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

FINAL REPORT

VOLUME I
STUDY SUMMARY AND CONCEPT SCREENING

JANUARY 1978

PREPARED FOR

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

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JANUARY 1978

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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 NSFC-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:

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Dr. George Chang Dr. Al Landgrebe Mr. Rufus Shivers Dr. Wayne Coffman	Division of Energy Storage Systems, ERDA
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INTRODUCTION

The viability and uncertainty of output associated with production and use of potentially available energy from photovoltaic and wind conversion systems has led to the investigation of energy storage as a means of managing the available power when immediate, direct use is not possible or desirable. Concepts for energy storage have been in existence for some time and the use of some forms of energy storage, notably hydro systems, batteries, and flywheels, have been successfully used for some specific applications in the United States and elsewhere for many years. Variations in the forms and scope of energy storage use have received accelerated attention since the 1973 oil crisis. Potentially important new sources of future energy include electricity generated by solar activated photoelectric cells and/or wind driven generating units. This study was directed at a review of storage technologies, and particularly those which might be best suited for use in conjunction with wind and photovoltaics. The potential "worth" added by incorporating storage was extensively analyzed for both wind and photovoltaics. This report summarizes the investigations performed and presents the results, conclusions and recommendations pertaining to the use of energy storage with Photovoltaic and/or Wind energy conversion systems, in both dedicated and utility system/multiple-source charging modes.

PART A

STUDY SUMMARY

SECTION 1

SUMMARY AND GENERAL CONCLUSIONS

1.1 OVERALL SUMMARY OF STUDY ACTIVITY

1.1.1 OBJECTIVES

The overall objective of this study was a broad assessment of the attractiveness of energy storage and energy storage methods for use with photovoltaic and wind energy conversion systems. The principal areas of investigation included:

- Assessment of selected energy storage concepts.
- Evaluation of the "worth" of energy storage.
- Investigation of the effects of selected parameters on the use and worth of storage.

1.1.2 SCOPE

The study scope included the following major elements:

- Utility applications of photovoltaic and wind energy.
- Non-utility applications.

  Residential Systems
  Intermediate Systems

- Cost goals for each application
- Attractiveness of both dedicated and multiple-source charging of energy storage systems.
- The potential for added benefits from forecasting winds and insolation levels.
- The value of transient smoothing of photovoltaic and wind energy system output.

1.1.3 MAJOR GROUND RULES

In order to assure the maximum degree of general applicability of study results, the following boundary conditions were established:

- Use of a "representative" utility size and load
- Photovoltaic and wind energy system penetrations of 10%, 20%, 30% of total utility generation.
- A generalized and constant "mix" of conventional generation in the utility system.
- Use of average photovoltaic/wind generation output.
- Average fuel costs.
- Representative electricity costs
- Utility wind conversion system unit size of 1.5 MW (nameplate rating).
- Residential PV/Wind conversion system size of 10 KW.
- Intermediate PV/Wind conversion system unit size of 500 KW.

1.1.4 STUDY APPROACH

A selected list of eleven principal storage methods or concepts were considered as possible candidate systems. These included:

Pumped Hydro
- Above Ground
- Underground

Thermal
- Oil
- Steam

Compressed Air
- Underground
- Pneumatic

Batteries
- Lead-Acid
- Advanced

Inertial/Flywheel

Hydrogen Systems

Superconducting Magnetic Systems

The general concepts for these storage systems and their use were examined with respect to their principal features and current status. Areas of concern and interest to the possible application of these storage methods in conjunction with photovoltaic and wind systems were identified and assessed for impact.

The effect of various parameters on the attractiveness and worth of storage was examined. Parameters considered included:

Storage capacity
Location
Penetration
Efficiency
Fuel price escalation
Start year

Additional investigations included:

a. The effects of multiple source charging
b. Comparison of results with Utility Simulation Planning Analysis
c. Worth of output smoothing.

Representative geographic locations selected as data sites were:

<u>Photovoltaic Data Sites</u>

Phoenix, AZ
Miami, FL
Boston, MA

<u>Wind Data Sites</u>

Lubbock, TX
Blue Hill, MA
Great Falls, MT

Time-frame requirements established were:

- Start-years for system implementation from 1976 through the year 2000, with emphasis on 1985 (near term) and 2000 (far term).
- Annual analysis of load demand and photovoltaic/wind system generation.

1.1.5 STUDY ACCOMPLISHMENTS

- Modeling and match-up of a full year of projected photovoltaic and wind system power generation versus load data for each application level on an hour-by-hour basis.
- Examination of storage impact over a wide range of storage system capacities.
- Analysis of improvement in energy capture and resultant value associated with use of energy storage.
- Interpretation of results for selected storage technologies based on estimated costs and efficiencies.
- Projection of conditions for achievement of viability of dedicated and system-wide energy storage.
- Assessment of interface limitations of selected storage methods with wind and photovoltaic systems.
- Assessment of the ability of energy storage to improve the overall worth of photovoltaic and wind conversion systems.
- Comparison of study findings with those resulting from a specific utility system simulation.
- Evaluation of the possible value of photovoltaic/wind system output smoothing.

1.2 OVERALL STUDY FINDINGS

1.2.1 UTILITY APPLICATIONS

- Utility energy storage should generally be used on a system-wide basis rather than dedicated exclusively to a wind or photovoltaic system.

- At current costs and energy prices, energy storage dedicated to wind or photovoltaic system charging is not economically attractive for any of the storage concepts considered.

- System-wide storage charging can be economically justified at present or in the near term for several storage concepts at current costs or near term cost projections.

- Energy storage benefits will not contribute to wind and photovoltaic system viability until the base costs for PVCS and WECS approach break-even levels without storage.

- Ability to accurately forecast wind or insolation levels provides only a modest improvement in the worth of energy storage.

- Short term output smoothing may be a technical requirement in certain cases, but is not economically attractive per se when accomplished by energy storage.

1.2.2 RESIDENTIAL AND INTERMEDIATE APPLICATIONS

- Energy storage can increase total PVCS/WECS system energy capture over a range of 45-70%.

- Further increases in economic pressure must occur before residential and intermediate use of storage becomes generally attractive on its own merits.

- At realistically achievable future storage costs, storage can only increase the worth of the basic wind or photovoltaic system in the order of 25-40%.

- Residential application of storage with WECS/PVCS is much more attractive than the intermediate case under present electrical rate structures and tax policy.

1.2.3 OVERALL CONCLUSIONS

- While most of the energy storage concepts examined can be interfaced with wind or photovoltaic conversion systems in some manner, battery storage is the most universally attractive method for near-term (1985) use at all application levels.

- Future use of energy storage is so heavily dependent on achievement of projected cost goals that it would be premature to rule out continued development effort of longer term candidate concepts.

- In order to offer near term viability, the cost of an energy storage system should achieve the following approximate goals in 1976 dollars:

  Utility Systems*

  300-400 $/kW (System wide charging)

  Residential Systems

  60-100 $/kWh

  Intermediate Systems

  15-25 $/kWh

* Utility cost goal is presented on a $/kW basis to be consistent with normal utility practice.

- On an overall basis, the relative technical desirability of storage concepts for use with photovoltaic and wind conversion systems in the near term is as given in Table 1.2-1 below.

TABLE 1.2-1. RELATIVE TECHNICAL DESIRABILITY OF STORAGE SYSTEMS FOR PHOTOVOLTAIC AND WIND SYSTEM USE

UTILITY APPLICATION (Multiple source charging)	Rank	RESIDENTIAL APPLICATION	Rank	INTERMEDIATE APPLICATION	Rank
Batteries	1	Batteries	1	Batteries	1
Pumped Hydro Underground Compressed Air	2*	Inertial Pneumatic	2	Hydrogen Inertial	2
Hydrogen Inertial	3			Pumped Hydro Underground Compressed Air	3**

* Suitable siting required

** Limited special applications only

Table 1.2-2 presents in summary form, the key characteristics of the eleven storage concepts examined.

TABLE 1.2-2. ENERGY STORAGE SYSTEM KEY CHARACTERISTICS, AVAILABILITY AND APPLICABILITY

ENERGY STORAGE CONCEPT	KEY CHARACTERISTICS							AVAILABILITY		APPLICABILITY			NOTES
	SYSTEM EFFIC.	USEFUL LIFE	NOMINAL RANGE OF PLANT SIZES		RELIABILITY	SPECIAL HAZARD POTENTIAL	MAJOR LIMITATIONS	DEVELOPMENT STATUS	DEVELOPMENT REQUIREMENTS	U	R	I	
	%	YEARS	POWER RATING (MW)	ENERGY RATING (MWh)									
ABOVE-GROUND PUMPED HYDRO	70-75	50	100-2000	1000-20,000	HIGH	NONE	SITING, ENVIRONMENTAL	CURRENT STATE-OF-THE ART	INCIDENTAL IMPROVEMENTS ONLY	H	NO	L	LACK OF SUITABLE SITES AND ENVIRONMENTAL CONCERNS LIMIT FUTURE POTENTIAL. WECS/PVCS SOURCE VARIABILITY LIMITS DEDICATED APPLICATIONS
UNDERGROUND PUMPED HYDRO	70-75+	50	200-2000	1000-20,000	HIGH	FLOODING	SITING, ENVIRONMENTAL	BASIC TECHNOLOGY AVAILABLE	HIGHER HEAD EQUIPMENT	H	NO	L	
THERMAL STORAGE-OIL	65-75	25-30	50-200	500-2000	UNKNOWN-EXPECTED TO BE HIGH	SPILLAGE AND FLAMMABILITY	BEST WITH THERMAL CHARGING	TECHNOLOGY AVAILABLE	APPLICATION DESIGN	H	NO	L	APPLICABLE TO WASTE HEAT CONSERVATION. NOT ATTRACTIVE FOR WIND OR PHOTOVOLTAICS
THERMAL STORAGE-STEAM	65-75	25-30	50-200	500-2000	UNKNOWN-EXPECTED TO BE HIGH	NONE BEYOND NORMAL HIGH PRESSURE STEAM	BEST WITH THERMAL CHARGING	TECHNOLOGY AVAILABLE	APPLICATION DESIGN	H	NO	L	
UNDERGROUND COMPRESSED AIR	65-75	30	200-2000	2000-20,000	UNKNOWN-EXPECTED TO BE HIGH	METHANE ACCUMULATION IN CAVERN	SITING, CAVERN CHARACTERISTICS	INITIAL IMPLEMENTATION UNDERWAY	APPLICATION DESIGN	H	NO	L	WECS/PVCS SOURCE VARIABILITY LIMITS DEDICATED APPLICATIONS
PNEUMATIC STORAGE	55-65	20-30	UP TO ~25 kW	UP TO ~100 kWh	UNKNOWN-EXPECTED TO BE MODERATE	RUPTURE OF HIGH PRESSURE TANKS, HIGH TEMP. DISCHARGE	SMALL SCALE	PROOF OF CONCEPT STAGE	SYSTEM & COMPONENT DEVELOPMENT	NO	M	L	
LEAD-ACID BATTERIES	70-75	TO ~10	<10 kW TO 10 MW (MODULAR)	<50 kWh TO 50 MWh (MODULAR)	HIGH	ELECTROLYTE SPILLAGE	CYCLE LIFE	TECHNOLOGY AVAILABLE	ADVANCED DESIGNS FOR LONGER LIFE	H	H	H	MODULARITY AND SMALL SIZE PROVIDE FLEXIBILITY. PRESENT HIGH COST LIMITS APPLICATIONS
ADVANCED BATTERIES	70-80	10-25	SIMILAR TO LEAD-ACID BATTERIES		UNKNOWN	CHEMICAL LEAKAGE AND/OR ABNORMAL REACTIONS	SYSTEM CONTROL	UNDER DEVELOPMENT AVAILABLE ~ 1985	DEMONSTRATE LONG CYCLE LIFE AND RELIABILITY	H	H	H	BATTERY PERFORMANCE ADVANTAGES EXPECTED COMBINED WITH LOW COST/LONG LIFE
INERTIAL STORAGE (FLYWHEEL)	70-85	20-30	<10 kW TO 10 MW	< 50 kWh TO 50 MWh	UNKNOWN FOR ADVANCED SYSTEMS	WHEEL DISINTEGRATION	SYSTEM COMPLEXITY	CONCEPTUAL DESIGNS & EXPERIMENTAL PROTOTYPES	COMPOSITE FLYWHEEL & SYSTEM DEVELOPMENT	L/M	M	L/M	HIGH COST IS A MAJOR BARRIER TO IMPLEMENTATION
HYDROGEN STORAGE	40-50	10-25	< 10 kW TO 50 MW	< 50 kWh TO 500 MWh AND ABOVE	EXPECTED TO BE MODERATE TO HIGH	EXPLOSION AND FIRE	LOW EFFICIENCY	SMALL SCALE UNITS AVAILABLE. SCALE-UP WORK UNDERWAY	ALTERNATIVE PROCESS CONCEPTS FOR IMPROVED EFFICIENCY	M	NO	M	APPLICABLE WHERE UNFAVORABLE COST AND EFFICIENCY ARE OFFSET BY OTHER ADVANTAGES
SUPER-CONDUCTING MAGNETIC STORAGE	70-90	20-30	GREATER THAN 1000	GREATER THAN 10,000	UNKNOWN	POSSIBLE MAGNETIC FIELD EFFECTS	SUITABLE SITING	CONCEPTUAL COMPONENTS UNDER DEVELOPMENT	FURTHER CONCEPT DEVELOPMENT	H	NO	NO	TOO EARLY TO ACCURATELY ASSESS IMPACT

U - UTILITY
R - RESIDENTIAL
I - INTERMEDIATE

H - HIGH
M - MODERATE
L - LOW

1.3 AREAS FOR FURTHER RESEARCH AND DEVELOPMENT INVESTIGATIONS

The beneficial use of energy storage with photovoltaic and wind energy conversion systems is heavily dependent on the further development and reduction in cost of both the basic PVCS/WECS system and its components, as well as energy storage systems themselves. The areas of investigation which appear to offer the greatest opportunity to increase the potential for energy storage with wind and photovoltaic systems are identified and discussed in the following sections by application and storage technology.

1.3.1 UTILITY APPLICATIONS

Although there may be some cases where storage could be appropriately dedicated to a photovoltaic or wind system, study results indicate better utilization on a multi-source charging basis. Consequently, for utility applications, the areas for further investigation relate to interaction of both the PVCS/WECS systems and storage with the utility grid. These areas as identified during the study include:

1. Dispatching techniques for use of the basic PVCS/WECS system and for the energy storage system.

2. Sensing,control and monitoring systems for use in generation source control as well as integrated control of the storage system.

3. Concepts and designs for placement and/or decentralization of both the generation and storage systems which could minimize gathering system or tie-line requirements.

There are a number of possible approaches to the dispatching logic for PVCS/WECS and storage. These result from the inherent variability of the energy source which in turn requires that practical and optimum strategies for use of stored energy be made available to operating personnel.

The usefulness of the basic PV/wind system and the storage system depend on ability to monitor and control their operation. The cost of fulfilling this requirement could be substantial and appears to have received relatively little attention to date. This is certainly understandable in an area of developing technologies, but should not be overlooked or minimized in the future.

Placement of PV/wind systems and/or storage units offers both challenges and opportunities with regard to physical location and plant sizing. The situation will be different for different utilities, but attention should be given to these considerations so that pilot installations can be of maximum benefit, assuming continued pursuit of these new technologies. Plans for such installations could be made along the lines now being followed for the implementation of underground compressed air storage.

1.3.2 RESIDENTIAL APPROACH

The use of energy storage with wind or photovoltaic systems at the residential level has both technical and non-technical impacts which must be dealt with. The latter are discussed elsewhere in this report and are believed to be of sufficient importance to merit separate consideration in the future apart from strictly R&D requirements.

Developmental work which could help advance the future prospects for energy storage at the residential level include:

1. Identification of standard specification requirements for the installation, utility tie-in and operation of energy storage systems and advanced wind/PV generating sources.

2. Establishment of baseline PV/wind system and storage system designs for various types of residential units both present and future.

3. Design and development of low cost system components for the residential interface and the basic storage device.

It is recognized that the incentive to pursue the implementing details of residential systems is dependent upon the degree of success in achieving satisfactory energy storage, wind turbine and photovoltaic-cell designs and costs. Nevertheless, reasonably early attention to the preceding items appears advisable to prevent a hodge-podge of marginal designs from creating a bad image in the early stages of market introduction.

1.3.3 INTERMEDIATE APPLICATIONS

Elements of both utility and residential requirements may be found in the broad range of intermediate applications. It is clear that if use of energy storage with PV or wind systems is eventually realized in significant market penetrations, a range of component sizes will be necessary. These could and probably should be standardized to some degree. The intermediate application category is so broad that it will always offer opportunities for single installation ingenuity. Examples of unique applications of various sizes, mostly small in scale, are already beginning to appear. For example, photovoltaics for remote signaling and communications stations. The areas of investigation which could promote intermediate storage system applications include:

1. Application surveys.

2. Early pilot system designs in cooperation with various types of industrial and commercial consumers.

3. Storage system component development for economic quantity production.

1.3.4 STORAGE TECHNOLOGY DEVELOPMENT AREAS

The development of advanced energy and energy storage systems is currently receiving significant and appropriate attention in several key areas. For example, pilot installations for water pumping, irrigation and battery testing. These essential types of investigations should be continued and supported on a priority basis. Establishing of priorities for energy storage systems is difficult in most cases because the future possibilities of some systems may be masked by current limitations in data or technology. Although this study and others have indicated priorities in attractiveness of storage devices or systems, it would be unwise to discourage a broad range of future investigations. Table 1.3-1 summarizes the major areas of needed development for storage technology as identified during the study.

TABLE 1.3-1. STORAGE TECHNOLOGY DEVELOPMENT AREAS

STORAGE SYSTEM AND APPLICATIONS	GENERAL REQUIREMENTS	PV/WIND SYSTEM REQUIREMENTS
Pumped Hydro	Development of higher head pump turbines capable of high efficiencies over a wide range of operation.	Modular system design, trade-off study, utility applications.
Underground Compressed Air	System designs, cavern monitoring.	Same as for pumped hydro.
Pneumatic	System components, particularly air-turbine.	Preliminary design, performance study and testing, residential applications.
Lead-Acid Batteries	Lower-cost package designs for non-utility applications.	Same as for advanced batteries.
Advanced Batteries	General system development and testing.	Advanced monitoring, control and interface concepts, residential and intermediate applications.
Flywheel	Proof-of-concept development and testing for composite wheel and other components.	Preliminary design performance study, non-utility applications
Hydrogen	Fuel cell/reaction efficiency improvement.	Preliminary package designs, non-utility applications.
Magnetic	Evaluation of concepts for system elements.	Not presently applicable.

SECTION 2

PHOTOVOLTAIC STORAGE ASSESSMENT

Principal findings and conclusions pertaining to use of energy storage in conjunction with photovoltaic energy conversion systems are summarized in this section.

2.1 UTILITY APPLICATION

Energy storage was added to a photovoltaic system in the utility application to enhance the value of the photovoltaic produced energy by:

1. Storing photovoltaic produced energy at those times when it would have little value to the utility grid.
2. Discharging from storage when the energy would be of high value to the utility grid.

The characteristics of photovoltaic energy permit a large portion of the energy to be put directly on line, displacing high cost peaking energy. As photovoltaic system penetration into the utility generation mix was increased, direct PV energy use was found to displace energy of steadily decreasing value, thus increasing the opportunity for energy storage value enhancement. The effect is clearly seen in Figure 2.1-1 which presents the annual savings in purchased fuel, for the utility model of this study, versus storage capacity and photovoltaic system penetration. Savings are unitized on a dollars per year per kilowatt hour of storage basis.

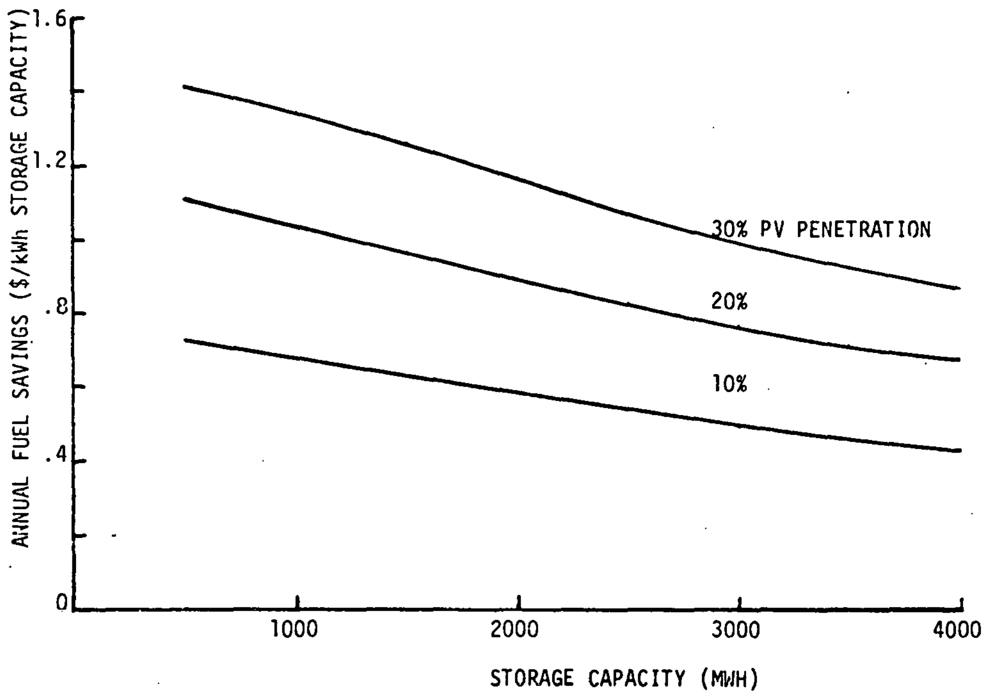

FIGURE 2.1-1 UTILITY ANNUAL FUEL SAVINGS - PHOTOVOLTAIC DEDICATED STORAGE

The above data represent mean savings for the three locations investigated - Phoenix, Miami, and Boston and should be representative of expectations for photovoltaic energy storage throughout much of the contiguous U.S.

It may be noted that photovoltaic dedicated energy storage produces about twice the fuel savings at 30% PV penetration as are produced at 10% PV penetration.

An important, but not unexpected finding, was that utility-wide or multiple source charging of storage significantly increases the savings in purchased utility energy and thus the value of energy storage to the utility. Figure 2.1-2 shows the annual fuel savings for 5 and 10 hour system-wide charging compared with the photovoltaic dedicated storage, 30 percent penetration savings. Annual fuel savings are increased by two to three times for system storage over dedicated storage. A difference between 5 and 10 hour storage system savings was not evidenced for the dedicated case, due to the much lower utilization of storage.

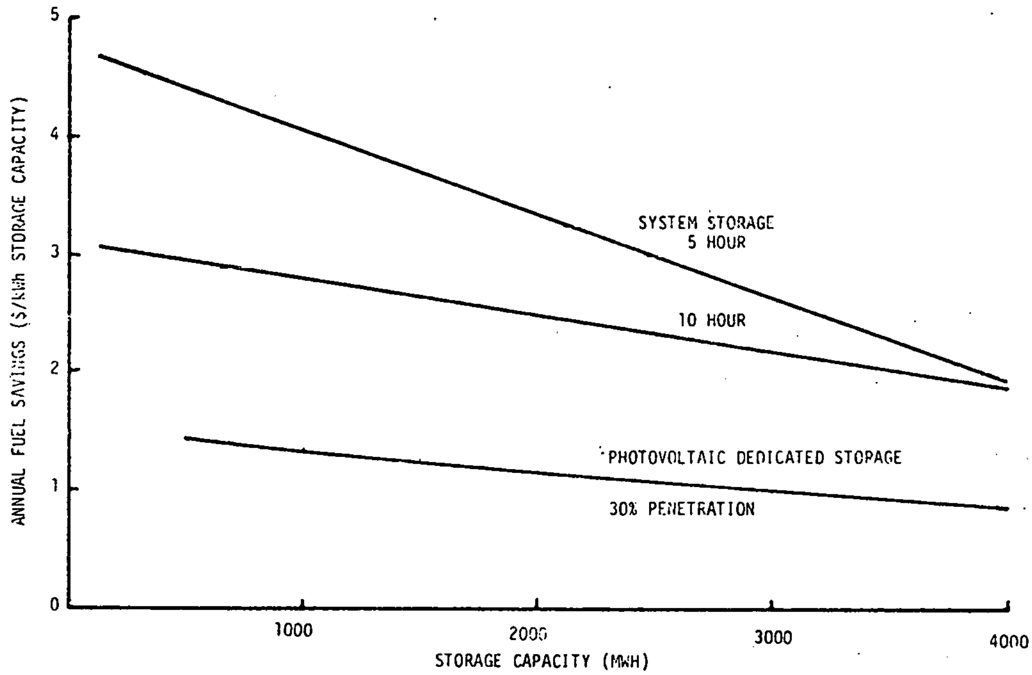

FIGURE 2.1-2 INCREASED FUEL SAVINGS DUE TO SYSTEM-WIDE STORAGE CHARGING.

It can be shown that energy storage will increase the reliability of a utility grid, expressed as the probability of meeting system load requirements. For a utility system with a specific reliability requirement, the addition of energy storage thus permits reductions in other equipment. The more reliable and predictable operation of system-wide storage permits greater displacement of conventional equipment and correspondingly higher annual cost savings than result from dedicated storage. Savings in generation capacity were computed for the utility modeled and used in the break-even cost computations. In an actual operating situation, capacity savings would be computed for the particular utility and its generation mix. Certain types of storage are easily adaptable to modularization and can be sited within a utility grid such as to reduce the requirements for transmission and distribution facilities and thus provide further savings to the utility. Battery storage systems are the best example; although other storage systems, such as flywheels and possibly hydrogen may provide savings of this nature.

The annual savings resulting from purchased fuel reductions, conventional generation displacement and reduced transmission and distribution facilities were computed for seven of the candidate energy storage concepts deemed most feasible for use in photovoltaic energy in a utility system. Savings were then used to derive break-even costs or cost goals for each of the storage technologies. Examples are presented in Table 2.1-1 for 1000 MWh, 5 and 10 hour storage systems operating on a system-wide or multiple-source charging basis. A nominal set of economic conditions are used in this example; however, the study data can also be used to project other cases of particular interest out to year 2000.

TABLE 2.1-1. ENERGY STORAGE BREAK-EVEN COST GOALS - UTILITY-WIDE SYSTEM CHARGING

	BREAK-EVEN COST $/kW		CURRENT ESTIMATES* $/kW	
	5 HR	10 HR	5 HR	10 HR
Above Ground Pumped Hydro	301	364	160	190
Underground Pumped Hydro	301	364	190	230
Underground Compressed Air	264	308	250	340
Lead-Acid Batteries	354	415	495	840
Advanced Batteries, 10, 20 Yr	340,364	396,431	220	370
Inertial Storage	287	339	1120	2170
Hydrogen Storage	235	268	870	940

1000 MWh

1985 START

6% FUEL ESCALATION

* Certain of the current cost estimates will be subject to drastic change within a few years, particularly those associated with the last three technologies. See Table 5.3-1 for summary cost parameters and references.

Both types of pumped hydro storage show viability at the above conditions, which is not surprising since many utility systems presently employ this form of energy storage. Advanced battery and compressed air storage also indicate potential for viability at current system cost estimates. Figure 2.1-3 presents conditions leading to economic viability for each of the above energy storage systems.

Inertial storage and hydrogen become economic only under the severe conditions of a year 2000 start and 10% fuel price escalation rate. Lead-acid batteries showed viability slightly beyond 1990, under 8% fuel escalation conditions.

	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 2.1-3. ECONOMIC VIABILITY OF UTILITY ENERGY STORAGE CONCEPTS-MULTI-SOURCE CHARGING

The energy storage concepts which are economic in the near term have demonstrated ability to technically interface with a utility grid. Pumped hydro and compressed air storage entail specific site requirements which greatly limit future application potential. Battery storage is, however, principally limited only by the ability to achieve the cost goals shown above.

The technology-sensitive differences between power and storage related system costs tend to make batteries more economic on a 5 hour basis, while pumped hydro storage is better on a 10 hour basis. This implies that a mix of storage technologies would be appropriate for many utility systems, depending on the particular load characteristics and conventional generation mix.

2.2 RESIDENTIAL APPLICATION

Energy storage with photovoltaic energy in the residential application was employed to store excess PV array output until it could be absorbed by the house load. Photovoltaic array output and typical residential loads have a significant mismatch which provides a strong potential for energy storage. For the three broadly representative locations investigated - Phoenix, Miami and Boston, the addition of 24 kWh of energy storage to a 10 kW photovoltaic array improved total system energy capture by 46 to 58% as shown in Figure 2.2-1.

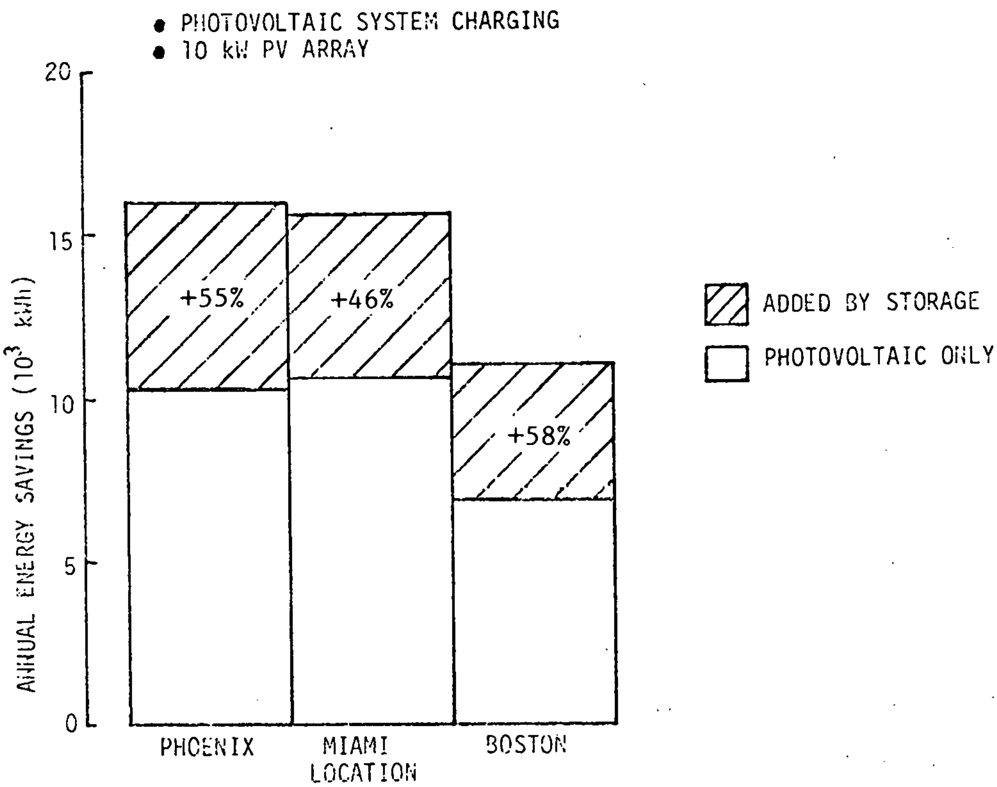

FIGURE 2.2-1 INCREASED ENERGY CAPTURE DUE TO ENERGY STORAGE FOR RESIDENTIAL PHOTOVOLTAIC CONVERSION.

This increase in total system energy capture can only be reflected in increased allowable cost for the basic photovoltaic system if energy storage is priced below its break-even cost. For realistically achievable storage system costs, the basic photovoltaic system value can be improved by 25 to 40 percent.

Mean energy storage savings versus storage capacity is shown in Figure 2.2-2.

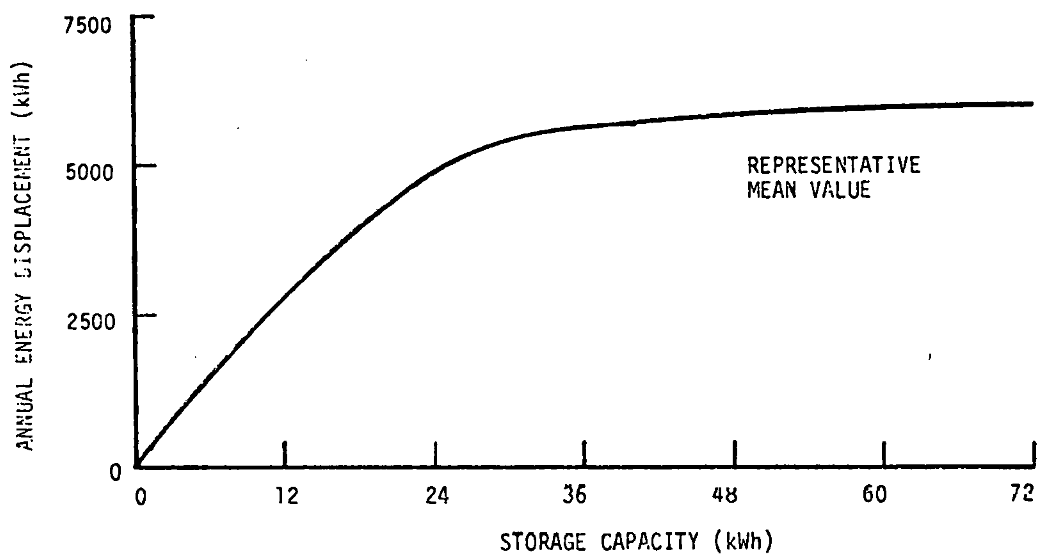

FIGURE 2.2-2 MEAN ANNUAL ENERGY DISPLACEMENT - RESIDENTIAL PHOTOVOLTAIC ENERGY STORAGE

The sharp "knee" in the above curve was typical of residential and intermediate photovoltaic storage applications.

For the residential application a maximum storage capacity in the range of

24 to 36 kWh is indicated, with little improvement in energy capture beyond that range.

The annual energy displacement from storage in the residential application proved to be relatively insensitive to storage system efficiency as shown in Figure 2.2-3.

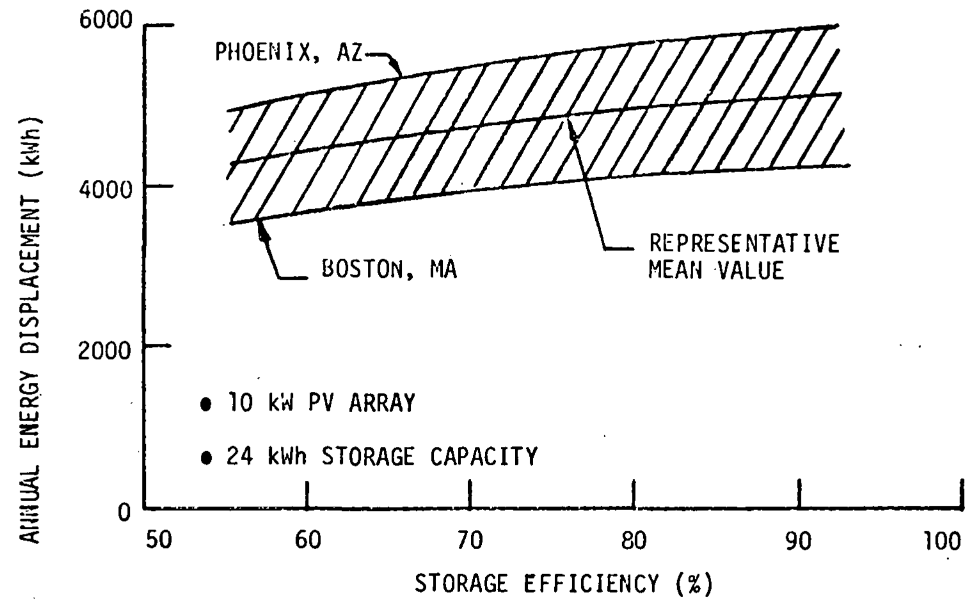

FIGURE 2.2-3 EFFECT OF STORAGE EFFICIENCY - RESIDENTIAL PHOTOVOLTAIC ENERGY CONVERSION

An increase in storage efficiency from 60 to 90 percent results in only about 14 percent increase in annual energy savings. This suggests the possibility of designing a residential storage system with less emphasis on efficiency if sufficient manufacturing cost advantages can be gained.

Break-even cost goals for residential storage systems are presented in Table 2.2-1 for nominal 1985 start year, 6% fuel price escalation rate conditions. At present only an advanced battery shows viability potential.

TABLE 2.2-1. ENERGY STORAGE BREAK-EVEN COST GOALS, PHOTOVOLTAIC ENERGY CONVERSION - RESIDENTIAL APPLICATION

	BREAK-EVEN COST $/kWh	CURRENT ESTIMATES* $/kWh	
Advanced Batteries 10,20 Yr	93, 130	92	24 kWh
Lead-Acid Batteries	91	200	1985 START
Inertial Storage	109	250	6% ESCALATION
Pneumatic Storage	105	270	

* See Table 5.3-2 for summary cost parameters and references

Battery energy storage, despite some hazard potentials, is technically well suited to residential use. Pneumatic and inertial storage, however, presently have equipment characteristics which severely limit both their application and consumer acceptance.

Future research and development effort should be aimed at improving the technology and specific designs while reducing operational problems and hazards. Achievement of the break-even costs shown above is necessary under current conditions. However, there could be additional opportunity for improvement if incentives such as off-peak charging rates for residential customers become available.

Figure 2.2-4 presents break-even costs of residential batteries as a function

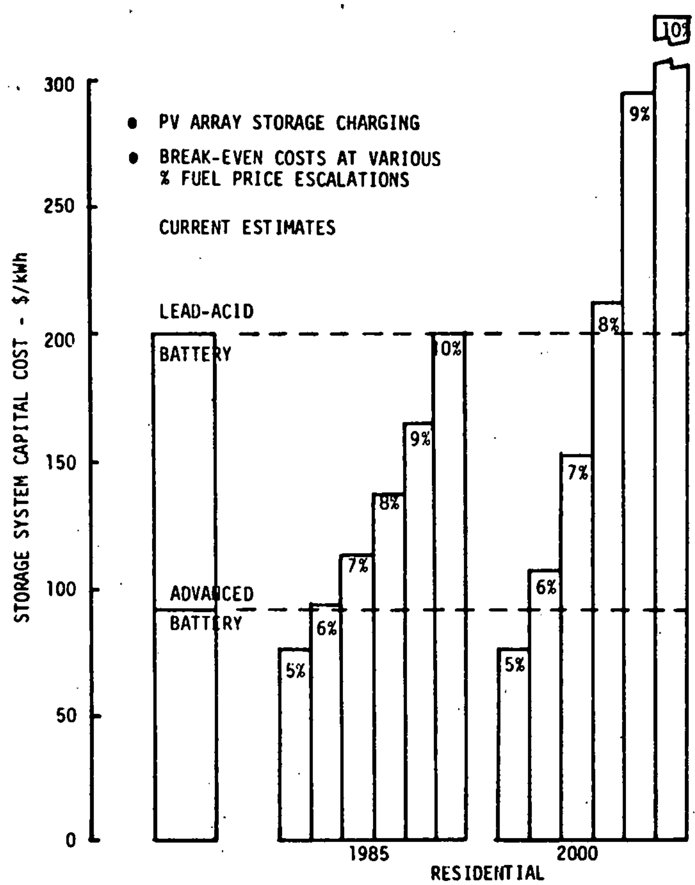

FIGURE 2.2-4 CONDITIONS LEADING TO ECONOMIC VIABILITY RESIDENTIAL BATTERIES WITH PHOTOVOLTAICS

of start year and electricity price escalation rate. Also shown are cost estimates for lead-acid and advanced batteries. The reader can use these or any other estimates to evaluate the time frame and economic conditions under which battery energy storage will become economic with photovoltaic energy in the residential application.

2.3 INTERMEDIATE APPLICATION

The intermediate application was characterized by a relatively constant load from 10 A.M. to 10 P.M., dropping to a maximum of one-fourth of this level for the remaining 12 hours. This type of loading would be most typical for the case of a shopping center or cluster of small stores. Photovoltaic energy from a 500 kW array thus has excess energy during sunlit hours for any peak loads of less than 500 kW. Typical energy displacement from storage in the intermediate application is shown in Figure 2.3-1.

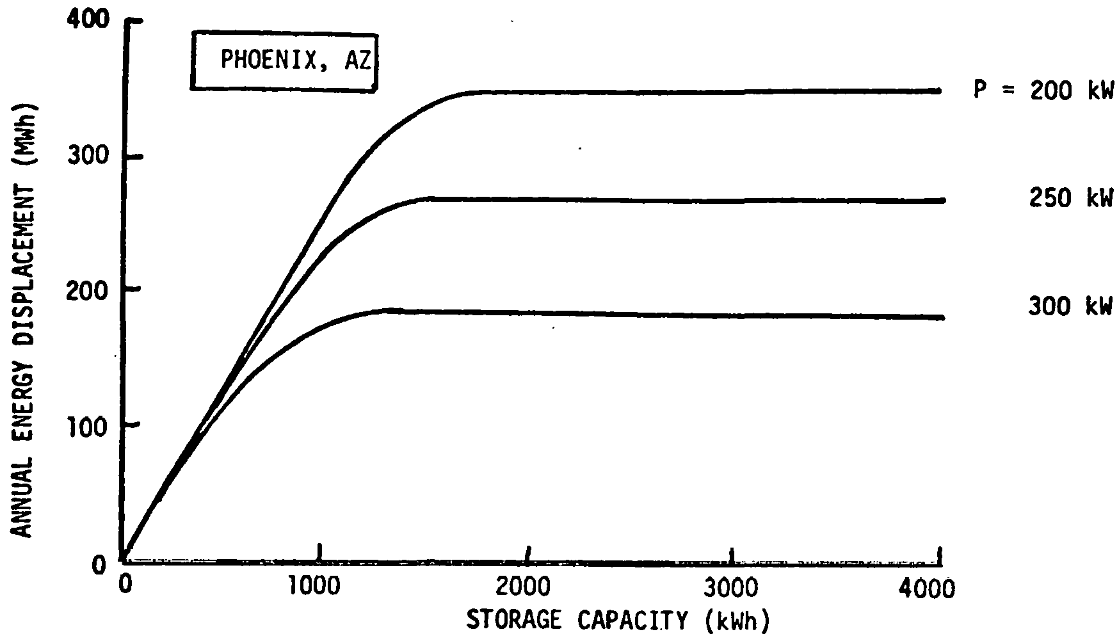

FIGURE 2.3-1 ANNUAL ENERGY DISPLACEMENT, INTERMEDIATE SYSTEM-PHOTOVOLTAIC ENERGY STORAGE

The "knee" observed in the residential displacement curve also is evident in the intermediate case, at about 1000 to 1500 kWh storage capacity. Note that the energy displacement is strongly dependent on peak power demand. A 250 kW load was selected for analysis, with results scalable to multiples of both load and photovoltaic array size. Break-even costs are presented in Table 2.3-1 below.

TABLE 2.3-1. ENERGY STORAGE BREAK-EVEN COST GOALS, INTERMEDIATE SYSTEM – PHOTOVOLTAIC ENERGY STORAGE

	BREAK-EVEN COST $/kWh	CURRENT ESTIMATE* $/kWh
Above Ground Pumped Hydro	24	19
Underground Pumped Hydro	24	23
Underground Compressed Air	19	34
Lead-Acid Batteries	26	140
Advanced Batteries, 10,20 Yr	23, 26	67
Inertial Storage	22	217
Hydrogen	16	45

1000 kWh

1985 START

6% ESCALATION

* See Page 5-17 and Tables 5.3-1 and 5.3-2 for discussion of cost basis and parameters.

It can be seen that only pumped hydro and compressed air storage even approach viability, and the application of these concepts to intermediate applications is highly doubtful due to their large scale and site requirements.

The intermediate application for energy storage was by far the least promising, due primarily to two factors - electricity rate schedules and federal tax policy. Under typical commercial and industrial block rate schedules coupled with demand charges, alternate energy devices such as photovoltaic energy and energy storage systems can only displace energy in the lowest value blocks and generally can not reduce peak requirements for back-up by the utility. Thus displaced energy is worth considerably less than in the residential application. Energy is also tax deductible for businesses which further reduces the effective cost as compared to the homeowner.

2.4 UTILITY SYSTEM PLANNING ANALYSIS

A detailed utility system simulation was performed for realistic 1995 operating conditions in the New England Power Pool. The objective was to compare this detailed analysis with the generalized results of the storage study.

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.

Results of the power pool simulation as compared to the representative utility analysis performed in the study are presented in Figure 2.4-1, in terms of storage break-even cost. Note that the presence of photovoltaic

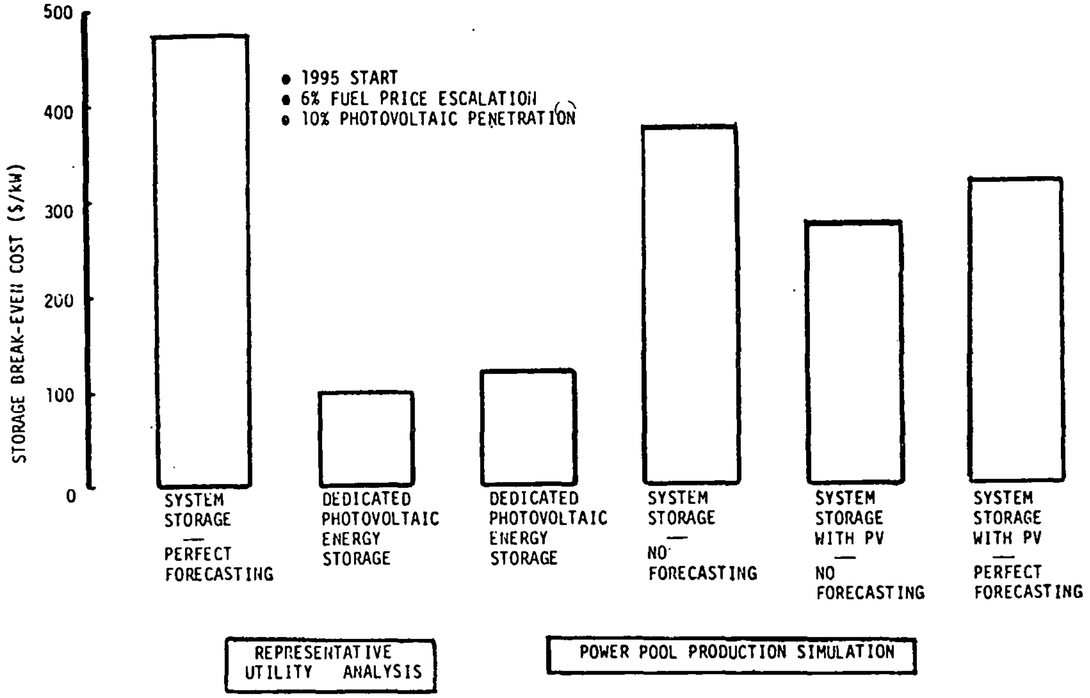

FIGURE 2.4-1 COMPARATIVE RESULTS - REPRESENTATIVE UTILITY ANALYSIS AND POWER POOL SIMULATION.

systems in the utility grid yields a reduction in potential storage system worth.

SECTION 3

WIND ENERGY STORAGE

Principal findings and conclusions pertaining to use of energy storage in conjunction with wind energy conversion systems (WECS) are summarized in this section.

3.1 UTILITY APPLICATION

Energy storage was added to a wind energy system in the utility application to enhance the value of the WECS produced energy by:

1. Storing the energy at those times when it would have little value to the utility grid.
2. Discharging from storage when the energy would be of high value to the utility grid.

The characteristics of wind energy enable a considerable portion of the energy to be put directly on line, displacing high cost peaking energy. This is similar to photovoltaic energy but to a lesser degree. Unlike the photovoltaic case, however, the value of energy storage was found to be relatively insensitive to penetration of WECS in the utility grid. Figure 3.1-1 presents mean annual savings in purchased fuel versus storage capacity, for the utility modeled in this study. Savings are unitized on a dollar per year per kilowatt hour of storage basis.

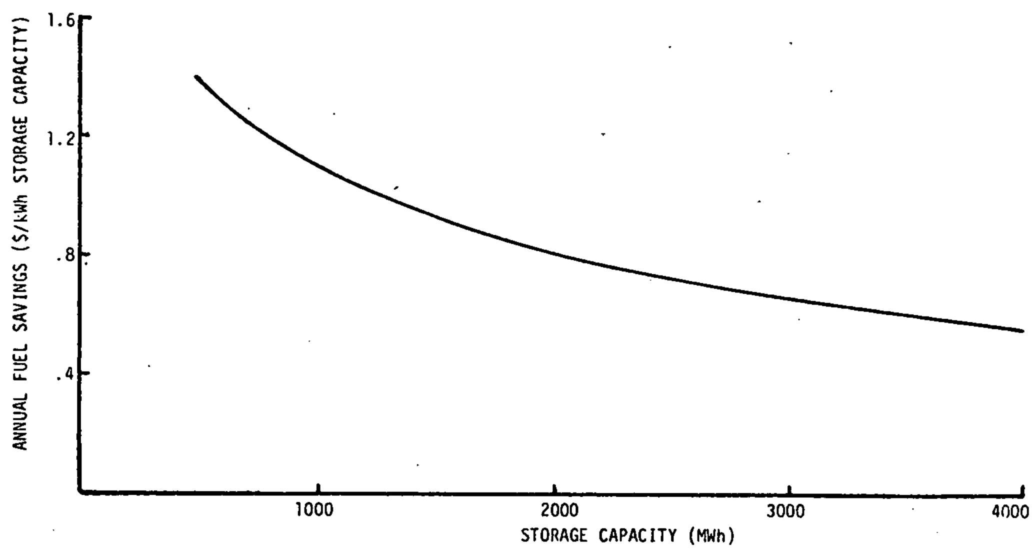

FIGURE 3.1-1. UTILITY ANNUAL SAVINGS - WECS DEDICATED STORAGE

The above data represents mean savings for the three locations investigated - Great Falls, Montana and Blue Hills, Massachusetts in moderate wind regimes (4-7 $MWh/m^2/Yr$ energy) and Lubbock, Texas in a low regime (2-4 $MWh/m^2/Yr$ energy), and are representative of WECS energy storage potentials in a large portion of the country.

An important finding, not unexpected, was that utility-wide or multiple-source charging of storage significantly increases the savings in purchased utility energy and thus the value of energy storage to the utility. Figure 3.1-2 shows the annual fuel savings for 5 and 10 hour system-wide charging compared with the WECS dedicated storage savings. Annual fuel savings are increased by two to three times for system storage over dedicated storage. A difference between 5 and 10 hour storage system savings was not evidenced for the dedicated case, due to the much lower utilization of storage.

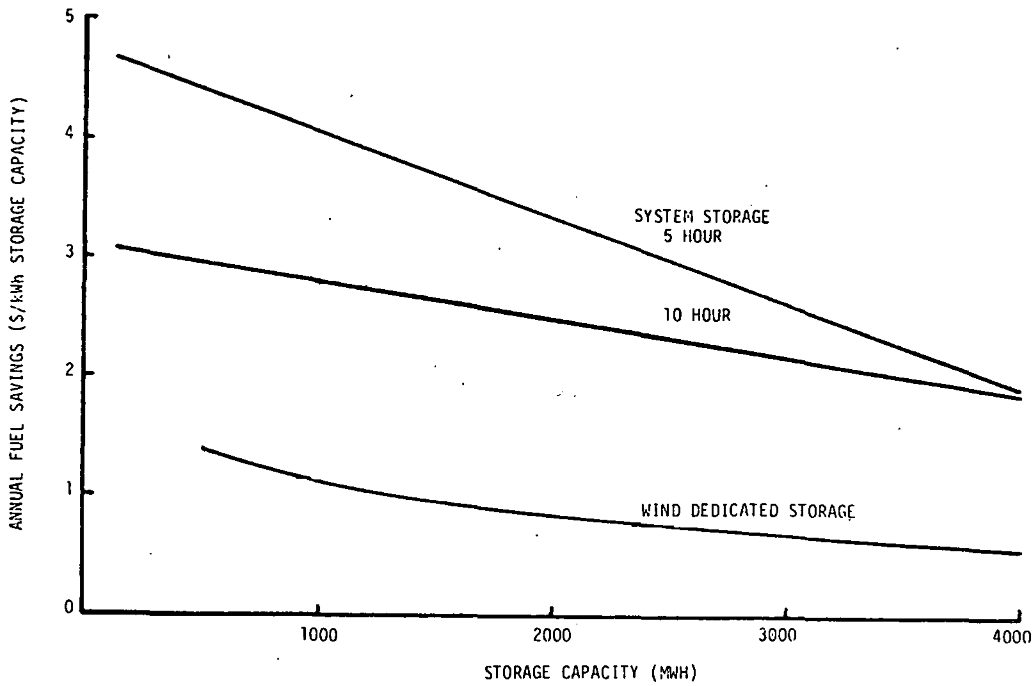

FIGURE 3.1-2. INCREASED FUEL SAVINGS DUE TO SYSTEM-WIDE STORAGE CHARGING

It can be shown that energy storage will increase the reliability of a utility grid, expressed as the probability of meeting system load requirements. For a utility system with a specific reliability requirement, the addition of energy storage thus permits reductions in other equipment. The more reliable and predictable operation of system-wide storage permits greater displacement of conventional equipment and correspondingly higher annual cost savings than result from dedicated storage. Savings in generation capacity were computed for the utility modeled and used in the break-even cost computations. In an actual operation situation, capacity savings would be computed for the particular utility and its generation mix.

The annual savings resulting from purchased fuel reductions, conventional generation displacement and reduced transmission and distribution facilities were computed for seven of the candidate energy storage concepts deemed most feasible for use with wind energy in a utility system. Savings were then used to derive break-even costs or cost goals for each of the storage technologies. Examples are presented in Table 3.1-1 for 1000 MWh, 5 and 10 hour storage systems operating on a system-wide or multiple-source charging. A nominal set of economic conditions are used in this example; however, the study data can also be used to project other cases of interest out to year 2000.

TABLE 3.1-1. ENERGY STORAGE BREAK-EVEN COST GOALS-
UTILITY-WIDE SYSTEM CHARGING

	BREAK-EVEN COST $/kW		CURRENT * ESTIMATES $/kW	
	5 HR	10 HR	5 HR	10 HR
Above ground Pumped Hydro	301	364	160	190
Underground Pumped Hydro	301	364	190	230
Underground Compressed Air	264	308	250	340
Lead-Acid Batteries	354	415	495	840
Advanced Batteries, 10,20 Yr	340,364	396,431	220	370
Inertial Storage	287	339	1120	2170
Hydrogen Storage	235	268	870	940

1000 MWh

1985 START

6% FUEL ESCALATION

* Certain of the current cost estimates will be subject to drastic change within a few years, particularly those associated with the last three technologies. See Table 5.3-1 for summary cost parameters and references.

Both types of pumped hydro storage show viability at the above conditions, which is not surprising since many utility systems presently employ this form of energy storage. Advanced battery and compressed air storage also indicate potential for viability at current system cost estimates. Figure 3.1-3 presents conditions leading to economic viability for each of the above energy storage systems.

Inertial storage and hydrogen become economic only under the severe conditions of a year 2000 start and 10% fuel price escalation rate. Lead-acid batteries showed viability slightly beyond 1990, under 8% fuel escalation conditions.

	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 3.1-3. ECONOMIC VIABILITY OF UTILITY ENERGY STORAGE CONCEPTS - MULTI-SOURCE CHARGING

The energy storage concepts which are economic in the near term have demonstrated ability to technically interface with a utility grid. Pumped hydro and compressed air storage entail specific site requirements which greatly limit future application potential. Battery storage is, however, principally limited only by the ability to achieve the cost goals shown above.

The technology-sensitive differences between power and storage related system costs tend to make batteries more economic on a 5 hour basis, while pumped hydro storage is better on a 10 hour basis. This implies that a mix of storage technologies would be appropriate for many utility systems, depending on the particular load characteristics and conventional generation mix.

3.2 RESIDENTIAL APPLICATION

Energy storage with wind energy in the residential application was employed to store excess WECS output until it could be absorbed by the house load. Wind energy distribution and typical residential loads have a significant mismatch which, although not as severe as with photovoltaic energy, still provides considerable potential for energy storage. For the three broadly representative locations investigated - Great Falls, Blue Hill and Lubbock, the addition of 24 kWh of energy storage to a 10 kW wind turbine system improved total system energy capture by 22 to 28% as shown in Figure 3.2-1.

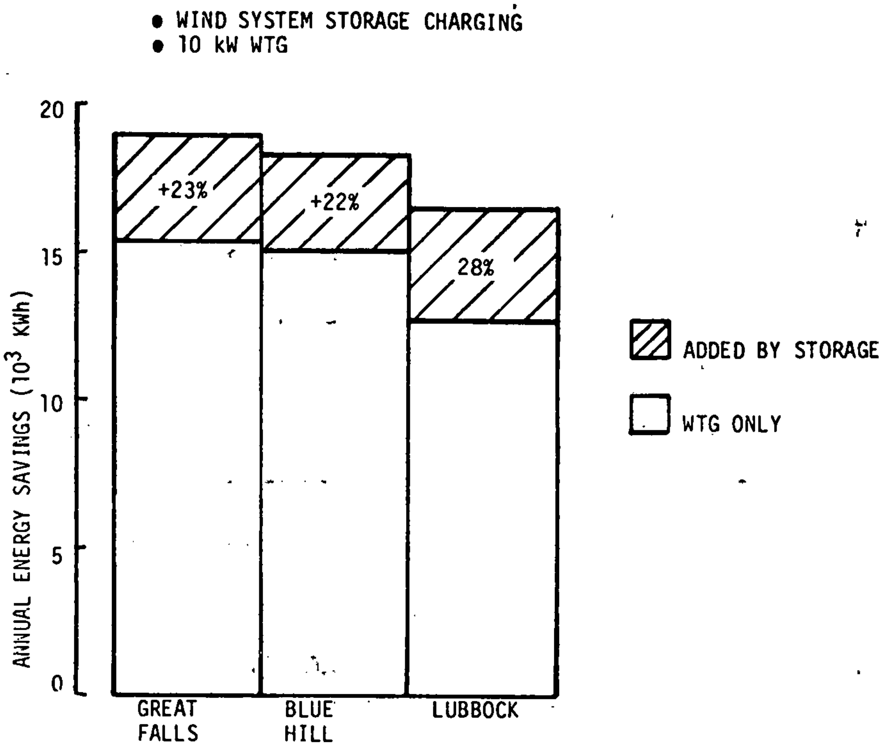

FIGURE 3.2-1. INCREASED ENERGY CAPTURE DUE TO ENERGY STORAGE FOR RESIDENTIAL WIND ENERGY CONVERSION

This increase in total system energy capture can only be reflected in increased allowable cost for the basic wind energy if energy storage is priced below its break-even cost. For realistically achievable storage system costs, the basic wind energy system value can only be improved by about 10 to 20 percent.

Annual energy storage savings versus storage capacity is shown in Figure 3.2-2, for the three locations studied. A mean curve of savings was used in the analysis.

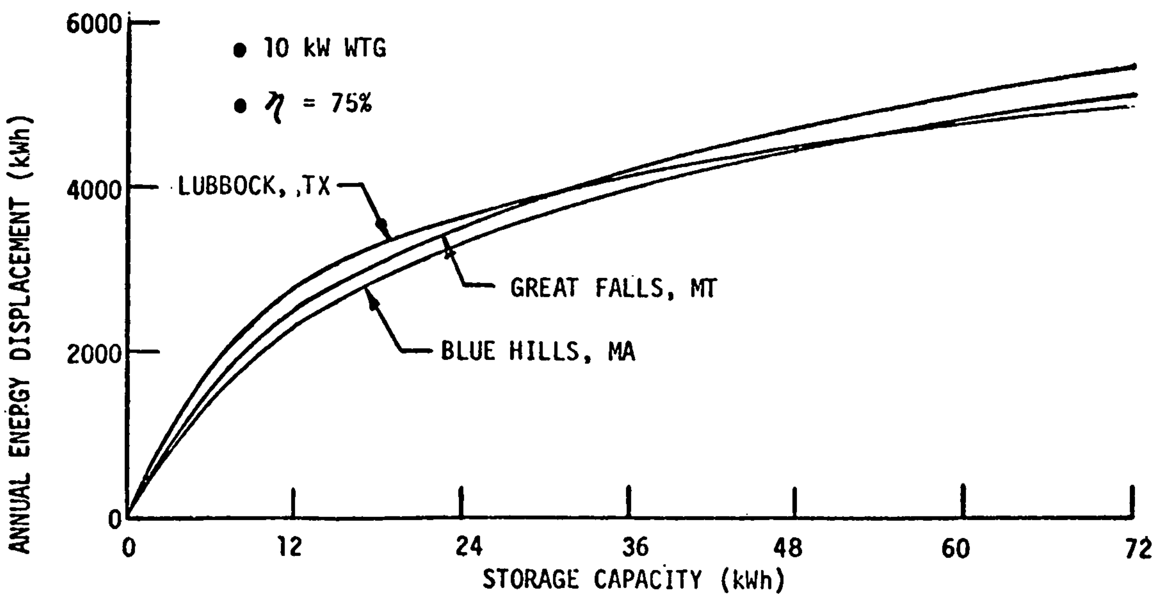

FIGURE 3.2-2. ANNUAL ENERGY DISPLACEMENT - RESIDENTIAL WECS ENERGY STORAGE

Energy savings from storage proved to be only slightly affected by location over the range studied, as the above figure shows.

The sharp "knee" observed for photovoltaic residential storage was not seen in the wind energy case. Thus, although storage capacity beyond about 12-24 kWh yields steadily decreasing additional savings, larger capacities may be economically justified under certain conditions.

The annual energy displacement from storage in the residential application proved to be relatively insensitive to storage system efficiency as shown in Figure 3.2-3.

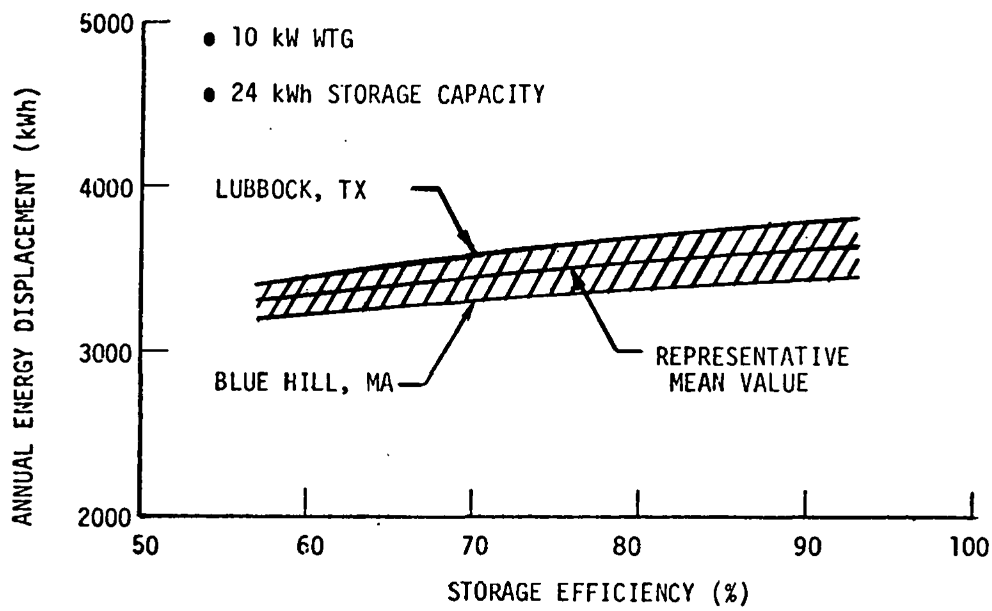

FIGURE 3.2-3. EFFECT OF STORAGE EFFICIENCY - RESIDENTIAL WIND ENERGY CONVERSION

An increase in storage efficiency from 60 to 90 percent results in only about 8 percent increase in annual energy savings. This again suggests, as in the case of photovoltaic energy, the possibility of designing a residential storage system with less emphasis on efficiency if sufficient manufacturing cost advantages can be gained.

Break-even costs for residential storage systems are presented in Table 3.2-1 for nominal 1985 start year, 6% fuel price escalation rate conditions. At present none of the storage concepts demonstrate viability potential for these conditions.

TABLE 3.2-1. ENERGY STORAGE BREAK-EVEN COST GOALS - WIND ENERGY CONVERSION - RESIDENTIAL APPLICATIONS

	BREAK-EVEN COSTS $/kWh	CURRENT ESTIMATES* $/kWh
Advanced Batteries, 10, 20 Yr	66,93	92 $/kWh
Lead-acid Batteries	65	200
Inertial Storage	82	250
Pneumatic Storage	80	270

24 kWh
1985 START
6% ESCALATION

* See Table 5.3-2 for summary cost parameters and references.

Figure 3.2-4 presents break-even costs of residential batteries as a function of start year and electricity price escalation rate. Also shown are cost estimates for lead-acid and advanced batteries. The reader can use these or any other estimates to evaluate the time frame and economic conditions under which battery energy storage will become economic with wind energy in the residential application.

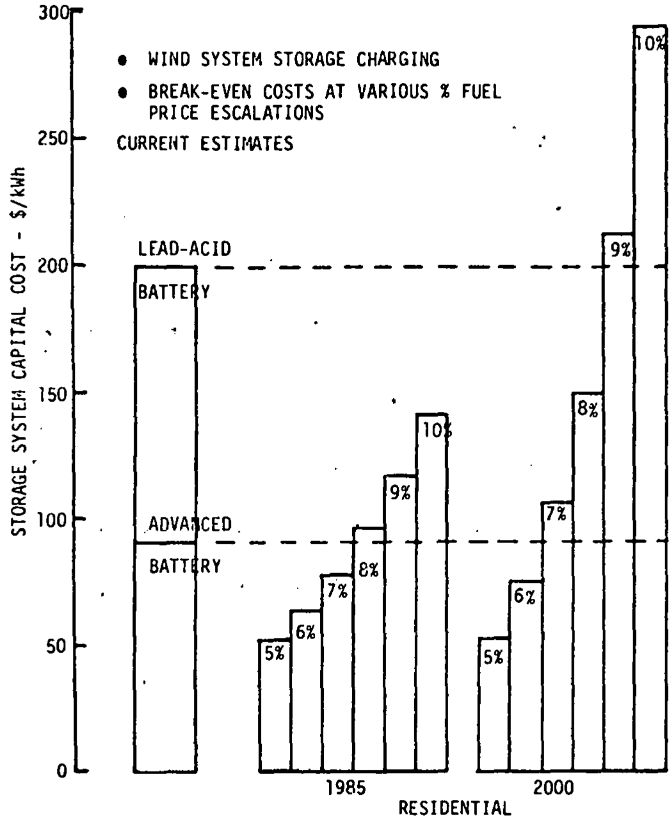

FIGURE 3.2-4. CONDITIONS LEADING TO ECONOMIC VIABILITY - RESIDENTIAL BATTERIES WITH WIND ENERGY

Battery energy storage, despite some hazard potentials, is technically well suited to residential use. Pneumatic and inertial storage, however, presently have equipment characteristics which severely limit both their application and consumer acceptance.

Future research and development effort should be aimed at improving the technology and specific designs while reducing operational problems and hazards. Achievement of the break-even costs shown above is necessary under current conditions; however, there could be additional opportunity for improvement if incentives such as off-peak charging rates for residential customers become available.

3.3 INTERMEDIATE APPLICATION

The intermediate application was characterized by a relatively constant load from 10 A.M. to 10 P.M., dropping to a maximum of one-fourth of this level for the remaining 12 hours. This type of loading would be most typical for the case of a shopping center or cluster of small stores. Wind energy from a 500 kW wind turbine generator thus has excess energy when operating near rated power for any peak loads of less than 500 kW. Energy displacement from storage in the intermediate application is shown in Figure 3.3-1.

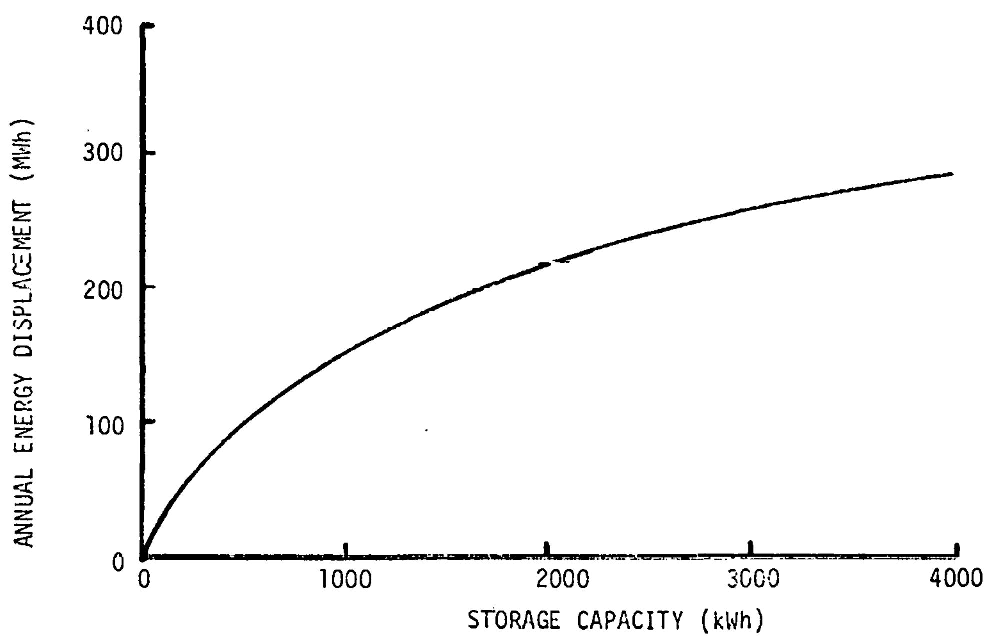

FIGURE 3.3-1. ANNUAL ENERGY DISPLACEMENT, INTERMEDIATE SYSTEM-WIND ENERGY STORAGE

The "knee" observed in the photovoltaic intermediate displacement curve was not evident in the wind case. Energy displacement proved to be relatively insensitive to peak power demand in the range of 200-300 kW. A 250 kW load was selected for analysis, with results scalable to multiples of both load and wind turbines. Break-even costs are presented in Table 3.3-1 below.

TABLE 3.3-1. ENERGY STORAGE BREAK-EVEN COST GOALS, INTERMEDIATE SYSTEM, WIND ENERGY STORAGE

	BREAK-EVEN COST $/kWh	CURRENT ESTIMATE* $/kWh
Above Ground Pumped Hydro	20	19
Underground Pumped Hydro	20	23
Underground Compressed Air	17	34
Lead-Acid Batteries	21	140
Advanced Batteries, 10,20 Yr.	19, 22	67
Inertial Storage	19	217
Hydrogen	16	45

1000 kWh
1985 START
6% ESCALATION

* See Page 5-17 and Tables 5.3-1 and 5.3-2 for discussion of cost basis and parameters.

It can be seen that only pumped hydro and compressed air storage even approach viability, and the application of these concepts to intermediate applications is highly doubtful due to their large scale and site requirements.

The intermediate application for energy storage was by far the least promising, due primarily to two factors - electricity rate schedules and federal tax policy. Under typical commercial and industrial block rate schedules coupled with demand charges, alternate energy devices such as wind energy and energy storage systems can only displace energy in the lowest value blocks and generally cannot reduce peak requirements for back-up by the utility. Thus, displaced energy is worth considerably less than in the residential application. Energy is also tax deductible for businesses which further reduces the effective cost as compared to the homeowner.

3.4 UTILITY SYSTEM PLANNING ANALYSIS

A detailed utility system simulation was performed for realistic 1995 operating conditions in the New England Power Pool. The objective was to compare this detailed analysis with the generalized results of the storage study.

The results indicate:

1. Identical break-even results for use of dedicated storage both in the special case study and in the general study analysis.

2. Nearly identical results with the assumption of perfect WECS output forecasting and system-wide storage.

3. A small reduction in break-even cost when WECS is added to the system under no-forecast conditions with system-wide storage.

4. An improvement in break-even cost of about 25% when perfect forecasting of WECS output is projected with system-wide storage.

5. Superiority of system-wide storage by about 2.3:1 over dedicated storage.

Results of the power pool simulation as compared to the representative utility analysis performed in the study are presented in Figure 3.4-1, in terms of storage break-even cost. Note that the presence of wind energy systems in the utility grid yields a slight reduction in potential storage system worth.

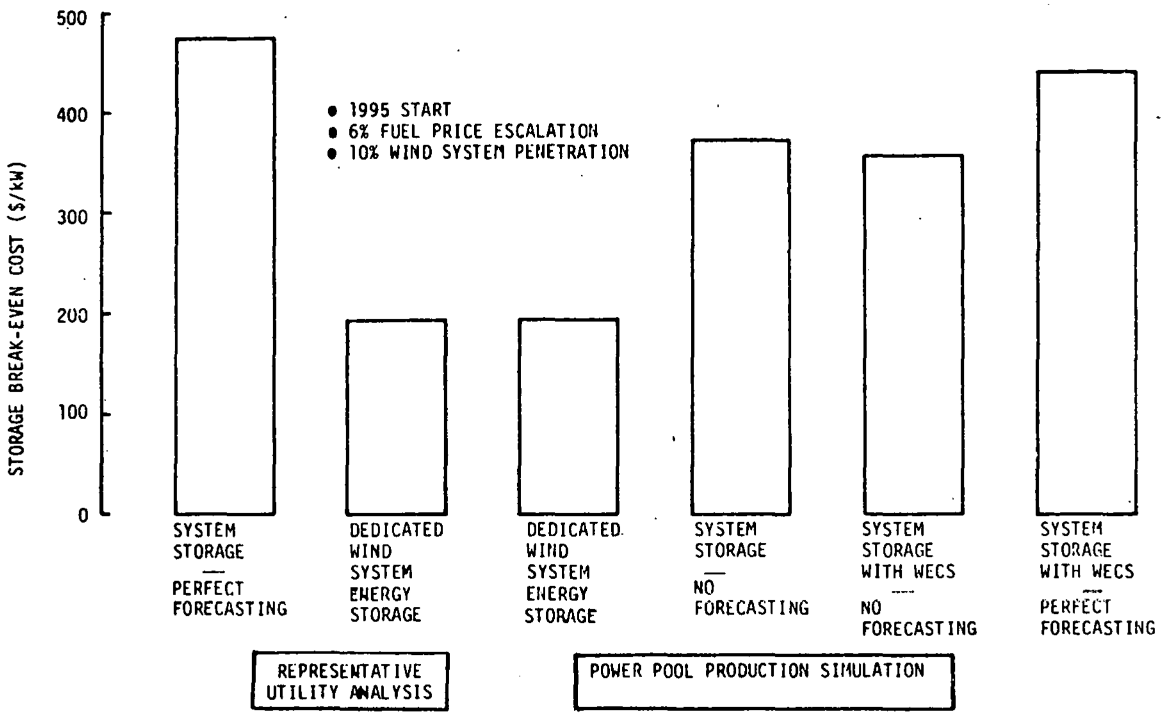

FIGURE 3.4-1. COMPARATIVE RESULTS - REPRESENTATIVE UTILITY ANALYSIS AND POWER POOL SIMULATION

PART B

REVIEW OF CANDIDATE ENERGY STORAGE SYSTEMS

SECTION 4

ENERGY STORAGE CONCEPTS

As a prelude to further investigation of the use of energy storage with photovoltaic and wind energy conversion systems, eleven types of energy storage were reviewed. The principal purpose of this part of the study effort was to provide a background against which to assess the desirability of various concepts by summarizing each concept, its key characteristics, cost ranges and development status. The information presented in this section should, therefore, be regarded as an overview rather than an in-depth analysis. A large body of knowledge already exists for some of these technologies including several recent and comprehensive studies. These sources were used extensively along with other contacts and supplementary investigations and are noted throughout the section.

The candidate storage technologies considered included:

1. Above ground pumped hydro
2. Underground pumped hydro
3. Thermal Storage - Oil
4. Thermal Storage - Steam
5. Underground Compressed Air
6. Pneumatic Storage
7. Advanced Batteries
8. Lead-Acid Batteries
9. Inertial Storage
10. Hydrogen Generation and Storage
11. Superconducting Magnetic Energy Storage

The relative merits of these concepts are considered on a preliminary ranking basis in Section 5 and the effects of key concept characteristics are presented and discussed along with representative costs selected for use in subsequent analyses. The investigation of the matching of photovoltaic and wind energy tc various loads is covered in Volumes II and III along with the effects of variation of other selected parameters.

4.1 ABOVE GROUND PUMPED HYDRO STORAGE

4.1.1 GENERAL

The only economical mode of large scale energy storage now available to utilities is above ground pumped hydro. Pumped storage operates much like the hydroelectric power generation common in the Northwestern part of the United States, except that the water to operate the turbines must first be pumped up hill by use of electricity generated during off-peak hours. The water thus stored is subsequently released to drive the turbine generators during periods of high power demand. This method of storage is about 70-75% efficient; that is, about 4 watt-hours of energy expended to pump the water to the upper reservoir is exchanged for 3 watt-hours of generated electricity when the stored water is returned via the turbine discharge, to the lower reservoir. The cost of electricity generated in this manner can be less than if additional gas turbines or older fossil-fueled steam turbines were used to meet peak demands.

The first pumped hydro storage facility in the United States was built in western Connecticut nearly 50 years ago and had a power capacity of about 30 megawatts. Now, much larger plants are in successful operation and more are planned.[1,2] The largest (approximately 1,900 megawatts and 15,000 megawatt hours of stored energy) is operated jointly by the Consumers Power Company and Detroit Edison at Ludington, Mich. The Ludington plant uses Lake Michigan as the lower reservoir and a man-made lake about 2 miles long by 1 mile wide as the upper reservoir. The plant was ten years in the planning stage and 4-1/2 additional years were required to complete the construction. The total cost exceeded $340 million.

4.1.2 CONCEPT DESCRIPTION AND DEVELOPMENT STATUS

Generally, two reservoirs or reservoir sites are chosen such that with a moderate amount of surface contour re-arrangement, a large upstream pondage area can deliver water to the turbines to meet peaking loads, emergency needs or other system power requirements. The lower reservoir must be large enough to handle the outflow until it can be returned to the higher reservoir or transfer excess water to an on-going stream system. Figure 4.1-1 illustrates the physical "head" relationships for the principal pumped storage concept elements.

Pumped storage is conveniently used in conjunction with conventional hydroelectric plants which typically are located on sizeable rivers. Some natural storage is usually built into this type of hydro plant, often utilizing natural terrain along with dams allowing deliberate flooding of adjacent areas to varying depths. Since pumping is accomplished using electric motors, there is no reason why available energy from other types of electric generating plants cannot be used to pump water for storage.

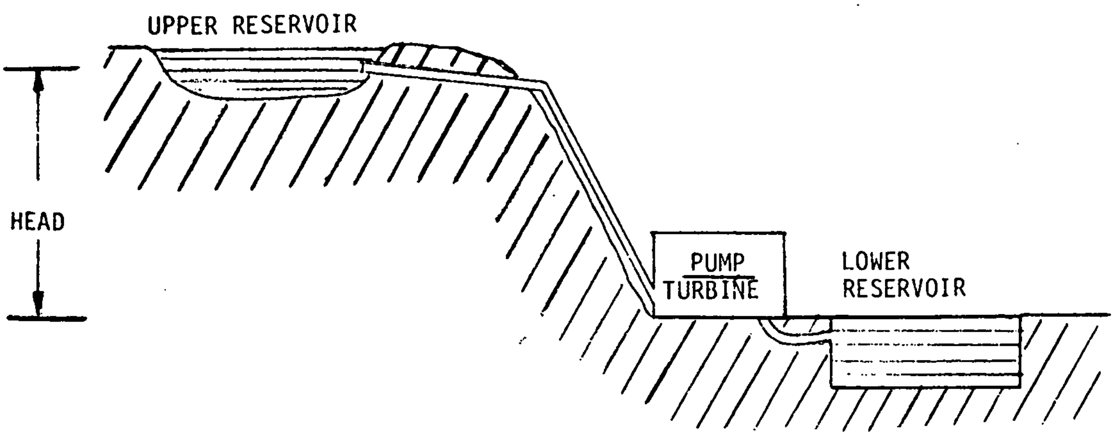

Figure 4.1-1 ABOVE GROUND PUMPED HYDRO STORAGE

The fundamental characteristics of this concept are well known, and the literature has a wealth of data from many recent hydro and pumped storage projects. There is no mystery about the technical details. It may be worth noting, however, that the larger projects are usually associated with locations where massive foundation structures can be securely placed and where nature has lent a helping hand in terms of river basins, natural gorges or other topography. The search for such locations makes above ground hydro storage very site limited. Also, suitable sites and inexpensive land continue to dwindle.

Above ground pumped hydro storage is not, therefore, a viable concept for many parts of the country. Even where sites are available, local opposition is often considerable, the objections include interference with aquatic life and otherwise altering or spoiling the natural environment. The Consolidated Edison plan for a 2000 megawatt pumped hydro storage plant (The Storm King project on the Hudson River near Cornwall, N.Y.)was successfully blocked for 10 years by environmentalists. Pumped hydro facilities are often far from the areas they serve, thus necessitating long distance power transmission lines which continue to become more costly.

4.1.3 TECHNICAL ASSESSMENT

4.1.3.1 Plant and Equipment

The surface reservoirs and structures of above ground hydro storage facilities require land areas typically ranging from 100-1600 acres depending on reservoir depth and head. The minimum economic size for electric utility storage use is from about 100 MW up.[3] However, some pumped hydro facilities rated at much less than 100 MW have been built.[4] The latter may be useful for smaller scale installations (non-utility) in the future, particularly where needs for autonomy of operation exist. Planned projects call for total capacities to 2,100 MW. Physical layouts and cascading techniques are being considered to heads of 5000 feet. Figure 4.1-2 shows a representative plan view of a major above ground pumped storage installation.

The key equipment component for implementing pumped storage is the pump-turbine unit. While separate pumps and hydraulic turbines of conventional design can and have been used, the development of the reversible pump turbine and its later refinements have made pumped storage much more attractive. A number of types and designs exist, but the Francis type pump-

Blenheim-Gilboa Pumped-Storage Project

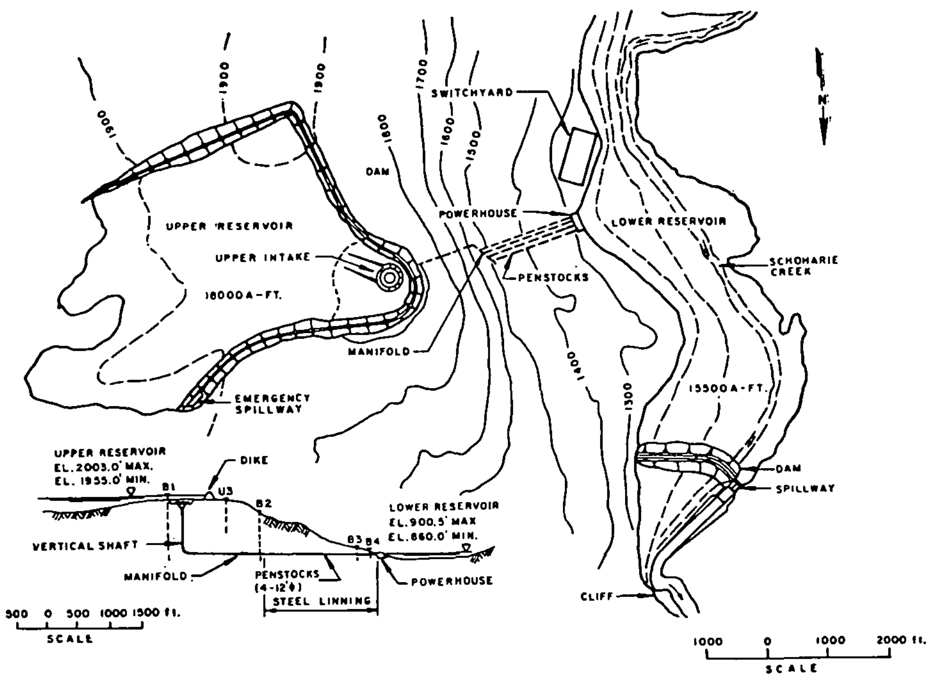

Figure 4.1-2 ABOVE GROUND PUMPED STORAGE INSTALLATION (Vasilescu et al[12])

turbines and/or modern Pelton impulse turbines are used for the higher head installations, the Francis being more prevalent because of its economy and higher speed. Single stage reversible pump-turbine units can be built for heads up to 1,200 ft. Beyond this, multiple-stage units and/or cascading is required. Future development work will likely continue to focus on obtaining higher head capabilities based on the extensive progress of the last 25 years.[2]

The best efficiency, with reversible pump-turbines, occurs at a lower speed when generating than when pumping. This can be compensated for by using a generator-motor capable of two speed operation at a single frequency. Units of this type have been built, but are more costly than single speed units. The relationship between pumping and generating performance of pumped turbines is fixed and design modifications are required to obtain variations of this performance. Pumping time is typically up to 20% longer than generating time due to pump vs turbine discharge rate differences.

4.1.3.2 Efficiency

The system efficiency is usually defined as the ratio of generated energy output to the pumping energy input. A consensus in the literature reports on efficiency range from about 67-75%. 75% is considered achievable now for modern pumped storage projects as a result of equipment improvements over recent years.[5]

4.1.3.3 Useful Life

Operable units have been in service for 50 years, and while large scale pumped storage projects have a history of only about 15 years, this life span appears to be clearly predictable for the newer systems.

4.1.3.4 Other Performance Characteristics

Experience with conventional hydro generating facilities including those with pumped storage has been very satisfactory with respect to operational reliability and maintenance. Forced outage rates have been experienced with pumped storage at a level somewhat higher than for fossil plants or hydroelectric generation without storage. However, the forced outages have been significantly lower than those for combustion turbines. The scheduled outage rates for the period 1965-1974 have been reported comparable to fossil plants but not quite as favorable as combustion turbines.[5]

4.1.3.5 Environmental Impact

The areas of environmental impact to be considered with above ground pumped storage systems include priority of land use, alteration of natural landscape, thermal discharge effects and other factors which may be location-peculiar. Aesthetic objections should be largely resolved by proper landscaping, careful placement of transmission lines, and attention to protection of surrounding communities.

Hydroelectric and pumped storage projects can actually help increase the local fish population. A newly constructed surface reservoir may add not only to available water volume in the area, but can also help stabilize water levels and assist in flood control. Recreational use of reservoirs is possible and is frequently permitted. Favorable comments on the blending of hydro facilities with the environment are not uncommon. The Blenheim-Gilboa Plant is a positive example of what can be accomplished in this regard.[6]

4.1.3.6 Safety and Inherent Hazards

Principal problem areas for pumped storage are: (1) flooding, (2) dam safety, and (3) hazards due to operation near high voltage equipment. With proper design, construction and operation, these should be controllable, notwithstanding some unfortunate experiences.

4.1.4 COSTS AND ECONOMIC CONSIDERATIONS

Considerable capital and operating cost data exists for plants built to date. These costs are generally expressed in terms of two components: (1) a cost or investment associated with a storage system of a given power rating, I_p, in $/kW and (2) a cost associated with the energy storage capacity of the system, I_s, expressed in $/kWh. For storage capable of a maximum discharge capability (per cycle) of t hours at rated power, the total capital investment or cost, I_c (in $/kW) is given by:

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

Representative ranges of power related costs, I_p, have been reported by various sources.[3,5,7,8] The span of these numbers, overall, is from $90/kW to $180/kW. The overall range of storage related costs, I_s, as reported by these same sources runs from $3/kWh to $20/kWh. Slightly higher or lower numbers are also occasionally seen. Generally, these costs are stated without allowance for interest during construction. Balance of plant costs for the installation must be added in some cases, and care must be taken to identify the "price year" before using any numbers. It is also appropriate to note that estimates using such figures will generally not account for major variations between sites, designs, and other conditions relevant to a specific case.

Fixed operation and maintenance costs are applicable to above ground pumped hydro facilities. $1.60/kW/yr. was recommended[3] for pumped hydro in making comparisons with other technologies.

4.2 UNDERGROUND PUMPED HYDRO STORAGE

4.2.1 GENERAL

This storage concept is closely related to conventional hydro-electric generation and above ground water storage. It is reasonable to expect that underground storage concepts may be helpful in the future in geographically extending the range of hydro storage usefulness. In addition, it is likely that more extensive participation in use of hydro storage by conventional generating plants would be possible as opposed to above ground systems.

Operation, efficiencies and costs of underground hydro storage concepts closely parallel those of above ground storage.

4.2.2 CONCEPT DESCRIPTION AND DEVELOPMENT STATUS

The underground pumped hydro storage concept requires use of two reservoirs, one or both of which may be located below normal ground surface level. This makes this concept somewhat less site dependent since natural caverns, old mines and man-made excavations become possible reservoirs where natural topography does not provide above ground options. The number of possible sites thus may be significantly increased over those for above ground pumped hydro. Since the power capacity of stored hydro is directly related to head, or elevation difference between the two reservoirs, high heads are needed to reduce the amount of excavation and/or cavern size and, in turn, costs. Lower reservoirs placed as much as 3000-4000 feet below ground have been discussed.[3,5,9] Figure 4.2-1 illustrates the physical relationships involved. Locations facilitating tie-in of existing generating plants, transmission lines, and loads should be chosen.

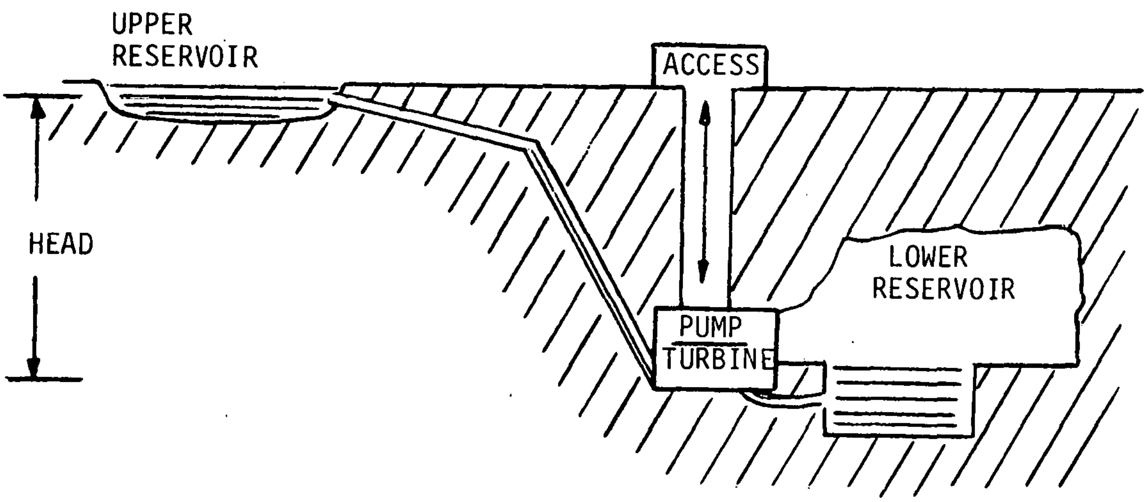

Figure 4.2-1 UNDERGROUND PUMPED HYDRO STORAGE

Waterways between the pump-turbine station and the two reservoirs may be entirely underground or partially above ground. Construction of the power house underground may prove to be economically and environmentally beneficial in some cases. A concept for an underground installation is shown in Figure 4.2-2. At the present time, underground concepts [2] are

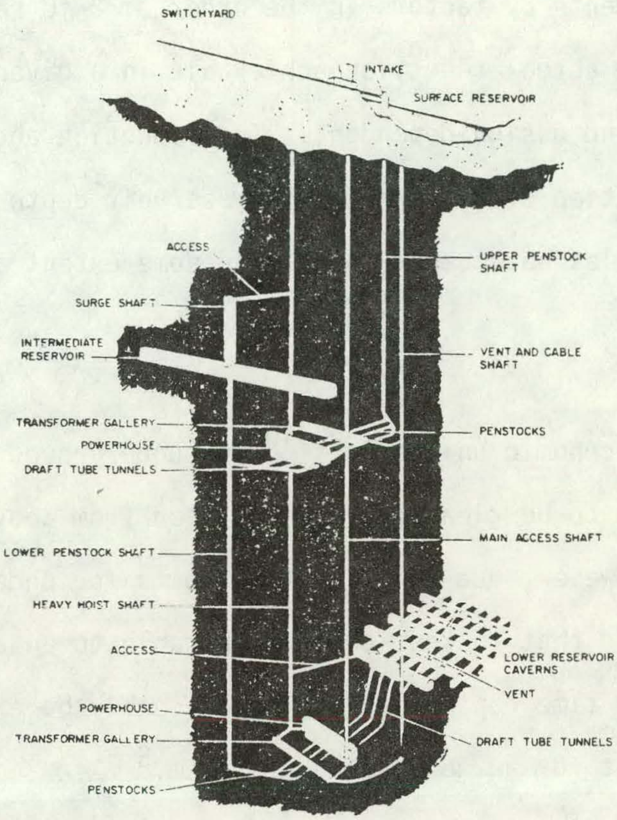

Figure 4.2-2. UNDERGROUND PUMPED HYDRO CONCEPT
(Seoni et al[2])

being pursued in several countries and one U.S. underground plant is in the licensing stage.[3]

4.2.3 TECHNICAL ASSESSMENT

4.2.3.1 Plant and Equipment

Underground pumped storage systems have the potential of reducing land area requirements by factors in the order of 2-10 relative to above ground systems. The actual reduction achievable in a given case would be entirely site and design dependent. The reduction and the range are primarily a function of differences in reservoir depth and head. These latter variables have been examined to some extent and put in perspective by others.[3,5]

The minimum economic unit size [3,10] for underground pumped storage systems does not seem to be clearly differentiated from above ground at the utility level. However, due to excavation costs for underground systems it has been suggested that to keep costs comparable to an above ground system, the discharge time capability might reasonably be expected to be about 60-70% of that for an above ground system.[5]

The reversible pump turbine remains the key component, although more development work will be required for turbines and the overall system if the high heads desired (above 2000 ft.) are to be achieved satisfactorily. As inferred above, the higher heads are helpful in reducing the amount of underground excavation and its associated costs.

4.2.3.2 Efficiency

Similar to above ground pumped hydro except that there is potential for using shorter water passages which would help improve efficiency. Efficiencies of up to 80% have been postulated.[5]

4.2.3.3 Useful Life

Similar to above ground systems - about 50 years.

4.2.3.4 Other Performance Characteristics

Reliability and maintainability should be comparable to above ground systems since the equipment involved is the same or very similar. The fact that below ground plant operation is involved may introduce additional considerations similar to those affecting mine operation, particularly safety of personnel. The cost of maintenance operations could be slightly higher as a result of additional access and procedural requirements.

4.2.3.5 Environmental Impact

Building the pumped storage plant entirely or partially underground raises the question of the disposition of excavated material. Uses for the rock and soil removed are readily conceivable for some locations but disposition of this material would clearly require careful planning. A reduction in surface area requirements should make the above ground plant components easier to blend into the natural surroundings. Other than these somewhat counterbalancing factors, the other concerns would be similar to an above ground system. The specific consequences of any drainage or discharge from the lower reservoir would need to be part of each site survey. The possible disposition of excavated material has been similarly discussed elsewhere.[2,3]

4.2.3.6 Safety and Inherent Hazards

For underground storage, safety problems may be increased due to the underground construction and operation. Flooding of the underground plant is of more concern since drainage capability might well be limited. The potential for serious equipment damage is present should even moderate flooding take place. The possibility of having the underground storage system subjected to the full hydrostatic head was pointed out in the recent PSE&G study.[3] Other safety concerns would be similar to above ground systems, but possibly lessened in magnitude with only one reservoir above ground.

4.2.4 COSTS AND ECONOMIC CONSIDERATIONS

Power related costs, I_p, have been reported by various sources.[3,5,7,8,10] An overall range from $110/kW to $180/kW appears representative. Storage related costs, I_s, from these sources range from $3/kWh to $20/kWh. Balance of plant costs must be added in some cases. Operation and maintenance costs of $1.60/kW/yr. were reported [3] and appear compatible with earlier estimates [11] if inflation is accounted for.

The lead times to plan and build any type of large hydro facility are long. Typically, 5-8 years is required from construction to full operation.[5,7,12] Total times in excess of ten years may be involved if some or all of the planning lead time is counted. This lead time reduces, in effect, the amount of money that can be spent on the capital equipment for a hydro project, since interest during the long construction period consumes a considerable sum. With careful planning, the early outlays can be reduced and thereby minimize this problem. Costs are generally stated without allowance for this factor. Computations must subsequently account for this item. The allowances for both underground pumped storage and above ground storage would be similar as would the allowance for any large project involving similar construction and lead times. The general scheduling and funding factor computation process has been described elsewhere [13] and a set of such factors is given in a recent PS&G study.[3]

4.3 THERMAL STORAGE - OIL

4.3.1 GENERAL

Oil is potentially a desirable medium for energy storage under some conditions. It has an advantage over water because of lower vapor pressure. It can be pumped and otherwise handled for storage purposes utilizing conventional equipment and present technology. A major negative factor in the use of oil is the flammability hazard, another is the possibility of leaks or spills. As with other forms of thermal storage, it is necessary to use insulation to reduce loss of heat content during the time between storage and the extraction of the heat energy for subsequent use. Since the energy stored must eventually be connected to a directly usable output, the nature of the conversion process and its efficiency is a major consideration. There are some other problems inherent to the use of oil but probably not too severe to cope with. Examples of the latter are the specific heat (much lower than water), degradation, coating effects which make immersion heating relatively unattractive as a means of inserting stored energy, and the requirement for heat exchangers.

4.3.2 CONCEPT DESCRIPTION AND DEVELOPMENT STATUS

As presently visualized, the concept would be applied in conjunction with utility systems as a means of improving conventional generating efficiency. Heat energy would be removed from a normal turbine cycle by extraction of steam at times of relatively lower system demand. The extraction steam and/or a portion of the main steam supply would be used to heat oil pumped from an insulated tank via a heat exchanger system into a second tank. The energy extracted would be preserved as sensible heat and subsequently extracted by using it to pre-heat boiler feedwater lines and increase turbine output. The tankage used to store the oil would require insulation to prevent heat loss during the storage portion of the cycle.

Integration of this system into the power plant operation is shown in simplified form in Figure 4.3-1. Refs. 14 and 15 provide extensive additional discussion of this general approach. Condensate and final feedwater temperatures would determine the overall temperature difference in the cycle. As much as 300°F Δt is estimated. A design for such a system at the 1000 MW level is reported to be complete.[15] Various possibilities exist with respect to the choice of configuration of the heat exchanger and turbines. Choice of the most effective oil also requires further work.

On the order of 1-1/2 million gallons of oil have been estimated for storage of 2600 MWh [14]. A very significant trade-off exists in relation to the land area requirements. Some area must be considered for containment of oil spillage, and the size and number of tanks determine to a large extent how small the area can be made. The range of possibilities runs from about three to twenty acres in the case cited, with smaller tank unit sizes reducing the area requirement at the expense of reliability and other factors. Underground tank placement is also a possibility. It

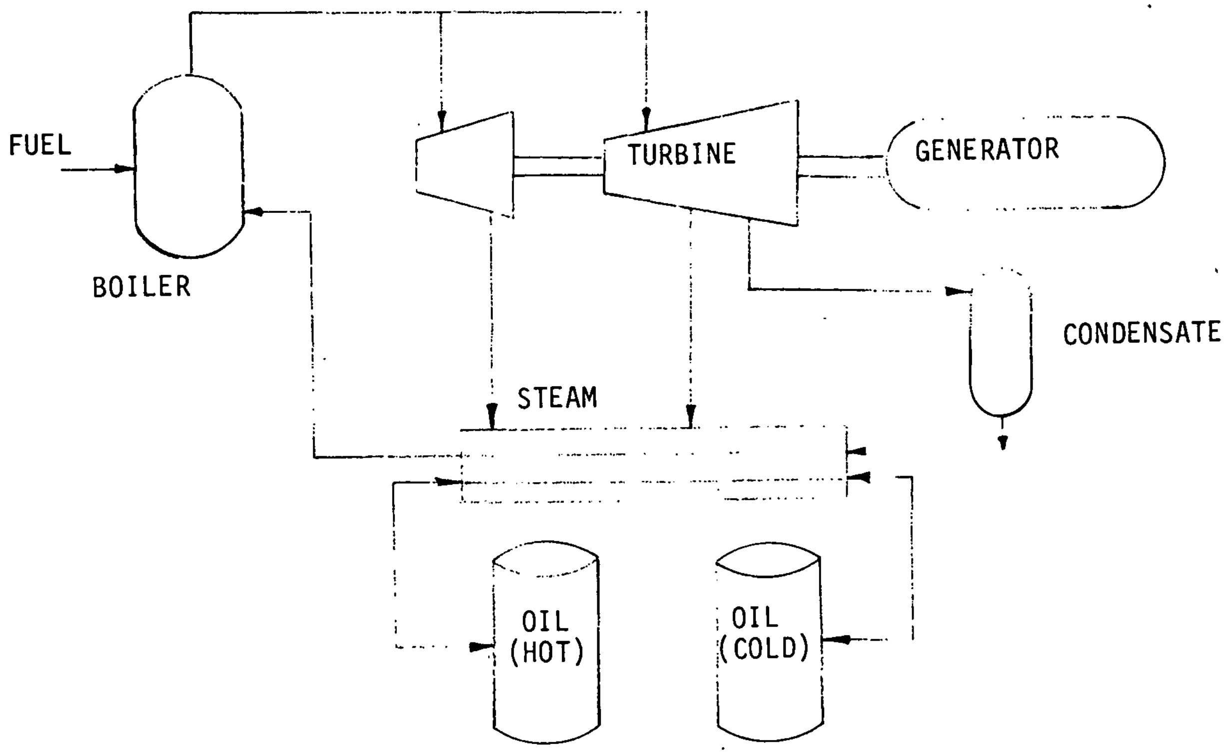

Figure 4.3-1 THERMAL - OIL ENERGY STORAGE

is important to recognize that the "cold" oil is really likely to be at temperatures at or above those of domestic hot water tanks, with the "hot" oil stored in the vicinity of 500°F.

The thermal energy storage design described [14] is based on existing technology and experience. Long and expensive research and development programs are not believed required in order to design commercial facilities. Construction of a prototype test facility, in conjunction with a fossil fuel power plant, would provide valuable operating experience with a thermal-oil energy storage system.

4.3.3 TECHNICAL ASSESSMENT

4.3.3.1 Plant and Equipment

The designs for a thermal-oil energy storage system as reported [3,15] are based on use in conjunction with a large nuclear power plant. The projected storage capacity (2600 MWh) is well within the range of preliminary estimates made earlier in this study with respect to desirable amounts of storage for utility plants. There does not appear to be any basic reason why such a plant could not be scaled up or down somewhat from the size described in the above references. However, the complex nature of the plant, the necessity for having highly competent operating personnel and the need for oil spill precautions rule out other than utility-scale applications. A specific study would be required to fully determine the economics of other plant sizes. A minimum plant size of 50-200 MW was recommended,[3] and no reason has been found to suggest otherwise.

This storage concept has the advantage of a much smaller degree of geographic dependence as compared to pumped hydro or compressed air. With proper precautions it should be feasible to select suitable sites with constraints no more severe than those for refinery storage and handling of comparable amounts of oil. Some utility plants could be expected to have adequate land available already to accept the installation required for this type of storage. The oil transmission distances should be kept quite short to assure minimum heat losses.

4.3.3.2 Efficiency

Hot oil thermal storage system efficiencies reported in the literature range from 65-80%. A range of 65-75% was estimated in one case.[3] Ref. 16 reported a range of 65-80%, based on underground storage.

4.3.3.3 Useful Life

Projected life of a thermal-oil system was found to be 25-30 years.[3] No other estimates were found for this type of system. However, the nature of the storage equipment would be such that the major components (i.e. tankage units and oil transfer lines) should last 30 years with proper maintenance, and the operating components such as pumps, gauges and valves would be replaceable units not necessarily expected to have the same life.

4.3.3.4 Other Performance Characteristics

Although this concept is based on state-of-the-art technology, the lack of other than a paper design precludes a meaningful assessment of reliability performance or possible operational problems. The authors of this concept are presumed to have considered these factors although published information does not really cover these points in any detail.

4.3.3.5 Environmental Impact

In case of a tank or pipe rupture, containment of the oil is the major environmental concern. Designs to minimize the potential for environmental impact of oil leakage would be mandatory. These could take the form of dike-type enclosures around individual tanks.

4.3.3.6 Safety and Inherent Hazards

The major safety problem with thermal storage in oil tanks is the potential fire hazard attendant with storing large quantities of oil. Proper designs and procedures could insure safety of operation along the lines of refinery storage operations. The elevated hot-oil temperature would also be of concern in event of a leak.

Leakage becomes a particular safety concern when this concept is integrated with a nuclear power plant[3]. Precautions must be taken to avoid leaking oil into the feedwater stream which under certain conditions could radioactively contaminate the oil. Proper system monitoring and control would be required, but the technology for this is available.

4.3.4 COSTS

Recommended capital cost ranges are given[3,15,16] where power related costs, I_p, range from \$150/kW to \$250/kW, and storage related costs range from \$10/kWh to \$15/kWh.

Reported fixed operation and maintenance costs of \$3.20/kW/yr. and variable O&M costs of \$.0002/kWh are recommended[3] for use in comparing thermal-oil storage with other concepts.

4.4 THERMAL STORAGE - STEAM

4.4.1 GENERAL

As in the thermal-oil storage concept, the use of steam or saturated water provides storage in the form of "sensible" heat. Water is well suited to this purpose because of its high specific heat, ease of handling, and natural abundance. The properties of steam at various temperatures and pressures are widely known and the techniques for making use of steam with minimal hazard to operating personnel have long since been mastered. However, to attain and utilize temperature differentials required for the thermal storage concepts under consideration necessitates the use of expensive pressure vessels because of high vapor pressures encountered with hot water. Insulation of storage tanks and lines is essential to preserve heat content. A large quantity of hot water would be involved; therefore, some care would be required to insure that catastrophic loss of this storage media could not do excessive damage. The concept is site dependent only to the extent that the storage system needs to be located adjacent to the basic power plant which it serves.

With today's technology, there appears to be no reason why a utility-scale storage system of this type could not be built.[17,18]

4.4.2 CONCEPT DESCRIPTION AND DEVELOPMENT STATUS

The basic principle of operation with this storage concept, as currently conceived, is very much like that for thermal oil. The implementation is somewhat different, however, since the storage media and working fluid are one and the same. Figure 4.4-1 shows a simplified diagram of the concept based on detailed work documented by PSE&G[3] and Golibersuch et al.[19] Steam extracted from the normal cycle in a steam-turbine generating

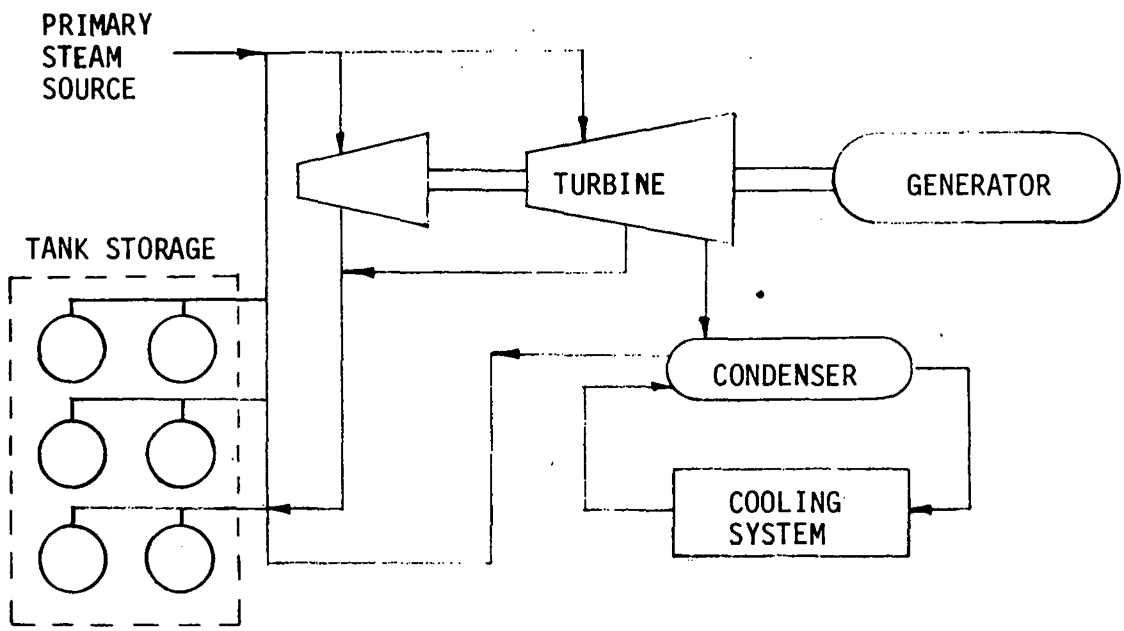

Figure 4.4-1 THERMAL-STEAM ENERGY STORAGE

plant is injected via submerged nozzles into partially water-filled pressure vessels transferring heat to the stored water. This raises both the temperature and pressure of water already within the vessel and also increases the water level. During portions of the peak load demand, when it becomes desirable to increase the output of the turbine-generators, a deliberate reduction of storage tank pressure causes a portion of the water to change to steam instantaneously. The steam thus formed is piped to the turbines (or to a separate "peaking" turbine) increasing its output to meet the high load demand.

Even though present technology will permit building such a system, there are significant limitations, the most severe being the cost of high pressure storage vessels. Methods other than use of conventional welded steel tanks have been suggested for investigation. The latter include pre-stressed concrete containers and use of underground (pressurized) caverns (similar to the dry-cavity concept for compressed air).

4.4.3 TECHNICAL ASSESSMENT

4.4.3.1 Key Characteristics

Plant size, efficiency and expected useful life of a thermal-steam storage system are considered very similar to those of the thermal-oil concept. Reference 3 provides estimates for a storage capacity of 2000 MWh that include about 3-5 acres of land and as many as 440 individual storage tanks.

As in the case of thermal-oil storage, a number of configuration tradeoffs are possible, depending on specific site requirements for accessways and tank location and separation.

Most concept implementations for this type of storage are discussed in relation to nuclear power plants where some advantages are associated with the integral design of the basic plant and the storage system to assure properly coordinated design of the low pressure turbines. Additional development work on this concept would be primarily in the area of storage vessel design.

The minimum effective plant size, efficiency, and useful life for thermal-steam storage are approximately the same as for thermal-oil (Section 4.3) and are, respectively, 50-200 MW, 70% and 30 years.

4.4.3.2 Other Performance Characteristics

The operating reliability and maintainability of such a system should be similar to classic steam plants. Tank corrosion has been discussed as a major maintenance problem.

4.4.3.3 Environmental Impact

When steam storage is integrated with a nuclear power plant, possible radioactive contamination in the system could result. Reference 3 reports that if boiling water reactors are used instead of pressurized water reactors, the potential exists for the leakage of fission products into the primary cooling water which could be transferred to the storage vessels. Improved designs can overcome this problem.

4.4.3.4 Safety and Inherent Hazards

Safe handling of high pressure steam is not a problem in today's technology. However, proper system monitoring and control should be emphasized to guard against the possible radioactive contamination of the system as described above. Personnel safety procedures would have to parallel those of modern steam plants. Design and procedural precautions would be needed to prevent catastrophic loss of the hot water and steam in event of tank rupture.

4.4.4 COSTS

The recommended power-related capital cost ranges for steam thermal energy storage, as reported in References 3 and 15, are identical to those of oil thermal energy storage, i.e., I_p ranges from 150 to 250 $/kW. However, the storage related costs range from 30 to 70 $/kWh according to Reference 3. Reference 3 also recommends that the operating and maintenance costs for steam storage be taken as identical to those for thermal-oil storage (See Section 4.3.4).

4.5 UNDERGROUND COMPRESSED AIR STORAGE

4.5.1 GENERAL

The concept of storing energy in the form of compressed air is not new. It has recently been investigated with renewed interest based on larger scale use. A comprehensive review of the entire compressed air storage technology was recently completed for ERDA by the General Electric Co.[20]

Initial patents [21,22,23] involving compressed air storage were issued in the late 1940's and early 1950's. More recent studies (e.g. References 24 through 29) of this concept are providing new approaches for this developing technology.

In practice, this concept would make use of electrical energy, generated by power plants during off-peak load periods, to compress air which could be stored by suitable containment. During periods of peak power loads, the compressed air and a fuel (probably fossil in nature) would be combined in a combustion chamber. The heated air and combustion products would be expanded through a turbine, producing electricity in the usual manner by driving a generator.

4.5.2 CONCEPT DESCRIPTION AND DEVELOPMENT STATUS

Conversion of compressed air to electricity can be accomplished in at least two ways. The air can be directly expanded to drive air turbines, or it can be injected into gas turbines in place of the usual compression stages. Initially, the latter step is considered more desirable, the principal reason being the elimination of problems inherent in the direct expansion of high-pressure air. A block diagram of the current concepts using fueled turbines is shown in Figure 4.5-1.

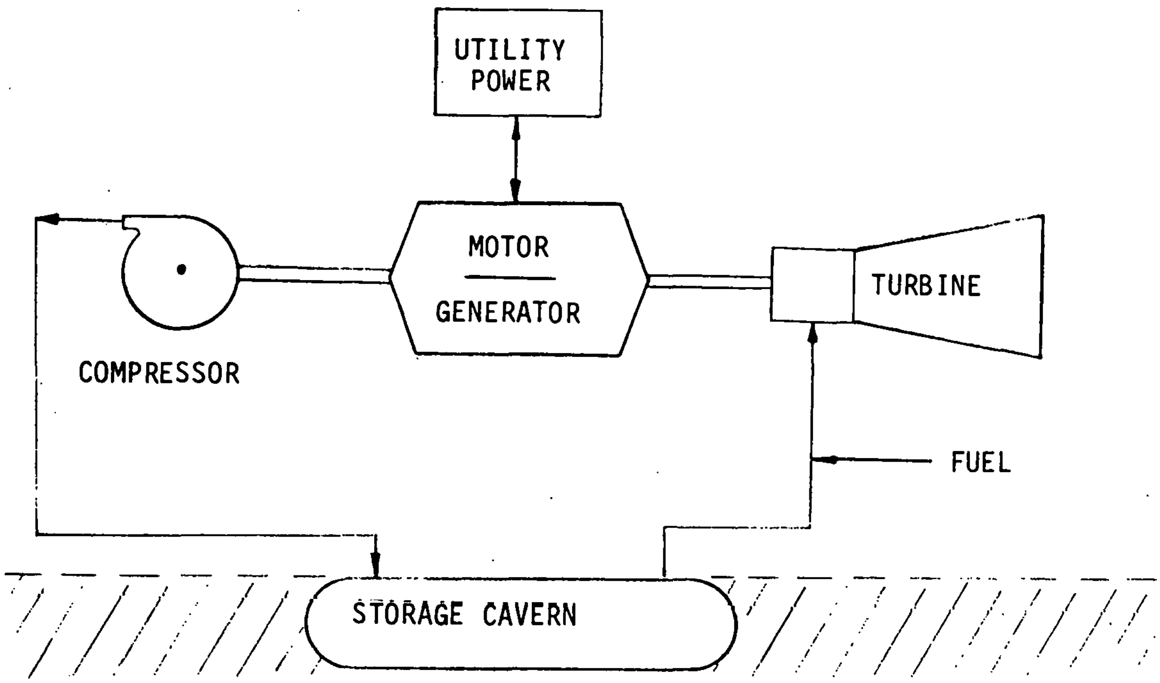

Figure 4.5-1 SCHEMATIC OF UNDERGROUND COMPRESSED AIR STORAGE

Conventional gas turbines may be modified so that the compressor stages, generator and power stage are separated by clutches. In the storage mode, the generator, operating as a motor, draws power from the network to drive an air compressor. Compressed air is delivered to storage. The power turbine is inoperative so that no fuel is consumed.

When the demand for power exceeds the on-line capacity, the compressor is disengaged and the power turbine is connected to the generator. Fuel is added and compressed air is released from storage. The generator then supplies power to serve the load. The fuel saving due to use of the compressed air supply will amount to about 66 percent, compared to conventional turbine operation.[31]

Operation of the system in this charge-discharge cycle eliminates the need for matching the mass flow in the turbine and the compressor. It is conceivable that a system could be designed with components capable of operating as a conventional gas turbine unit, allowing both the compressor and turbine to remain connected to the motor-generator. This would allow conventional operation of the unit after exhaustion of the compressed air.

Compressed air energy storage systems have been conceptualized to both constant pressure and constant volume. The constant pressure system would use a hydrostatically pressurized subterranean reservoir. Such a reservoir might be a natural acquifer, with the operating pressure determined by naturally occurring conditions. Alternatively, the reservoir might be either a natural or artificial cavern utilizing water piped from a surface reservoir to provide pressurization. The latter would be based on consideration of both technical and economic parameters for the particular case.

A constant pressure system is expected to require cooling of the air after compression in order to bring the temperature of the compressed air down to approximately 50^{o}C. This cooling is needed to prevent excessive heat transfer to the pressurizing water, which in turn would be subject to evaporation. The heat removed by the cooling process constitutes an energy loss in the overall storage system operation. High storage pressures tend to be attractive in that they reduce the amount of cavern space that might otherwise have to be excavated at considerable expense. It is believed that high pressure turbines would be desirable in order to avoid throttling losses that might occur with use of the higher storage pressures.

In selecting a suitable site for a water-pressurized compressed air storage system, it would be necessary to consider the feasibility of obtaining water for pressurization, and whether land-use for surface reservoirs would be acceptable.

The constant volume or variable pressure system needs only a suitable air storage reservoir. Fabricated tankage would be excessively costly at low compressed air densities; however, underground caverns could be effective. Both natural and man-made storage sites are of possible interest. This system concept makes storage of the compressed air possible at temperatures more compatible with compressor discharge temperatures. It is visualized that at discharge the reservoir pressure could drop as much as 50%. Turbine design would have to accommodate this range as optimally as possible.

There is considerable precedent for this second compressed air storage concept in that storage of natural gas has been satisfactorily accomplished in this manner for some time.[30] The natural gas industry has made use of depleted oil and gas fields, acquifers and man-made caverns. In the latter instance nuclear detonation and solution mining of salt are alternatives to conventional excavation methods. Figure 4.5-2 illustrates a solution mining concept.[31]

Diagram of leaching process for an air reservoir in an underground salt deposit.

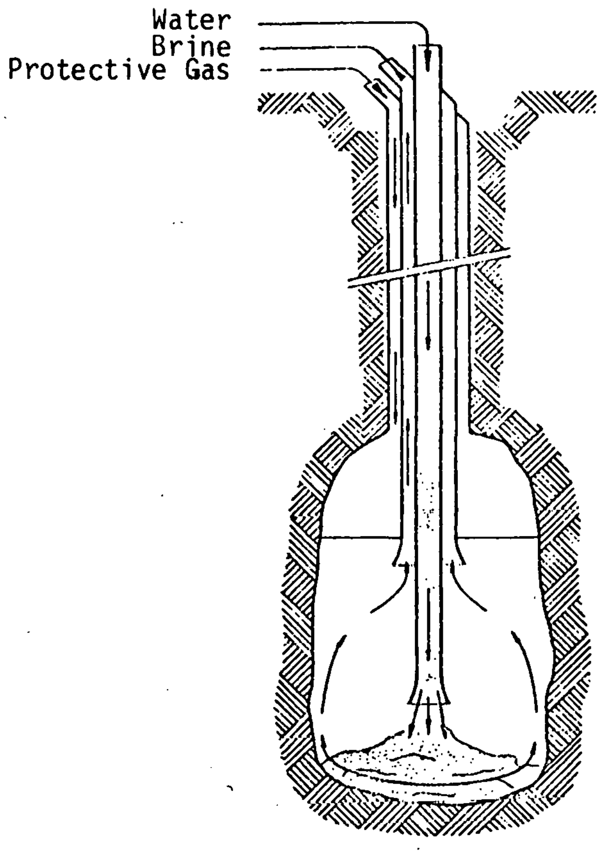

Figure 4.5-2 SOLUTION MINING PRINCIPLE - DIAGRAM OF LEACHING PROCESS FOR AN AIR RESERVOIR IN AN UNDERGROUND SALT DEPOSIT. (From STYS [31])

There are two components of the underground pressure that have been identified as applicable to storage in subterranean areas. One is the gravity or hydrostatic pressure of water from whatever water table exists above the cavern. The other is an overburden pressure contributed by overlying rock formations. The combined resultant pressure, or "geopressure" as it is known, can range up to about one psi per foot of depth. Cavern depths of 2000 feet or more are discussed in the literature.[9]

Abandoned mines in New Mexico are cited [20] as desirable low cost test sites.

Natural water-bearing strata, often referred to as "acquifers", are believed to offer the most widely available storage sites. Acquifers may have very long underground passageways or channels which change both in elevation and direction. If gas or compressed air is injected at a pressure higher than the "geopressure", it displaces the water and creates an air bubble within the underground formation. The individual nature of the acquifer's structure will determine the behavior of the displaced water and the amount of pressure which can be tolerated. The water within the acquifer will generally be the containing element in the horizontal direction along the underground passageways.

Research work is necessary to investigate the various types of underground sites as well as specific sites. It is important to ascertain the degree to which daily pressure and temperature variations can be handled by the cavern structures. When the stored, compressed air is released, it must not force harmful contamination or particulates within the cavern to migrate to the turbines and cause damage. More must be learned about these site-related specifics.

The implementation of the compressed air storage project in West Germany[32,33,34] illustrates the present state of readiness for exploitation of this concept. The plant at Huntorf, Germany, is scheduled to go into operation in 1977.

Contract negotiations with three utilities are presently (mid-1977) underway for preliminary design and site exploration related to the future application of this concept in the United States. Candidate storage reservoirs include aquifers (Public Service of Indiana), rock caverns (Potomac Electric Power), and solution-mined salt caverns (Mid-South Services).

The concept of combining underground pumped hydro and compressed air storage is the subject of a patent application by E.S. Loane of the GPU Service Corporation. This combination offers possible cost reductions due to better integration of equipment, and improved system optimization.

Reference 3 reports land area requirements for a 1000 MW storage system ranging between 5 and 68 acres depending on storage pressure and reservoir depth.

4.5.3 TECHNICAL ASSESSMENT

4.5.3.1 Plant and Equipment

Reference 3 reports that the net power output of an air storage combustion turbine will be three times that of a conventional gas turbine, and concludes that since the largest conventional gas turbine is rated about 100 MW, power levels approaching 300 MW should be possible for a combustion turbine unit operating from compressed air storage. A 1000 MW system output could be provided by four 250 MW units.

One basic construction method useful in rock formations, designated "room and pillar", results in an underground cavern for the storage plant as shown in Figure 4.5-3.[20] The Huntorf, Germany Plant used a solution mined cavern.

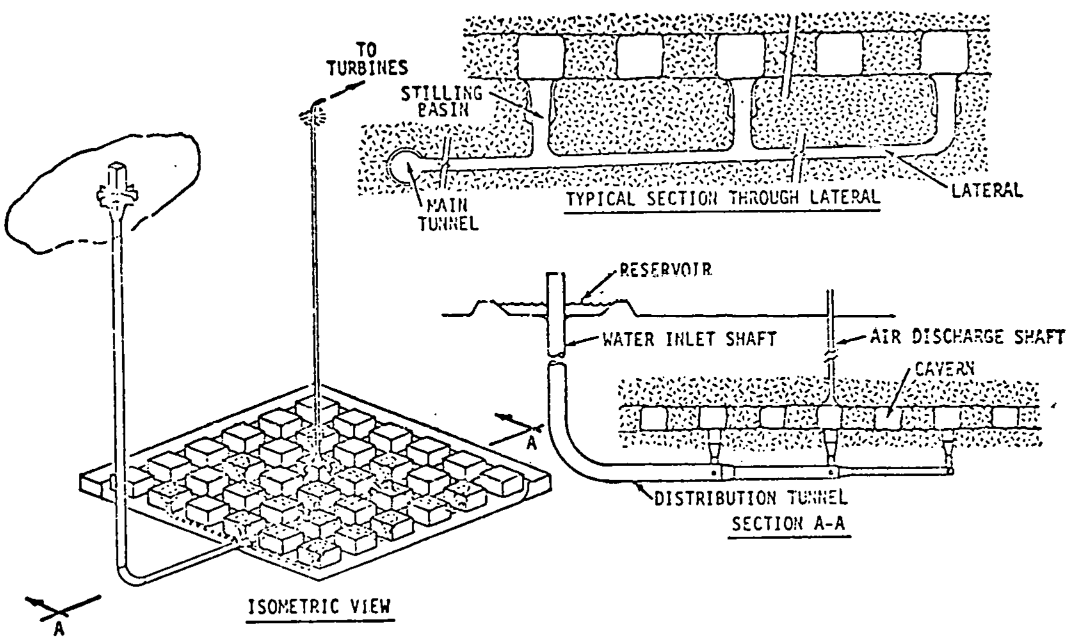

Figure 4.5-3 CONCEPTUAL ROOM AND PILLAR COMPRESSED AIR STORAGE CAVERN (From Bush et al [20])

4.5.3.2 Efficiency

There are two ways to define efficiency for the compressed air storage system: (1) an "energy conversion" efficiency and (2) an "energy storage system" efficiency. The energy conversion efficiency is defined as the efficiency of conversion of the energy input to electrical output. Reference 3 reports energy conversion efficiencies ranging from 40 to 53% for heat rates of 5800 to 4200 Btu/kWh and compressed air pumping requirements from 0.8 to 0.6 kWh (out), respectively. For comparison with other storage technologies, the storage system efficiency (in terms of the fuel utilization efficiency of the baseload plus the compressed air system versus the baseload fuel utilization efficiency) is more useful. Reference 3 reports corresponding storage system efficiencies ranging from 69 to 93% for the same range of heat rate and compressed air pumping requirements given above. References 16, 35 report efficiencies ranging from 65 to 75% for compressed air storage.

4.5.3.3 Useful Life

The projected life of compressed air storage systems as reported in Reference 20 is 28 to 40 years. Reference 3 reports an expected life of 20 to 25 years. Kalhammer [16] projects a life of 30 years which, for comparison purposes, will be assumed representative for compressed air storage systems.

4.5.3.4 Other Performance Characteristics

Compressed air system reliability is discussed [20] as possibly being approximately equal to that for gas turbines. However, the reliability and maintainability of the air storage facility is a major unknown at present due to lack of operating experience.

4.5.3.5 Environmental Impact

Four areas of possible environmental impact to be considered with underground compressed air storage systems are: (1) aesthetic land use, (2) water quality, (3) air pollution, and (4) noise.

Equipment will be housed in suitable structures, somewhat similar to ordinary power plants. In order to prevent the deterioration of water quality, compressed air storage uses confined acquifers, not the form of acquifer used as a water supply.

For air pollution control, water injection into the turbine combustion chamber is commonly used to lower the flame temperature and decrease the concentrations of the oxides of nitrogen.

4.5.3.6 Safety and Inherent Hazards

Hazards posed by the large quantities of high pressure air in this storage concept include the possibility of line ruptures throughout the system. In addition, the use of abandoned coal mines and gas wells as storage reservoirs poses the potential problem of accumulation of significant amounts of methane. It would be necessary to maintain continuous monitoring of these storage cavern hazards.

4.5.4 COSTS AND ECONOMIC CONSIDERATIONS

Representative capital investment and operating cost ranges for compressed air storage are reported in Refs. 3, 20. These costs are based on a comprehensive compilation of cost data obtained from other sources. The power related costs, I_p, range from 100 to 210 \$/kW and the storage related costs, I_s, range from 4 to 30 \$/kWh.

For underground compressed air, construction lead times of about two to three years have been estimated.[35,36] This seems to be consistent with the Huntorf experience. Including the planning phase, the total time would be about 5 years.

4.6 PNEUMATIC STORAGE

4.6.1 GENERAL

Intuitively, the use of pneumatic storage or compressed air as a technique for energy accumulation would seem well suited to residential-sized applications. However, an extensive search of library holdings, periodical literature and technical documents failed to uncover descriptions of any systems of this size, although there is much information available for utility-configured installations as discussed in the previous section.

A contact[37] with the AiResearch Manufacturing Co. of Arizona, Garrett Corp., a well-known manufacturer of auxiliary power units for aircraft, did lead to the identification of an energy storage prototype system within reasonable scaling size for a home system. That organization is fabricating an air-turbine driven alternator with a rated output of 80 kW for a proof-of concept experiment being conducted by the Hydro-Quebec Institute of Research (IREQ) in Canada. A discussion with an engineer in that organization indicated that the demonstration employs a steel tank to store compressed air developed by a multi-staged piston compressor powered from electric motors which received energy from a windmill-driven generator. The wind generator has a peak output of 40 kW and the storage tank has been designed to store approximately 40 kWh of energy. Although the size of the windmill and output alternator for this demonstration are somewhat larger than the nominal residential load of 4 kW and peak rating of 10 kW, the storage capacity is comparable to that selected for nominal residential energy storage in this study. Thus, the elements of this system can be used as a model which would have fewer scaling errors than would be expected from utility-sized components.

The limited information on this concept further indicates the immaturity in the development of suitable residential system components and therefore a low expectation for early economic viability for such an arrangement.

4.6.2 CONCEPT DESCRIPTION AND DEVELOPMENT STATUS

The configuration conceived for residential pneumatic storage is based upon that to be tested by the Canadian proof-of-concept experiment.[38] A conceptual and very much simplified block diagram of the pneumatic storage system is shown in Figure 4.6-1.

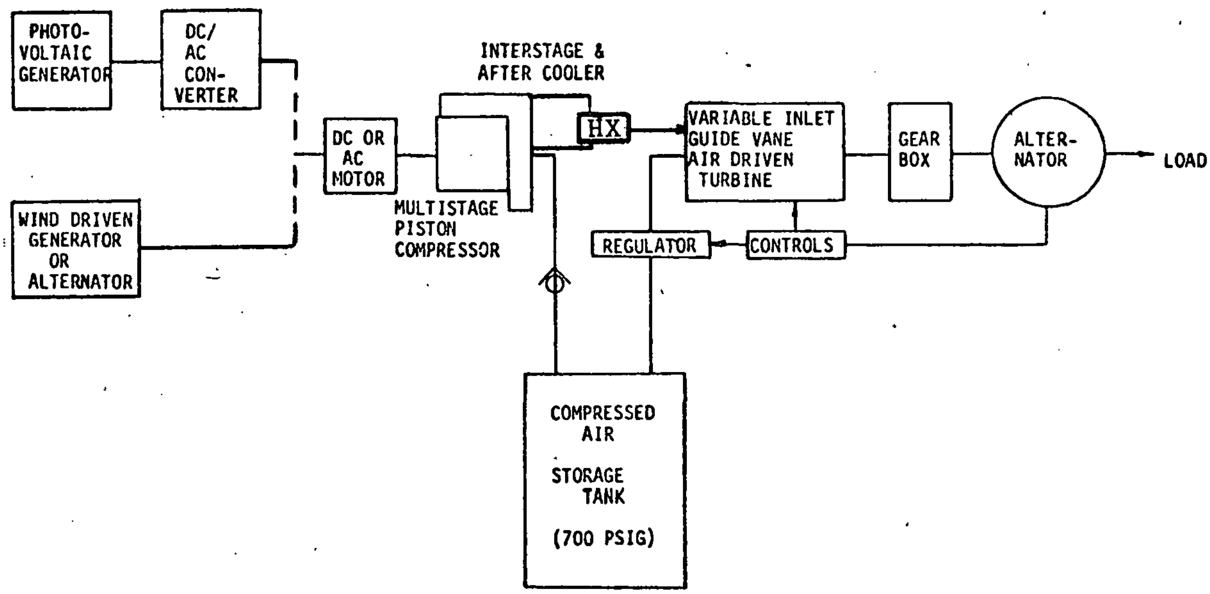

FIGURE 4.6-1. SIMPLIFIED BLOCK DIAGRAM OF PNEUMATIC STORAGE SYSTEM

For a photovoltaic system, the electric energy collected as dc may be converted to ac for use in driving an ac electrical motor, although the Canadian system uses dc for its compressor drive. A wind driven alternator can supply either an ac or dc output which would be compatible with the compressor drive motors selected. Since in the home system it is unlikely that a natural cavern or aquifier would be economically available, a steel constant-volume tank could be employed for storage. To charge the tank, a positive displacement, piston compressor is utilized to achieve a pressurization of 50 atmospheres (about 700 psig). For an adiabatic or isentropic compression cycle (the temperatures that would theoretically exist at these pressure ratios are approximately 1150°F), an interstage cooler would be necessary. The system could also be configured to utilize the energy removed from the air for heating domestic hot water or heating and cooling of the residence, although this addition will increase complexity and thus costs and may seriously affect overall storage system efficiency.

Air-driven turbines operate most efficiently when supplied from an essentially constant pressure source. Therefore, a regulator would be utilized to maintain an inlet pressure of approximately 75 psig (5 atmospheres) even though this technique will result in some decrease in efficiency due to throttling losses. Turbines also operate most efficiently at extremely high speed. The unit for the IREQ experiment operates at a speed of 42,000 rpm with the rated output from the alternator of 80 kW. According to the engineers contacted, this speed would be considerably higher for the smaller, 10 kW drive that would be used for the home systems. Since alternators usually operate at a speed of about 1800 rpm, a gearbox would be interposed. The speed of the alternator is maintained at a constant value by using a control which regulates the position of the inlet guide vane to the turbine.

The components for the experiment being conducted by Hydro-Quebec Institute of Research are effectively off-the-shelf available items and have not been specifically designed to an optimal size for integration into such a system. IREQ does not expect to have publishable results available before the end of 1977. It should be emphasized that the system concept described above is based upon limited conversations and is greatly simplified compared with the experimental project cited.

4.6.3 TECHNICAL ASSESSMENT

4.6.3.1 Unit Size

The peak output identified for either the photovoltaic or wind generators associated with a residential energy storage system is 10 kW. This size would equate approximately to a 7.5 hp piston compressor - a size that is commercially available from a number of manufacturers. The tank size is directly determined by the energy storage capacity established for the application (approximately 50 kWh). The tank being procured by IREQ has been sized for that storage rating and is 5 ft. in diameter and 45 ft. long. The maximum storage pressure is 800 psig which dictated wall thicknesses of 1.5 in. for that use. The air-driven turbine for that installation had a wheel diameter of about 7 in. with an output rating of 80 kW. Since the 10 kW residence rating results in a much higher speed, its size would be smaller, making it almost insignificant when compared to the elements in the system. No data is readily available on the high speed gear reducer needed, but the power rating is such that it should be available as a designed component. A synchronous, single phase generator with a 10 kW continuous rating would be approximately 2 ft. long and 1 ft. in diameter.

4.6.3.2 Efficiency

The IREQ engineer estimated that the overall "energy conversion" efficiency of the system that is being assembled for the experiment is about 25 to 30 percent. This value is based on the useful energy available at the electrical output from the output alternator as compared to the energy developed at the windmill shaft. The efficiencies of some of the components might drop slightly with smaller sized units, but the AiResearch engineer was of the opinion that the efficiencies of the output turbine-alternator would remain about the same for the smaller unit which would be used for a residence installation.

The equivalent "energy storage system" efficiency for pneumatic storage is estimated to be on the order of 60 percent. This efficiency value assumes some turbine pre-heat using waste energy from the compression cycle. This is consistent with the underground compressed air efficiencies of 40 percent for overall energy conversion and 70 percent for the storage system itself reported in Section 4.5.

4.6.3.3 Useful Life

Although the system is relatively immature, the components used that are unique to pneumatic storage do not represent any extension of the state-of-the-art. With the exception of the steel storage tank, all of the components are smaller versions of the devices employed in the underground compressed air storage discussed in Section 4.5. Since the service life of the tank would be much longer than dynamic elements, the life of the latter would be limiting. This life was assumed to be 30 years for the experimental system.

4.6.3.4 Other Performance Characteristics

The cylindrical storage tank represents a very sizeable investment ($40,000 for the IREQ unit - admittedly a one-of-a-kind cost element) in a large, heavy (48,000 lbs) tank, with both characteristics creating acceptance problems to the average homeowner. A spherical tank (12 ft. in diameter) would weigh much less (about 15,000 lbs) but would still cause siting problems. The 1.5 in. thick walls for the cylindrical tank accounts for its large weight.

The reliability and maintainability of the equipment used for a pneumatic storage system can be estimated since the elements used have an extensive commercial application background. An unknown factor would be the effect of the well-known absence of preventive maintenance care by the average home owner.

4.6.3.5 Environmental Impact

For the home installation there are three areas of concern from an environmental point of view. These are: (1) requirements for zoning restrictions due to noise, hazards, (and aesthetics if components are outdoors), (2) localized thermal pollution from the high temperature compression discharge air, (3) the overall noise level of the reciprocating compressor and a high speed turbine.

The compressor and alternator units could be housed in an acceptable outdoor enclosure, since it is doubtful if the noise and vibration of the equipment would be acceptable in the home. The tank would probably be enclosed or placed underground to minimize its land usage and also to provide protection in the event of a tank failure. Tank burial would also provide some insulation which could improve cycle efficiency. The thermal rise could probably be controlled by using the heat of compression for domestic hot water heating and home heating or cooling. Attention would have to be given to the design of the equipment enclosure so that it would serve as a sound and vibration absorber and prevent annoyance to the homeowner and nearby residents. These items would add to the expense of installation.

4.6.3.6 Safety and Inherent Hazards

The highly pressurized (800 psi) tank forms the greatest potential safety hazard since high pressure pneumatics are very dangerous if a failure occurs. Burial of the tank and some restraining devices probably would be necessary to minimize the risk to nearby personnel. All of the high pressure lines, valves, etc., are potentially dangerous elements and would have to have safety equipment and interlocks to minimize risks to nearby people. The temperature at the compressor discharge is extremely high at this pressure ratio and adequate shields would have to be provided to protect humans and pets in the home. The high speed turbine is also a potential threat should a wheel fracture occur. A restraining enclosure would have to be provided to contain any fragments should that event transpire.

4.6.4 COSTS AND ECONOMIC CONSIDERATIONS

Since it was not possible to identify any pneumatic storage systems of the exact size range applicable to residential use, there is no data directly available on system costs. The equipment is similar in nature to but smaller in size than that used for the underground compressed air storage system discussed in Section 4.5, some of the cost data there is applicable. In Section 4.5.4, a range of power related costs, I_p, are given. Since the residential equipment is smaller, its costs would lie near or above the upper end of the range, or for estimating purposes, about $225/kW could be used. The costs of the cylindrical tank mentioned above is not far from the dollars per pound cost of smaller, ASME coded tanks which have been recently priced. Thus, this storage tank would represent $800/kWh in itself. Absolute minimum tank costs for quantity production are estimated to be in the range of 200-250 $/kWh.

A recent contract award to A.D. Little, Inc., by ERDA through Sandia Laboratories,will focus on the development of a pneumatic system based on the use of a highly efficient ($\sim$ 80%) scroll compressor-expander. Results of this study may reveal improved economics of the pneumatic system under consideration.[37a]

4.7 LEAD-ACID BATTERIES

4.7.1 GENERAL

Lead-acid storage cells are currently available in an extremely wide range of sizes and in several basic types. In addition to the common automotive type there are cells ranging in size from a fraction of an ampere hour (for powering electronic devices) to over ten thousand ampere hours (submarine propulsion and for standby emergency power systems). Because of the wide range of possible sizes, lead-acid battery systems are potential candidates at the utility, residential or intermediate application levels in conjunction with wind and photovoltaic energy conversion. For general utility system service, lead-acid or advanced lead-acid batteries are currently of interest to planners, principally for handling relatively short duration peaking loads. Considerable investigation of this possibility has recently been accomplished.[39,40] Although longer discharge times are of interest for load leveling, the use of 3-5 hour batteries has been recognized as a key to reducing costs to achieve economic viability.

4.7.2 CONCEPT DESCRIPTION AND DEVELOPMENT STATUS

Figure 4.7-1 illustrates the generic arrangement of a battery storage system. The input power for general utility system use would be supplied by off-peak power from the utility grid. With appropriate power conversion and/or conditioning, the input may be supplied by either a wind or photovoltaic energy conversion system. The power conversion provides the appropriate dc voltage level to the battery depending on its electrical configuration. The water system provides battery make-up water, and in some configurations, battery

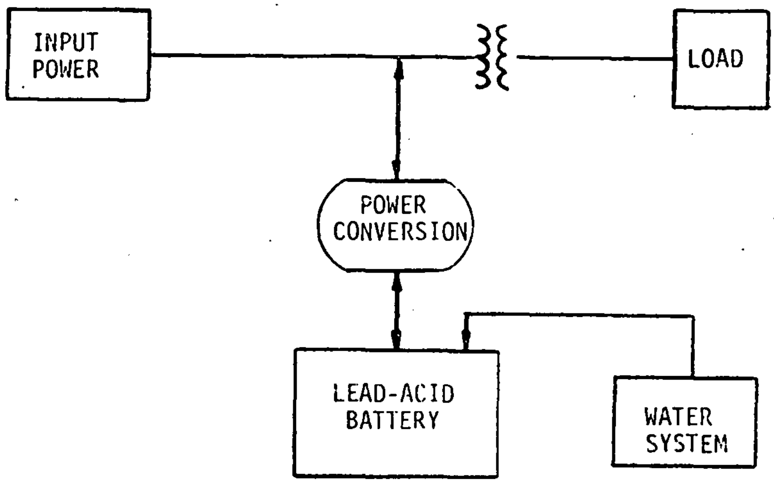

FIGURE 4.7-1. BASIC LEAD-ACID BATTERY STORAGE SYSTEM

cooling. There are additional auxiliary systems required for a large battery system, which generally include provision for the following functions: ventilation, monitoring, charge/discharge control, power bus, isolation, fusing and fault protection, ground leak path detection, acid containment, fire equipment, hydrogen detection, and stibine and arsine detection. When called upon to discharge in response to load demands, power conversion back to ac permits energy transfer at a voltage, suitably transformed, which conforms to the particular load being supported by the battery. Residential or intermediate versions of a battery system are merely smaller-scale systems in which some of the sophistication may be omitted. At the residential level, the auxiliaries would be minimal, but not unimportant functionally.

For a utility scale battery system, parallel strings of series cells would be used to provide the voltage and power levels desired. A number of arrangements are possible and the optimum sizing and voltage levels have received considerable attention.[41,42] Figure 4.7-2 illustrates the storage system-to-utility interface via an overall schematic of a peaking battery concept defined in a recent study of lead-acid battery auxiliaries.[42]

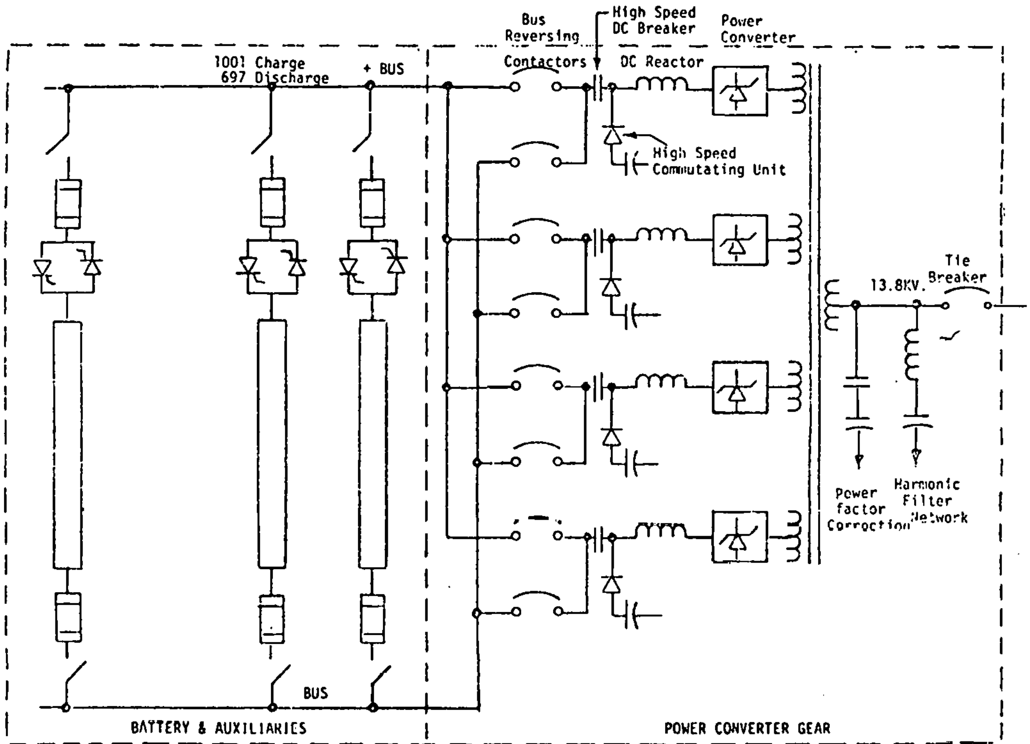

FIGURE 4.7-2. BATTERY SYSTEM ONE-LINE DIAGRAM [42]

Various alternatives for closed vs. open cells and single layer vs. tiered or stacked battery modules have also been examined. Figures 4.7-3 and 4.7-4 provide a visualization of the arrangement and handling of cells for these

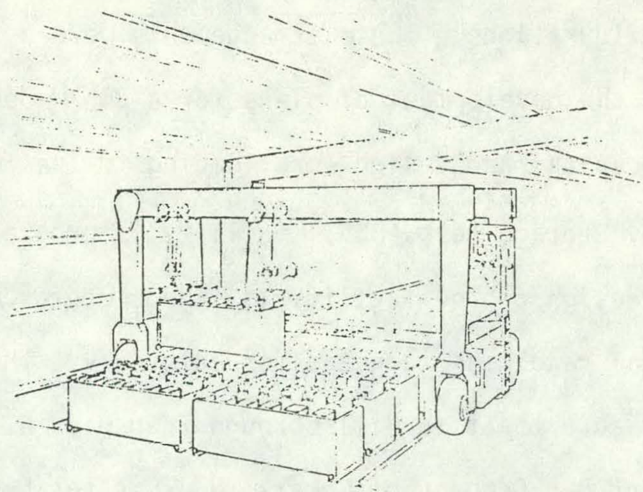

FIGURE 4.7-3. CELL HANDLING EQUIPMENT FOR A SINGLE-LAYER 20 MW BATTERY PLANT. (Bechtel[41])

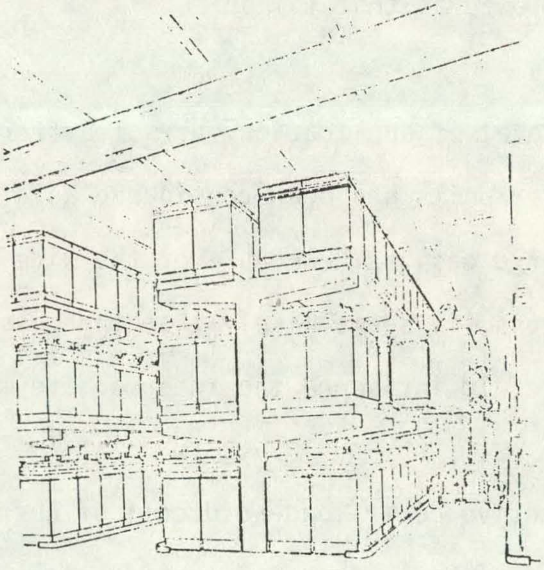

FIGURE 4.7-4. TIERED CELL CONFIGURATION FOR A 20 MW LEAD-ACID BATTERY ENERGY STORAGE DEMONSTRATION PLANT. (Bechtel[41])

two respective configurations. These arrangements were a part of a study in connection with the development of plans for a 20 MW demonstration plant.[41] The conceptual and design work leading to the implementation of a Battery Energy Storage Test (BEST) facility is progressing rapidly.[43] Final engineering design of the facility is scheduled for mid 1977, with facility operational readiness targeted for late 1979. The facility will be located on a 32 acre tract in Hillsborough Township, N.J. Public Service Electric and Gas Company of Newark, N.J. is the contractor for the design, construction and implementation of this facility. Plans for use include the eventual testing of lead-acid and various other advanced batteries. The design of the BEST facility was reviewed[44] at the February 1977 BEST Workshop II. Various major components and subsystems for BEST were also reviewed at that time.[44, 45, 46]

For the intermediate level of application, use of batteries similar to present day motive power units has been considered as a possible point of departure for specific designs. Because of the wide range of possible intermediate applications, it seems likely that the results of utility scale battery testing could influence the intermediate market also.

Figure 4.7-5 shows a motive power lead-acid cell of current, mature design. Less attention has been given to date to a residential energy storage battery specifically designed and packaged for storing significant amounts of the energy needed for daily home use. Such a battery could be built in suitable quantities very rapidly if the market incentives materialized.

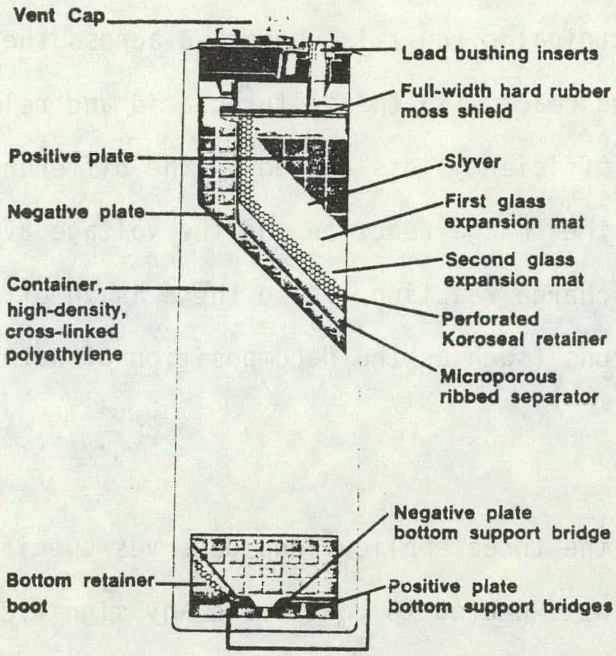

FIGURE 4.7-5. LEAD-ACID CELL

All of the present day lead-acid batteries have rather similar basic components and function in a similar fashion. Lead peroxide positive plates and spongy lead negative plates are used with a sulfuric acid electrolyte. In general, both plates have a lead-antimony alloy grid as a current collector. In recent years lead-acid cells used for standby service have substituted a lead-calcium alloy for the lead-antimony grid material and battery life was extended beyond twenty years. The lead-acid cells required for the applications covered by this study program are of a "hybrid" type which contain lead-antimony positive grid material and lead calcium negative grid material to increase cycle life.

Energy storage is accomplished by an electro-chemical process in which lead sulfate and water are converted to lead peroxide, lead, and sulfuric acid by the addition of electrical energy. The reaction is reversible so that when an external electrical circuit is connected across the cell the lead peroxide and lead react with the sulfuric acid and release electrical energy. There is an efficiency loss caused by the difference in the cell voltage required for the charge reaction and the voltage available at the terminals for the discharge reaction. Also there is an efficiency loss caused by side reactions (such as the decomposition of water) which are not reversible.

The type of user for the three applications deserves specific consideration. The homeowner cannot be expected to contribute any significant amount of operating control or maintenance, whereas, in the utility case, it is expected that at least part-time trained operating and maintenance personnel will be available. Because of the very common application of the lead-acid battery in the automobile, and the fact that a residential battery is of moderate size, it is likely that a homeowner would accept the responsibility of a lead-acid battery in his home.

4.7.3 TECHNICAL ASSESSMENT

4.7.3.1 Plant and Equipment

Lead-acid battery technology is available to support the design and fabrication of batteries which will meet the basic technical requirements for residential and intermediate applications. The main questions are more in the area of tailoring the designs and packaging for the specific use. The overriding question beyond this, of course, is cost. From a size standpoint, the complete residential battery system has been estimated to require only about 100 square feet of space within the residential structure.

Possibly, this can be reduced and/or an adjacent enclosure devised for outside use. A common 250 ampere hour battery could be used. An intermediate application battery could use about a 2500 ampere-hour cell which can be built in limited quantities with existing manufacturing facilities.

The utility application, as indicated by the previous concept description, is clearly an extension of the state-of-the-art. The manufacturers have proposed designs[40] that address the issues of repeated cycling and the need to make costs attractive. It seems probable that the benefits of this effort will be reflected back into existing technology for smaller size batteries, but this remains to be seen. There is a basis for converter design using HVAC experience,and this area is receiving attention as already indicated. Smaller scale converter equipment has achieved somewhat less efficiency and will need additional attention. There do not appear to be any fundamental barriers to achieving the energy levels desirable for the three application sizes. The battery testing program should confirm this for the utility case.

4.7.3.2 Efficiency

Battery storage efficiencies are variously reported in the general literature all the way from 60-85%. For lead-acid batteries, a voltaic efficiency of 85% and a coulombic efficiency of 95% are reasonable to expect, and would give an overall efficiency of approximately 81%.[47] If a 90% conversion is also included, the battery system efficiency becomes about 72% which is at the mean of the range reported recently for a 5 hour utility battery by several battery manufacturers.[40]

4.7.3.3 Useful Life

The cycle life of the lead-acid batteries used for motive power service (forklift trucks) exceeds 2000 cycles, and 2500 cycles is obtainable with derating of cells.

For the utility scale batteries, the cycle life is not firmly established but a consensus[40] places it at about 2000 cycles or 10 years.

4.7.3.4 Other Performance Characteristics

Lead-acid batteries have an advantage over most advanced batteries in their room temperature operation. No warm up period or cool-down periods is required, and no energy is expended in maintaining an elevated temperature. The batteries require a direct current input and, therefore, ac/dc conversion is generally required.

The lead-acid battery is considered to be one of the most reliable energy storage systems available to industry. It provides reserve power in communications, U.P.S. (Uninterruptible Power Source), emergency lighting, and security systems where a loss of power can be extremely critical. To obtain very high reliability, the lead-acid cells are generally derated for the specific application.

The primary materials used in the construction of lead-acid batteries are still available in large quantities as mineral deposits relatively easily mined throughout the U.S. and the world.[48] The cost of lead will probably not drop in the coming years, but the supply does not appear to be near exhaustion. In a similar manner, sulfuric acid base materials are available in virtually inexhaustible quantities.

4.7.3.5 Environmental Impact

For the residential application it is expected that lead-acid batteries will have no significant environmental impacts since the use of similar batteries in automobiles has not been identified as an environmental problem. Similarly, for the intermediate battery system no significant problems of atmosphere or water pollution or detrimental environmental effects have been identified. In the case of a very large utility size battery system the question of land area must be considered. However, "stacked" plant configurations under consideration could reduce this requirement to the order of 500 MWh/acre or under. Even for the large battery system, however, the use and pollution of water or other environmental problems do not appear significant provided effluents are carefully controlled.

A more significant question may be that of the handling of large quantities of lead in the manufacturing process. The increasing precautions required against contamination from process waste-water are already a burden on battery manufacturers.

The lead-acid batteries for all applications will be housed in structures which should not be objectionable from the aesthetic viewpoint. The large size of the central power station battery might possibly raise objections in some locations.

4.7.3.6 Safety and Inherent Hazards

From a safety viewpoint lead-acid batteries have an excellent record. Hydrogen gas is released in small quantities when batteries are charged, but with proper ventilation this is not a problem. Even on large battery systems, (e.g., submarines), the hydrogen is safely vented and accidents are extremely rare. Acid leakage or acid spray is a possibility but again this is controllable and serious accidents are extremely rare. The hazard to plant personnel of high voltage electrical power is probably the greatest safety problem, although precautions will be required in the utility installation to avoid undue acid mist contact and unusual concentrations of arsine, stibine or hydrogen gas.[42]

4.7.4 COSTS AND ECONOMIC CONSIDERATIONS

Detailed cost estimates for utility batteries have been made by various battery manufacturers.[39,40,41] Although there is a significant range to these estimates, the differences in costing assumptions appear to be well understood so that some consensus is possible. Power-related costs have been reported at $70/kW by several sources.[40,47] Estimates of storage-related capital costs have been brought lower during the past two years through concerted government-industry study. Approximately $55/kWh for a 5 hour battery appears to be representative of current estimates although at least one set of estimates falls well below this range.[39] It should be noted that 3, 4, and 5 hour batteries are all of interest and that their costs vary according to the specific hour rating.

Although there is a predominant effort in the area of utility battery development and cost, the residential and intermediate size batteries were also investigated on a limited basis. As a result of consultation with C&D Batteries, cost estimates of $138/kWh and $103/kWh were obtained for nominal size residential and intermediate size batteries respectively. In part at least, the higher cost of these latter sizes reflects a higher degree of installation-ready packaging and a lower production volume.

Operating and maintenance costs have been projected at about 2 mills/kWh by various sources until quite recently. Most recent investigations have now led to consistent estimates of .5 mill/kWh and even less.[40]

4.8 ADVANCED BATTERIES

4.8.1 GENERAL

Both aqueous and non-aqueous storage batteries with advanced design concepts are under intensive development in the United States at the present time.. Interest in battery development and use is very strong in European countries[49] as well as Japan[50], and in some areas may match or exceed efforts in this country. It is worth noting that the incentives overseas seem to place more of a premium on batteries for the transportation sector rather than utility load levelling although both are considered important. Principal objectives include achievement of long cycle life, improved efficiency and a dramatic reduction in present state-of-the-art battery costs. Advanced development work is also being carried out for alkaline batteries which include nickel-cadmium, silver-zinc, nickel-iron, manganese-zinc, silver-cadmium, nickel-zinc, and nickel-hydrogen. This family of batteries are primarily being pursued for ground vehicle and submarine uses where there is a premium on very high energy density at low cost.[16,51]

The aqueous-type batteries include zinc-chlorine, zinc-bromine and redox or iron-redox. Zinc-chlorine is probably the most advanced of these at the present time.

The non-aqueous advanced batteries operate at high temperatures and include lithium-iron sulfide batteries along with sodium-sulfur, sodium-antimony trichloride, and others. At the present time lithium-iron and sodium-sulfur are receiving most attention in the U.S. while sodium-sulfur is more dominant in Europe.

Five of the advanced batteries of most apparent interest were reviewed in more detail and will be briefly described here: (1) sodium-sulfur, (2) lithium-iron chloride, (3) zinc-chlorine, (4) sodium-antimony chloride, and (5) iron-redox.

4.8.2 CONCEPT DESCRIPTION AND DEVELOPMENT STATUS

The future integration of an advanced battery into utility systems in this country will, as now planned, follow the pattern being established via the "BEST" facility for testing. An intermediate demonstration plant may be implemented before any full scale system installations. The generic relationship of the batteries to the utility system is the same as for lead-acid (Figure 4.7-1) except that some form of additional temperature control equipment is required for the high temperature batteries. This additional auxiliary equipment involves a cooling system or cooling "shroud" and a heat exchanger. Air or inert gas are likely media for heat transport in the cooling system. At present, it is not clear which advanced battery or batteries might eventually dominate the market, but from the planner's viewpoint, the principal need is to meet the technical mission at or below about 50% of current state-of-the-art battery costs.

4.8.2.1 Sodium-Sulfur Battery

The generic development of high temperature materials goes back 20 years or more and for the sodium sulfur concept, ten years or more. A sodium sulfur battery is of interest for both vehicular use as well as utility load leveling.[52] The Ford Motor Company, Dow Chemical Company, General Electric Company and others in the U.S. and abroad[49,50] have been active in Na S battery research and development.

The sodium-sulfur cell is an electromechanical system which functions in a manner similar to the lead-acid battery except that the active electrode materials are liquid rather than solid. The cell must be maintained in a sealed condition. Sodium and sulfur act as the electrodes and are separated by a solid electrolyte consisting of either glass capillary tubes or a ceramic known as "beta alumina." An elevated temperature of about 300-350°C is required to keep the materials in the liquid state and at a reasonable electrical conductivity level. When electrical energy is added to the cell (charging) sodium sulfide is decomposed into sodium and sulfur. On discharge this reaction reverses and the sodium and sulfur combine and release electrical energy. Similar to the lead-acid cell there is an efficiency loss caused by the difference in charge and discharge voltage, but unlike the lead-acid cell there are no internal losses due to side reactions (coulombic efficiency is 100%). This results from the fact that the sodium and sulfur are in separate cell compartments and only sodium ions are free to move from one compartment to the other.

Figure 4.8-1 shows a prototype NaS cell and Figure 4.8-2 a cell stacking concept. Development of a sodium sulfur battery is dependent on a progressively phased program leading from cell development to a full size battery module.

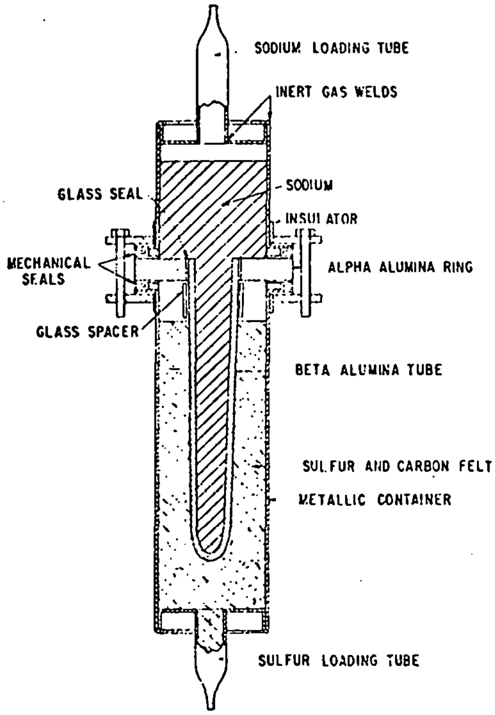

Figure 4.8-1 PROTOTYPE SODIUM-SULFUR CELL OF 16 Ah CAPACITY[53]

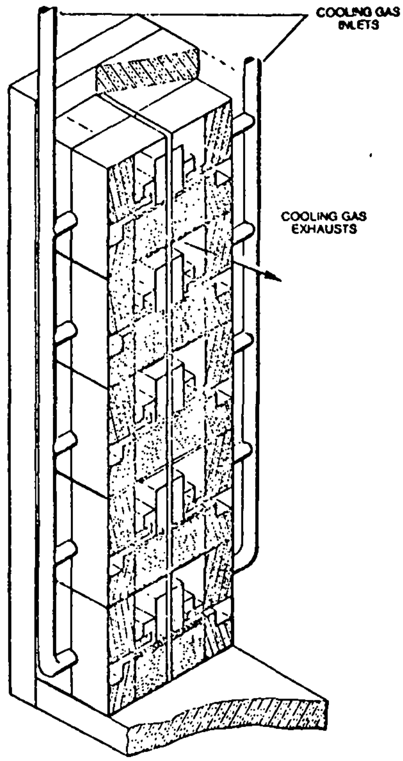

Figure 4.8-2 TWENTY CELL MODULE[53] (CONCEPT)

Siting constraints would be similar to those for lead-acid batteries except (1) since no hydrogen is evolved, the ventilation requirement is not critical; (2) since the battery must have its own temperature control system, the ambient temperature is not critical; (3) the volume of the sodium sulfur batteries plus their auxiliary equipment is expected to be less than for lead-acid batteries, the weight is much lower and batteries could be housed in multi-storied structures.

4.8.2.2 Lithium-Iron Sulfide Battery

Intensive research and development started prior to 1970 on the lithium sulfur cell. However, materials problems and loss of sulfur from the positive electrode limited the life and prevented the development of compact cells. The alternative use of lithium alloys, and metal sulfides was investigated as a result of these problems. Currently the lithium-aluminum iron sulfide cell and the lithium-silicon iron sulfide cell are being developed for use both in electric vehicles and in bulk energy storage for electric utility systems.[54]

The lithium-iron sulfide battery cell is an electrochemical system which operates like the lead-acid cell except that the electrolyte material is non-aqueous and is solid at room temperature. Therefore, the cell must operate at a temperature between 400° and 450°C, and be sealed. When electrical energy is added to the cell (charging) the lithium sulfide and iron react to produce lithium and iron sulfide. On discharge this reaction reverses and the lithium and iron sulfide react with the release of electrical energy. The lithium iron sulfide cell has a positive electrode made of iron and lithium sulfide plus additives, and a negative electrode of aluminum. The electrodes are separated with a boron nitride separator plus a zirconia cloth retainer. This cell has both voltaic and coulombic inefficiency much as a lead-acid cell. Figure 4.8-3 shows a lithium aluminum iron sulfide prismatic cell design.[55]

Siting restrictions would be similar to those for sodium-sulfur cells. Although ambient temperature is not critical since the battery must have its own temperature control system, insulation may be needed.

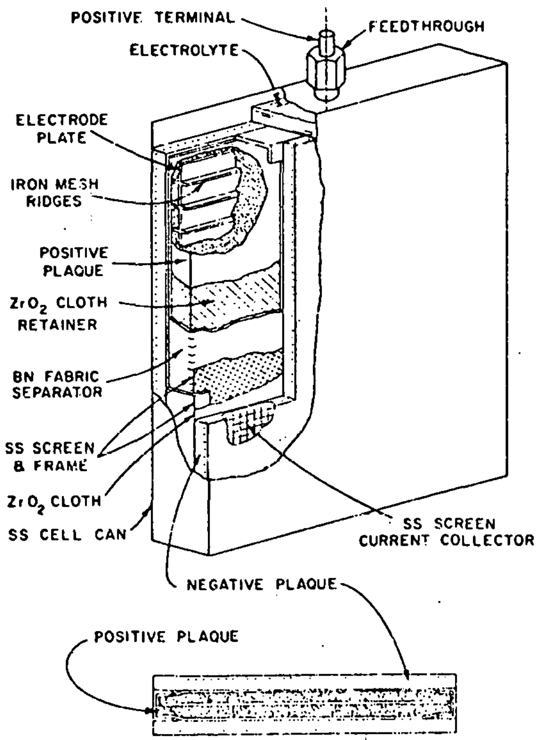

Figure 4.8-3 LITHIUM-ALUMINUM IRON SULFIDE CELL DESIGN[55]

4.8.2.3 Zinc-Chlorine Battery

Although the zinc-chlorine cell is not a new discovery,it was given little consideration as a practical energy storage device until very recently. Its advantage is that it operates at room temperature and, like several other advanced batteries, it has a high energy density in watt hours per kilogram. Its disadvantages are that the chlorine storage as a hydrate is at 4-6°C, necessitating refrigeration and that a substantial plumbing system is required to circulate the chlorine and the zinc chloride electrolyte. Gould Inc. and Energy Development Associates have been the principle U.S. researchers of this type of system.[56,57]

The zinc-chlorine battery cell is an electrochemical system except that the active materials are not stored within the cell, but in separate reservoirs or storage tanks.

The cell consists of a graphite electrode which serves as a current collector for the zinc and a porous ruthenized titanium electrode which serves as a current collector for the chlorine. The zinc chloride electrolyte and chlorine are pumped between the electrodes and they are then separated and stored. The chlorine is refrigerated to change it to a solid "hydrate" and permit low pressure storage. Figure 4.8-4 is a schematic diagram of a zinc-chlorine cell.

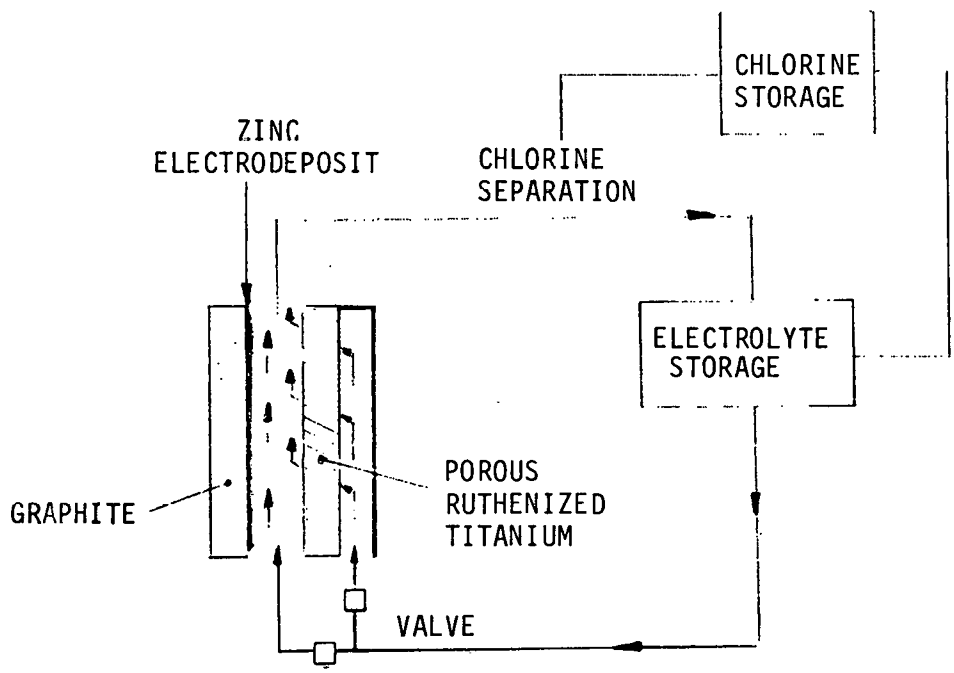

Figure 4.8-4 SCHEMATIC OF ZINC-CHLORINE CELL[56]

When the aqueous zinc chloride electrolyte is pumped through the cell and electrical energy is added,zinc is deposited on the negative electrode and chlorine is generated at the positive electrode. On discharge this reaction reverses and zinc and chlorine react to produce zinc chlorine with the release of electrical energy. This cell has both voltaic and coulombic inefficiency. For a 1 kWh battery, an average efficiency of over 74% has been reported.[57]

Comparing zinc chlorine cells with lead-acid batteries, the principle difference is the external storage of active material (chlorine). A zinc-chlorine battery system will resemble a chemical plant in appearance more than a battery as commonly recognized.

Siting restrictions may be similar to those for lead-acid batteries except that since the battery has its own temperature control system the ambient temperature is not critical. The weight and volume of a zinc chlorine cell is not yet fixed relative to an equivalent lead-acid cell.

4.8.2.4 Sodium-Antimony Chloride Battery

The sodium antimony chloride cell is one of the most recent developments and the principle investigator has been ESB Inc.[58] Its advantages are that it has a high energy density but operates at the comparatively low temperature of 200°C where corrosion and seal problems are relatively mild. A disadvantage is that the positive electrode is a fairly complicated mix of carbon and antimony dissolved in a molten salt.

The sodium antimony chloride battery cell is an electrochemical system except that the active materials are liquid rather than solid, and must operate in a temperature range of 200° to 250°C. Operation is based on sodium ion transfer through beta alumina. Flat plate and tubular cell construction have been considered, however, the tubular construction seems to be easier to fabricate. The negative electrode is liquid sodium in the one compartment, and the positive electrode is antimony dissolved in molten sodium chloride and aluminum chloride. Figure 4.8-5 is a schematic of a sodium antimony chloride cell.

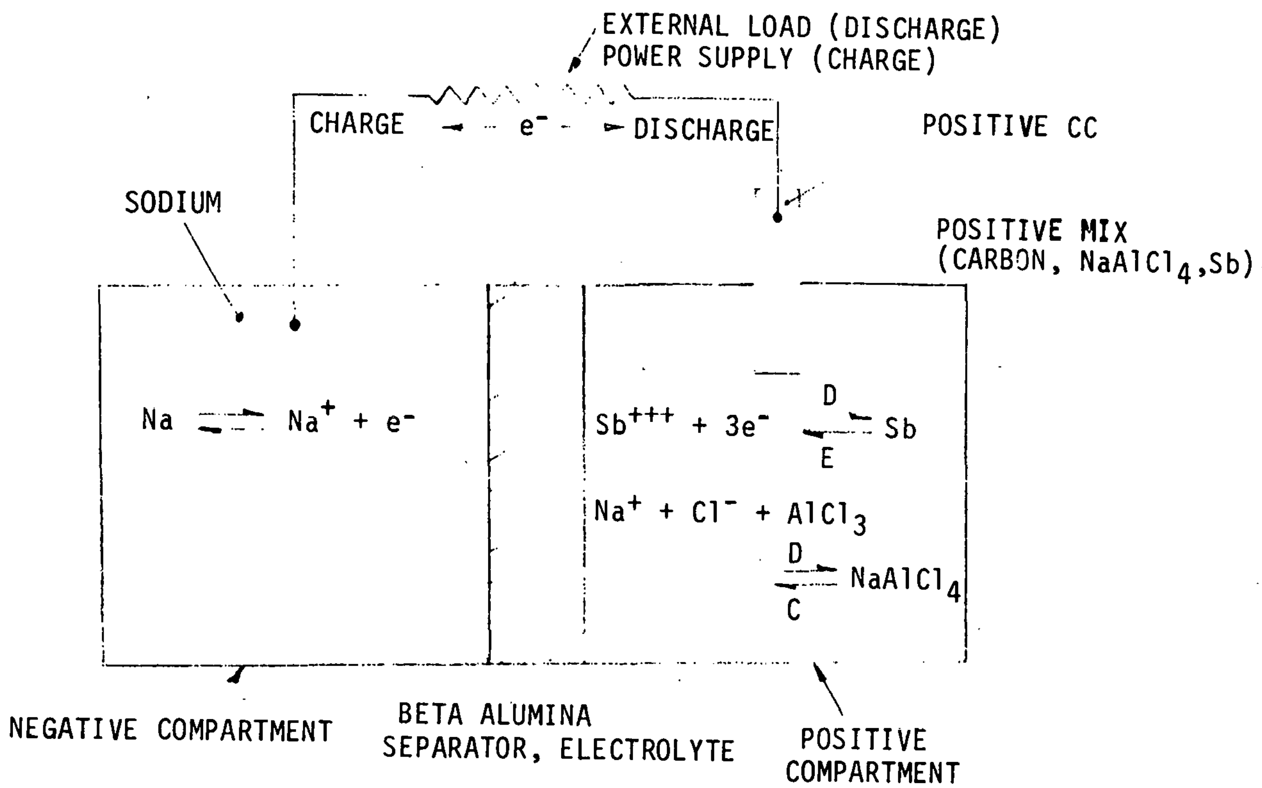

Figure 4.8-5 SCHEMATIC OF SODIUM-ANTIMONY CHLORIDE CELL [58]

The cell must be maintained in a completely sealed condition. On discharge, sodium and antimony chloride react to release electrical energy. Similar to lead-acid cells there is an efficiency loss caused by the difference in charge and discharge voltage, but unlike lead acid cells the coulombic efficiency is 100%.

The auxiliary equipment required for the high temperature operation is substantial and could impact the flexibility of the battery system.

Siting restrictions are similar to lead-acid except: (1) since no hydrogen is evolved, the ventilation is not critical, (2) since the battery must have its own temperature control system the ambient temperature is not critical, (3) the volume of the sodium-antimony chloride batteries with their auxiliary equipment is expected to be less than for lead-acid batteries. The weight is much lower and batteries could be housed in multi-storied structures.

4.8.2.5 Iron-Redox Battery

Redox batteries, in which the positive and/or negative active materials are dissolved in the electrolyte, have been proposed for large-scale energy storage.[59,60] The potential advantage of this approach (compared with more conventional battery designs) is that external reactant storage in tanks tends to result in relatively low capital costs for the storage-related part of capital costs. This characteristic might qualify redox batteries for accumulating and storing energy over longer periods than can be handled economically by conventional batteries.

The redox batteries that have been proposed use various inorganic couples in aqueous solution. Those that use dissimilar metal couples (e.g., the iron-titanium system) are likely to be handicapped by the need for frequent reconditioning of the electrolyte because of mixing. Systems that use a single metal which is stable in aqueous solution at different oxidation levels are more promising. In these, the mixing problem is minor and is significant only as a reduction in overall electrical efficiency. Iron redox appears to be one of the most suitable of the single-metal systems. The battery (Figure 4.8-6) is relatively compact (comparable in size to the lead-acid battery). However, reduced efficiency and chemical imbalance may result from possible thermodynamic instability of the charged reactants with respect to water. Heat generation is not a difficult problem in redox battery systems because they employ flowing electrolytes. The size of a redox-flow-cell system would be less than 2 percent of a comparable pumped hydro plant[60].

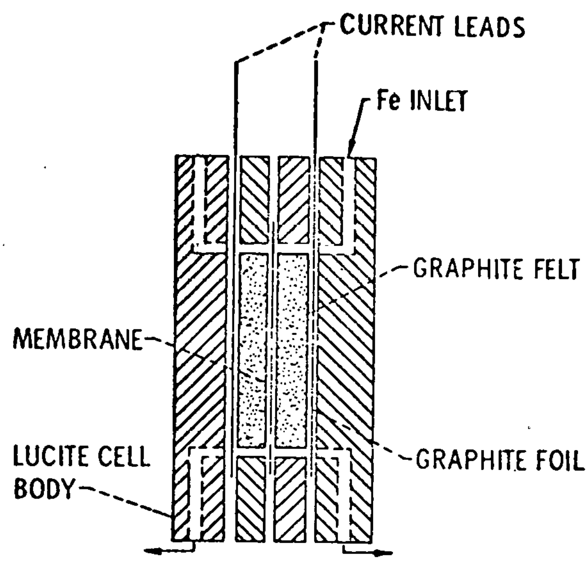

Figure 4.8-6 IRON-REDOX FLOW CELL

Because the development of redox batteries is at an early stage, research and development over another three to five years are likely to be required before the true potential of this new battery type for large-scale energy storage can be assessed. Testing performed at NASA's Lewis Research Center has shown encouraging results.

4.8.3 TECHNICAL ASSESSMENT

4.8.3.1 General

The size of sodium sulfur cells that have been built and tested has been limited to a few ampere hours, however, capabilities into the hundreds of ampere hours range are being developed. Somewhat larger cell sizes have been reported for lithium-iron sulfide cells and certain mechanical constraints may be less severe in the lithium-iron cell. Experimental zinc-chlorine cells of substantially larger capacities have been built and appear amenable to further scale-up. Size estimates exist for an iron-redox cell system of 10 MW, 60-85 MWH capacity.[60]

Overall, although there are important differences between various advanced batteries with respect to individual cell sizes and the physical and materials cost limitations encountered, development work is underway to overcome the detail problems. The outcome of this area of work is uncertain, however, it would appear that suitable unit sizes will evolve for one or more advanced batteries leaving only the requirement for design configurations which are compatible physically as well as electrically.

4.8.3.2 Efficiency

For batteries, the voltaic efficiency is the ratio of the average discharge voltage and the average charge voltage. The coulombic efficiency is the ratio of the ampere hours discharged and the ampere hours required to fully recharge the battery. The total efficiency is the product of the voltaic and coulombic efficiencies.

Table 4.8-1 lists the approximate efficiencies for various classes of advanced batteries as projected for utility applications.

TABLE 4.8-1. ADVANCED BATTERY EFFICIENCIES* - UTILITY APPLICATIONS

BATTERY	VOLTAIC EFFICIENCY, %	COULOMBIC EFFICIENCY, %	OVERALL BATTERY EFFICIENCY, %
Sodium-Sulfur	~ 85	~ 100	75 - 85 +
Lithium-Iron Sulfide	70 - 80	95 - 100	69 - 77
Zinc-Chlorine	~ 90	85 - 90	75 - 80
Sodium-Antimony Chloride [58]	70 - 80	~ 100	75 - 80 +
Iron Redox [16,60]	--	--	~ 70

* Specific design conditions may cause significant deviations from composite estimates shown. Current estimates of Ref. 43 fall within the overall range of efficiencies shown for the first four battery types. Ref. 56, 53 and 47 provided additional data.

The overall battery storage system efficiency would be somewhat lower than the battery efficiency itself. For example, an overall storage system efficiency ranging from 70-80% has been projected for sodium-sulfur.[16, 3]

It should be noted that battery efficiency in the 70-85% range (of interest here) is a function of allowable battery cost. In other words, what one is willing to pay for the battery.

4.8.3.3 Useful Life

A life of ten years or about 2500 cycles is generally projected as a minimum goal for advanced batteries. Twenty to twenty-five years life would be a major advantage for batteries as a storage medium if achieved. Some sources have projected these higher goals. At present, although considerable work will be required, there is no reason to discount the possibility of achieving extended battery life.

4.8.3.4 Other Performance Characteristics

In comparing the high temperature advanced batteries with lead-acid batteries, a principal operational difference is the necessity for warming up, maintaining temperature, and cooling down the advanced type batteries. The additional auxiliary equipment required for high temperature operation is substantial and will have some impact on the flexibility of the battery systems. Although failure modes have been identified, reliability analysis for all classes of advanced batteries cannot be undertaken at this time since no final hardware design has been made. It should be noted that a similar observation may be made for other advanced storage technologies.

4.8.3.5 Environmental Impact

The sodium-sulfur, lithium-iron sulfide and sodium-antimony chloride cells are totally sealed units and no environmental impact has been identified with normal use. It is not expected that leaks from the system would cause any environmental contamination. As already mentioned, it is expected that the utility size advanced battery systems will occupy significantly less real estate than the equivalent lead-acid battery.

The zinc-chlorine battery system resembles a chemical plant and circulates chlorine. A failure in the system could release chlorine gas and cause injury to persons in the area. The iron-redox cell system is expected to have little environmental impact.[60]

4.8.3.6 Safety and Inherent Hazards

The safety of sodium-sulfur batteries has been questioned due to the high temperature and the characteristics of sodium. Sodium reacts with oxygen in air. Moist air, if present, can lead to violent reaction. Sulfur, if involved in a direct reaction, burns with toxic fumes. Preliminary tests have shown that breaks in the ceramic or glass electrolytes do not yield explosions and great heat release, because the reaction product appears to be a solid which greatly slows down further reaction of electrode materials. Also, battery designs can include the surrounding of the cells with nitrogen gas which performs the dual function of a heat transfer medium and an inert atmosphere shielding the cells from water vapor and oxygen.

The safety of the zinc-chlorine batteries is dependent on the precautions taken to prevent leaks of chlorine and to protect personnel from leaks that might occur. This could add to the complexity of the system. Basically, similar safety precautions necessary for all of the advanced battery systems include: (1) limited access to the system, (2) high voltage precautions, and (3) precaution against leakage and high temperature/ pressure conditions where applicable.

4.8.4 COSTS AND ECONOMIC CONSIDERATIONS

Representative power-related capital costs (Ip) for advanced battery systems have been reported.[3] The storage-related capital costs (I_s) and variable operating and maintenance (O&M) costs for each class of advanced battery were also examined during the study. It was noted that for utility applications, a value of about $70/kw was representative of current estimates for power related costs for most advanced batteries. Storage related costs covered a wide range from about $15/kwh to $70/kwh, depending on the battery type. Similarly, O&M costs ranged from about $.0025 to $.0085 per kwh and not only are there exceptions to these ranges, but for O&M particularly there is, as yet, too little information to establish such costs with a high degree of certainty. A subsequent section of this report deals with the trends and projections of future system costs in the 1985 to 2000 time period.

For residential and intermediate applications, no estimates of advanced battery costs were found. For purposes of subsequent analyses, storage-related costs were assumed at the utility levels discussed above while the power related costs for the residential system were taken based on a prior residential system design study.[61]

4.9 INERTIAL STORAGE (FLYWHEEL)

4.9.1 GENERAL

The Inertial Flywheel System is a storage system which uses the kinetic energy stored in a rotating flywheel during periods of external energy availability, for use when this energy is not available.

Inertial flywheel systems have been used in various applications for many years, and these tend to be relatively unsophisticated devices mechanically, compared with the advanced or "super flywheels" now visualized for future energy storage use.

The storage size requirements for a residential system (10-70 kWh) differ from those of economical intermediate-size or utility-size systems by orders of magnitude, however the system configurations have certain similarities.[62]

4.9.2 CONCEPT DESCRIPTION AND DEVELOPMENT STATUS

The inertial flywheel energy storage system contains a number of elements: flywheel, motor and generator, power conditioners, controls and auxiliary equipment. A block diagram of a basic system is shown in Figure 4.9-1.

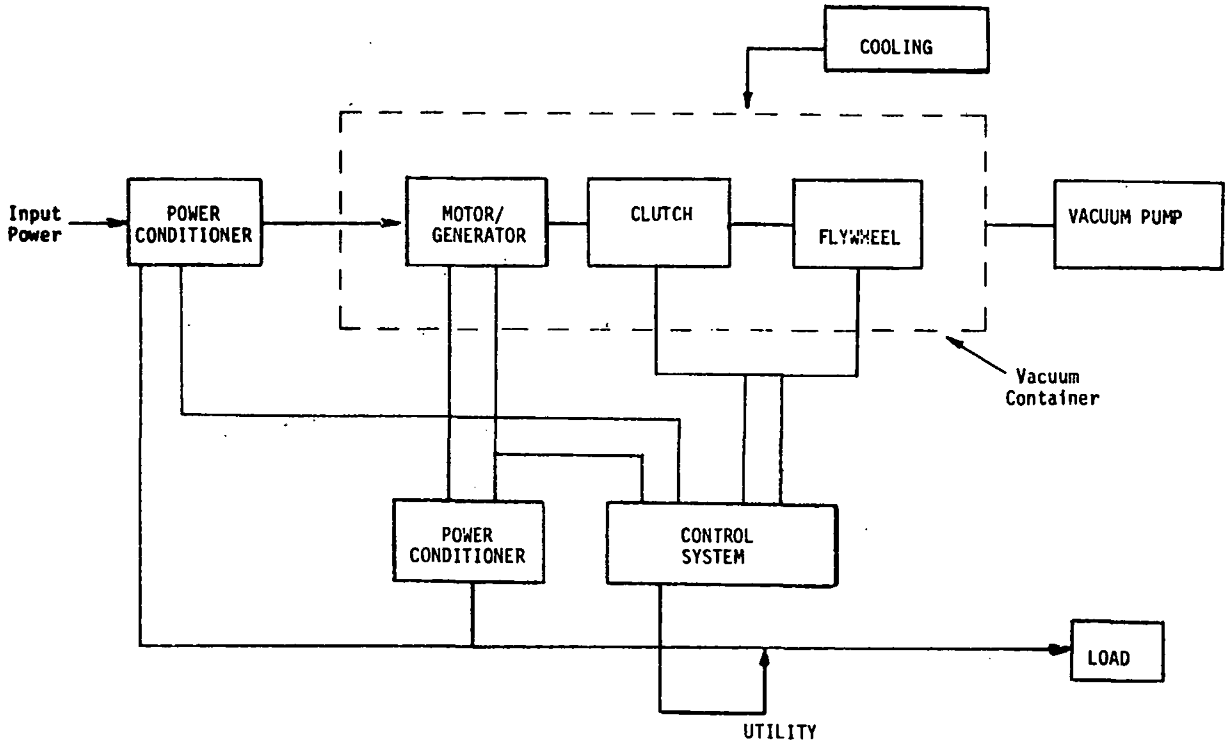

Figure 4.9-1 BASIC INERTIAL FLYWHEEL STORAGE SYSTEM

The motor is used to convert the energy to be stored from electrical to mechanical form and the generator converts the mechanical energy back into electricity. The motor and generator do not have to be two separate pieces of equipment but in the interests of cost and size, should be a single device that performs both functions. Power conditioners in the form of inverters and ac to ac converters are necessary interfaces between the electrical power input from the photovoltaic array and wind generator to the motor; and between the output power from the generator to the residential load or to the utility lines. Auxiliary equipment includes a clutch, vacuum pump, switches and fans for cooling. Depending upon the design and application, the clutch and vacuum pump may not be required. Control equipment will be needed for the electrical interfaces between the storage system, power conditioner and the electrical input and output lines. Controls will also be needed for the motor/generator and flywheel.

The basic parameters of the inertial flywheel system are governed by the number of kilowatt hours of stored energy required, the kilowatt output, and the input and output power interface characteristics of the residential, intermediate or utility systems. Other parameters that must be considered include the input and output power vs. time and the modes of operation of the system.

The selection of the various components necessitates a detailed trade-off between the operating characteristics of the components, the overall system requirements and the costs of implementing the selected approach. The critical components are the flywheel, bearings and power conditioning equipment. Of these, bearings would require the least development effort while the flywheel and power conditioning equipment will require more.

Recent tests have investigated the effects of various flywheel designs.[66] Speeds to 22,000 rpm have been achieved for wheels in the range of 1-3 hp. and plans call for increases in both speed and power ratings in future tests. To achieve high energy densities for the flywheel, multi-ring composite flywheels such as the one shown in Figure 4.9-2 are needed. High circumferential strength is needed without required radial strength in the flywheel material. Flywheel requirements are described in more detail in the next section.

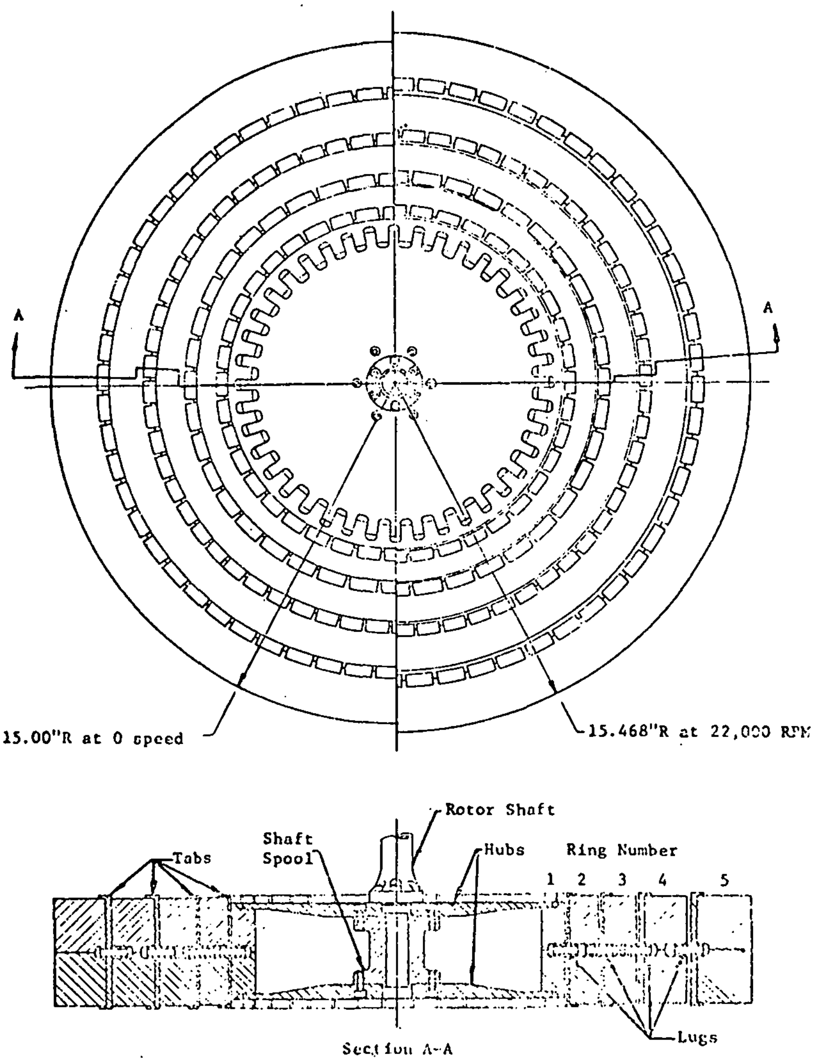

Figure 4.9-2 MARK III (FLYWHEEL) ROTOR
(BROBECK[66])

4.9.2.1 Flywheel

The fundamental criterion in addition to stored energy requirements which establishes the flywheel weight and size is the energy density (Wh/lb) which can be stored in the flywheel material. The energy density is the working stress in the material divided by the density of the material, as discussed below. The working stress must be considered from the standpoint of fatigue life since the flywheel is continuously cycled between different speeds. The energy density varies between very wide limits of roughly 1 Wh/lb to 100 Wh/lb. The lower limit is based on presently available materials such as steel and aluminum working at very conservative stress levels. These materials may be adequate for the smaller energy storage requirements (i.e., residential application). The upper limit is for advanced materials such as kevlar, glass and graphite epoxy composites. Energy densities in the range of 5 to 15 Wh/lb as a function of fatigue life for 4340 and maraging steels are within the realm of current technology. Energy density of about 10-14 Wh/lb for composite materials is current technology with up to 40 Wh/lb projected within the next five years. Energy densities of 60 to 70 Wh/lb are projected within a 7 to 10 year period.[62]

A second important parameter is the flywheel disk geometry. The disk geometry greatly influences the size, weight, fabrication and cost of the flywheel. There are a number of geometries which have been analyzed in the past.[63, 64] These include the constant stress, constant thickness, pierced and hoop shaped disks. In addition, "superflywheel" geometries have been examined including the fanned brush and circular brush which are most applicable to composite materials.

The energy stored in a flywheel is given by the familiar equation:

$$E = 1/2\, I \omega^2$$

where ω is the angular velocity of the flywheel. A useful form of this equation which defines the specific energy characteristics in terms of the flywheel parameters is:

$$\frac{E}{W} = 3.14\,(10^{-5})\ k_s\ \frac{\sigma}{\delta}$$

where E/W is the specific stored energy in Wh/lb, k_s is the shape factor, σ is the stress in psi, and δ is the density in lbs. per cubic inch.

The volumetric specific energy is given by:

$$\frac{E}{v} = 5.42\,(10^{-5})\ k_v\ \sigma$$

where E/v is the specific volumetric stored energy in Wh/ft^3, k_v is the volumetric factor for uniform density material, and v is the specific volume in ft^3/lb.

From the standpoint of weight, the constant stress disk is the most efficient. The constant stress disk is one in which the thickness varies as the radius goes from zero to infinity. This is not a practical design and is modified by not having the radius go to infinity but terminated at a finite distance. The disk weight lost by not going to an infinite radius is added back to the disk as a constant thickness rim at the outside radius. This results in a modified constant stress design with a k_s of .9 or more which is within 90% of the k_s for the theoretical constant stress.

The thickness of this modified constant stress design is still experimental. This design will be difficult to fabricate and a second modification should be made that will approximate the disk thickness with one or more straight lines. As a limit, this will have a k_s which approaches .8.

4.9.2.2 Motor-Generator

A motor is required to charge the flywheel by converting the input electrical power into mechanical power. Mechanical energy is extracted from the flywheel and converted into electrical energy by the generator. The motor and generator need not be two separate machines since a single machine acting as a motor or generator, as required, can perform both functions. The motor-generator could be either ac or dc; however, dc has a number of disadvantages. The major disadvantage is the requirement for brushes and commutators. A preferred approach entails having both the flywheel and motor-generator operating in a vacuum. However, because of the difficulties of brush wear and commutation in a vacuum, a dc motor-generator cannot be used.

An ac motor-generator is a satisfactory alternative to a dc machine. There are a number of types of ac systems that could be used; these include both synchronous and induction type machines. Synchronous systems include brushless field-excited and inductor machines; induction systems include squirrel cage and wound rotor types. An evaluation made at General Electric's Corporate Research and Development Operation indicates that the inductor-type synchronous machine offers the best match for flywheel applications.[65]

The output of the ac inductor generator is a variable voltage and variable frequency as a function of flywheel speed. Therefore, conversion equipment will be required to obtain constant voltage and constant frequency to meet the requirements of the load. Similarly, a variable frequency, constant current input is required to accelerate the motor from standstill or low speed operation. This necessitates equipment which will convert the dc power from the photovoltaic array, or the constant frequency ac power from the wind generator to variable frequency.

4.9.2.3 Clutch

A clutch placed between the motor-generator and the flywheel can be used to decouple the flywheel during an operational mode when there is no energy being added to or removed from the flywheel. This reduces bearing losses, windage loss and any core loss in the motor generator which would have to be supplied by the flywheel. The clutch would be an electro-magnetic type which would be energized only during the time that there was energy input or output from the flywheel.

4.9.2.4 Vacuum Housing

In order to have a minimum flywheel windage loss, the flywheel should operate in a vacuum. Depending upon the size and speed of the flywheel, the vacuum need not be too high, probably within the capability of a mechanical pump. Because it is much smaller than the flywheel, the motor-generator could either be located in the vacuum environment or placed external to it. Vacuum chamber operation would be preferable since this would eliminate the need for rotary seals between the flywheel and the motor-generator and also could eliminate the need for a vacuum pump entirely if a sealed unit were used.

The housing would be designed for mounting the flywheel, motor-generator and clutch and to withstand a pressure differential of 14.7 psi. It is anticipated that the container will be placed in a pit-type recess so that in event of a failure of the flywheel, all pieces would be contained within the recessed area. The container wall thickness will be designed based on the requirements as a housing for vacuum operation rather than as a device for flywheel containment in the event of failure. For example, if it were desired that the housing alone be the containment device, the resulting housing would have to be almost 3 inches thick for the residential application case.

4.9.2.5 Bearings

From the standpoint of safety and assembly, the flywheel should be mounted with its shaft vertical. This, however, may present a bearing problem since the lower bearing must support the entire weight of the flywheel, motor-generator and clutch, with the flywheel contributing most of the weight. Two types of bearings are applicable: anti-friction and hydrostatic. Magnetic bearings presently are capable of supporting several hundred pounds and could be considered for future application. Anti-friction type bearings are quite desirable from the standpoint of simplicity and performance. Their main disadvantage is limited thrust load capability and higher starting torque requirements than hydrostatic bearings. Hydrostatic bearings also require extensive auxiliary equipment for oil flow.

Anti-friction bearings are commercially available, with capabilities for carrying thrust loads somewhat in excess of 150,000 lbs. Flywheels having substantially greater weight could be made by having two flywheels each supported by a set of bearings and with their shafts attached through a coupling. An alternative to this would be having the shaft horizontal. A horizontal shaft installation would have a more difficult containment problem than a vertical shaft configuration. It does, however, permit the sharing of the load between two bearings rather than having only one bearings to take the entire thrust load.

The hydrostatic bearing has sufficient thrust load carrying capacity; however, it does necessitate auxiliary equipment in the form of pumps, valves and manifolds. In addition to having high thrust load capabilities, the hydrostatic bearing has lower starting torque characteristics than anti-friction type bearings.

4.9.2.6 Cooling

External cooling will have to be supplied to remove the heat produced by the losses in the motor-generator, clutch and bearings. If the motor-generator and clutch are mounted in the vacuum housing, the heat would first have to pass through the housing walls via a solid thermal conduction path. The heat would then be removed from the walls by external air flow. The volume of air required for cooling will not be excessive, being of the same order of magnitude as required for cooling the motor-generator alone. Some additional cooling capacity might be necessary, however, to offset the temperature gradients in the thermally conducting paths.

4.9.2.7 Siting

Residential flywheel storage concepts can be implemented in a nominal area of 100 square feet or less using existing or modified areas now common to residential construction of basements and attached garages.

For utility-size flywheel systems, underground and/or foundation vaults might require in excess of one acre of land,[3] primarily to house the flywheels themselves. An access road and utility connection right-of-way would likely add only about 15% to the basic site area requirement.

4.9.3 TECHNICAL ASSESSMENT

4.9.3.1 Unit Size

The nominal capacity of a residential size flywheel storage system is in the range of 20 to 30 kWh. Nominal intermediate-size storage capacities ranging from 10 to 40 MWh have been reported.[62] Minimum economical utility size flywheel storage systems ranging from 10 to 50 MWh are recommended,[3] although flywheel utility storage requirements may exceed 200 MWh.[62] It is believed that the single plant utility storage use will be an order of magnitude larger than this figure, if storage technology matures satisfactorily.

4.9.3.2 Efficiency

The estimated efficiencies of the flywheel storage system fall in a range

range of about 70-85%. The near-term efficiency is expected to be about 75%.[3,16,62] Efficiency is, however, heavily dependent on duty cycle and can be very high for short cycles, but very low for long storage durations.

4.9.3.3 Useful Life

The probable useful life for residential flywheel energy storage systems has been estimated at 20 years. A useful life of 20-25 years has been projected by a recent study[3], while another recent study[62] gives a range of 10-30 years covering both intermediate and utility applications.

4.9.3.4 Other Performance Characteristics

Flywheel storage systems have a high expected reliability, obtainable by conservative design, and are flexible to the extent that time variable inputs and loads may be accepted. Compatibility with a full range of power generation applications is good since input and output energy in electrical form is acceptable, and the inertial system can be sized to meet input and output characteristics. For a residential size system, cooling air is required for the electrical machinery. Water cooling may result in a better design for the larger application sizes.

4.9.3.5 Environmental Impact

There is no identifiable impact on the environment for any of the residential flywheel storage concepts employed in normal service, although noise is a design consideration.

For the utility size system, noise, cooling effluents and land requirements are the only items of environmental concern. The noise from this system will be equivalent to that of several large motors; however, sound-deadening baffles can be placed in exhaust hoods to meet sound ordinances. Land area requirements may be minimized by locating the facility along or within existing right-of-ways or utility plant areas.

4.9.3.6 Safety and Inherent Hazards

In the event of system failure, the main safety concern is the damage or injury caused by wheel disintegration or escape. For all application sizes, the flywheel must be mounted in a containment device for safety. The containment device would be preferably located below ground but an above-ground location may be acceptable. Limited access to the associated electrical equipment is also essential.

4.9.4 COSTS AND ECONOMIC CONSIDERATIONS

Representative power - related capital costs for flywheel storage range from 65-90 $/kW[3, 7]. Storage related costs have been estimated at 100-300 $/kWh. A variable operation and maintenance cost of 5.3 mills/kWh was recommended for use in technology comparisons.[3] For a residential system using existing technology, storage related costs were estimated at 250 $/kwh or above.[67]

4.10 HYDROGEN GENERATION AND STORAGE

4.10.1 GENERAL

Various methods are available for the generation of hydrogen on a reasonably large scale. These include the following:

1. Reactions with carbonaceous fuels
2. Electrolysis of water
3. Closed cycle thermochemical water splitting
4. Solar and biological hydrogen generation

Of these, electrolysis of water is the most widely recommended for consideration as a straightforward energy storage approach. Electrolysis avoids the direct use of a fossil fuel as a re-agent.

The use of hydrogen for energy storage as described in this study basically involves three major steps.

1. Generation of hydrogen gas using a solid polymer electrolyte electrolysis unit, powered by a photovoltaic array or a wind turbine.
2. Storage of hydrogen in tanks as a compressed gas.
3. Use of stored hydrogen with a fuel cell system to generate electricity when needed.

These process steps are highly adaptable to the characteristics and timing of energy available from both wind and photovoltaic sources. It is possible to size the electrolysis unit, the hydrogen storage tanks and the fuel cells individually to accommodate significant variations in input vs. load demands.

4.10.2 CONCEPT DESCRIPTION AND DEVELOPMENT STATUS

The use of hydrogen as an energy storage means involves consideration of the functions of gas generation, retention and finally retrieval of the gas from storage and its conversion back into electrical energy. The electrolysis of water for evolution of both hydrogen and oxygen and the recombination of these two elements back into water in fuel cells (to generate electricity) uses essentially the same electrochemical technology. This discipline has been significantly advanced in recent years through developments occurring in the aerospace industry.

A summary report[68] on the application of hydrogen energy storage was prepared by the General Electric - Direct Energy Conversion Programs Operation. This department has had responsibility for the fuel cells used on the Gemini and Biosatellite space programs, and more recently has been involved in the conceptual design of a large scale electrolysis plant. The various subsystems required for a complete hydrogen generation and storage system are discussed in this section based on the above report and various other current sources of information.

Figure 4.10-1 identifies the significant components of a hydrogen energy storage system configured with some of the more important auxiliary equipment which would be required.

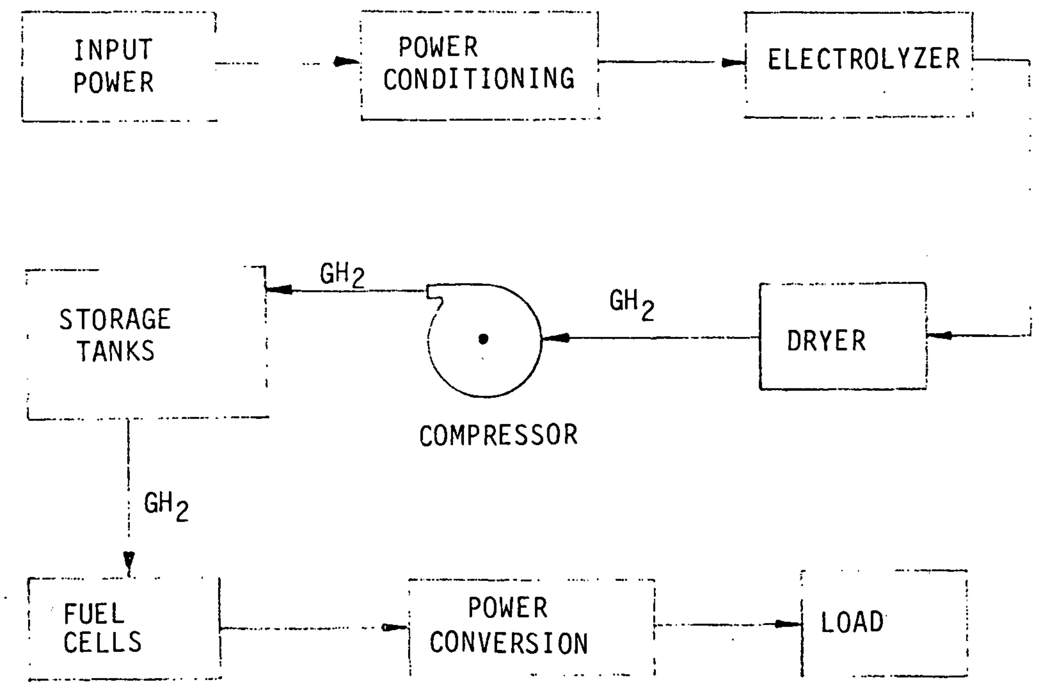

Figure 4.10-1 BLOCK DIAGRAM FOR HYDROGEN ENERGY STORAGE SYSTEM

4.10.2.1 Gas Generation

A solid polymer electrolyte system has frequently been identified as a promising process for the electrolysis of water into hydrogen and oxygen. It offers demonstrated small scale performance and the probability of achieving significant cost reductions by 1985. A design study for a large scale module (26 MWe) of such a system was accomplished under the direction of Brookhaven National Laboratory.[69] It is noted in this report that an alternative alkaline water electrolysis system has been conceptually designed by Teledyne Isotopes, Inc.

but pertinent data for this system was not available. Both the above referenced study as well as the recent study by Public Service Electric and Gas Company[3] mention electrolysis of water as the only practical way of generating hydrogen.

4.10.2.2 Hydrogen Storage

Compressed gas storage is currently considered to be the most effective means of storing the hydrogen in such a system[68]. The PSE&G report[3] notes that the considerable amount of experience with this technique makes it the recommended method of storage. Selection of storage vessel pressure would be a system design trade-off. Metal hydride systems are an attractive option and are the subject of several design studies, but their immaturity presents difficulties in making meaningful projections. Liquid storage of hydrogen on a large scale is possible but entails extensive facilities to maintain the necessary low temperature.

4.10.2.3 Power Generation

A solid polymer electrolyte fuel cell is preferred as the power generator, based on demonstrated performance and continued cost reduction in aerospace applications which are translatable into designs for industrial use. In the PSE&G report, fuel cells were considered to be good candidates for converting hydrogen into electrical energy because of minimal environmental impact and efficiencies above those of combustion engines. Direct use of hydrogen as a primary combustion engine fuel for power generation would be the major alternative at the present time.

4.10.2.4 Siting

Land area requirements were reported[3] for complete hydrogen storage systems of 50 MW, 500 MWh and 200 MW, 2000 MWh. This includes the electrolyzer, demineralization plant and oxygen storage. The land areas required are approximately 19 and 28 acres, respectively.

4.10.3 TECHNICAL ASSESSMENT

4.10.3.1 Plant Size

PSE&G[3] recommends an economic plant size for hydrogen storage ranging from 20 to 50 MW. Modular sizing of the electrolyzer and fuel cell units is reported to have beneficial effects on cost, and therefore, such modules would be used to form the larger capacity systems required for utility installations. This finding is in concert with information supplied by GE-DECP.[68]

4.10.3.2 Efficiency

Unfortunately, the overall efficiency of a hydrogen system is relatively low compared with many other forms of storage. This results from the low efficiency (~50%) of the fuel cell unit and the cascading effect of the efficiencies of the other in-line equipment. Notwithstanding this lower efficiency, the other advantages of H_2 are significant and may eventually outweigh this disadvantage. A hydrogen storage efficiency range of 40 to 50% for complete systems is recommended in economic comparison studies.[3]

4.10.3.3 Useful Life

PSE&G reports that an expected life range of 10 to 25 years is possible for hydrogen storage systems.[3]

4.10.3.4 Other Performance Characteristics and Operational Requirements

The hydrogen plant as presently visualized will have the ability to accept a varying power input without difficulty. A reduction in input power will only cause less hydrogen to be generated until the power for a higher production rate is again available. On the output side, the fuel cell output may be adjusted (within the range of its rating) to accommodate different demand levels.

The system operation requires a dc input which may introduce an additional power conversion step (ac-dc). Since the output is also electrical, it may be conveniently interconnected to a utility bus, making the system convenient and compatible.

The storage system must be maintained in a secure fashion to protect it from acts of vandalism or unintentional damage. The security problem differs little from that of many comparable installations with the possible exception of the degree of the flammability and explosion hazard of the hydrogen itself.

The compressed gas storage requirements can be met by use of standardized storage vessels in any quantity desired.

4.10.3.5 <u>Environmental Impact</u>

This is an area of major advantage with respect to hydrogen since the latter is non-polluting and will not permanently upset any natural balances should a quantity of the stored gas be released to the environment. A hydrogen storage plant should not pose any threat to the environment due to its other functional characteristics.

4.10.3.6 Safety and Inherent Hazards

The handling of hydrogen requires care in order to avoid explosion and fire hazards. The prospects of avoiding such hazards are good, based on known techniques now in use.

A hydrogen storage plant would require observance of operating and safety practices which are or could be reflected in zoning restrictions. It is not considered likely that such regulations would impose undue restraints beyond those that would be necessitated by voluntary safety practices on the part of the electric utility companies.

4.10.4 COSTS AND ECONOMIC CONSIDERATIONS

Costs for hydrogen storage systems generally are projected with the power-related costs being very dominant. In total $/kW, estimates range from about $400/kW to $1200/kW.[3,68] Storage-related costs are at $15/kWh or less. The low end of the above range essentially reflects learning out to year 2000 or beyond and/or unequal charge-discharge times.

4.11 SUPERCONDUCTING MAGNETIC ENERGY STORAGE

4.11.1 GENERAL

A superconducting magnetic energy storage system retains electrical energy in the magnetic field produced by a circulating dc current in the winding of a magnet. Because the energy is stored directly as electromagnetic energy, losses due to conversion of mechanical, thermal, or chemical energy to electrical energy are avoided. Energy losses do occur, however, with ac/dc conversion in addition to losses from refrigeration power required for inductor supercooling.

The application of superconducting magnetic energy to power systems is in a very early stage of development. The proposed use of a superconducting inductor for energy storage makes use of the principle that energy can theoretically be stored in an inductor of zero resistance (via supercooling) for an infinite amount of time. The superconducting magnet would be charged from off-peak or other energy sources with stored energy discharged to the power system during peak load periods.

4.11.2 CONCEPT, DESCRIPTION AND DEVELOPMENT STATUS

A "pumped" magnetic storage system connected to a three-phase line would consist of a large superconducting coil, a helium refrigerator and dewar system to keep the temperature well below the critical temperature for the superconductor, and an ac/dc converter. Referring to Figure 4.11-1, the storage inductance to be "charged" is the only load on the rectifier inverter.

The voltage E is given by an equation of the form:

$$E = E_{d0} \cos\alpha - IX = L \frac{dI}{dt}$$

E_{d0} is the voltage across the bridge when the current I is equal to zero and X is the commutating reactance. For a given set of constants, the delay angle α (which can be varied from 0 to 180 degrees ideally) is the key to the control of rate of charge, including both positive and negative, the latter corresponding to discharging the inductance L. This provides inherently continuous control of the reversible process throughout both the charge and discharge portions of the cycle. For example if L is 3440 henries and E is held at 8000 volts for 4.3×10^4 seconds or 12 hours, then 4800 MWh can be stored at 10^5 amps at an average rate of 400 MW. The thyristor firing angles can be varied so that zero voltage is impressed across the storage inductor. Thus, at full charge the storage current which flows in the inductor line can be held constant. Alternatively, the inductor could be shorted with an internal superconducting switch and disconnected from the system when fully charged.

Energy stored in the superconducting magnet is returnable to the ac system under smooth and continuous control. Distortion to the voltage waveform of the ac system would result, as is well known. Converter systems with variable firing angles such as are implied here are essentially no different from those used in modern high voltage direct current (HVDC) power transmission. Appropriately designed filters must be used to reduce harmonics to acceptable levels compatible with quality power standards.

The system losses encountered are those in the conventional ac system, in the converter bridge and the refrigeration required to balance electrical, magnetic, mechanical and thermal losses in the cryogenic enclosure. Loss estimates indicate that, in total, they could be less than 1 kW for each 2 kW recovered.

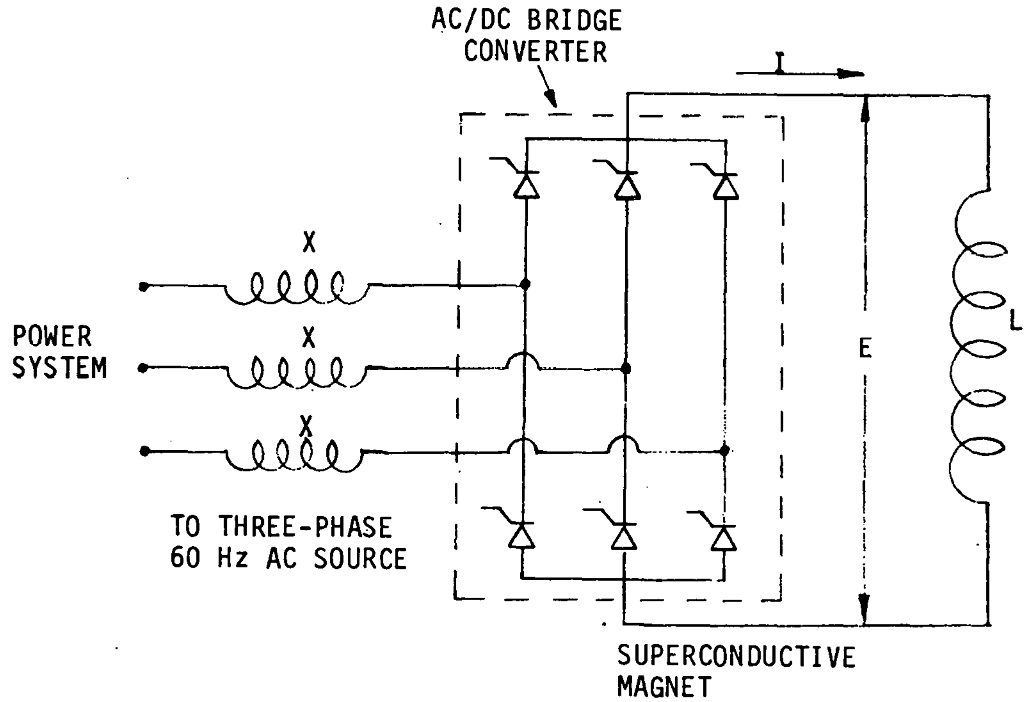

FIGURE 4.11-1. BASIC MAGNETIC STORAGE CONCEPT

Most of the present effort on superconducting systems for energy storage is being carried out at Los Alamos Scientific Laboratory[70] and the University of Wisconsin,[71,72] concentrating on small-scale work using current technology to aid conceptual development.

Two French groups[73,74] have also experimented with magnetic energy storage. Their work has centered around the technical feasibility of various coil configurations, including studies of mechanical and thermal stresses, possible shapes and methods of construction, and the coupling of energy into and out of the coil.

Land area requirements for a superconducting magnetic energy storage system could be substantial due to the uncertainty concerning the extent of magnetic field effects. Magnetic storage has some requirements similar to those for pumped hydro facilities; e.g. both require a sizable area and solid natural foundation strata to provide the containment strength required by the storage "reservoir".

4.11.3 TECHNICAL ASSESSMENT

Since superconducting magnetic energy storage technology is in a very early stage of development, its characteristics are not yet sufficiently well defined for an adequate assessment. The key characteristics pertaining to efficiency and useful life have been examined and brief discussions of these plus environmental impact, safety, and estimated costs follow.

4.11.3.1 Plant Size

Although storage capacities in the order of 1000 MWh have been mentioned[3], the consensus of all the studies to date seems to clearly indicate an economic plant size in excess of 10,000 MWh. The specialized siting requirements and the critical nature of the supercooling of the inductor would seem to substantiate the advisability of a large scale installation in order to justify the cost and operational attention required.

4.11.3.2 Efficiency

Efficiencies expected for magnetic storage systems are very high because of the direct storage of electrical energy. Ranges for efficiency have been reported from 70-85%[3] and 80-90%.[16]

4.11.3.3 Useful Life

A life of 20-30 years has been estimated[3] and considering the nature of the installation and type of equipment, there is no apparent reason why a thirty year life could not be attained.

4.11.3.4 Environmental Impact

A superconducting magnetic energy storage station consists of both above-ground and sub-surface installations. Due to the tremendous weight of the magnet, sites must be of suitable bedrock composition, such as granites, dolomites, sandstones, limestones, etc. The major environmental impacts would be on land requirements due to the magnetic field and above-ground placement of cryogen storage tanks.[3]

4.11.3.5 Safety and Inherent Hazards

Because of projected currents in excess of 100,000 amps and the huge quantity of energy stored in the magnetic field, high reliability is required to meet safety requirements.

Biological effects of magnetic field exposure to humans and animals are unknown at this time and safe limits have not yet been established. Results of present small scale development work should be expected to provide data on the magnitude of this problem.

4.11.4 COSTS AND ECONOMIC CONSIDERATIONS

At this stage of conceptual development of magnetic storage systems, cost estimates should not be given as much credibility as for the more near term technologies.

Power related costs of \$50/kW have been reported[3,16] along with storage cost components from 30-\$140/kWh[3] and 35-\$200/kWh.[16] The lower limit of these ranges is acknowledged to have inadequate supporting detail and could be very optimistic. Little basis exists for establishing operating and maintenance costs other than to assume that they will be in the order of those for conventional steam plant operation.

SECTION 5

RELATIVE MERIT OF STORAGE ALTERNATIVES

Following a general review and assessment of candidate storage technologies and current implementation concepts, these were evaluated on a broad basis to determine their attractiveness for use with wind and photovoltaic energy conversion systems. This evaluation included three categories:

1. Effects of Key Concept Characteristics.
2. Specific Applicability to Wind/Photovoltaic Systems.
3. Relative System Costs

The immediate objective was not to select a "best" concept but to provide a preliminary screening and to select systems for further evaluation.

5.1 EFFECTS OF KEY CHARACTERISTICS

An extensive list of energy storage evaluation criteria was examined during the early part of the study and subsequently narrowed down to major criteria - those that could serve as primary discriminators for overall decisions on use of a storage technology in a given application. Table 5.1-1 presents these major criteria. The application of these criteria are discussed with regard to the suitability screening of storage concepts for further evaluation. System costs are discussed in Section 5.3, and the subsequent analysis of the benefits from use of storage systems are detailed in Volumes II and III. Results of applying the major non-economic criteria to each of the eleven storage concepts at the utility, residential, and intermediate application levels are shown in Table 5.1-2.

TABLE 5.1-1. MAJOR STORAGE CONCEPT EVALUATION CRITERIA

Economic Viability
- System Cost
- Economic Benefits
Technical Suitability
- Storage Efficiency
- Inherent Hazards
- Materials and Technology Availability
- Reliability and Maintainability
- Plant Size
Environmental Impact

TABLE 5.1-2. KEY CHARACTERISTICS AFFECTING USE OF ENERGY STORAGE CONCEPTS WITH WIND AND PHOTOVOLTAIC SYSTEMS

▨ CONCEPT ELIMINATOR

? QUESTIONABLE

P PACING ITEM

STORAGE CONCEPT	APPLICATION*	STORAGE EFFICIENCY	INHERENT HAZARDS	TECHNOLOGY AVAILABILITY	RELIABILITY AND MAINTAINABILITY	PLANT SIZE	ENVIRONMENTAL IMPACT
ABOVE GROUND PUMPED HYDRO	U						
	R					▨	
	I					?	
UNDERGROUND PUMPED HYDRO	U						
	R					▨	
	I					?	
THERMAL -OIL	U	▨					
	R	▨				▨	
	I	▨					
THERMAL - STEAM	U	▨					
	R	▨				▨	
	I	▨					
UNDERGROUND COMPRESSED AIR	U						
	R					▨	
	I					?	
PNEUMATIC STORAGE	U					▨	
	R						
	I					▨	
ADVANCED BATTERIES	U			P			
	R			P			
	I			F			
LEAD-ACID BATTERIES	U						
	R						
	I						
INERTIAL STORAGE	U			P			
	R			P			
	I			P			
HYDROGEN STORAGE	U	?					
	R		▨				
	I	?					
SUPERCONDUCTING MAGNETS	U			▨			
	R			▨		▨	
	I			▨		▨	

U-UTILITY
R-RESIDENTIAL
I-INTERMEDIATE

5.1.1 DISCUSSION OF SCREENING RESULTS

5.1.1.1 Pumped Hydro

Both hydro concepts were eliminated from further study in the residential application due to the very large plant size requirements of present concepts and equipment. In addition, hydro is of questionable applicability for intermediate applications due again to the minimum economic plant size and also the specific land requirements.

5.1.1.2 Thermal Storage (Oil/Steam)

Thermal storage options considered included energy transformed to sensible heat in both oil and saturated water form. Current concepts use these methods as an auxiliary process in a conventional steam-turbine plant cycle. Although the mechanics are slightly different, the end product in such concepts is the use of stored heat energy to regulate turbine flow-through and to pre-heat boiler feedwater. In order to use the output of a wind or photovoltaic energy conversion system to contribute to this process, the basic electrical output of such units would have to be converted to heat (an energy-degrading process) and transferred to a suitable storage medium. The storage medium would in turn be subject to continuing thermal losses over the time period of the energy storage. Although there are ways of making an electric to thermal conversion (i.e., resistance heating or electric steam generators), the idea of converting a highly usable form of energy such as electricity into a thermal form and then back again is not attractive because of the efficiency losses involved in the reconversion to electricity.

For the utility application, the thermal storage degradation effect would result in a greatly reduced conventional fuel displacement by the storage output, with a correspondingly severe economic penalty. Table 5.1-3 shows typical heat rates, or fuel requirements, for utility generation equipment.

TABLE 5.1-3. TYPICAL HEAT RATES FOR UTILITY GENERATION EQUIPMENT

TYPE UNIT	UNIT RATING (MW)	NET STATION HEAT RATE (BTU/kWh)
Nuclear	1000	10,000
Fossil (coal)	1000	9,270
Fossil (oil)	1000	9,370
Fossil (gas)	600	9,800
Peaking Steam (oil)	500	9,800
Peaking Steam (gas)	500	10,300
STAG	400	8,070
R/C G/T	75	9,900
S/C G/T	75	11,280

Based on the data of Table 5.1-3 the thermal storage penalty may be explained as follows: Assume a kWh of electricity charges a 100% efficient storage system. If the same one kWh is discharged from the storage system as electricity, it will displace anywhere from 8000 to 11,000 BTU's of fuel, as shown in the table. If, on the other hand, the storage system degrades the same kWh into its heat equivalent of 3413 BTU, the latter value becomes the maximum fuel displacement potential. The effective performance of the system is thus reduced to 30 to 40 percent of the value achievable by an electrical output storage system.

The residential and intermediate applications encounter similar economic drawbacks to use of thermal-oil and thermal-steam storage with a wind or photovoltaic system. A kWh of electricity from storage currently has a typical value of from 2 to 5 cents, depending on the user, the rate structure, etc. Converted to 3413 BTU's of heat, and assuming fossil fuel at $3 per million BTU, the value of this same kWh would be lowered to about 1 cent. Thus, the economics of the thermal storage system must be analyzed with an output "worth" considerably less than the output from an electrical storage system such as batteries. This would reduce the allowable system cost, making viable only very inexpensive storage systems or existing thermal-to-thermal systems such as hot water tanks.

Thermal energy storage systems are most cost effective when used with a thermal charging source. This thermal charging may be accomplished with solar thermal energy systems or alternatively, with waste heat from another process. Current concepts for use of extracted or exhaust steam in a utility cycle to conserve heat for feedwater pre-heat or to provide added turbine steam flow-through follow this general pattern. In their own right, such methods appear to have merit for such use. As can be seen from the preceding discussion, however, the introduction of an electric to thermal conversion for wind and photovoltaic energy would be unattractive. Thermal-oil and thermal-steam systems were therefore eliminated from further consideration for dedicated use with wind and photovoltaic energy conversion.

5.1.1.3 Underground Compressed Air

Underground compressed air systems are inherently too large for the residential application and questionable for the intermediate. Pneumatic storage, on the other hand, is small in scale and thus only the residential application was considered.

5.1.1.4 Battery And Inertial Systems

Although neither advanced batteries nor high-density inertial (flywheel) storage can be classified as immediately available technology, the extensive R&D work now being done and the strong interest in these energy storage concepts make them continuing candidates for all levels of application.

5.1.1.5 Hydrogen Systems

Hydrogen generation and storage for the residential application was eliminated due to the need for technology adaptation at the residential use level and the inherent hazard potential which poses psychological barriers.

5.1.1.6 Superconducting Magnets

Energy storage in superconducting magnets was eliminated for all three applications with wind and photovoltaics due to the immaturity of the technology.

5.1.1.7 Concepts For Further Evaluation

Based on the initial examination of the effects of these key concept-related characteristics, the number of storage concepts for further investigation was reduced to seven for the utility and intermediate applications and four for the residential application. These are listed in Table 5.1-4.

TABLE 5.1-4. REMAINING CONCEPTS AFTER KEY CHARACTERISTICS SCREENING

UTILITY AND INTERMEDIATE APPLICATIONS	RESIDENTIAL APPLICATIONS
Above-ground Pumped Hydro	Pneumatic
Underground Pumped Hydro	Lead-Acid Batteries
Underground Compressed Air	Advanced Batteries
Lead-Acid Batteries	Inertial
Advanced Batteries	
Inertial	
Hydrogen	

5.2 APPLICABILITY OF SCREENED CONCEPTS TO PHOTOVOLTAIC AND WIND ENERGY CONVERSION SYSTEMS

The remaining storage concepts as given in Table 5.1-4 were examined further from the standpoint of compatibility for direct interconnection with wind and/or photovoltaic systems. The principal concerns included:

1. Technical compatibility requirements
2. Additional interconnection costs
3. Development status/availability

This section provides a summary of the probable consequences of the use of these storage concepts in conjunction with wind or photovoltaic systems. The detailed evaluations are provided in Section 2 of Volume II, and Section 2 of Volume III for photovoltaics and wind systems, respectively.

5.2.1 PUMPED HYDRO STORAGE

Since the principal differences in above ground and underground pumped hydro storage relate to reservoir location, both concepts may be treated together with respect to their use with wind and photovoltaic systems. Geographically, suitable wind and insolation regimes can be found where storage sites are feasible. The limited number of potentially suitable pumped hydro sites will restrict expanded use. The water pumping required by this concept is based on use of an electric motor drive, which is compatible with the electrical output inherent in PV and wind system concepts. Use of an ac motor drive is probable, and since current thinking appears to favor an ac power output design for WECS, the power systems are fully compatible. Although photovoltaic arrays provide dc output, the expected conversion to ac for direct on-line use of PV output may be considered part of the basic system cost and therefore would not penalize the storage system. Modular system designs would be based on the design power output level provided by the wind turbines or PV array. Interruption of the pumping operation would be acceptable, provided appropriate procedures were incorporated for monitoring, shutdown and restart of the pumps in event of loss of drive power.

Pumped hydro is an available technology with proven benefits on a utility scale and could be utilized jointly with other utility generation or separately with utility-integrated wind or photovoltaic systems on a dedicated basis. (Subsequent study investigations led to the conclusion that system-wide use of storage is preferable).

5.2.2 UNDERGROUND COMPRESSED AIR STORAGE

This was found to be basically a large scale storage method, but one to which a wind system or photovoltaic system output could be applied. Electric motor drive of compressor units is power-system compatible and interruption of operations could be tolerated with proper procedure. Electrical reconversion of stored energy involves use of a turbine-generator either air-driven or in conjunction with burning of conventional fuel. The latter is presently preferred. This storage concept appears most appropriate to a combined utility operation rather than one dedicated to wind or photovoltaics alone.

5.2.3 PNEUMATIC STORAGE

This concept was identified with possible small scale use in residential size applications. Although similar to underground compressed air storage in operation, it would require high strength storage tanks and present significant cost and hazard barriers. It is operationally compatible with input from PV or WECS systems, and the cycle could be interrupted should the wind or insolation level drop.

5.2.4 BATTERY STORAGE

Both present lead-acid batteries and a number of advanced batteries under development are compatible with photovoltaic and wind energy storage requirements. Possible constraints associated with certain of the advanced battery systems are covered in other portions of this report. Batteries are well suited for adaptation to system sizes ranging from residential to utility scale. The principal obstacles at present are the need to achieve long cycle life and proven designs.

5.2.5 FLYWHEEL ENERGY STORAGE

This method of storage can be integrated with wind and photovoltaic systems but presents some serious problems. Several pieces of expensive equipment are required to make the necessary electrical conversion to and from storage. The required storage density is achievable only with an advanced type of composite flywheel not yet available in adequately developed form.

5.2.6 HYDROGEN GAS GENERATION AND STORAGE

This storage technique can be implemented in several ways, but is basically compatible conceptually with both wind and photovoltaic systems. Since current concepts use dc electricity in the electrolysis of water, a photovoltaic system (dc output) may, in some cases, eliminate one power conversion step. The process can be interrupted without any significant problem. The overall efficiency of this concept is quite low, primarily due to the fuel cell component. Work now underway on a hydrogen-chlorine system offers an opportunity for significant improvement in efficiency to almost double that for a hydrogen-oxygen cycle.

5.3 SYSTEM COSTS

The levelized annual cost represents the dollar amount required to own, operate, and maintain a system during each year of the life of the system. This parameter was used as a preliminary measure of relative economic attractiveness in assessing various storage techniques. Specifically, the levelized annual cost accounts for:

(a) "paying off" system capital costs

(b) paying for operation and maintenance expenses

(c) paying taxes

(d) paying a return to investors and interest to creditors

(e) building a capital fund for periodic component replacement, overhaul and retirement of debt.

5.3.1 METHODOLOGY

The levelized annual cost, in current dollars, denoted by $\overline{AC}$, is given by:

$$\overline{AC} = I_C \cdot FCR \cdot CCF + M \cdot A_{OM} \qquad (1)$$

Here, I_C is the total capital cost of the system and CCF is the construction cost factor accounting for interest during construction of the storage system. The parameter FCR is the fixed charge rate and represents the yearly cost of ownership, expressed as a percent of the capital investment, I_C. These costs consist of capital outlay, taxes, and insurance. A_{OM} is the annual system operation and maintenance cost. The parameter M, defined as the levelized value of an escalating cost stream, accounts for the fact that A_{OM} is increasing over the lifetime of the system because of inflation.

In the case of storage systems, the capital costs usually are separated into two components: (1) an investment associated with a storage system of a given power rating, I_P, expressed in \$/kW, and (2) an investment associated with the energy storage capacity of the system, I_S, expressed in \$/kWh. For a device with a maximum discharge capability of t hours at rated power, the total capital cost, I_C, in \$/kW is:

$$I_C = I_P + I_S \cdot t \qquad (2)$$

Expressing $\overline{AC}$ in current dollars establishes equal yearly costs over the system life. This is analogous to the case of a home mortgage. The home-owner borrows money at some interest rate. It is paid back in equal monthly (hence, yearly) installments over the life of the mortgage (i.e., he pays \$X/month in the first year and \$X/month in the 30th year).

An alternative method, more appropriate to the cost evaluation and comparison of systems for future implementation, is that of expressing levelized annual costs referenced to a particular base year, e.g., 1976. The result is the levelized annual cost in constant (base year) dollars:

$$\overline{AC} \text{ (constant \$)} = \left(\frac{CRF'}{CRF}\right) \cdot I_C \cdot FCR \cdot CCF + A_{OM} \qquad (3)$$

Here, CRF is the capital recovery factor, defined as the uniform periodic payment, as a fraction of the original principal, that will fully repay a loan (including all interest) in yearly periods over the loan lifetime at a specified yearly interest rate. The interest rate used to calculate CRF is called the discount rate and represents the weighted average cost of capital.

The discount rate varies with the application. Values of .09, .072, and .10 were used for the utility, residential and intermediate applications, respectively.

CRF' is the corresponding capital recovery factor in constant (base year) dollars.

The derivation of equations (1) and (3) and a more complete discussion of the system cost methodology, including explanations of FCR, CRF, CRF', etc., is given in Appendix B.

5.3.2 CURRENT STORAGE SYSTEM COST ASSUMPTIONS

The cost parameters used for analysis purposes were selected as representative values and were derived from literature searches, telephone conversations and other investigations. Table 5.3-1 presents the cost parameters for the utility application storage system concepts discussed in the preceding section. Note that the fixed charge rate (FCR) is adjusted to a common 30 year life basis for all systems, with component replacement costs included. Capital costs include balance of plant costs, where applicable.

Table 5.3-2 presents cost parameters used in residential analyses. Interest during construction (CCF) was not included, the assumption being that a complete residential storage system will be purchased, ready to operate, after relatively minimal installation. The residential fixed charge rates assumed a 20 year, 9 percent mortgage by an individual in a 20 percent incremental tax bracket and include 2 1/2 percent for local taxes and insurance.

TABLE 5.3-1. SUMMARY OF COST PARAMETERS - UTILITY APPLICATION

ENERGY STORAGE CONCEPT	NOMINAL EXPECTED LIFE(YRS)	NOMINAL EFFICIENCY (%)	CCF [3]	FCR[a]	CAPITAL COSTS [b]		O&M COSTS [b]	
					I_p($/kW)	I_S($/kWh)	FIXED $/kW/Yr	VARIABLE $/kWh
1. Underground Pumped Hydro	50	75	1.40	.18	140	8	1.6	0
2. Above ground Pumped Hydro	50	75	1.40	.18	120	6	1.6	0
3. Thermal Storage-Oil	30	70	1.17	.18	200	12	3.2	.0002
4. Thermal Storage-Steam	30	70	1.17	.18	200	50	3.2	.0002
5. Underground Compressed Air	30	70	1.17	.18	155	17	0	.0053
6. Advanced Batteries	10/20	75	1.05	.22	70	30	0	.003
7. Lead-Acid Batteries	10	70	1.05	.22	70	77[c], 85[d]	0	.0005
8. Inertial (Flywheel) Storage	20	75	1.05	.19	70	200	0	.0053
9. Hydrogen Storage	20	45	1.05	.19	750	15	0	.0027
10. Superconducting Magnetic Energy Storage	30	80	1.40	.18	50	125	1.6	.0002

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

b. Cost parameters shown are representative values selected from costs/cost ranges shown in the PSE&G Report[3] and/or other sources as discussed in Section 4. Battery costs are based on consensus data from most recent EPRI/ERDA workshops and include allowance for balance-of-plant costs.

c. 10 hour battery.

d. 5 hour battery.

(All costs are stated in 1975 dollars except for batteries which are in 1976 dollars).

TABLE 5.3-2. SUMMARY OF COST PARAMETERS - RESIDENTIAL APPLICATION

ENERGY STORAGE CONCEPT	NOMINAL EXPECTED LIFE(YRS)	NOMINAL EFFICIENCY (%)	FCR[a]	TOTAL SYSTEM CAPITAL COST ($/kWh)[b]	VARIABLE O&M COST ($/kWh)[b]
1. Advanced Batteries	10	75	.15	92	.003
2. Lead-Acid Batteries	10	70	.15	200	.0005
3. Inertial (Flywheel)	20	75	.12	250	.005
4. Pneumatic	20	60	.12	270	.003

a. Provides adjustment for comparison of all systems on a common 20 year basis.

b. Cost parameters shown were derived from various sources as discussed in Section 4, with balance-of-plant costs extracted from Ref. 61. An 8-10 hour/day storage system daily cycle is assumed,

(All costs are stated in 1976 dollars).

FCR for batteries was adjusted to account for 10 year life and one replacement. The effect of achieving 20 year life for an advanced battery system was also computed and is discussed in the study summary, Section 1.

Energy storage costs for intermediate applications will range between the utility and residential values depending on the scale of the application. Obviously, very large storage systems will closely approximate utility level costs, while very small systems will be more typified by residential costs. Utility costs were used in the intermediate analysis, except for advanced and lead-acid batteries for which specific capital cost estimates of 67$/kWh and 140 $/kWh respectively, were obtained. Fixed charge rates for the intermediate application can be expected to be slightly higher than the utility case. Table 5.3-3 gives the intermediate fixed charge rates assumed in the study, again corrected to 30 year life and associated component replacement requirements.

TABLE 5.3-3. FIXED CHARGE RATES - INTERMEDIATE APPLICATION

	STORAGE CONCEPT	FIXED CHARGE RATE - (FCR)
1	Underground Pumped Hydro	.22
2	Above-ground Pumped Hydro	.22
3	Underground Compressed Air	.22
4	Advanced Batteries	.26
5	Lead-Acid Batteries	.26
6	Inertial Storage	.23
7	Hydrogen Storage	.23

5.3.3 ENERGY STORAGE FUTURE COST PROJECTIONS

The storage system costs of Tables 5.3-1 and 5.3-2 are based on current cost estimates which, for many of the storage concepts, are continually being changed, updated and improved upon. Substantial cost reductions are projected for some concepts while others such as pumped hydro may have difficulty holding costs to today's level due to land costs which are increasing at a greater rate than general inflation, and also because of depletion of inexpensive sites. Figure 5.3-1 presents consensus learning curve storage-related capital cost projections (I_S) for the utility-applicable storage systems. The curves were generated using standard learning curve procedure based on a logarithmic scale straight line reduction of cost vs. number of units produced. Estimates of 20% cost reduction by the year 2000 were

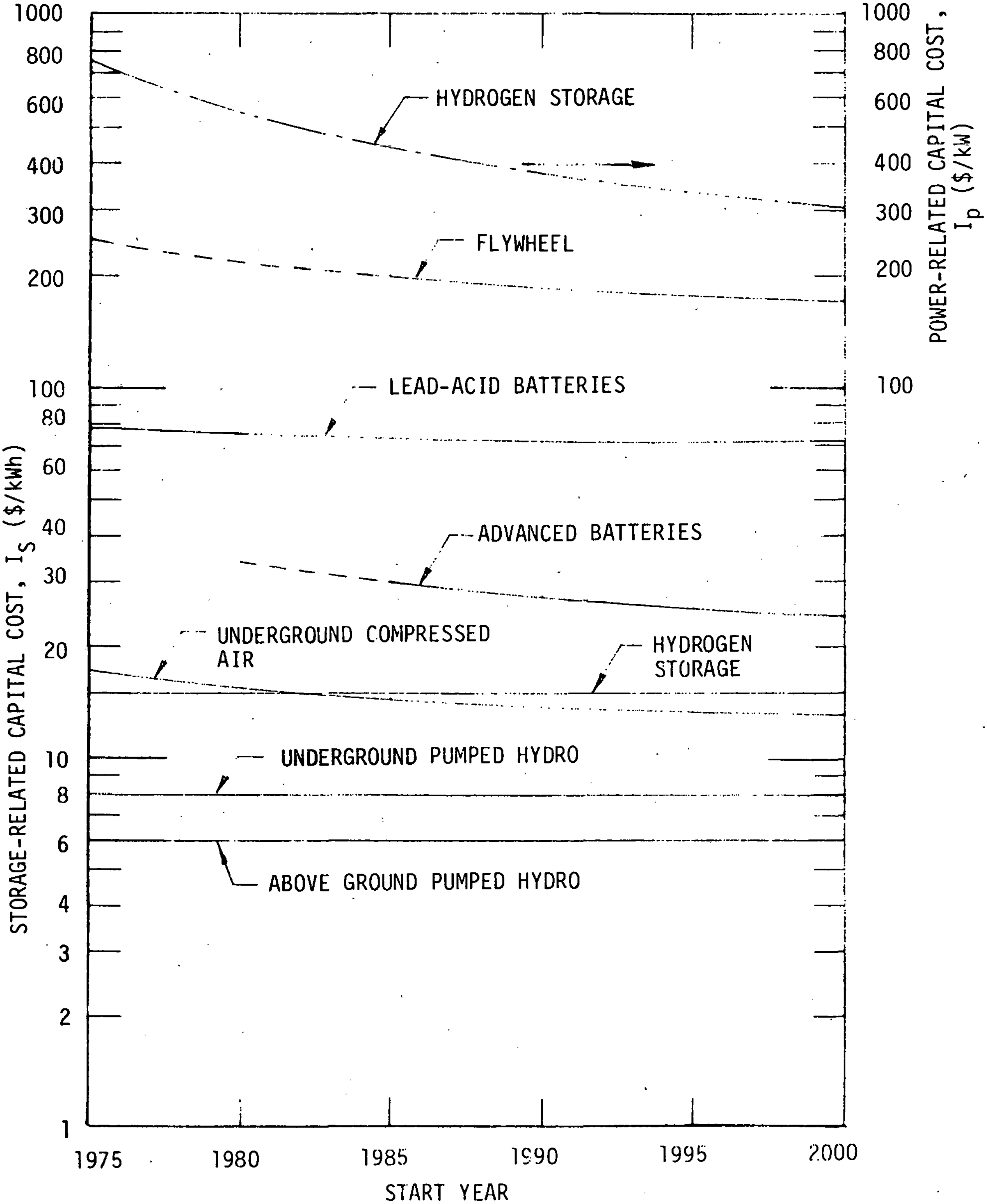

Figure 5.3-1. LEARNING CURVE PROJECTION OF FUTURE STORAGE SYSTEM COSTS - UTILITY APPLICATION

assumed for the immature storage systems, including underground compressed air, advanced batteries and flywheels. A cost reduction of 10% by the year 2000 was estimated for the relatively mature lead-acid battery system. The relatively steep learning curve for hydrogen storage was based on data from a supporting study. These learning curves were used only for viability screening purposes due to the fact that current cost estimates for the developing technologies are not yet well enough established, whereas the mature technology learning will likely be small. The cost projections presented in Figure 5.3-1 were used, however, to test the utility-applicable storage systems for viability at the most optimistic condition by the year 2000. Although learning curve cost projections were not used in the worth of storage analyses of Volumes II and III, the results are formatted in a manner that will permit evaluation of system viability using any cost estimate.

5.3.4 SAMPLE COMPUTATION

Table 5.3-4 presents an example levelized annual cost, $\overline{AC}$, computation done for above ground pumped hydro storage in a utility application. Capital cost data was obtained from Table 5.3-1 in 1975 dollars. For a system lifetime of 30 years, and a utility discount rate of .09, the fixed charge rate, (FCR) and capital recovery factors (CRF and CRF') were computed to be .18, .0973, and .0565, respectively. The first two steps of the calculation procedure consist of escalating the capital cost as well as the operating and maintenance costs to 1976 dollars at an inflation rate of 5%. Then equation (3) is employed to obtain the levelized annual cost, in this case, $29.33 $/kW/Yr. (1976 dollars).

TABLE 5.3-4. SAMPLE COST CALCULATION

EXAMPLE: Above Ground Pumped Hydro Storage	
Specific Conditions	
• Capital Costs:	• System Lifetime, n = 30 years
I_P = 120 \$/kW (1975\$)	• CCF = 1.40
I_S = 6 \$/kWh (1975 \$)	• FCR = .18
• O&M Costs: Fixed =	• Discount Rate, r, = .09
1.6 \$/kW/Yr (1975 \$)	• CRF = .0973
• Discharge Capability = 10 hrs.	• CRF' = .0565
• No. charges/yr., N = 250	
• Inflation Rate, g = 5%	

Sample Calculation (1976 \$)

1. $I_C = I_P + I_S \cdot t$ = 1.05 (120 \$/kW + 6 \$/kWh · 10 Hr) = 189 \$/kW
2. A_{OM} (Fixed) = 1.05 (1.6 \$/kW/Yr) = 1.68 \$/kW/Yr
3. $\overline{AC} = \frac{.0565}{.0973}$ (189) (.18) (1.4) + 1.68 = 29.33 \$/kW/Yr (1976\$)

5.3.5 SYSTEM LEVELIZED ANNUAL COST TABULATION

Using the calculation procedure described, levelized annual costs were computed for the seven concepts screened for the utility and intermediate applications plus the four residential concepts. Results are shown in Table 5.3-5.

TABLE 5.3-5. LEVELIZED ANNUAL COST RANKING OF CANDIDATE STORAGE SYSTEMS

STORAGE METHOD	UTILITY			INTERMEDIATE	
	$\overline{AC}$ $/kW/Yr	RANK		$\overline{AC}$ $/kW/Yr	RANK
Above-ground Pumped Hydro	29	1		36	1
Underground Pumped Hydro	35	2		44	2
Underground Compressed Air	56	3		66	3
Advanced Batteries	57	4		117	4
Lead-Acid Batteries	114	5		229	6
Hydrogen Storage	117	6		143	5
Inertial Storage	266	7		327	7

RESIDENTIAL STORAGE SYSTEMS	$\overline{AC}$ $/kWh/Yr	RANK
Advanced Batteries	9	1
Lead-Acid Batteries	19	2
Inertial Storage	20	3
Pneumatic Storage	21	4

Hydro storage systems show a clear cost advantage in large scale systems (as might be expected) with some type of advanced battery having the highest potential for the residential application. It should be noted that in the utility application, however, the storage systems which are predominantly storage-cost related will look more attractive at discharge times less than ten hours. The ten hour time was used only to make a common comparison. The discharge times for a given set of utility requirements should be individually matched to one or more storage methods to obtain the optimum results.

Levelized annual cost provided a first-cut economic ranking of the candidate storage concepts and was used along with the other evaluation criteria to help decide which systems were most attractive for further study. More detailed overall worth of storage evaluations required consideration of duty cycle, efficiency and specific output/load characteristics for the photovoltaic and wind energy conversion systems in each of the three applications. Volumes II and III of this report present the detailed analyses and data for photovoltaic and wind energy conversion systems, respectively, with the above and other factors included.

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APPENDICES

APPENDIX A - GLOSSARY AND DEFINITIONS

APPENDIX B - SYSTEM COST METHODOLOGY

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 $\div$ 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

APPENDIX B

SYSTEM COST METHODOLOGY

The levelized annual cost represents the dollar amount required to own, operate, and maintain a system during each year of the life of the system. This parameter was used as a preliminary measure of relative economic attractiveness in assessing various storage techniques. Specifically, the levelized annual cost accounts for:

(a) "paying off" system capital costs

(b) paying for operating and maintenance expenses

(c) paying taxes

(d) paying a return to investors and interest to creditors

(e) building a capital fund for periodic component replacement, overhaul, and retirement of debt.

The levelized annual cost, denoted by $\overline{AC}$, is given by:

$$\overline{AC} = CRF \times PW \tag{1}$$

where CRF is the capital recovery factor and PW is the present worth of the year by year revenue requirements throughout system life.

The following sections describe the analytics for computing $\overline{AC}$ as applied to storage, and as used for preliminary evaluation of storage concepts.

A1.1 CAPITAL RECOVERY FACTOR, CRF

The capital recovery factor is the uniform periodic payment, as a fraction of the original principal, that will fully repay a loan (including all interest) in yearly periods over the loan lifetime at a specified yearly interest rate. The interest rate used to calculate CRF is called the discount rate and represents the weighted average cost of capital.

Analytically, the capital recovery factor is given by:

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

where r is the appropriate discount rate and n is the system lifetime. The discount rate, r, varies with the application. Values of .09, .072, and .10 were used for the utility, residential and intermediate applications, respectively.

A1.2 PRESENT WORTH, PW

The present worth is analogous to that amount which, if deposited in an interest bearing account at the discount rate, would permit annual withdrawals to pay all system costs and diminish to zero at the end of system life. For the evaluation of storage concepts, the PW is comprised of two components: (1) a component accounting for capital costs and (2) a component accounting for the cost of operation and maintenance (O&M).

The total present worth is given by:

$$PW = PW_{FIXED\ CHARGE} + PW_{O\&M} \tag{3}$$

The fixed charge component is given by:

$$PW_{FIXED\ CHARGE} = \frac{I_C \cdot FCR \cdot CCF}{CRF} \tag{4}$$

Here, I_C, is the total capital cost of the system and CCF is the construction cost factor accounting for interest during construction of the storage system.

The parameter FCR is the fixed charge rate and represents the yearly cost of ownership, expressed as a % of the capital investment, I_C. These costs consist of capital outlay, taxes and insurance. An explanation of the fixed charge rate and its derivation is given in the following subsection. In the case of storage systems, the capital costs can be separated into two components: (1) an investment associated with a storage system of a given power rating, I_P, expressed in $/kW, and (2) an investment associated with the energy storage capacity of the system, I_S, expressed in $/kWh. For a device with a maximum discharge capability of t hours at rated power, the total capital cost, I_C, in $/kW is:

$$I_C = I_P + I_S \cdot t \tag{5}$$

The second component in equation (3) accounts for system operation and maintenance . This is given by:

$$PW_{O\&M} = \frac{A_{OM} \cdot M}{CRF} \tag{6}$$

This is similar in form to equation (4), but with different parameters. A_{OM} is the cost of operating and maintaining the system.

The parameter M, defined as the levelized value of an escalating cost stream, accounts for the fact that A_{OM} is increasing over the lifetime of the system because of inflation.

$$M = \frac{r(1+g)}{r-g} \left[\frac{(1+r)^n - (1+g)^n}{(1+r)^n - 1} \right] \qquad (7)$$

where g is the annual inflation or escalation rate.

Substituting equations (4) and (6) into equation (3) yields:

$$PW = \frac{1}{CRF} \left[I_C \cdot FCR \cdot CCF + M \left(A_{OM} \right) \right] \qquad (8)$$

A1.3 FIXED CHARGE RATE

The fixed charge rate (FCR) represents the yearly cost of ownership, expressed as a % of the investment, I_C. These costs consist of debt interest and principal payments, return on equity (where applicable), insurance, local taxes and the net effect of Federal taxes. The concept of the fixed charge rate comes from electric utility financial analysis, but has proven to be applicable and convenient in the analysis of other sectors as well.

The residential energy user has one important difference from other energy consumers in that energy is not a tax deductible expense. The effect is best shown by example. Consider an industrial and a residential user in 48 and 20 percent tax brackets, respectively. Assume each has $1000 of before-tax income and is evaluating a $100 energy purchase:

Corporation	Without Energy	With Energy
Gross Income	1000	1000
Deductible Expenses	0	100
Taxable Income	1000	900
Federal Taxes (48%)	480	432
Net Income	520	468

Residential User	Without Energy	With Energy
Gross Income	1000	1000
Deductible Expenses	0	0
Taxable Income	1000	1000
Federal Taxes (20%)	200	200
Net Income	800	800
Less Energy	-	100
		700

After Tax Energy Cost = \$520 - 468 = \$52 \$800 - 700 = \$100

Thus, while the homeowner pays the full \$100, the corporation effectively pays only \$52 (\$100 X (1 - tax rate)) since taxes are reduced by \$48. It is due to this tax effect that costs of alternate energy systems must be evaluated on an after-tax basis for the homeowner and on a before-tax basis for the corporation. Only in this way can system costs be compared with prevailing energy costs.

A detailed discussion of fixed charge rate, its various components, and corporate tax effects is presented in "The Cost of Energy from Utility-Owned Solar Electric Systems" (Reference B-1). The residential sector presents a much simpler case. Assuming a 9 percent loan for a homeowner in a 20 percent incremental tax bracket, the effective after-tax rate can be shown to be 7.2 percent (.9 X (1 - .2)). Computing the appropriate CRF and adding local taxes and insurance yields the fixed charge rate. For example, assume a 10 year life system and 2.5 percent for local taxes and insurance:

$$FCR = \frac{.072\ (1.072)^{10}}{1.072^{10} - 1} + .025 = .1687 \cong .17$$

Typical fixed charge rates (FCR) as a function of system life n and application are tabulated below:

SYSTEM LIFE n YRS.	FCR		
	UTILITY	RESIDENTIAL	INTERMEDIATE
10	.23	.17	.27
20	.19	.12	.23
30	.18	.10	.22
50	.18	.10	.22

These values will be used in the analysis that follows:

A1.4 LEVELIZED ANNUAL COST IN CURRENT DOLLARS

If equation (8) is substituted into equation (1):

$$\overline{AC} = I_C \cdot FCR \cdot CCF + M \left(A_{OM}\right) \tag{9}$$

In this case, the levelized annual cost is expressed in terms of current dollars.

Expressing $\overline{AC}$ in current dollars establishes equal yearly costs over the system life. This is analogous to the case of a home mortgage. The home-owner borrows money at some interest rate. It is paid back in equal monthly (hence, yearly) installments over the life of the mortgage (i.e., he pays

$X/month in the first year and $X/month in the 30th year).

A1.5 LEVELIZED ANNUAL COST IN CONSTANT DOLLARS

An alternative method of expressing levelized annual costs is to reference the costs to a particular base year, e.g., 1976. The result is the levelized annual cost in constant (base year) dollars.

To calculate $\overline{AC}$ in constant dollars, a discount rate that accounts for inflation over the system life is determined. This rate, denoted by r', is given by:

$$r' = \frac{(1 + r)}{(1 + g)} - 1 \qquad (10)$$

where g is the annual inflation rate. This r' is then used in the CRF equation to yield a capital recovery factor in constant (base year) dollars:

$$CRF' = \frac{r' (1 + r')^n}{(1 + r')^n - 1} \qquad (11)$$

Substituting CRF' for CRF in equation (1) gives:

$$\overline{AC} \text{ (Constant \$)} = CRF' \cdot PW \qquad (12)$$

Further substitution of equation (8) into (12) results in:

$$\overline{AC} \text{ (Constant \$)} = \frac{CRF'}{CRF} \left[I_C \cdot FCR \cdot CRF + M \left(A_{OM}\right) \right] \qquad (13)$$

Combination of equations (2), (7), and (11) results in an identity:

$$\frac{CRF'}{CRF} \cdot M \equiv 1 \qquad (14)$$

provided that g, the annual inflation or escalation rate, is the same for O&M as for the general rate of inflation used in computing r'. This expression, in turn, reduces equation (13) to:

$$\overline{AC}\text{ (Constant \$)} = \left(\frac{CRF'}{CRF} \cdot I_C \cdot FRC \cdot CCF\right) + A_{OM} \quad (15)$$

REFERENCE

B-1. "The Cost of Energy from Utility-Owned Solar Electric Systems", Doane, J.W., et. al., June 1976, Report JPL 5040-29, Jet Propulsion Laboratory