involving space heating and hot water heating.

Integrated System Concept

A number of storage mediums have been proposed, and some have been tried with varying degrees of success reported. Among these are hot water systems, heated rock storage and others. Figure 2.2-5 shows the major components of such a system based on use of a fluid heat exchange and energy storage system.

The photovoltaic output in this case would be used to provide power to residential electrical loads directly whenever possible. Utility power provides the remainder of the residence electrical needs. Excess photovoltaic energy would be used to heat the thermal storage fluid, probably water, suitably enclosed in an insulated tank or similar device. The energy thus stored would not be reconverted to electricity but could be delivered via hot water or hot air distribution systems to directly serve home heating and hot water needs.

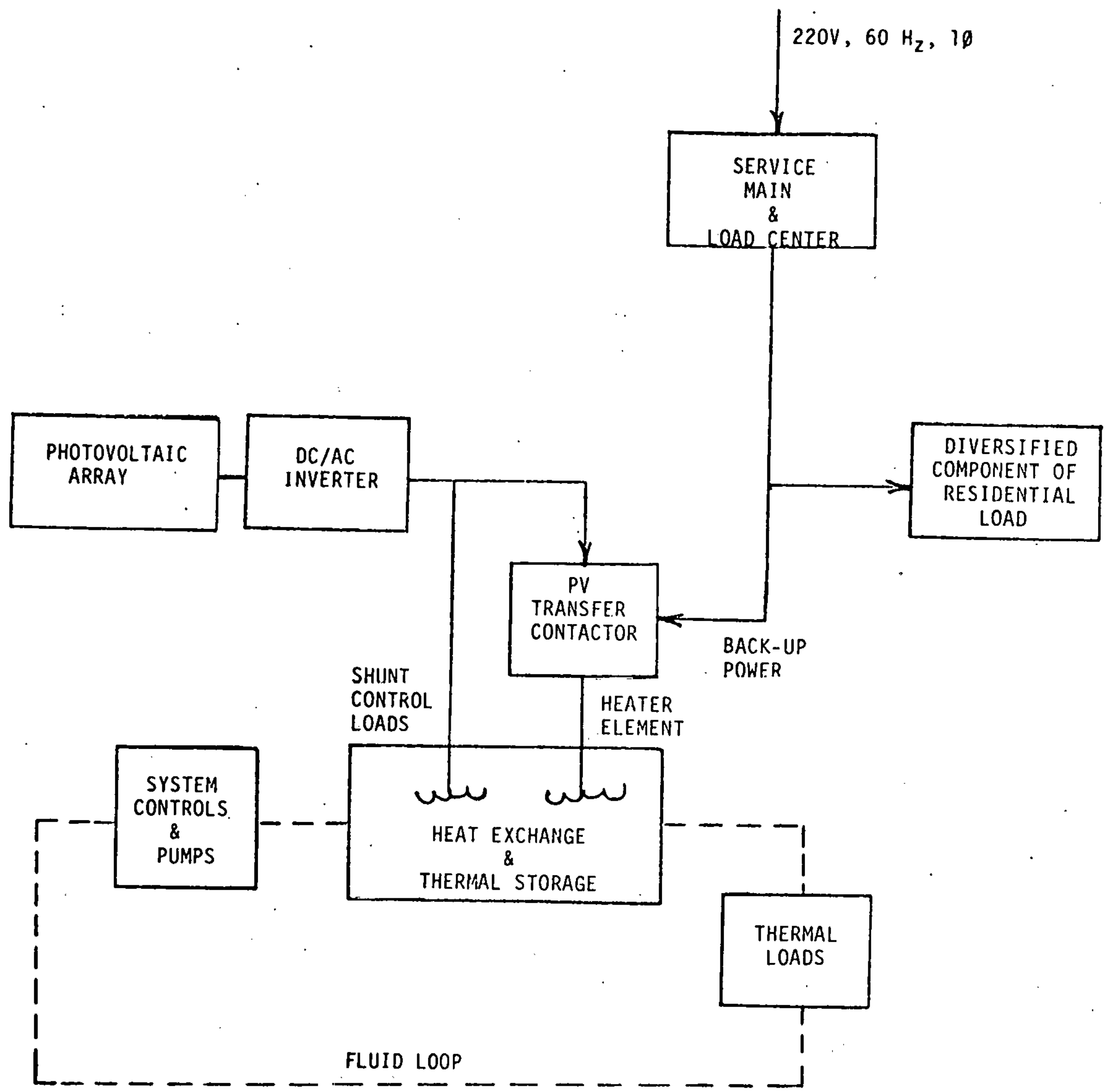


FIGURE 2.2-5. RESIDENTIAL THERMAL ENERGY STORAGE SYSTEM - PHOTOVOLTAIC ENERGY CONVERSION

Functional Assessment

The efficiency of conversion from electricity to thermal energy would be very high (.95 - 1.0) so that the system losses overall would depend only on the insulation of the storage device and the distribution system and the amount of time between storage and use. The equipment requirements would generally include pumps, valves, fans and other mechanical equipment which would yield to fairly low technology development and production where existing equipment was not adequate. Further investigation and sizing of such a system was beyond the intended scope of this study, but should not be difficult to accomplish as related work has been done in the field.

Conclusions

1. This process of charging storage is highly amenable to unplanned interruptions, and interface problems would be relatively simple.

2. The attractiveness of such a system would require formulation of a detailed design and a detailed cost estimate.

3. The economic evaluation of such a system would require a direct comparison with results obtainable with all electric systems on a cost per Btu basis.

2.3 INTERMEDIATE SYSTEMS

2.3.1 BASIC ENERGY CONVERSION SYSTEM

A nominal 500 kW photovoltaic array was used as the basic unit for the intermediate application category. Multiple units of this array size would be a suitable means of meeting load demands of the larger intermediate applications. For study purposes, however, a single 500 kW array was used. Principal parameters of interest are given in Table 2.3-1 for the 500 kW array.

TABLE 2.3-1. 500 kW PHOTOVOLTAIC SYSTEM CHARACTERISTICS

Rated Power	500 kW
Insolation Level	1 kW/M^2
Temperature	60°C
Array Area	4371 M^2

2.3.2 STORAGE SYSTEM INTEGRATION AND INTERCONNECTION TO THE PHOTOVOLTAIC CONVERSION SYSTEM

The intermediate applications for photovoltaic conversion and storage systems will require physical, electrical and operational approaches which relate to those already described for the utility and residential usages. The principal determining factor will be one of application scale. In some cases, a hybrid situation would be appropriate. The principal matter of concern here, however, was whether hardware or other technical barriers could be expected, unique to the intermediate application, which would prevent satisfactory system integration using various storage concepts.

No major new equipment constraints were identified with the intermediate-level system, although a range of component sizes will be needed. General technical considerations relating to installation and use will be quite different in some respects. Examples of these include:

1. Compatible location of PV arrays.
2. Compatible locations for storage units.
3. Planning, design and/or modifications of plant or facility layouts to accommodate interconnection with utility power.

Some non-technical considerations will also be very significant in certain applications.

1. The management of the additional facilities and equipment pose additional responsibilities for owners and operators. A particular case in point would be that of a shopping center having general management by the ownership and individual billing or allocation of costs to each business enterprise within the complex.
2. Negotiation of service contracts with local service organization.
3. Negotiation of rates with the area utility company.

These examples of the so called "institutional" problems are cited here as a reminder that the technical designs are still highly dependent on other operational questions. On the surface the latter may appear simple, but in reality, they may not be easily resolved. This class of implementation constraint should not be overlooked.

The previous discussion of utility and residential concept technical interface issues are generally applicable to the intermediate application situation. No additional problems should be encountered as a result of intermediate sizing provided suitable system scaling is employed.

SECTION 3

PHOTOVOLTAIC ENERGY STORAGE ASSESSMENT

3.1 GENERAL

This portion of the study was directed at determination of appropriate cost goals for the effective use of energy storage with photovoltaic energy conversion systems. Applications of energy storage to systems sized for residential, intermediate and utility use were considered. The economic benefit from storage for the utility case includes both net fuel cost savings and credits derived from reduced requirements for conventional generating equipment and for transmission and distribution facilities. For the residential and intermediate cases, the principal economic benefit defined was the potential saving in the consumer's cost of electricity, although other less tangible benefits were considered. As part of the basic benefits analysis, it was also desired to determine the effects of the following factors relative to storage capacity and cost goals:

1. Location/Insolation Characteristics
2. Effect of various rates of fuel escalations and general inflation
3. Storage system efficiency
4. Penetration of photovoltaic energy relative to total system capacity (Utility case only).

The following special cases were also investigated:

1. Multiple source charging
2. Effect of transient photovoltaic system output smoothing

The results of these investigations were translated into summary curves for use in relating a range of alternative conditions to the effect on allowable break-even capital cost and optimum storage capacity. Further conclusions were drawn concerning economic viability of various storage methods, which in turn were used to refine the results of initial program evaluations of various storage concepts.

3.2 METHOD OF ANALYSIS

3.2.1 UTILITY APPLICATIONS

Several possible approaches were considered as a means of projecting the value of adding storage to a photovoltaic energy system. It was decided for the purposes of this study, to measure the value increase when various levels of storage were added to a specific no-storage baseline system. This method inherently results in maximizing the amount which a utility might be willing to pay for dedicated storage, since none of the storage benefit is used to increase the worth of the basic photovoltaic system. The potential for the storage system to aid overall photovoltaic system viability is then assessed in the light of cost goals derived for storage on its own merits.

3.2.1.1 Basic Procedure

The following comprise the general steps involved in this portion of the Study:

1. Photovoltaic power output was computed for Phoenix, Arizona, Miami, Florida, and Boston, Massachusetts. Actual hour-by-hour insolation levels were taken from data tapes prepared on a previous program.[16] The computations matched the insolation characteristics to the performance characteristics of the photovoltaic array to obtain hour-by-hour photovoltaic system power and energy output. Array sizes corresponding to 10, 20 and 30% generation penetration were examined.

2. A representative utility system hourly load profile was compiled based on Representative System "B" defined in a recent study by Public Service Electric and Gas Company of Newark, N.J. (PSE&G).[17] Seasonal load duration curves were used to more accurately assess loads over the entire year modeled.

3. A generalized system model was established and cost strata were assigned for energy generation by various types of equipment.

4. Computer runs were utilized to match the load with photovoltaic system outputs, and establish the baseline "no-storage" case fuel costs.

5. Energy storage was added and employed to reduce fuel costs, according to pre-determined energy management cycles for charging and dispatch of stored energy.

6. The amount of displaced generation (i.e., conventional utility generation supplanted by PV system output), was assessed and, in turn, the break-even costs based on fuel savings plus applicable "credits" were computed.

3.2.2 RESIDENTIAL APPLICATIONS

The residential analysis was necessarily different from the above although similar techniques were employed. Similarities and differences are discussed below.

3.2.2.1 Basic Procedure

1. Step one from Section 3.2.1.1 above was followed except that a 10 kW photovoltaic array was utilized.

2. Representative residential loads were selected for use with each of the same three locations.

3. Computer runs were made to match the photovoltaic output energy to the load on an hour-by-hour basis for a one-year period. Required utility energy purchases were computed for this time period.

4. Energy storage was added and used to store photovoltaic excess energy for later use. New values of required utility purchased energy were computed.

5. Residential break-even costs were computed based on the reduction in purchased energy due to use of storage. Analysis was performed for each location and case variation of interest.

3.2.3 INTERMEDIATE APPLICATIONS

The intermediate application analysis method was similar to the one used for the residence case, but with the following modifications:

1. A 500 kW photovoltaic array was utilized.
2. A load profile was assumed based on a shopping center type of operation with fixed hours and a stable load pattern.
3. The effects of a sizeable increase or decrease in load were examined to provide results analogous to the utility penetration effect.

3.3 ANALYSIS AND PROJECTION OF COST GOALS IN UTILITY APPLICATIONS

3.3.1 ENERGY MANAGEMENT

3.3.1.1 Allocation of Wind System Energy Contribution

For the utility case it can be shown that a very high percentage of any photovoltaic system output can be immediately and directly used on line by the utility. This is so in part because of the fact that the total utility load is projected as being much larger than the photovoltiac system output, thus eliminating most of the "excess" that would be experienced in a case where the load was smaller than the photovoltaic system output. The possibility of enhancing the value of photovoltaic energy by using storage depends, in the utility case, on being able to employ energy storage at times when the photovoltaic output, even if it could be used by the load, would be of relatively low value to the utility. Figure 3.3-1 illustrates the desired "relocation" of photovoltaic energy from off-peak to peak load times when it will have a more value to the utility in terms of cost-of generation.

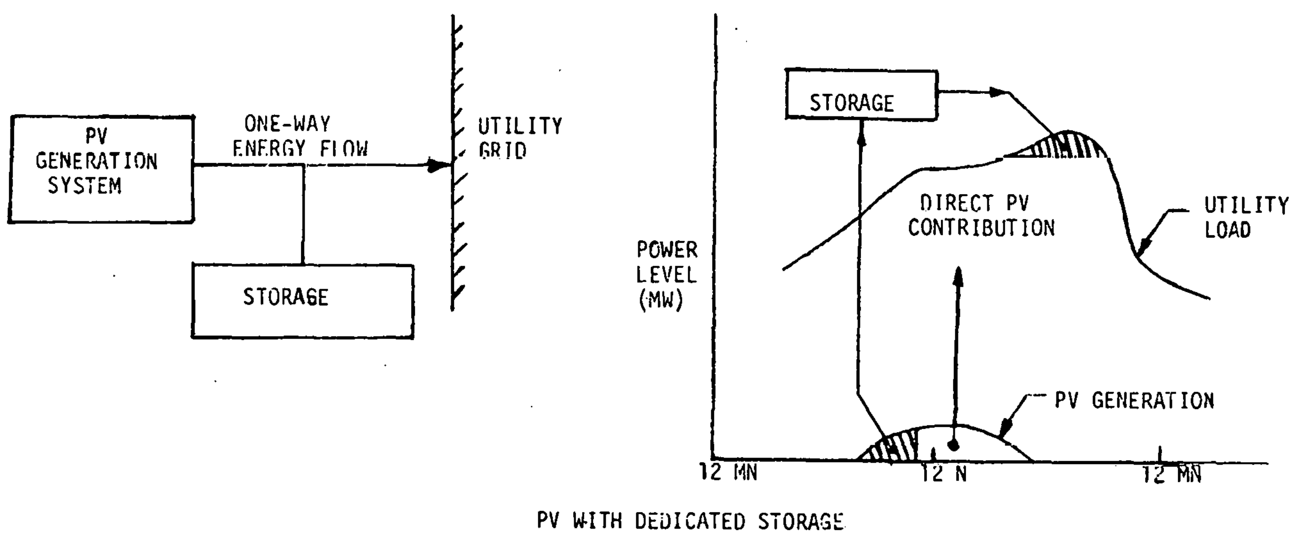


FIGURE 3.3-1. PHOTOVOLTAIC ENERGY WITH DEDICATED ENERGY STORAGE FOR UTILITY APPLICATIONS

It is also significant to point out the one-way nature of the power flow to the utility grid, as the charging of the storage system is entirely dependent in this case, on the PV system. As will be shown later, the effect of this arrangement is to lessen the storage utilization and in turn its value as compared with other configurations. It should also be noted that there is a large, but not total coincidence of the available photovoltaic energy with the utility peak load times. Whenever load demand matches well with photovoltaic energy availability, storage can be avoided and consequently, the storage efficiency losses also. To the extent that the photovoltaic energy direct-to-load component and the stored energy contribution can be reliably delivered, both conventional generation and generation capacity may be reduced.

In terms of a utility system load duration curve as portrayed in Figure 3.3-2, the economic usefulness of the PV direct and stored contributions can be depicted within each cost-of-generation strata.

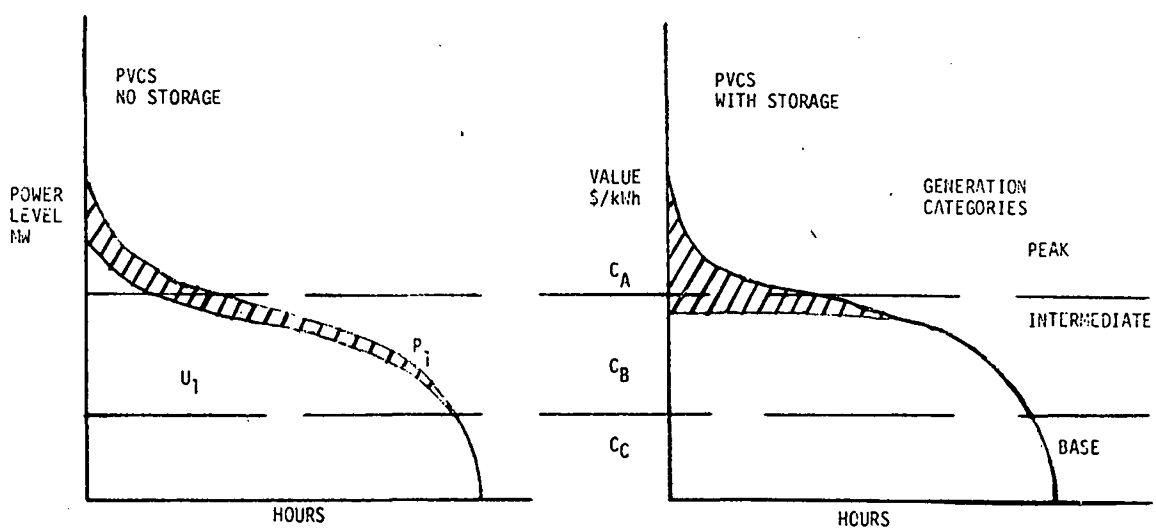


FIGURE 3.3-2. PHOTOVOLTAIC ENERGY RE-DISTRIBUTION UTILIZING ENERGY STORAGE - UTILITY APPLICATION

photovoltaic energy without storage may be contributed in either the peak, intermediate or base generation portions of the load duration curve, or may be spread throughout (as shown) depending on the time of day of photovoltaic system output. The photovoltaic contribution without storage could be concentrated in only one region of the load duration curve, but this would unlikely be based on examination of representative load distribution patterns. Storage can be used to re-arrange a major portion of the photovoltaic energy to the peak and/or intermediate regions while reducing or eliminating contributions in the base load region. Since the total external load on the utility grid is unchanged by the source of the energy contributions, for any one region:

$$U_1 + P_1 = U_2 + P_2$$

$$\Delta \text{ Cost} = C \ (U_1 - U_2) = C \ (P_2 - P_1)$$

where

U_2, U_1 = utility contribution to load with and without storage

P_2, P_1 = photovoltaic system energy contribution to load with and without storage

C = incremental cost of generation per unit load (e.g., \$/kWh).

Summing the Δ cost for all regions yields the total equivalent fuel saving benefit of adding storage to the photovoltaic system. In the base-load region, the value goes negative and must be subtracted. This is because the utility must now deliver more energy in the base load region, since the photovoltaic energy contribution has been "relocated" to the higher cost regions.

The above described generation cost saving can be easily capitalized to determine the maximum amount one would be willing to pay for a storage system based on fuel savings alone.

3.3.1.2 Theoretical Maximum Value of Storage - Utility Application

Computation of a theoretical maximum value or worth of energy storage is a relatively simple task with a very useful output - a standard against which the effectiveness of storage operational strategies can be measured. The theoretical maximum value is identical for dedicated and multi-source charging, the former merely falls much shorter of the maximum due to the variability of the photovoltaic system output. Assume 1 kilowatt-hour of storage capacity with an overall input-output efficiency of η. Let:

V_p = value or incremental cost of peaking energy - \$/kWh

V_b = value or incremental cost of base load energy - \$/kWh

N = number of storage cycles per year

FCR = fixed charge rate

M_f = fuel savings multiplier

(FCR and M_f: See Section 3.3.5.6 for a fuller explanation).

Maximum value per cycle is achieved when energy is stored at the lowest value (base load) and discharged when energy is most costly (peaking). The energy cost savings (A_E) for full capacity operation becomes simply:

$$A_E = N\,(V_p - V_b/\eta)$$

Levelizing with the fuel multiplier and dividing by FCR to capitalize yields:

Capitalized Energy Credit (value of storage as an energy saver).

$$C_E = M_f\ N\ (V_p - V_b/\eta)/FCR \quad \$/kWh$$

Figure 3.3-3 presents C_E versus the incremental costs of base load and peaking energy for storage efficiency of 75%, fixed charge rate of .18 and 250 annual operational cycles. The latter figure is a typical annual business

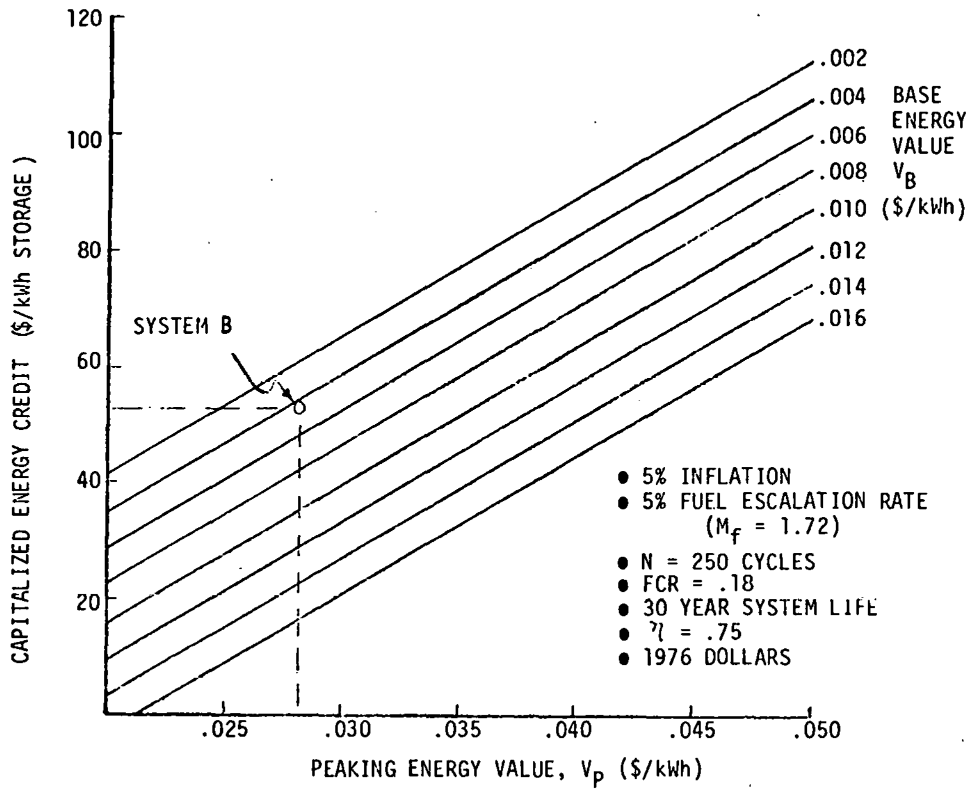


FIGURE 3.3-3. THEORETICAL MAXIMUM ENERGY CREDIT FOR STORAGE UTILITY APPLICATION

day figure when allowances are made for weekends and holidays. Inflation and fuel price escalation rates of 5% correspond to zero differential fuel price escalation. Shown on the curve is the theoretical maximum energy credit for the representative utility system "B" cited earlier in this report. Comparison of the theoretical maximum for another set of utility costs with the cost computed with rates assumed for this study and the system "B" load (point shown in Figure 3.3-3) will enable a rough extrapolation of the report results to the other utility system. It is obvious from Figure 3.3-3 that the energy credit is a strong function of the system energy cost characteristics.

Capacity credit and transmission and distribution credit, where applicable, must be added to the capitalized energy credit to obtain the total storage break-even cost. For example, taking capacity credit of 140 $/kW for assumed gas turbine displacement and a T&D credit of 45 $/kW (for battery systems only) gives the following theoretical maximum break-even cost results for a system "B" type load:

	5 Hour System	10 Hour System
Energy Credit	$53.35	$53.35
Capacity Credit	28.00	14.00
T&D Credit (Batteries only)	9.00	4.50
Break-even Costs (except batteries)	$81.35	$67.35
Break-even Costs (batteries)	$90.35	$71.85

All costs in 1976 $/kWh

These represent the maximum storage break-even costs for a 5% energy price escalation rate. Figure 3.3-4 can be easily used to extrapolate the energy credit portion of the above break-even costs to other escalation rates and various start years.

For example, a 1988 start with 8% escalation gives about 2.0 times the levelized energy savings of the base 5% case. Maximum break-even cost for a 5 hour battery would then become (using the same credits):

Energy Credit	$106.70
Capacity Credit	28.00
T&D Credit	9.00
	$143.70 /kWh

This represented a 59% increase in break-even cost over the base 5% escalation case.

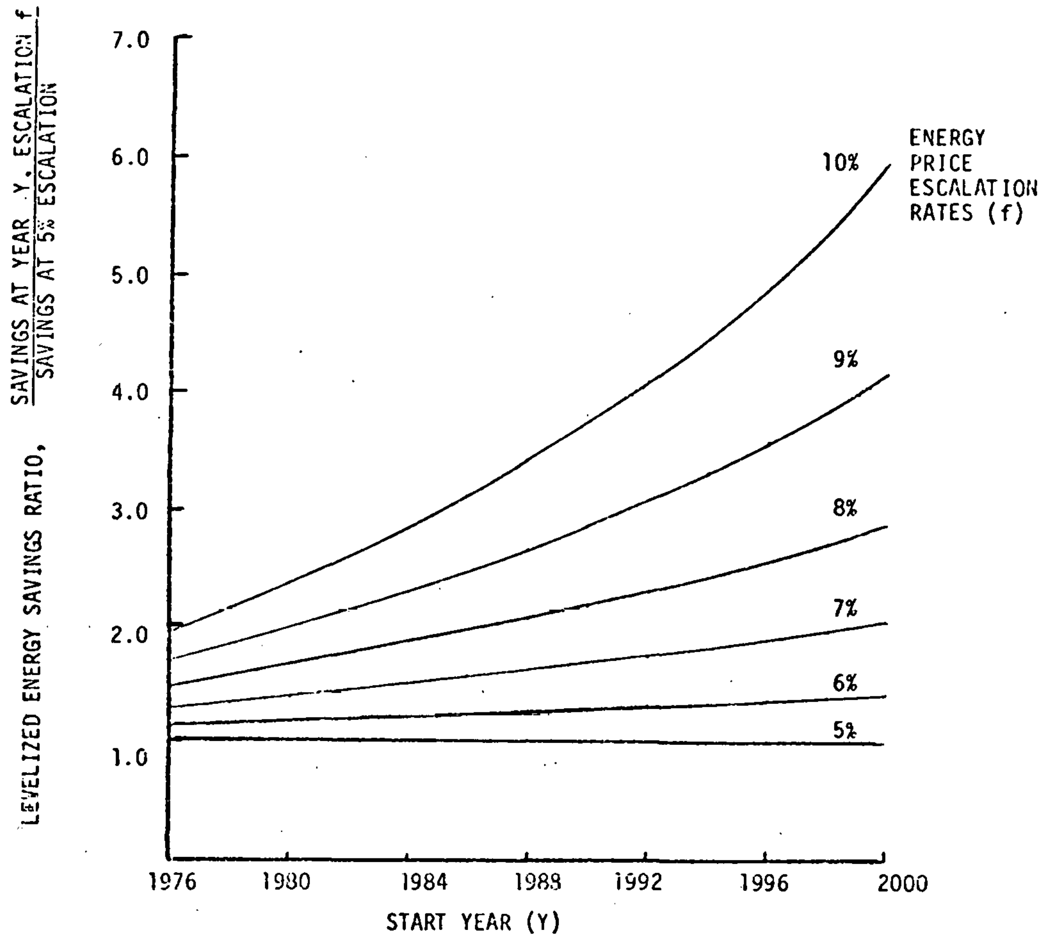


FIGURE 3.3-4. EFFECTS OF START YEAR AND ENERGY PRICE ESCALATION RATE ON LEVELIZED ENERGY SAVINGS-UTILITY APPLICATION

Practical Limits to Storage Value

There are several reasons why the theoretical maximum energy credit cannot be achieved in practice. Operation and maintenance requirements, component replacement costs and interest during construction must be considered. These factors are concept-dependent and, for some systems, substantially affect the net savings. System efficiency varies among concepts. The principal limitation on energy credit, however, is that only at very small storage sizes can energy be continually moved from the lowest cost level (base load) to the highest level (peaking). Utility system "B", used in the majority of the utility analysis in this report, has four main levels of generation costs, to which the following representative values were assigned:

Level	Incremental Cost	
A	.0281 $/kWh	More discussion
B	.0215	of this subject
C	.0120	will be found in
D	.00435	Section 3.3-4.

The savings in moving a kilowatt hour from one level to another was shown in the previous section to be equal to:

$$\text{Savings per cycle;}\quad S_c = V_{discharge} - \frac{V_{charge}}{\text{Efficiency}}$$

where

$V_{discharge}$ and V_{charge} are values or incremental costs at the levels of discharge and charge, respectively. Using the costs assigned, S_c can be calculated for exchange between any two levels: (@ 75% efficiency).

DISCHARGE LEVEL

CHARGE LEVEL	A	B	C	D
A				
B	-.0006			
C	+.0121	+.0055		
D	+.0223	+.0157	+.0062	

Savings per charge/discharge cycle $\frac{(\$)}{(kWh)}$

Note that discharge to a level at or above the charge level was eliminated and, in addition, transfer from level B to level A proved uneconomic. The rapid fall off in value when a level D to level A transfer cannot be made is evident. A level D to B transfer is worth 30% less and a level C to A about 46% less.

The characteristics of system "B" demonstrate the typical manner in which storage value falls off as size is increased:

1. For a small amount of storage (less than 100 MWh for this example) the storage can cycle year round between levels D and A, and thus closely achieve maximum value.
2. As storage size is increased, the spring and fall peaks are eliminated and additional storage energy is forced to transfer to level B.
3. A further increase in size will eliminate the winter peaks, resulting in more level D to level B transfer.
4. At some level of storage size, the capacity for base load charging is depleted and level C must be used (or costs must be incurred to increase base load charging capacity). Level C can discharge to the peaking or "A" level only in the summer and is forced to displace B level energy the remainder of the year which provides a very low storage benefit.

A winter peaking utility system would see a similar pattern. Some utility characteristics may result in depletion of base load charging ability before peaks are eliminated, but the net effect is identical - a steady decrease in storage value per kilowatt-hour as storage size is increased.

This does not say that low storage size is most economic. Net savings, considering the actual cost of storage, will determine optimum economic storage size. Once storage is economic, further cost reductions increase the optimum size of storage in terms of MWh capacity.

3.3.2 PHOTOVOLTAIC ENERGY AVAILABILITY AND CONVERSION

3.3.2.1 Insolation Patterns

Previous studies on solar thermal as well as photovoltaic energy systems have resulted in a much clearer understanding of some of the key factors that must be considered when harnessing this source of energy. Since the annual energy available is almost directly proportional to the annual incident solar radiation (insolation), geographic site selection is of prime importance. Figure 3.3-5 shows the sites selected for analysis spotted on a national map showing annual insolation in langleys. Note that the sites selected roughly span the national range from a low in Boston to a high in Phoenix.

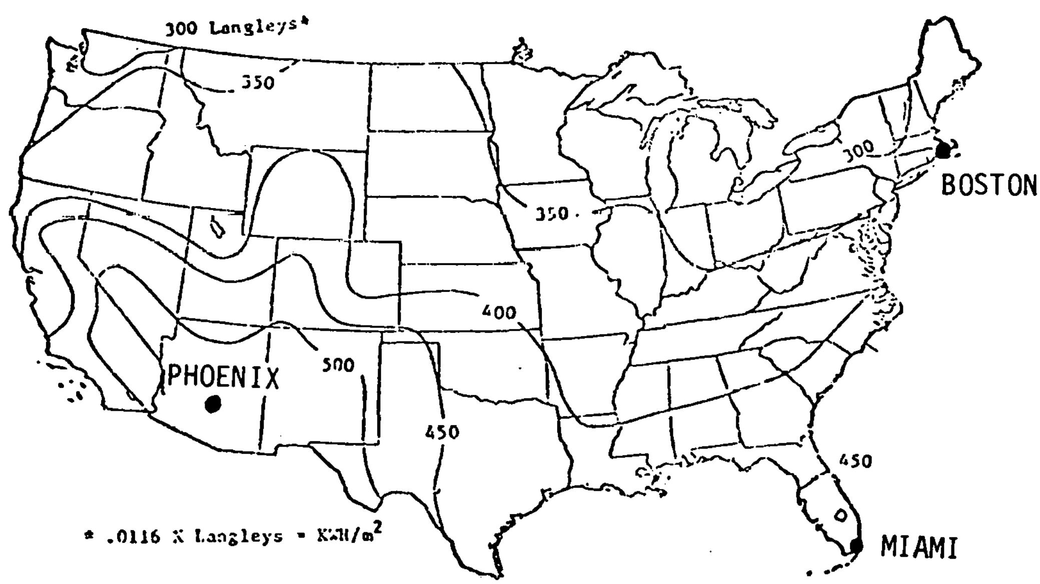


FIGURE 3.3-5. ANNUAL MEAN DAILY TOTAL HORIZONTAL INSOLATION IN LANGLEYS [18]

Diurnal photovoltaic energy patterns are quite predictable as shown in Figure 3.3-6 for a typical sunny day. Intermittent cloud cover would distort the pattern and a totally overcast day would show little or no output. The sites with high annual insolation levels can be characterized by a high percentage of sunny days more than by high insolation levels on the sunny days.

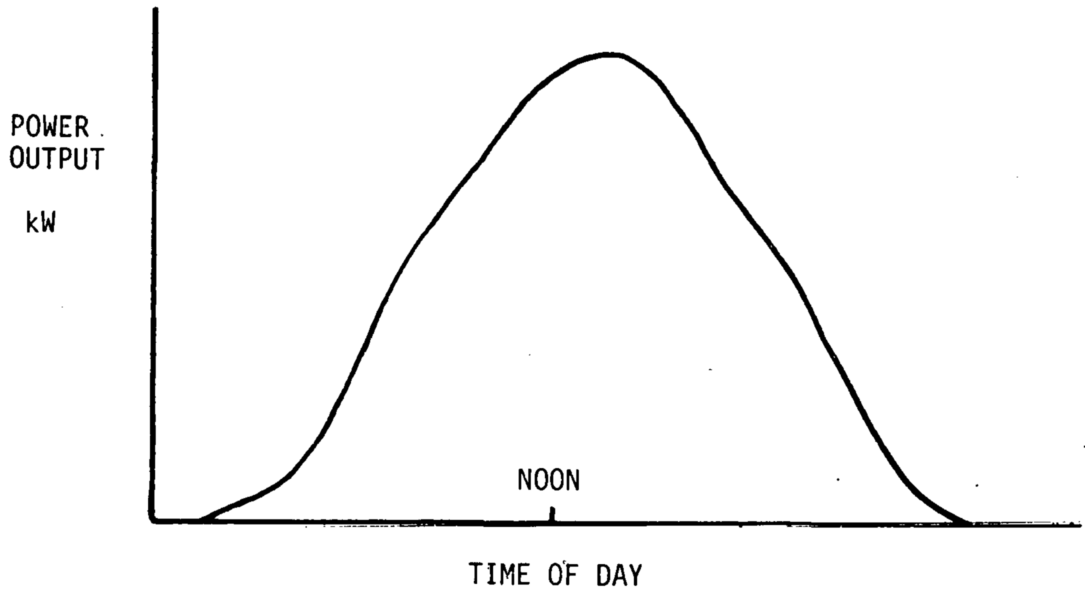
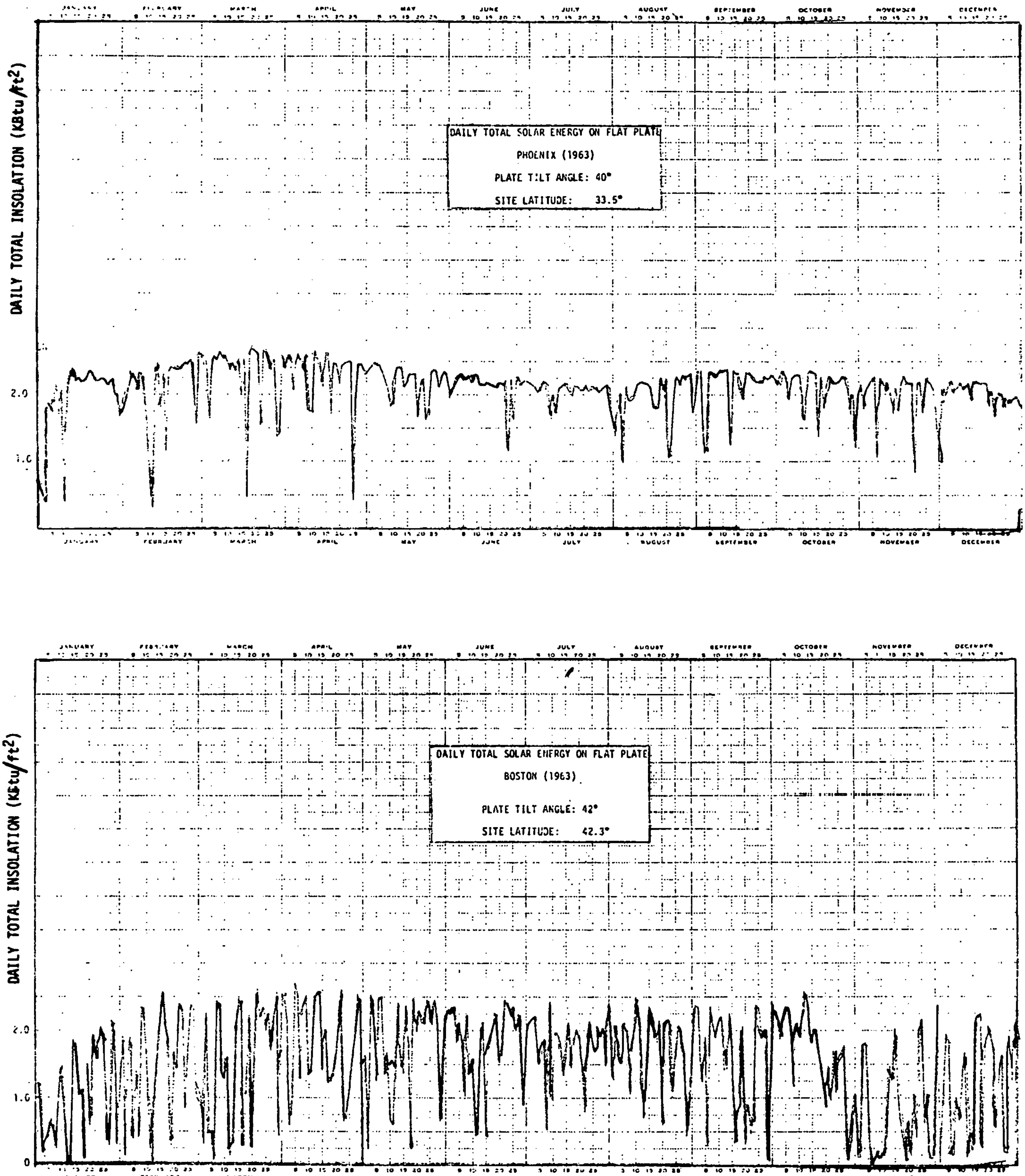


FIGURE 3.3-6. TYPICAL DIURNAL VARIATION OF PHOTOVOLTAIC ENERGY

Typical seasonal variations of insolation can be seen in Figure 3.3-7 which presents a full year's data for Phoenix and Boston.[19] Note the steady solar availability of the former as compared to high variability in Boston, particularly in the winter months of November through January.

An additional solar characteristic not shown here, but one which will be discussed in a subsequent section, is short term variability due to intermittent clouding. This characteristic can result in large increases or decreases in the power available from the photovoltaic array, and necessitates consideration of energy storage device ability to follow PV output variations.



FIGURF 3.3-7. TYPICAL ANNUAL INSOLATION PATTERNS

3.3.2.2 Selection of Data Sites

For purposes of assuming a representative range of conditions under which storage might be attractive, data was selected from three different locations. Each location was to be representative of different climate, terrain, insolation conditions, geographic region and costs of fuel and electricity. Previous General Electric photovoltaic studies resulted in hour-by-hour data tapes containing insolation, temperature, wind and other weather characteristics for several locations. Data for Phoenix, Arizona, Miami, Florida, and Boston, Massachusetts were selected for use in response to the range of representation desired.

3.3.2.3 Photovoltaic System Output

The hourly photovoltaic system output was established by matching the hourly weather data tapes with photovoltaic array performance characteristics. Table 3.3-1 presents the annual array energies for each of the three sites and penetration levels of 10, 20 and 30 percent. Figure 3.3-8 presents the cumulative hourly PV output for the entire year for each of the 24 daily hours. Note the close correlation of profile shape, but the different totals corresponding to annual insolation levels.

TABLE 3.3-1. PHOTOVOLTAIC SYSTEM BASELINE DATA

UTILITY APPLICATION	LOCATION								
	PHOENIX			MIAMI			BOSTON		
	PENETRATION			PENETRATION			PENETRATION		
	10%	20%	30%	10%	20%	30%	10%	20%	30%
Array Area ($10^6 m^2$)	3.28	6.55	9.83	3.28	6.55	9.83	3.28	6.55	9.83
Rated Array Output (MW)	374	747	1121	374	747	1121	374	747	1121
Max. Annual Array Energy (10^6 MWh)	.910	1.82	2.73	.830	1.66	2.49	.646	1.29	1.94
Utility Annual Load (10^6 MWh)	17.84			17.84			17.84		

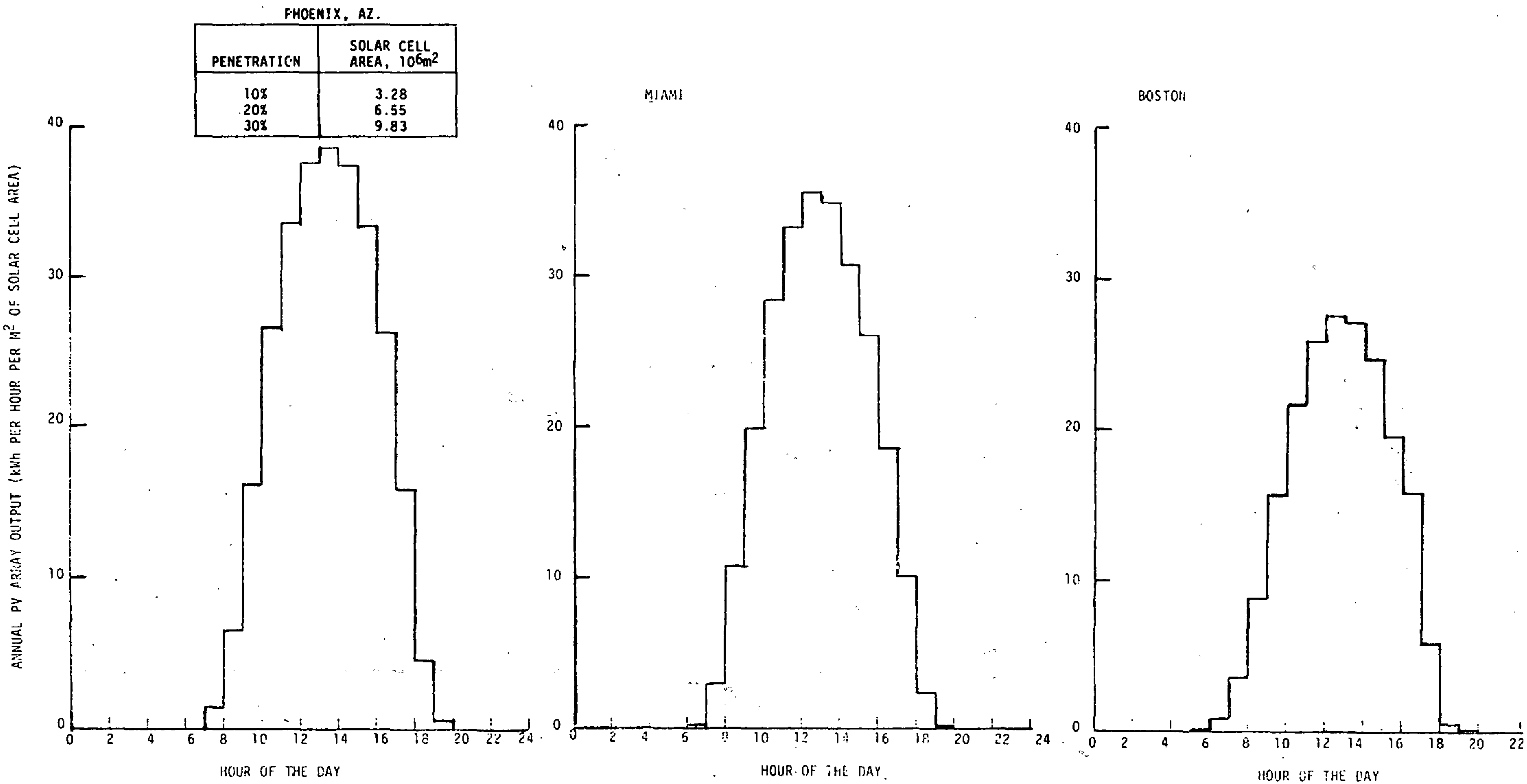


FIGURE 3.3-8. ANNUAL PV ARRAY OUTPUT BY HOUR OF DAY

3.3.3 UTILITY LOAD DEMANDS

3.3.3.1 Load Selection

The objectives of this area of the study were directed toward the effect energy storage might have on the worth of photovoltaic supplied energy in a utility application. Consequently, it was desired to assess the effects of different parameters pertinent to photovoltaic and storage system use while serving a representative load. This representative system load was selected based on results of an exhaustive analysis in a recent study performed by Public Service Electric and Gas Company of Newark, N.J.[17] The system used is designated system "B". Figure 3.3-9 shows the approximate load shape of system "B" for a representative one week period, with summer load peaks superimposed.

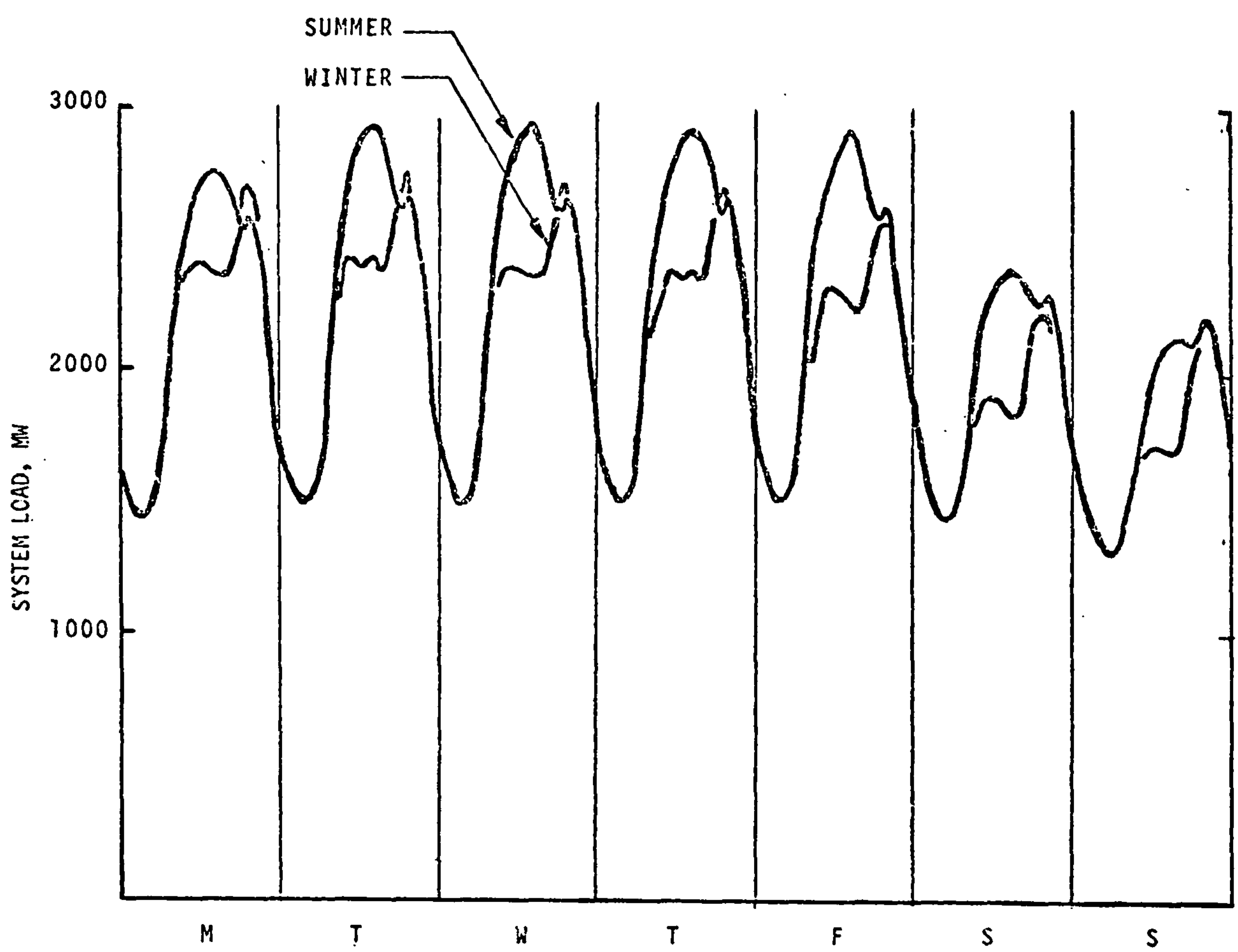


FIGURE 3.3-9. REPRESENTATIVE WEEK - SYSTEM "B" LOAD DEMAND

Originally, it was planned to examine only one or perhaps several "representative weeks". It became obvious, however, that such an approach might leave many unanswered questions; therefore, with the help of a computer model, a full year or 8760 hours was examined with a minimum of difficulty.

3.3.3.2 Load Duration Curves

Seasonal load duration curves were plotted and examined in order to establish operating cost strata for use in further modeling. Figure 3.3-10 shows the summer load duration curves for system "B".

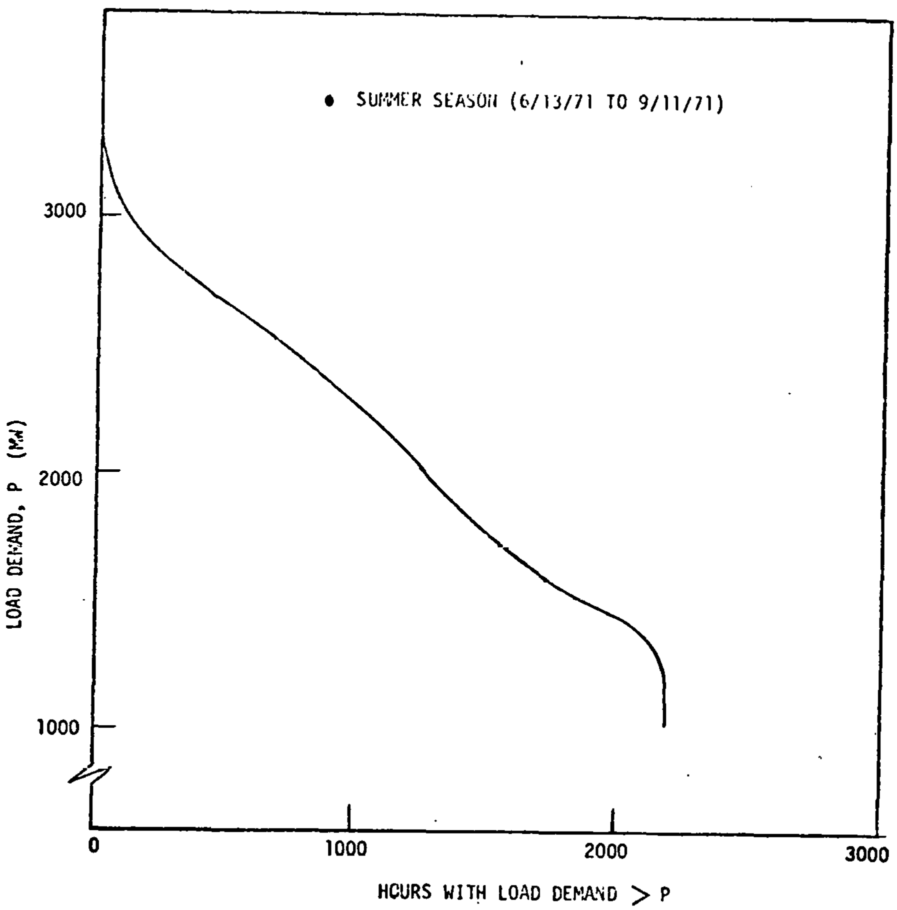


FIGURE 3.3-10. SUMMER SEASON LOAD DURATION CURVE FOR SYSTEM "B"

3.3.3.3 Generation Mix

Due to the generalized results desired for the storage worth analysis, it was decided that mix of generation be considered only to the extent necessary to establish modeling assumptions. Table 3.3-2 and 3.3-3 give the assumed generation mix and energy allocation for use with the loads typified by system "B". Note that this mix is not intended to reflect any specific current system mix, but rather a possible mix which could deliver energy to meet the generation load shape of the representative system.

TABLE 3.3-2. ASSUMED GENERATION MIX FOR SYSTEM "B" TYPE LOAD PROFILE

TYPE OF GENERATION	WINTER Cut-In Load Level MW	WINTER In Service Capability MW	SPRING Cut-In Load Level MW	SPRING In Service Capability MW	SUMMER Cut-In Load Level MW	SUMMER In Service Capability MW	FALL Cut-In Load Level MW	FALL In Service Capability MW
Gas Turbines	2500	480	2350	266	2850	458	2650	780
Oil - Steam	2300	200	2200	150	2500	350	2300	350
Coal - Steam	1900	400	1900	300	1900	600	1900	400
Nuclear - Steam	700	1200	700	1200	700	1200	700	1200
Minimum Out-Put Level	0	700	0	700	0	700	0	700

TABLE 3.3-3. ENERGY ALLOCATION FOR ASSUMED GENERATION MIX SYSTEM "B" LOAD SHAPE

TYPE OF GENERATION	ENERGY SUPPLIED - MEGAWATT HOURS WINTER	SPRING	SUMMER	FALL	ANNUAL TOTAL
Gas Turbines	36,882	19,311	41,203	45,111	142,507
Oil-Steam	92,909	89,394	170,952	170,225	523,480
Coal-Steam	407,180	285,357	642,875	432,083	1,767,495
Nuclear-Steam	2,330,383	2,230,057	2,362,689	2,351,142	9,274,271
Minimum Out-Put Level	1,545,600	1,528,800	1,528,800	1,528,800	6,132,000
TOTALS	4,412,954	4,152,919	4,746,519	4,527,361	17,839,753

3.3.4 GENERATION AND LOAD MATCHING

3.3.4.1 Analytical Computer Model

The large number of computations involved required the use of a functional computer model as diagrammed in Figure 3.3-11.

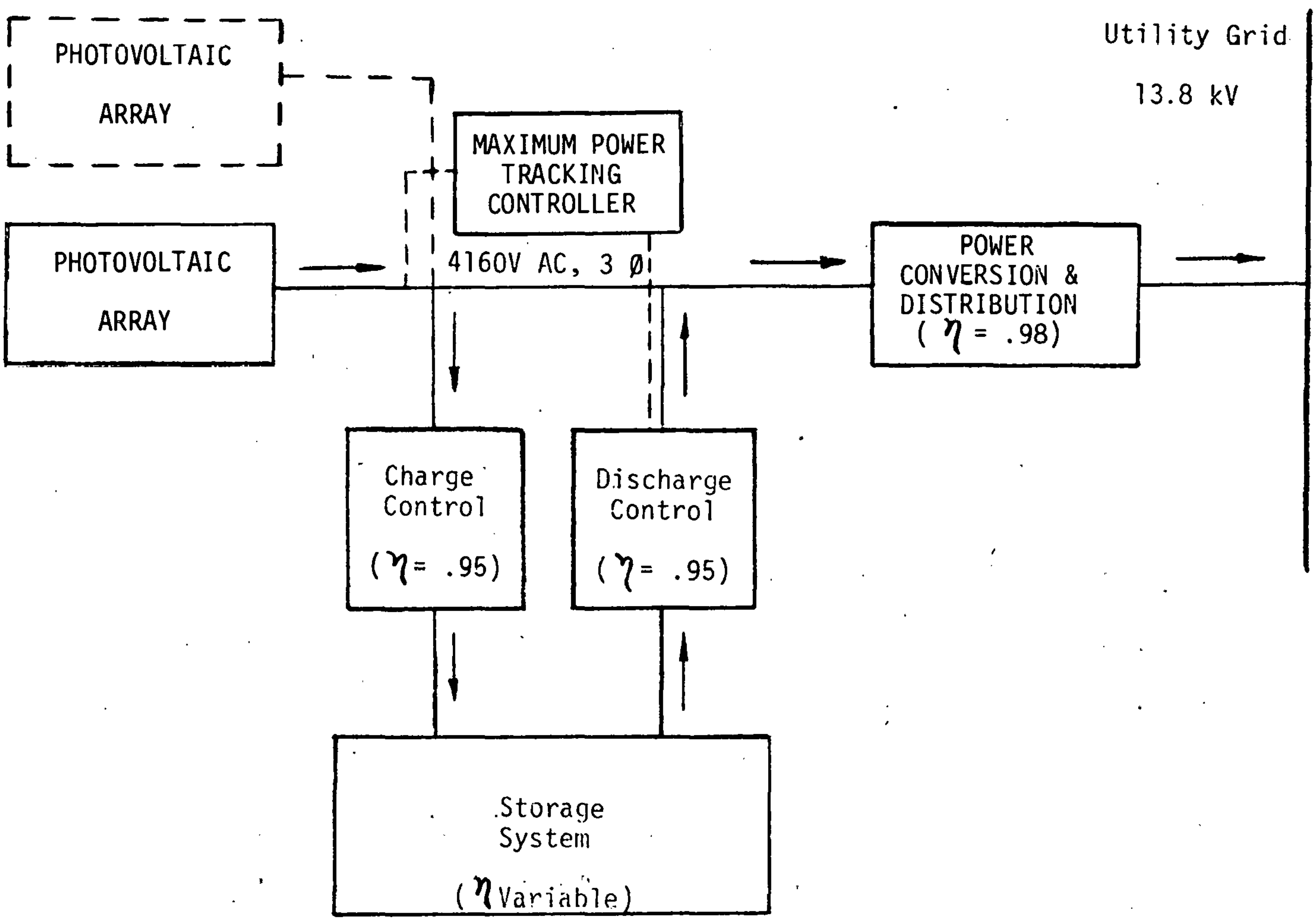


FIGURE 3.3-11. COMPUTER MODEL - PHOTOVOLTAIC ENERGY CONVERSION - UTILITY APPLICATION

Photovoltaic array area was adjusted to simulate penetrations of 10, 20 and 30% of the utility installed generation capacity (4000 MW nominal). The arrows in the diagram represent the allowable directions for energy flow. For this dedicated storage configuration, energy flow from the utility grid for use in charging the storage system was not permitted. The charge and discharge power handling devices were each assigned a 95% efficiency as noted in the figure. These devices were also considered to be power limited, and this limit was considered as an input parameter in the evaluation of system performance.

A storage system overall energy efficiency was assigned for each data run and treated as an independent variable in the investigation of system performance. An additional in-line efficiency of 98% was included to account for voltage transformation and distribution losses between the non-conventional energy sources under investigation and the point of measurement of the utility system load demand. This latter loss did not disturb the overall evaluation of the benefits of storage since the same loss allowance was included in both the storage evaluation runs and in the no-storage base case.

3.3.4.2 Generation and Load Matching Without Storage

To establish a reference baseline for each set of storage run conditions, the photovoltaic system output was matched directly to the load demand on an hour by hour basis for an entire year of use (8760 hours). This course was chosen as a means of reducing the potential bias that could result from selection of some shorter span of time which might in actuality be less than "representative". (It is, of course, recognized that different annual insolation data or longer terms than one year might be even more desirable than the time period chosen). During the zero storage run, no PV energy was allowed to pass through the storage system. The conventional energy displacement, resulting from use of the PV energy to serve a portion of the load, was tabulated for each hour and summed to monthly and annual totals for subsequent analysis. Basically, any energy which the photovoltaic system delivers to meet load demands goes on line regardless of the time of day, and it is assumed that any required adjustment of total utility system output will be accomplished without cutting off the photovoltaic array.

3.3.4.3 Generation and Load Marching Incorporating Storage

For purposes of computing the energy displacement effects of adding storage, all the blocks in Figure 3.3-11 become operative. Increasing amounts of storage system capacity (MWh) were assigned to the storage block as successive data computations were taken. A storage efficiency of 75% was assumed for the majority of the cases, with alternative cases taken at 60 and 90% efficiency to determine the efficiency effect on output results. The utility system load is met by a combination of directly supplied PV energy, energy delivered from storage and a net make-up furnished by the conventional generation plant. The computer logic required to carry out the incorporation of storage is described in the following section.

3.3.4.4 Storage Charging and Dispatch Logic

The energy management of the charge-discharge cycle employs an operating strategy based on the following groundrules:

1. Charging of storage will only occur when source output would otherwise displace the lowest value energy category (designated in the model as category D).

2. Storage dispatch will be permitted only to displace load quality of category C or higher.

3. No storage discharge will occur on weekends or holidays.

4. The storage system state-of-charge (SOC) is managed on a weekly basis to provide a near-optimum displacement of the highest quality energy. To this end the program logic determines, on a daily basis, that value of system load which is required to drive the SOC to an allowable value for each day. This value of minimum allowable SOC is a function of the day-of-the-week according to the following algorithm.

$$SOC_A = \frac{(5-I)\ SOC_M + SOC_L}{6-I}$$

where

SOC_A = Allowable minimum SOC for the day

I = day-of-the-week number (Monday = 1)

SOC_L = low limit on storage system SOC

SOC_M = SOC at midnight of the preceding day

These constraints were arrived at after trial runs in which daily vs. weekly cycles were tested as were the results of raising the charge-discharge cut-off point higher on the load duration curve. The analysis assumes ability to fully predict and manage hourly source output and load demand on a daily basis to drive the storage system SOC to the pre-determined minimum allowable value for each day.

3.3.4.5 Computational Format and Typical Load Matching Results

Table 3.3-4 lists a typical computer data output format for a storage analysis run.

TABLE 3.3-4. SAMPLE COMPUTER OUTPUT FOR PV SYSTEM STORAGE - UTILITY APPLICATION

2000 MWh STORAGE CAPACITY
PHOENIX, AZ

MON	DAY	HR	GROSS SYSTEM B LOAD DEMAND (MW)	TOTAL SA OUTPUT (MW)	NET SYSTEM B LOAD DEMAND (MW)	TOTAL LOSSES (MW)	STORAGE SOC	STATUS CHARGE/ DISCHARGE POWER (MW)	DISPLACED GENERATION A (MW)	B (MW)	C (MW)	D (MW)	E (MW)
8	1	0	1647.	0.	1647.00	0.	0.100	0.	0.	0.	0.	0.	0.
8	1	1	1536.	0.	1536.00	0.	0.100	0.	0.	0.	0.	0.	0.
8	1	2	1468.	0.	1468.00	0.	0.100	0.	0.	0.	C.	C.	0.
8	1	3	1431.	0.	1431.00	0.	0.100	0.	0.	0.	0.	C.	0.
8	1	4	1331.	0.	1381.00	0.	0.100	0.	0.	0.	0.	0.	0.
8	1	5	1364.	0.	1364.00	0.	0.100	0.	0.	0.	C.	0.	0.
8	1	6	1421.	0.	1421.00	0.	0.100	0.	0.	0.	0.	0.	0.
8	1	7	1577.	27.11	1577.00	1.36	0.110	25.76	0.	0.	C.	0.	0.
8	1	8	1772.	94.00	1772.00	4.70	0.143	89.30	0.	0.	0.	0.	0.
8	1	9	1955.	176.42	1900.00	7.14	0.186	114.29	0.	0.	55.00	0.	0.
8	1	10	2140.	281.95	1900.00	6.75	0.199	35.20	0.	0.	240.00	0.	0.
8	1	11	2261.	318.54	1948.83	6.37	0.199	0.	0.	0.	312.17	0.	0.
8	1	12	2327.	336.94	1976.80	6.74	0.199	0.	0.	0.	330.20	0.	0.
8	1	13	2363.	359.38	2010.81	7.19	0.199	0.	0.	0.	352.19	0.	0.
8	1	14	2371.	336.79	2040.94	6.74	0.199	0.	0.	0.	330.06	0.	0.
8	1	15	2373.	293.24	2085.62	5.86	0.199	0.	0.	0.	287.38	0.	0.
8	1	16	2357.	235.29	2126.42	4.71	0.199	0.	0.	0.	230.58	0.	0.
8	1	17	2340.	171.87	2171.56	3.44	0.199	0.	0.	0.	168.44	0.	0.
8	1	18	2380.	76.65	2304.88	1.53	0.199	0.	0.	0.	75.12	0.	0.
8	1	19	2463.	27.09	2436.46	0.54	0.199	0.	0.	0.	26.54	0.	0.
8	1	20	2405.	0.	2405.00	0.	0.199	0.	C.	0.	0.	0.	0.
8	1	21	2203.	0.	2203.00	0.	0.199	0.	0.	0.	0.	0.	0.
8	1	22	1930.	0.	1980.00	0.	0.199	0.	0.	0.	0.	0.	0.
8	1	23	1776.	0.	1776.00	0.	0.199	0.	C.	0.	0.	0.	0.
8	2	0	1648.	0.	1648.00	0.	0.199	0.	C.	0.	0.	0.	0.
8	2	1	1572.	0.	1572.00	0.	0.199	0.	0.	0.	0.	0.	0.
8	2	2	1534.	0.	1534.00	0.	0.199	0.	0.	0.	0.	0.	0.
8	2	3	1548.	0.	1548.00	0.	0.199	0.	0.	0.	0.	0.	0.
8	2	4	1600.	0.	1600.00	0.	0.199	0.	0.	0.	0.	0.	0.
8	2	5	1775.	0.	1775.00	0.	0.199	0.	C.	0.	0.	0.	0.
8	2	6	2115.	0.	2115.00	0.	0.199	0.	0.	0.	0.	0.	0.
8	2	7	2470.	21.80	2448.63	0.44	0.199	0.	0.	0.	21.37	0.	0.
8	2	8	2771.	98.60	2674.37	1.97	0.199	0.	C.	96.63	0.	0.	0.
8	2	9	2962.	182.98	2782.68	3.66	0.199	0.	112.00	67.32	0.	0.	0.
8	2	10	3046.	258.05	2795.11	5.16	0.199	0.	198.00	54.89	0.	0.	0.
8	2	11	3140.	311.33	2834.90	6.23	0.199	0.	290.00	15.10	0.	0.	0.
8	2	12	3204.	324.60	2885.89	6.49	0.199	0.	318.11	0.	0.	0.	0.
8	2	13	3221.	323.69	2903.78	6.47	0.199	0.	317.22	0.	0.	0.	0.
8	2	14	3202.	329.79	2878.81	6.60	0.199	0.	323.19	0.	0.	0.	0.
8	2	15	3139.	305.56	2839.55	6.11	0.199	0.	289.00	10.45	0.	0.	0.
8	2	16	3059.	248.77	2815.20	4.98	0.199	0.	209.00	34.80	0.	0.	0.
8	2	17	2959.	173.67	2788.80	3.47	0.199	0.	109.00	61.20	0.	0.	0.
8	2	18	2923.	78.22	2846.35	1.56	0.199	0.	73.00	3.65	0.	0.	0.
8	2	19	2977.	26.81	2913.00	3.33	0.179	-40.53	64.00	0.	0.	0.	0.
8	2	20	2879.	0.	2879.00	0.	0.179	0.	0.	0.	0.	0.	0.
8	2	21	2585.	0.	2585.00	0.	0.179	0.	0.	0.	0.	0.	0.
8	2	22	2260.	0.	2260.00	0.	0.179	0.	0.	0.	C.	0.	0.
8	2	23	1993.	0.	1993.00	0.	0.179	0.	0.	0.	0.	0.	0.
8	3	0	1821.	0.	1821.00	0.	0.179	0.	0.	0.	0.	0.	0.
8	3	1	1715.	0.	1715.00	0.	0.179	0.	0.	0.	0.	0.	0.
8	3	2	1619.	0.	1619.00	0.	0.179	0.	0.	0.	0.	0.	0.
8	3	3	1601.	0.	1601.00	0.	0.179	0.	0.	0.	0.	0.	0.

A typical profile resulting from the dispatch technique selected is shown in Figure 3.3-12. As shown by the state-of-charge curve, storage is dispatched to meet the early evening peak load. Direct contributions from the PV output are taken as available during the heavier load periods and can be seen segregated at the bottom of the plot.

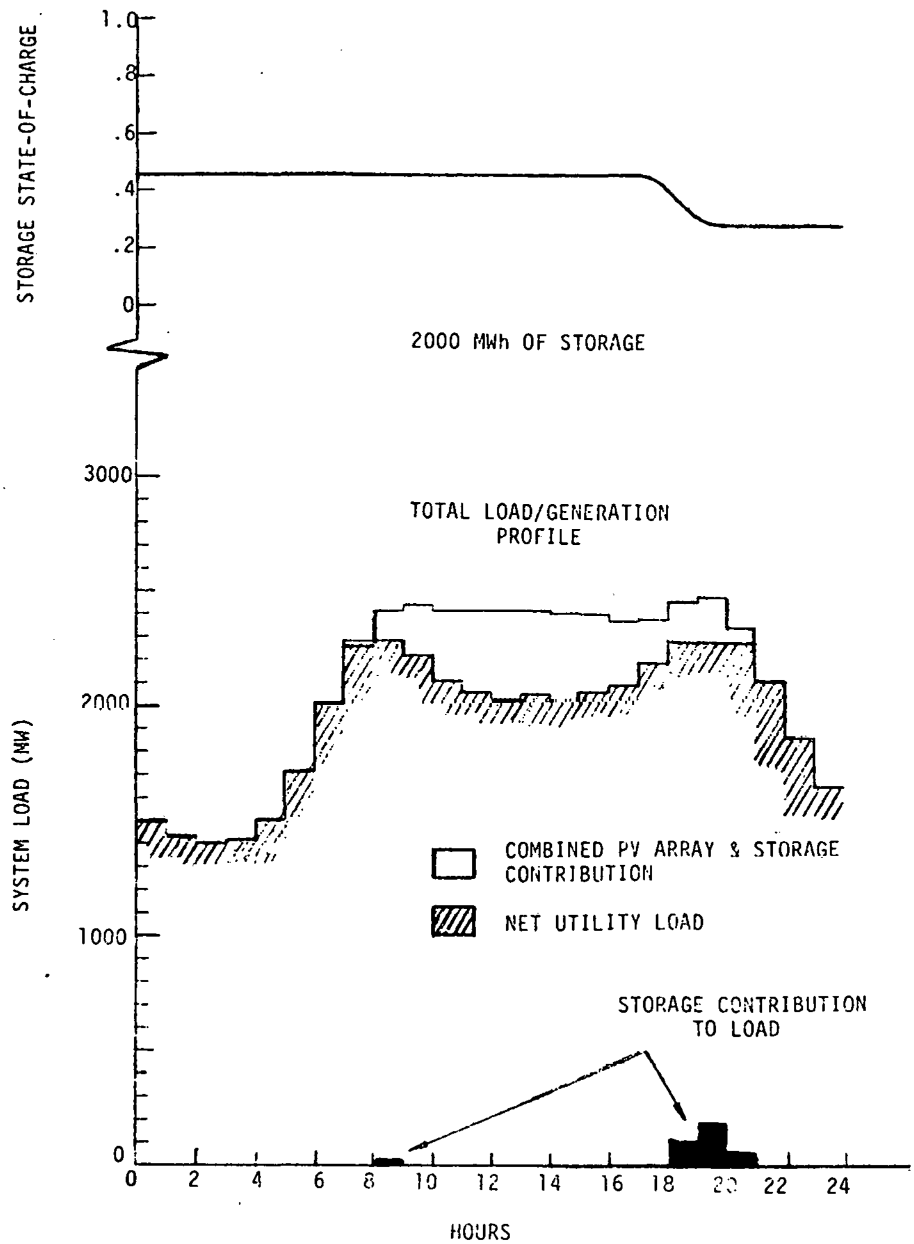


FIGURE 3.3-12. TYPICAL DAILY PROFILE OF LOAD AND GENERATION MATCHING RESULTS

Figure 3.3-13 shows similar data taken over a representative week. The dashed lines in Figure 3.3-13 divide the various cost-of-energy-generation regions. Comparison with the state-of-charge curve above the load/generation profile reveals the storage response to peak load demands as "dips". At week's end, the last (and lowest) dip reaches the 0.1 low limit on state-of-charge as a result of the storage dispatch strategy. It then rises as a result of weekend recharging.

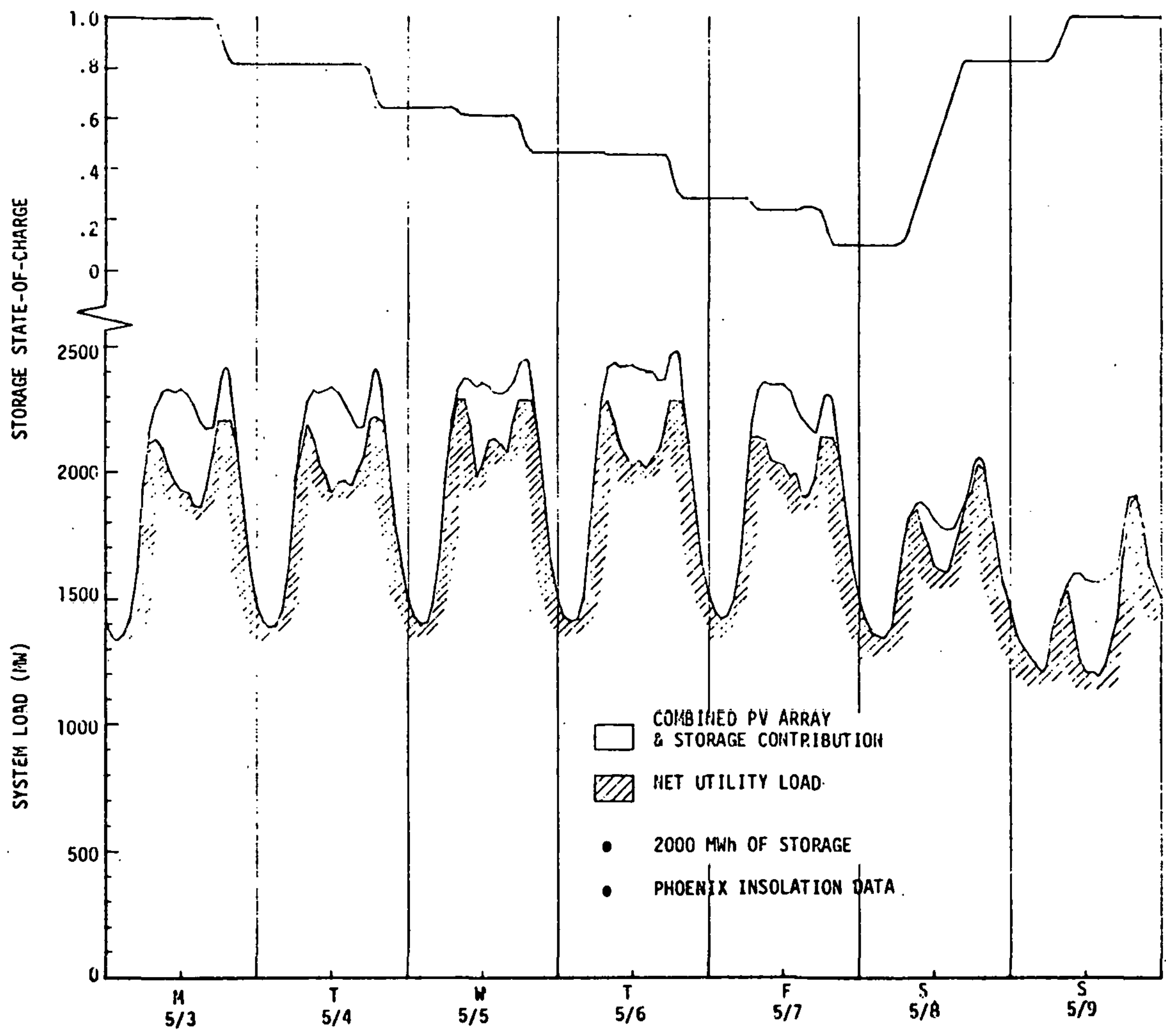


FIGURE 3.3-13. TYPICAL WEEKLY PROFILE OF LOAD AND GENERATION MATCHING RESULTS

As can be seen in Figure 3.3-13, the storage operating groundrules chosen assure a fairly equal distribution over the week of the displacement of the highest quality energy. This operating strategy does not account for the unequal distribution of the source generation over the entire week. This influence is revealed by the varying total system displacements on successive days in the above figure as the PV energy output changed. If the storage system dispatch could be managed to account for such weekly variation in source capability, it might be possible to slightly improve the value of the displaced energy. An investigation of the feasibility of such operation was beyond the scope of this study, but the results obtained suggest that operating logic options would be a useful area for additional investigation.

The month by month results of modeling the photovoltaic and storage contributions are shown for a representative case in Figure 3.3-14. The plot on the right hand side of the figure shows the change in delivered energy by cost of generation region which results from the addition of 2000 MWh of storage to the photovoltaic-only results shown to the left.

While the total photovoltaic system output is the same in both cases, the right hand plot contains a lower amount of total energy due to losses in charging and utilizing storage. A careful inspection, however, will reveal that categories A, B, and C increase in area with addition of storage while category D decreases. This reflects the upgrading of the value of energy which the PV system alone would have to deliver at the lower value.

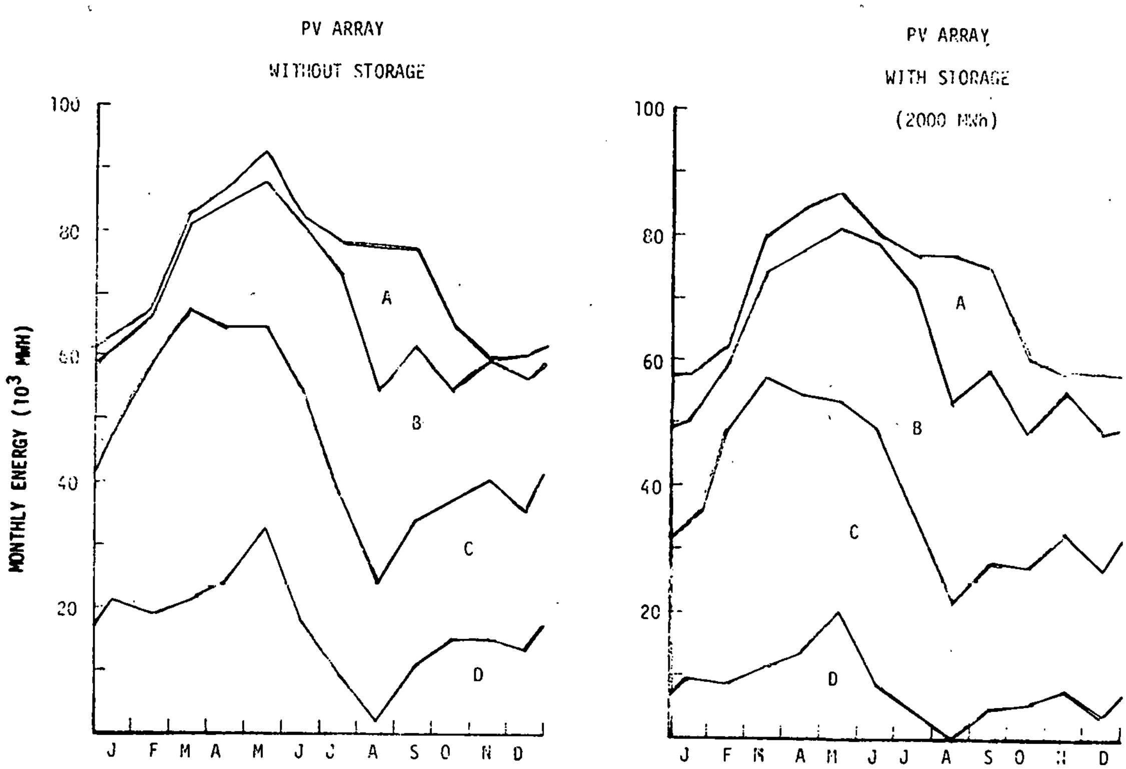


FIGURE 3.3-14. DELIVERED ENERGY PERFORMANCE WITH AND WITHOUT ENERGY STORAGE (PHOENIX, AZ, PV DATA)

3.3.5 BREAK-EVEN COST METHODOLOGY

The numerics required to carry out the analysis of the utility cost goal evaluation are developed and the results presented in this section based on the methods, operating strategy, and other assumptions previously described.

3.3.5.1 Determination of Energy Storage Break-Even Costs

The process of determining a bottom-line energy storage break-even cost involves not only the analysis of the energy dispatch reflected in Figure 3.3-2 as it applies to cost of generation savings (fuel) but also other applicable savings. The latter include credits for displaced generating units and/or spinning reserve units which might be shut down. Savings in transmission and distribution (T&D) equipment is a further potential benefit of certain storage technologies.

Break-even cost determination employed the following basic steps:

1. Selection of: PV conversion system, Load Profile, PV penetration and Storage capacity.
2. Determination of system annual performance:
   a. Without storage
   b. With energy storage
3. Determination of representative values of fuel-related energy cost ($/kWh) for the various levels of power generation.
4. Computation of annual energy benefit due to addition of storage.
5. Determination of capitalized value of annual energy benefits.
6. Estimate of storage O&M costs (capitalized and deducted from capitalized energy benefits).
7. Adjustment of net credit above to account for interest during construction.
8. Estimate of net capacity credit and other applicable credits, which add to adjusted net credit above to yield storage break-even cost.
9. Comparison of storage system break-even cost with actual or estimated storage system costs.

3.3.5.2 Cost Regions

It was necessary to assign cost-of-generation values for the various portions of the system load based on fuel cost differences. These occur because utilities typically use a combination of different types of generating units to meet various segments of the system load. Utility data available for the Washington, D.C. area and for Phoenix, Arizona, and

Miami, Florida, were examined and used as the basis for establishing these cost-of-generation dollar values. Table 3.3-5 provides this data in summary form. The variation across this geographic spread was very small and therefore an average value was taken for fuel cost for each type of generation. Multiplied by a representative heat rate for each type of generation, a dollars-per-megawatt hour cost of generation figure results as shown.

TABLE 3.3-5. REPRESENTATIVE COSTS OF GENERATION*

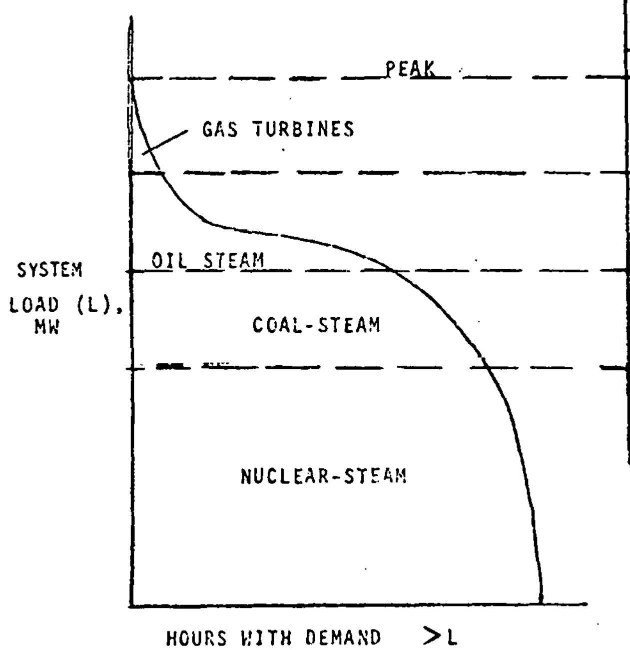
GENERATION TYPE	FUEL COST $/MBTU**				HEAT RATE MBTU/MWh	FUEL COST OF GENERATION $/MWh**
	W	P	M	AVG		
Gas Turbine	2.26	2.36	2.41	2.34	12	28.10
Oil-Steam	2.00	2.20	2.00	2.07	10.4	21.50
Coal-Steam	1.31	.79	1.36	1.15	10.4	12.00
Nuclear-Steam	.42	.42	.42	.42	10.4	4.35

* Based on Utility Data for Washington, D.C., Phoenix, and Miami

** 1976 Dollars

Figure 3.3-15 relates these costs of generation to the areas under the "Representative System B" load curve where they might typically apply. The separation levels shown were selected to provide about 1000 hours of annual peaking duty and a base load set just slightly above the normal "valleys" of the annual load curve. The intermediate levels were likewise set to reflect typical capacity factors for the applicable types of generation equipment.

In a specific system case study, utility operating data and experience would be used directly. As indicated by the column heading of Figure 3.3-15 the cost-of-generation figures can also be considered as the "worth" per MWh of any energy provided subsequently by PV and/or storage. Levels were set for each season since the differences are significant in strata A and B. No further consideration of generation mix details is involved beyond this point in the analysis.



COST STRATA	SEPARATION LEVELS, MW				WORTH OF GENERATION $/MWh
	WINTER	SPRING	SUMMER	FALL	
	2980	2616	3308	3430	
A					28.10
	2500	2350	2850	2650	
B					21.50
	2300	2200	2500	2300	
C					12.00
	1900	1900	1900	1900	
D					4.35

FIGURE 3.3-15. COST-OF-GENERATION STRATA VS. ANNUAL UTILITY SYSTEM LOAD

3.3.5.3 Energy Credit

The fuel saving or "energy credit" achieved, based on use of 2000 MWh of storage with a discharge limit of 10 hours at 75% storage device efficiency, a 10% penetration of photovoltaic generation and representative System "B" annual load is further reviewed in this section as an example case.

Table 3.3-6 shows a comparison of the annual benefit of PV energy without storage and with 2000 MWh of storage added.

TABLE 3.3-6. ANNUAL ENERGY BENEFIT (CREDIT) OF STORAGE (2000 MWh) (PV CHARGING) (PHOENIX, AZ)

GENERATION STRATA OR "WORTH CATEGORY"	ENERGY WORTH $/MWh	WITHOUT STORAGE		WITH STORAGE	
		ANNUAL ENERGY DISPLACED 10^3 MWh	ANNUAL WORTH 10^6 $	ANNUAL ENERGY DISPLACED 10^3 MWh	ANNUAL WORTH 10^6 $
A	28.10	73	2.051	102	2.867
B	21.50	255	5.492	287	6.171
C	12.00	364	4.368	374	4.488
D	4.35	201	.874	97	.422
TOTALS	- - -	893	12.785	860	13.948

The value of the increase resulting from use of storage is found as shown below:

Annual Energy Benefit of Storage = $(13.948 - 12.785) \times 10^6$ =

$1.163 million

= $1,163,000/2,000,000 kWh of storage capacity

= $.5815/kWh of storage capacity.

Figure 3.3-16 shows the monthly value of PV dedicated charging with 2000 MWh of storage.

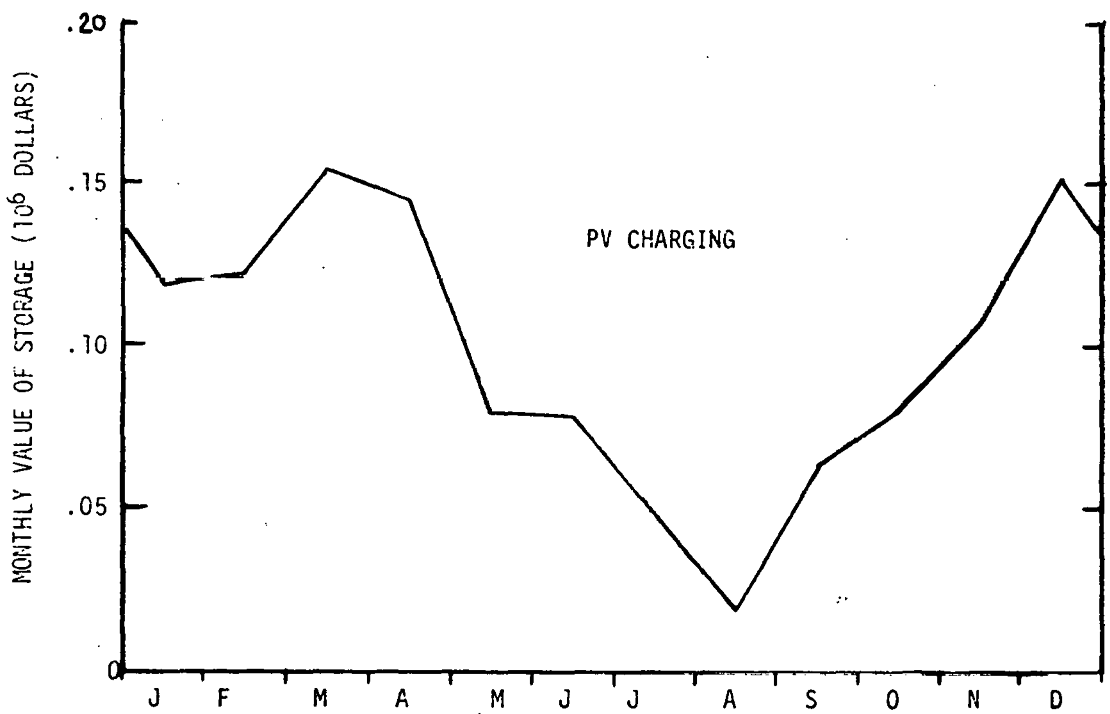


FIGURE 3.3-16. MONTHLY VALUE OF STORAGE WITH PV CHARGING

The energy displacement effect of adding storage at capacity levels other than 2000 MWh was also investigated. Figures 3.3-17 and 3.3-18 show the annual fuel savings benefit results of these investigations.

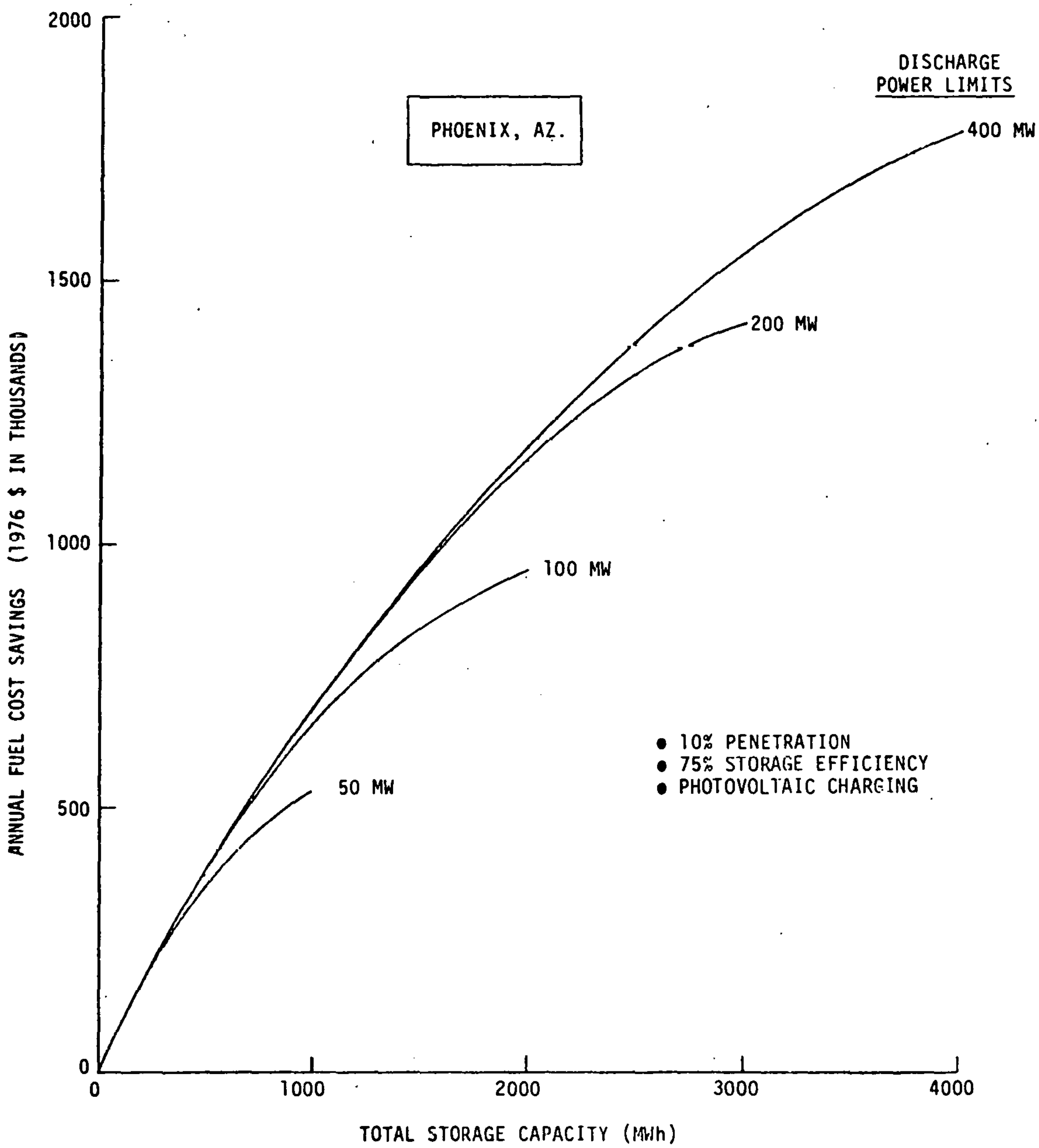


FIGURE 3.3-17. ANNUAL FUEL COST SAVINGS WITH STORAGE FOR PHOENIX, AZ

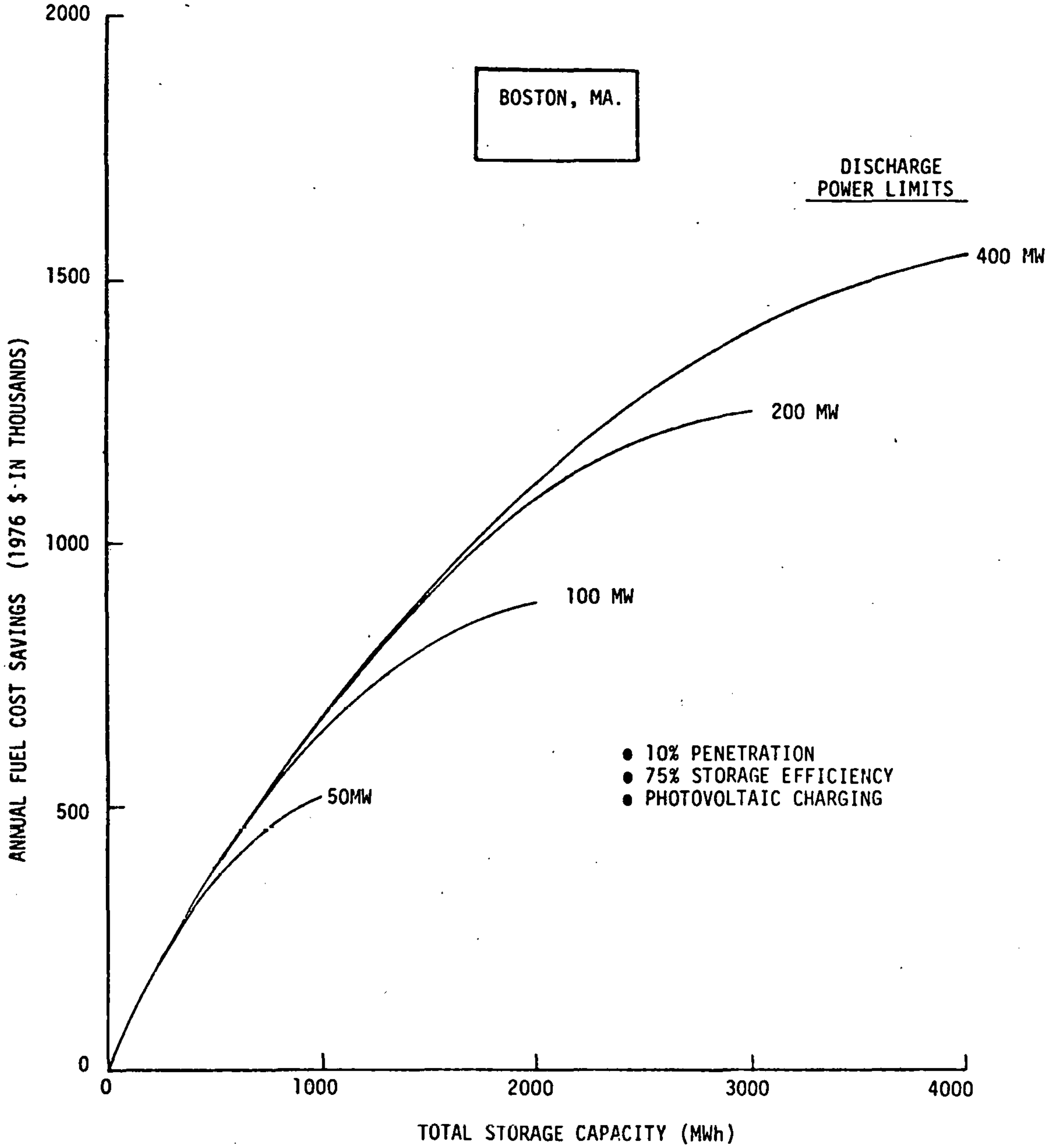


FIGURE 3.3-18. ANNUAL FUEL COST SAVINGS WITH STORAGE FOR BOSTON, MA.

3.3.5.4 Capacity Credit

Energy storage, within a utility generation mix, will actually reduce re-requirements for conventional generating capacity and thus derive capacity credit. It was desired that an approximate and relatively simple method be employed for estimating capacity credit of storage systems. For this purpose, use is made of Garver's equation[1] which defines effective capacity for a new unit as follows:

$$C^* = C - m \ln (1.0 - R + R_e^{c/m})$$

where

C^* = effective load carrying capability

C = rated power capacity

R = Units forced outage rate (risk)

m = Characteristic slope of the generating system.

The slope m is a measure of the system LOLP sensitivity to changes in its peak load demand. It is the load change that will change LOLP by 2.718 times or the value of "e", the base of the natural logarithmic system. Values of "m" for typical utilities fall in the range of 500 to 700 MW.

A value for R was determined by comparing the energy displacement results of baseload charging of storage vs. PV charging of storage. The method is as follows:

1. Storage charged with off-peak utility power each day is assumed to have an availability factor of one.

2. With PV energy charging of storage, the long-term (annual) energy displacement was found to be about one-third as great as in Step 1. The ratios of the energy for these two conditions (for the same amount of storage capacity) are then taken as a measure of the degree to which a dedicated PV-charged storage system could fulfill a capacity replacement commitment.

Putting this in risk terms:

$$R \equiv \text{Forced Outage Rate} \cong 1 = \frac{E_{DPV}}{E_{DU}}$$

where E_{DPV} is the annual energy displaced by PV storage charging and E_{DU} is the annual energy displaced by comparable utility off-peak storage charging. Table 3.3-7 shows computed values of R for various storage capacities and discharge rates.

TABLE 3.3-7. RISK FACTOR FOR VARIOUS ENERGY STORAGE DISPLACEMENTS*

HOURLY DISCHARGE RATE LIMIT (HRS)	STORAGE CAPACITY (MWh)	E_{DW} (MWh)	E_{DU} (MWh)	R
10	250	10,195	51,350	.801
	500	19,760	101,053	.804
	1000	38,057	194,897	.805
	2000	70,780	361,459	.804
5	250	10,923	74,676	.854
	500	20,891	146,985	.858
	1000	89,397	284,057	.861
	2000	72,178	504,604	.857

* PV charging data for Phoenix, AZ, 10% PV system penetration, 75% efficiency.

The value of C* based on the algebraic relationships of Garver's equation may be determined as shown below, using a value of 500 for "m". This value was selected based on examination of typical numbers from utility studies[20]. For a storage capacity of 2000 MWh and a discharge rate limit of 10 hours, the power rated capacity is:

$$C = 200 \text{ MW}$$

From Table 3.3-7, the risk factor is:

$$R = .804$$

and the effective capacity C* (using Garver's equation) is

$$C^* = 33.4 \text{ MW}$$

The effective load carrying capacity, C*, thus determined is used as a means of establishing a consistent value for a capacity credit that might fairly reflect the ability of dedicated storage to meet load demands. A dollar value for this credit is determined by multiplying the value of C* by an amount,

$\overline{C}$ reflecting the cost of the conventional generation equipment most likely to be displaced. Based on a representative value of \$140/kW for gas turbine peaking units (See Table 3.3-8), a resultant capacity credit for the example shown would be:

$$CC = C^* \cdot \overline{C} = 33.4 \times 10^3 \cdot 140 = \$4.67 \times 10^6 \text{ or } \$23/kW.$$

It should be noted that even though energy displacement from storage occurs in several regions, the most likely capacity displacement is the peaking generation units. Very large scale storage systems could be expected to also displace some higher valued intermediate load capacity, but the value would be partially offset by the increased interest during construction of the large systems. Thus the 140\$/kW was used as a realistic yet conservative capacity credit.

TABLE 3.3-8 REPRESENTATIVE GENERATING EQUIPMENT COSTS

LOCATION	GAS TURBINE PEAKING UNIT CAPITAL COST[15] (\$/kW)
Miami	150
Wash., D.C.	130
Phoenix	130
Average	140

3.3.5.5 Other Cost Factors

Operation and Maintenance Costs

O&M costs may be either fixed or variable in nature and both elements may be present, depending on the type of storage and the form of operation and maintenance needs. Fixed O&M costs are essentially incurred by virtue of ownership of an in-place system regardless of the amount of use. The total amount of such fixed costs relate to the storage system power rating or may be converted from $/kW/Yr to $/kWh/Yr if a storage discharge rate is specified. The variable portion of O&M costs are a function of the amount of use of a storage system and may be presented in terms of dollars per kilowatt hour of discharge energy. In computing storage system benefits, the latter must be reduced by the amount of the O&M costs as will be shown in break-even computations in the next section.

Other Generation, Transmission and Distribution Credits

Transmission and distribution credits for an energy storage system may be appropriate in certain cases. These credits result from system re-arrangements or alternative planning which allows strategic placement of storage units so as to reduce or eliminate the need for larger tie lines, substations or other high capital cost items. Evaluation of credits for such cost reductions is dependent on specific information for cases of interest. Only those storage systems which have a relatively small physical size and the flexibility of module/generating system interconnection to make distrbuted siting practical should receive such credits. Battery systems appear to offer the most possibility for distributed siting. It is conceivable but less clear that inertial storage systems might also qualify. The amount of such credits as discussed by others[17,21] who have considered this factor ranges from $0 - $75 kW or more. In computing the final adjusted break-even costs for battery systems, a nominal allowance ($45/kW) has been added for transmission and distribution credits to indicate the effect that this benefit could have on viability.

An energy storage system could also add value due to shutdown of spinning reserve units as a fuel saving measure (but not necessarily as a capital cost saving), and for improvement of system reliability and/or voltage control and stability. Very large combined credits for these and other items discussed above have been projected by some sources[22]. It is recommended here, however, that the matter of credits be either made the subject of specific evaluations for several actual operating cases or left to the discretion of individual utility planning operations when new storage systems are actually incorporated in a utility system.

3.3.5.6 Break-Even Cost Sample Calculation

Break-even costs resulting from investigations of a dedicated PV/utility use of storage are presented in this section. A sample calculation is given below for pumped hydro-storage. A "capitalized" cost approach is used for convenience in handling the energy and capacity credits while at the same time obtaining answers in familiar capital outlay terms.[23,24]

Specific Conditions

- 10% PV-system penetration (375 MW)
- 2000 MWh - pumped hydro storage
- 10 hour discharge rate
- 5% inflation rate, g.
- 10% fuel escalation rate, f
- 30 year system life, n
- 9% discount rate, r
- 75% storage efficiency
- Fixed charge rate, FCR = .18
- Annual O&M Cost, A_{OM} = $1.68 KW of storage power rating/Yr (fixed)
- Annual Energy Credit, A_E^o = $1.17 million (representative U.S. mean value at 2000 MWh - See Figure 3.3-22).
- C* = 35.5 MW (representative mean value at 2000 MWh - See Figure 3.3-24).
- Year 2000 start
- Results in 1976 dollars.

The first step involves capitalization of the annual energy credit, A_E and the annual O&M cost, A_{OM} . This is accomplished by introducing the parameters M_g and M_f, the levelizing values for an escalating cost stream, defined as:

$$M_g = \frac{r\,(1+g)}{r-g}\left[\frac{(1+r)^n-(1+g)^n}{(1+r)^n-1}\right]$$

and

$$M_f = \frac{r\,(1+f)}{r-f}\left[\frac{(1+r)^n-(1+f)^n}{(1+r)^n-1}\right]$$

where

- g = general inflation rate
- f = fuel price escalation rate
- r = discount rate
- n = storage system life, years.

Note that when f (or g) is equal to r, the levelizing multiplier is:

$$M_f = \frac{n\,r\,(1+r)^n}{(1+r)^n-1}$$

The capitalized values for A_E and A_{OM} become:

$$C_E^o = \left(\frac{1+f}{1+g}\right)^{\delta} \frac{M_f}{FCR} A_E^o$$ (capitalized energy credit based on fuel savings)

$$C_{OM} = \frac{M_g}{FCR} A_{OM}$$ (capitalized O&M costs)

where   is the number of years from 1976 to the start year and FCR is the fixed charge rate applicable to the particular storage system. Superscript "o" refers to values obtained for 75% storage efficiency. A correction factor C_η adjusts for efficiency other than 75%. (See Figure 3.3-21).

The break-even cost, $\overline{C}_{BE}$, adjusted for efficiency effects and the cost of money during construction is given by:

$$\overline{C}_{BE} = \frac{C_\eta \; C_E^o - C_{OM}}{CCF} \qquad \text{(without credits)}$$

where the factor CCF accounts for interest during construction and is storage system related. The capacity credit, CC, and any applicable transmission and distribution credits, TDC, are then added to obtain total break-even cost, C_{BE} .

$$C_{BE} = \overline{C}_{BE} + CC + TDC$$

Using the input data given, M_f = 3.3746, M_g = 1.7228 and TDC = 0 for pumped hydro.

$$C_E^o = \left(\frac{1.1}{1.05}\right)^{2000-1976} \left(\frac{3.3746}{.18}\right) \qquad (\$1,170,000)$$

$$= \$67.0 \text{ million or } \$33.50/\text{kWh for 2000 MWh}$$

$$C_{OM} = \frac{1.7228}{.18} \quad (\$.168/\text{kWh}) = \$1.608/\text{kWh}$$

C_η = 1 since η = 75% and CCF = 1.4 for pumped hydro storage.

$$\therefore \quad \bar{C}_{BE} = \frac{1.0\ (33.50) - 1.608}{1.4} = \$22.78/\text{kWh}$$

capacity credit:

CC = \$140/kW X 35,500 kW = \$4.97 million

and

$$C = 22.78 + \frac{4{,}970{,}000}{2{,}000{,}000} = \$25.27/\text{kWh}$$

3.3.6 COST GOALS AND PARAMETRIC ANALYSIS

3.3.6.1 General

This section presents the findings of PV/utility storage analyses based on the techniques described in the preceding sections. The effects of location, start year, fuel price escalation rate, PV system penetration, storage discharge rate and storage efficiency are presented in terms of break-even capital costs of storage versus storage capacity. Data developed from the previously described modeling was translated into projected economic results for the following types of energy storage systems:

1. Pumped Hydro
   a. above ground
   b. underground
2. Underground Compressed Air
3. Batteries
   a. lead-acid
   b. advanced
4. Inertial (Flywheel)
5. Hydrogen

For discussion of the implications of these analyses with respect to preferred storage systems for dedicated photovoltaic system use, reference should be made to Section 1.1.

3.6.6.2 Factors Affecting Annual Energy Credits

Effect of Location

The results of the analysis in terms of annual energy credits resulting from energy storage are depicted in Figure 3.3-19. As can be seen from the figure, value[25] is highest and about the same for Phoenix and Miami, with Boston showing considerably lower savings. The major difference between locations, which results in lower energy credit for Boston, appears to be the insolation levels and corresponding PV array output.

Effect of Penetration

As can also be seen, the effect of PV system penetration on storage energy credit is significant. Higher penetrations of photovoltaic energy result in steadily decreasing value for direct use of this energy, thus storage potential benefits are greater.

Effect of Discharge Rate

The 5 hour discharge rate seemed to improve the energy credit over a ten hour rate only at high penetration levels, as indicated in Figure 3.3-19, and this was interpreted as a more effective use (cycling) of storage capacity at the 5 hour rate. As expected, overall annual energy credit increased with storage capacity, but decreased on a per-unit-of-storage basis as will be seen in subsequent plots.

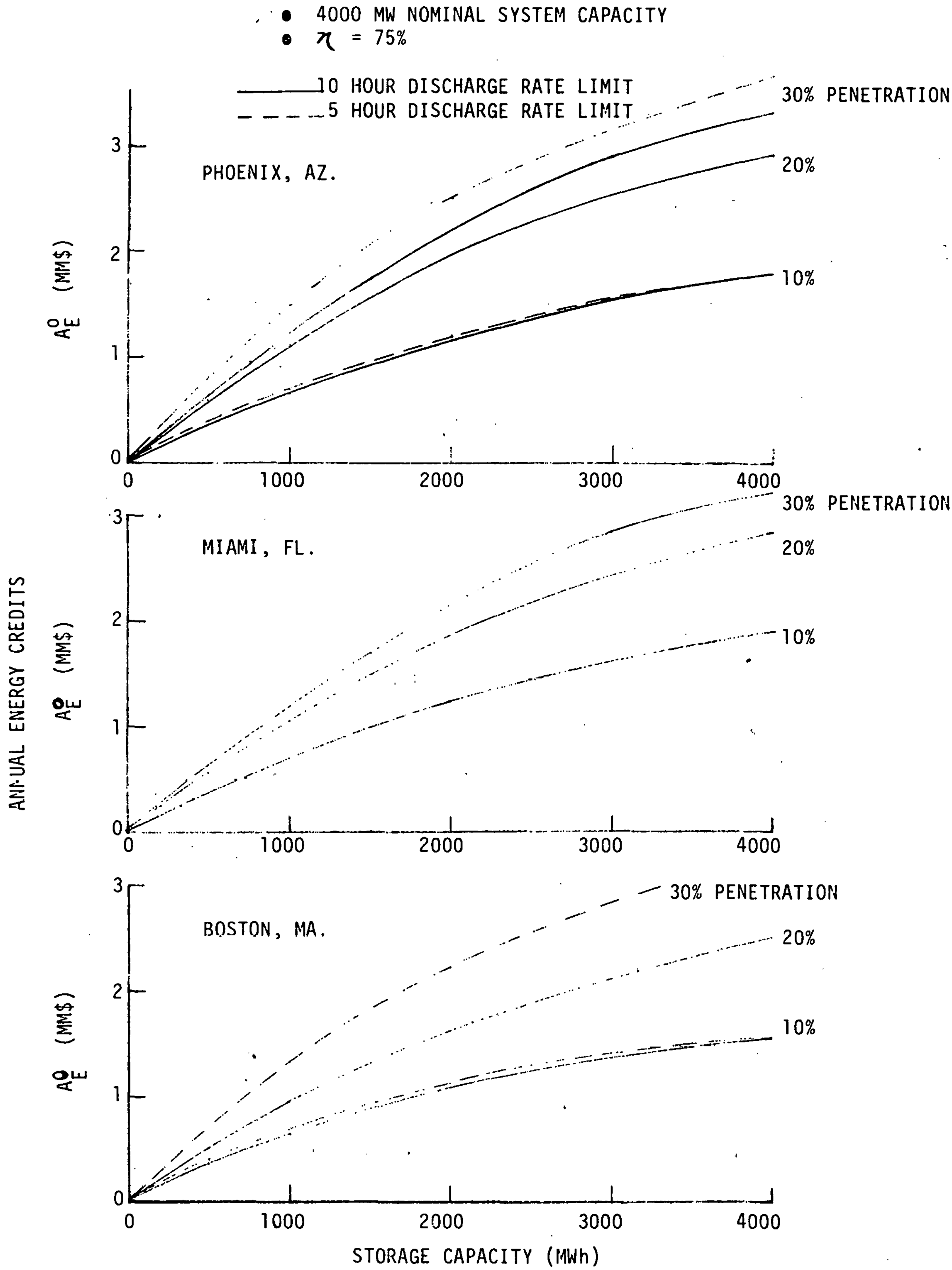


FIGURE 3.3-19. LOCATION, PENETRATION AND STORAGE CAPACITY EFFECTS, PHOTOVOLTAIC ENERGY CONVERSION - UTILITY APPLICATION

Effect of Storage Efficiency

The computer model was run for several values of storage efficiency ranging from 60 to 90%. Figure 3.3-20 shows the range of effects on annual energy credit for the Phoenix and Boston PV data.

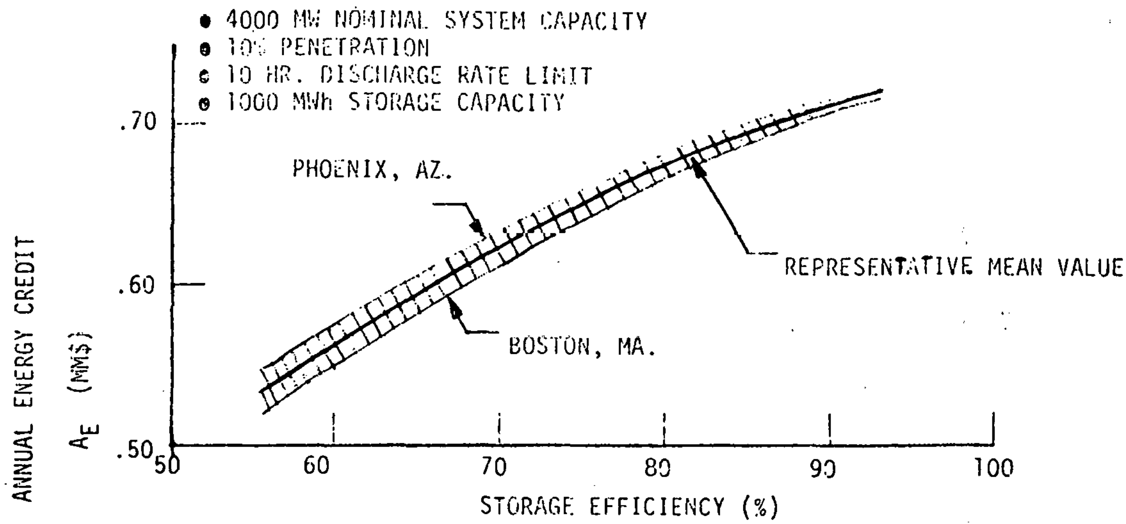


FIGURE 3.3-20. ANNUAL ENERGY CREDIT COMPARISON FOR VARIOUS EFFICIENCIES

A representative mean value for the annual energy credit as a function of storage efficiency was used to generate a correction factor for the efficiency effect. This correction factor, denoted as C_η is defined by:

$$C_\eta = A_E / A_E^o$$

where A_E^o is the annual energy credit at 75% efficiency. Figure 3.3-21 illustrates C_η versus storage efficiency.

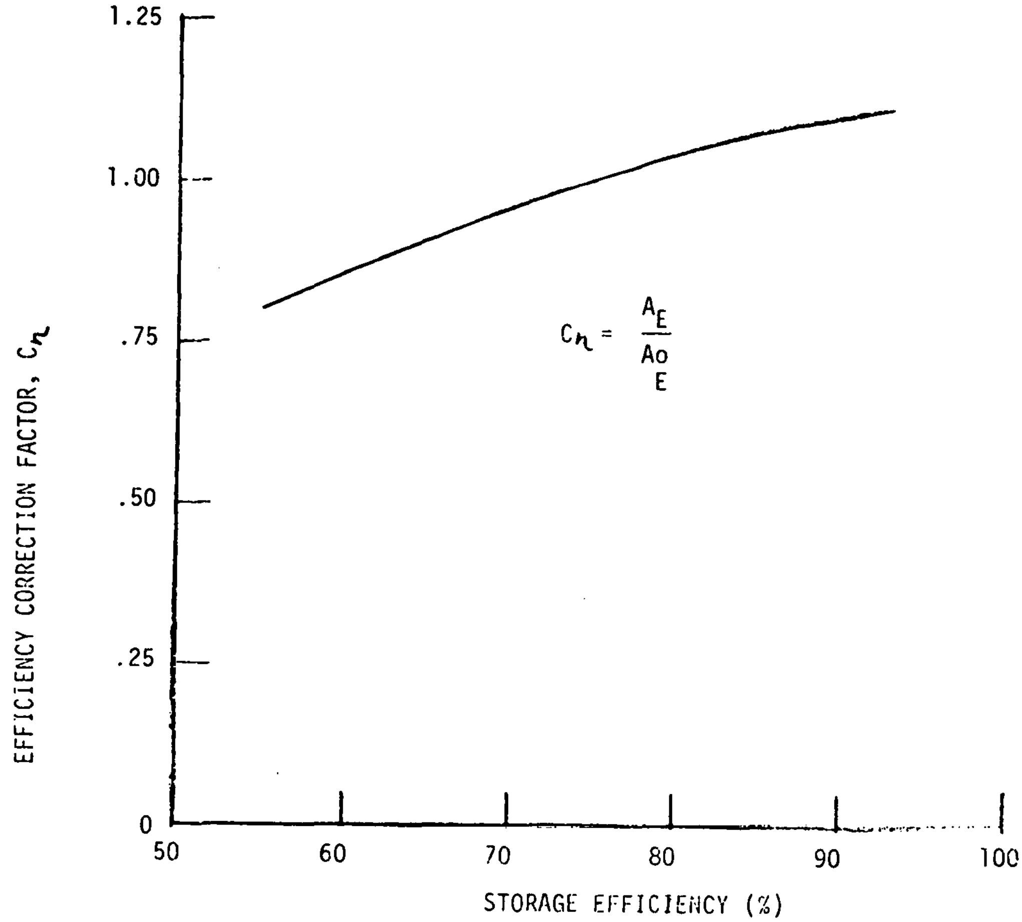


FIGURE 3.3-21. STORAGE EFFICIENCY CORRECTION FACTOR, PHOTOVOLTIAC ENERGY CONVERSION - UTILITY APPLICATION

3.3.6.3 Correlation of Effects on Annual Energy Credits

As can be seen from Figure 3.3-19, the further analysis and interpretation of the various factors affecting energy storage economics could involve a very large number of variables or "degrees of freedom". A representative mean value approach was evolved in order to simplify and narrow this process to manageable proportions and assist in meaningful interpretation of the results.

Figure 3.3-22 shows the upper and lower bounds of annual energy credit for each penetration level as shown in Figure 3.3-19, along with the representative mean value that was used in the subsequent analysis on the utility application of photovoltiac energy storage.

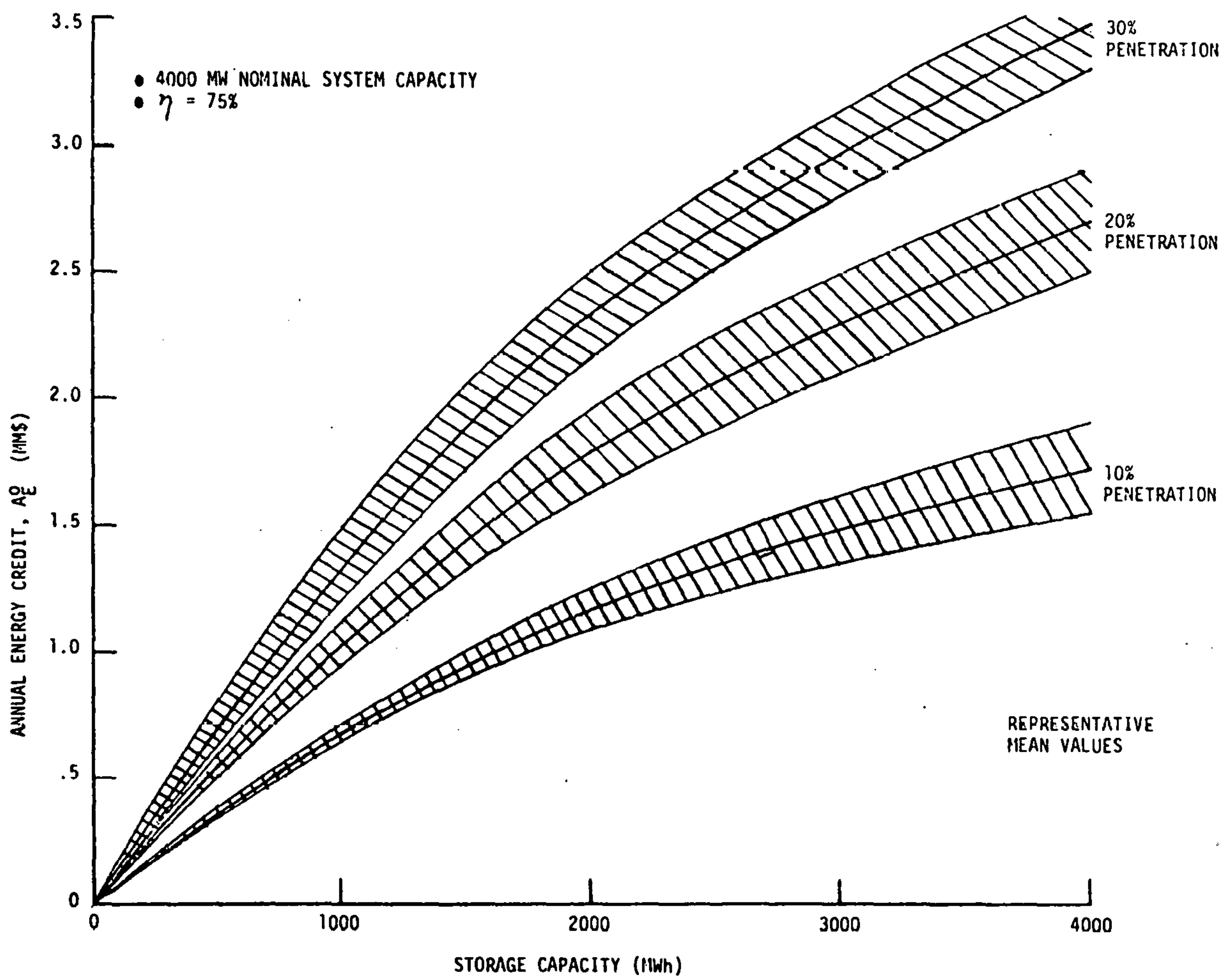


FIGURE 3.3-22 COMPOSITE ENERGY CREDIT, PHOTOVOLTAIC ENERGY CONVERSION - UTILITY APPLICATION

The capitalization of the annual energy credit, A_E^o, was discussed in Section 3.3.5.6 with the capitalized energy credit (C_E^o) expression repeated here as:

$$C_E^o = \left(\frac{1+f}{1+g}\right)^{\delta} M_f \frac{A_E^o}{FCR}$$

A table of the quantity $\left(\frac{1+f}{1+g}\right)^{\delta} M_f$ for the utility application is presented below as a function of start year and fuel escalation rate (f).

TABLE 3.3-9. ANNUAL ENERGY CREDIT MULTIPLIER - UTILITY APPLICATION

START YEAR	δ	$\left(\frac{1+f}{1+g}\right)^{\delta} M_f$ (g = 5%)					
		f=5%	6%	7%	8%	9%	10%
1976	0	1.7227	1.9504	2.2197	2.5159	2.9200	3.3746
1979	3	↓	2.0067	2.3490	2.7378	3.2667	3.8801
1982	6	↓	2.0645	2.4858	2.9792	3.6544	4.4612
1985	9	↓	2.1241	2.6306	3.2419	4.0882	5.1293
1988	12	↓	2.1854	2.7838	3.5278	4.5734	5.8975
1991	15	↓	2.2484	2.9459	3.8389	5.1163	6.7808
1994	18	↓	2.3133	3.1175	4.1775	5.7235	7.7963
1997	21	↓	2.3780	3.2990	4.5458	6.4029	8.9639
2000	24	↓	2.4486	3.4912	4.9467	7.1629	10.3064

Storage break-even cost computations for all of the storage systems considered in this study were adjusted to account for the major differences in concept-peculiar parameters; such as efficiency, operation and maintenance and component replacement requirements. Replacement requirements are accounted for in adjusted fixed charge rates (FCR) for the affected systems. For a detailed explanation of how FCR was determined, see Appendix A of Vol. I. In addition, the cost of money during construction is accounted for through the application of the construction cost factor (CCF)[17,26]. Table 3.3-10 lists the values for CCF and FCR for each of the 7 storage systems.

TABLE 3.3-10. CONSTRUCTION COST FACTORS AND FIXED CHARGE RATES - UTILITY APPLICATION

STORAGE SYSTEM	NOMINAL EXPECTED LIFE (YRS)	CCF	FCR*
Pumped Hydro Above ground Underground	50	1.40	.18
Underground Compressed Air	30	1.17	.18
Batteries Lead-acid Advanced	10	1.05	.22
Inertial (Flywheel)	20	1.05	.19
Hydrogen	20	1.05	.19

* Provides adjustment for comparison of all systems on a common 30 year basis.

3.3.6.4 Estimation of Annual O&M Costs

The best available data for estimating operation and maintenance costs of various storage technologies were used in conjunction with computer model results to compute annual O&M costs, A_{OM} . Fixed and/or variable component of O&M cost are applicable, depending on the type of storage. For the variable component, the energy storage discharge energy was used as the basis of estimation according to:

$$A_{OM} \text{ (variable)} = a_{OM} \times ASDE$$

where a_{OM} is the variable storage O&M cost in $/kWh of discharge energy (See Table 5.3-1 in Volume I) and ASDE is the annual storage discharge energy. Again, representative mean values of ASDE, shown in Figure 3.3-23, were used in the computation of A_{OM}.

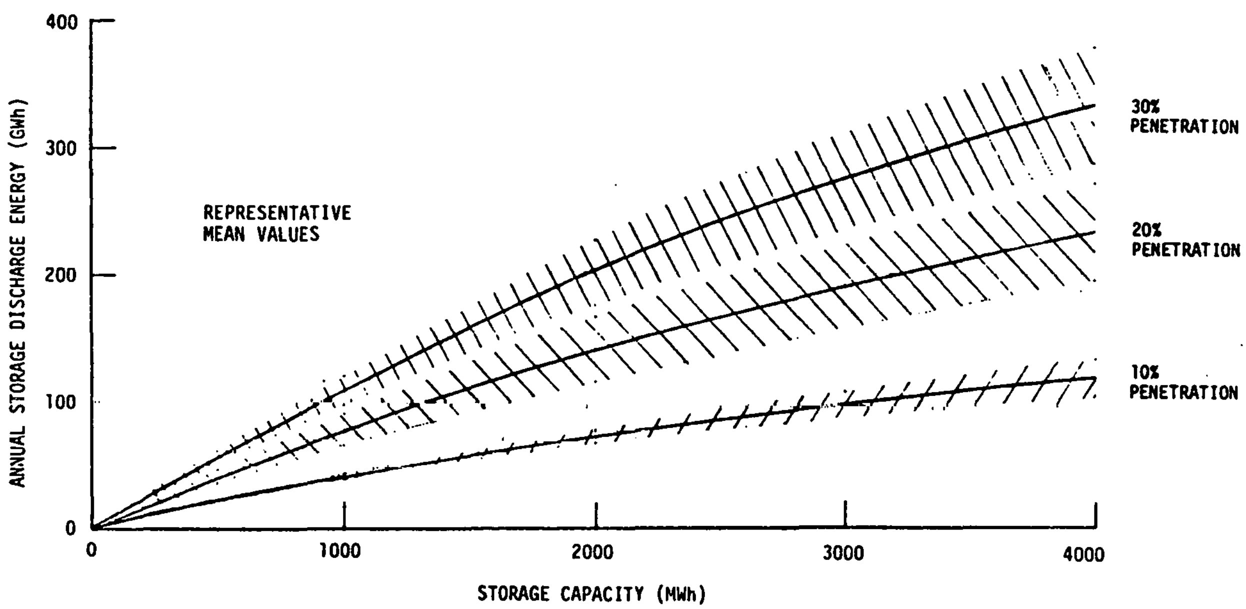


FIGURE 3.3-23. MEAN VALUE OF STORAGE DISCHARGE ENERGY - UTILITY APPLICATION

Table 3.3-11 below lists the computed annual O&M costs for each of the storage systems investigated at 1000 MWh storage capacity and 10 hour discharge rate limit.

TABLE 3.3-11. ANNUAL STORAGE OPERATION AND MAINTENANCE COSTS (1000 MWh, 30% PENETRATION)

STORAGE SYSTEM	A_{OM} (1976 $/kWh)
Underground Pumped Hydro	.168*
Above-ground Pumped Hydro	.168*
Underground Compressed Air	.601
Lead-Acid Batteries	.054
Advanced Batteries	.324
Inertial (Flywheel)	.601
Hydrogen	.306

* Fixed Component only (10 hour discharge rate limit)

3.3.6.5 Capacity Credit Effects

The energy storage capacity credit for the utility application was estimated using the expression:

$$CC = C^* \times 140 \ \$/kW$$

where C* is the effective capacity rating of the dedicated storage system and $140/kW corresponds to the cost of peaking generation equipment (gas turbines). Although some storage systems in specific utility systems may displace some higher-valued intermediate capacity, the $140/kW is a conservative but realistic estimate.

Figure 3.3-24 illustrates the variation of C* with storage capacity and penetration level and shows the representative mean values employed in further analyses.

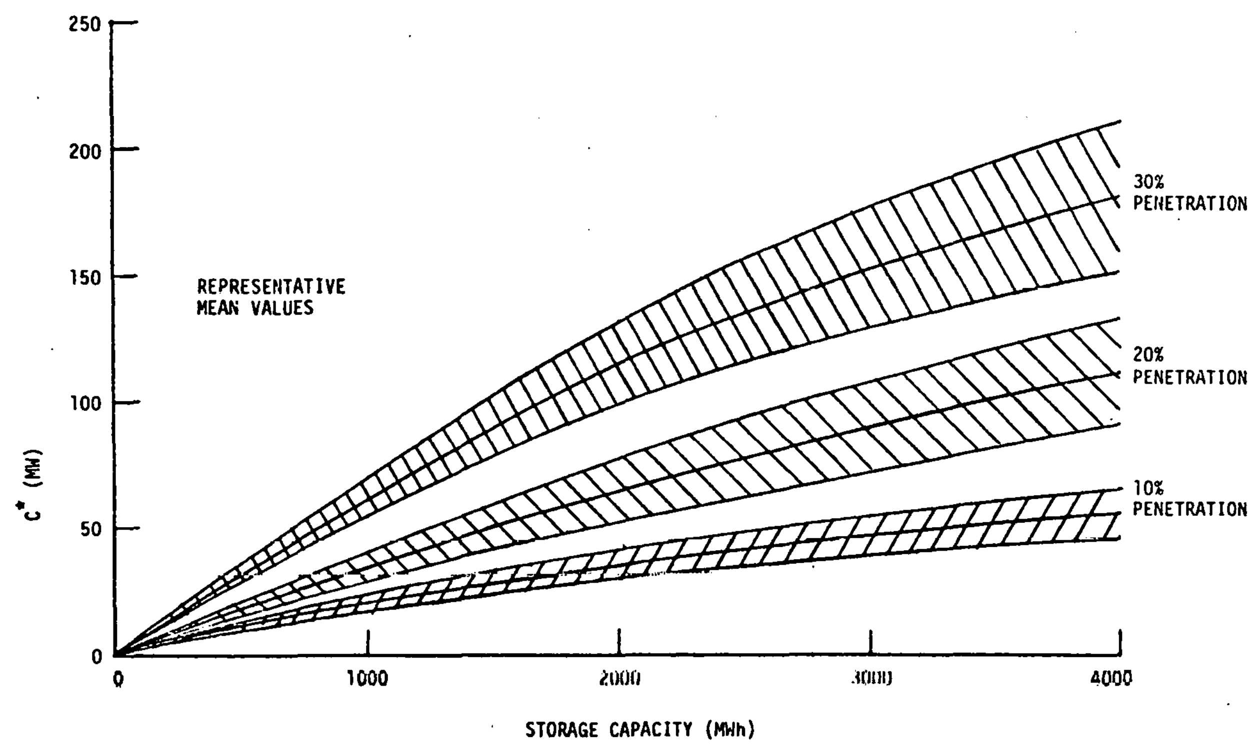


FIGURE 3.3-24. ESTIMATED EFFECTIVE LOAD CARRYING CAPACITY FOR DEDICATED PV CHARGING OF ENERGY STORAGE - UTILITY APPLICATION

3.3.6.6 Capital Cost Comparisons

Break-even capital costs and projected system costs were first computed for one set of conditions for each of the storage types considered in the study. This was done in order to provide more insight into the rankings based on levelized annual cost (Section 1.1). Adjusted break-even costs were computed for 1000 MWh of storage capacity, 30% penetration, 10 hour discharge rate and the extreme economic conditions of 10% fuel price escalation rate and 2000 start year. Comparisons with system cost estimates is presented in Table 3.3-12 which provides a measure of relative economic potential.

TABLE 3.3-12. BREAK-EVEN COSTS WITH PV CHARGING COMPARED TO SYSTEM COST ESTIMATES - YEAR 2000, 10% FUEL ESCALATION

STORAGE CONCEPT	BREAK-EVEN COST	COST ESTIMATE *	Δ	POTENTIAL VIABILITY
Underground Pumped Hydro	648	230	+418	Yes
Above-Ground Pumped Hydro	648	190	+458	Yes
Underground Compressed Air	700	300	+400	Yes
Lead-Acid Batteries	732	790	-58	No
Advanced Batteries	732	310	+422	Yes
Inertial Storage(Flywheel)	758	1850	-1092	No
Hydrogen	572	450	+122	Yes

All Costs in 1976 $/kW

* Figures include learning curve estimates from Vol. I, Section 5.3.3, and reflect most optimistic costs.

Capacity credit and transmission and distribution credits (where applicable) are included in the above data as part of the break-even cost goal. The results indicate five systems of potential viability: both types of hydro, compressed air, advanced batteries, and hydrogen. The first four, plus lead-acid batteries (due to general interest in this technology) were selected for the detailed analysis which follows. Hydrogen was not analyzed further due to its lower indication of potential even with "learning". The above screening affords maximum opportunity for a storage concept to demonstrate economic potential, with cost estimates taken from the year 2000 projected values of Figure 5.3-1 of Volume I. A broad range of comparative analyses were made for the five technologies of interest for the utility application. Break-even costs at a nominal storage capacity of 1000 MWh are shown in Table 3.3-13 along with the capitalized values of energy credit, O&M, capacity credit, and (where applicable) a nominal T&D credit.

TABLE 3.3-13. BREAK-EVEN COST COMPONENTS

- 1000 MWh Storage Capacity
- 10 Hour Discharge Rate Limit
- 30% Penetration

COST ($/kW)	PUMPED HYDRO		UNDERGROUND COMPRESSED AIR		LEAD-ACID BATTERIES		ADVANCED BATTERIES	
	1985 f=6%	2000 f=10%	1985 f=6%	2000 f=10%	1985 f=6%	2000 f=10%	1985 f=6%	2000 f=10%
C_E	165	801	160	775	131	634	135	655
C_{OM}	16	16	58	58	4	4	25	25
C_{BE} (no credits)	106	561	87	613	121	600	105	600
CC	87	87	87	87	87	87	87	87
TDC	0	0	0	0	45	45	45	45
C_{BE}	193	648	174	700	253	732	237	732

The preceding table is principally useful in showing the relative magnitudes of the major factors affecting break-even cost. It also reveals the dominance of the energy credit with future start date and the higher rates of fuel escalation. Differences in results at 5 hour discharge rates. vs. 10 hour are treated further in data and discussions which follow.

Figures 3.3-25 and 3.3-26 show the break-even results vs. estimated system costs for a nominal 6% escalation case as well as for boundary cases of zero differential fuel escalation and a ten percent fuel escalation with a year 2000 start. The amount by which the break-even cost exceeds the system cost in each reflects the degree of economic viability, if any, for storage dedicated to PV system charging.

An important finding of the break-even analysis is that energy saving credit alone is not sufficient to achieve early viability. There must be some form of benefit due to displacement of other equipment. Estimates of capacity credit have been developed in this study. Values for T&D credits as developed by others[17,21,22] were reviewed, and a nominal value added where applicable.

3.3.6.7 Viability Comparison of the Selected Storage Systems

For the four systems selected for more detailed comparison, Figure 3.3-27 presents the difference between break-even cost and system cost estimates versus storage capacity. A positive value indicates potential viability with the extreme 10%, year 2000 conditions assumed as before. It can be seen that pumped hydro storage has the highest potential, although advanced batteries are close on a 5 hour basis. Lead-acid batteries do not achieve

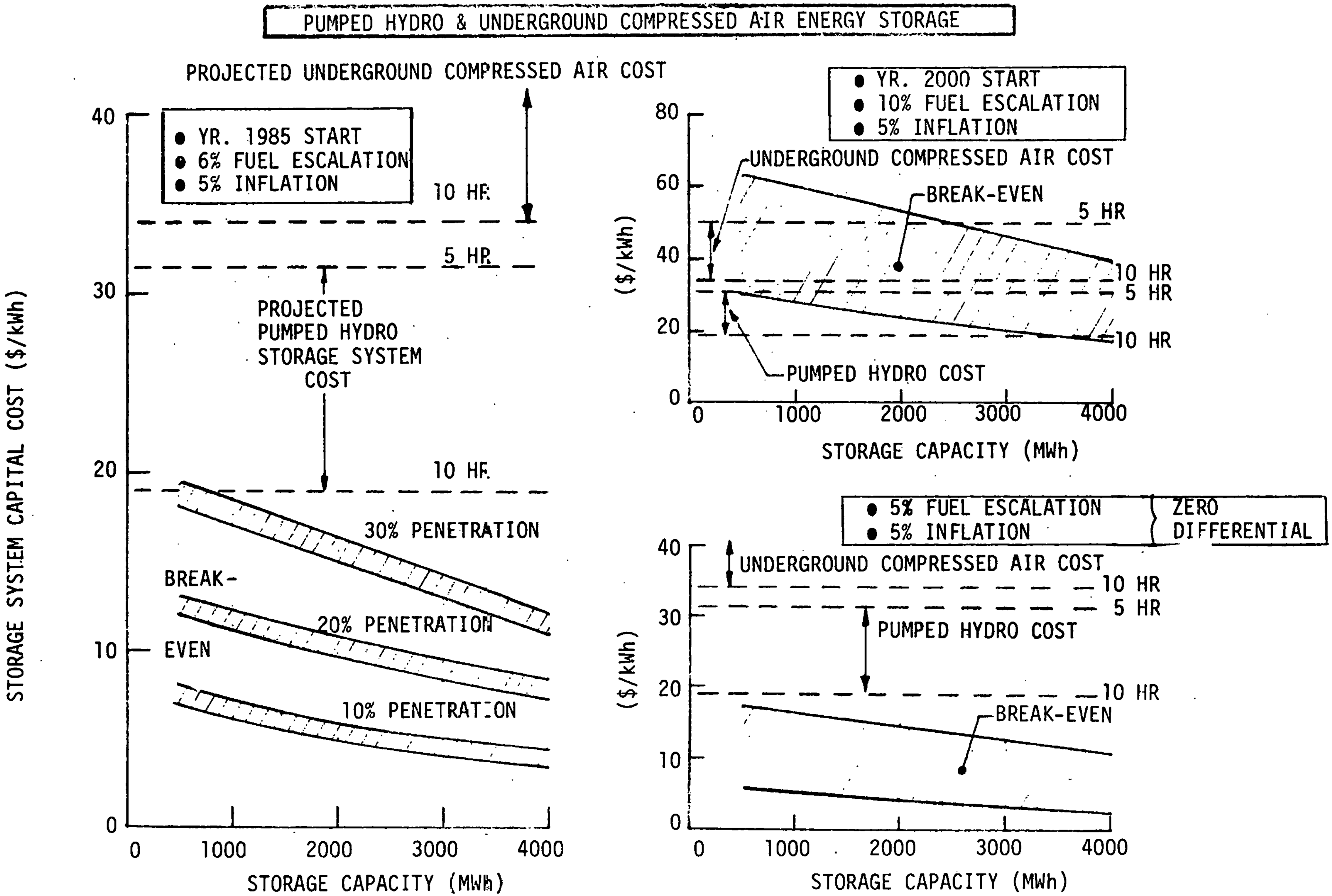


FIGURE 3.3-25. RANGE OF BREAK-EVEN COSTS AND PROJECTED STORAGE SYSTEM COSTS FOR SELECTED ECONOMIC CONDITIONS, PHOTOVOLTAIC ENERGY CONVERSION-UTILITY APPLICATIONS

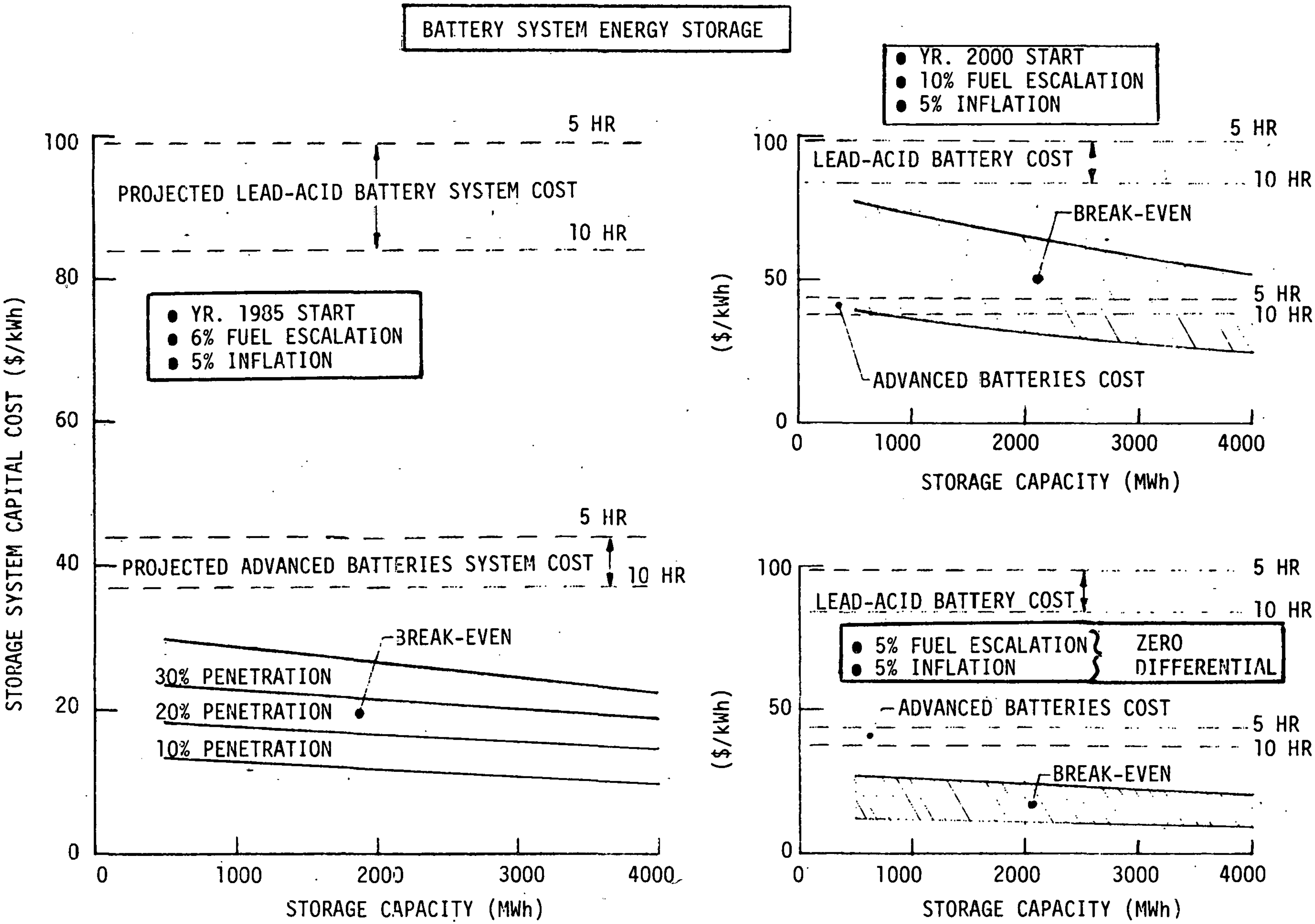


FIGURE 3.3-26. RANGE OF BREAK-EVEN COSTS AND PROJECTED STORAGE SYSTEM COSTS FOR SELECTED ECONOMIC CONDITIONS, PHOTOVOLTAIC ENERGY CONVERSION-UTILITY APPLICATIONS

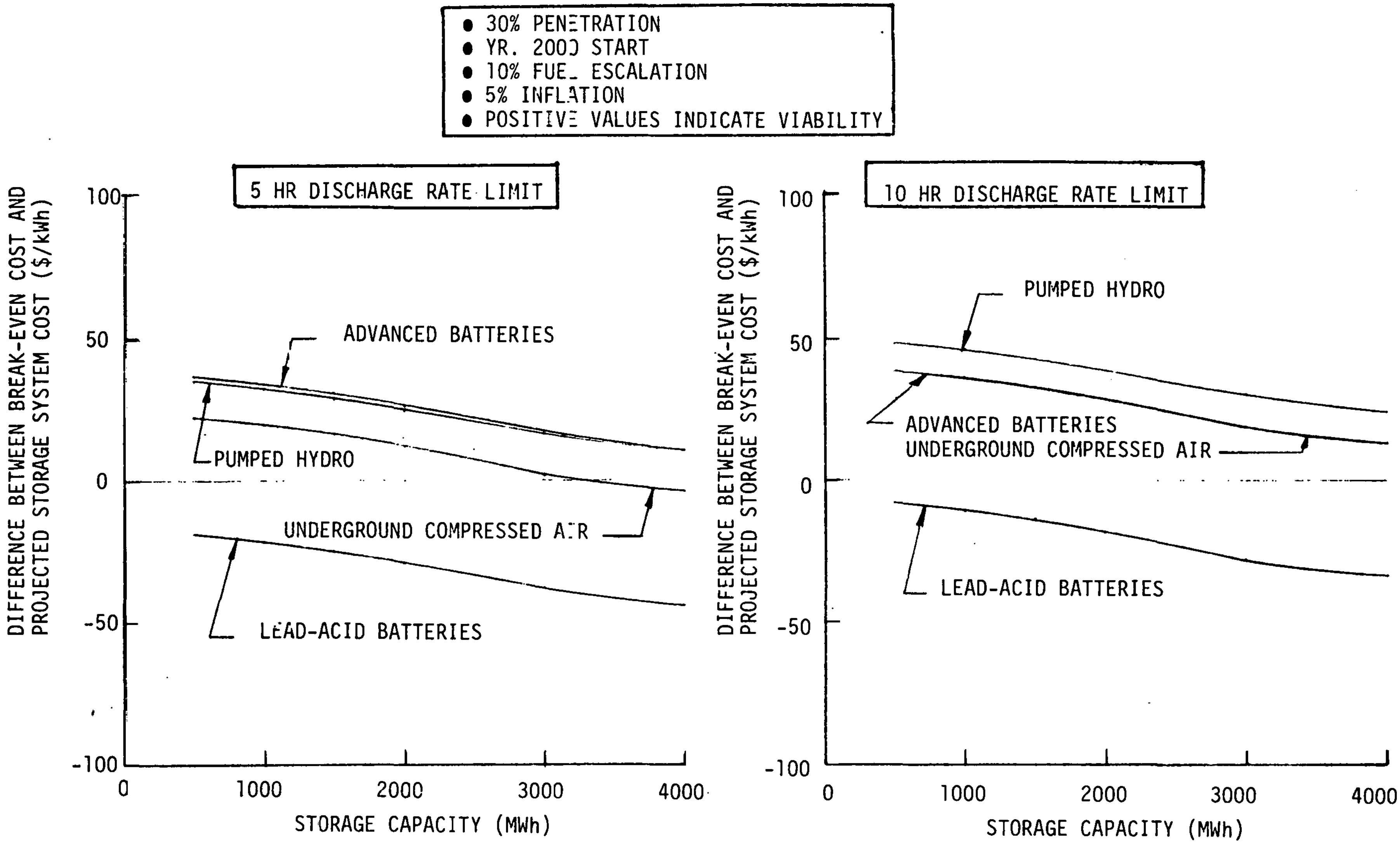


FIGURE 3.3-27. VIABILITY COMPARISONS FOR SELECTED ENERGY STORAGE TECHNOLOGIES, PHOTOVOLTAIC ENERGY CONVERSION - UTILITY APPLICATIONS

viability for dedicated utility PV system use under the conditions assumed here. There are obviously many escalation rate-start year combinations under which a given storage system will become economic. Figure 3.3-28 shows the break-even cost for pumped hydro and underground compressed air storage (which are virtually identical) plotted versus start year and fuel price escalation rate. Also shown are current cost estimates. Thus, if the escalation rate is 8%, pumped hydro reaches viability by about 1980 but at 7% escalation would not be viable until 1989. The reader can test viability against any estimates of system cost, escalation rate and start year. Figure 3.3-29 is a similar chart for advanced batteries.

It should be pointed out that the break-even results of Figure 3.3-28 are those for pumped hydro. The compressed air break-even curves very nearly coincide with those for pumped hydro; therefore, it was convenient to show the system costs for both concepts on one plot.

3.3.6.8 Optimum Storage Size

The optimum size of energy storage is determined by finding the maximum difference between break-even value and total system cost. Table 3.3-14 below shows the process for advanced batteries (5 hour) at the 10%, year 2000 condition.

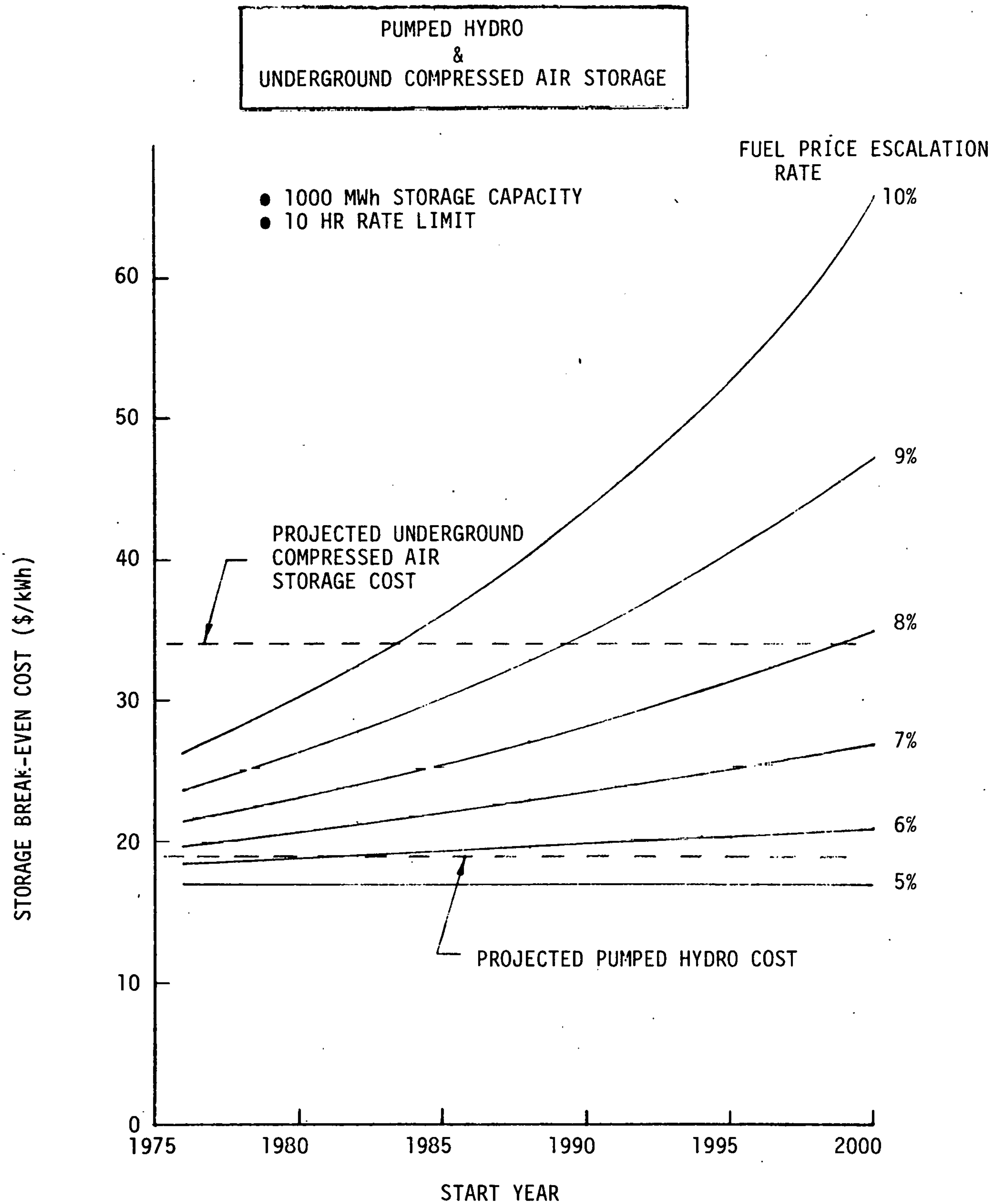


FIGURE 3.3-28. IMPACT OF START YEAR AND FUEL PRICE ESCALATION (COST OF GENERATION) ON STORAGE BREAK-EVEN COST GOALS, PHOTOVOLTAIC ENERGY CONVERSION - UTILITY APPLICATION

ADVANCED BATTERIES

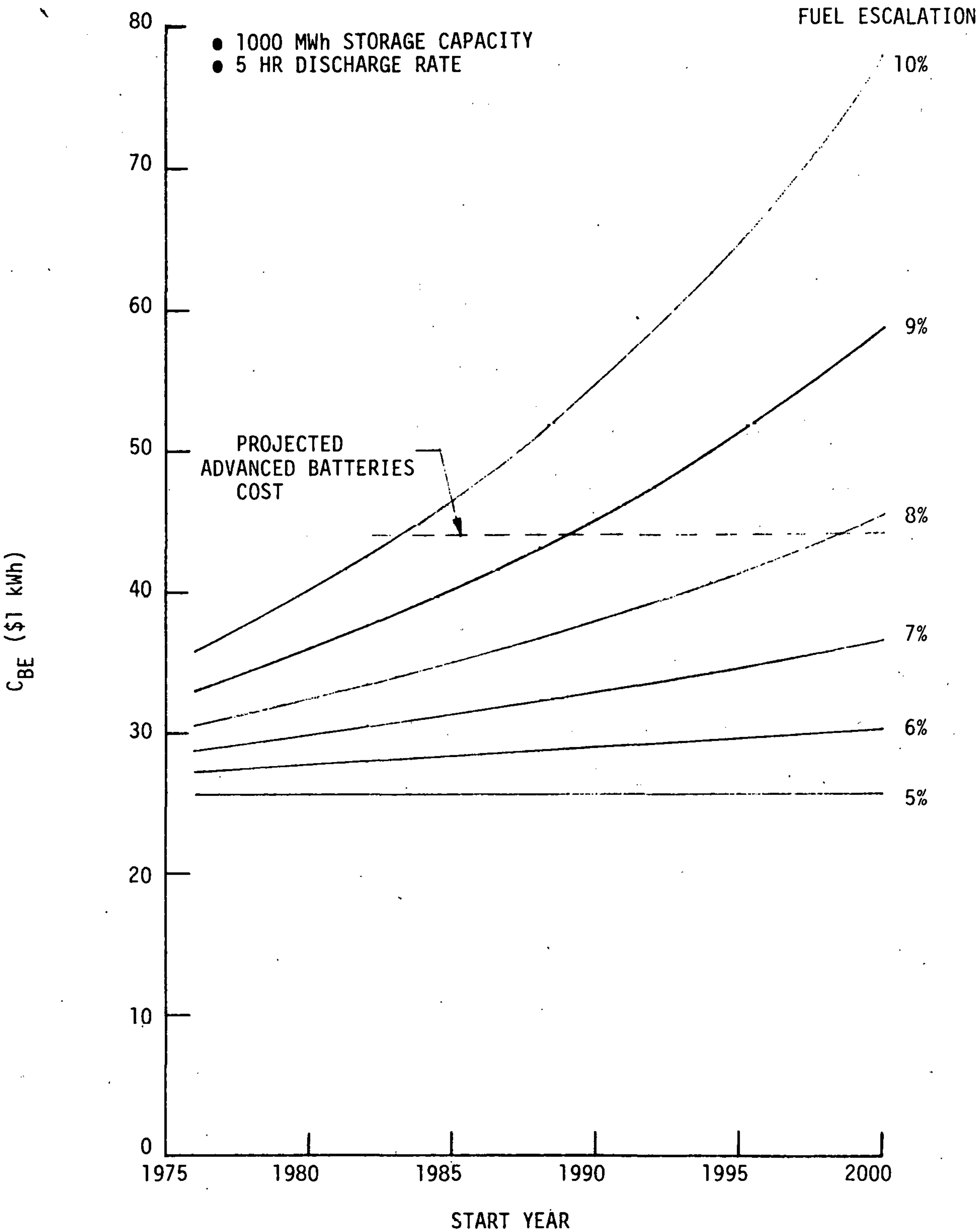


FIGURE 3.3-29. IMPACT OF START YEAR AND FUEL PRICE ESCALATION (COST OF GENERATION) ON STORAGE BREAK-EVEN COST GOALS, PHOTOVOLTAIC ENERGY CONVERSION-UTILITY APPLICATION

TABLE 3.3-14. STORAGE SIZE OPTIMIZATION VALUES - ADVANCED BATTERIES (5 HR)

STORAGE SIZE (MWh)	BREAK-EVEN COST ($/kWh)	SYSTEM COST ($/kWh)	SAVINGS ($/kWh)	TOTAL CAPITALIZED SAVINGS (10^6 $)
500	80.5	44	36.5	18.2
1000	77.7	↓	33.7	33.7
1500	74.2	↓	30.2	45.3
2000	69.9	↓	25.9	51.8*
3000	60.7	↓	16.7	50.1
4000	54.6	↓	10.6	42.5

* optimum

The above data is shown graphically in Figure 3.3-30, along with similar curves for underground compressed air and pumped hydro. Note that the better economics of pumped hydro seen in Figure 3.3-27 are reflected in a larger capacity when the system is optimized.

As fuel price escalation rate increases and the start year is moved out further in time, storage economics obviously improve. This results in a steady increase in the optimum storage size. The effect is illustrated in Figure 3.3-31 for pumped hydro storage. For example, at 9% fuel escaltion about 1800 MWh is optimum for a 1985 start, but at year 1995 this has more than doubled to over 4000 MWh.

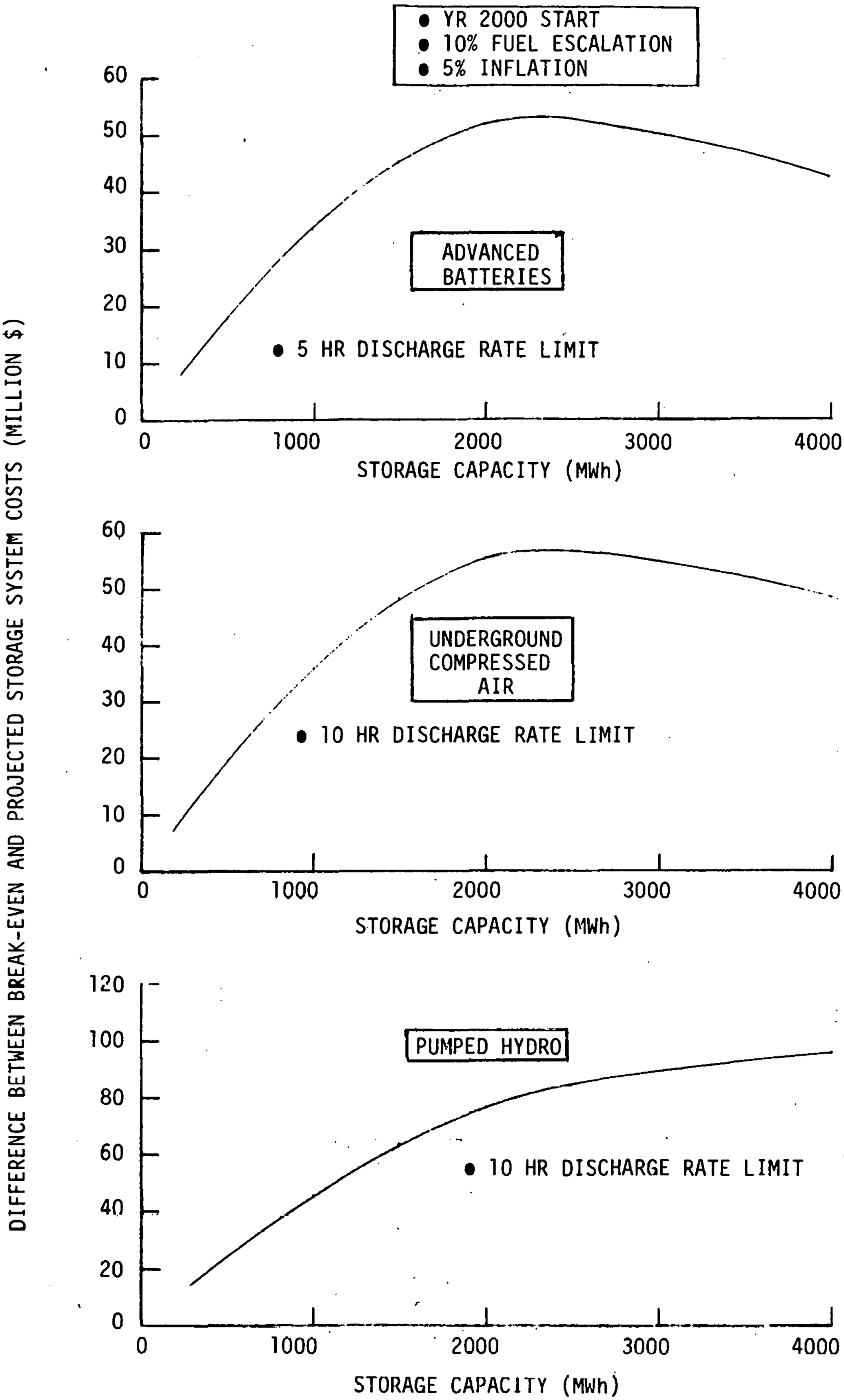


FIGURE 3.3-30. OPTIMUM (ECONOMIC) SYSTEM SIZES FOR SELECTED ENERGY STORAGE METHODS, PV ENERGY CONVERSION, UTILITY APPLICATION

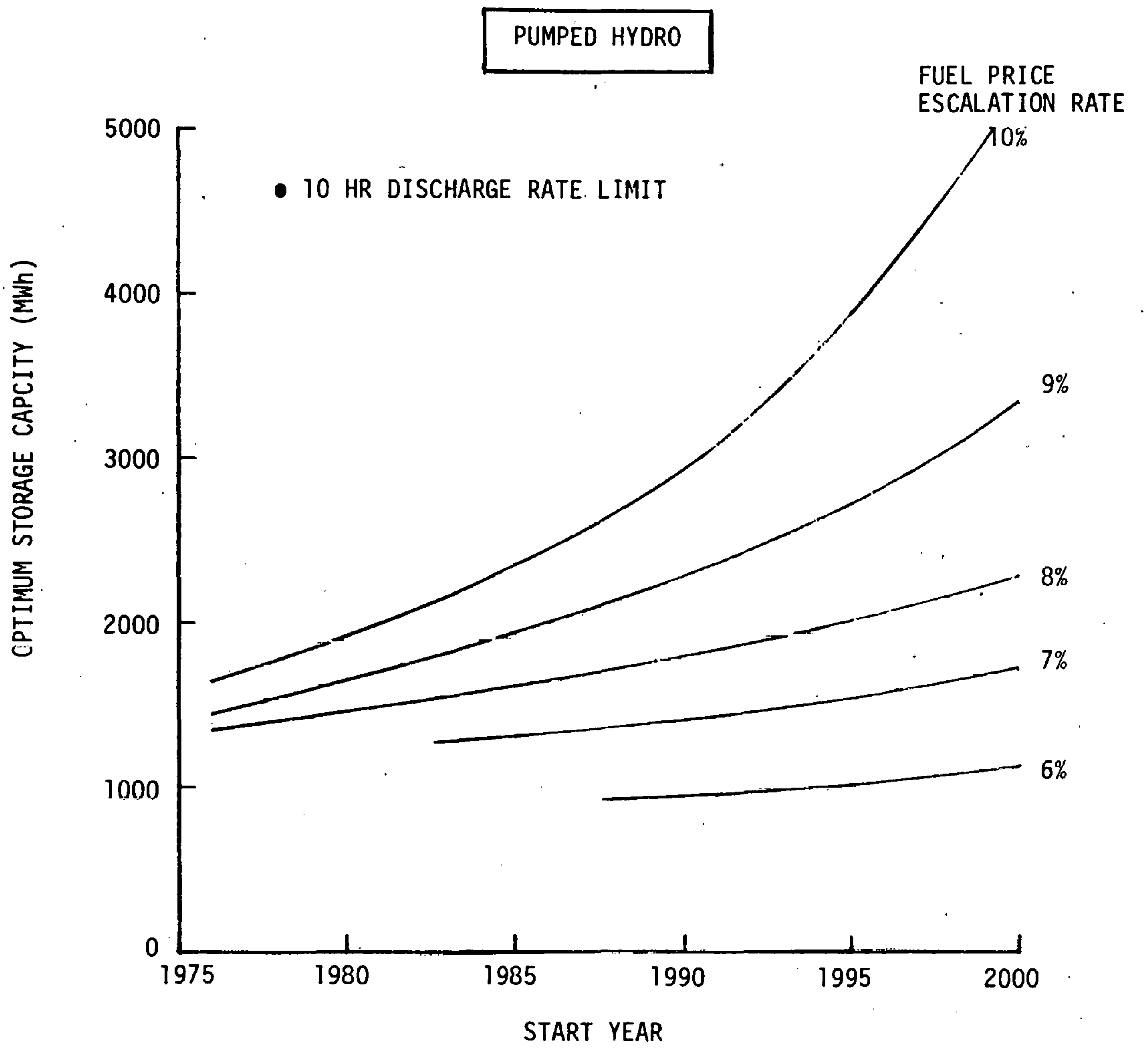


FIGURE 3.3-31. IMPACT OF START YEAR AND FUEL PRICE ESCALATION ON OPTIMUM ENERGY STORAGE SYSTEM CAPACITY, PHOTOVOLTAIC ENERGY CONVERSION, UTILITY APPLICATION

3.3.7 UTILITY SYSTEM PLANNING ANALYSIS

This section contains the analysis and results of a case study performed using a Monthly Energy Production Simulation program for a large utility pool. The overall purpose of this analysis was to determine the worth of energy storage based on a full scale utility planning simulation in which the generation mix effects and loss of load probabilities could be calculated. The results were used as a point of comparison with other data obtained during the overall energy storage study and also as a means of obtaining answers to other specific questions including energy source forecasting and load management effects. This case study was performed by General Electric Company's Electric Utility Systems Engineering Department, Schenectady, N.Y. in cooperation with GE - Advanced Energy Programs, Valley Forge, Pa. The case selected is based on projected conditions of load, generation mix and other factors as they might exist in the New England Power Pool in the year 1995. It should be noted that generally available information was used in this analysis and no inference is intended that the conditions postulated will in fact occur in the manner described. Dr. H.G.Stoll, A. L. Desell, and L. L. Iovinelli of GE-EUSED were the principal investigators for this work.

POTENTIAL ENHANCEMENTS OF STORAGE GENERATION TO PVCS:
A CASE STUDY OF NEW ENGLAND POWER POOL IN 1995

1.0 GENERAL

The specific objective of this study was to evaluate the benefits of storage to PVCS on the New England Power Pool System. System representative data was gathered from Federal Power Commission Reports. The PVCS output characteristics of Boston, Massachusetts, were developed by GE-Advanced Energy Programs. These characteristics were integrated into a power system analysis to determine the potential value of PVCS and several storage devices.

2.0 STUDY METHODOLOGY

The Monthly Production Simulation and Single Area Reliability Programs have been modified to accept as input an hourly representation of PVCS. This hourly incorporation of PVCS enhances the utility power system simulation package. This model is illustrated in Figure 3.3.7-1.

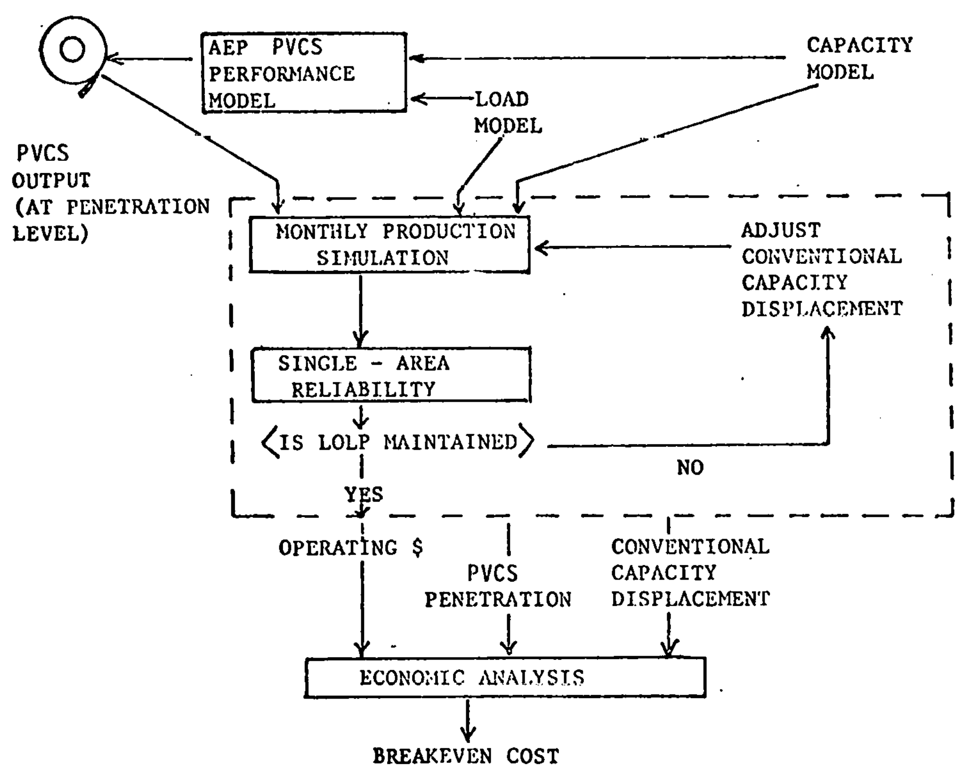


FIGURE 3.3.7-1. STUDY ANALYSIS TOOLS

The chronological hour by hour power output of the PVCS energy devices (obtained from GE-Valley Forge in this case) was input into the Monthly Production Simulation Program along with the utility load and capacity model. The utility/pool model is a chronological hour by hour description of the electricity demand of the utility/pool. The capacity model is a description of the capacity characteristics of the utility/pool including, capacity of units, fuel-type, forced and scheduled outage rates and heat rates. Also, input into the program is the PVCS penetration and the amount of conventional capacity displacement as a result of the PVCS penetration.

The results of the Monthly Production Simulation are a monthly and annual projection of the operating expenses of the utility for a given PVCS penetration and corresponding conventional capacity displacement.

The Single Area Reliability Program performs an evaluation of the number of hours of expected shortage of capacity (LOLP) for a given penetration of PVCS and corresponding conventional capacity substitution.

The results of the production simulation (operating $) can be combined with the capital costs of the capacity displaced by PVCS for an economic analysis of the breakeven costs of the PVCS and storage.

These two programs also have the capability to model system storage plants on an hour by hour basis, such as pumped storage hydro. This capability can be exploited when studying the applicability of storage systems with PVCS. Activities of the storage device over typical weeks can be printed to illustrate the role of the storage device.

2.1 ILLUSTRATION OF STUDY ANALYSIS

This section will illustrate how the models in Figure 3.3.7-1 may be utilized in evaluating the benefits of system storage in coordination with PVCS.

Step 1. Base Case—No PVCS. The power system is simulated in the horizon year, say 2000, without any penetration of PVCS. The system mix is adjusted to an economic mix of generation types; nuclear, coal, gas turbine, combined cycle, and storage. The reliability for the system is measured (LOLP = .1 days/year). The levelized annual operating $ of the power system results in 300 million.

Step 2. 10% PVCS Penetration, 0% Additional Storage. Since additional capacity is added to the system, in the form of 10% PVCS penetration (for example 1000 MW), the system would be more reliable than the Base Case (i.e., .005 days/year LOLP). Since this is more reliable than the target criteria of .1 days/year LOLP, conventional capacity can be displaced. The choices of displacement capacity would be based on the utilities experience. This displaced capacity could be nuclear, coal, combined cycle, or gas turbine. Or, the displaced capacity could be a combination of all these types. For this example, consider only the case of nuclear and gas turbine units being displaced.

Step 2A. Gas Turbine Displacement Only. In this step, gas turbine capacity is removed from the system until the system LOLP increases to the target level of .1 day/year (this may actually require 2 or 3 computer simulations of the Single Area Reliability Program to evaluate this MW quantity of gas turbines to be displaced). Suppose this answer is 500 MW of gas turbines. The power system is then simulated using the complete analysis capability of Figure 3.3.7-1. The levelized production cost result is $250 million.

The breakeven cost is evaluated as that capital cost of the PVCS such that the production and investment charges are indifferent between the base case and the Step 2A case. Suppose the capital cost of the gas turbines are 150 $/KW. The breakeven cost of the PVCS is then (assuming 18% fixed charge rate):

$$\$300 = \$250 - .18^{*} (.150)^{*}500 + BE_{PVCS} * .18$$

Then

$$BE_{PVCS} = 353 /KW$$

<u>Step 2B.</u> <u>Gas Turbine-Nuclear Displacement.</u> In this step rather than displacing 500 MW of only gas turbines, 200 MW of nuclear units are displaced and 350 MW of gas turbines are displaced. (The actual amount of gas turbines displaced is evaluated using the Single Area Reliability Program and reducing gas turbines until a LOLP of .1 days/year is achieved.) The levelized power system production cost is $260 million.

The breakeven cost is then computed as (assume nuclear units have a capital cost of 600 $/KW):

$$\$300 = \$260 - .18^{*} (.150^{*}350 + .600^{*}200) + BE_{PVCS} * .18$$

Then

BE_{PVCS} = 395 \$/kW

Step 2C. Gas Turbine - Nuclear Displacement. In this case more nuclear generation is displaced and another breakeven cost of PVCS is computed. For example, 400 MW of nuclear and 200 MW of gas turbine. Suppose the breakeven cost is 300 \$/kW.

Step 2D. Evaluation of Optimal Displacement. The three breakeven costs corresponding to the three capacity displacements can be graphed as is illustrated in Figure 3.3.7-2.

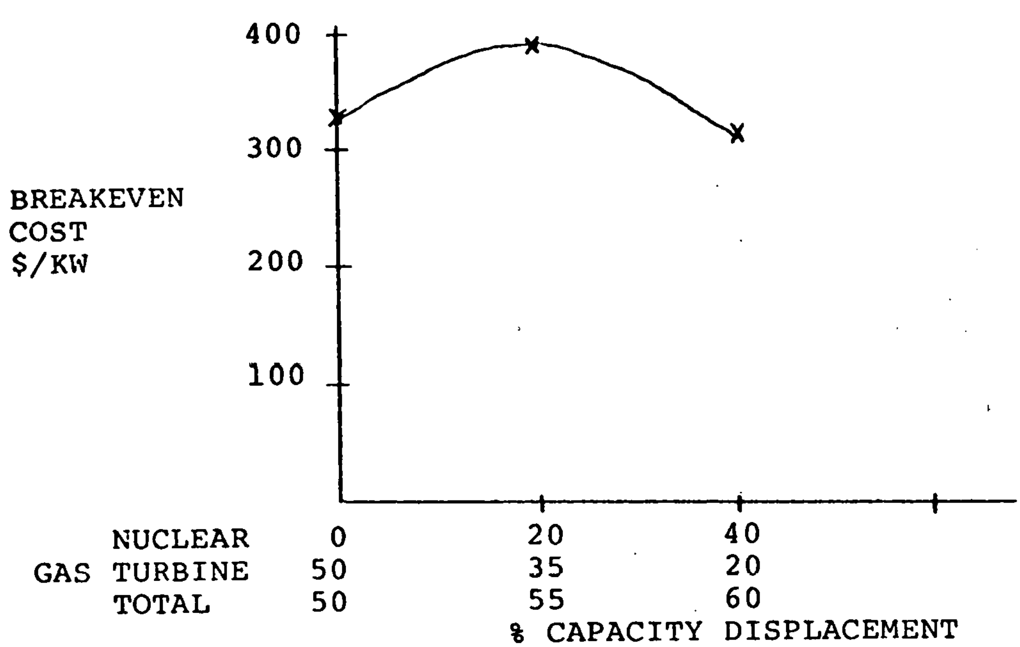


FIGURE 3.3.7-2. CAPACITY DISPLACEMENT RESULT

The point at which the maximum occurs is the optimal capacity displacement at a 10% PVCS penetration. A greater MW amount of nuclear than gas turbines must be displaced to maintain the identical system reliability. Thus, a greater total percent capacity displacement as more nuclear is chosen.

Step 3. 10% PVCS Penetration, 3% (of System Capacity) Additional Storage-5 Hour Reservoir Storage. In this case, the PVCS are added as in Step 2 and also storage capacity is added. The same capacity displacement analysis similar to Step 2A, 2B, 2C and 2D is performed. This is illustrated in Figure 3.3.7-3 for two values of storage plant capital cost.

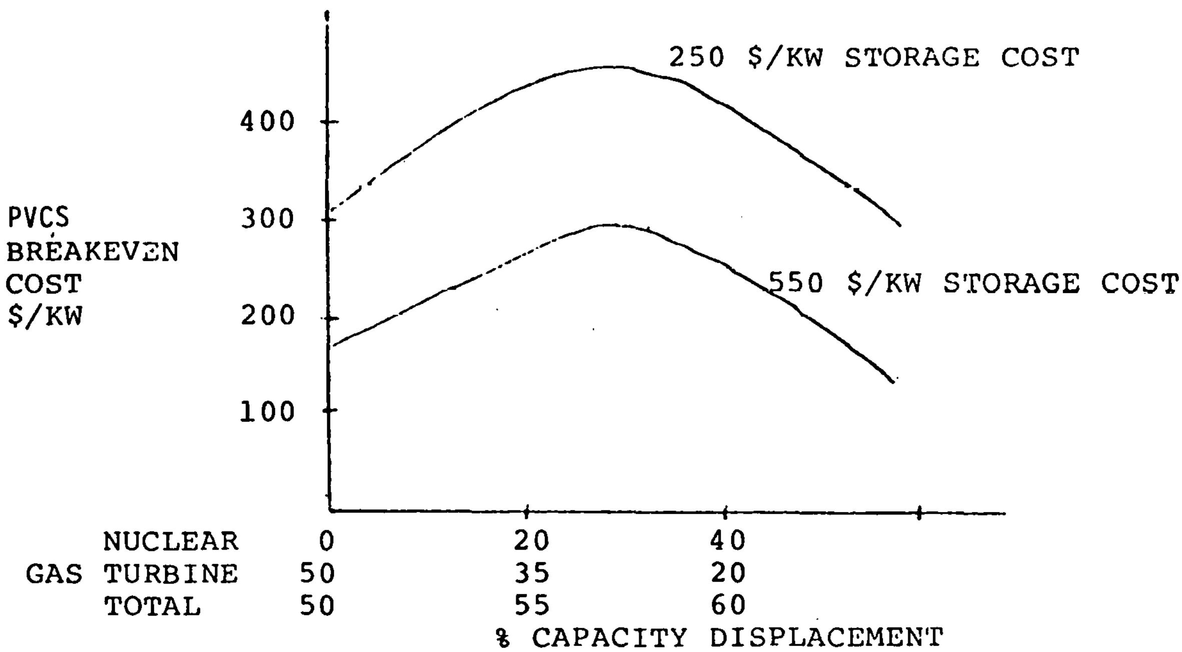


FIGURE 3.3.7-3. PVCS BREAKEVEN COST WITH STORAGE

The breakeven value of storage can be computed by using the maximum value of the PVCS breakeven cost in Figure 3.3.7-3 and plotting the result versus the capital cost of the storage device. This is illustrated in Figure 3.3.7-4.

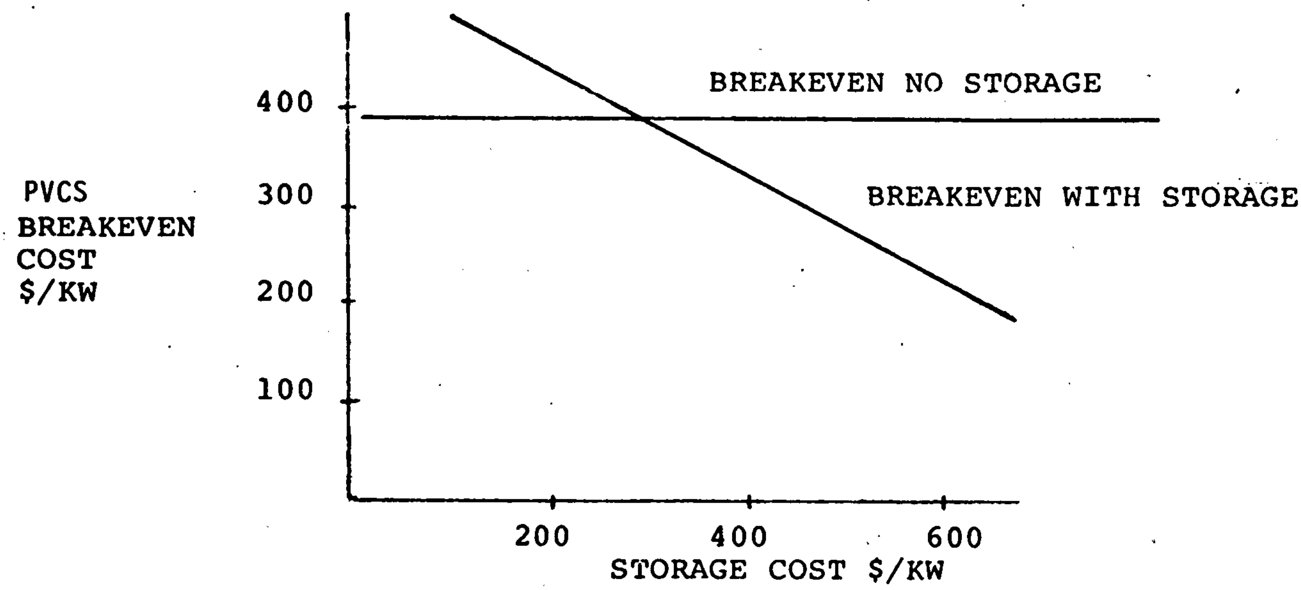


FIGURE 3.3.7-4. STORAGE BREAKEVEN VALUE CALCULATION

Also plotted on Figure 3.3.7-4 is the breakeven cost of PVCS with no storage (Step 2B). The breakeven value for storage of 300 $/kW results when the two curves intersect.

Also from Figure 3.3.7-4, the added value of storage can be computed. The added value of storage is defined to be the difference between the breakeven cost and the actual equipment cost of storage. In this example, if the actual equipment cost were 250 $/KW, the added value of storage would be 300 - 250 = 50 $/KW.

The simulation of storage devices can be performed in two ways; (1) storage dedicated to the output, (2) power system wide storage. In dedicated storage, the power operation of the storage device and reservoir management is performed using only the energy from the PVCS. Thus if the PVCS devices are not operative, then the storage plant will not recharge. On the other hand, system storage operates regardless of the PVCS. In general, a storage device operated on a power system basis will be of greater value to the utility and therefore have a higher breakeven cost.

3.0 POWER SYSTEM DATA

Plant Costs ($/KW Including Escalation & AFDC)

	(1980) $/KW	1995 $/KW	Escalation %/YR
Nuclear	850	1767	5
Coal with Scrubber	700	1455	5
Gas Turbine	190	395	5
Combined Cycle	400	831	5
Pumped Hydro	300*	623	5

* Note 70% efficiency of the PSH cycle

Fixed Charge Rate	18.0%
Present Worth Rate	10.0%

Fuel Costs	¢/MBTU (1980)	¢/MBTU (1995)	Escalation %/YR
Nuclear	75	176	6
Coal	170	401	6
Residual Oil	270	641	6
Distilled Oil	300	722	6

Operation and Maintenance Costs

	1980 $/KW/YR	1995 $/KW/YR	Escalation %/YR
Nuclear	15	31	5
Coal with Scrubber	25	32	5
Oil	13	27	5
Gas Turbine	3	6	5
Combined Cycle	10	21	5
Pumped Hydro	1	2	5

Availability of New Plants
(Accounting for Immaturity)

	Average Availability
Nuclear	68
Coal Steam	73
Gas Turbine	88
Combined Cycle	86
Pumped Storage	98
Oil Steam	78

Peak Load

	1980	1995	Growth Rate
Peak Load MW	16850	37000	5.4
Load Factor %		61.2	

LOLP 6 HOURS/YEAR

4.0 NEW ENGLAND GENERATION ADDITION PLANS

New England Power Pool currently (end of 1975) has the following generating units on the power system.

Nuclear	Coal	G.T.	Oil Steam	Hydro	Combined Cycle	Total
3460	485	1715	11025	2910	25	19595

The projected additions out to 1988 are listed below ("Data on Coordinated Regional Bulk Power Supply Programs", Northeast Power Coordinating Council, April 1977).

	Nuclear	Coal	Gas Turbine	Oil Steam	Hydro	Combined Cycle
76	830			960		
77				96		
78				600		
79						
80						
81	1150				12	270
82	1150		205	75		
83				75		
84	2380					147
85						
86	3450					
87						
88	1150					
Capability Total 1988	13570	485	1920	12681	2922	452

In developing the base case, consideration must be given to the amount of capacity that can be added from now until the horizon year, 1995. Lead time requirements of base load generation is a primary consideration. For nuclear units, which are the most economic units in NEPOOL, the lead time is approximately 10 to 11 years. Thus, the soonest a new nuclear unit could be placed in service, if decided upon today, would be 1988 and thereafter. Consequently, the maximum MW of nuclear capacity addition from 1988 to 1995 could be computed as

Peak Load 1995	=	37000
Peak Load 1987	=	25695
Load Growth	=	11304
Max. Nuclear Additions 1987 - 1995	=	Load Growth x Reserve Level
	=	11304 x 1.30 = 14,695

The maximum nuclear capacity in 1995 is approximately

14695 + 13570 = 38265 MW

5.0 DETERMINATION OF THE OPTIMAL GENERATION EXPANSION THROUGH 1995

5.1 INITIAL BASE CASE

The composition of the generating system in 1995 is assumed to be based upon minimizing the power supply costs subject to the constraint that the system reliability measure, LOLP = 2.5 days/year, is achieved. To determine the optimal composition requires that economic studies be made for various types of generation additions. In NEPOOL, these types would be nuclear, gas turbine and pumped storage hydro (PSH). Other types of generation additions were not considered largely because they would not be economic in NEPOOL or that their use would not be consistent with the national energy policy of reducing oil consumption.

As a basis upon which to proceed, one generation addition plan was postulated. In 1995 this plan had the following characteristics:

1995 Capacity (MW)

Nuclear	25694
Coal	337
Oil Steam	12194
Gas Turbine	4635
Combined Cycle	500
PSH	2600
Pondage Hydro	1350

1995 LOLP = 2.81 Days/Year

1995 Production Costs

Fuel	$5656.05 MILLION
O&M	$1187.41 MILLION
TOTAL	$6843.471 MILLION

5.2 ECONOMIC EVALUATIONS

Generation equipment has a life of 30 to 50 years. Thus, an economic evaluation cannot be made entirely upon 1 year of economic evaluation. Rather, the evaluation should be made over several years. One method for accounting for the several year evaluation requirement is to compute a levelized annual cost that correctly factors into account inflation and present worthing.

Consider the matter of production costs. If one were to assume inflation increased at 6% per year and all costs were present worthed at 10% per year, a $1.00 production cost in 1995 would escalate in subsequent years as illustrated below.

5 Year Inflation and Present Worth Example

	95	96	97	98	99	Cumulative Total
Prod. Cost	1.00	1.06	1.12	1.19	1.26	
Present Worth Factor	1.00	.91	.83	.75	.68	4.17
Present Worth Prod. Cost	1.00	.96	.93	.89	.86	4.64

A levelized production cost is defined as that single production cost number which if it applied over the entire 5 year period would yield the same cumulative present worth total as the actual year by year present worth total. For the example above, the 5 year levelized production cost is

$$4.64/4.17 = \$1.11$$

Intuitively, the levelized value is near the average of the yearly production cost values, but with a slight bias toward the early years as a result of the present worthing.

While 5 years was a good levelizing period for the above example, utilities will generally use a longer period of time. Utility practice ranges from a 10 year levelizing period to a 20 and 30 year period. While one might think that since the generation equipment has an expected life of 40 years, a levelizing period of 40 years should be used. The thinking behind using a levelizing period less than the physical plant life in making economic evaluations is founded upon several arguments. Two of these are discussed as follows:

(1) Levelizing over a long period (40 years) may lead to an alternative which does not payoff, or crossover, with competing alternatives until after 30 years. In this period, many of the economic projections made in justifying this long range decision may not be realized. Thus, one could make a decision which, if conditions are adverse, lead to an alternative never being economic.

(2) Expanding further upon argument 1, a decision which does not payoff for 30 years means that the added costs of that alternative in the near term will be borne by today's electric consumer. If a similar decision is made the next year, and the year after and so on, as is the case with a growing electric utility, it may be that the ultimate payoffs are always continued to be pushed out 30 years. Hence, what might look like a 30 year payoff in the case of 1 decision, actually may be a continually deferred payoff that is never achieved in the dynamic case of an expanding electric utility.

In this study, a 15 year levelizing period was chosen to represent an average of the utility industry practices.

In this case, the levelizing factor is 1.49.

5.3 <u>BASE CASE OPTIMAL GENERATION EXPANSION</u>

Several alternative generation expansion cases were made from the initial base case, described in 5.1. able 3.3.7-1 presents the results. The results are presented relative to the initial base case. The costs are summarized in the last column. The first item is the levelized (15 year) production cost. The second and third items are the levelized investment charges associated with the change in capacity from the base case. The last item for each case is the total decision cost.

In Case 2, nuclear generation is added and gas turbines are removed. This case shows a marked improvement over the initial base case.

In Cases 3 and 4, variations were made in the nuclear - PSH composition. These results illustrate that nuclear generation is more economic than PSH in the region of the initial base case.

In Case 5, the sensitivity PSH and gas turbines were examined.

In Cases 6 and 7, the addition of nuclear and subtraction of gas turbines was further examined as an extension of Case 2 since Case 2 showed a marked economic gradient toward greater nuclear composition. Comparison of Cases 2, 6 and 7 reveal that the optimal nuclear - gas turbine tradeoff is with Case 6.

On the basis of these simulations, it can be concluded that the base case from which all PVCS storage cases should be run from is Case 6. It is the case with the lowest economic cost. Furthermore, this case doesn't violate any nuclear construction constraints. Even though it does not lie exactly at the optimal point in the minimum cost, because a slight gradient exists for substituting PSH for gas turbines, on a practical basis the difference in cost between Case 6 and the mathematical exact optimal will be very small.

TABLE 3.3.7-1. RESULTS SUMMARY

#	Case	Description of MW Capacity Nuclear	G.T.	PSH	Item	Costs
1	Initial Base	25694	4635	2600	Prod Cost	10196.8
2	Add 1150 Nuclear	26844	3735	2600	Prod Cost	9782.1
	Subtract 900 GT				Nuclear Inv	365.8
					GT Inv	-64.0
					Total	10083.9
3	Subtract 1150 Nuc	24549	4635	3400	Prod Cost	10629.8
	Add 800 PSH				Nuclear Inv	-365.8
					PSH Inv	119.4
					Total	10383.5
4	Add 1150 Nuclear	26844	4635	1800	Prod Cost	9855.6
	Subtract 800 PSH				Nuclear Inv	365.8
					PSH Inv	119.4
					Total	10102.0
5	Add 1000 PSH	25694	3535	3600	Prod Cost	10143.9
	Subtract 1100 GT				PSH Inv	149.3
					GT Inv	-71.0
					Total	10221.1
6	Add 2300 Nuclear	27994	2835	2600	Prod Cost	9435.3
	Subtract 1800 GT				Nuc Inv	731.6
					GT Inv	-128.6
					Total	10038.9
7	Add 3450 Nuclear	29144	2035	2600	Prod Cost	9131.8
	Subtract 2600 GT				Nuc Inv	1097.3
					GT Inv	-185.0
					Total	10044.1

6.0 CONCLUSION

Several alternative generation plans have been examined in the process of determining the base case generating composition of NEPOOL in the horizon year 1995. The base case was chosen as the economic optimal considering nuclear, gas turbines and PSH generating types.

7.0 RESULTS AND ANALYSIS

The base case of the simulated New England Power Pool was described in Section 3. The composition of the 1995 power system is:

	Nuclear	Oil Steam	Coal Steam	Gas Turbines	Pondage Hydro	Pumped Storage Hydro
MW Capacity	27994	12681	485	2835	1350	2600
Capacity Factor %	66	28	53	3	40	20

The 15 year levelized production costs are $9435 million/year.

7.1 SYSTEM CHARACTERISTICS OF PVCS

The PVCS device has a daily output profile as illustrated in Figure 3.3.7-5. The PVCS device provides output for only a few hours of the day. However, the hours of the day during which the device provides output also coincides with the time of day of greatest utility power system demand. There is a tendency, however, for the PVCS device's output to decay near 5 PM whereas the utility power system demand may persist until 10 PM as in the winter months and 8 PM during the summer months.

7.2 DEDICATED VERSUS SYSTEM STORAGE

The simulation of storage devices can be performed in two ways: (1) stor-

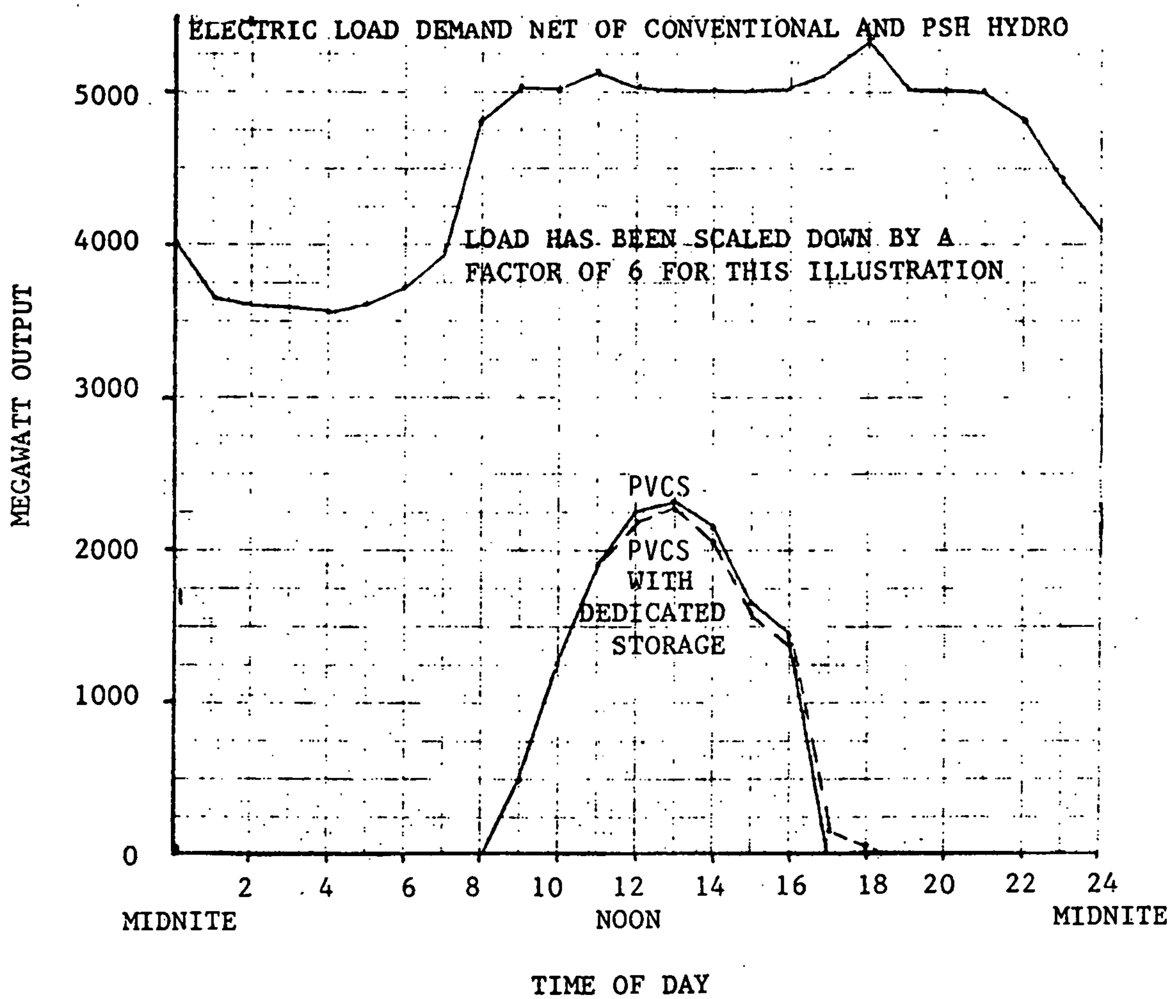


FIGURE 3.3.7-5. ILLUSTRATION OF PVCS AND PVCS WITH DEDICATED STORAGE FOR THE MONTH OF JANUARY

age dedicated to the PVCS output and (2) power system wide storage.

In dedicated storage, the storage device cannot operate unless the PVCS device has supplied energy to it.

In system storage, the storage device may receive energy from either the PVCS device or any other generating unit on the power system. This added flexibility renders system storage of greater value to the utility. However, since PVCS are not a deterministic devices whose output can be accurately predicted several days to a week ahead of time, PVCS presents some difficulties from system storage reservoir management viewpoint. In these system storage simulations of this study it was assumed that either (1) no weekly reservoir management advance planning would include consideration of PVCS or (2) perfect weekly forecasting and advance planning of PVCS. Neither these two cases are entirely accurate, but they do tend to bound the problem. Realistically, weather projections can be made one or two days in advance with some accuracy. Longer weather projections up to 1 week are needed, however, for storage reservoir planning. In the case of no forecasting of PVCS, if PVCS energy were available during an hour, the energy would be utilized for storage at the expense of some other type of energy, such as nuclear. For example, the reservoir's management plan would be developed assuming no PVCS. Suppose as a result of this plan nuclear generation was to supply 1000 MWHR between 1 AM and 2 AM on Tuesday, May 5th. If the PVCS output during this hour were 500 MWHR, the storage plan would be adjusted so that 500 MWHR of PVCS and 500 MWHR of nuclear energy supplied the storage device. Furthermore, it was assumed that the storage device would have adequate storage capability to supply power during the peak load demand periods in the event that it was called upon to do so for system reliability purposes.

Figure 3.3.7-6 illustrates the differences between dedicated storage. Furthermore,the PVCS dedicated storage is used hardly at all.

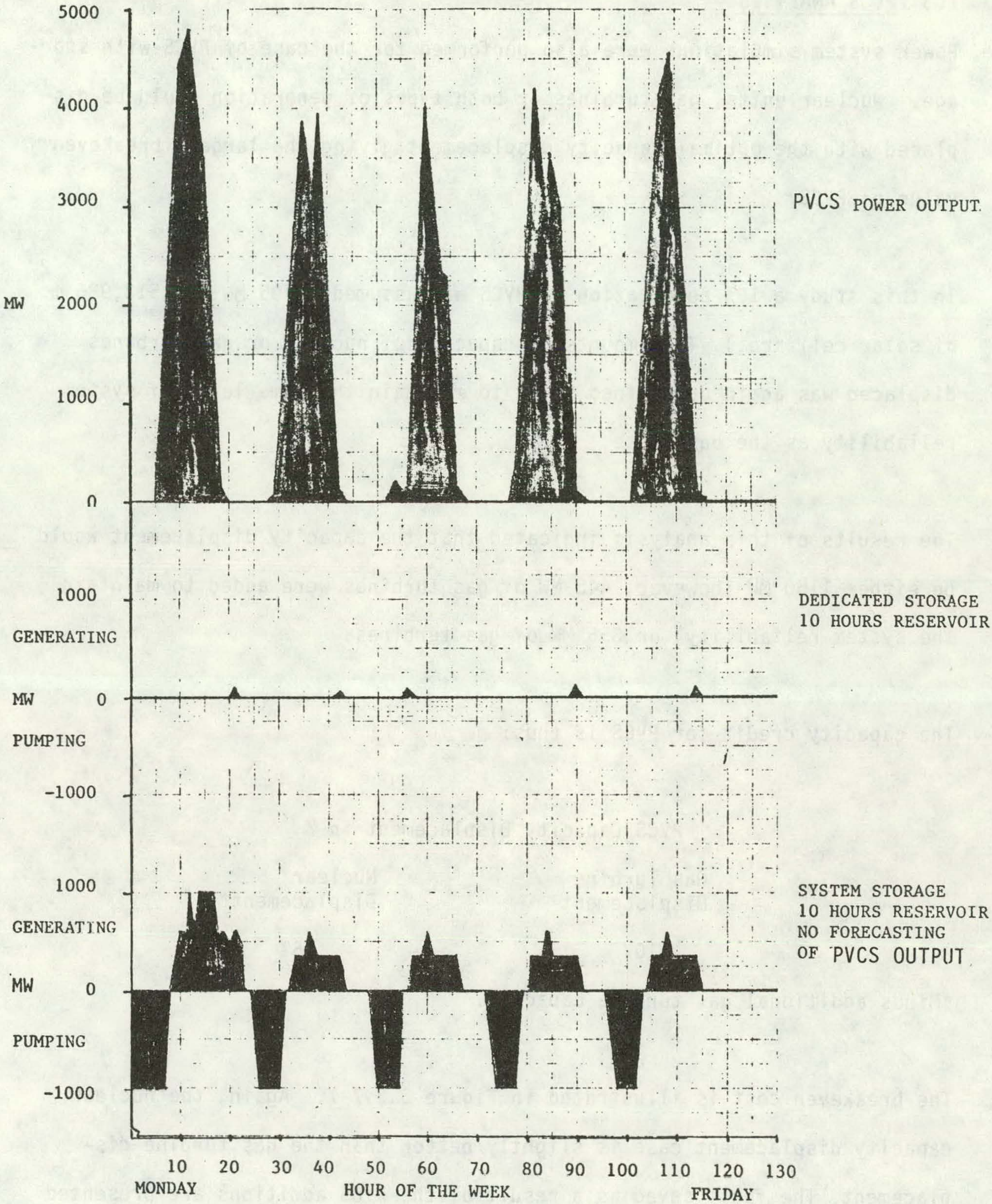


FIGURE 3.3.7-6. CONTRAST OF DEDICATED AND SYSTEM STORAGE FOR PVCS

7.3 PVCS ANALYSIS

Power system simulations were also performed for the case of PVCS with storage. Nuclear units, gas turbines or both types of generation could be displaced with the optimal capacity displacement giving the largest breakeven value of PVCS.

In this study a 10% penetration of PVCS was assumed (4405 MW: 38,513,986 m^2 of solar cell area). The amounts of capacity of nuclear or gas turbines displaced was again determined so as to maintain the same level of system reliability as the base case.

The results of this analysis indicated that the capacity displacement would be either 1150 MW (however, 445 MW of gas turbines were added to maintain the system reliability) or 355 MW of gas turbines.

The capacity credit for PVCS is thus:

PVCS Capacity Displacement in %

Gas Turbine Displacement	Nuclear Displacement*
10%	16%

*Minus additional gas turbine capacity.

The breakeven cost is illustrated in Figure 3.3.7-7. Again, the nuclear capacity displacement case is slightly better than the gas turbine displacement. The fuels saved as a result of the PVCS additions are presented in the bottom section of Figure 3.3.7-7.

The next step in the analysis, Figure 3.3.7-8, was to add storage to the power system and to accrue any additional benefits beyond that of the PVCS result. Adding 1000 MW dedicated storage to the PVCS output, results in a small capacity savings (400 MW gas turbine displacement). Similarly, the fuel savings is small. The breakeven cost is $120/KW which again is significantly less than the $375/KW incremental value of storage with no PVCS.

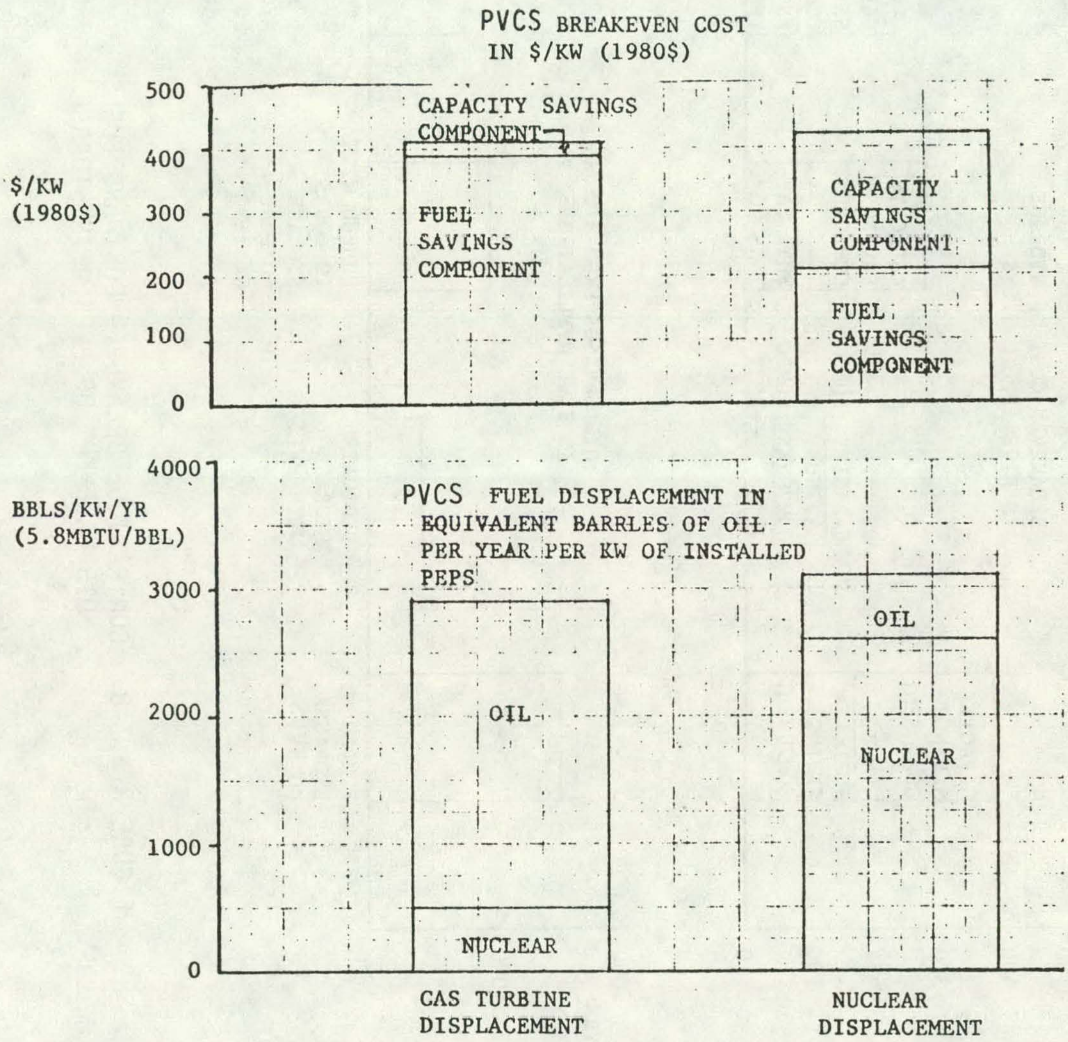


FIGURE 3.3.7-7. CONTRAST OF PVCS BREAKEVEN COST AND FUEL DISPLACEMENT FOR GAS TURBINE VS. NUCLEAR DISPLACEMENT

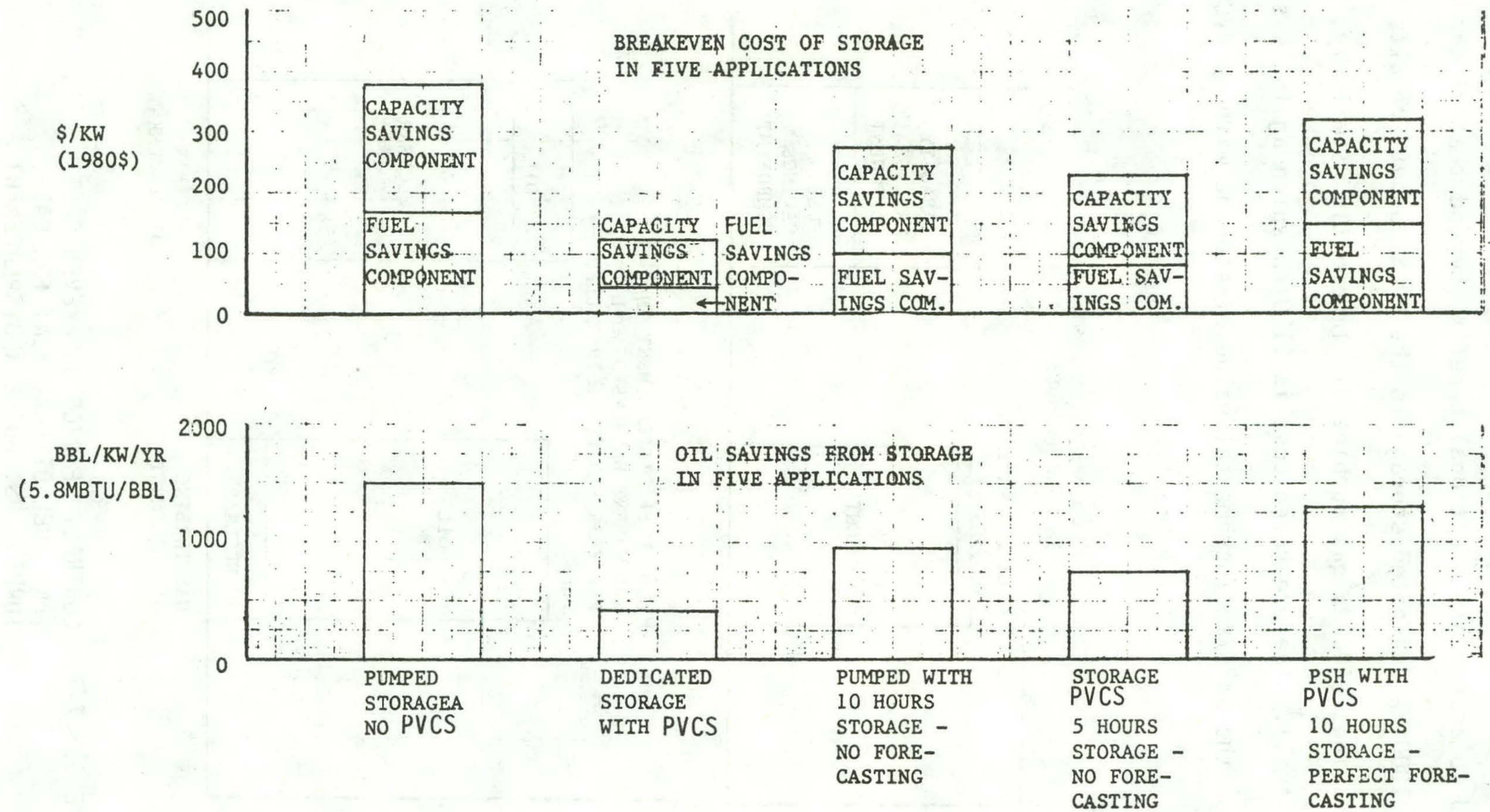


FIGURE 3.3.7-8. CONTRAST OF BREAKEVEN COST AND FUELS DISPLACEMENT OF PVCS WITH STORAGE

The next application of storage is that of system storage with the PVCS with no weekly forecasting of PVCS output. In this application two cases were examined for 1000 MW of system storage, ten and five hour reservoir storage capacity. Both cases showed that the value of storage with PVCS was significantly smaller than the incremental value of storage with the smaller reservoir storage being least. However, it should be noted that the value of the five hour reservoir storage case was only 85% of that of the 10 hour reservoir case.

The final application of storage with 1000 MW of system storage with 10 hours reservoir and with perfect weekly forecasting of PVCS output. The value of the storage improved in this case, but it was still not equal to the value of the system storage device with no PVCS.

Conclusions from the PVCS results are:

1. Operating storage in a dedicated or system manner can lead to a severe economic penalty.

2. System storage with PVCS does not enhance the value of PVCS on the basis of these studies.

8.0 OVERALL CASE STUDY CONCLUSIONS FOR PVCS WITH ENERGY STORAGE

On the basis of the simulations conducted for New England Power Pool in 1995, the following conclusions were obtained:

- Operating storage in a dedicated manner with PVCS can lead to a significant economic penalty.

- There is a significant potential to improve the value of system storage in PVCS applications by accurate weekly forecasting of PVCS output.

- Storage has a greater potential application with WECS than with PVCS. This is because PVCS energy is available during the time of the utility peak. In this sense, PVCS approximately follows the utility load demand. (The WECS analysis is presented in Volume III of this study report).

3.4 ANALYSIS AND PROJECTION OF RESIDENTIAL STORAGE SYSTEM COST GOALS

3.4.1 ENERGY MANAGEMENT

The residential application differs from the previously discussed utility case in several significant aspects. The power flow is in one direction; however, it feeds the house load directly rather than a power system grid. The utility is the backup energy source. Figure 3.4-1 schematically depicts system operation

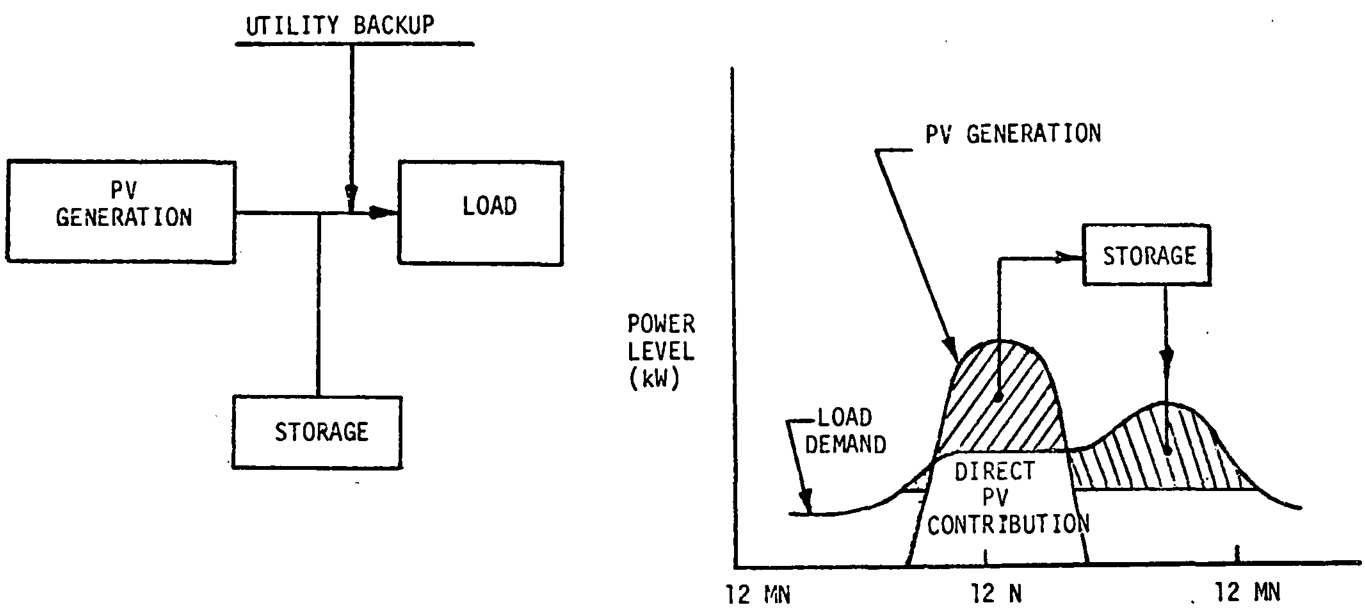


FIGURE 3.4-1 PHOTOVOLTAIC ENERGY CONVERSION WITH DEDICATED STORAGE

The storage operational strategy is quite simple. When the photovoltaic system (PV) output exceeds the load demand, the excess energy is put into storage and subsequently drawn out when the load exceeds PV output. When the sum of PV output and storage cannot meet the load, the utility backup is called upon. Figure 3.4-1 shows non-coincident PV output and load peaks typical of many residential photovoltaic applications. For this situation, the role of energy storage is to accumulate the excess mid-day PV energy and dispense it during the late afternoon - early evening load peaks. Although these are typical PV output and load patterns, it should be noted that wide variations occur. An important option, not considered in this study, is utility "feedback", in which excess PV energy is fed back to the utility grid and credited at some pre-determined rate. This is an area which has been covered in other studies [1] and should be considered as an alternative to on-site energy storage.

3.4.2 PHOTOVOLTAIC ENERGY AVAILABILITY AND CONVERSION

The characteristics of photovoltaic energy conversion discussed in Section 3.3.2 apply to the residential application as well as utility applications. Solar insolation data for the residential analysis was taken from hourly tapes developed on a previous program for three locations - Phoenix, Arizona, Miami, Florida and Boston, Massachusetts.

A 9.6 kW (nominal 10 kW rating) photovoltaic system was selected for performance analysis using the above hourly insolation tapes. Design characteristics for the basic PV system are presented in Table 3.4-1.

TABLE 3.4-1 9.6 kW PHOTOVOLTAIC SYSTEM CHARACTERISTICS

Rated Power	9.6 kW
Insolation	1 kW/m^2
Array Temperature	60°C
Solar Cell Area	84 m^2

Combining the above performance curve with the insolation tape data for each site yields hour by hour PV output for 8760 hours or one year of projected operation. Table 3.4-2 presents the total annual output for the three residential locations.

TABLE 3.4-2 9.6 kW (84 m^2 SOLAR CELL) PHOTOVOLTAIC SYSTEM ANNUAL ENERGY OUTPUT

LOCATION	ANNUAL OUTPUT (kWh)
Phoenix, AZ	23,362
Miami, FL	21,302
Boston, MA	16,588

Obviously, the portion of the above energy that can be supplied directly to the load is a function of the absolute magnitude of the load and its phasing with PV output.

3.4.3 LOAD DEMANDS

The residential loads were selected from those established for representative cities during a prior study for NASA-Lewis.[16,27] The loads are associated with an all-electric single family residence and include space heating/cooling, hot water heating and diversified house loads. The diversified load component includes lighting, appliances and other miscellaneous household equipment. The hot water heating load pertains to representative domestic requirements. In order to simplify the analyses, both the diversified and hot water heating loads are assumed to have a fixed profile over the entire year. The space heating and cooling loads, which are clearly location sensitive, are computed separately on an hourly basis using the Building Transient Thermal Load (BTTL) program.[1] This program considers loads produced by: conduction heat losses/gains, infiltration losses/gains, internal sensible and latent heat gains from occupants, electrical appliances, showers and solar heat gains through windows. A standard residence area of 169 m^2 (1819 ft^2) was used for all sites. Conversion from thermal to electrical demand is based on the heat pump coefficient of performance treated as a function of outside ambient temperature.

The three major residential load components described above are summed to form the total load for each residential storage analysis.

Figures 3.4-2, 3.4-3 and 3.4-4 show typical profiles for the three components of the residential load model. Table 3.4-3 lists the actual total combined loads for the three locations examined in this study.

TABLE 3.4-3 RESIDENTIAL ANNUAL LOADS

LOCATION	ANNUAL HEATING LOAD	ANNUAL COOLING LOAD	DIVERSIFIED HOUSE LOAD	HOT WATER HEATING LOAD	TOTAL ANNUAL LOAD
Phoenix, AZ.	1,292	7,410	7,665	5,110	21,477
Miami, FL	33	8,758	↓	↓	21,566
Boston, MA	8,790	1,180			22,745

All Values in kWh

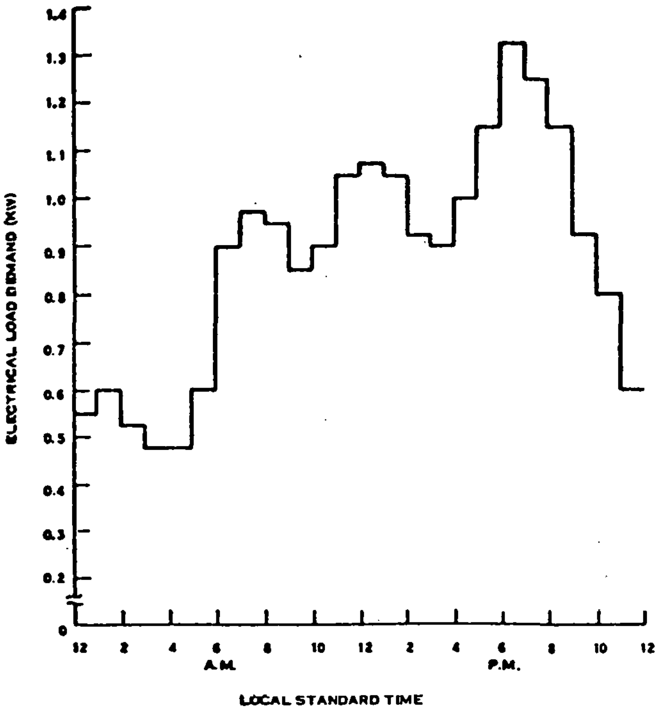


FIGURE 3.4-2. DIVERSIFIED RESIDENTIAL LOAD DEMAND PROFILE

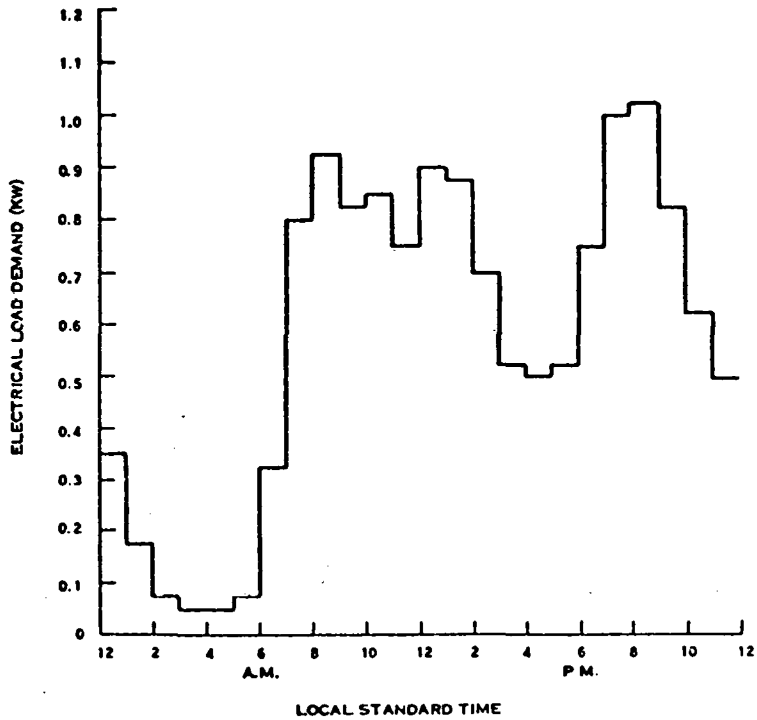


FIGURE 3.4-3. RESIDENTIAL HOT WATER HEATER ELECTRICAL LOAD DEMAND PROFILE

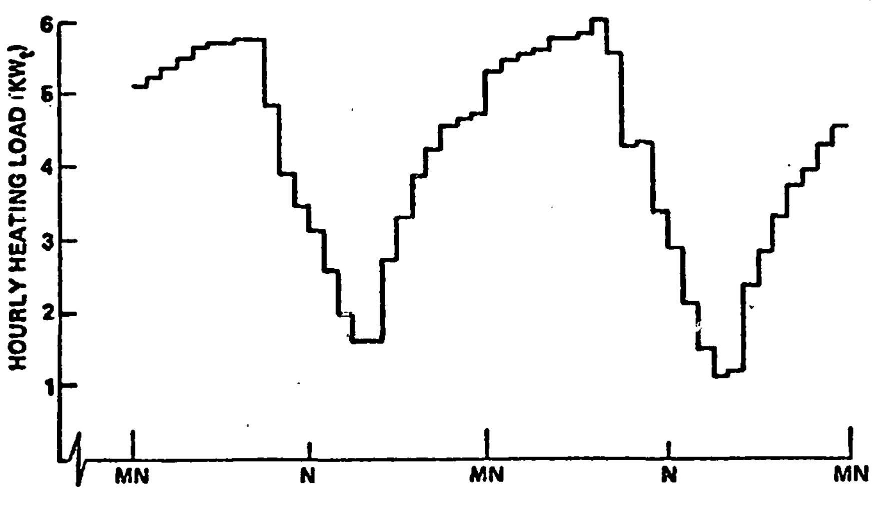


FIGURE 3.4-4. TYPICAL RESIDENTIAL WINTER HEATING DEMAND PROFILE

3.4.4 GENERATION AND LOAD MATCHING WITHOUT STORAGE

A baseline no-storage case was computed initially for each residential location. The hour-by-hour tapes of PV output and total residence electrical demands were compared by computer program to determine what portion of the PV output could be supplied direct to the load. Excess PV energy and required utility makeup energy were also computed and summed for the full 8760 hours. Results are presented in Table 3.4-4.

TABLE 3.4-4. RESIDENTIAL LOAD MATCHING - 9.6 kW (84 m^2 SOLAR CELL AREA) PV SYSTEM - NO STORAGE

LOCATION	DEMAND	PV SYSTEM OUTPUT	PV SYSTEM UTILIZED	PV SYSTEM EXCESS	PURCHASED ENERGY
Phoenix	21,477	23,362	10,337	13,025	11,140
Miami	21,566	21,302	10,694	10,608	10,872
Boston	22,745	16,588	6,981	9,607	15,764

All Values in kWh

3.4.5 GENERATION AND LOAD MATCHING INCORPORATING STORAGE

The next step in the analysis was the addition of energy storage to use excess PV energy to offset the remaining purchased electrical energy shown in Table 3.4-4. Storage was added in 12 kilowatt hour capacity increments and an hour-by hour computer analysis performed as in the no storage case. System operational strategy is as follows:

1. Photovoltaic system output is supplied directly to the load when it can be used.

2. When PV output exceeds the load, excess is put into storage. When storage is full (completely charged), excess PV output is dissipated.

3. When PV output is less than the house load, storage output is used, within the constraints of the discharge rate limit and the minimum allowable state of charge.

4. When total load cannot be met with PV output and/or storage output, utility makeup is permitted.

Inherent in the above strategy is the assumption that purchased electrical energy has a constant value throughout the day. Under several proposed peak load and time of day pricing schedules this would no longer be true, thus making some alternative storage operational strategy more economic. Such an alternate strategy might include utility off-peak charging if the rate differential was substantial.

Table 3.4-5 presents a sample hour-by-hour computer run using the four part operational strategy given above. Most of the column headings are self-explanatory. SOC is storage state-of-charge representing the decimal fraction of total storage capacity (24 kWh for the sample case) charged and available at any given time. Minimum allowable state of charge (SOC) is .1, while only at the maximum SOC of 1.0 can excess PV energy be dissipated. This occurs at hours 15 through 17 of day 1 in the example case. Conversion and power handling equipment efficiencies of .95 are assumed for charging and discharging of storage, in addition to the variable storage efficiency (.75 in the sample case). Inverter efficiency is set at .90. The AUX PWR

TABLE 3.4-5. SAMPLE COMPUTER OUTPUT - RESIDENTIAL PHOTOVOLTAIC STORAGE

24 kWh STORAGE CAPACITY
PHOENIX, AZ

MON	DAY	HR	HOT WATER + DIVER-SIFIED LOAD (KW)	A/C OR HEAT PUMP LOAD (KW)	TOTAL LOAD (KW)	SA OUTPUT PWR (KW)	SOC	BATT PWR (KW)	AUX PWR (KW)	EXCESS PWR (KW)	PWR LOSS (KW)
2	1	0	0.	0.	1.296	0.	0.415	-1.516	0.	0.	0.220
2	1	1	0.	0.	1.333	0.	0.351	-1.560	0.	0.	0.226
2	1	2	0.	0.	1.281	0.	0.288	-1.498	0.	0.	0.217
2	1	3	0.	0.	1.275	0.	0.226	-1.491	0.	0.	0.216
2	1	4	0.	0.	1.292	0.	0.163	-1.512	0.	0.	0.219
2	1	5	0.	0.	1.578	0.	0.100	-1.512	0.286	0.	0.219
2	1	6	0.	0.	2.235	0.	0.100	0.	2.235	0.	0.
2	1	7	0.	0.	2.827	0.	0.100	0.	2.827	0.	0.
2	1	8	0.	0.	2.858	0.101	0.100	0.	2.767	0.	0.010
2	1	9	0.	0.	2.416	1.913	0.100	0.	0.694	0.	0.191
2	1	10	0.	0.	1.981	5.496	0.198	3.131	0.	0.	0.385
2	1	11	0.	0.	1.800	7.597	0.364	5.317	0.	0.	0.480
2	1	12	0.	0.	1.975	9.293	0.575	6.744	0.	0.	0.574
2	1	13	0.	0.	1.925	9.816	0.803	7.293	0.	0.	0.598
2	1	14	0.	0.	1.625	7.736	0.979	5.634	0.	0.	0.477
2	1	15	0.	0.	1.425	7.716	1.000	0.681	0.	5.416	0.194
2	1	16	0.	0.	1.500	6.139	1.000	0.	0.	4.473	0.167
2	1	17	0.	0.	1.675	4.120	1.000	0.	0.	2.259	0.186
2	1	18	0.	0.	2.075	0.509	0.921	-1.891	0.	0.	0.325
2	1	19	0.	0.	2.250	0.	0.812	-2.632	0.	0.	0.382
2	1	20	0.	0.	2.175	0.	0.706	-2.544	0.	0.	0.369
2	1	21	0.	0.	1.750	0.	0.620	-2.047	0.	0.	0.297
2	1	22	0.	0.	1.425	0.	0.551	-1.667	0.	0.	0.242
2	1	23	0.	0.	1.116	0.	0.496	-1.306	0.	0.	0.189
2	2	0	0.	0.	1.055	0.	0.445	-1.234	0.	0.	0.179
2	2	1	0.	0.	1.006	0.	0.396	-1.176	0.	0.	0.171
2	2	2	0.	0.	0.833	0.	0.355	-0.975	0.	0.	0.141
2	2	3	0.	0.	0.788	0.	0.317	-0.921	0.	0.	0.134
2	2	4	0.	0.	0.765	0.	0.280	-0.895	0.	0.	0.130
2	2	5	0.	0.	0.979	0.	0.232	-1.145	0.	0.	0.166
2	2	6	0.	0.	1.603	0.	0.154	-1.875	0.	0.	0.272
2	2	7	0.	0.	2.209	0.	0.100	-1.293	1.103	0.	0.188
2	2	8	0.	0.	2.367	0.134	0.100	0.	2.247	0.	0.013
2	2	9	0.	0.	1.865	1.796	0.100	0.	0.249	0.	0.180
2	2	10	0.	0.	1.750	5.309	0.200	3.196	0.	0.	0.363
2	2	11	0.	0.	1.800	8.790	0.401	6.450	0.	0.	0.539
2	2	12	0.	0.	1.975	10.325	0.643	7.724	0.	0.	0.626
2	2	13	0.	0.	1.925	11.471	0.920	8.866	0.	0.	0.681
2	2	14	0.	0.	1.625	11.197	1.000	2.564	0.	6.692	0.316
2	2	15	0.	0.	1.425	10.266	1.000	0.	0.	8.683	0.158
2	2	16	0.	0.	1.500	8.484	1.000	0.	0.	6.817	0.167
2	2	17	0.	0.	1.675	5.692	1.000	0.	0.	3.831	0.186
2	2	18	0.	0.	2.075	0.513	0.921	-1.887	0.	0.	0.325
2	2	19	0.	0.	2.250	0.	0.812	-2.632	0.	0.	0.382
2	2	20	0.	0.	2.175	0.	0.706	-2.544	0.	0.	0.369
2	2	21	0.	0.	1.750	0.	0.620	-2.047	0.	0.	0.297
2	2	22	0.	0.	1.585	0.	0.543	-1.853	0.	0.	0.269
2	2	23	0.	0.	1.342	0.	0.478	-1.570	0.	0.	0.228
2	3	0	0.	0.	1.231	0.	0.418	-1.440	0.	0.	0.209
2	3	1	0.	0.	1.233	0.	0.358	-1.442	0.	0.	0.209
2	3	2	0.	0.	1.100	0.	0.304	-1.287	0.	0.	0.187

column represents purchased utility energy, which is summed for the 8760 hour run, with results as shown in Table 3.4-6.

TABLE 3.4-6. SUPPLEMENTAL UTILITY ENERGY REQUIRED-RESIDENTIAL ENERGY STORAGE ADDED TO PHOTOVOLTAIC ENERGY SYSTEM

STORAGE SIZE kWh	PHOTOVOLTAIC SITE LOCATION		
	PHOENIX	MIAMI	BOSTON
0	11,140	10,872	15,764
12	7,901	7,838	13,402
24	5,492	5,906	11,729
36	4,628	5,449	---
48	4,487	5,309	10,693
72	4,383	5,191	10,489

All values in kWh

Subtraction of purchased utility energy using storage, from the quantity required with no storage yields the savings in kWh due to energy storage:

TABLE 3.4-7. REDUCTION IN RESIDENTIAL ANNUAL ENERGY CONSUMPTION DUE TO STORAGE

STORAGE SIZE (kWh)	PHOTOVOLTAIC SITE LOCATION		
	PHOENIX	MIAMI	BOSTON
12	3,239	3,034	2,362
24	5,648	4,966	4,035
36	6,512	5,423	---
48	6,653	5,563	5,071
72	6,757	5,681	5,275

All Values in kWh

The above data is presented graphically in Figure 3.4-5.

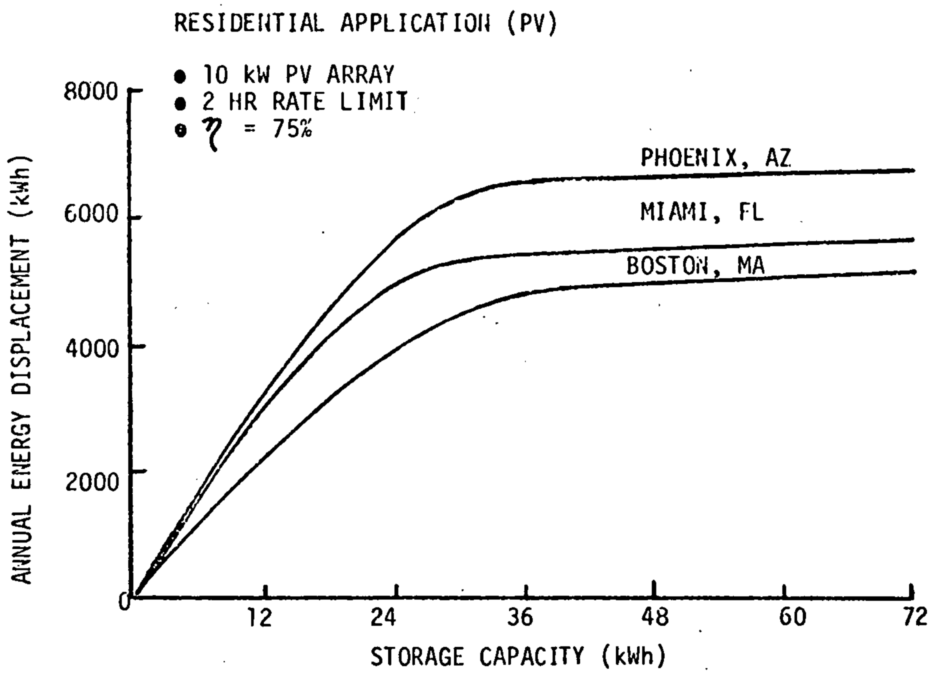


FIGURE 3.4-5. LOCATION EFFECT ON RESIDENTIAL ENERGY DISPLACEMENT USING STORAGE.

A representative mean energy displacement curve was constructed from the individual site data for use in the further, more detailed analysis that follows. This representative mean is shown in Figure 3.4-6.

3.4.6 COST GOALS AND PARAMETRIC ANALYSIS

The numerics required to carry out the residential cost goal evaluation are explained and the results presented in this section. The types of storage systems to be compared include: lead-acid batteries, advanced batteries, inertial (flywheel), and pneumatic storage. The selection of these candidates for residential use was discussed in Section 1.2 and in Volume I of this report.

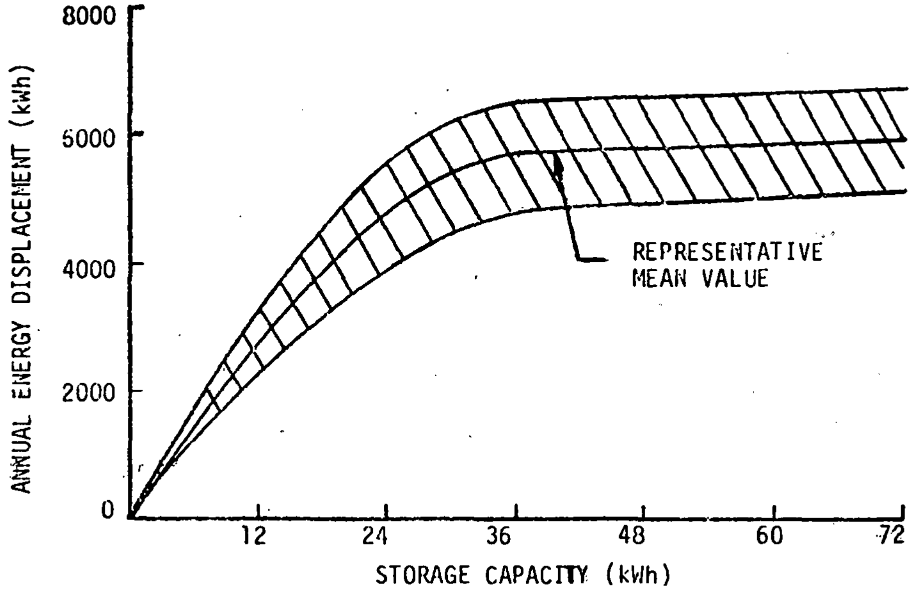


FIGURE 3.4-6. REPRESENTATIVE MEAN RESIDENTIAL ENERGY DISPLACEMENT DUE TO STORAGE.

It should be noted here, however, that the selection of these systems for further analysis is not indicative of a final recommendation for their use, but merely a further step in their assessment. The immediate purpose here is to apply the results of the computer modeling to these specific concepts.

3.4.6.1 Determination of Energy Storage Break-Even Costs

The break-even cost for residential energy storage systems was determined by finding the difference between the capitalized annual displaced energy credit and capitalized O&M costs. The overall procedure for determining the break-even cost consisted of the following steps:

1. Selection of the storage system, Photovoltaic array (solar cell) size, location and storage capacity.
2. Determination of the PV annual energy performance with and without storage.
3. Determination of the annual displaced energy credit due to addition of storage using the average cost of electricity.
4. Determination of the capitalized displaced energy credit, accounting for the effects of storage efficiency.
5. An estimate of the capitalized O&M costs for subtraction from the step 4 result.
6. Comparison of storage system break-even cost from step 5 with projected actual or estimated system costs.

The first two steps above were discussed in the previous section; discussion of the remaining steps follows.

3.4.6.2 Cost of Electricity

The principal economic benefit associated with addition of residential storage to PV conversion systems is a reduction in the cost of purchased electricity. Recent residential electricity price data for the three selected PV sites and the U.S. as a whole is presented in Table 3.4-8. The United States average value of 4¢/kWh was used in subsequent analysis and corresponds closely to the average of the prices at the three PV sites. Analysis was also performed at several electricity price escalation rates.

TABLE 3.4-8. REPRESENTATIVE RANGE OF RESIDENTIAL ELECTRIC ENERGY COSTS

LOCATION	CONSUMER COST OF ELECTRICITY (¢/kWh)[25]
Phoenix, AZ	4.0
Miami, FL	4.0
Boston, MA	5.0
U.S. Average	4.0

3.4.6.3 Displaced Energy Credit

An annual displaced energy credit for energy storage at 75% storage efficiency, A_E^O is determined by multiplying the annual energy displacement by the cost of electricity. Using the mean energy displacement as presented in Figure 3.4-6 and the 1976 national average residential price of electricity (4¢/kWh) the A_E^O versus storage capacity curve of Figure 3.4-7 is readily computed.

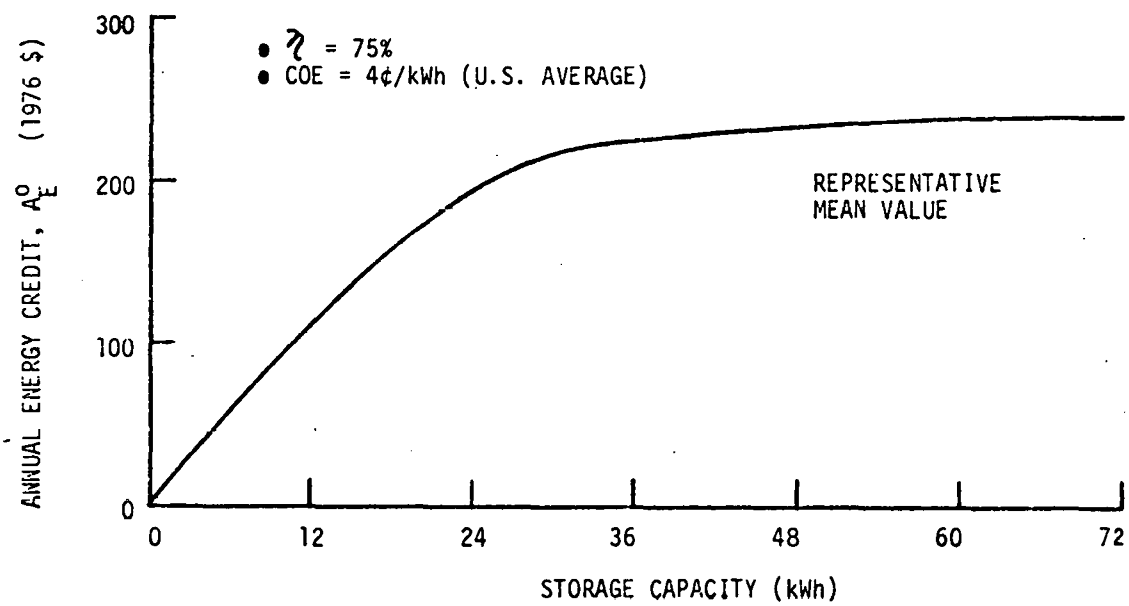


FIGURE 3.4-7. ANNUAL RESIDENTIAL MEAN ENERGY CREDIT VERSUS STORAGE CAPACITY

Electricity price escalation beyond 1976 is accounted for by computing $\overline{M_e}$, the levelizing value of an escalating cost stream:[23,24]

$$M_e = \frac{r\,(1 + e)}{r - e} \left[\frac{(1 + r)^n - (1 + e)^n}{(1 + r)^n - 1} \right] \quad (1)$$

where

r = discount rate

e = annual electricity price escalation rate

n = storage system life - years

The discount rate, r, for the homeowner is assumed to be the after-tax cost of a 9% loan to an individual in a 20% incremental tax bracket, which can be shown to be 7.2%. Using the capital recovery factory (CRF) or mortgage rate equation:

$$CRF = \frac{r\,(1 + r)^n}{(1 + r)^n - 1} \quad (2)$$

and adding an additional 2.5% annually for taxes and insurance, annual fixed charges can be expressed as a percent of the initial investment. This percent or fixed charge rate (FCR) is presented below versus n, the storage system life.

TABLE 3.4-9. RESIDENTIAL FIXED CHARGE RATES

SYSTEM LIFE (n), YRS	FIXED CHARGE RATE (FCR)
10	.17
20	.12
30	.10

An adjustment was made to the fixed charge rate in the case of battery storage to account for a 20 year system life, but with battery replacement at 10 years with 30 percent salvage value. An equivalent 20 year fixed charge rate was computed at .15 and used in battery break-even cost computations.

Equating fixed charges to energy savings for a start year δ years from 1976 gives:

$$C_E^o \ (1 + g)^{\delta} \ FCR = (1 + e)^{\delta} \ M_e \ A_E^o$$

where

C_E = capitalized energy credit

g = general inflation rate

and, solving for C_E^o:

$$C_E^o = \left(\frac{1 + e}{1 + g}\right)^{\delta} \frac{M_e}{FCR} \quad A_E^o \qquad (3)$$

A table of the quantity $\left(\frac{1 + e}{1 + g}\right)^{\delta}$ M_e is presented at the end of this section.

Up to this point, energy displacement and credits have been evaluated for 75% storage efficiency. For storage systems with efficiencies other than 75%, a correction factor, C_{η}, was determined, which yields a capitalized energy credit:

$$C_E = C_{\eta} \times C_E^o \qquad (4)$$

Figure 3.4-8 presents the results of computer runs evaluating the effect of storage efficiency on energy displacement.

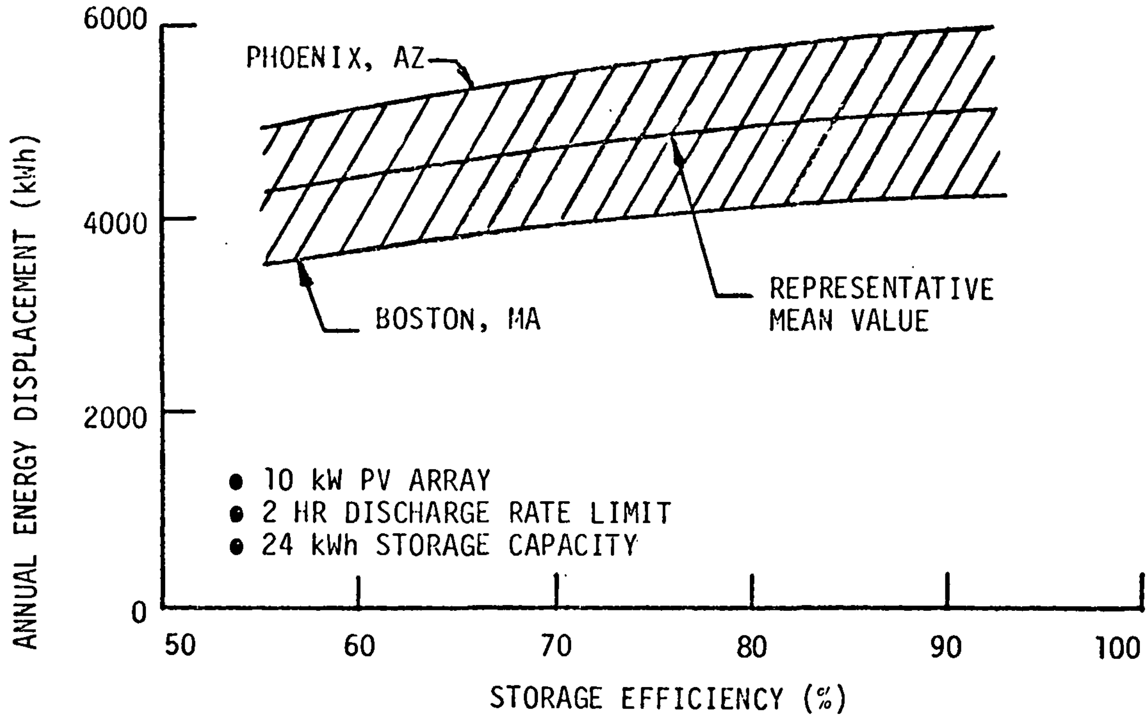


FIGURE 3.4-8. EFFECT OF STORAGE EFFICIENCY ON RESIDENTIAL ENERGY DISPLACEMENT

The data of Figure 3.4-8 was used to construct a curve of C_η, the efficiency correction factor, versus storage efficiency. This is shown in Figure 3.4-9.

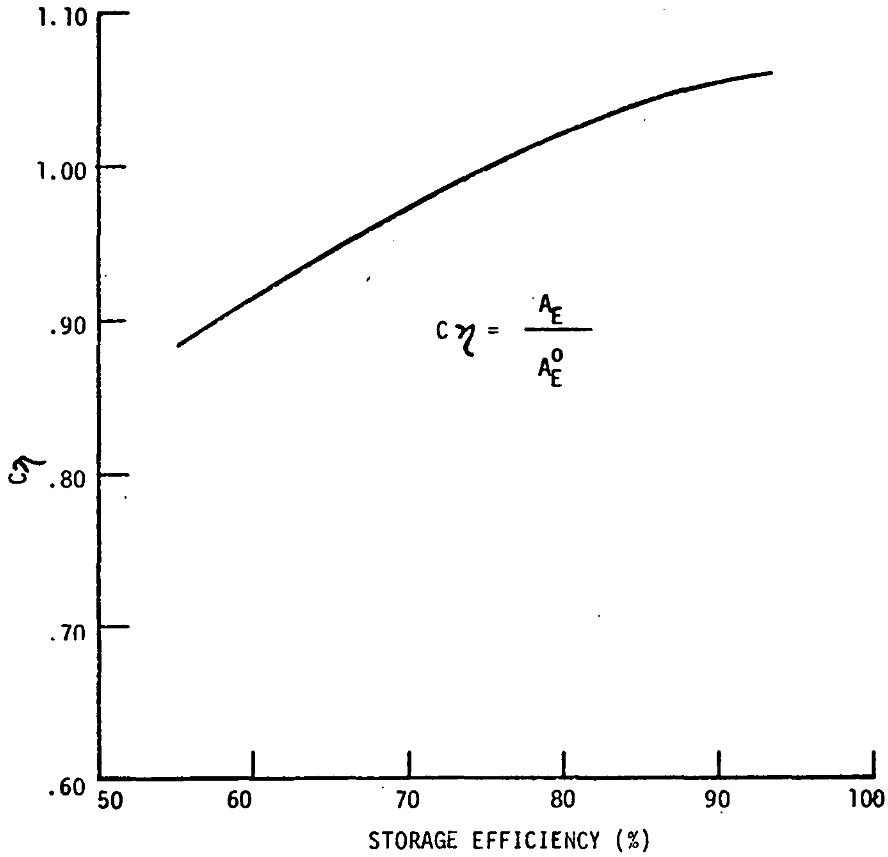


FIGURE 3.4-9. RESIDENTIAL STORAGE EFFICIENCY CORRECTION FACTOR

Energy Credit Multiplier

Presented below is a table of the energy credit multipliers for use in computing break-even costs at various escalation rates and points in time.

$$\text{Energy Credit} = \left(\frac{1 + e}{1 + g}\right) \quad M_e \quad X \quad \frac{\text{1976 Savings}}{\text{Fixed Charge Rate}}$$

TABLE 3.4-10. ENERGY CREDIT MULTIPLIER $\left(\frac{1 + e}{1 + g}\right)^{\delta}$ M_e,
RESIDENTIAL APPLICATION

YEAR	e ELECTRICITY PRICE ESCALATION RATE					
	5%	6%	7%	8%	9%	10%
1976	1.5532	1.7071	1.8802	2.0749	2.2942	2.5413
1982		1.8071	2.1056	2.4570	2.8711	3.3595
1985		1.8592	2.2282	2.6736	3.2119	3.8627
1988		1.9182	2.3579	2.9094	3.5931	4.4412
1994		2.0247	2.6406	3.4452	4.4967	5.8711
2000		2.1432	2.9571	4.0796	5.6275	7.7614

$r = .072, \quad g = .05$

3.4.6.4 Operation and Maintenance Costs

The annual operation and maintenance cost, A_{OM}, is storage system related and estimated according to the expression:

$$A_{OM} = a_{OM} \times ASDE \qquad (5)$$

where

a_{OM} = variable storage O&M costs in \$/kWh of discharge energy

ASDE = annual storage discharge energy

A_{OM} for various types of storage is computed from cost data given in Volume I, Table 5.3-2, and the energy displacement values shown in Figure 3.4-7.

A minimum annual O&M cost of $15 was set, corresponding to a minimum type residential service check to be performed by a local service organization. The annual O&M cost is capitalized in an analogous manner to the energy savings capitalization:

$$C_{OM} = \frac{M_g}{FCR} A_{OM} \qquad (6)$$

where

C_{OM} = capitalized O&M costs

M_g = levelizer for a cost stream escalating at the general inflation rate (same form as M_e previously described)

3.4.6.5 Break-Even Cost

The break-even cost for the residential storage system is the difference between the capitalized energy credit and the capitalized O&M cost:

$$C_{BE} = C_E - C_{OM} \qquad (7)$$

A sample break-even cost computation for lead-acid battery storage is presented below.

Specific Conditions

- 10 kW PV system
- 24 kWh capacity - lead-acid battery
- 2 hour discharge rate limit
- 5% inflation rate, g
- 10% electricity price escalation rate, e
- 20 year system life, n

- 7.2% discount rate, r
- 70% (lead-acid battery) storage efficiency
- Fixed charge rate, FCR = .15
- Variable O&M cost rate, a_{OM} = \$.0005/kWh
- Annual energy displacement = 4842 kWh (mean value); ASDE = 5663 kWh (mean value)
- Start year - 2000
- Results in 1976 dollars

The energy credit A_E^o then becomes:

$$A_E^o = .04\ (4842) = \$193.68$$

From equation (1), M_e = 2.5413 and the capitalized energy credit, C_E^o becomes, from equation (3):

$$C_E^o = \left(\frac{1.10}{1.05}\right)^{24} \left(\frac{2.5413}{.15}\right) (193.68) = \$10{,}021$$

The efficiency correction factor, C_η for lead-acid batteries (70% efficiency) is .974 from Figure 3.4-10. Therefore, the corrected energy credit becomes from equation (4):

$$C_E = .974\ (10{,}021) = \$9760$$

The annual O&M cost, A_{OM}, obtained from equation (5) is:

$$A_{OM} = .0005\ (5663) = \$2.83$$

which is less than \$15.00. Therefore, A_{OM} is set equal to \$15.

$$M_g = 1.5532$$

and the capitalized O&M cost, C_{OM} , becomes from equation (6):

$$C_{OM} = \frac{1.5532}{.15} \quad (15) = \$155$$

The resulting break-even cost from equation (7) is then:

$$C_{BE} = 9760 - 155 = \$9605$$

or

$$C_{BE} = \frac{9605}{24} = \$400.2/\text{kWh of storage capacity}$$

Storage system breakeven costs were computed, using the above methodology, for electricity price escalation equal to general inflation (5%), for a 1985 start year with 6% escalation (1% over inflation), and at an extreme for 10% electricity price escalation with a year 2000 start. Results are tabulated in Table 3.4-11 for the four residential technologies analyzed.

TABLE 3.4-11. STORAGE BREAKEVEN COSTS - RESIDENTIAL APPLICATION

ADVANCED BATTERIES			
kWh	5%	6%-1985	10%-2000
12	84	103	470
24	76	93	410
36	60	73	324
48	46	56	248
72	34	41	181

LEAD-ACID BATTERIES		
5%	6%-1985	10%-2000
81	100	457
75	91	400
60	73	317
46	56	243
34	41	177

FLYWHEEL			
kWh	5%	6%-1985	10%-2000
12	102	126	585
24	88	109	506
36	70	86	400
48	53	66	306
72	39	48	223

PNEUMATIC		
5%	6%-1985	10%-2000
94	116	537
86	105	469
68	83	371
52	64	284
38	46	207

All values in $/kWh of storage capacity.

Differences in efficiency, O&M costs and FCR combine to create a separation in the breakeven costs for each concept. By themselves these breakeven costs do not indicate the desirability of a particular concept.

A comparison of breakeven costs versus storage cost projections is presented for batteries in Figure 3.4-10. The nominal case of 6% electricity price escalation and 1985 start year shows marginal viability for advanced batteries at about 24 kWh capacity and a price of 92 $/kWh. At year 2000 with 10% escalation, both types of batteries show breakeven costs greater than system cost estimates, and would therefore offer economic viability under these conditions. Flywheel and pneumatic energy storage breakeven costs are shown in Figure 3.4-11. Note that neither demonstrate viability until the 10%, 2000 case. System cost estimates shown on the figures are taken from Volume I of this study report. These were selected as reasonably representative for the respective technologies, based on currently available information. With cost data continually changing, the format of the charts was made such that the reader could easily use updated cost estimates as they become available.

There are obviously many start year -escalation rate combinations that will achieve economic viability for a given storage system. Figure 3.4-12 shows battery storage system breakeven costs versus start year and electricity price escalation rate. Cost estimates for lead-acid and advanced batteries are overlaid as dashed lines. At 10% escalation, the figure shows lead-acid batteries becoming economic in 1985, while at 8% viability is delayed until about 1998. The reader can use any source for system cost estimates and electricity price projections and test viability with this chart. Figure 3.4-13 is a similar chart for flywheel and pneumatic storage. Note that only at very high 9 and 10% escalation rates is economy achieved.

TABLE 3.4-12. VALUES FOR OPTIMUM STORAGE DETERMINATION

STORAGE SIZE (kWh)	C_{BE} $\left(\frac{\$}{KWh}\right)$	COST $\left(\frac{\$}{kWh}\right)$	SAVINGS $\left(\frac{\$}{kWh}\right)$	TOTAL CAPITALIZED SAVINGS ($)
12	470	92	378	4536
24	410	↓	318	7632
36	324	↓	232	8352*
48	248	↓	156	7488
72	181	↓	89	6408

* Optimum

Optimum storage size for residential photovoltaic systems is in the 24 to 36 kWh range, for the systems and loads studied. This is probably due to the pronounced "knee" in the energy savings curves (Figure 3.4-6) that occurred in this capacity range for the three locations investigated. Beyond 36 kWh of storage, little additional energy savings were achieved. Whether this result is typical of energy storage in conjunction with photovoltaic systems is not known at this time, but a distinct trend is evident.

3.4.6.7 <u>Photovoltaic System Enhancement</u>

Once storage is available at a cost below its breakeven value, the cost difference can be reflected in an increased allowable price for the basic photovoltaic energy system. Another perspective is that the total PV plus storage system has a breakeven value. As cost of storage is lowered, PV cost can rise and still meet total system breakeven. Figure 3.4-14 shows this effect for three increasingly severe conomic conditions.

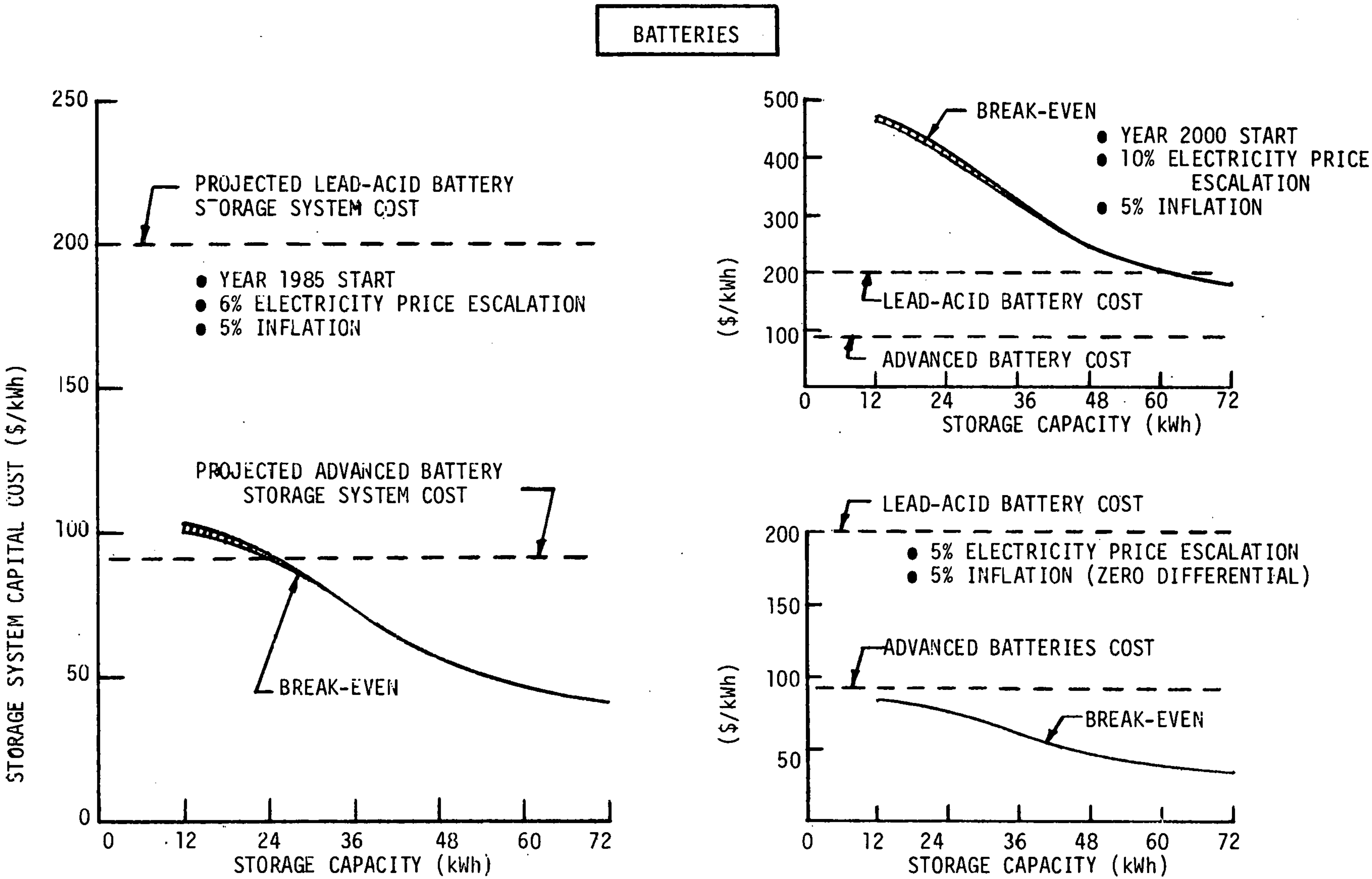


FIGURE 3.4-10. ENERGY STORAGE BREAK-EVEN COST GOALS FOR RESIDENTIAL BATTERY SYSTEMS

INERTIAL (FLYWHEEL) & PNEUMATIC STORAGE

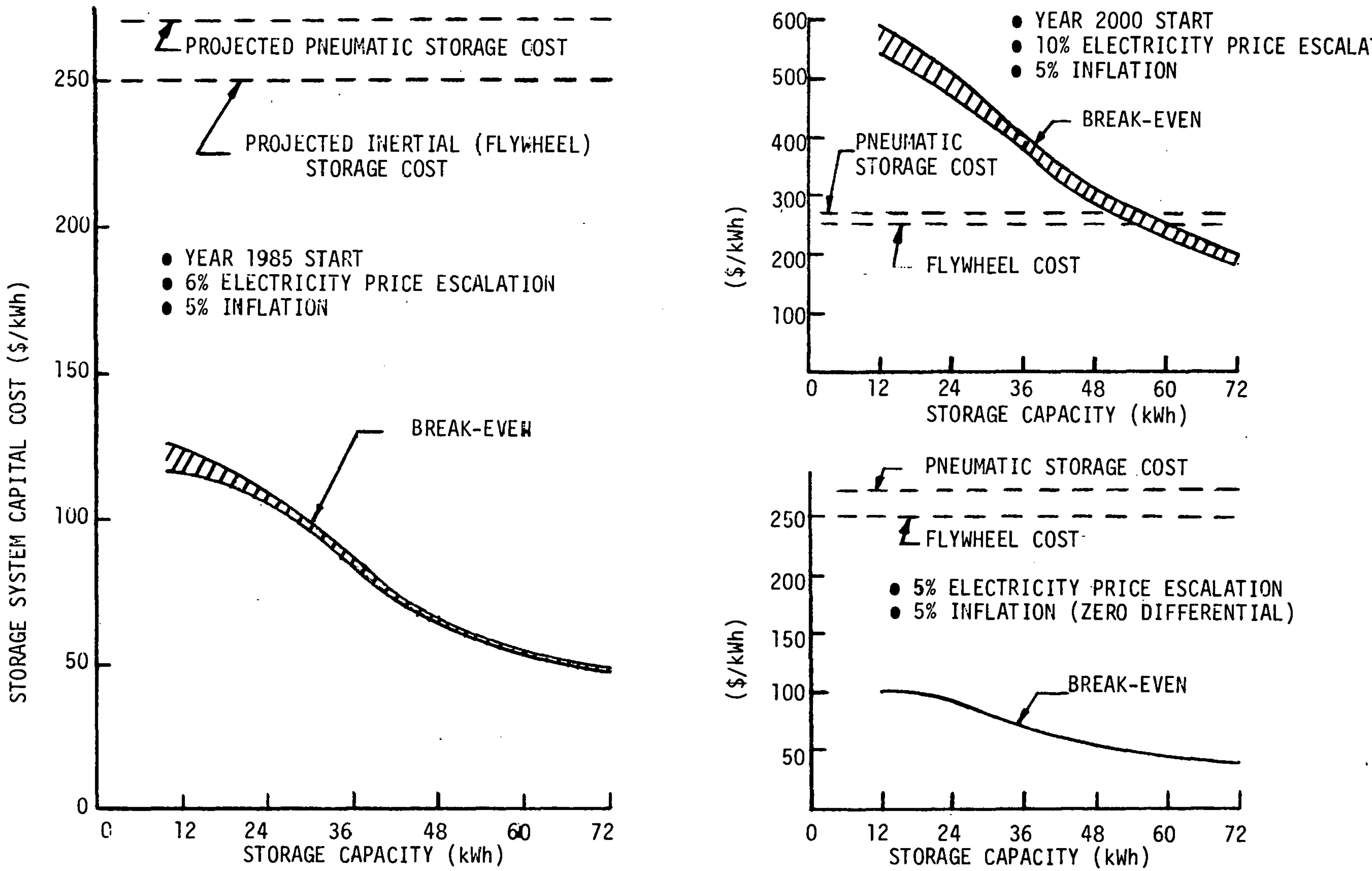


FIGURE 3.4-11. ENERGY STORAGE BREAK-EVEN COST GOALS FOR RESIDENTIAL PV SYSTEMS WITH FLYWHEEL OR PNEUMATIC STORAGE

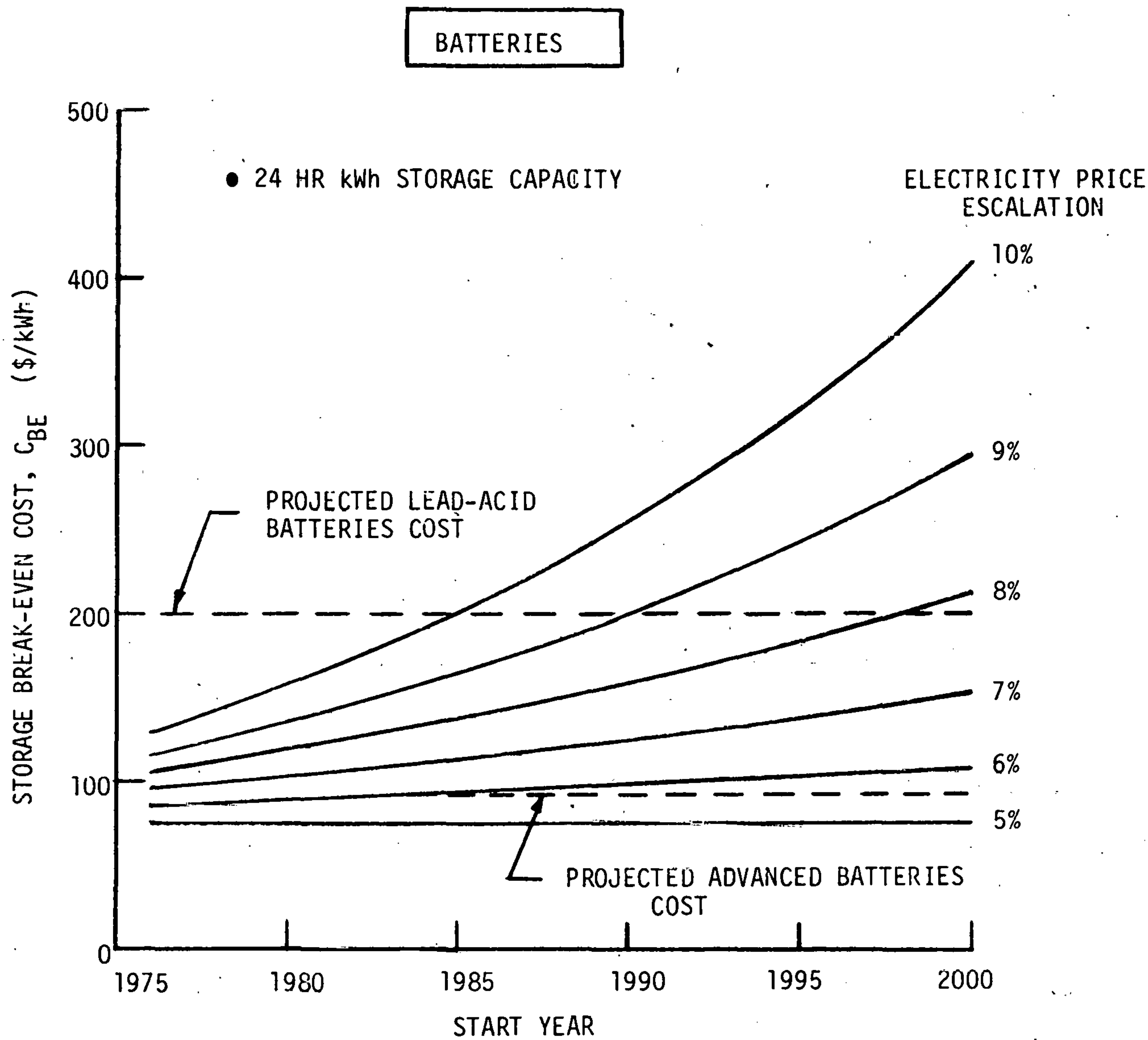


FIGURE 3.4-12. STORAGE BREAK-EVEN COST VS. START YEAR FOR RESIDENTIAL PV BATTERY STORAGE SYSTEMS

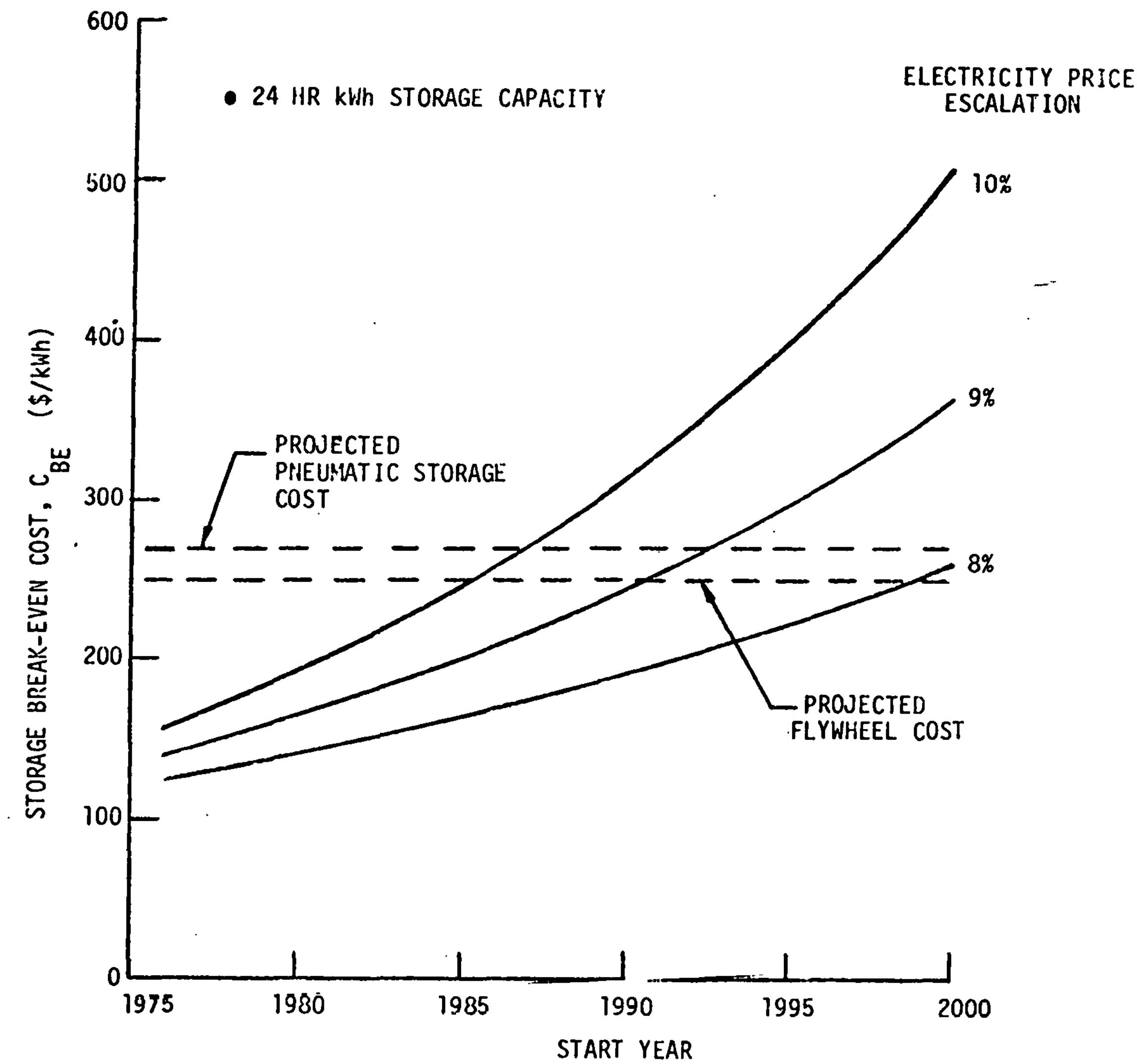


FIGURE 3.4-13. STORAGE BREAK-EVEN COST VS. START YEAR FOR RESIDENTIAL FLYWHEEL AND PNEUMATIC STORAGE SYSTEMS

3.4.6.6 Storage Capacity Optimization

When viability is achieved, the optimum storage size is determined by the maximum capitalized savings. For example, advanced batteries at year 2000, 10% escalation give the following data:

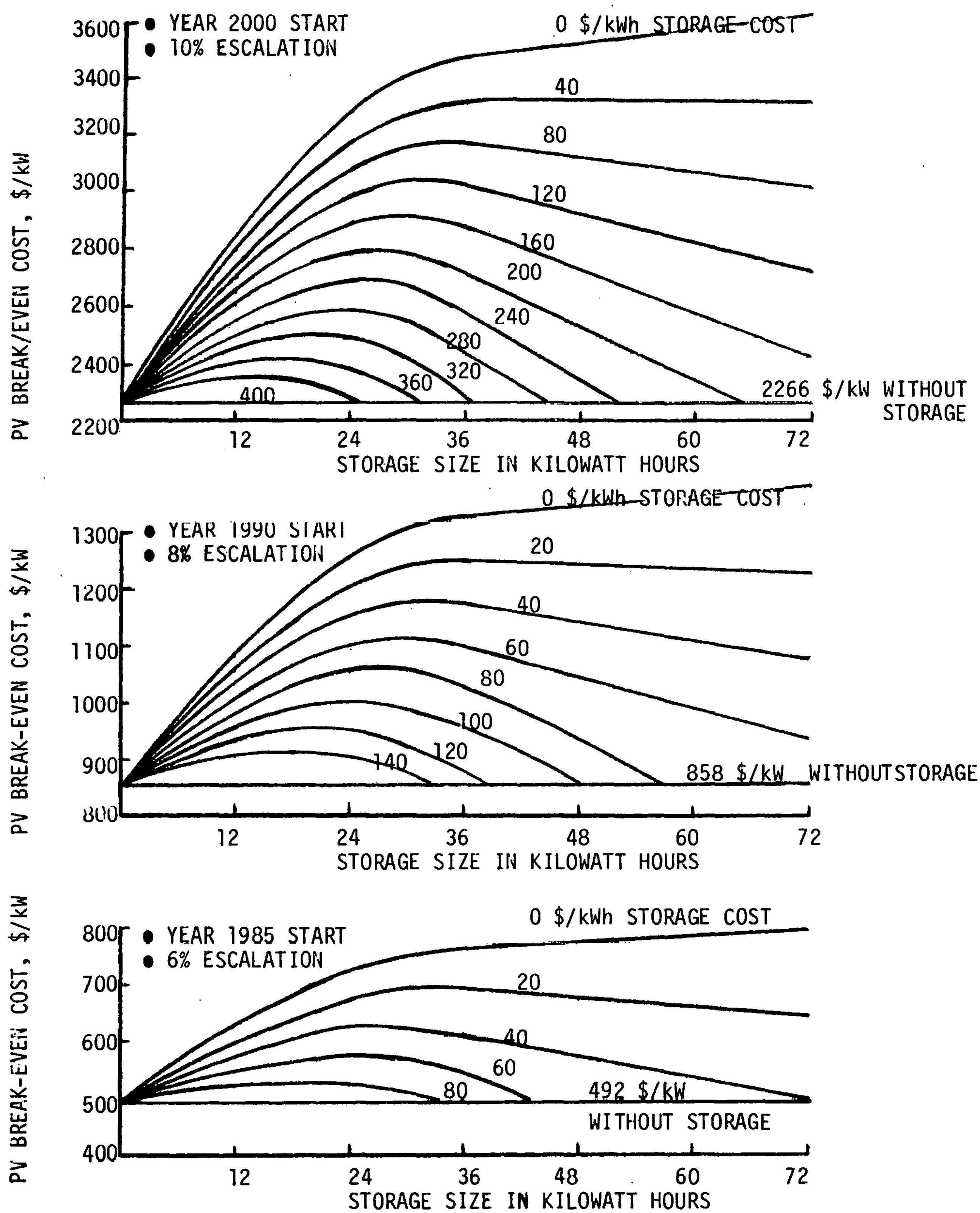


FIGURE 3.4-14. INCREASE IN PHOTOVOLTAIC SYSTEM BREAK-EVEN COSTS DUE TO ENERGY STORAGE

with 6% escalation, 36 kWh of 20 $/kWh storage increases PV allowable cost from $492/kW to about 700 $/kW. The potential for system economic enhancement increases with escalation rate and start year delay. Notice again the clustering of optimum storage levels in the 24 to 36 kWh range.

3.5 ANALYSIS AND PROJECTION OF INTERMEDIATE PHOTOVOLTAIC SYSTEM COST GOALS

3.5.1 ENERGY MANAGEMENT

The intermediate size applications for photovoltaic energy conversion and energy storage cover a very broad range. Individual industrial plants offer one possibility but require specific analyses which are not necessarily broadly representative. After due consideration of candidate applications, it was decided that examination of a complex typical of a shopping center or cluster of small businesses might be most useful for purposes of this study. The energy management/energy storage problem can be seen to have two significant aspects:

1. The need to meet some portion of the total load demand with PV or PV plus storage in order to reduce the overall energy cost of electricity.

2. The need to reduce the costs of electricity based on the power demand rate portion of typical rate schedules.

Because of the variability of insolation and precision of dispatch planning for stored energy that would be involved, Item 2 was found to require special analyses which would involve assumptions of uncertain value. More specifically, the ability to limit power demand charges to some predetermined level by use of stored energy requires that storage output be 100% reliably available on call. Since this criteria could not be met with PV-dedicated storage charging (within reasonable storage size limits), Item 2 was eliminated from further consideration; however, the economics and potential value of peak reductions and load leveling with storage are discussed in Section 3.7.

In the case of Item 1, the availability of photovoltaic energy at times of light load demands can be made more attractive by use of storage which accepts excess generation and saves the PV energy until needed. The improvement (reduction in utility energy use) resulting from the use of storage was analyzed for selected conditions of load and photovoltaic system output. As in the residential case, a one way power flow to the load was assumed, with the utility providing a net "Make-Up" to fully meet the actual load demands.

3.5.2 PHOTOVOLTAIC ENERGY AVAILABILITY AND CONVERSION

The previous discussion in Section 3.3.2 pertaining to characteristics of photovoltaic energy conversion applies to the Intermediate case also. A 500 kW array was used as the basic photovoltaic conversion system. Its principal characteristics are shown in Table 3.5-1.

TABLE 3.5-1. 500 kW PHOTOVOLTAIC SYSTEM CHARACTERISTICS

Rated Power	500 kW
Insolation	1 kW/m^2
Array Temperature	60°C
Solar Cell Area	4371 m^2

Annual energy output for the two PV site locations analyzed were found to be:

Phoenix, AZ	1218 MWh
Boston, MA	864 MWh

3.5.3 LOAD DEMANDS

A daily load pattern was assumed as shown in Figure 3.5-1. Several levels of P, the maximum demand, were investigated in the analysis. This maximum load was assumed to occur from 10 A.M. to 10 P.M. daily and drop to 25% of peak value the remainder of the time, thus reflecting an "idealized" load curve for a shopping center or commercial complex. Table 3.5-2 presents annual energy demand as a function of the maximum power demand.

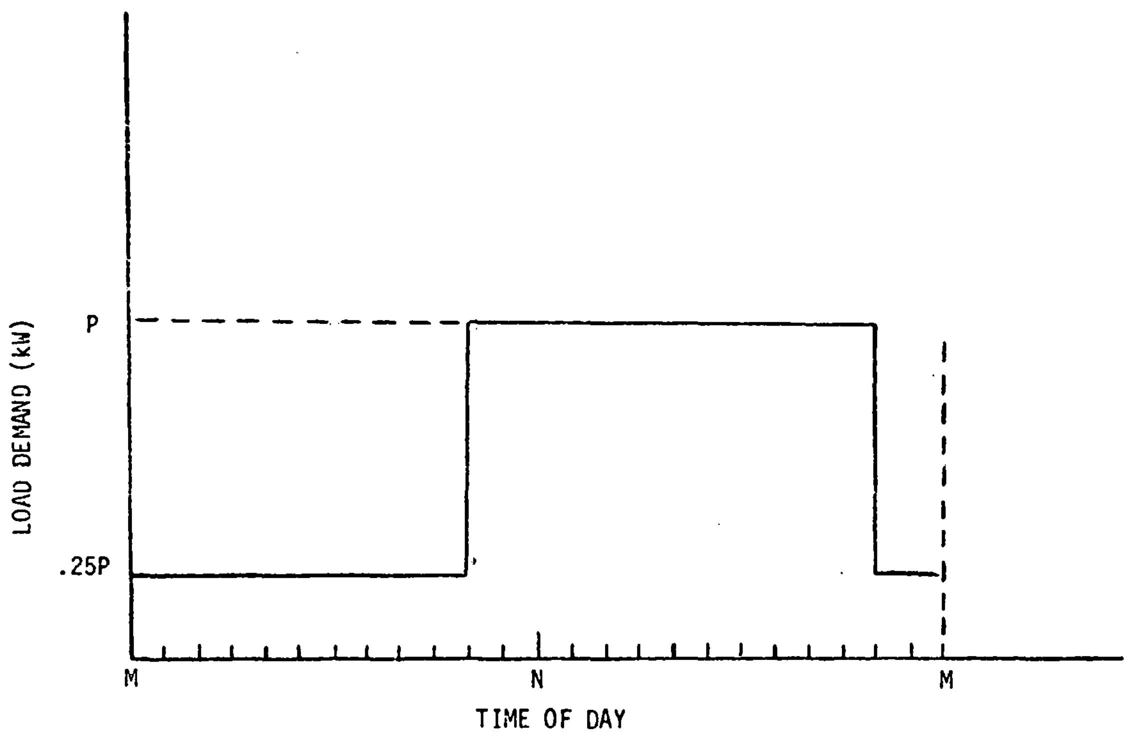


FIGURE 3.5-1. ASSUMED LOAD PROFILE FOR INTERMEDIATE APPLICATION

TABLE 3.5-2. ANNUAL LOADS - INTERMEDIATE APPLICATION

PEAK LOAD DEMAND, P (kW)	ANNUAL LOAD (MWh)
200	1,095
250	1,369
300	1,643

The range of loads which could be matched to the intermediate size photovoltaic system is clearly very large, and this load - PV relationship is somewhat analogous to "penetration" as defined for the utility case. The sizing reflected by Table 3.5-2 is primarily one of convenience for the purpose of analysis. In many intermediate applications, much larger photovoltaic arrays would be appropriate. A very large suburban shopping center, for example, could be expected to require total energy inputs in the order of 5-6 MW, and 20 X 10^6 MWh/year. Having already dealt with multiple units in the utility case, it was deemed of greater interest here to investigate the effects of a different type of load pattern and rate structure.

3.5.4 GENERATION AND LOAD MATCHING WITHOUT STORAGE

Baseline no-storage cases were computed for each location and the range of total load demands. The hour-by-hour tapes of photovoltaic output and electrical demand were matched by computer program to determine what portion of PV output could be supplied directly to the load. Excess PV energy and required utility makeup power were also computed and summed for the full 8760 hours. Results are shown in Table 3.5-3.

TABLE 3.5-3. INTERMEDIATE LOAD MATCHING WITH A 500 kW PV SYSTEM-NO STORAGE

LOCATION	PEAK LOAD (kW)	PV ENERGY UTILIZED (MWh)	EXCESS PV ENERGY (MWh)	UTILITY PURCHASED ENERGY (MWh)
Phoenix, AZ	200	610.9	572.6	484.1
	250	740.2	436.4	628.5
	300	857.0	313.5	785.5
Boston, MA	200	457.1	382.0	637.9
	250	536.8	296.1	832.0
	300	605.6	225.7	1036.9

3.5.5 GENERATION AND LOAD MATCHING INCORPORATING STORAGE

Further analysis consisted of adding incremental storage quantities in order to use photovoltaic excess energy to further offset purchased electrical energy. Hour-by-hour modeling was performed for a full year. System operational strategy was similar to that for the residence (Section 3.4.5) with one exception. In the intermediate case, a one-hour delay in changing from the utility power back to PV power was introduced in order to avoid excessive switching and also to provide an operational sequence adaptable to equipment already available or conceptually defined. Results of the computer analysis are presented in Table 3.5-4 in terms of utility purchased electricity. Subtraction from the baseline no storage case yields the quantity of purchased electricity saved due to energy storage. Results are shown in Table 3.5-5.

TABLE 3.5-4. PURCHASED UTILITY ENERGY WITH INTERMEDIATE PV SYSTEM ENERGY STORAGE

STORAGE	PHOENIX			BOSTON		
	LOAD DEMAND (kW)			LOAD DEMAND (kW)		
SIZE (kWh)	200	250	300	200	250	300
0	484.1	628.5	785.5	637.9	832.0	1036.9
500	355.3	507.4	675.0	550.8	757.9	975.6
1000	226.5	397.7	605.7	476.7	696.6	931.0
1500	140.4	358.4	598.5	427.5	663.7	913.7
2000	133.6	356.8	598.3	410.5	656.3	912.4
3000	129.2	356.3	597.9	403.0	655.8	912.0
4000	127.5	356.0	597.5	401.9	655.5	911.7

PURCHASED ENERGY IN MWh

TABLE 3.5-5. ANNUAL ENERGY DISPLACEMENT DUE TO STORAGE

STORAGE	PHOENIX			BOSTON		
	LOAD DEMAND (kW)			LOAD DEMAND (kW)		
SIZE (kWh)	200	250	300	200	250	300
500	128.8	121.0	110.4	87.1	74.0	61.4
1000	257.6	230.8	179.7	161.2	135.4	106.0
1500	343.7	270.1	187.0	210.4	168.2	123.2
2000	350.5	271.7	187.2	227.4	175.7	124.5
3000	355.0	272.1	187.6	234.8	176.1	124.9
4000	356.6	272.5	188.0	236.0	176.5	125.2

ENERGY DISPLACEMENT IN MWh

The stored energy displacement (energy savings due to storage) of Table 3.5-5 are presented graphically in Figure 3.5-2 which shows that peak load demand has a very strong effect on maximum energy savings. A sharp "knee" was observed, as in the residential PV application, in this case occurring for storage capacity of about 1000-1500 kWh. The 250 kW mean displacement curve of Figure 3.5-3 was used in the analysis that follows.

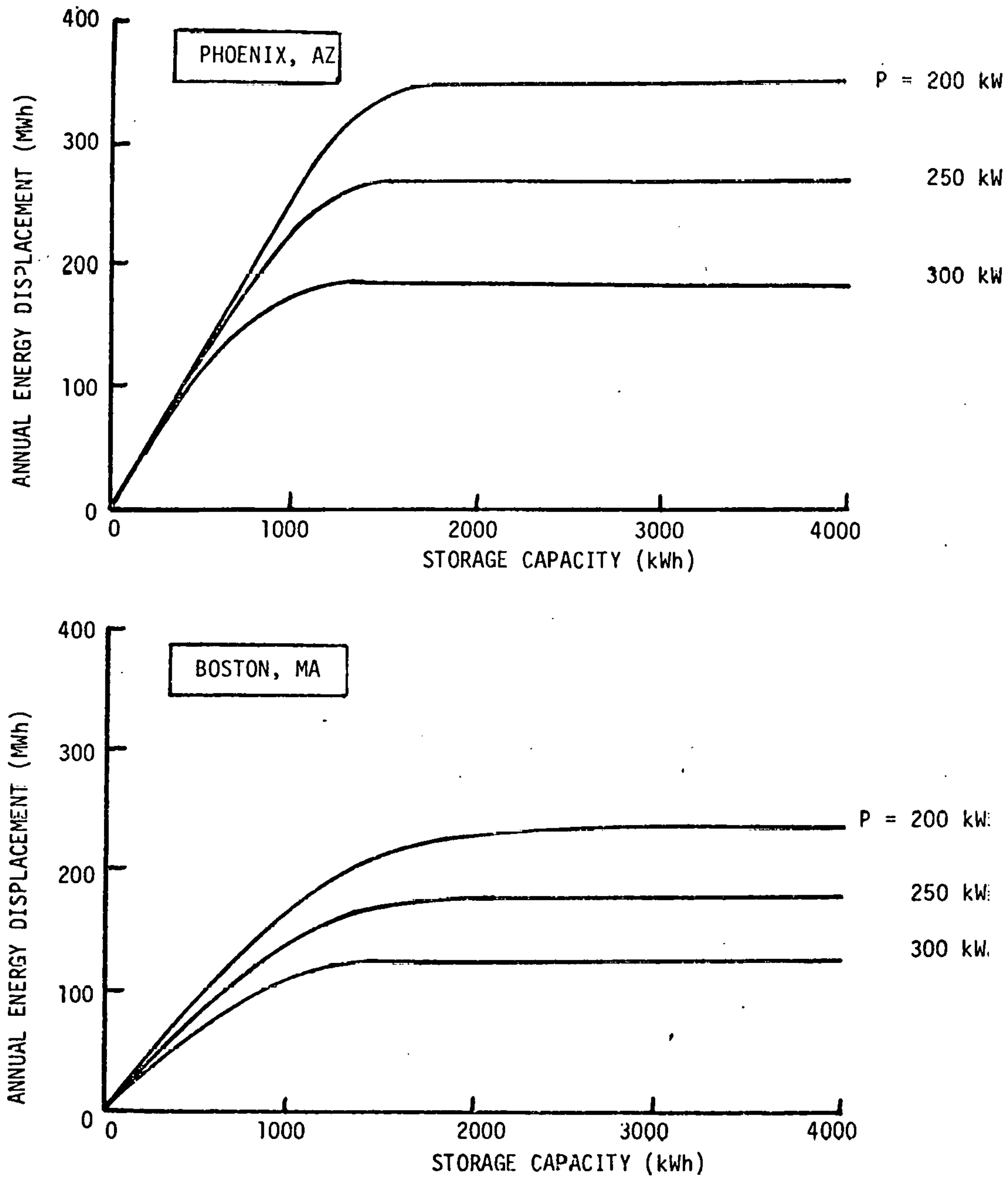


FIGURE 3.5-2. ANNUAL ENERGY DISPLACEMENT - INTERMEDIATE APPLICATION

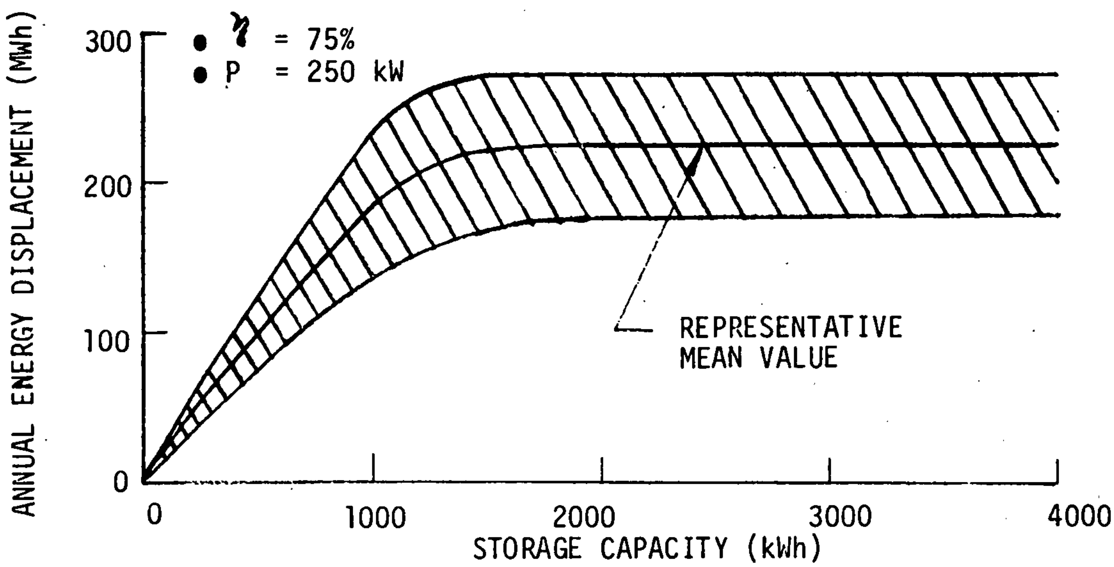


FIGURE 3.5-3. MEAN ENERGY DISPLACEMENT DUE TO ADDITION OF STORAGE - INTERMEDIATE APPLICATION

3.5.6 COST GOALS AND PARAMETRIC ANALYSIS

Candidate energy storage concepts selected for further cost goal determination for use with photovoltaic energy systems in intermediate applications include:

1. Pumped Hydro
   a. Above ground
   b. Underground
2. Underground Compressed Air
3. Batteries
   a. Lead-acid
   b. Advanced
4. Inertial (Flywheel)

5. Hydrogen

Several of these storage systems are applicable only to very large scale intermediate applications. Included in this category are pumped hydro and underground compressed air storage which, in addition, have highly site-specific requirements.

The numerics required to carry out the intermediate cost goal evaluation are explained and the results presented in detail in this section.

3.5.6.1 Determination of Energy Storage Break-Even Costs

The break-even cost for intermediate energy storage systems was determined by finding the difference between the capitalized annual displaced energy credit and capitalized O&M costs divided by a factor accounting for the cost of money during construction. The procedure for determining the break-even cost consisted of the following steps:

1. Selection of the storage system, PV system size, location and storage capacity.

2. Determination of the PV system annual energy performance with and without storage.

3. Determination of the annual displaced energy credit for the addition of storage, using average cost of electricity.

4. Determination of the capitalized displaced energy credit, accounting for the effects of storage efficiency.

5. An estimate of the capitalized O&M costs for subtraction from the Step 4 result.

6. Application of a construction cost factor (CCF) to account for interest during the construction phase, where applicable.

7. Comparison of the storage system break-even cost with projected actual or estimated system costs.

Steps 1 and 2 were discussed in the previous section; Steps 4 through 6 are included in the following sections.

3.5.6.2 Cost of Electricity

Intermediate size commercial and industrial applications typically have utility rate schedules with both an energy (kilowatt hour) and a power demand (kW) component. Energy storage employed with a photovoltaic energy system can only reduce the energy component and, under typical declining block rate structures, only the lower valued blocks of energy. The reason for this is that the variability of PV system output reduces the probability of always having stored energy to limit the kW demand peak, and thereby assure a lower power demand rate. Also, with respect to the energy demand component, the PV/storage combination acts, in effect, to reduce the need for energy which, if purchased from the utility, would have been billed at the lower end of the rate structure. 1976 cost date of the Federal Power Commission[27] show an average national price of about 4¢/kWh for industrial electricity in the consumption range of this application. Due to the non-elimination of demand charges and the declining block structures, 2¢/kWh electricity was assumed for the value of the incremental energy displaced by storage. It is, of course, recognized that strong Congressional action is underway which might eliminate the declining block structure. When this occurs, the value of stored energy will be dramatically increased and would generally show dollar results per kWh similar to residential values. Further discussion on the effects of rate structures on storage economics will be found in Section 3.7.

3.5.6.3 Displaced Energy Credit

The annual displaced energy credit at 75% storage efficiency, A_E^o, is given by:

$$A_E^o = \text{C.O.E. X ANNUAL ENERGY STORAGE DISPLACEMENT} \quad (1)$$

where

C.O.E. = Cost of Electricity

Using the values from the mean energy storage displacement curve of Figure 3.5-4 and the assumed 2¢/kWh value of energy saved, the A_E^o versus storage capacity curve of Figure 3.5-4 results:

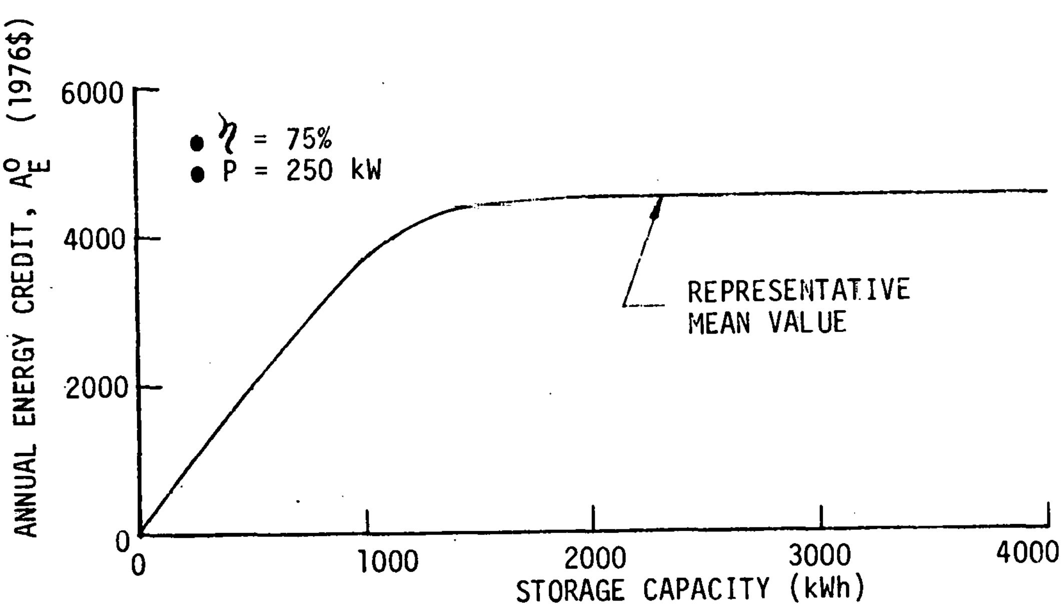


FIGURE 3.5-4. MEAN ENERGY CREDIT VERSUS STORAGE CAPACITY - INTERMEDIATE APPLICATION

Determination of the capitalized value, C_E^o, of this energy credit was accomplished in the same general manner as for the residential application (Section 3.4.6.3), thus:

$$C_E^o = \left(\frac{1 + e}{1 + g}\right)^{\delta} \frac{M_e}{FCR} A_E^o \qquad (2)$$

where

- C = capitalized energy credit, $
- e = electricity price escalation rate
- g = general inflation rate
- δ = years from 1976 to start
- M_e = energy savings multiplier
- FCR = fixed charge rate

Principal differences from the residential case are in r, the discount rate and FCR the fixed charge rate. An after tax cost of capital of 10 percent was used for the discount rate in intermediate applications. The fixed charge rate must be on a before-tax basis in order to account for the tax deductibility of energy. The FCR's for various storage system lifetimes are given below:

TABLE 3.5-6. INTERMEDIATE FIXED CHARGE RATES

SYSTEM LIFE	FCR
10 YEAR	.27
20	.23
30	.22

In the case of battery systems, which were assumed to require 10 year replacement of the batteries only, with 30 percent salvage value, an equivalent 30 year fixed charge rate of .26 was computed.

The energy savings derived up to this point assumed 75 percent storage efficiency. For storage systems with efficiencies other than 75 percent, a correction factor, C was applied with the capitalized energy credit becoming:

$$C_E = C_\eta \times C_E^o \qquad (3)$$

Figure 3.5-5 presents the results of computer runs evaluating the effect of storage efficiency on annual energy displacement due to storage use. Figure 3.5-5 also gives the related dollar value of the annual energy credit for different storage efficiencies.

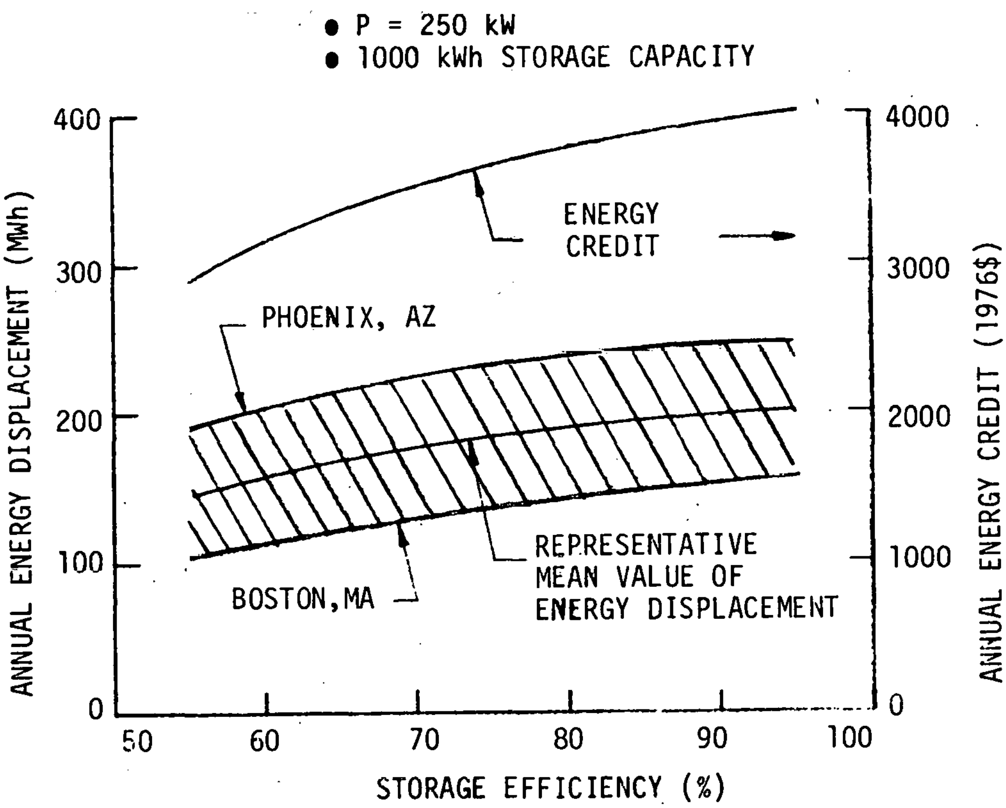


FIGURE 3.5-5. EFFECT OF STORAGE EFFICIENCY ON ENERGY DISPLACEMENT DUE TO STORAGE - INTERMEDIATE APPLICATION

The energy credit data shown in the curve of Figure 3.5-5 was used to calculate the efficiency correction factor, C_η , for intermediate applications. This result is shown in Figure 3.5-6 below:

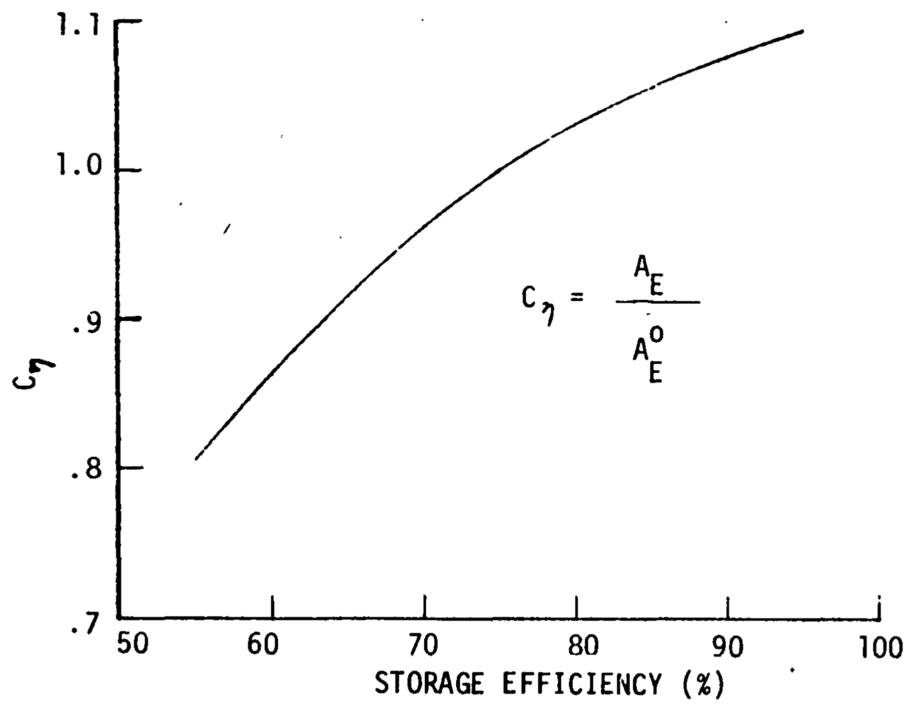


FIGURE 3.5-6. STORAGE EFFICIENCY CORRECTION FACTOR - INTERMEDIATE APPLICATION

Energy Credit Multiplier

Presented below, for reader convenience, are values of the energy credit multiplier, $\left(\frac{1 + e}{1 + g}\right)^\delta$ M_e, as used in the energy credit equation at the start of this section.

TABLE 3.5-7. ENERGY CREDIT MULTIPLIER $\left(\frac{1 + e}{1 + g}\right)^{\delta} M_e$ - INTERMEDIATE APPLICATION

YEAR	ELECTRICITY PRICE ESCALATION RATE (e)					
	5%	6%	7%	8%	9%	10%
1976	1.6759	1.8858	2.1330	2.4249	2.7710	3.1824
1982	↓	1.9962	2.3886	2.8715	3.4678	4.2070
1985		2.0538	2.5277	3.1247	3.8794	4.8371
1988		2.1130	2.6750	3.4002	4.3399	5.5615
1994		2.2366	2.9956	4.0264	5.4312	7.3521
2000		2.3675	3.3547	4.7678	6.7971	9.7192

$r = .1, \quad g = .05$

3.5.6.4 Operation and Maintenance Costs

The annual operation and maintenance cost, A_{OM}, is storage system related and was estimated according to the expression:

$$A_{OM} = a_{OM} \times ASDE \qquad (4)$$

where

a_{OM} = variable storage O&M cost in $/kWh of discharge energy

ASDE = annual storage discharge energy

Table 3.5-8 below lists the computed O&M costs at a storage capacity of 1000 kWh for each of the intermediate size candidate storage systems investigated.

TABLE 3.5-8. ANNUAL ENERGY STORAGE OPERATION AND MAINTENANCE COSTS - PV SYSTEM STORAGE CHARGING

STORAGE SYSTEM	A_{OM} (1976 $/kWh)*
Underground Pumped Hydro	.168
Above Ground Pumped Hydro	.168
Underground Compressed Air	1.386
Lead-Acid Batteries	.124
Advanced Batteries	.747
Inertial (Flywheel)	1.386
Hydrogen	.706

* 1000 kWh

The capitalized value, C_{OM}, is then:

$$C_{OM} = \frac{M_g}{FCR} A_{OM} \tag{5}$$

where M_g is the general inflation multiplier discussed in Section 3.4.6.4.

3.5.6.5 Break-Even Cost

The break-even cost goals for an intermediate application reflect the difference between the capitalized values of energy credit and O&M cost as adjusted by a storage system related factor to account for interest during construction.[21, 28]

$$C_{BE} = \frac{C_E - C_{OM}}{CCF} \tag{6}$$

where CBE = break-even storage

CCF = construction cost factor

The construction cost factor was taken in a range from 1.05 for short lead-time systems, such as batteries, to 1.4 for pumped hydro systems. Table 3.5-9 lists the construction cost factors and fixed charge rates for the storage systems considered for intermediate application.

TABLE 3.5-9. CONSTRUCTION COST FACTORS AND FIXED CHARGE RATES - INTERMEDIATE APPLICATION

STORAGE SYSTEM	LIFE (YRS)	CCF	FCR
1. Pumped Hydro	50	1.40	.22
2. Underground Compressed Air	30	1.17	.22
3. Batteries	10	1.05	.26
4. Inertial (Flywheel)	20	1.05	.23
5. Hydrogen	20	1.05	.23

A sample break-even cost calculation is presented below for lead-acid battery storage.

Specific Conditions

- 250 kW load power demand
- 1000 kWh storage capacity - lead-acid batteries
- 2 hour discharge rate limit
- 5% inflation rate, g
- 10% electricity price escalation rate, e
- 30 year system life, n
- 10% discount rate, r
- 70% storage efficiency
- Fixed Charge Rate (FCR) = .26
- Variable O&M rate (a_{OM}) = \$.0005/kWh
- Annual Energy Displacement = 183.1 MWh (mean value)
- ASDE = 249 MWh (mean value)
- Start year 2000
- Results in 1976 dollars

From equation (1)

$$A_E^o = .02\ (183{,}100) = \$3{,}622$$

From equation (2) and Table 3.5-7

$$C_E^o = \frac{9.7192}{.26}\ (3{,}622) = \$136{,}891$$

The efficiency correction factor for lead-acid batteries (70% efficiency), obtained from Figure 3.5-6 is:

$$C_\eta = .96$$

Therefore, from equation (3)

$$C_E = .96\ (136{,}891) = \$131{,}415$$

The annual O&M costs from equation (4) is

$$A_{OM} = .0005\ (249{,}000) = \$124.50$$

From equation (5) and Table 3.5-7

$$C_{OM} = \frac{1.6759}{.26} (124.5) = \$802$$

From Table 3.5-9: CCF (lead-acid batteries) = 1.05 and the break-even cost is obtained from equation (6) as:

$$C_{BE} = \frac{131{,}415 - 802}{1.05} = \$124{,}393$$

or \$124.4/kWh of storage capacity

3.5.6.6 Capital Cost Comparisons

Table 3.5-10 shows the results of the computation of break-even capital costs and comparison with projected system costs for one set of conditions for all of the storage methods considered in this portion of the study, without regard to the assessment of suitability for use with photovoltaic energy conversion. This comparison was made in order to provide more insight into the original rankings based on levelized annual cost. The results of these viability computations are discussed further in Section 1.1. Break-even costs were computed at 1000 kWh of storage capacity and a storage system duty cycle of ten hours. The extreme economic conditions of 10% fuel price escalation rate and a year 2000 start, which were also used, provide a maximum opportunity within the overall economic groundrules used in the study, for any particular concept to demonstrate a potential for viability.

TABLE 3.5-10. BREAK-EVEN COSTS COMPARED WITH SYSTEM COST ESTIMATES FOR YEAR 2000, 10% FUEL ESCALATION, PV SYSTEM CHARGING - INTERMEDIATE APPLICATION

STORAGE CONCEPT	BREAK-EVEN CAPITAL COST	COST ESTIMATE	Δ	POTENTIAL VIABILITY
Underground Pumped Hydro	115	23	+92	Yes
Above-Ground Pumped Hydro	115	19	+96	Yes
Underground Compressed Air	124	34	+90	Yes
Lead-Acid Batteries	124	140	-16	No
Advanced Batteries	126	67	+59	Yes
Inertial Storage (Flywheel)	138	217	-79	No
Hydrogen	95	45	+50	Yes

All Costs in 1976 $/kWh

The results listed in Table 3.5-10 indicate five storage methods of potential viability for the intermediate application in a dedicated storage mode of operation: both types of pumped hydro, underground compressed air, advanced batteries, and hydrogen. The first four, plus lead-acid batteries (due to widespread interest) were selected for further detailed economic analysis.

Using the methodology outlined previously, storage system break-even costs for these concepts as a function of storage capacity were computed for (1) electricity price escalation equal to general inflation (5%), (2) a 1985 start year with 6% escalation (1% over inflation), and (3) the extreme of a year 2000 start with a 10% electricity price escalation rate. The resulting cost goals provide values for a nominal case and upper and lower bounds. A comparison of these break-even costs, with each of the four storage system cost projections overlaid, is presented in Figure 3.5-7. The nominal case of 6% electricity price escalation and a 1985 start year shows viability for pumped hydro at storage capacities of less than 1000 kWh assuming a projected cost of $19/kWh. Projected costs for both battery systems must be significantly reduced in order to obtain viability in the nominal case. At year 2000 with 10% escalation, advanced batteries indicate viability for storage capacities of less than 2000 kWh at a projected cost of $67/kWh. The system cost projections represented as dashed lines on the figure are taken from Volume I of this study report. As in the utility and residential applications, these costs for the intermediate case were selected as representative of the respective technologies based on information currently available. The system cost projection used for lead-acid batteries was obtained from data and consultation supplied by C&D Batteries, while the cost projection for the remaining technologies were taken at the utility values in the absence of suitable information to permit meaningful scaling. Due to the fact that much of the cost data is subject to continued change, the format of Figure 3.5-7 was structured to facilitate the application of updated cost information as it becomes available.

For a given storage system, there exists a range of start year-escalation rate combinations that will result in economic viability. Pumped hydro and compressed air storage break-even costs for several escalation rates

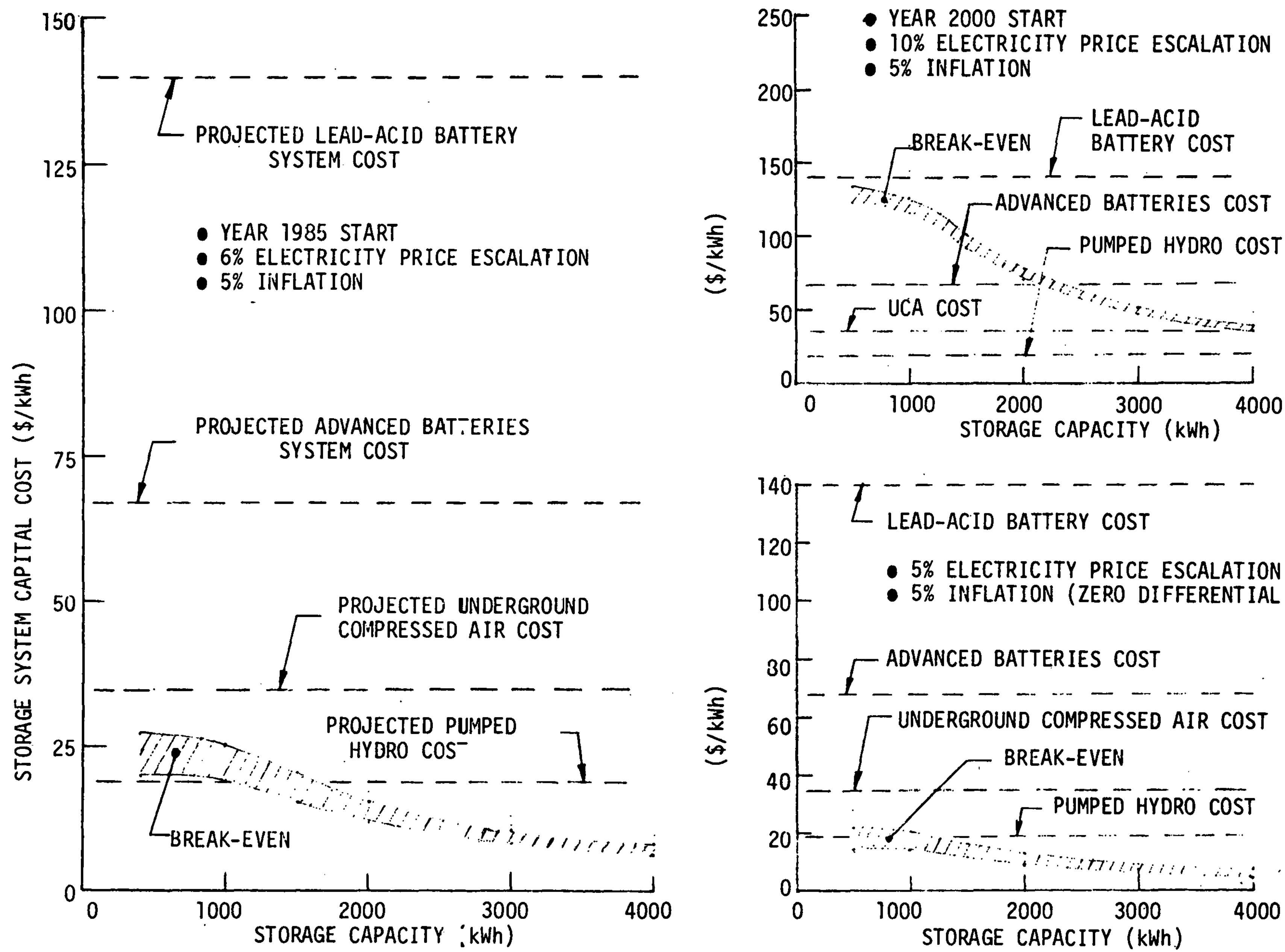


FIGURE 3.5-7. ENERGY STORAGE BREAK-EVEN COST GOALS - INTERMEDIATE APPLICATION

are presented as a function of start year in Figure 3.5-8 for a nominal storage capacity of 1000 kWh. Projected system costs are overlayed as dashed lines. At 5% escalation, it is seen that pumped hydro (above ground) is presently marginally viable.

In contrast, compressed air reaches viability by 1978 at 9% escalation and becomes economic by 1983 at 8% escalation. This figure affords the reader an opportunity to test viability of these storage systems using any source for projected costs. Figure 3.5-9 is a similar chart for battery storage. Note that only at very high (9 and 10%) escalation rates is economy achieved for advanced batteries.

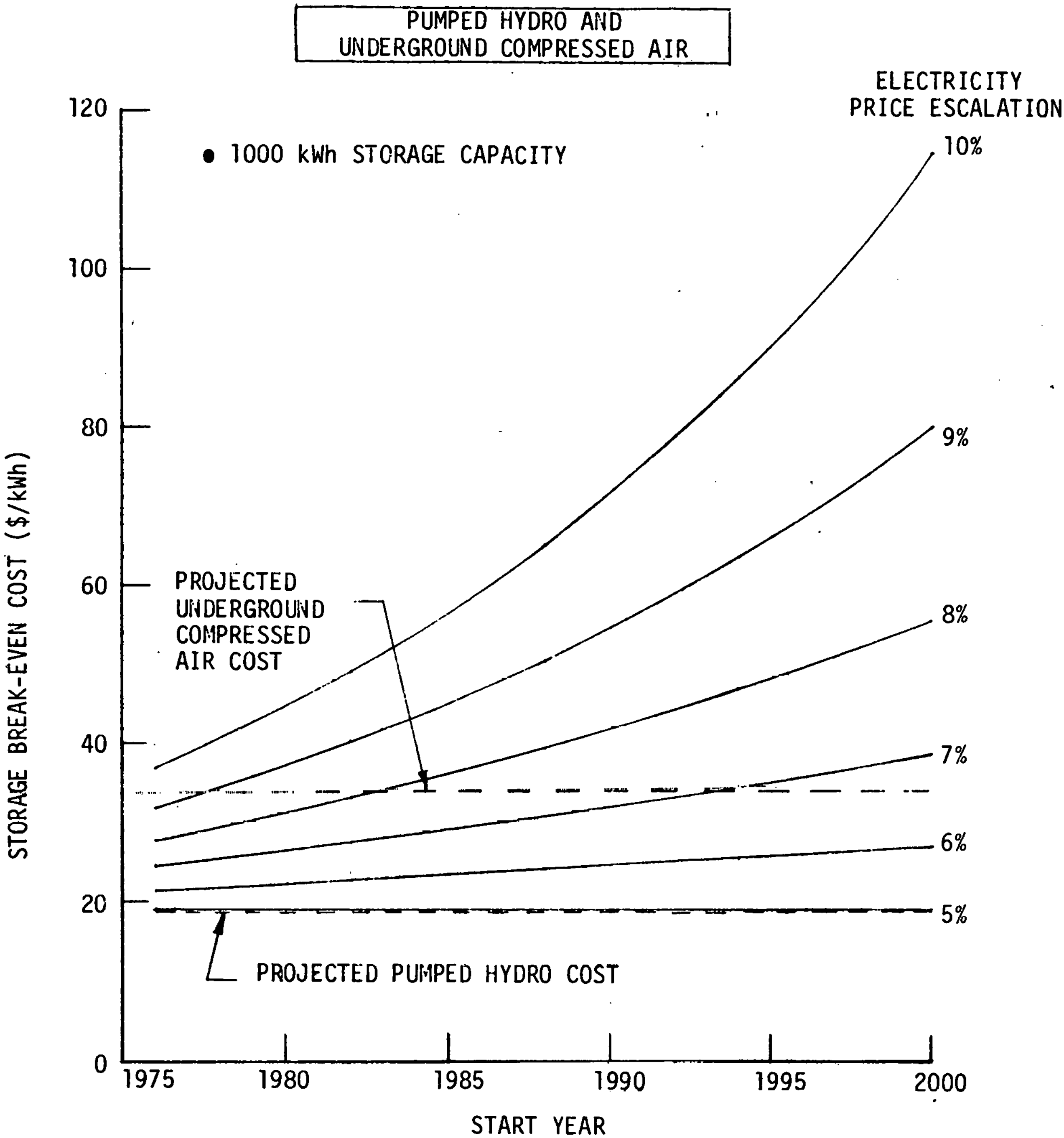


FIGURE 3.5-8. STORAGE BREAK-EVEN COST VS. START YEAR FOR PUMPED HYDRO AND UNDERGROUND COMPRESSED AIR - INTERMEDIATE APPLICATIONS

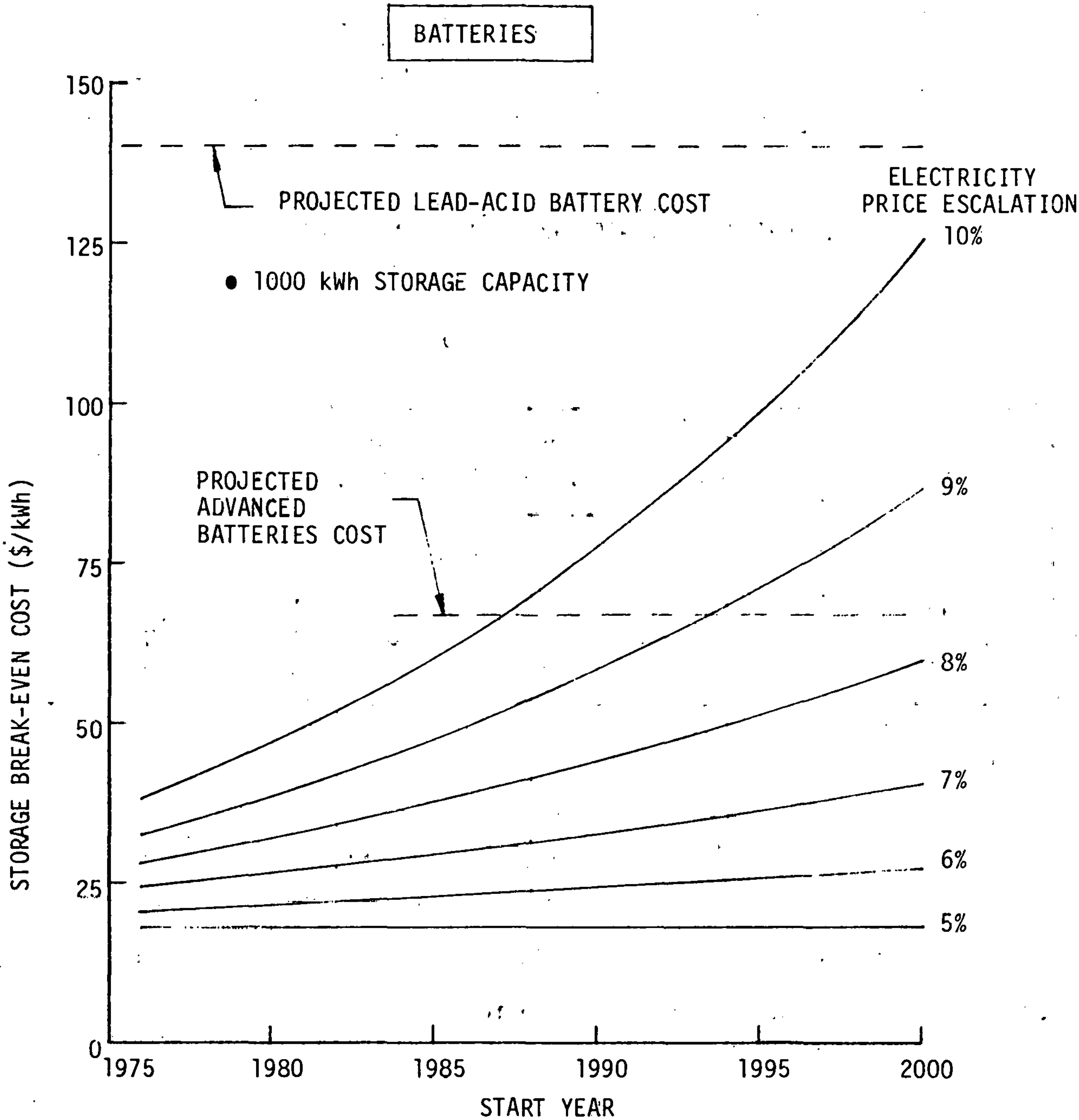


FIGURE 3.5-9. STORAGE BREAK-EVEN COST VS. START YEAR FOR BATTERY STORAGE SYSTEMS - INTERMEDIATE APPLICATIONS

2.5.6.7 <u>Storage Capacity Optimization</u>

The optimum storage capacity for the intermediate case was determined in a manner analogous to the residential application, by maximizing the capitalized savings when viability is achieved. As an example, Table 3.5-11 presents cost data as a function of storage size for advanced batteries at year 2000 and 10% escalation.

TABLE 3.5-11. OPTIMUM STORAGE SIZE FOR ADVANCED BATTERIES - INTERMEDIATE APPLICATION

(Year 2000, 10% escalation)

STORAGE SIZE (kWh)	C_{BE} ($/kWh)	COST ($/kWh)	SAVINGS ($/kWh)	TOTAL CAPITALIZED SAVINGS ($)
500	133	67	66	33,000
1000	126	67	59	59,000 *
1500	100	67	33	49,500
2000	77	67	10	20,000

* Optimum

As seen from the table, the optimum economic situation for advanced batteries occurs at the relatively small capacity of 500 kWh, even when computed at the extreme economic conditions of this example. Obviously, as storage costs drop and electricity price escalation rates increase, the optimum storage size will increase with time.

3.6 EFFECTS OF MULTIPLE-SOURCE CHARGING AND INSOLATION FORECASTING

The use of energy storage to improve the value and usability of photovoltaic generated energy has been treated in depth in previous sections on the basis of a direct tie of the storage device to the PV source for storage charging. As shown, this results in a certain value being realized from the addition of storage capacity to the PV system. It is possible, however, to define alternative concepts in which the storage system is in reality shared by and made available to all of the generating units in the utility system. This method was defined for study purposes as "multiple source charging". It offers a means of compensating for the low energy capture on days of low photovoltaic output when dedicated storage could not be fully charged. This concept is evaluated further in the remainder of this section, along with the implications of having varying degrees of prior knowledge of PV energy availability through forecasting.

3.6.1 UTILITY SYSTEM ENERGY ALLOCATION

Two key factors concerning photovoltaic energy use in a utility grid need to be kept in mind:

1. Presence of energy storage is not a pre-requisite for the use of PV energy in a utility system.

2. PV energy at any point in time has a value which corresponds with the incremental cost of the energy which it displaces.

As a result of the above, photovoltaic energy may be considered as merely another source of generation in the overall utility grid. Storage capacity which could not be charged due to low PV output is brought into operation by the rest of the grid providing off-peak charging energy. Figure 3.6-1 illustrates the process.

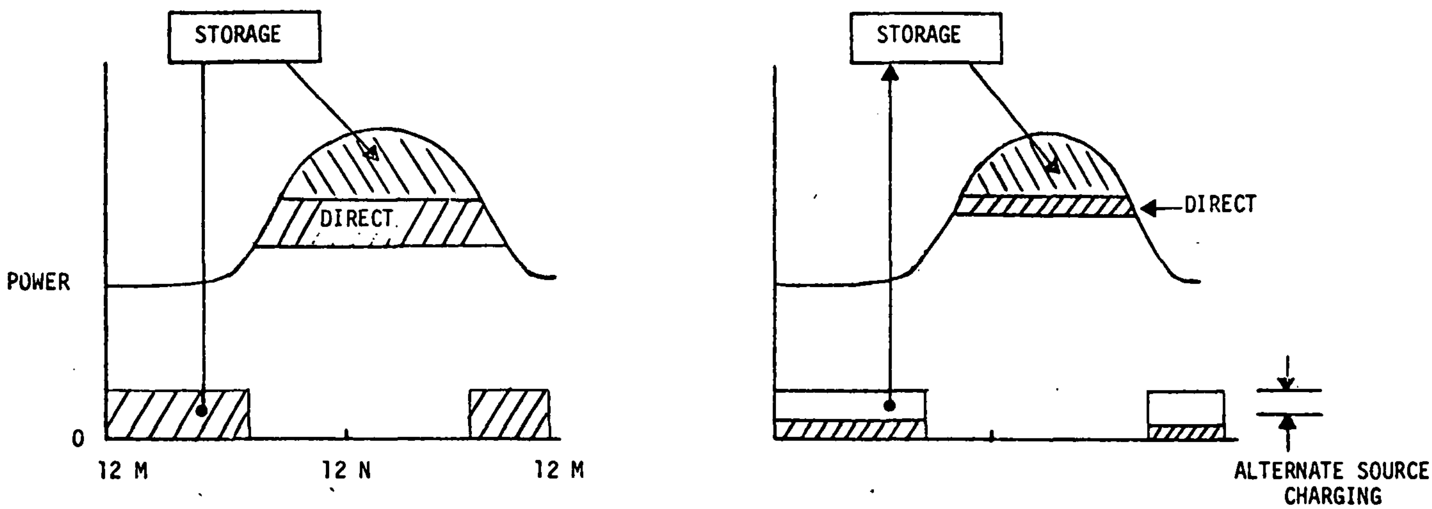


FIGURE 3.6-1. THE ROLE OF UTILITY MAKE-UP IN MULTIPLE SOURCE CHARGING

The left-hand side of the diagram shows the normal situation in which a PV plus storage system provides both a direct load contribution and a stored energy contribution. In the right hand portion of the diagram, a depleted storage system is depicted along with lesser direct and stored energy contributions. With alternate or multiple source charging, the difference would be made up by the total grid capacity. The limit case occurs when storage cannot be charged at all by the PV system due to low output. In this case, multiple source and utility-only off-peak charging become equivalent. Any PV energy present under these conditions may be used immediately as available and becomes part of the total utility generation capability, even though the timing of its availability may be unsuited to off-peak charging.

Since the entire utility may potentially contribute to the storage charging requirement, the benefits of more predictable charging cycles will be realized and better storage capacity utilization (more energy cycles) will occur.

3.6.2 MODEL FOR MULTIPLE SOURCE CHARGING

The operating strategy for this situation is based on the following groundrules:

1. Storage discharge will only occur to displace load of quality C or higher.

2. Storage will be charged with the energy difference between the system load and the strata D (lowest value) generation capacity.

3. The storage system SOC is managed on a daily basis to provide a near optimum displacement of the highest quality energy. To this end, the program logic determines daily, that value of system load which is required to drive the SOC to its pre-determined minimum value for each day.

The system "B" load tape was processed by the computer model on an hour-by-hour basis for 8760 hours and the results tabulated. Table 3.6-1 shows a typical data page from this computer run.

3.6.3 COST GOALS AND PARAMETRIC TRADE-OFFS

The results of model data runs are shown in Figure 3.6-2 for a wide range of storage capacities. A comparison of the above energy savings for PV system dedicated storage is shown in Figure 3.6-3. The improved results from system wide charging over dedicated charging are evident, with an improvement in the order of 3:1.

TABLE 3.6-1. SAMPLE COMPUTER OUTPUT FOR UTILITY/MULTIPLE SOURCE STORAGE CHARGING

1000 MWh STORAGE CAPACITY

MON	DAY	HR	GROSS SYSTEM B LOAD DEMAND (MW)	TOTAL PV OUTPUT (MW)	NET SYSTEM B LOAD DEMAND (MW)	TOTAL LOSSES (MW)	STORAGE SOC	STATUS CHARGE/ DISCHARGE POWER (MW)	DISPLACED GENERATION A (MW)	B (MW)	C (MW)	D (MW)	E (MW)
3	60	1	1501.	0.	1711.53	10.53	0.696	200.00	0.	0.	0.	0.	0.
3	60	2	1433.	0.	1643.53	10.53	0.846	200.00	0.	0.	0.	0.	0.
3	60	3	1382.	0.	1592.53	10.53	0.996	200.00	0.	0.	0.	0.	0.
3	60	4	1374.	0.	1379.17	0.26	1.000	4.91	0.	0.	0.	0.	0.
3	60	5	1404.	0.	1404.00	0.	1.000	0.	0.	0.	0.	0.	0.
3	60	6	1522.	0.	1522.00	0.	1.000	0.	0.	0.	0.	0.	0.
3	60	7	1727.	0.	1727.00	0.	1.000	0.	0.	0.	0.	0.	0.
3	60	8	1999.	0.	1999.00	0.	1.000	0.	0.	0.	0.	0.	0.
3	60	9	2243.	0.	2243.00	0.	1.000	0.	0.	0.	0.	0.	0.
3	60	10	2351.	0.	2329.00	1.16	0.977	-23.16	0.	22.00	0.	0.	0.
3	60	11	2384.	0.	2329.00	2.89	0.919	-57.89	0.	55.00	0.	0.	0.
3	60	12	2373.	0.	2329.00	2.32	0.873	-46.32	0.	44.00	0.	0.	0.
3	60	13	2362.	0.	2329.00	1.74	0.838	-34.74	0.	33.00	0.	0.	0.
3	60	14	2351.	0.	2329.00	1.16	0.815	-23.16	0.	22.00	0.	0.	0.
3	60	15	2320.	0.	2320.00	0.	0.815	0.	0.	0.	0.	0.	0.
3	60	16	2280.	0.	2280.00	0.	0.815	0.	0.	0.	0.	0.	0.
3	60	17	2249.	0.	2249.00	0.	0.815	0.	0.	0.	0.	0.	0.
3	60	18	2396.	0.	2329.00	3.53	0.744	-70.53	0.	67.00	0.	0.	0.
3	60	19	2621.	0.	2431.00	10.00	0.544	-200.00	121.00	69.00	0.	0.	0.
3	60	20	2653.	0.	2463.00	10.00	0.344	-200.00	153.00	37.00	0.	0.	0.
3	60	21	2551.	0.	2361.00	10.00	0.144	-200.00	51.00	139.00	0.	0.	0.
3	60	22	2373.	0.	2331.00	2.21	0.100	-44.21	0.	42.00	0.	0.	0.
3	60	23	2122.	0.	2122.00	0.	0.100	0.	0.	0.	0.	0.	0.
3	60	24	1871.	0.	1900.00	1.45	0.121	27.55	0.	0.	0.	0.	0.
3	61	1	1668.	0.	1878.53	10.53	0.271	200.00	0.	0.	0.	0.	0.
3	61	2	1546.	0.	1756.53	10.53	0.421	200.00	0.	0.	0.	0.	0.
3	61	3	1484.	0.	1694.53	10.53	0.571	200.00	0.	0.	0.	0.	0.
3	61	4	1453.	0.	1663.53	10.53	0.721	200.00	0.	0.	0.	0.	0.
3	61	5	1481.	0.	1691.53	10.53	0.871	200.00	0.	0.	0.	0.	0.
3	61	6	1580.	0.	1761.53	9.08	1.000	172.45	0.	0.	0.	0.	0.
3	61	7	1792.	0.	1792.00	0.	1.000	0.	0.	0.	0.	0.	0.
3	61	8	2067.	0.	2067.00	0.	1.000	0.	0.	0.	0.	0.	0.
3	61	9	2258.	0.	2258.00	0.	1.000	0.	0.	0.	0.	0.	0.
3	61	10	2346.	0.	2303.00	2.26	0.955	-45.26	0.	43.00	0.	0.	0.
3	61	11	2361.	0.	2303.00	3.05	0.894	-61.05	0.	58.00	0.	0.	0.
3	61	12	2329.	0.	2303.00	1.37	0.866	-27.37	0.	26.00	0.	0.	0.
3	61	13	2321.	0.	2303.00	0.95	0.847	-18.95	0.	18.00	0.	0.	0.
3	61	14	2318.	0.	2303.00	0.79	0.832	-15.79	0.	15.00	0.	0.	0.
3	61	15	2312.	0.	2303.00	0.47	0.822	-9.47	0.	9.00	0.	0.	0.
3	61	16	2280.	0.	2280.00	0.	0.822	0.	0.	0.	0.	0.	0.
3	61	17	2243.	0.	2243.00	0.	0.822	0.	0.	0.	0.	0.	0.
3	61	18	2371.	0.	2303.00	3.58	0.751	-71.58	0.	68.00	0.	0.	0.
3	61	19	2572.	0.	2382.00	10.00	0.551	-200.00	72.00	118.00	0.	0.	0.
3	61	20	2609.	0.	2419.00	10.00	0.351	-200.00	109.00	81.00	0.	0.	0.
3	61	21	2510.	0.	2320.00	10.00	0.151	-200.00	10.00	180.00	0.	0.	0.
3	61	22	2356.	0.	2308.00	2.53	0.100	-50.53	0.	48.00	0.	0.	0.
3	61	23	2129.	0.	2129.00	0.	0.100	0.	0.	0.	0.	0.	0.
3	61	24	1856.	0.	1900.00	2.20	0.131	41.80	0.	0.	0.	0.	0.
3	62	1	1663.	0.	1873.53	10.53	0.281	200.00	0.	0.	0.	0.	0.
3	62	2	1552.	0.	1762.53	10.53	0.431	200.00	0.	0.	0.	0.	0.
3	62	3	1470.	0.	1680.53	10.53	0.581	200.00	0.	0.	0.	0.	0.
3	62	4	1451.	0.	1661.53	10.53	0.731	200.00	0.	0.	0.	0.	0.

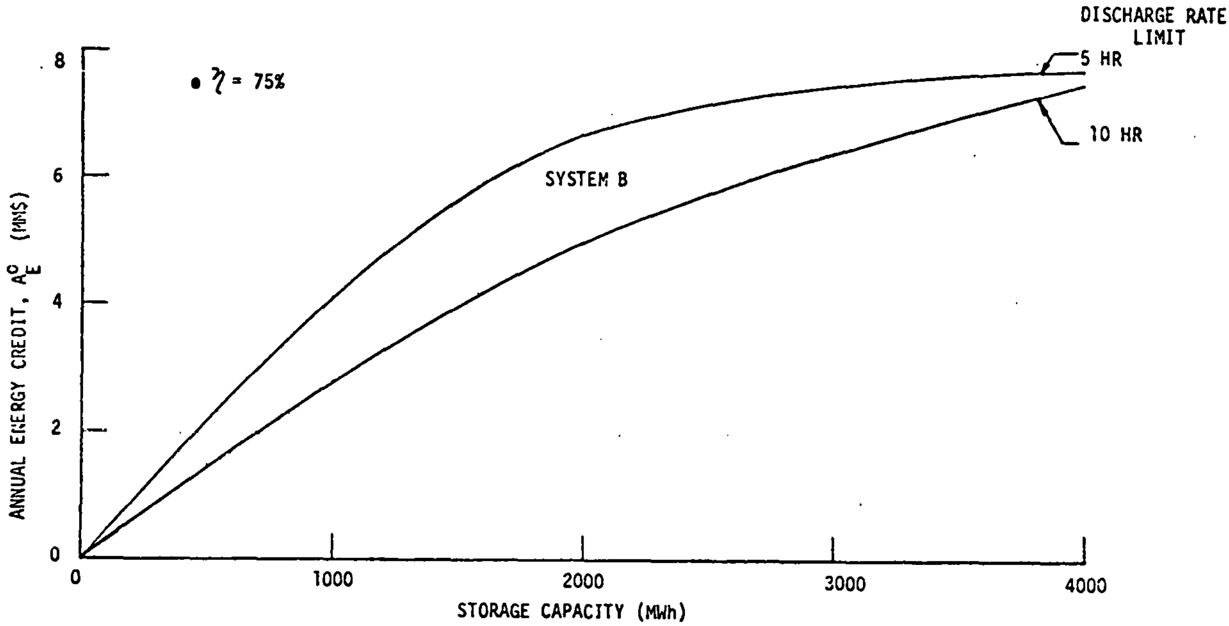


FIGURE 3.6-2. ANNUAL ENERGY SAVINGS - UTILITY ONLY CHARGING

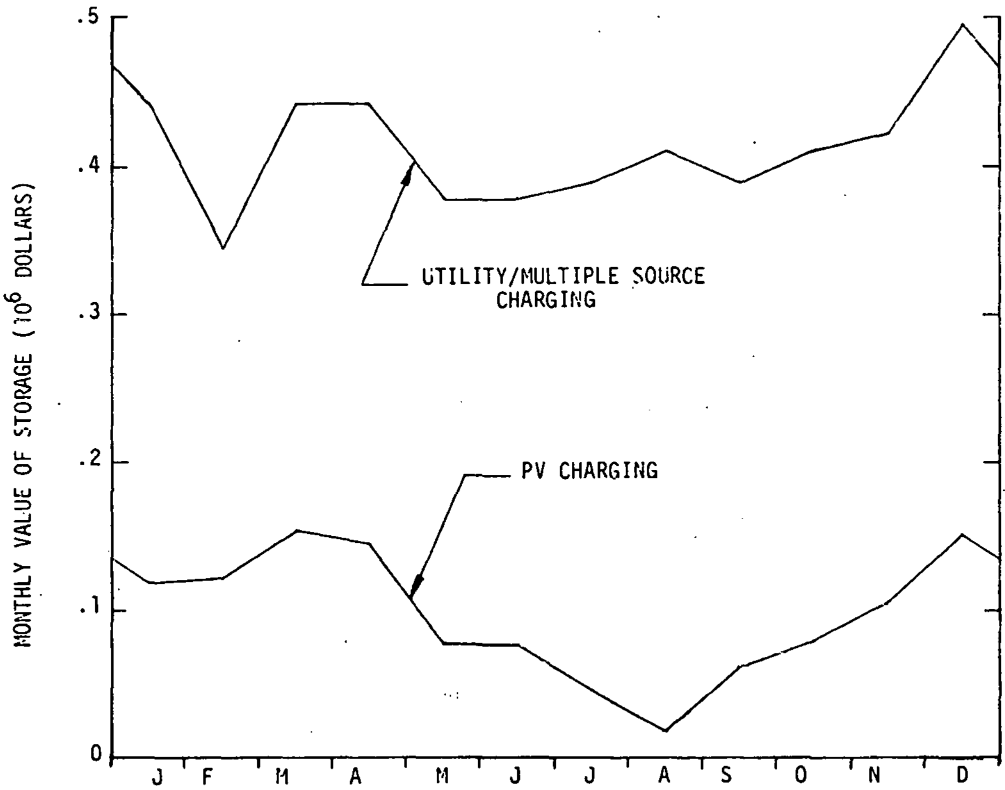


FIGURE 3.6-3. COMPARISON OF STORAGE ENERGY CREDIT WITH PV CHARGING VS. BASELOAD CHARGING (2000 MWh STORAGE CAPACITY)

Storage system break-even costs were computed in the same manner as described previously with one exception. Capacity credit was taken at a full $140/kW, which accounts for the full availability of stored energy on demand. This credit was established on the basis of the improved availability of stored energy under the conditions described. The capacity credit assumes displacement of peaking units only (Gas Turbines). Figures 3.6-4 and 3.6-5 present the results of break-even cost computations at 5 hour and 10 hour discharge rates respectively, along with present storage system cost estimates. The improved storage economics are readily apparent. At the nominal case of 6% fuel price escalation rate and a 1985 start, all storage systems except lead-acid batteries showed some degree of viability. By or prior to year 2000 the latter also shows viability. The more competitive position of batteries at 5 hours vs. 10 hours is also evident. Figures 3.6-6 and 3.6-7 present break-even cost vs. start year and fuel price escalation rate for lead-acid batteries. This portrayal more clearly displays the time frame of potential viability for lead-acid batteries. It may be noted that at 9% escalation, viability for a 5 hour battery occurs by 1984 while a 10 hour battery would take ten years longer to show viability under the same economic conditions. These charts may be used to test approximate viability for any start year, fuel price escalation rate and storage system cost. The reader is cautioned, however, against thinking of these results as having pinpoint accuracy since numerous assumptions are required in the analysis. Further, it is conceivable that system costs shown will vary and will also very possibly continue to drop with technology advances. Hence, these values should be considered as indicative of ranges $\geq$ +10%.

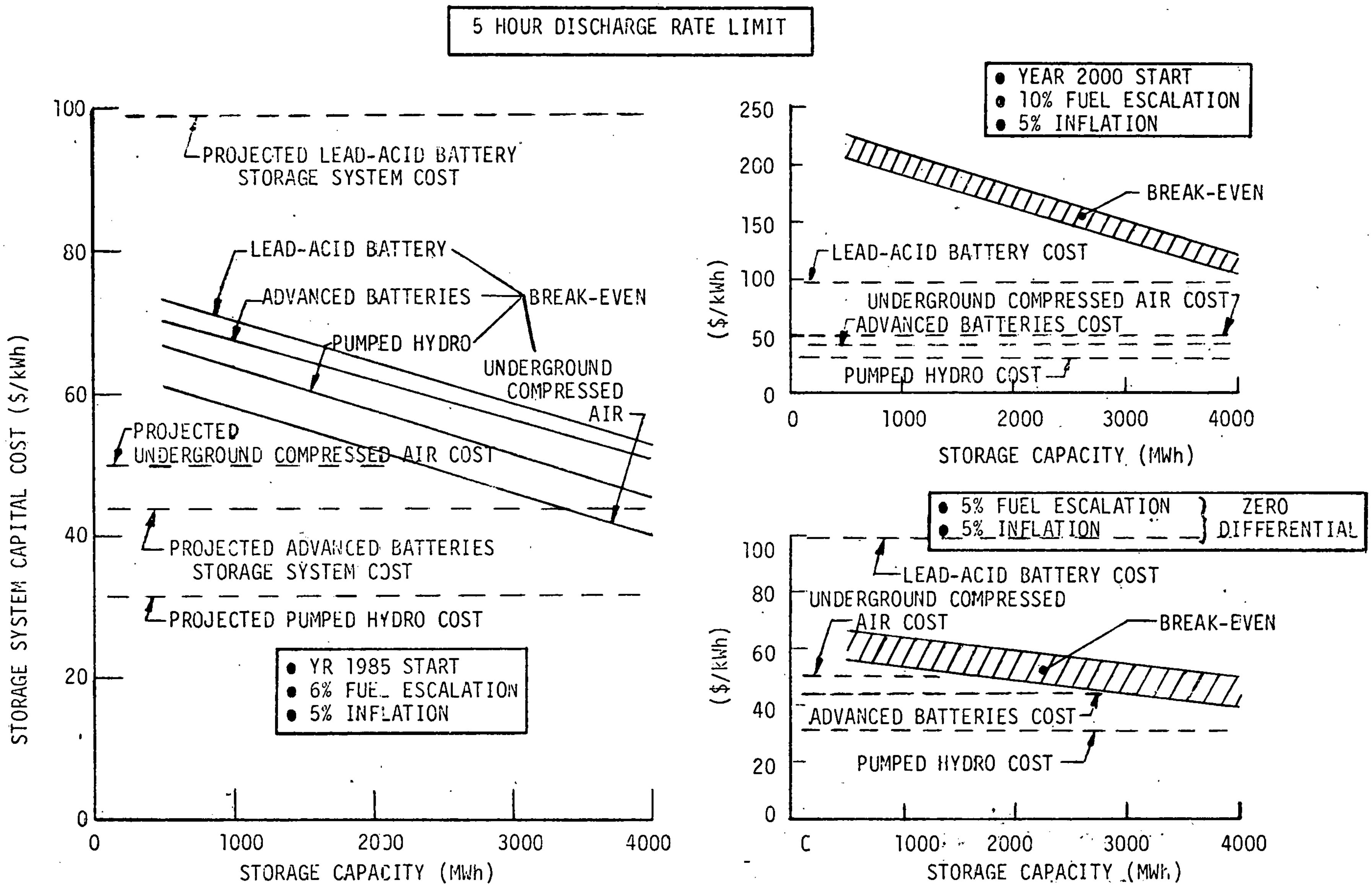


FIGURE 3.6-4. RANGE OF BREAK-EVEN COSTS AND PROJECTED STORAGE SYSTEM COSTS FOR SELECTED ECONOMIC CONDITIONS - UTILITY ONLY CHARGING (MULTIPLE SOURCE)

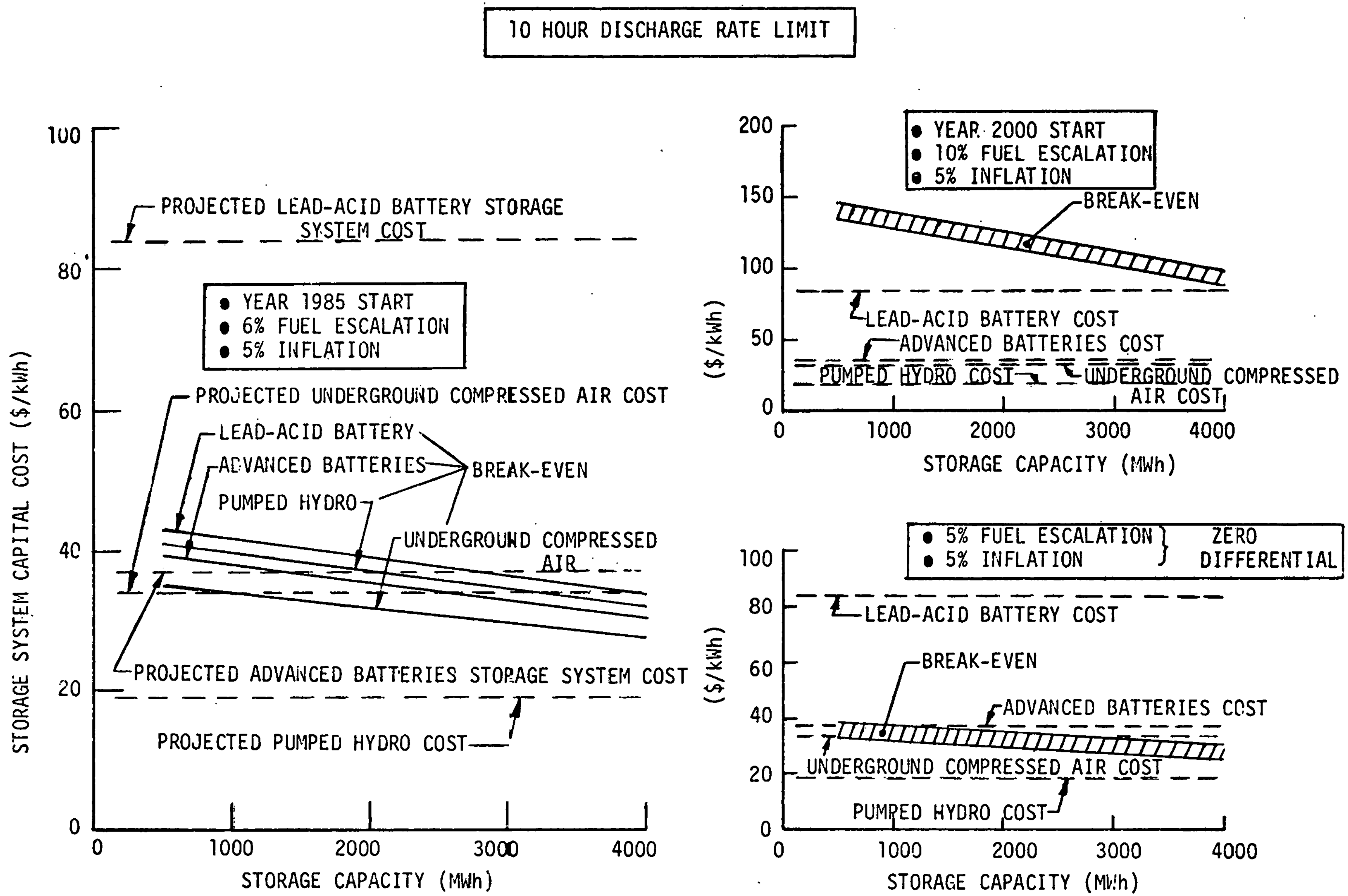


FIGURE 3.6-5. RANGE OF BREAK-EVEN COSTS AND PROJECTED SYSTEM COSTS FOR SELECTED ECONOMIC CONDITIONS - UTILITY ONLY CHARGING (MULTIPLE SOURCE)

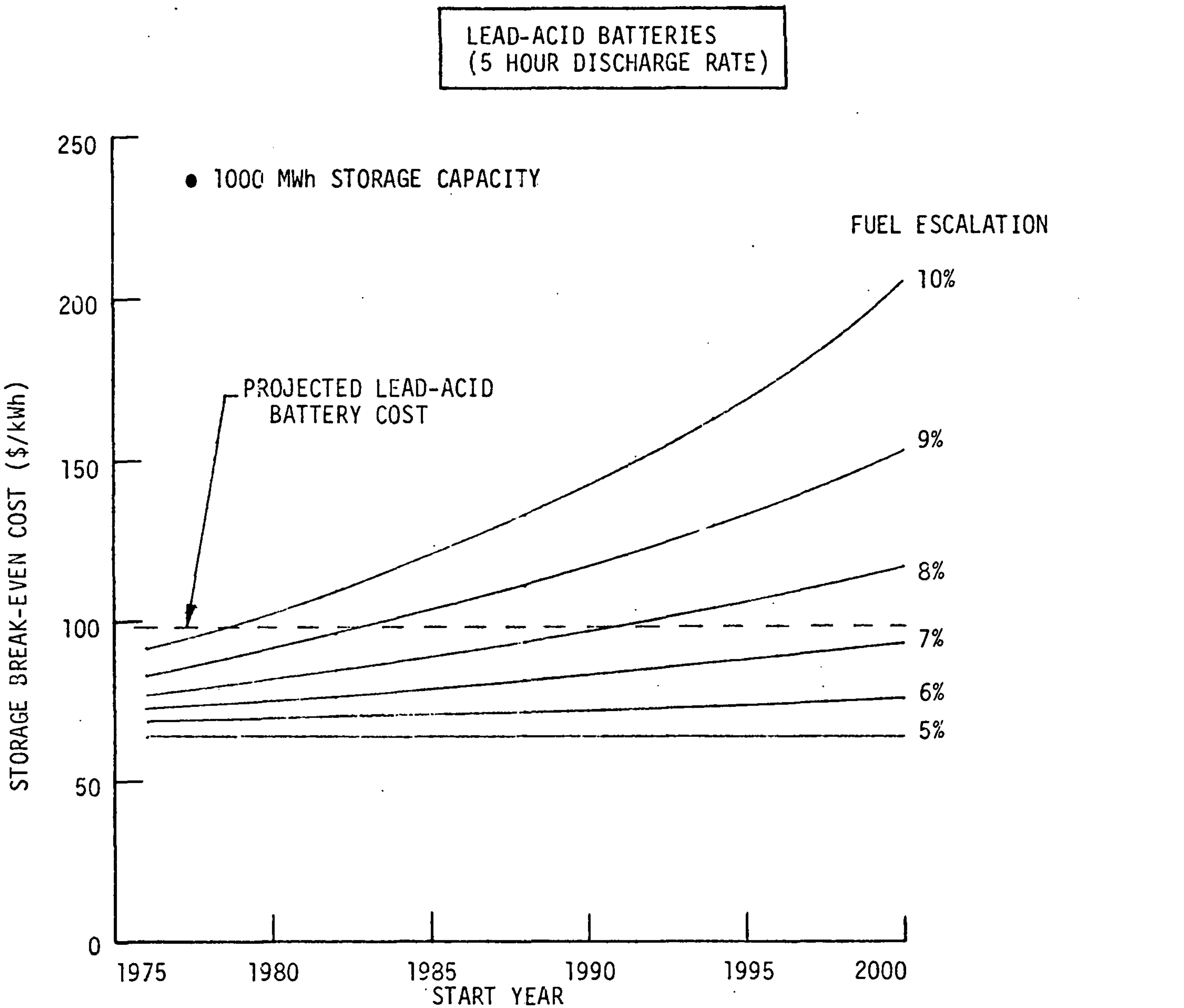


FIGURE 3.6-6. IMPACT OF START YEAR AND FUEL PRICE ESCALATION (COST OF GENERATION) ON STORAGE BREAK-EVEN COST GOALS - UTILITY ONLY CHARGING (MULTIPLE SOURCE)

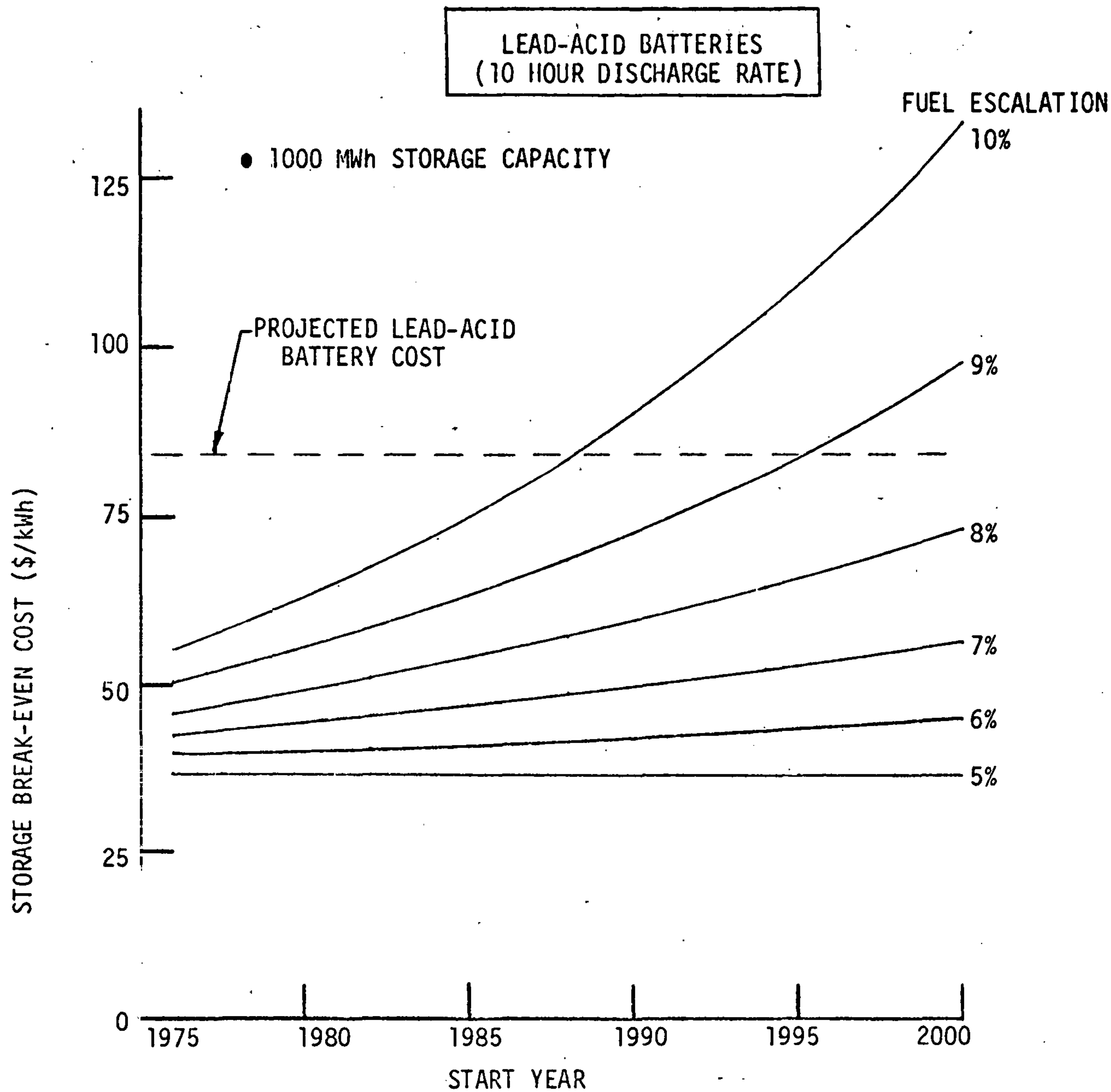


FIGURE 3.6-7. IMPACT OF START YEAR AND FUEL PRICE ESCALATION (COST OF GENERATION) ON STORAGE BREAK-EVEN COST GOALS - UTILITY ONLY CHARGING (MULTIPLE SOURCE)

3.6.4 EFFECTS OF INSOLATION FORECASTING

Forecasting must necessarily involve not only prediction of insolation and the resultant PV output, but other factors which affect a utility system's load demand. The objective of this area of investigation was to consider the impact on resultant energy values with the presence of such knowledge.

3.6.4.1 Storage Dispatch with 100% Forecasting Accuracy

This condition will require perfect knowledge of the insolation and load demand for some period of time prior to commitment of storage discharge to meet the load. The further in advance, obviously the more perfect the planned dispatch results. Because the previous utility-only charging case accomplished short term (up to 24 hours) management of the state of change values in the model , this case was taken as the standard for comparison with more random logic alternatives.

3.6.4.2 Storage Dispatch Without Forecasting

Whereas it appears reasonable to assume some degree of weather forecasting ability based on current weather prediction technology, and probably an even higher degree of utility load forecasting, based on historical as well as real time data, the question then becomes: What should the operating strategy be if the forecast fails? "Failure" was herein defined as either non-avilability of a forecast, or a near real-time set of events contrary to the forecast. Use of some operational dispatch strategy different from the normal or planned strategy with good forecasting present appeared to be indicated. Accordingly, several alternative strategies were explored.

Selection of Alternative Operational Strategies

The selection of a good operational strategy for storage utilization is a difficult task in itself and appears to merit further investigation beyond the scope of this study. Factors affecting the strategy choice include such items as knowledge of system load characteristics, equipment in service, short term load trends, storage capacity (if any), and status, seasonal factors and for PV systems, normal output levels and penetration. It was deemed unlikely that an operator could cope with all of these in real time; therefore, one or more standby operational modes for storage dispatch would be necessary if the normal mode was disrupted by lack of usual forecast data.

The task of selecting alternative strategies was simplified for study purposes by examining the gain in values as a unit of energy is moved from one load strata to another (Refer to Figure 3.3-20 for one illustration of the strata concept). Table 3.6-2 as presented previously in Section 3.3.1.2 is helpful here also, as it gives the dollar savings provided by charging 1 kilowatt hour of storage capacity at one level and discharging to a higher valued level for a utility system "B" type load and costs of generation as in Figure 3.3-20.

TABLE 3.6-2. SAVINGS PER CHARGE/DISCHARGE CYCLE IN $/kWh

		DISCHARGE LEVEL			
		A	B	C	D
CHARGE LEVEL	A				
	B	-.0006			
	C	+.0121	+.0055		
	D	+.0223	+.0157	+.0062	

Two basic storage strategies of advantage can be identified by examining the above table:

1. Charge from C and D levels - discharge to A and B levels only. (C level discharge not permitted due to the possibility of charging at that level).

2. Charge from D level only - discharge to A, B and C levels.

Trial computational runs indicated that operational strategy 2 (above) was best for the utility load characteristics selected for study. This result appeared to be a function of the base load (level D) charging capacity available. (In this case quite large over a wide range of storage capacity). As storage size was increased to the point where level D was inadequate for charging, it was also observed that a large portion of the potential level A and B displacement had already taken place; therefore, little additional benefit was gained by level C charging.

Once the basic strategy was established, several variations of discharge priorities were tried for a representative week of system operation. Table 3.6-3 shows a representative computation table for these analyses:

TABLE 3.6-3. STORAGE DISPATCH OPTION ANALYSIS

Option 3-Day 6 (Typical)*

HOUR	UTILITY LOAD DEMANDS BY STRATA (MW)				STORED ENERGY (MWh)	SOC	STORED ENERGY DELIVERED TO LOAD (MWh)			
	A	B	C	D (EXCESS)			A	B	C	D
1				349	200	.250				
2				489	200	.400				
3				541	200	.550				
4				559	200	.700				
5				552	200	.850				
6				506	200	1.000				
7				371	-	1.000				
8				39	-	1.000				
9			246		-	1.000				
10		55	300		-	1.000				
11		125	300		-	1.000				
12	7	150	300		-7.37	.993	7			
13	26	150	300		-27.37	.965	26			
14	41	150	300		-43.16	.922	41			
15	17	150	300		-175.9	.746	17	150		
16		125	300		-131.58	.615		125		
17		98	300		-103.16	.512		98		
18		123	300		-129.47	.382		123		
19	84	150	300		-200.0	.182	84	106		
20	127	150	300		-82.11	.1000	78			
21	28	150	300		-					
22		7	300		-					
23			71		-					
24				254						
							253	602		

*1000 MWh Storage Capacity

The value of the stored energy discharge was found to be $14,588 for the example shown, whereas if the match had been perfect, the value would have been $15,066.

The discharge options examined are shown in Table 3.6-4, along with total results for the representative week.

TABLE 3.6-4. ALTERNATIVE DISCHARGE OPTIONS AND RESULTS OF 7 DAY USE

STORAGE DISCHARGE STRATEGY	7 DAY SAVINGS ($) DUE TO STORAGE	% MAX. SAVINGS
1. Discharge to cost of generation strata A or B only, whenever they occur; Weekend discharge to A, B or C without priority	75,767	87.7
2. No discharge until hour 11. Once strata A demand appears, discharge only to A until it disappears, then discharge to level B. Weekend discharge as in 1 (above)	79,521	92.0
3. Discharge to strata A only until hour 15, then to strata A and B. Weekend discharge to A, B or C as they occur.	79,786	92.4
4. Same as 3, but discharge to load strata C permitted from hour 22 on.	80,961	93.7
5. Discharge to exactly meet load demands in order of highest priority, (i.e., requires "A" first). (This option requires 100% knowledge of net load demands).	86,390	100.0

The first four strategies above are based on knowledge of load characteristics which a utility system dispatcher could be expected to have. In addition, it is highly probable that other knowledge such as the previous day's load demands or the rate of increase of load demand could be employed to further improve the utilization and in turn, the resultant value of storage.

3.6.4.3 Interpretation of Results

As the data in Table 3.6-3 shows, the achievable energy savings values for the week closely approach the maximum value with 100% daily knowledge of the load. If the basic storage charge logic (#2) identified from Table 3.6-1 is coupled with any one of the dispatch options analyzed above, the range of results falls within about 12% of those obtained with approximately 100% forecasting of the PV/load combination. This indicates, in essence, that any good operational strategy coupled with undedicated or multi-source charging can give effective results without forecasting. Since some degree of wind/load forecasting can be expected, the gap between actual and maximum possible savings will be still narrower. A "50% forecasting" accuracy as considered in the original task becomes somewhat of a moot point under these conditions . Furthermore, there are a multitude of strategy possibilities for achieving results falling between 0-100% forecasting.

The presence of PV energy generation in the utility system is compatible with the results shown since charging of the energy storage system is still done with excess base load energy whether or not the excess is the result of PV-supplied energy. When photovoltaic energy is present, it has the effect of lowering the demand on other generating units and stored energy would be dispatched accordingly. Unpredictable short term changes could cause a slight loss in stored energy value for the day if the PV system were displacing a high percentage of strata A and B energy, thereby causing the storage system not to be fully discharged that day. In the normal situation, insolation conditions would likely be anticipated adequately on an hour-by-hour basis to allow efficient and complete dispatch of stored energy.

One final note of caution may be appropriate. Although less than perfect forecasting might appear to lie between the extremes identified here, in actuality, adherence to operational modes based on an incorrect forecast could produce worse results than having no forecast at all. An example would be the discharge of storage to a low value level of the load strata in anticipation of a predicted high PV output during a peak load time. When the PV energy fails to materialize under these conditions, expensive peaking equipment must be used. With no forecast at all, use of a specific operational strategy, similar to those discussed previously, would very likely have assured an adequate stored energy reserve to meet the peak demand.

3.7 VALUE OF TRANSIENT SMOOTHING

3.7.1 OBJECTIVE OF INVESTIGATION

The principal purpose of study investigations in this area was to determine the value attributable to smoothing of transient photovoltaic conversion system output via energy storage. "Value" was examined in terms of technical necessity as well as economic impact.

3.7.2 DESCRIPTION OF THE SMOOTHING PROBLEM

The variability of PVCS energy conversion system output is well known and encompasses rather large swings in instantaneous power output, primarily due to cloud cover variations. The need and-or benefit of smoothing this output has at least two aspects of particular interest:

1. The technical need to limit output power variations in order not to disrupt the magnitude and/or synchronism of the of the power flow to an assigned load or to a jointly fed power grid.

2. The potential for economic improvement in value of the photovoltaic system output if smoothing were accomplished by energy storage.

In addressing these issues, it is necessary to distinguish between outputs devoted to single loads and those contributing to a larger network. The characteristics of each of these situations is discussed in the following section.

3.7.3 EFFECT OF GENERATION AND LOAD RELATIONSHIPS

3.7.3.1 Single Loads with a Single Generating Source

For the case of single loads served by single photovoltaic array, the requirement for energy storage is largely dependent on the requirements of the specific type or types of load to be served. Some loads for specific applications of photovoltaic power are "interruptible" by their nature. Two possible examples are the pumping of water for reservoir storage or irrigation purposes, and resistive heating loads. In the water pumping example, the consistency of flow rate may be of lesser significance than the total quantity of water pumped over a specified time span. Consequently, the principal requirement resulting from PVCS output fluctuations would be selection of pump motors and contactor devices rated for this type of duty. Other inquiries made during the study (Section 2), have indicated that selection of equipment with such ratings is feasible. In the resistance heating example, no power input regulation would be required as long as specified voltage limits were not exceeded. Power variability could affect thermostatic duty cycles, and the need for back-up, but the integrated heating output of the PVCS over a period of time would be identical for the same total energy input.

Unfortunately, however, most of the electrical equipment encountered in diversified loads is designed to produce acceptable results when operating within narrow limits of power, voltage and frequency (the latter in the case of ac loads). This fact necessitates that some form of power conditioner be used in conjunction with the generating source in order to match it to the load.

One straightforward method for matching the source to the load is to simply over-design the source and then by use of series or shunt regulating techniques, discard a certain percentage of the source power so that the delivered power exactly matches the load demand. When the source power falls below the demand, the supply is simply interrupted until the energy source can once again provide an adequate output level. This method has been used on numerous occasions for simple, photovoltaic-powered satellites where interruptions in operation can be tolerated while the satellite is shadowed in passing behind the earth. Systems of this type are generally energy-wasteful due to oversizing of the power source, and as indicated, operation of load devices is severely limited.

A second method for matching a single source and load would be to introduce energy storage. The regulation characteristics of the storage device may be adequate in some cases for the needs of the loads being served, so that, in addition to absorbing excess power from the source, the power is also available to the load at compatible voltage levels. With this approach, the load is still served during temporary periods of no generation. The character of the load again determines whether storage is required. The amount of storage capacity is determinable based on specification of the time which loads must be carried should source power be interrupted.

The general functioning of load dedicated systems may be considered further based on the overall relationships shown in Figure 3.7-1.

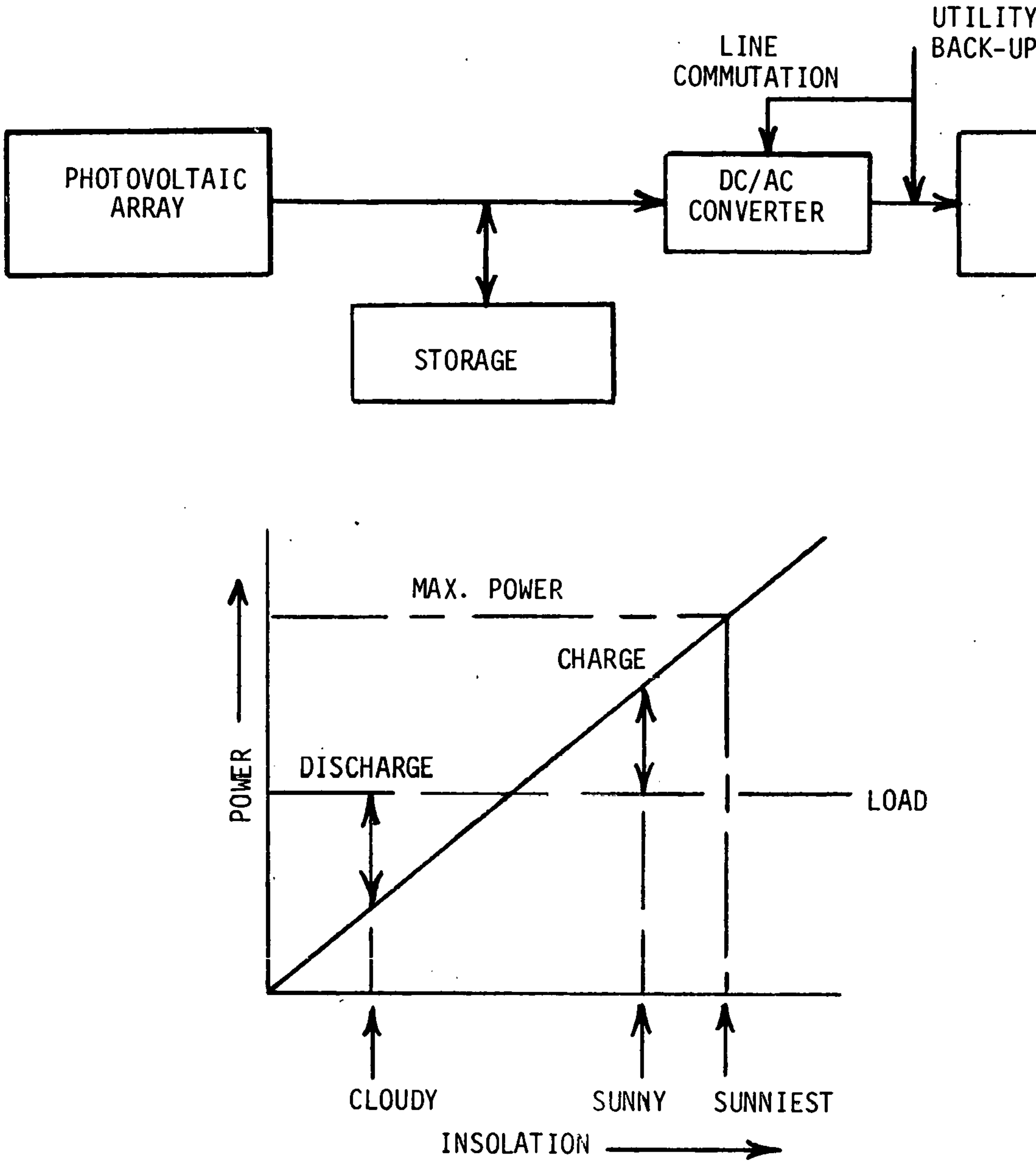


FIGURE 3.7-1. LOAD DEDICATED SYSTEMS

Besides the basic generation and storage systems, functions are included for DC to AC conversion, a means of back-up (utility) and line commutation to synchronize the DC/AC inverter output with the utility back-up. This latter function is important with respect to load transients for the following reasons:

The ability of the DC/AC inverter to meet load transients will be limited by its rating. A large transient load, such as that associated with motor starts, might require an uneconomically large inverter. The arrangement shown overcomes the need for a large inverter by placing the burden for the large transient on the utility back-up. Although the details of control transfer are not shown here, this function is relatively straightforward to accomplish. By limiting the inverter output to a pre-set level, the utility back-up is forced to make up the load difference. This points out the basic inability of the storage system to smooth transients which are greater than the capacity of the smallest link, in this case, the rating of the inverter. Thus, although the storage may in itself be adequate, other restrictions within the system may limit its transient smoothing capability. Although this limitation was illustrated for a particular arrangement, it is representative of limitations that will be encountered.

Considering transients associated with generation rather than load demands, the lower portion of Figure 3.7-1 indicates the situation for a photovoltaic power source. A linear relationship between insolation and photovoltaic power output is assumed. This is very nearly the case, ignoring the effects of solar cell temperature which are of second order importance regarding the issue of concern. The main point on this plot is that the maximum photovoltaic power output is naturally limited by the sunniest conditions with minor adjustment due to temperature. With such well-established limits, it is a straightforward matter to design storage that can accept the maximum generation under conditions of minimum load, thereby preventing the occurrence of severe generation source fluctuations.

Within the range of the photovoltaic system capabilities, sudden increases or decreases in output must be considered. Examination of plots of insolation level variations with time shows a wide range of instantaneous or short term values which are in turn reflected in variation of the photovoltaic array output. Figure 3.7-2 shows a typical example. This plot is especially interesting in that it shows several types of time-variant changes in insolation. These include:

1. Ripples on the basic trace in the order of 0-5%, lasting only a matter of seconds.

2. Short term dips in insolation level ranging from perhaps 40-75% in amplitude over periods of 2-8 minutes.

3. Long term loss of insolation where the level drops to about 10% of the level for a smoothed trace. Duration of this low is roughly two hours and twenty minutes.

Examination of annual traces of insolation highs and lows reveals that the total number of such cycles per year varies widely with location. Further, the magnitude of the variation varies similarly. A sunny southern U.S. location can be shown to have the more favorable characteristics (fewer and shorter dips in insolation). For Miami, FL, the annual frequency of days having below average insolation was examined and found to be about 3 days out of each week on a year-round basis. Based on the foregoing, an approximation of the storage requirements for output smoothing may be projected as follows: Given a representative daily insolation such as the one shown in Figure 3.7-2, the magnitude of short term fluctuations would be reduced

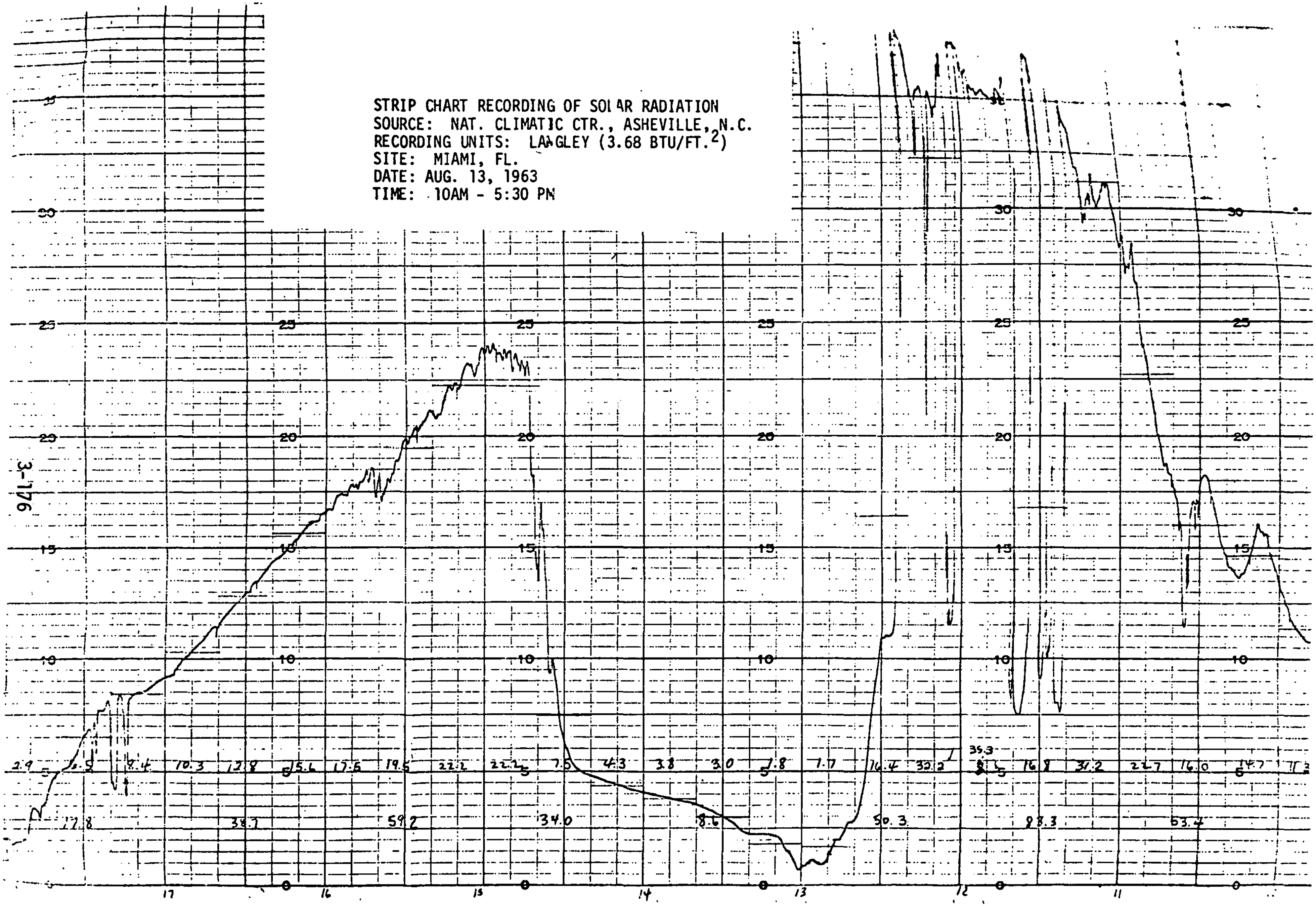


FIGURE 3.7-2 REPRESENTATIVE INSOLATION LEVELS

to the order of $\pm$ 5-6% of a smoothed output if storage capacity sufficient for about eight minutes of load-carrying were provided. To accommodate a minimum of two of the short term dips (2. above) back-to-back which would prevent any storage recovery, 15-20 minutes of storage capacity would be needed. The storage system power rating would need to be based on the nominal system output rating and the storage capacity would be determined by the time interval for load carrying. Thus, at 100 kW of demand, the storage system output would need to be capable of operating at this level for about 15 minutes or in energy terms, would have to provide 25 kWh (.25 kWh/kW of output). The daily cycle of such occurrences based on the insolation levels shown would be in the order of twenty. The ripples (1. above) would be handled in one of two ways: (a) by allowing them to pass through to the inverter or (b) by absorbing them if a "clamped" battery arrangement were possible as in a residential type system. It is unlikely that switching storage in and out would be practical because of the excessive number of cycles that would be required. The longer interval drops in output (3. above) would have to be either: (a) accepted as a normally-expected outage time or (b) established as load-critical and used to justify increasing the storage capacity to 200 kWh or a factor of 8-10. This latter type of decision should only be made with specific load requirements in mind. In any case, the requirement for storage is dependent on the type of load and the storage capacity should be kept as small as possible to minimize costs. At least 10% of reserve storage capacity should be added to the requirement to prevent 100% discharge from occurring. For the relatively small amounts of storage described above, replenishment would normally occur daily during the positive swings in insolation. A further decision would be required to determine how much to hedge for the "down" days. Normal use of storage on an average day followed by one or more low output days would mean that some reserve of storage smoothing capacity might be desirable. Only much larger storage capacities, such as analyzed previously in Section 3, could alleviate the problem of a day with low overall average and a load which must be met.

The cost of providing the capability to handle 100 kW output at \$70/kW + \$40/kWh would be \$8,000. Since only about 25% of the daily smoothing cycles would require full storage capability any savings in annual kWh of energy would be reduced. If the balance of the 20 daily cycles occurred at the 25 kW level, the annual savings at 4¢/kWh would amount to \$624/yr. This would have a 20 year capitalized value at or below the above estimated cost, making storage for smoothing uneconomical for residential or intermediate use. The value at the utility application level would be still less. An allowance for storage cycle life would reduce the economic attractiveness still further since the large number of annual cycles would prevent realization of long storage system life based on present concepts. Thus, the real benefit from short term smoothing with storage was assessed as being primarily one of assuring good equipment operation for those loads requiring constant input levels.

3.7.3.2 Multiple Loads with Multiple Generation Units

For distributed generation and load systems, the situation may be depicted as in Figure 3.7-3.

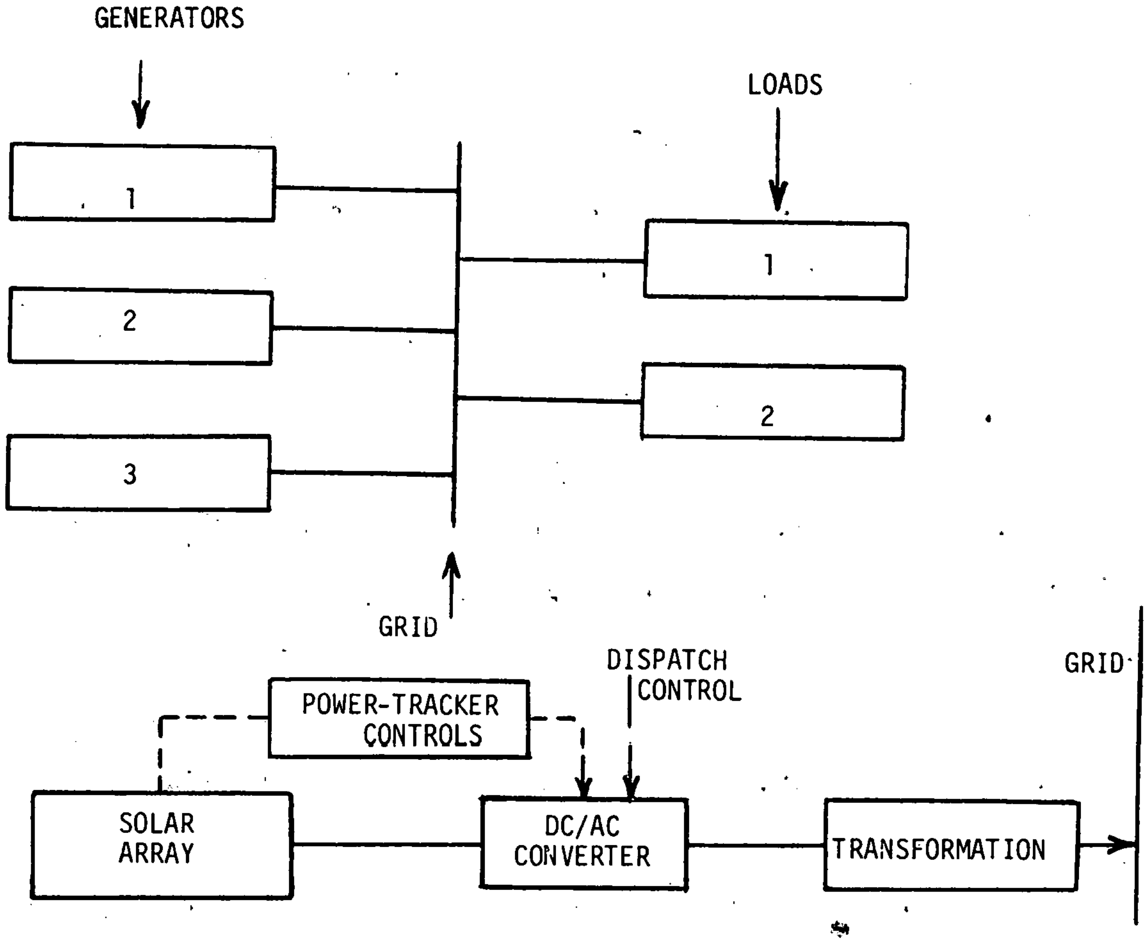


FIGURE 3.7-3. MULTIPLE UNIT SYSTEMS WITH DISTRIBUTED LOADS

The effect of fluctuations in the output power of any one array sector is levelized at the grid since the transient conditions at all locations in a dispersed array are not likely to be the same at any particular time. The fluctuations in total output may therefore be considered self-smoothing to a certain extent. Spinning reserve or general system storage would be used to modify the resultant toal power supplied by the utility system to its loads.

The effect is believed to be similar to that of a varying output from dispersed wind turbines. This effect has been investigated and found to be better controlled, when necessary, by other means as explained above.

As shown in Figure 3.7-3, the power tracker controls sense the best voltage and current values - resulting from insolation and temperature conditions. The effective impedance of the DC/AC converter is accordingly adjusted so that operation at these optimum values is assured. The converter AC output is properly synchronized with the utility grid through signal commutation techniques and the output inserted into the grid after appropriate transformation. The power output level will vary according to the insolation level and, as indicated earlier, spinning reserve and system storage units will be continuously called upon so that total system supply exactly matches the total system demand. For relatively small photovoltaic penetration, on the order of 5-10% of total utility system rating, this method would be similar to modes of control associated with normal load variations.

The above discussion provides a perspective on the transient smoothing capability of storage used with photovoltaic generator systems. The economic benefits provided by the transient smoothing capability of energy storage is marginal at best. For certain cases, the consequence of not using energy storage is fully acceptable in terms of the resulting transient behavior. In other cases, storage may be a necessary adjunct for assuring technical performance. However, in these latter cases, it was not possible to identify a clear economic benefit, per se, associated with short-term transient smoothing. On the other hand, the long-term benefits of energy storage are beyond question as established previously in an earlier section.

3.7.4 SPECIAL CASE - POTENTIAL VALUE OF SMOOTHING FOR INTERMEDIATE APPLICATIONS

Output smoothing from energy storage can substantially enhance the value of energy from a PV energy system under many existing and proposed utility rate schedules. The basic objective of the storage smoothing in this case is to alter the purchased electricity versus time of day profile to one which is less expensive for the utility to supply and for which the utility is therefore able to offer preferential rates.

Figure 3.7-4 presents the Philadelphia Electric Company industrial rate schedule applicable to the Valley Forge General Electric facility. This schedule puts a strong premium on load leveling as does the Georgia Power Company schedule, also shown. For example, a Philadelphia customer with a maximum demand of 1000 kW, using 360,000 kWh in a month would pay a monthly bill of $8961 for an average energy price of $.025 per kWh. For a perfectly level load of 500 kW, for 720 hours, the same 360,000 kWh would cost only $6616, dropping the average energy price to $.018 per kWh.

Addition of a photovoltaic energy conversion system to an application with a previously level load will reduce the total electric bill but, if peaks are not reduced also, the energy supplied will be worth only the lowest price increment - $.0116/kWh in the Philadelphia Electric rate schedule. This is easily shown by assuming a 500 kW PVCS with capacity factor of .25 is added to the level load plant and computing the old and new electric bills:

RATE PD PRIMARY-DISTRIBUTION POWER

Availability

Untransformed electric service from the primary supply lines of the Company's distribution system where the Customer installs, owns, and maintains, any transforming, switching and other receiving equipment required. However standard primary service is not available in areas where the distribution voltage has been changed to 13 kV unless the Customer was served with standard primary service prior to the conversion of the area to 13 kV.

Current Characteristics.

Standard primary service.

Monthly Rate Table

Capacity Charge Prices: Per KW of billing demand:

$4.07 per kW for the first 50 kW
$2.17 " " " " excess over 50 kW

Energy Charge Prices:

2.40¢ per kWh for the first 150 hrs use of billing demand but not less than 5,000 kWh.
1.60¢ per kWh for the next 150 hrs use of billing demand
1.16¢ " " " " additional use.

State Tax Adjustment Clause and Fuel Adjustment Clause apply to this rate.

- Philadelphia Electric Company

MONTHLY RATE - ENERGY CHARGE INCLUDING DEMAND CHARGE:

First 25 KWH or less	@	$3.05
Next 75 KWH	@	7.00¢ per KWH
Next 1,400 KWH	@	5.18¢ per KWH
Next 8,500 KWH	@	4.33¢ per KWH
Next 199,000 KWH	@	3.00¢ per KWH
Over 200,000 KWH	@	2.50¢ per KWH
All consumption in excess of 200 KWH per KW of Demand, which is also in excess of 1000 KWH	@	0.86¢ per KWH
All consumption in excess of 400 KWH per KW of Demand, which is also in excess of 2000 KWH	@	0.62¢ per KWH

Minimum Monthly Bill:

A. $3.05 per meter plus $3.05 per KW of Demand in excess of 5 KW.

B. Athletic Field Lighting: $12.00 per meter for lighted athletic fields, provided service is limited to the field lighting equipment itself and such incidental load as may be required to operate coincidentally with field lighting equipment.

FUEL ADJUSTMENT:

The amount calculated at the above rate is subject to increase or decrease under the provisions of the Company's Fuel Adjustment Rider, Schedule "PA-1".

- Georgia Power Company

FIGURE 3.7-4 TYPICAL INDUSTRIAL ELECTRIC RATE SCHEDULES

Monthly PVCS output = .25 (24) (30) (500) = 90,000 kWh

New electric demand = 360,000 - 90,000 = 270,000

Maximum demand = 500 kW (with and without PVCS)

Pricing Blocks = 150 x 500 = 75,000 kWh

OLD BILL

4.07	x 50	$ 203.50
+2.17	x 450	976.50
+75,000	x .024	1800.00
+75,000	x .016	1200.00
+210,000	x .0116	2436.00
	TOTAL	$6616.00

NEW BILL

4.07	x 50	$203.50
+2.17	x 450	976.50
+75,000	x .024	1800.00
+75,000	x .016	1200.00
120,000	x .0116	1392.00
	TOTAL	$5572.00

The savings of 1,044.00 divided by PVCS contribution of 90,000 kWh yield $.0116/kWh for the PVCS energy value which is also evident from comparison of the two bills.

Now suppose energy storage is added such that the PVCS output is smoothed to a constant 110 kW. Energy delivery is reduced to 79,200 kWh (110x30x24) due to storage inefficiency but maximum utility demand has been reduced to 390 kW. This makes the billing blocks 58,500 kWh and the bill is reduced to:

4.07 (50)	\$ 203.50
+2.17 (340)	737.80
+58,500 (.024)	1,404.00
+58,500 (.016)	936.00
+163,800 (.0116)	1,900.08
TOTAL BILL WITH STORAGE	\$5,181.38

Thus storage has provided a savings of \$390.62 per month over the savings from the PVCS alone. Capitalization of this savings will yield the storage break-even cost. Assuming a fixed charge rate (FCR) of .22, system life of 30 years and fuel price escalation of 5%, or zero differential to the baseline inflation rate, the break-even cost is:

$$Cost_{BE} = \frac{M_f \text{ x annual savings}}{FCR}$$

where M_f = fuel price multiplier (1.6759 for 5%, 30 years)

$$Cost_{BE} = \frac{1.6759(12)\ (390.62)}{.22} = 35,708$$

Storage requirements to completely level the output of a 500 kW PVCS may prove quote large for certain regions. A combination of energy storage and load management techniques may offer the most economic solution. Philadelphia Electric is one of many utilities encouraging load management for high energy consuming industrial or commercial users. To this end they offer consulting services and low night rates in addition to the load leveling incentive inherent in their basic structure.

Storage also has load leveling value for intermediate applications without PVCS present. Assume a commercial operation with an electric demand of 1000 kW from 8 AM to 4 PM and 200 kW for the remaining 16 hours per day. Total demand is 336,000 kWh per month and the PE rate schedule will yield a monthly electric bill of $8,682.60. Now suppose storage were added to produce a level load. At .75 efficiency, 3840 kWh of storage would produce a level demand of 520 kW from the utility. Charging energy would be 16 hours x 320 kW or 5120 kWh, which is reduced to 3,840 available due to the .75 efficiency. Discharging for 8 hours gives 480 kW which, added to the 520 kW utility supply gives the 1000 kW daytime requirement. Computation of an electric bill for a 520 kW constant demand yields $6876.84 per month for a savings of $1805.76. Capitalizing as before:

$$\text{Cost}_{BE} = \frac{1.6759(12)(1805.76)}{.22}$$

$$= \$165{,}069.45$$

on a kWh basis:

$$\left(\frac{\$}{\text{kWh}}\right)_{BE} = \frac{165{,}069.45}{3840} = \$42.99 \ \frac{\$}{\text{kWh}}$$

This is a conservative value and will be greater for higher fuel escalation rates and delayed start year. For example, at 70% fuel escalation rate and 1990 start, the above break-even value increases to $71.26/kWh.

The value of storage employed in this manner is highly susceptible to utility rate structure changes. One rate structure change that is now underway and will likely continue, is time-of-day or peak load pricing.

This would alter the storage operational strategy and very likely change the economic storage size. Peak load pricing might also extend the benefits of load leveling to the residential sector, which now has little incentive in present rate structures.

REFERENCES AND BIBLIOGRAPHY

VOLUME II

CITED REFERENCES

1. Kirpich, A., et. al., "Conceptual Design and Systems Analysis of Photovoltaic Systems", General Electric Co., Final Report, ERDA Contract EY-76-C-04-3686, March 1977.

2. Bush, J.B., et. al., "Economic and Technical Feasibility Study of Compressed Air Storage", General Electric Company, Final Report, ERDA 76-76, March 1976.

3. "Lead-Acid Batteries for Utility Application", Workshop II, EPRI Special Report, March 1977.

4. "Proceedings of the Symposium and Workshop on Advanced Battery Research and Design", Chicago Section - The Electromechanical Society and Argonne National Laboratory, ANL-76-8, March 1976.

5. "Engineering Study of a 20 MW Lead-Acid Battery Energy Storage Demonstration Plant", Bechtel Corp., Final Report, ERDA Contract E(04-3)-1205, October 1976.

6. Berkowitz, D.G. and Brown, J.T., "Advanced Technology Lead-Acid Storage (Atlas) Batteries on Electric Utilities", Westinghouse Electric Corp.

7. Birk, J.R., "The Lead-Acid Battery for Electric Utilities", Electric Power Research Institute, December 1976.

8. "Summary of Workshop on Battery Considerations for the Best Facility", January 1975.

9. "Battery Considerations for the Best Facility Study", the BEST Facility Study Project Team, January 1977.

10. "The Best Facility Workshop II", EPRI, April 1977.

11. "Economic and Technical Feasibility Study for Energy Storage Flywheels", Rockwell International, ERDA Document 76-65, December 1975.

12. "Energy Storage Systems Study (Hydrogen)", General Electric Co., Direct Energy Conversion Programs Report, September 1976.

13. "Development of Sodium Sulfur Batteries for Utility Application", General Electric Co., Annual Report, EPRI Project 128-3, December 1976.

14. Bush, K., Private Communication, AiResearch Mfg. Co., of Arizona, Garrett Corp., February 1977.

15. Van Sant, J.H., Private Communication, The Hydro-Quebec Institute of Research, Varennes, Quebec, Canada, February 1977.

16. Shepard, N.F., et. al., "Definition Study for Photovoltaic Residential Prototype System", General Electric Co., Space Division, NASA-LeRC, Contract NAS-19769, September 1976.

17. "An Assessment of Energy Storage Systems Suitable for Use by Electric Utilities", Public Service Electric and Gas Company of N.J., Final Report - EPRI Research Project 225, Report EM 264, July 1976.

18. Climatic Atlas of the United States, June 1968, Environmental Sciences Services Administration, U.S. Department of Commerce.

19. GE Weather Data Tape Serial No. 03374 (Derived from U.S. Weather Bureau Data).

20. Private Communication - H. Stoll, GE/EUSED, March 1977.

21. Berkowitz, D.G., and Brown, J.T., "Advanced Technology Lead-Acid Storage (ATLAS) Batteries on Electric Utilities", Proc. Energy Storage Symposium, Electrochemical Society, 1976.

22. Cooper, V.R., Pepper, J.W., "Rationale for the EPRI Thermal-Mechanical Energy Storage Program", EPRI, Proc. American Power Conference, Vol. 38, 1976.

23. Grant, E.L., Principles of Engineering Economy, The Ronald Press Co. NY, 1950.

24. Doane, J.W., O'Toole, R.P., and Chamberlin, R.G., Jet Propulsion Laboratories, Bos, P.B., Electric Power Research Institute, Maycock, P.D., Division of Solar Energy, "The Cost of Energy from Utility-Owned Solar Electric Systems, A Required Revenue Methodology for ERDA/EPRI Evaluations, ERDA, ERDA/JPL-1012-76/3, June 1976.

25. "Typical Electric Bills 1976 (Residential, Commerical, Industrial)", Federal Power Commission, Report No. FPC R88, January 1976.

26. Comtois, W.H., "Power Plant Construction Schedules, Escalations and Interest During Construction", Westinghouse Electric Corp., American Power Conference, April 1976.

27. "All Electric Homes in the United States", Federal Power Commission, FPC R-87, 1976.

VOLUME II

SUPPLEMENTAL BIBLIOGRAPHY

Asbury, J.G., et. al., "Solar Energy and Electric Utilities, Can They Be Interfaced?", Argonne National Laboratory, ANL/ES-52.

Braun, C., Cherniavsky, E.A., and Salzano, F.J., "The Economic Incentives for Introducing Electric Storage Devices into the National Energy System", Brookhaven National Laboratory, 1975.

Braunstein, A., Tel-Aviv University, and Biran, D., IDF, "Solar-Electrical Systems - Theory and Applications".

"Digest of Current Research in the Electric Utility Industry", Electric Power Research Institute, Report RD-2, May 1976.

Eldridge, F.R., "Mitre Photovoltaic Energy System Study", The Mitre Corp., October 1973.

"Energy Storage and Conversion for Photovoltaic and Wind Energy Systems", Public Service Electric and Gas Co. of Newark, N.J., September 1976.

"Energy Storage", NASA Literature Search, 33159, August 1976.

"Energy Storage (I): Using Electricity More Efficiently", Science, Vol. 184, May 1974.

Federmann, E.F. and Ferber, R.R., "New Concepts in Solar Photovoltaic Electric Power Systems Design", Westinghouse Electric Corp., 11th IECEC, 1976.

"Insolation Data Base Available from the Aerospace Corp.", Aerospace Corp., Report ATR-76 (7523-11)-9.

"Investigation of Storage System Designs and Techniques for Optimizing Energy Conversion in Integrated Utility Systems", Battelle Columbus Laboratories, Final Report, NASA Contract NAS 9-14628, March 1976.

Kalhammer, F.R., and Zygiellbaum, P.S., "Potential for Large-Scale Energy Storage in Electric Utility Systems", Winter Meeting, ASME, November 1974.

Landgrebe, A.R., and Klunder, K.W., "Energy Storage Technology", ERDA, Proc. Energy Storage Symposium, Electrochemical Society, March 1976.

Marsh, W.D., "Energy Storage in Electric Utility Generating Systems", General Electric Co., Report 143, June 1976.

Miller, D.B., Purdue University, and Boer, K.W., University of Delaware, "Solar-Electric Residential System Tests".

Noll, E.M., Wind/Solar Energy for Radiocommunications, and Low-Power Electronic/Electric Application, 1975.

Schneider, T.R., and Snow, R.V., "Assessment of Storage Systems: The Device Utility Interface", Public Service Electric and Gas Co., IEEE Winter Power Meeting, 1976.

Schueler, D.G., "The ERDA Photovoltaic Systems Definition Project", Sandia Laboratories, 11th IECEC, 1976.

Shurtleff, W.W., "Solar Total Energy Control Data Acquisition Systems", Sandia Laboratories, Report SAND 76-0506, November 1976.

Sulzberger, V.T., and Zemkoski, J., "The Potential for Application of Energy Storage Capacity on Electric Utility Systems in the United States", PT I and II, Public Service Electric and Gas Co., 1976.

"Terrestrial Photovoltaic Measurements", Workshop Proceedings, NASA/LeRC and ERDA, March 1975.

APPENDICES

APPENDIX A

GLOSSARY AND DEFINITIONS

ABBREVIATIONS AND SYMBOLS	MEANING
A	Ampere
ac	Alternating current
$\overline{AC}$	Levelized Annual Cost
A/C	Air Conditioning
A_E	Annual Energy Credit (dollar savings due to storage)
AH	Ampere - hour
a_{om}	O&M Cost per kWh of storage discharge energy
A_{OM}	Annual O&M Cost
ASDE	Annual storage discharge energy
A_W	Annual Worth (dollar saving from base system plus storage)
BE	Break-Even
bhp	Brake horsepower
Btu	British Thermal Unit
C	Capitalized (or capital) cost
°C	Degrees Celsius
C_{BE}	Break-even capital cost
CC	Capacity credit
C_E	Capitalized energy credit
CCF	Construction cost factor
C_η	Efficiency correction factor
COE	Cost of electricity

ABBREVIATIONS AND SYMBOLS	MEANING
C_{OM}	Capitalized value of O&M Costs
CRF	Capital recovery factor
C*	Effective carrying capacity, MW
Δ	Delta, difference
dc	Direct current
e	Electricity price escalation rate
E_{DPV}	Energy supplied to load from storage/PV
E_{DU}	Energy supplied to load from undedicated storage
E_{DW}	Energy supplied to load from storage/WECS
f	Fuel price escalation rate
°F	Degrees Fahrenheit
FCR	Fixed charge rate
gal.	Gallon
g	General inflation rate
gpm	Gallons per minute
h	Hour (or Hr)
H	Head, hydrostatic
H_2	Hydrogen (system)
hp	Horsepower
HV	High voltage
Hz	Hertz (frequency)
kV	Kilovolt
kW	Kilowatt
kWh	Kilowatt-hour

ABBREVIATIONS AND SYMBOLS	MEANING
M	Multiplier for an escalating cost stream
m	Meter
MPH	Miles per hour
m/s	Meter per second
MW	Megawatt
MVA	Megavolt ampere
MWe	Megawatt-electric
MWh	Megawatt hour
n	Life (system) years
η	Efficiency
Ø	Phase (electric power)
P	Power
PF	Power factor
Psi	Pressure, pounds per square inch
Psig	Pressure, pounds per square inch-gauge
ρ	Air density, value of
R	Risk factor
r	Discount rate
R/C G/T	Regenerative Cycle - gas turbine
RPM	Revolutions per minute
SCF	Standard cubic foot
sec	Second (time)
SG	Specific gravity
S/C G/T	Simple cycle - gas turbine
SOC	State of charge

ABBREVIATIONS AND SYMBOLS	MEANING
STAG	Combined cycle steam and gas turbine system (GE Trademark)
t	time (or temperature)
T	Torque (lb. ft.)
v	Velocity, linear
V	Volt
W	Watt
$[\ ]^{o}$	Any value taken at 75% efficiency (superscript zero)

ACRONYMS	MEANING
AEP	Advanced Energy Programs, General Electric Company
ASME	American Society of Mechanical Engineers
BEST	Battery Energy Storage Test (facility)
BOP	Balance of Plant
BTTL	Building Transient Thermal Load (a computer program)
CVT	Continuously variable transmission
DECP	Direct Energy Conversion Programs, General Electric Company
EUSED	Electric Utility Systems Engineering Department, General Electric Company
IEEE	Institute of Electrical and Electronic Engineers
LOLP	Loss of Load Probability
MPS	Monthly Production Simulation (a computer program)
O&M	Operation and Maintenance
PPS	Pure pumped storage
PSH	Pumped storage - hydro
PV	Photovoltaic
PVCS	Photovoltaic conversion system
SA	Solar Array
T&D	Transmission and Distribution
WECS	Wind energy conversion system
WTG	Wind Turbine Generator

Definitions

Annual Energy Displacement	- Quantity of energy replaced by PVCS, WECS and/or Energy Storage discharge
Array (PV)	- Photovoltaic cells complete with mounting fixtures.
Baseload	- The generally constant portion of utility generated power output.
Breakeven Cost	- The cost at which two alternative methods are equivalent from the owner's viewpoint.
Bus	- A major electrical interconnection or tie.
Capacity Credit	- A credit earned for ability to replace a conventional generating unit.
Capital Costs	- The investment associated with initial purchase of major equipment or facilities.
Capitalized Value	- An equivalent present value (dollars) representing cost (or worth) of an annual sum of money for a given period of time.
Capacity Factor	- The ratio of actual (realized) energy output to maximum output at rated power for some period of time (usually a year).
Cell	- The smallest electro-chemical unit in a battery energy system.
Concentration Ratio	- The factor by which basic insolation is multiplied or "concentrated" by a given type of PV/solar array.
Converter	- A class of devices for performing DC/AC power conversion or "inversion".
Cost Goal	- Break-even cost, or a minimum objective to economically justify an alternative method.
Cut-in Velocity	- The wind velocity at which a WTG commences power generation.
Cut-out Velocity	- The wind velocity at which a WTG terminates power generation.

Dedicated Storage	- An energy storage system charged solely from WECS/PVCS or any single energy source.
Discharge/Charge Rate	- The time rate for transferring energy to or from storage at rated power.
Diversified Load	- A mix of different types of power consuming devices, in residential use, various appliances, motors, etc. as opposed to space heating or water heating loads.
Duty Cycle	- The duration and periodicity of operation of a device.
Effective Carrying Capacity	- The power capacity that can be reliably furnished from storage.
Escalation Rate	- The annual percent by which fuel (or other commodity) increases in price. May be different from general inflation.
Forced Outage Rate	- The annual amount of unscheduled out-of-service time for power generation units.
Heat Rate	- The amount of thermal input to a power generating unit necessary to produce 1 kWh of output (3413 Btu/kWh ÷ heat rate = unit efficiency).
Insolation	- Solar radiation received at some specific point, e.g., a solar cell. Has both direct and diffuse components.
Intermediate Application	- A broad class of commercial or industrial energy consumers below the utility scale and above the residential scale. (study definition).
Levelized Annual Cost	- An annual sum which, if expended each year over a specified time for equipment or services, would be equivalent to the summation of all actual costs, during the same period, for fixed and variable charges, including burdens.

Load Duration - The time during which the load (utility power demand) exceeds a given magnitude. Usually summed for time periods of particular interest.

Mix - The specific combination within a utility system of various generating units using different types of fuels (i.e., coal, nuclear, oil, etc.).

Multiple Source - Refers to power supplied from system-wide generation and/or a mix of power sources.

Off-Peak - Refers to utility load demand or power generation occurring at other than peak load hours of the day.

Peaking Units - Utility generating units assigned solely to respond to the periods of highest load demand.

Penetration - The percent of total power generation capacity contributed by PVCS/WECS based on peak power output rating.

Shunt Regulator - A device or devices with the function of dissipating excess power from a PVCS or other source in order to maintain desired power levels.

Start Year - The first year of system operation and benefit return.

Storage System Cost - A current estimated cost of a storage system or a projected future cost.

System-wide Storage - An energy storage system accessible to and chargeable by any generating source in the system having available and/or excess capacity.

Zero Differential Escalation - A condition where the general inflation rate and the escalation of a specific commodity (such as fuel) are identical.

Conversion Factors

Unit/Quantity	Multiplying Factor	Converted/Equivalent Unit/Quantity
Solar cell area, m^2	.114	PV output, kW (@ 60°C and 1 kW/m^2 normal insolation)
Langley	3.68	Btu/ft^2
m/s	2.237	MPH

TABLE B-1. PHOTOVOLTAIC ENERGY CONVERSION SYSTEM STORAGE CHARGING - UTILITY APPLICATION

(PHOENIX, AZ, INSOLATION DATA η = 75%)

STORAGE CAPACITY (MWh)	C (MW)	ANNUAL ENERGY DISPLACEMENT (MWh)				F^{O}_{UPV} (MWh)	ASDE (MWh)	A^{O}_{W} (MM$)	A^{O}_{E} (MM$)
		COST REGIME A	B	C	D				
				10% PENETRATION					
0	0	73,016	255,566	363,603	201,243	--	--	12.785	--
DISCHARGE RATE LIMIT = 5 HR.									
250	50	79,219	259,460	364,429	185,106	10,923	11,732	12.982	.198
500	100	84,328	263,349	365,399	170,379	20,891	22,440	13.157	.372
1000	200	92,267	271,777	367,538	143,037	39,397	42,318	13.468	.683
2000	400	102,726	287,926	373,711	94,608	72,178	77,528	13.973	1.183
3000	600	106,057	303,669	382,802	52,996	100,343	107,781	14.333	1.548
DISCHARGE RATE LIMIT = 10 HR.									
250	25	78,528	259,316	364,536	186,180	10,195	10,951	12.966	.181
500	50	83,474	263,015	365,456	172,050	19,760	21,225	13.134	.349
1000	100	91,769	270,939	367,534	145,017	38,057	40,878	13.445	.660
2000	200	101,949	287,433	373,583	96,674	70,780	76,026	13.948	1.163
3000	300	105,949	303,319	382,749	53,753	99,832	107,231	14.325	1.540
4000	400	107,538	313,542	393,953	19,749	122,848	131,953	14.576	1.791
DISCHARGE RATE LIMIT = 15 HR.									
250		77,642	259,239	364,800	187,212	9,496	10,201	12.947	.162
375	25					(14,000)			
500		81,859	262,812	365,950	174,006	18,436	19,802	13.099	.314
750	50					(27,000)			
1000		89,021	269,999	368,458	149,100	35,293	37,910	13.376	.591
1500	100					(51,000)			
2000		99,017	284,381	374,610	103,998	65,823	70,701	13.844	1.059
3000	200	104,265	298,112	383,089	63,431	93,281	100,195	14.212	1.427
				20% PENETRATION					
DISCHARGE RATE LIMIT = 10 HR.									
0	0	88,990	332,756	717,206	647,903	--	--	21.080	--
500	50	101,155	349,326	731,798	583,892	43,327	46,539	21.674	.594
1000	100	110,461	365,143	747,387	523,746	84,039	90,267	22.201	1.121
2000	200	120,892	392,636	781,671	417,067	156,247	167,827	23.033	1.953
4000	400	127,655	423,774	842,040	271,885	254,517	273,381	23.985	2.905
				30% PENETRATION					
DISCHARGE RATE LIMIT = 10 HR.									
0	0	93,999	361,152	917,968	1,307,164	--	--	27.108	--
750	75	111,247	387,596	949,216	1,196,450	74,940	80,494	28.054	.946
1500	150	122,655	410,746	983,872	1,094,193	144,154	154,838	28.844	1.736
3000	300	132,718	447,558	1,054,530	920,553	261,687	281,082	30.011	2.903
6000	600	138,222	478,453	1,179,185	681,666	422,741	454,072	31.286	4.178
DISCHARGE RATE LIMIT = 5 HR.									
1000	200	120,816	407,544	956,007	1,142,809	111,248	119,494	28.600	1.492
2000	400	129,751	439,444	1,016,271	993,448	212,347	228,084	29.611	2.503
4000	800	136,187	466,186	1,123,328	785,622	352,582	378,713	30.747	3.639

TABLE B-2. PHOTOVOLTAIC ENERGY CONVERSION SYSTEM STORAGE CHARGING - UTILITY APPLICATION

(MIAMI, FL, INSOLATION DATA, η = 75%)

STORAGE CAPACITY (MWh)	C (MW)	ANNUAL ENERGY DISPLACEMENT (MWh)				E^{o}_{DPV} (MWh)	ASDE (MWh)	A^{o}_{W} (MM$)	A^{o}_{E} (MM$)
		COST REGIME A	B	C	D				
				10% PENETRATION					
DISCHARGE RATE LIMIT = 10 HR.									
0	0	64,489	232,141	318,425	199,588	--	--	11.492	--
250	25	70,626	235,723	319,203	184,079	10,497	11,276	11.684	.192
500	50	76,001	239,427	319,960	169,546	20,333	21,841	11.860	.368
1000	100	85,048	247,375	321,611	142,000	38,979	41,869	12.185	.693
2000	200	97,430	264,445	326,171	91,751	72,991	78,401	12.736	1.244
4000	400	105,632	291,823	339,626	19,308	122,026	131,071	13.402	1.910
				20% PENETRATION					
DISCHARGE RATE LIMIT = 10 HR.									
0	0	79,541	304,367	654,826	590,549	--	--	19.206	--
500	50	92,450	319,090	665,296	534,260	38,102	40,925	19.766	.560
1000	100	102,244	333,707	675,999	482,382	73,216	78,642	20.258	1.052
2000	200	113,947	360,752	698,973	391,196	134,938	144,938	21.047	1.841
4000	400	123,121	395,600	747,819	253,994	227,806	244,689	22.044	2.838
				30% PENETRATION					
DISCHARGE RATE LIMIT = 10 HR.									
0	0	85,368	331,673	853,353	1,173,530	--	--	24.875	--
750	75	104,093	357,215	877,125	1,073,013	68,039	73,080	25.798	.923
1500	150	115,890	382,168	902,932	980,591	130,596	140,274	26.574	1.699
3000	300	127,108	422,057	961,057	819,214	239,828	257,602	27.742	2.867
6000	600	134,307	461,194	1,069,315	590,821	394,422	423,653	29.091	4.216

TABLE B-3. PHOTOVOLTAIC ENERGY CONVERSION SYSTEM STORAGE CHARGING - UTILITY APPLICATION

(BOSTON, MA, INSOLATION DATA, η = 75%)

STORAGE CAPACITY (MWh)	C (MW)	ANNUAL ENERGY DISPLACEMENT (MWh) STORAGE CAPACITY A	B	C	D	E^o_{DPV} (MWh)	ASDE (MWh)	A^o_W (MM$)	A^o_E (MM$)
				10% PENETRATION					
0	0	60,640	190,175	228,177	155,376	--	--	9.207	--
DISCHARGE RATE LIMIT = 5 HR.									
125	25	64,521	192,003	228,550	146,389	6,082	6,534	9.320	.113
250	50	67,764	193,749	228,882	138,530	11,403	12,248	9.419	.212
500	100	73,029	197,384	229,531	124,422	20,952	22,505	9.591	.384
1000	200	80,979	204,161	231,310	100,036	37,458	40,234	9.876	.669
2000	400	90,708	218,255	235,570	58,546	65,541	70,399	10.323	1.116
4000	800	96,808	235,318	244,967	10,442	98.101	105,373	10.765	1.558
DISCHARGE RATE LIMIT = 10 HR.									
250	25	66,892	193,586	229,000	139,882	10,486	11,264	9.398	.191
500	50	72,117	196,847	229,691	126,324	19,663	21,122	9.564	.357
1000	100	80,270	203,303	231,167	102,562	35,748	38,398	9.847	.640
2000	200	90,195	217,268	235,050	61,531	63,521	68,229	10.294	1.087
4000	400	96,763	235,035	244,949	10,955	97,755	105,000	10.759	1.552
DISCHARGE RATE LIMIT = 15 HR.									
375	25	68,217	195,157	229,439	134,956	13,821	14,846	9.453	.246
750	50	74,423	199.756	230,603	117,274	25,790	27,702	9.653	.456
1500	100	83,623	208,481	232,962	87,307	46,074	49,489	10.007	.800
3000	200	92,615	223,492	239,116	42,751	76,231	81,882	10.463	1.256
6000	400	96,919	237,448	248,891	1,334	104,266	111,995	10.821	1.614
				20% PENETRATION					
DISCHARGE RATE LIMIT = 10 HR.									
0	0	74,367	268,048	484,031	442,288	--	--	15.585	--
500	50	88,222	279,851	490,312	395,088	31,939	34,307	16.098	.513
1000	100	98,988	290,897	496,332	353,967	59,771	64,201	16.531	.946
2000	200	111,671	313,194	509,002	283,568	107,421	115,383	17.213	1.628
4000	400	122,778	343,637	541,636	173,989	181,605	195,064	18.095	2.510
				30% PENETRATION					
DISCHARGE RATE LIMIT = 5 HR.									
0	0	78,168	301,142	657,862	865,929	--	--	20.332	--
1000	200	108,329	338,117	679,344	735,009	88,618	95,185	21.663	1.331
2000	400	121,381	365,324	714,043	624,267	163,576	175,699	22.549	2.217
4000	800	131,762	402,480	770,805	469,886	267,875	287,727	23.649	3.317

TABLE B-4. UTILITY/MULTIPLE SOURCE STORAGE CHARGING EFFICIENCY - 75%

STORAGE CAPACITY (MWh)	C (MW)	ANNUAL ENERGY GENERATED (MWh)				E_{DU} (MWh)	ASDE (MWh)	A_E^o (MM$)
		COST REGIME A	B	C	D			
SYSTEM B		142,507	523,480	1,767,495	15,406,271	--	--	--
DISCHARGE RATE LIMIT = 5 HR.								
125	25	126,412	511,362	1,758,169	15,461,731	37,539	39,515	.583
250	50	112,603	497,419	1,748,784	15,516,596	74,676	78,606	1.145
500	100	90,616	465,447	1,730,434	15,623,424	146,985	154,721	2.206
1000	200	64,138	391,114	1,694,173	15,825,931	284,057	299,008	4.102
2000	400	50,776	268,692	1,609,405	16,151,769	504,609	531,167	6.710
4000	800	50,383	239,065	1,519,977	16,328,238	624,057	656,902	7.663
DISCHARGE RATE LIMIT = 10 HR.								
125	12.5	133,229	513,819	1,760,587	15,444,457	28,547	27,207	.385
250	25	124,655	503,776	1,753,701	15,482,135	51,350	54,053	.761
500	50	110,062	482,256	1,740,108	15,555,571	101,053	106,376	1.477
1000	100	87,022	437,473	1,714,090	15,694,208	194,897	205,155	2.797
2000	200	61,896	349,501	1,660,626	15,940,283	361,459	380,484	4.965
4000	400	50,666	245,547	1,538,468	16,290,927	598,801	630,317	7.456
DISCHARGE RATE LIMIT = 15 HR.								
375	25	124,455	501,339	1,751,972	15,488,585	55,716	58,648	.811
750	50	109,793	477,777	1,736,166	15,568,407	109,746	115,522	1.572
1500	100	86,955	430,335	1,704,095	15,719,618	212,097	223,259	2.961
3000	200	61,896	344,225	1,632,212	15,989,169	394,549	415,315	5.200
6000	400	50,666	243,209	1,480,845	16,379,510	658,712	693,433	7.813
SYSTEM B'		59,204	314,884	813,179	7,473,757	--	--	--
DISCHARGE RATE LIMIT = 10 HR,								
125	12.5	51,883	303,878	807,250	7,509,591	24,256	25,532	.358
250	25	45,745	292,345	801,793	7,543,761	47,384	49,878	.695
500	50	36,285	269,085	791,511	7,607,291	90,386	95,143	1.308
1000	100	25,947	226,203	771,061	7,716,128	164,056	172,690	2.292
2000	200	22,589	181,384	731,693	7,845,467	261,601	264,843	3.260
4000	400	22,589	174,972	685,874	7,922,632	303,832	319,824	3.612

TABLE B-5. EFFICIENCY EFFECTS (1000 MWh STORAGE CAPACITY, 10 HR DISCHARGE RATE LIMIT)

TYPE STORAGE CHARGING	SITE	η (%)	ANNUAL ENERGY DISPLACMENT (MWh) COST REGIME A	B	C	D	E_{DPV} (MWh)	A_E (MM$)
				10% PENETRATION				
PV	PHOENIX, AZ	60	91,115	270,132	367,287	134,116	36,349	.574
		75	91,769	270,939	367,534	145,017	38,057	.660
		90	91,893	271,637	367,700	153,173	39,045	.716
PV	BOSTON, MA	60	79,303	202,355	230,871	93,442	33,537	.549
		75	80,270	203,303	231,167	102,562	35,748	.640
		90	81,001	204,003	231,438	109,268	37,450	.708
BASELOAD		η (%)	ANNUAL ENERGY GENERATED (MWh) COST REGIME A	B	C	D	E_{DU} (MWh)	A_E (MM$)
SYSTEM B		60	90,903	454,724	1,720,285	15,715,728	167,570	2.149
		75	87,022	437,473	1,714,090	15,694,208	194,897	2.797
		90	84,026	420,479	1,708,171	15,678,116	220,806	3.387

APPENDIX C

SOLAR ARRAY PERFORMANCE PREDICTION

C.1.1 ELECTRICAL MODEL

The synthesis of solar array current-voltage characteristics is based on a set of solar cell characteristics which represent the predicted performance for high grade, large volume production terrestrial cells with the following characteristics:

1. N on P
2. Phosphorus diffused, 2000Å junction depth
3. Tantalum oxide A-R coating
4. Silver collector grid
5. Czochralski Si, B-doped, 2ohm-cm

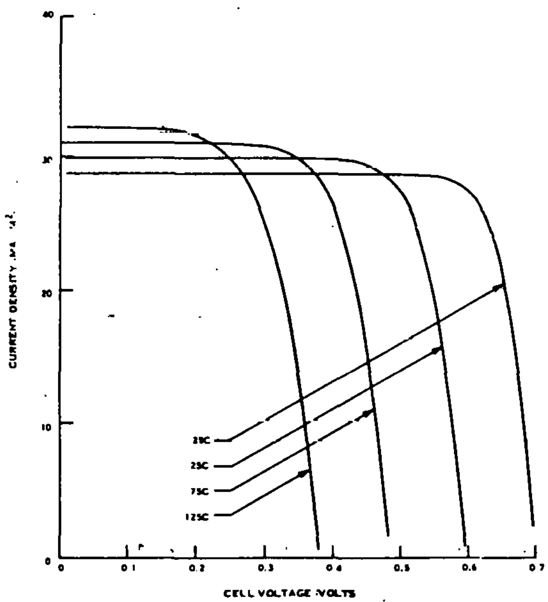
Figure C-1 shows these cell I-V characteristics at 100 mw/cm^2 with the spectral distribution as given in reference (1). These characteristics are represented by the following relationships:

$$I = CI_{sc} - \frac{V}{R_p} - I_o \left\{ \exp\left[K \cdot (V+IR_s)\right] -1 \right\}$$

where:

I = Cell output current

V = Voltage across cell terminals



• Cell efficiency 13.4%
100 mw/cm^2, 28°C, AM1

Figure C-1. Terrestrial Solar Cell I-V Characteristics

I_{sc} = Illumination current (virtually equal to short-circuit current)

C = Ratio of the total insolation incident on the solar cells to the reference insolation for the basic cell characteristics (100 mw/cm^2)

R_p = Shunt resistance of the cell

I_o = Reverse saturation current of the ideal diode characteristic

K = Coefficient of the exponential

R_s = Series resistance of the cell

I_{sc}, R_p, I_o, K, and R_s are represented as six-degree polynominals of temperature.

The total solar array output characteristics is calculated based on the single cell characteristic by multiplying the voltages and currents by the number of cells in series and parallel, respectively. In addition, the isolation diode voltage drop (as a function of temperature and fraction of rated forward current) and the series resistance of panel wiring are included in the array characteristic.

The value for total incident insolation (direct plus diffuse) is obtained by taking the total insolation incident on a horizontal surface (H_{TO}) as read from the insolation data base tape, and separating it into direct (H_{DIR}) and diffuse (H_{DIF}) components using a curve fit of the results of Liu and Jordan shown on Figure C-2 taken from Reference (2).

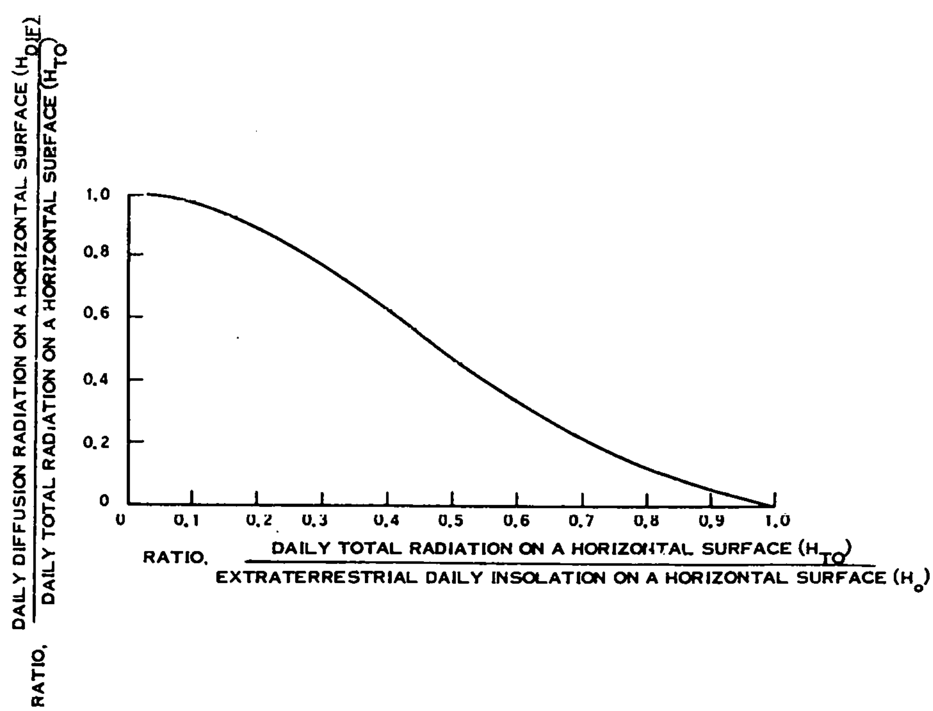


Figure C-2. Determination of Diffuse Insolation

The total flux incident on the tilted solar array surface (H_T) is given by: (from Reference 3)

$$H_T = H_{DIR} R_{DIR} + H_{DIF} \left(\frac{1 + \cos \beta}{2}\right) + (H_{DIR} + H_{DIF}) \left(\frac{1 - \cos \beta}{2}\right)$$

where:

R_{DIR} = Factor to correct horizontal incident direct radiation to that on the inclined array surface

β = Angle between horizontal and solar array surface

ρ = Reflectance of the surrounding ground (= 0.15)

The factor R_{DIR} is given by:

$$R_{DIR} = \frac{\cos \theta_i}{\cos \theta_j}$$

where:

θ_i is the solar incidence angle on the array and θ_j is the solar incidence angle on a horizontal surface. These are given as a function of the day of the year, time of day and surface location and orientation in accordance with the following relationship:

$$\cos \theta_i = \sin \delta \, (\sin \phi \cos \beta - \cos \lambda \cos \phi \sin \beta) + \sin \lambda \sin \beta \cos \delta \sin \omega + \cos \delta \cos \omega \, (\cos \lambda \sin \phi \sin \beta + \cos \phi \cos \beta)$$

where:

ϕ = Site latitude (north is positive)

δ = Solar declination angle

β = Angle between horizontal and solar array surface

λ = Solar array surface azimuth angle (zero is due south, west of south is positive)

ω = Hour angle (zero is solar noon)

For a horizontal surface this expression reduces to

$$\cos \theta_j = \sin \delta \sin \phi + \cos \delta \cos \omega \cos \phi$$

C.1.2 THERMAL MODEL

The thermal model considered the solar cells to be mounted directly to a roof structure as shown in Figure C-3. Cooling occurs principally by natural convection from the top surface. The significant heat transfer mechanisms for determining the equilibrium cell temperature are as follows:

1. Heat transfer through the solar array roof to the attic, $Q_1 (w/m^2)$
2. Heat transfer through the opposite roof (without solar cells) from the attic, $Q_2 (w/m^2)$
3. Heat transfer from the attic to the occupied space of the building, $Q_3 (w/m^2)$

The simultaneous solution of expressions describing these heat transfer mechanisms yields the desired value of cell temperature. The expressions used are as follows:

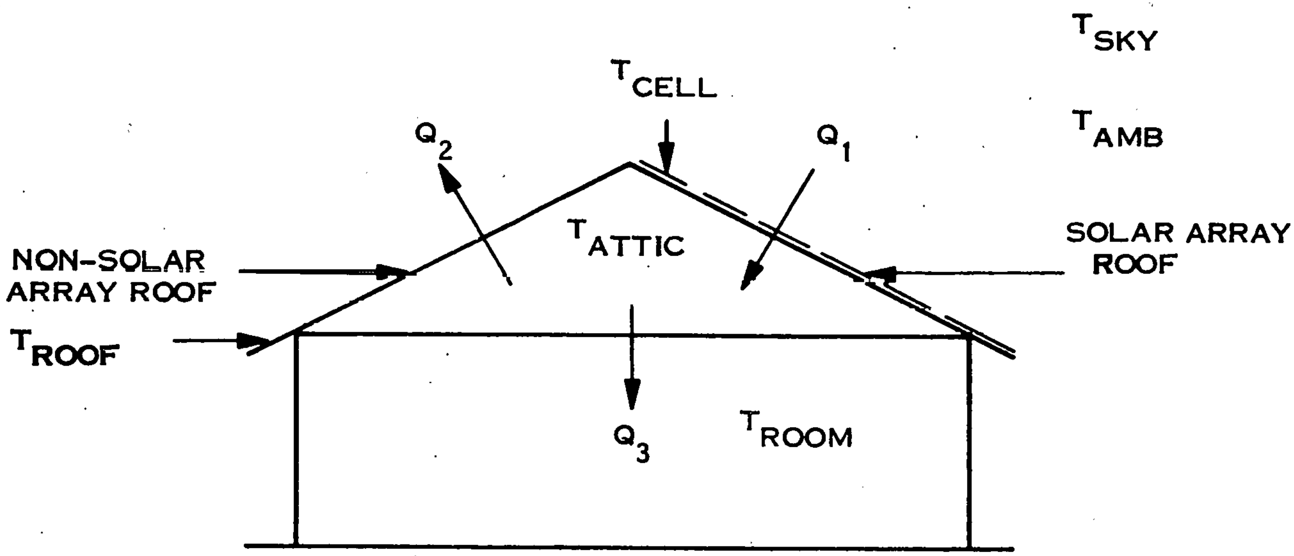


Figure C-3. Solar Array Heat Transfer Mechanisms

Equation 1 for Q1

$$Q_1 = U_1 (T_{cell} - T_{attic}) = \left[\alpha_c p + \alpha_p (1-p)\right] H_T - h_r (T_{cell} - T_{sky}) - h_o (T_{cell} - T_{amb}) - \eta_c p H_T$$

Equation 2 for Q2

$$Q_2 = U_2 (T_{attic} - T_{roof}) = \alpha_r H_R - h_r (T_{roof} - T_{sky}) - h_o (T_{roof} - T_{amb})$$

Equation 3 for Q3

$$A_3 Q_3 = A_1 Q_1 - A_2 Q_2$$

$$A_3 U_3 (T_{attic} - T_{room}) = A_1 U_1 (T_{cell} - T_{attic}) - A_2 U_2 (T_{attic} - T_{roof})$$

where:

T_{cell} = Temperature of solar array, °K

T_{attic} = Temperature of attic air, °K

T_{sky} = Temperature of sky, °K

T_{amb} = Temperature of ambient air, °K

T_{roof} = Temperature of non-solar array roof, °K

T_{room} = Temperature of living space, °K

U_1 = Heat transfer coefficient of solar array roof, W/m^2 °K

U_2 = Heat transfer coefficient of non-solar array roof, W/m^2 °K

U_3 = Heat transfer coefficient of attic floor, W/m^2 °K

α_c = Solar cell absorptivity

α_p = White paint absorptivity

p = Solar cell packing factor

α_r = Non-solar array roof absorptivity

H_T = Solar radiation incident on the solar array, W/m^2

H_R = Solar radiation incident on the non-solar array roof, W/m^2

η_c = Solar cell efficiency, adjusted to temperature T_{cell}

h_r = Radiative film coefficient, $W/m^2\,^oK$

h_o = Natural convection film coefficient, $W/m^2\,^oK$

A_1 = Solar array roof area, m^2

A_2 = Non-solar array roof area, m^2

A_3 = Attic floor area, m^2

The cell, attic, and non-solar array roof temperatures are the dependent variables to be determined by the solution of the equations presented. All other terms are established independently from weather data, the residence physical characteristics, and available formulations for certain terms as described below:

1. The sky temperature, T_{sky}, can be calculated according to Reference (4) by the following formula:

   $$T_{sky} = 0.0552\ T_{amb}^{1.5} \text{ (degrees K)}$$

2. The radiative film coefficient can be calculated by:

   $$h_r = \epsilon\,\sigma\,\frac{T_{cell}^4 - T_{sky}^4}{T_{cell} - T_{sky}}$$

   where:

   ϵ = Emissivity of solar array (= 0.80)

   σ = Stefan - Boltzmann constant

3. The film coefficient, h_o, according to Reference (5), can be calculated as follows:

   $$h_o = 5.7 + 3.8\ V$$

   where:

   V = wind speed, m/s

Using equation (1), (2), and (3), a plot of cell temperature as a function of insolation, wind speed, and ambient temperature is shown on Figure C-4. Table C-1 lists the assumed values of the other terms used in developing the plot. The plot indicates the dominance of wind speed in effecting the cell temperature rise above ambient. The greatest reduction in temperature occurs at low wind speeds with diminishing reductions as the wind speed increases.

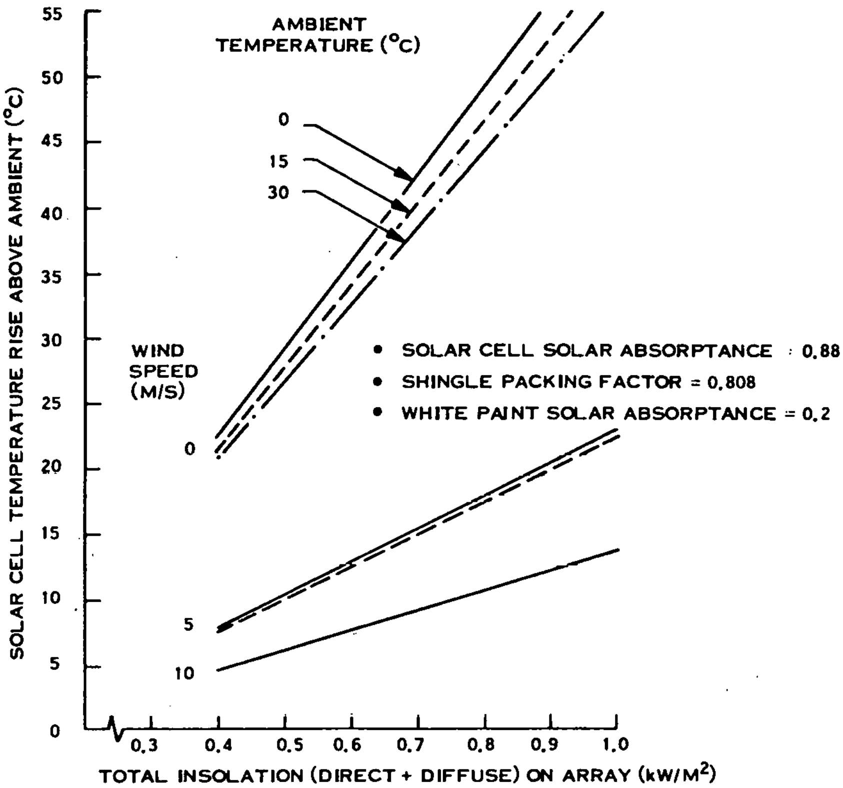


Figure C-4. Results of Solar Cell Temperature Prediction Model

Table C-1. Assumed Parameters for Array Temperature Determination

Parameter	Value
U_1	$2.61\ WM^{-2}\ K^{-1}$
U_2	$2.67\ WM^{-2}\ K^{-1}$
U_3	$0.27\ WM^{-2}\ K^{-1}$
α_c	0.88
α_p	0.2
p	0.808
α_r	0.9
A_1	$84.0\ m^2$
A_2	$84.0\ m^2$
A_3	$69.8\ m^2$
T_{room}	$20\ ^oC$

C.1.3 SOLAR ARRAY PERFORMANCE RESULTS

When the aforementioned models are used to determine the hourly solar array power output at the maximum power operating point for the three selected site locations, the results, on an annual basis, are as summarized in Table C-2.

Table C-2. Summary of Solar Array Performance at Selected Site Locations

	LOCATION		
	Boston, MA	Miami, FL	Phoenix, AZ
Year	1958	1963	1960
Solar Array Slope Angle (degrees from horizontal)	37.	17.	26.
Annual Horizontal Insolation (kWh/m^2)	1302.8	1949.6	2125.6
Annual Insolation on Inclined Array Surface (kWh/m^2)	1492.1	2052.7	2340.6
Annual Solar Array Output Energy at the Maximum Power Point (kWh/m^2 cell area)	197.5	253.6	278.1

REFERENCES

1. "Interim Solar Cell Testing Procedures for Terrestrial Applications", Brandhorst, H., et al, July 1975, Lewis Research Center

2. Liu, B.Y.N.. and Jordan, R.C., "The Interrelationship and Characteristic Distribution of Direct, Diffuse and Total Radiation", Solar Energy, Vol IV, No. 3, July 1960, p 8

3. Duffie, J.A. and Beckman, W.A., "Solar Energy Thermal Processes", Wiley, 1974, p 54

4. Ibid, p 76

5. Ibid, p 83

6. Ibid, pp 120-177