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An Assessment of Energy Storage Systems Suitable for Use by Electric Utilities

AN ASSESSMENT OF ENERGY STORAGE SYSTEMS SUITABLE FOR USE BY ELECTRIC UTILITIES

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FOREWORD

This is the final report of "An Assessment of Energy Storage Systems Suitable for Use by Electric Utilities." It is separated into three volumes: Volume 1 contains the Executive Summary and Chapter 1, Overall Summary of Assessment; Volume 2 contains Chapters 2 through 7 and associated appendices, the essential elements of the report; Volume 3 is a separate topical report on hydro pumped storage. Selected material from Volume 3 is included in Volume 2.

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EXECUTIVE SUMMARY

Demand for electricity varies from hour to hour, day to day, week to week and season to season. If electrical energy could be stored, then the variation in the demands placed on generating equipment could be reduced. Electric energy is most difficult to store and the storage of electrical energy is seriously limited by the lack of suitable technology. Because of the variation in the demand for electric power, a portion of a utility's coal and nuclear fueled baseload generation capacity may be unused during off-peak or light load periods. This availability of off-peak baseload generation capacity makes energy storage attractive. Use of off-peak baseload capacity could also reduce oil consumption, substituting domestically available coal and uranium for expensive petroleum.

Until now, hydro pumped storage has been the only available method of storing electric energy for large scale electric power generation. But pumped storage does not provide the complete answer for future electric energy storage. There are other energy storage possibilities in various stages of technological development that offer unique characteristics that could provide attractive alternatives.

PURPOSE

The purpose of this study is to provide the required data to establish research and development priorities for energy storage technology by: (a) evaluating the potential role of energy storage in electric utility systems; and, (2) providing an impartial assessment of various energy storage technologies suitable for use by electric utilities. The specific objectives of this study are:

- Identify the potential effect of energy storage on the electric utility systems of the United States.
- Determine the status of development and the feasibility of commercialization of candidate energy storage technologies, and establish their key technical and cost characteristics.

- Evaluate the relative merits of energy storage options on the basis of economic, operational, and environmental factors.

- Identify research and development needed to advance the various storage technologies.

SCOPE

The study covers the implications of energy storage for electric utilities. It addresses in detail the benefits of utility energy storage.

The report also covers the entire range of energy storage technologies that are considered to have potential for utility use. Considerable effort was required in several instances to project advances in the state of technology for the purpose of assessment; these studies were necessarily limited in depth since a wide range of technologies had to be covered. Any assessment of emerging technologies should not be considered as definitive and final. The dynamic nature of scientific and engineering advancement, changing economic conditions, and government regulatory policies preclude definitive assessments of future possibilities.

Use of energy storage by individual utility customers could have an impact on energy storage owned by utilities. The assessment of these small scale applications involves the complex study of utility rate structure, customer acceptance and customer economics. Such an application is worthy of a separate study. Also energy storage will be important in conjunction with solar technologies, but this future application is not specifically addressed here.

PRINCIPAL FINDINGS AND CONCLUSIONS

- Energy storage can play an important role in providing generating capacity for peaking and intermediate electric loads, provided sufficient economic baseload capacity is available for charging energy storage systems with off-peak energy.

- With an energy storage efficiency of 75 percent, approximately 5 percent of U.S. electric energy requirements could be supplied by energy storage.

- With sufficient off-peak energy available from baseload coal and nuclear capacity, energy storage could provide generating capacity for up to 17 percent of peak load demand (kW).

- Weekly cycle operation of energy storage is particularly appealing since it could utilize 70 percent of available off-peak energy.

- A review of a wide range of energy storage concepts has identified technically feasible energy storage technologies which could be commercially available in the near-term, intermediate-term and long-term.

  -- Conventional hydro pumped storage is the only proven technology and is now in wide use.

  -- For the near-term (through 1985), hydro pumped storage with an underground reservoir; compressed air storage; and sensible heat thermal storage integrated with a central power plant appear to be feasible and economic for peaking and intermediate duty.

  -- For the intermediate-term (1985-2000), in addition to advances in the technologies named above, advanced batteries appear to be attractive, especially for peaking duty. Hydrogen storage systems may also prove to be economic for certain intermediate duty applications where large storage capacity is required and in which low efficiency (less than 50 percent) and high capital costs are offset by specific system operating and economic benefits.

  -- For the long term (beyond 2000), other concepts have potential to become viable storage options. However, accurate prediction of the potential of such technologies as superconducting magnetic energy storage is not possible at this time.

- Advanced battery systems appear to be sufficiently compact, economically attractive, and environmentally acceptable to be suitable for dispersed siting throughout utility systems. Continued R&D should be devoted to these systems, to seek improvements in battery life and development of low cost manufacturing processes.

- Thermal storage systems, integrated with nuclear plants, are identified as a potentially attractive near-term technology. Further conceptual design work and preliminary engineering studies will be particularly valuable to confirm the promise seen for these systems.

- Certain technologies were found to be generally unattractive. In particular, flywheel storage systems are too expensive except for special applications where high power, but little storage capacity, is required. State-of-the-art lead acid batteries, because of high cost and short life are of interest only where special benefits might be obtained, or for small storage capacities. Determination of the value of the operating benefits awaits further study.

- Storage technologies not considered in this study could prove to be attractive. Future investigations should consider systems not treated here.

Caveat

- It is important to remember that energy storage is not an intrinsic energy source. It will be necessary to continue to build and operate baseload nuclear and coal generating stations if energy storage is to fulfill its promise.

- The evaluation methods used in this study do not provide sufficient data for determining the optimum amount and type of storage facilities to be installed on any particular electric power system. Each specific application of energy storage will require separate evaluation.

Section 1

OVERALL SUMMARY OF ASSESSMENT

Energy resources are extracted and processed, converted and distributed, and utilized at different times in many different forms at different locations. Various modes of energy storage are utilized to permit a matching of supply and demand. Despite the complexity of energy supply and use, current technologies largely limit energy storage to the familiar forms of fuel storage such as oil tanks, gasoline tanks, natural gas holders and underground storage reservoirs, coal piles, and hydroelectric storage reservoirs.

Once generated from fuel, electricity is not easily stored. Basically, the electricity must be generated upon demand. This leads to a requirement for installed generating capacity to meet peak rather than average loads. Utilities with large variations in loads must use low-capital-cost peaking units to minimize cost to customers. These peaking units (diesels and combustion turbines) use light distillates or natural gas for fuel. Peak demand is also supplied by older steam units which are no longer used to meet baseload demand. These practices result in peak-load energy costs that are necessarily high. Energy storage permits the displacement of conventional peaking capacity by increasing the loading of baseload units which use primarily coal and nuclear fuels.

1.1 POTENTIAL FOR ENERGY STORAGE

Utility daily, weekly and seasonal load variations result in typical annual system load factors ranging from about 40 to 80 percent. System generating capacity is installed to meet annual peak load requirements with a specified degree of reliability. Because of the variations in the daily load profile, a portion of the baseload capacity is unused during off-peak periods. This availability of low cost off-peak energy makes the concept of storage attractive.

The extent to which energy storage systems can be effectively used in an electric utility system depends on several factors, including the utility's system load characteristics, the amount of installed baseload capacity as a percent of total system generating capacity, and the incremental cost of this off-peak energy. Other factors affecting energy storage systems are: anticipated duty cycles, expected storage system performance, the energy storage system capital costs, operating and maintenance costs, and particularly, the economics of energy storage capacity compared to other alternative types of peaking and intermediate generating capacity.

The potential impact of energy storage as future peaking and intermediate generating capacity of U.S. electric utility systems could be quite significant. The extent of need for energy storage is dictated by these major considerations: (1) load characteristics; (2) generation mix (level of installed baseload capacity); and (3) technoeconomic characteristics of available storage concepts.

There has been general agreement among electric utilities that energy storage could be significant, but no reliable estimate of this significance or the potential need for energy storage. To plan their research and development programs and establish the relative priority for energy storage projects, both ERDA and EPRI need quantitative estimates of the potential need for energy storage. To provide an analysis of energy storage, a complete survey of the U.S. electric utility need for energy storage was made. The approach taken and the results are described below and elaborated upon in Chapter 2 and its associated appendices.

Approach

To evaluate the potential of energy storage, the following steps were taken:

- Representative U.S. electric utility systems were selected after an extensive statistical analysis of the characteristics of U.S. electric utilities (Appendix B1).
- Actual hourly load data were analyzed for each representative system on an annual, seasonal, weekly and daily basis to determine:
  - availability of off-peak energy
  - distribution of this energy on a daily, weekly and seasonal base
  - amount of on-peak energy which could be supplied through energy storage

- -- amount of power capacity which could be supplied by energy storage
- -- typical operating (duty) cycles for energy storage

Data from this analysis were then used to establish results representative of the U.S. electric utility industry.

Off-Peak and On-Peak Energy

Analysis of system load characteristics and baseload capacity levels permits determination of the amount of distribution of off-peak energy available on annual, seasonal, weekly, and daily bases, and typical duty cycle requirements for energy storage systems.

For each of several representative utilities, a number of baseload generation capacity levels were assumed, and the amount and distribution of off-peak energy associated with each level were determined by analysis of the actual annual hourly load data. Capacity levels were adjusted on a seasonal basis for both maintenance and forced outages of the baseload generation units to provide a realistic indication of the available off-peak energy. U.S. industry average outage rates were applied. Maintenance was not scheduled during the peak season of the year and the allocation of maintenance to the three other seasons was based on balancing outages against available reserve capacity.

Figure 1-1 illustrates how the off-peak and on-peak energy was calculated for representative U.S. electric utilities. The off-peak energy, calculated on a daily basis, is shown by the shaded area below the adjusted seasonal baseload capacity level and above the load profile. The shaded area above the adjusted seasonal capacity level and below the load profile represents system on-peak load requirements that must be supplied by other than baseload capacity. Energy storage systems charged by the available off-peak energy represent that which can be used to supply a portion of this on-peak load.

Figure 1-2 shows the general relation between the total annual amount of off-peak energy available, the system annual load factors, and the baseload capacity level represented as a percent of peak load. It also shows the total amount of off-peak energy available and the associated on-peak energy requirements for the various assumed baseload capacity levels ranging from 40 to 100 percent of system peak load for U.S. electric utility systems. The

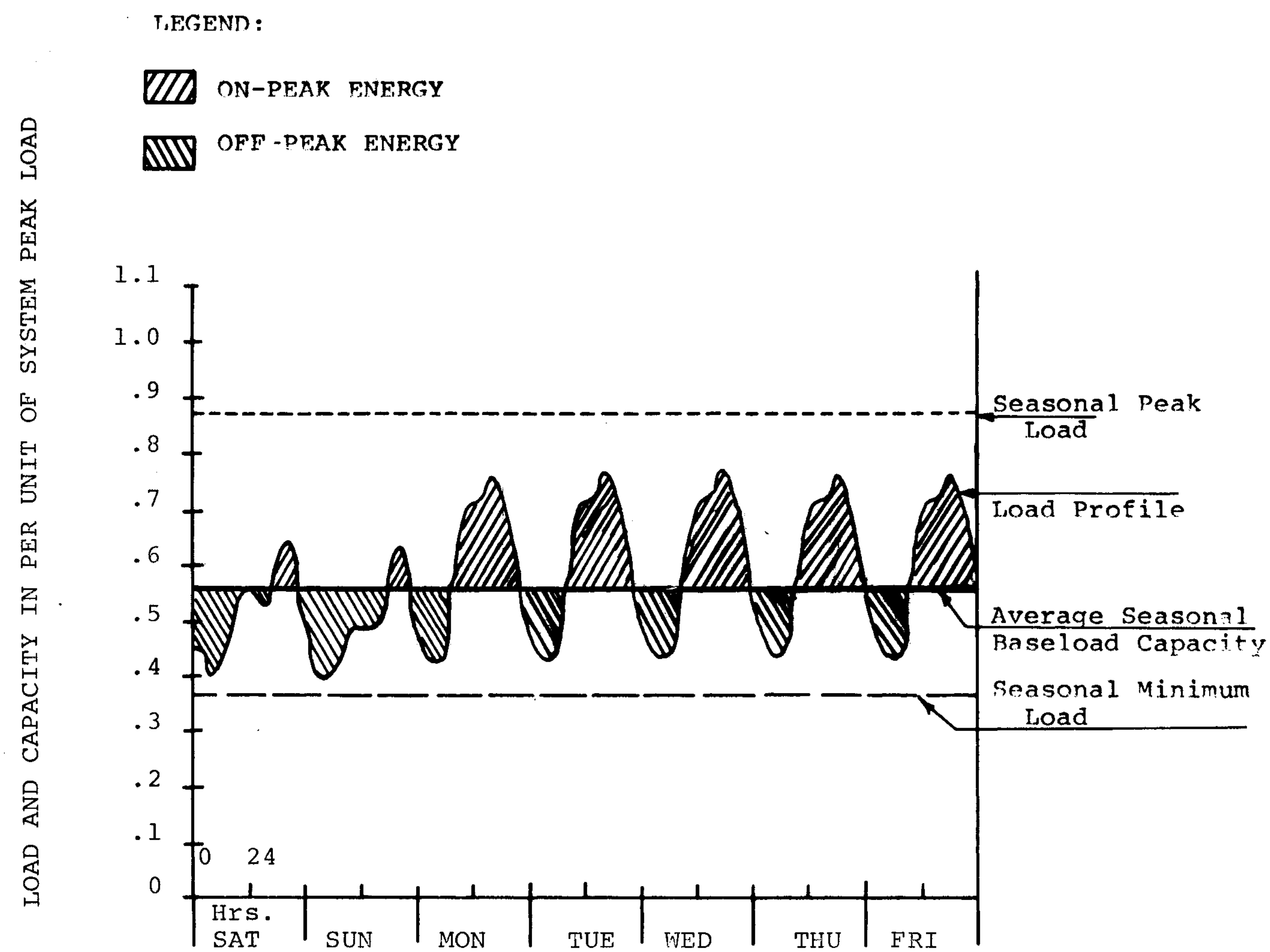


Figure 1-1 OFF-PEAK AND ON-PEAK ENERGY AS DEFINED BY CAPACITY LEVEL AND LOAD PROFILE

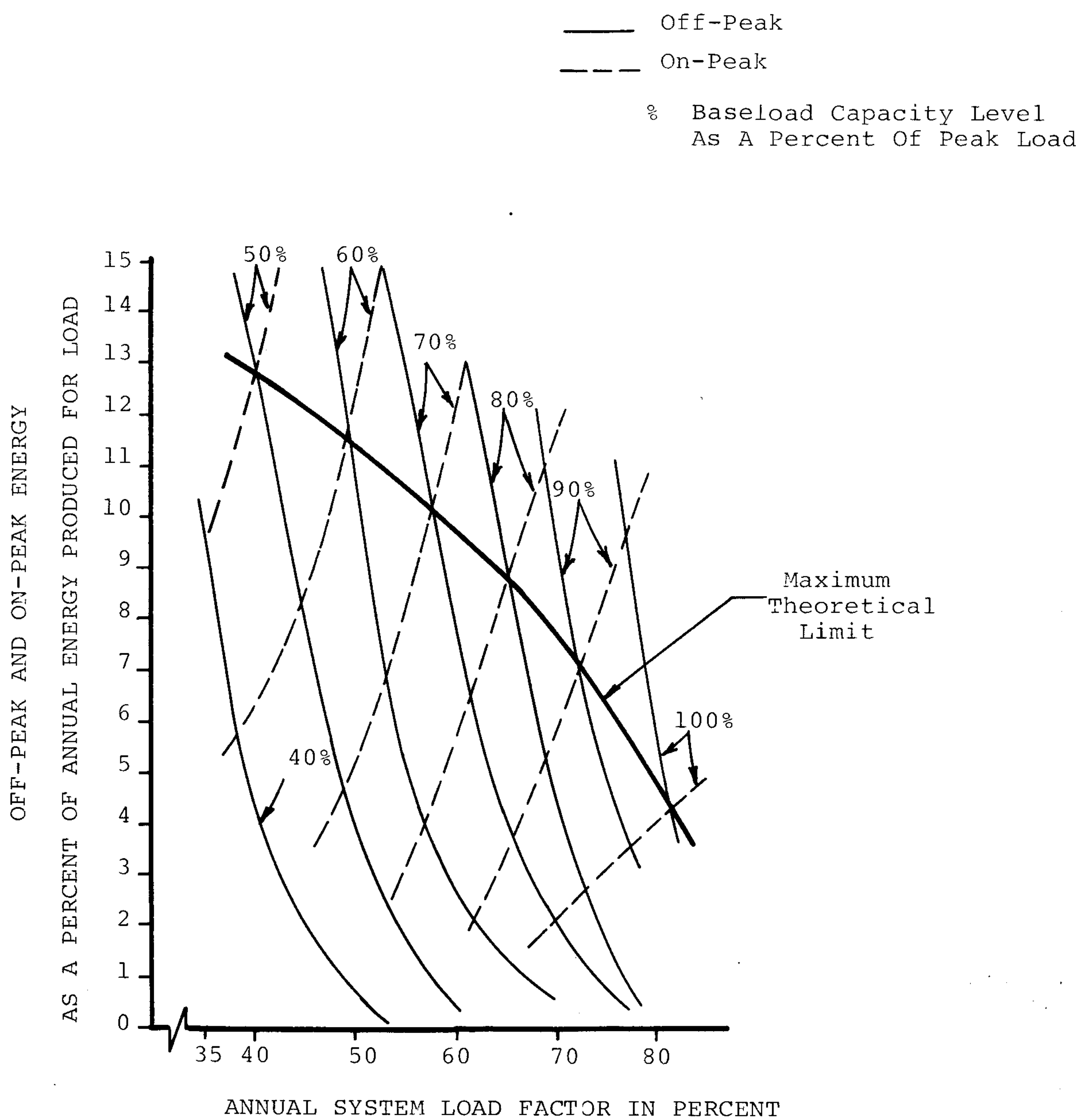


Figure 1-2 MAXIMUM ANNUAL OFF-PEAK AND ON-PEAK ENERGY LIMITS FOR U.S. ELECTRIC UTILITY SYSTEMS

negatively sloping solid lines indicate the amount of off-peak energy available on utilities with various assumed installed baseload capacity levels. The positively sloping dashed lines indicate the on-peak energy requirements of utilities above the assumed installed baseload capacity level.

For a specific capacity level, the intersection of the percent capacity lines identifies points for which the annual amount of off-peak energy available is equal to the on-peak energy requirements. The curve drawn through these points of intersection identifies, for any system, the maximum amount of on-peak energy that could be supported by off-peak energy and the required baseload capacity level for this condition. Because electric utilities with annual load factors of 55 to 65 percent produce about 80 percent of the electric energy in the U.S., the maximum amount of on-peak energy that could be supplied from off-peak energy sources is estimated to be about 10 percent of the total annual energy produced for load.

For these maximum level conditions, the distributions of the available off-peak energy and on-peak energy needs for the representative systems on a seasonal, weekly and weekday basis are shown in Figure 1-3. The off-peak energy is relatively evenly distributed over the entire year. This is the result of the scheduling of baseload generator maintenance outages to fill seasonal load valleys. As a percent of total annual off-peak energy, the typical seasonal, weekly, and weekday distribution of off-peak energy is approximately 25 percent, 2 percent, and 0.2 percent, respectively (4 seasons, 52 weeks, and 261 weekdays in each year).

The weekly off-peak energy was found to be divided evenly between the five weekdays and the weekend. More off-peak energy is available on an average Sunday than on an average Saturday.

An analysis of the frequency of occurrence of the available off-peak energy showed that approximately 70 percent of the maximum theoretical amount would be usable for energy storage on a weekly cycle. The other 30 percent does not occur on a consistent basis over the year. Therefore, the theoretical practical limit (100% efficiency) of on-peak energy capable of being supplied by the off-peak energy is approximately 7 percent of total energy produced by U.S. electric utilities as shown in Table 1-1. In order to supply this practical limit of 7 percent, energy storage capacity capable of operating

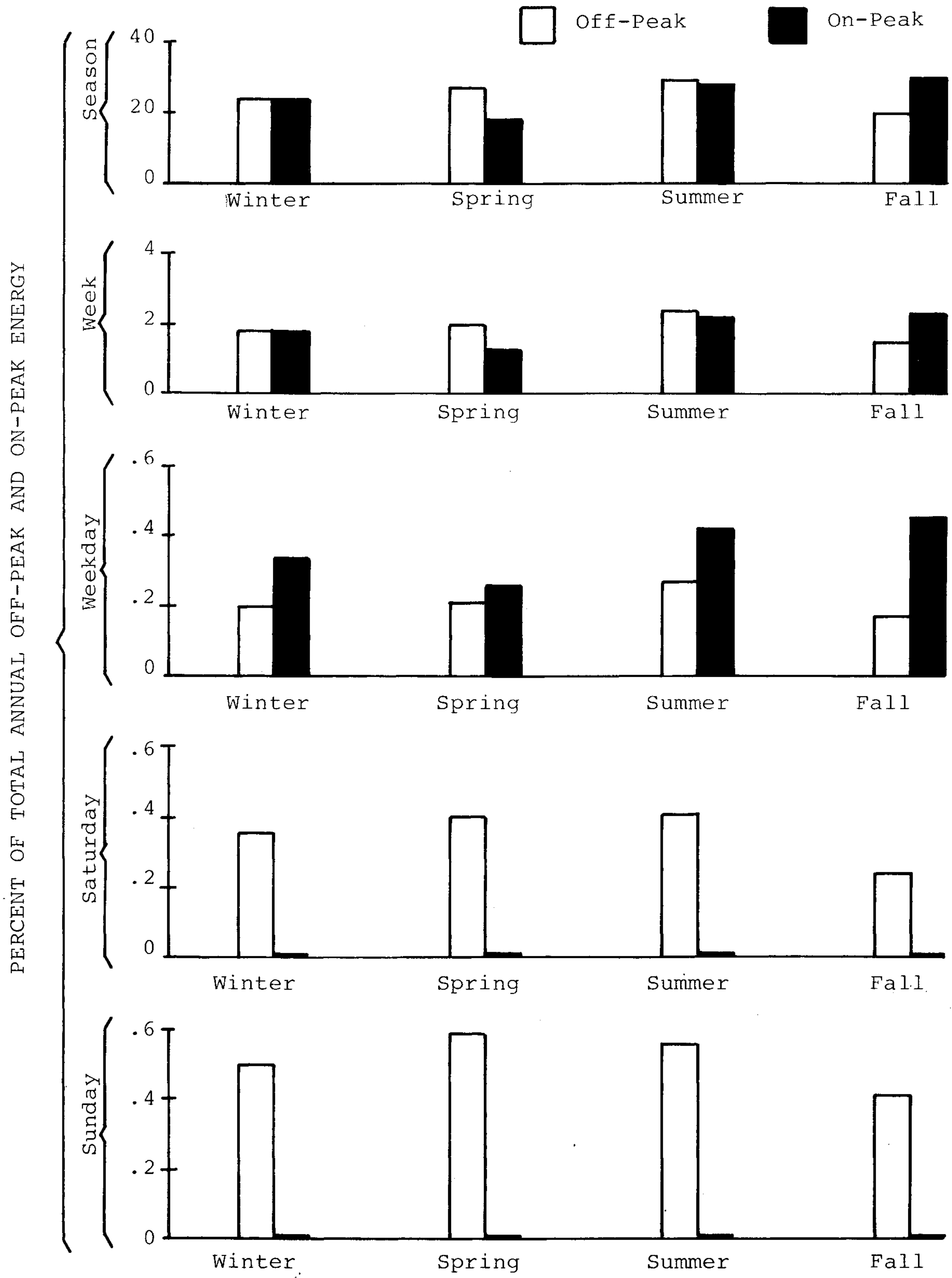


Figure 1-3 DISTRIBUTION OF OFF-PEAK AND ON-PEAK ENERGY ON U.S. ELECTRIC UTILITY SYSTEMS

TABLE 1-1 PRACTICAL ON-PEAK ENERGY LIMITS CAPABLE OF BEING SUPPLIED BY THE OFF PEAK ENERGY ON U.S. ELECTRIC UTILITIES

Efficiency of Conversion	Practical* Annual Percentage Limit (Weekly Cycle)	Practical* Annual Percentage Limit (Daily Cycle)
100%	7	4
75%	5	3
50%	3.5	2

*Percent of Total Energy Produced for Load

on a weekly cycle would be required since most of the on-peak energy demand occurs on weekdays and not weekends whereas nearly one-half of the off-peak energy is available on weekends. If use of energy storage was limited to a daily cycle operation, the practical limit would be reduced to about 4 percent of total energy produced for load.

Utilization of the available off-peak energy at a lower conversion efficiency will linearly reduce these limits. For example, a 75 percent conversion efficiency reduces the practical limits from 7 and 4 percent to 5 and 3 percent, respectively. These results are illustrated in Figure 1-4. For the year 1975, 5 percent of energy produced for load by electric utilities is approximately 100 billion kilowatt hours.

Operation and Duty Cycles for Energy Storage

The period of charging (storing energy) followed by a period of discharging is called a duty cycle. The two types of duty cycles commonly used in connection with electric utility applications are:

- Daily Cycle - the storage system is charged at night and during the early morning hours, and discharged during the day's peak load period.
- Weekly Cycle - the storage system is charged during the off-peak periods of the weekdays and on the weekend and discharged during the peak load periods of the weekdays.

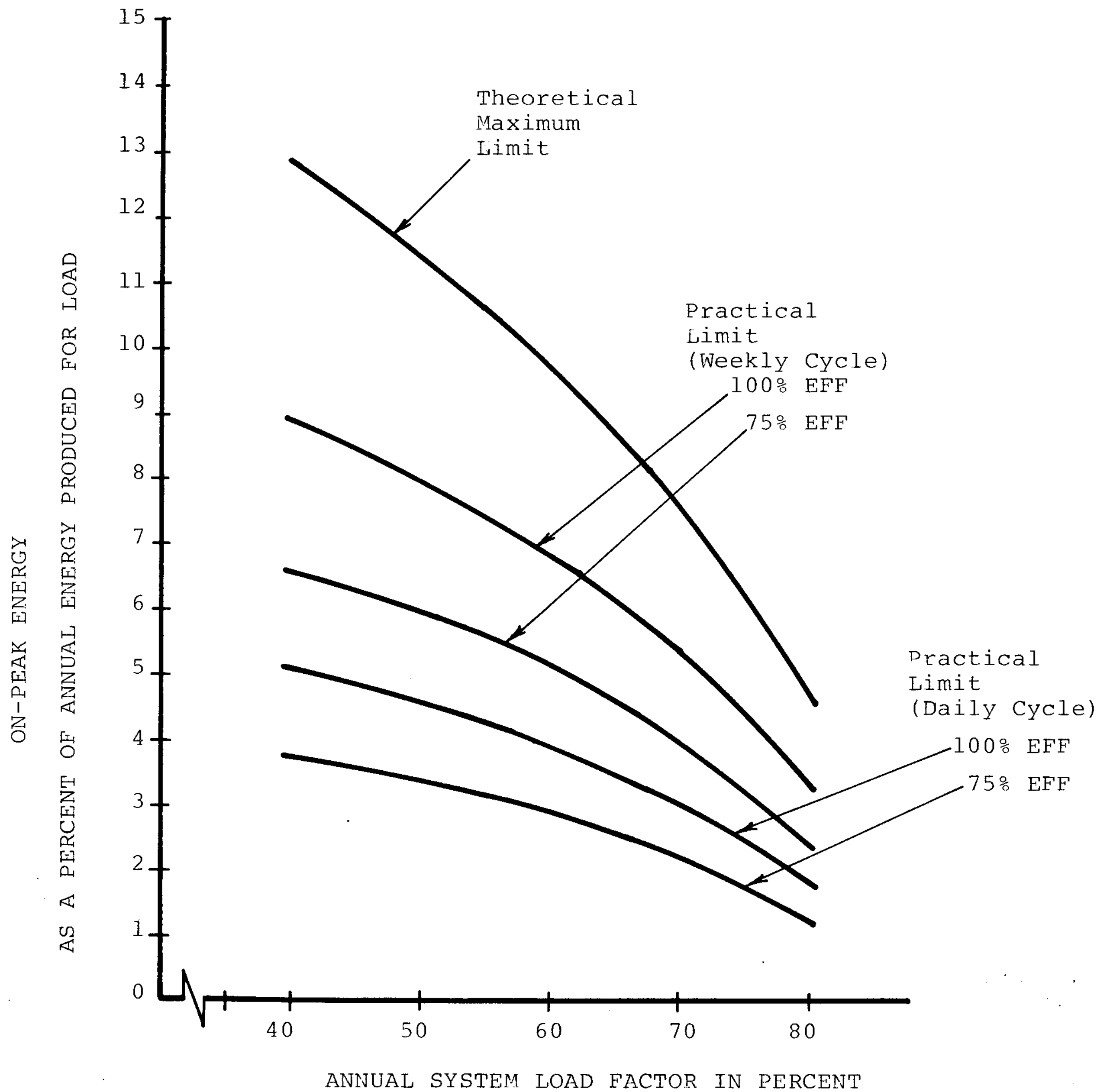


Figure 1-4 PRACTICAL LIMITS OF ON-PEAK ENERGY (INCLUDING THE EFFECT OF EFFICIENCY OF CONVERSION) CAPABLE OF BEING SUPPLIED BY THE OFF-PEAK ENERGY AVAILABLE ON U.S. ELECTRIC SYSTEMS

A daily cycle requires the smallest energy storage discharge capability (kWh), while a weekly cycle requires two or more times as much discharge capability as the daily cycle.

The above classification of duty cycles is desirable for general planning and analysis. It is possible that some forms of composite duty cycles may be suitable for certain specific applications. Such analysis is not considered to be necessary for a generalized study.

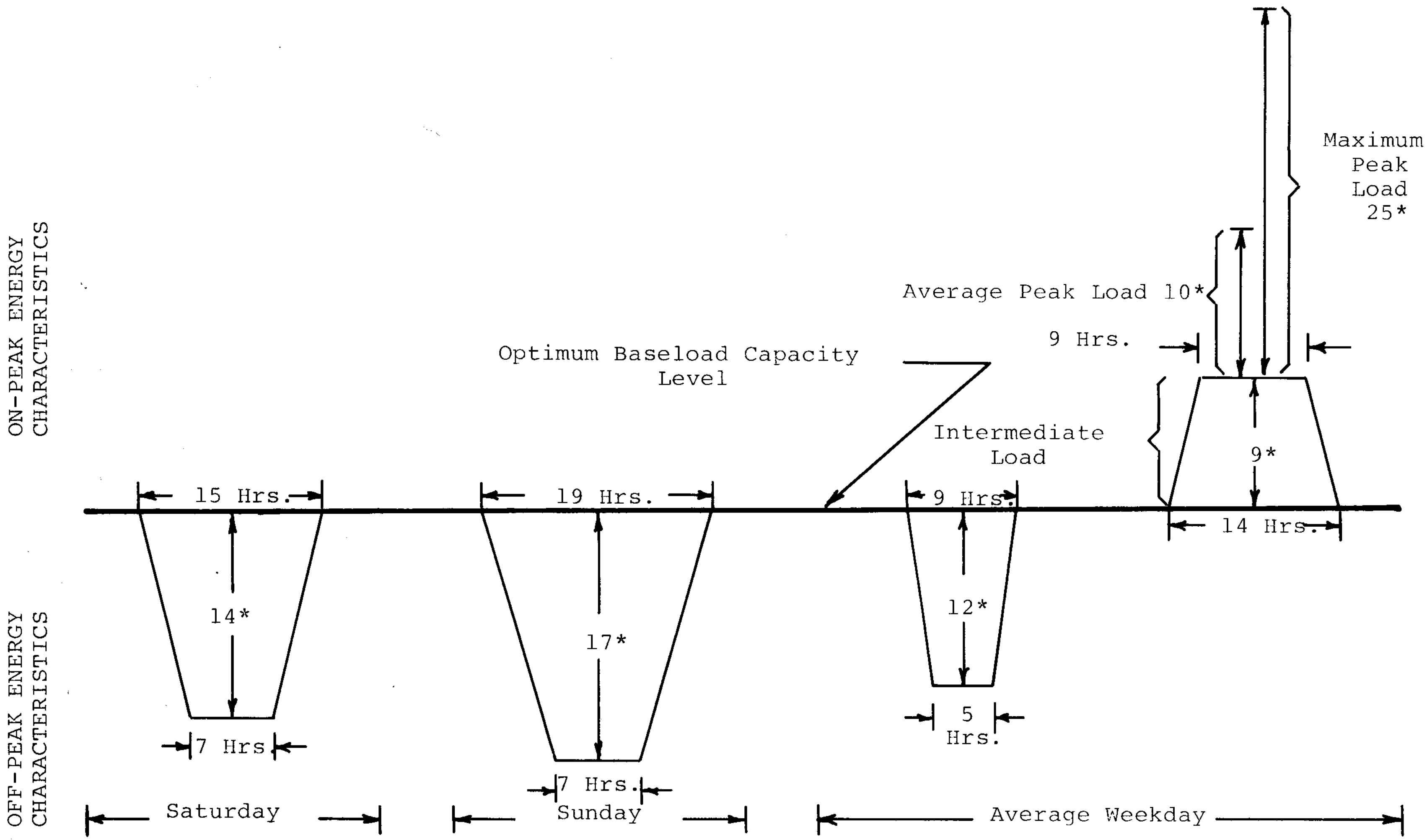
Detailed analyses of available off-peak energy and on-peak energy requirements permit development of duty cycles for each of the representative electric systems. The duty cycle parameters include required charging hours, discharge hours, discharge capability, and frequency of energy storage operation for both the peaking and intermediate duty application.

The average off-peak and on-peak load characteristics for U.S. electric utilities is shown in composite form in Figure 1-5. These characteristics are weighted industry averages and detailed in Chapter 2 and associated appendices. The on-peak energy requirements shown in Figure 1-5 consists of two types of load, intermediate load and peaking load. The duration of the intermediate loads fall in a range of 9 to 14 hours. Peaking loads fall in a range of 1 to 8 hours. The complete range of duty cycle operating parameters for energy storage on U.S. electric utilities is given in Table 1-2.

A change in energy storage system efficiency affects the charge/discharge ratios shown in Table 1-2. Lowering the energy storage efficiency would increase the required charging time for meeting the same discharge requirements.

Supportable Capacity

Table 1-3 shows as a function of conversion efficiency, the maximum amount of energy storage capacity which could be supported on a typical U.S. electric system. These estimates are based on supplying the on-peak energy requirements with a wide range of combinations of peaking duty and intermediate-duty energy storage devices. A more detailed description of this method is given in Chapter 2.



* Magnitude as a percent of system annual peak load

Figure 1-5 OFF-PEAK AND ON-PEAK ENERGY CHARACTERISTICS OF U.S. ELECTRIC SYSTEMS IN COMPOSITE FORM

Table 1-2 RANGES OF DUTY CYCLE OPERATING PARAMETERS FOR ENERGY STORAGE DEVICES SUITABLE FOR APPLICATION ON U.S. ELECTRIC SYSTEMS

	Type of Operation			
	Intermediate Duty		Peaking Duty	
Duty Cycle Characteristics	Daily Cycle	Weekly Cycle	Daily Cycle	Weekly Cycle
Discharge Time - T_d (hours/day)	9 - 14	9 - 14	1 - 8	1 - 8
Charge Time				
Weekday - T_{cd} (hours/day)	5 - 9	5 - 9	5 - 9	5 - 9
Weekend - T_{cw} (hours/weekend)	-	14 - 34	-	14 - 34
Annual Operation				
Discharge (hours/year)	2000 - 4000	2000 - 4000	250 - 1200	250 - 1200
Charge (hours/year)	1000 - 2500	2000 - 4000	1000 - 2500	2000 - 4000
Charge/Discharge Rated Power Ratio - C/D*				
Device Efficiency 75%	1.3 - 3.7	.8 - 2.4	.1 - 2.1	.1 - 1.4
" " 50%	2.0 - 5.6	1.1 - 3.6	.2 - 3.2	.1 - 2.1
Storage Capability (hours at rated discharge power)	9 - 14	24 - 34	1 - 8	3 - 19

For daily cycle applications, the total amount of energy storage discharge power capacity capable of being supported varies from 14 percent to 10 percent of annual peak, based on efficiencies of 100 and 50 percent, respectively. For weekly cycle applications, the amount of energy storage discharge power capacity capable of being supported is approximately 40 percent greater than that of the daily cycle. The total amount was estimated to range from 20 percent at a 100 percent conversion efficiency to 14 percent at 50 percent efficiency.

Table 1-3 ESTIMATED MAXIMUM ENERGY STORAGE POWER CAPACITY CAPABLE OF BEING SUPPORTED ON A TYPICAL U.S. ELECTRIC UTILITY SYSTEM

Cycle	Efficiency (Percent)	Installed Energy Storage Power Capacity (Percent of Annual System Peak)
Daily	100	14
	75	12
	50	10
Weekly	100	20
	75	17
	50	14

1.2 ASSESSMENT OF ENERGY STORAGE TECHNOLOGIES

While hydro pumped storage has been the only approach to utility storage of energy in widespread use, several other concepts have been proposed, and extensive research and development work has been undertaken to pursue the more attractive technologies. This section presents the summary results from the assessment of the technical and economic feasibility of the storage technologies.

Approach

The literature on energy storage is extensive. However, it is not possible to base a technical assessment on data available in the literature. Common definition of terms are often not used, complete system designs are not presented, and cost characteristics are not given or else provided without sufficient detail. It was necessary then in this study to:

- Review the stage of development of proposed approaches to energy storage
- Establish technical characteristics
- Estimate installed costs

In addition, the overall objective of this work required that this study establish the economic competitiveness of the technologies and identify research and development needs for the technologies. Chapter 3 describes the technologies considered in this study. Chapter 4 presents the results of specific cost estimates; Chapter 5 details the economic comparison; Chapter 6 identifies the environmental factors; and Chapter 7 reviews the research and development requirements.

The two sections which follow summarize a comparison of the technologies considered and present a relative ranking based on their projected economic competitiveness.

Comparison of Candidate Storage Technologies

Of the identified technologies for utility energy storage in the initial screening process, seven survived (Table 1-4). With two separate concepts for thermal storage and the separation of battery energy storage systems into near-term and advanced categories, a total of nine concepts are considered.

Status of Technologies

Each energy storage technology was judged on the basis of technical feasibility and stage of development. Such analysis provides an evaluation of time periods for commercial availability, but does not distinguish between economic and non-economic systems. It does permit the identification of systems that are candidates for later economic comparisons.

The results of assessing the technical feasibility of storage options can be summarized by classifying expected commercial availability of the storage technologies into time frames: near-term, intermediate-term, and long-term. Near-term refers to those systems which exist today or which may be commercially available by 1985 (not necessarily in service). Intermediate-term

Table 1-4 CANDIDATE TECHNOLOGIES SELECTED FOR DETAILED STUDY

"Mechanical" Storage Systems	
Hydro Pumped Storage	- Conventional - Underground Reservoir
Compressed Air Storage	- with Combustion Turbine - Storage in excavated Caverns, aquifers and salt cavities
Thermal Energy Storage	- Sensible Heat Storage - Pressurized Water in Above-ground Tanks - Hot Oil in Atmospheric Tanks
Flywheel Energy Storage	- Factory Fabricated Composite Wheels
"Chemical" Storage Systems	
Battery Energy Storage	- Lead-Acid, Lithium-Iron Sulfide, Sodium-Sulfur, Sodium-Chloride and Zinc-Chlorine
Hydrogen Storage	- Electrolyzer, Metal Hydride or Compressed Gas, and Fuel Cell or Combined Cycle
"Electromagnetic" Storage Systems	
Superconducting Magnetic Energy Storage	- Warm Reinforcement and Underground Construction

includes those systems which are expected to be commercially available in the period 1985 to 2000. Technologies expected to be available beyond 2000 are considered long-term.

In any analysis of projected characteristics of future technologies, some prophesies may be self-fulfilling. A technology that is not pursued through an effective R&D program will certainly never become a commercial success.

Near-Term Technologies. Technically feasible near-term technologies include: conventional and underground hydro pumped storage; storage of compressed air for combustion turbines; thermal energy storage in central power plants; and the lead-acid battery. The required development effort prior to commercialization of these technologies (excluding conventional pumped hydro which is already commercial) can best be described as "first of a kind" engineering. Suitable equipment and systems are likely to be extensions of existing technologies, and the actual selection of a specific approach will primarily involve carrying out specific engineering design and cost studies.

Hydro pumped storage systems are proven technologies with well documented technical and cost characteristics. Cost ranges do not reflect uncertainties but are due to variations in local conditions. Once a specific site is chosen, costs can be estimated with good confidence.

Compressed air storage with combustion turbines utilizes essentially state-of-the-art components. Major uncertainties relate to the thermo-physical properties of the storage cavern and the exact storage reservoir chosen.

Thermal energy storage appears to have two near-term variations that could utilize conventional equipment. Thermal energy can be extracted from several locations in the power cycle and stored as the sensible heat of water or oil. Each has its advantages and the power-related capital costs are similar (the oil system being somewhat more expensive). The storage-related capital costs show a wide variation. Steam storage, with reasonably conservative design, leads to high pressure-vessel costs. Sensible heat storage in oil near atmospheric pressure results in substantially lower storage costs and appears competitive with hydro pumped storage and compressed air.

A lead-acid battery energy storage station using existing cell designs for extended life and deep discharge, and line commutated converters could be designed today. However, although lead-acid batteries have been in use since 1880, and are widely used by utilities for emergency station power, large lead-acid energy storage stations have not been constructed recently, and batteries specifically designed for this application have not been manufactured. It appears commercialization could proceed relatively rapidly if a utility market for this expensive storage technology could be identified.

Intermediate-Term Technologies. Improvements are expected in the near-term technologies. In addition, new approaches may result from current research and could lead to the development of additional intermediate-term technologies. Candidate intermediate-term technologies identified in this study of utility energy storage include advanced batteries, flywheels and hydrogen.

Advanced battery systems and flywheel storage devices might prove suitable for dispersed siting. Hydrogen storage systems, with many separate components and either gas or hydride storage systems, seem bulkier and less likely to be effectively sited through a utility system. Although all of these systems could face siting problems, none needs to be remotely sited. Consequently, a definite transmission savings should result from their use on electric power systems.

Major problems have been identified for each of these technologies. In battery systems, life is a key problem when low cost must be simultaneously achieved. For flywheel systems, life is clearly a design parameter but achieving low cost is difficult. For hydrogen storage, both improvements in storage efficiency and reduction in capital cost are needed, together with identification of specific advantages in utility applications.

Long-Term Technologies. In the long-term, major advances could improve the attractiveness of existing near-term and intermediate-term options. In addition, two approaches currently under investigation could lead to commercial systems. These approaches are: (1) the various closed-cycle chemical energy systems; and (2) superconducting magnetic energy storage systems. Both concepts are in an early stage of development, and their characteristics are not yet sufficiently well defined for a definitive assessment. The development of superconducting magnetic energy storage has only been recently initiated. Mature chemical process technologies related to closed-cycle chemical energy storage systems exist, but little conceptual development has been directed toward the storage application.

Cost and Performance Characteristics

Capital cost and performance characteristics of selected energy storage systems are summarized in Table 1-5. These estimates provide the basis for an analysis of the economic competitiveness of the energy storage systems among themselves and with conventional non-storage forms of generation.

Cost Estimates. The capital costs of energy storage systems, in first approximation, can be described as a sum of two terms. The costs (Cp, in $/kW) for the power related equipment are associated with the power output (kW) of the device. The storage costs are determined by the specific costs (Cs, in $/kWh) of energy storage capacity and the time (T, in h) for which the storage system can deliver energy at rated output power. Analyzed in this fashion, the per unit capital cost (C, in $/kW) is:

$$C = Cp + Cs \cdot T$$

Estimates of the terms Cp and Cs are given in Table 1-5 for the specific energy storage technologies and systems considered in this study. These costs include both equipment and installation costs and normal contingencies and overheads, but do not include an allowance for interest during construction.

Expected Life. Equipment life is generally related to its basic design and operating mode. Achieving adequate life is usually accomplished by proper design, taking into account cost and performance trade-offs. Adequate life (20 years) is achievable for most of the systems considered. The exceptions worth noting are hydro pumped storage for which operational life of 50 years is common, and lead-acid battery storage for which cell life is likely to be 5 to 10 years. However, other components of the battery storage system have longer lives than the battery cells themselves.

Efficiency. A comparison of the technologies on the basis of their storage efficiency (Table 1-5) separates the technologies into three groups. The first and largest group of devices have efficiencies between 60 and 85 percent. This group contains all candidate technologies except hydrogen and compressed air storage. The second group, hydrogen storage, has a very low efficiency, less than 50 percent, primarily because the efficiency of converting hydrogen energy to electricity is relatively low. In group three (compressed air storage with combustion turbines), fuel is burned during the discharge portion of the cycle. This is not a pure energy storage system, therefore, a direct comparison of the energy efficiency of compressed air storage with other technologies would not be meaningful.

Construction Lead-Time. Estimates of construction lead-time are necessary to provide proper treatment of interest during construction. Construction

Table 1-5 EXPECTED TECHNICAL AND COST CHARACTERISTICS OF SELECTED ENERGY STORAGE SYSTEMS

Characteristics	NEAR TERM					INTERMEDIATE TERM			LONG TERM
	Hydro Pumped Storage	Compressed Air	Thermal: Steam	Thermal: Oil	Lead Acid Batteries	Advanced Batteries	Flywheel	Hydrogen Storage	Supercon-ducting Magnetic
Commercial Availability	Present	Present	Before 1985	Before 1985	Before 1985	1985-2000	1985-2000	1985-2000	Post 2000
Economic Plant Size (MWh or MW)	200-2000 MW	200-2000 MW	50-200 MW	50-200 MW	20-50 MWh	20-50 MWh	10-50 MWh	20-50 MW	Greater than 10,000 MWh
Power Related Costs (a) ($/kWh)	90-160	100-210	150-250	150-250	70-80	60-70	65-75	500-860	50-60
Storage Related Costs (a) ($/kWh)	2-12	4-30	30-70	10-15	65-110	20-60	100-300	6-15	30-140 (c)
Expected Life (Years)	50	20-25	25-30	25-30	5-10	10-20	20-25	10-25	20-30
Efficiency (d) (%)	70-75	(e)	65-75	65-75	60-75	70-80	70-85	40-50	70-85
Construction Lead Time (Years)	8-12	3-12	5-12 (f)	5-12 (f)	2-3	2-3	2-3	2-3	8-12

(a) Constant 1975 dollars, does not include cost of money during construction.
(b) Could be considerably higher.
(c) These numbers are very preliminary.
(d) Electric energy out to electric engery in, in percent.
(e) Heat rate of 4200-5500 Btu/kWh and compressed air pumping requirements from .58 - .80 kWh (out).
(f) Long lead time includes construction of main power plant.

Caveat - Data applies only to designs as considered in Chapter 4 lead-time is also important in considering when a particular technology could be in service. Examples are the long lead-time for hydro pumped storage and the short lead-time expected for battery systems. Hydro technology is available now while advanced batteries are not expected to be commercially available prior to 1985. Yet the difference in construction lead-time between these two technologies could result in similar first in-service dates.

Operating Characteristics

Operating characteristics are summarized in Table 1-6. Several of these characteristics are subject to the choice of designer, with the number of design choices limited by economic considerations.

The seven characteristics mentioned in Table 1-6 are: (1) load following, (2) part load operation, (3) on-line spinning reserve, (4) start-up time, (5) turnaround time, (6) black start, and (7) transient stability. Load following is a condition in which output is permitted to follow short-term variations in load. In part load operation output is readily set at values below maximum output. On-line spinning reserve is operation in a condition where output can be rapidly increased if loss of a generating unit occurs elsewhere in the power system. Start-up time is the time required to start from zero output. Turnaround time is the time required to go from full charge to full discharge. Black start capability is the capacity to start generation without external sources of electricity. Transient stability refers to the effect the storage system has on the system stability.

With the exception of their impact on transient stability, the storage technologies cannot be ranked on a qualitative basis solely as a result of the operating characteristics.

Dispersed Siting

The potential for dispersed siting is most attractive to electric utilities. This idea was originally considered for batteries, but has also been given consideration with respect to hydrogen storage and flywheels. In part, the potential advantage of dispersed siting is related to the possibility of developing compact and environmentally acceptable storage units that could be rapidly installed by electric utilities. Also capital cost savings due to decreased requirement for new transmission and distribution facilities could become significant (see Chapter 5). For systems or specific applications,

TABLE 1-6 STORAGE SYSTEM OPERATING CHARACTERISTICS

	Hydro Pumped Storage	Compressed Air with Combustion Turbine	Thermal: Separate Peaking Turbine	Thermal: Variable Extraction Turbine	Hydrogen with Fuel Cells or Batteries: Line-Commutated	Hydrogen with Fuel Cells or Batteries: Forced-Commutated	Flywheels	Superconducting Magnetic
Load Following	Yes (a)	Yes (a)	Yes	Yes	Yes	Yes (a)	Yes	Yes
Part-Load Operation	Yes (a)	Yes (a)	Yes	Yes	Yes	Yes (a)	Yes	Yes
Spinning Reserve On-Line	Yes (a)	Yes (a)	Yes	Yes	Yes	Yes	Yes	Yes
Start-Up Time	Minutes	Minutes	Minutes (b) Hours	Minutes	-Design Variable -Cycles to Minutes (c)		Few Cycles to Seconds	Few Cycles (c) to Seconds
Turnaround Time	Minutes	Minutes	Minutes (b) Hours	Minutes	-Design Variable -Cycles to Minutes		Few Cycles	Few Cycles to Seconds
Emergency Start (Black Start)	Yes	Yes	Yes	No	No	Yes (c)	Yes (d)	No (e)
Transient Stability	Normal Hydro	Normal Gas Turbines	Normal Steam Turbines		-Immune -Can Improve -Design Variable		-Immune -Can Improve -Design Variable	-Immune -Can Improve -Design Variable

(a) Yes, if sacrifice in efficiency acceptable.
(b) If turbine is at temperature.
(c) If source is at temperature.
(d) If at speed.
(e) If current-fed line-commutated converter.

where undergrounding is required, substantially higher savings are anticipated since underground transmission can be more than ten times as expensive as overhead. The importance of the potential savings in transmission and distribution is brought into perspective when it is recalled that the utilities have more capital invested in transmission and distribution facilities than in generating equipment.

Three factors must be considered in assessing suitability of a storage system for dispersed sites:

- Economic Size. This refers to the smallest plant or unit size below which economies of scale are unfavorable. In some systems economies of scale are controlled primarily by the power related component. For other systems, such as batteries, economies of scale are controlled by the amount of storage. Table 1-5 specifies the minimum economic size in megawatts or megawatt hour for each selected energy storage system.
- Land Requirements. Expected land area requirements are detailed in Appendix A and result in an effective ranking of the technologies as to land usage. Specific plant design approaches were assumed and care must be used in interpreting the data. However, these data can be used to identify compact devices.
- Environmental and Safety Factors. New generating capacity cannot be installed or operated unless it conforms to laws regulating environmental impact and safety. Although the review of the technologies identified some qualitative differences in environmental and safety factors, it did not provide a quantitative ranking.

The above considerations are summarized in Table 1-7. It is evident from the data that only two systems appear generally physically suitable for dispersed siting: advanced batteries and flywheels. In areas where large land areas are available it would also be possible to disperse hydrogen storage systems and lead-acid battery systems.

Economics

Two major results of this assessment are (1) the costs projected for the selected energy storage systems, and (2) the anticipated allowable costs. A comparison of these costs shows an economic competitiveness ranking of the technologies as shown in Figures 1-6 and 1-7. The graphs indicate the relative economic incentive in pursuing a given energy storage system. "Economic competitiveness," as used in these graphs, is the difference between the present worth of all future revenue requirements of the utility for using energy storage technologies versus conventional non-storage alternatives. Positive values of economic competitiveness indicate the economic benefit accrued from employing energy storage devices, negative values indicate the benefit accrued by utilizing conventional generation modes.

The graphs were developed from cost estimates that are described in Chapter 5. Figure 1-6 compares the operation of a gas turbine with energy storage systems operated for 2, 5, and 10 hours a day, which is considered a peaking duty application. Figure 1-7 compares the operation of a combined cycle plant with an energy storage system operated for 10, 12, and 15 hours a day which is considered as an intermediate duty application. The large range in the graph covers variations in economic parameters such as fuel costs, as well as uncertainties in the cost estimates.

Table 1-7 COMPARISON OF STORAGE TECHNOLOGIES, LAND AREAS AND ECONOMIC SIZE

	Economic Size	
	Moderate	Large
Land Requirements		
Moderate	Advanced Batteries Flywheels	Thermal (Steam;Oil) Compressed Air Underground Hydro Pumped Storage Superconducting Magnets
Large	Near-Term Lead Acid Batteries Hydrogen	Conventional Hydro Pumped Storage (Low Head)

The economic competitiveness defines a breakpoint below which an energy storage device is not as attractive as a conventional generating mode and above which is more attractive. Figures 1-6 and 1-7 represent trends rather than absolute statements on competitiveness. First, the validity of several of the cost estimates is not well established. Second, the assumed costs of fuels and other factors such as inflation are subject to variations that will affect the economics. A continuing analysis of these factors will be required to refine and confirm this comparison.

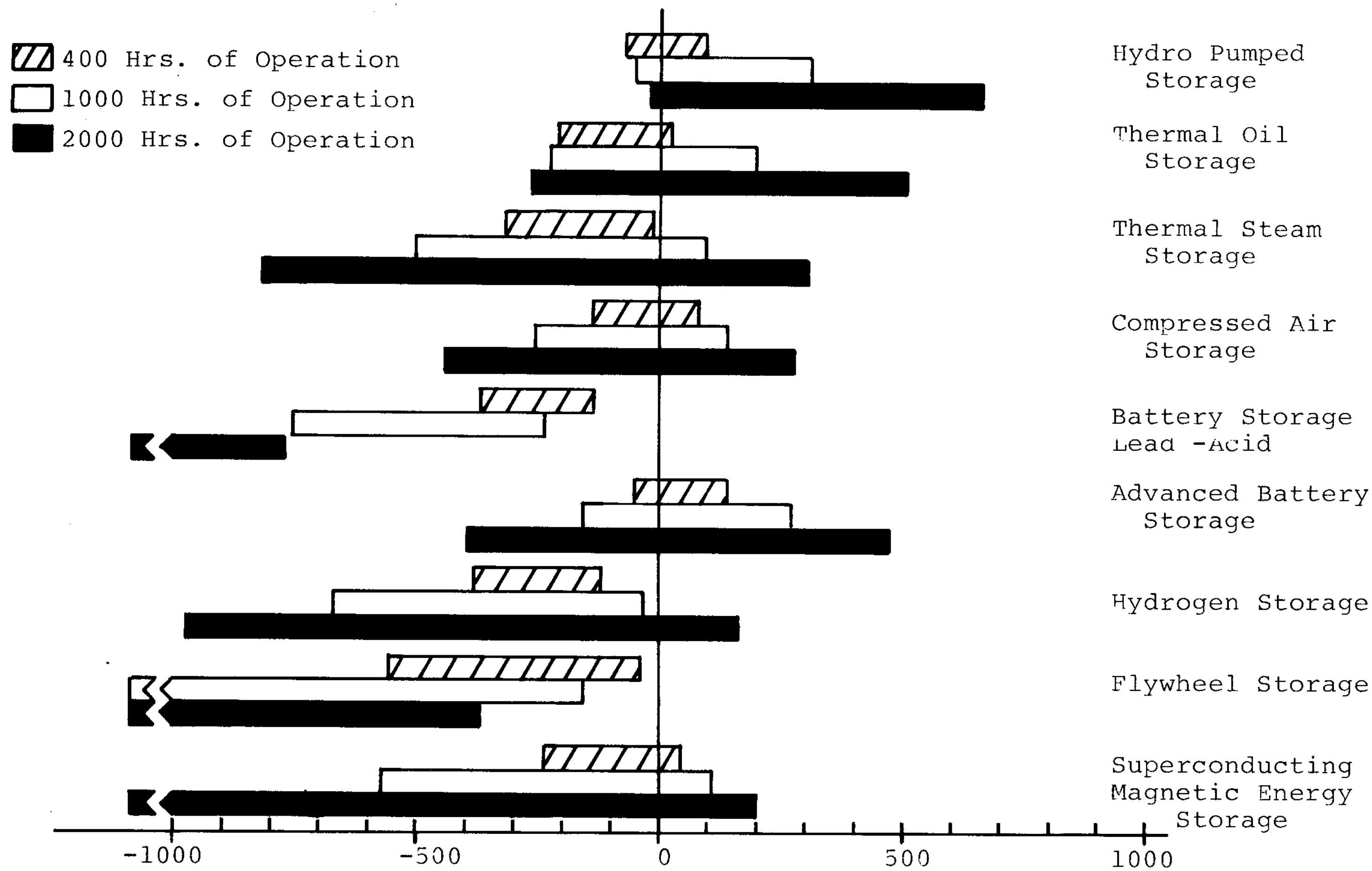


Figure 1-6 ECONOMIC COMPETITIVENESS OF ENERGY STORAGE VERSUS GAS TURBINE FOR PEAKING DUTY CYCLES

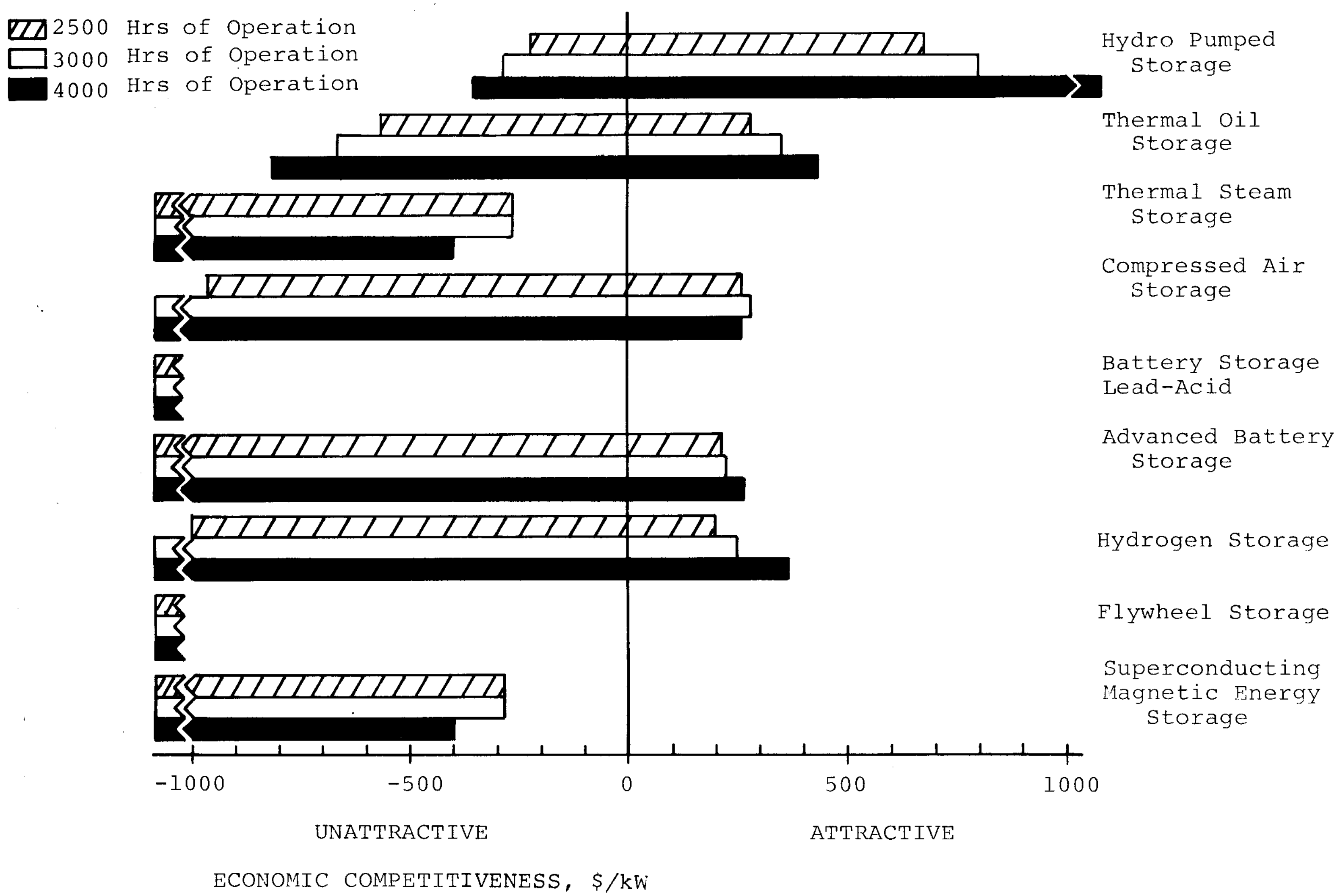


Figure 1-7 ECONOMIC COMPETITIVENESS OF ENERGY STORAGE VERSUS COMBINED CYCLE FOR INTERMEDIATE DUTY CYCLES

Ranking of Storage Technologies

A comparison of the energy storage concepts examined in this study identifies several promising near-term and future technologies (Tables 1-8 and 1-9) for application as peaking and intermediate generating capacity. In the near-term, hydro pumped storage, thermal storage integrated into a conventional power plant, and compressed air storage with combustion turbines appear technically and economically feasible. In the intermediate-term (1985-2000), advanced battery storage and hydrogen storage appear technically attractive and potentially economic. In the long-term (beyond 2000), superconductive magnetic energy storage systems could possibly become technically feasible and might prove to be economic if the most optimistic cost goals are achieved.

Additional distinguishing characteristics, other than economics, can be considered in ranking energy storage technologies. However, such efforts are fine tunings, not warranted given the doubtful accuracy of existing cost data for the future technologies and the fact that different characteristics will have different values for individual utility systems because of differences in generation mix, fuel cost and load shape. The overall ranking into three groups (attractive, attractive under favorable conditions, and unattractive) are not expected to change. Thus for any research and development effort, the primary emphasis should be on hydro pumped storage; advanced batteries; thermal storage integrated into central power plants; and compressed air storage.

Table 1-8 OVERALL RANKING OF NEAR TERM STORAGE TECHNOLOGIES

Rating	Application: Peaking	Application: Intermediate
Active	Hydro	Hydro
Attractive Under Favorable Conditions	Thermal Compressed Air	Thermal Compressed Air
Unattractive	Lead Acid Batteries	Lead Acid Batteries

Table 1-9 OVERALL RANKING OF NEAR TERM AND FUTURE TECHNOLOGIES

Rating	Application	
	Peaking	Intermediate
Attractive	Advanced Batteries Hydro Pumped Storage	Hydro Pumped Storage
Attractive Under Favorable Conditions	Thermal Oil Compressed Air Thermal Steam Superconducting Magnetic Hydrogen	Advanced Batteries Compressed Air Hydrogen Thermal Oil
Unattractive	Near Term Lead Acid Batteries Flywheels	Thermal Steam Near Term Lead Acid Batteries Superconducting Magnets Flywheels

1.3 OTHER FINDINGS AND CONCLUSIONS

The analysis of actual load data from electric utilities representative of the U.S. electric utility industry shows that:

- Energy storage can plan an important role in providing future generating capacity for peaking and intermediate electric loads, provided sufficient baseload generating capacity is installed. Energy storage can substitute for oil fueled conventional peaking plants.

- Regardless of the geographic location of the utility or the season in which the annual system peak load occurs, electric utilities have similar load characteristics at the daily or weekly level.

- For any electric utility, a maximum installed baseload capacity level (generally in the range of 60 to 80 percent of annual peak load) exists for which the on-peak energy requirement is approximately equal to the available off-peak energy.

- The distribution of both off-peak and on-peak energy on U.S. systems on a seasonal, weekly and daily basis is relatively even. This and the capital cost constraints on total storage capacity favor the application of energy storage on a daily and/or weekly cycle.

- Energy storage devices capable of weekly cycle operation are particularly appealing because nearly one-half of the off-peak energy is generally available over the weekend period and over 90 percent of the on-peak energy requirements occur on weekdays (Monday through Friday). Weekly cycle operation could utilize 70 percent of available off-peak energy.

- Based on a 75 percent overall efficiency, the maximum practical amount of installed energy storage power (MW) capacity available was estimated to be approximately 17 percent of annual system peak load.

- The maximum practical annual amount of on-peak energy (MWh) capable of being supplied by energy storage operating on a weekly cycle and 75 percent efficiency was estimated to be approximately 5 percent of total annual energy.

- Based on the daily cycle and 75 percent efficiency, the maximum power capacity (MW) was estimated to be up to 12 percent of annual peak load. The corresponding annual amount of energy would be approximately 3 percent.

- A spectrum of practical energy storage duty cycle parameters can be defined for the application of energy storage systems by electric utilities. The wide range of duty cycle operating parameters based on both the daily and weekly cycle modes of operation for both intermediate and peaking generation applications should facilitate the application of a number of different types of energy storage technologies to U.S. electric systems.

The analysis and assessment of energy storage technologies proposed as suitable for use by electric utilities showed that:

- Technically feasible and economically attractive energy storage technologies for near-term, intermediate-term, and long-term exist or are reasonable prospects for development.

- At the present time, conventional hydro pumped storage is technically feasible, economic, and in widespread use.

- For the near-term (through 1985), hydro pumped storage with an underground reservoir, compressed air storage, and thermal storage integrated with a central power plant appear to be feasible and economic for peaking and intermediate duty.

- For the intermediate-term (1985-2000), in addition to the technologies named above, advanced batteries appear to be attractive, especially for peaking duty. Hydrogen storage systems may also prove to be economic for certain intermediate duty applications which require large storage capacities and in which its low efficiency (less than 50 percent) is not a handicap.

- For the long-term (beyond 2000), other storage concepts could be developed to provide viable options. However, current perception of future state-of-the-art is not adequate to properly address technologies such as superconducting magnetic energy storage which are in early stages of conceptual development.

- Advanced battery systems appear to be sufficiently compact, economically attractive, and environmentally acceptable to be suitable for dispersed siting throughout utility systems. Continued R&D should be devoted to these systems to seek improvements in life and development of low cost manufacturing processes.

- Thermal storage systems, integrated with nuclear plants, are identified as a potentially attractive near-term technology. Further conceptual design work and preliminary engineering studies will be needed to confirm the promise currently seen for these systems.

- Certain technologies were found to be generally unattractive. In particular, flywheel storage systems are too expensive except for special applications in which high power, but little storage capacity, is required. Near-term state-of-the-art lead acid batteries, because of high cost and relatively short life are of interest only where significant benefits might occur from the operating characteristics of electrochemical storage systems or for applications requiring only very small storage capacities. Determination of the value of specific operating benefits awaits further study.

- Storage technologies, other than those considered in detail in this study, could prove to be attractive. Some consideration should be given to systems not treated herein. Specific examples include: thermal storage using underground storage of pressurized water; compressed air storage with thermal storage of the heat of compression; and use of fluids other than water and oil in thermal storage systems.

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