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ENERGY RESEARCH & DEVELOPMENT ADMINISTRATION

THE ECONOMICS OF THERMAL ENERGY STORAGE FOR COMPRESSED
AIR ENERGY STORAGE SYSTEMS

by

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ABSTRACT

The costs of compressed air energy storage (CAES) systems utilizing thermal energy storage are compared with the costs of conventional CAES systems and combustion gas turbine systems. Comparisons are made on the basis of system energy cost levelized over system operating lifetime (mills/kWh). The comparison was performed by Pacific Northwest Laboratory for the Department of Energy using information from reference studies by the Massachusetts Institute of Technology, Central Electricity Generating Board and Knutsen Research Services.

System energy costs were estimated using information from three reference CAES/thermal energy storage studies, a recent PNL research effort, and the EPRI Technical Assessment Guide. Capital investment cost estimates and system operating requirements were obtained from the reference studies. Current turbine fuel and compression energy prices were obtained from a July 1979 PNL research effort. Economic and financial input assumptions and a discounted cash flow-required revenue computational methodology were taken from the Technical Assessment Guide. Use of such a "normalization" procedure results in system energy cost estimates that are both realistic and comparable.

Two principal conclusions resulted from the study. First, given today's fuel prices and the expected fuel prices in the 1980's, conventional CAES systems yield lower energy cost estimates than combustion gas-turbine systems. Second, thermal-energy-storage/adiabatic CAES systems yield equivalent and, in some instances, slightly lower energy cost estimates than conventional CAES systems while requiring considerably less turbine fuel oil.

INTRODUCTION

The cost of energy from conventional compressed air energy storage (CAES) systems is highly dependent upon the cost of the turbine fuel oil used in this system. Due to the uncertainty and rapid escalation of fuel oil prices, this dependence upon fuel oil decreases the economic attractiveness of conventional systems and increases the attractiveness of systems that require little or no fuel.

The purpose of the study described in this paper was to assess the costs of one group of alternative near term CAES system concepts that require little or no turbine fuel. These alternative systems utilize thermal energy storage. In these systems, a thermal energy storage device is heated or charged using the heat of compression. Thermal energy is then stored for use during the system's power generation cycle. During power generation, compressed air is passed through the thermal energy storage device resulting in heating of the compressed air. The additional heat available from thermal energy storage replaces heat that in conventional systems would be generated by burning fuel oil. This substitution results in a decrease in system fuel cost. If the decrease in fuel cost more than offsets increases in compression energy cost and thermal energy storage device cost, the net effect of utilizing thermal energy storage is to reduce system energy costs. Under these circumstances, CAES/thermal energy storage systems are economically more attractive than conventional CAES systems.

The measure of system cost or economic performance used in the comparison is system energy cost levelized over the system's operating lifetime. The cost estimates are reported in 1979 price levels in terms of mills/kWh.

The study was performed by Pacific Northwest Laboratory for the Division of Energy Storage Systems, the Department of Energy.

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APPROACH

The approach taken to assess economic performance was to develop and compare alternative system levelized energy cost estimates. Estimates were developed for CAES systems utilizing thermal energy storage, conventional CAES systems, and combustion gas turbine systems. Assessments of economic performance were based on these energy cost estimates.

The procedure used to develop energy cost estimates is shown in Figure 1. It is important to recognize that this paper is not reiterating the findings of the reference studies. The study reported in this paper uses the reference studies as sources of input information only. In most instances, this study's energy cost estimates are different from the reference study estimates. This results from the use of very current (July-August 1979) price information in this study and outdated price information (pre-1979) in the reference studies.

FIGURE 1. Levelized Energy Cost Estimating Procedure

The reference studies are as follows:

- Advanced Compressed Air Energy, Central Electricity Generating Board, March 1979. (Preliminary Draft.)(2)
- Incremental Cost Analysis of Advanced Concept Compressed Air Energy Storage Systems, Knutsen Research Services, July 1979. (Preliminary Draft.)(3)
- Application and Design Studies of Compressed Air Energy Storage for Solar Applications, Massachusetts Institute of Technology, February 1979. (Draft Final Report.)(1)

The type of consolidation/update study described in this paper is useful in two respects. First, such a study reports the results of different studies collectively. Credibility is enhanced when independently generated studies arrive at similar conclusions. Second, this type of study provides for the updating of previously generated studies whose conclusions are invalid because they were based on now outdated input. Often, different yet valid conclusions can be drawn from older studies that are reworked with current input. Both these reasons indicate the usefulness of a consolidation/update study to the compressed air energy storage development program.

SYSTEM DESCRIPTIONS

Four generic near term peaking system concepts were examined in this study. Two compressed air energy storage (CAES) systems utilizing thermal energy storage, one conventional fired CAES

system, and one combustion gas turbine system. The conventional CAES system and combustion gas turbine system were included in the analysis for comparative purposes. The four generic system concepts are as follows:

- CAES/One Stage TES/Hybrid
- CAES/Two Stage TES/Adiabatic
- Conventional CAES
- Combustion Gas Turbine

Simplified system diagrams are shown in Figure 2 for the conventional CAES system concept, in Figure 3 for the one stage thermal energy storage/hybrid system concept, and in Figure 4 for the two stage thermal energy storage/adiabatic system concept. The one stage thermal energy storage/hybrid system utilizes thermal energy storage and is fired (i.e., requires fuel oil to operate). The two stage thermal energy storage/adiabatic system operates adiabatically (i.e., is not fired). The conventional CAES system does not use thermal energy storage and is fired. The reference conventional CAES system is assumed to be of second generation design.

FIGURE 2. Conventional CAES

FIGURE 3. CAES/One Stage TES/Hybrid

FIGURE 4. CAES/Two Stage TES/Adiabatic

System designs, operating requirements, and capital investment cost estimates were taken from the reference studies. This information was used as input to the calculation of leveled energy cost. This information is shown in Table 1.

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TABLE 1. System Descriptions

PNL System Designation	Reference Study	Reference Study System Designation	Fuel Heat Rate (Btu/kWh)	Coefficient of Performance (kWh Out/kWh In)	Capital Investment Cost (1979 \$/kW)
CAES/One Stage TES/Hybrid	CEGB ⁽²⁾	A5-Hybrid	2,646	.95	304.
CAES/One Stage TES/Hybrid	Knutsen ⁽³⁾	TES-1	4,074	1.31	344.
CAES/One Stage TES/Hybrid	Knutsen ⁽³⁾	TES-4	3,545	1.13	355.
CAES/Two Stage TES/Adiabatic	Knutsen ⁽³⁾	TES-3	--	.65	580.
CAES/Two Stage TES/Adiabatic	MIT ⁽¹⁾	Systems A-H	--	.70	334.
Conventional CAES	CEGB ⁽²⁾	2nd Generation Brown Boveri	4,085	1.20	266.
Conventional CAES	Knutsen ⁽³⁾	Reference	4,416	1.45	292.
Combustion Gas Turbine	Knutsen ⁽³⁾	GT	14,000	--	185.

ECONOMIC ANALYSIS

The computational methodology utilized to estimate levelized energy cost was taken from the EPRI Technical Assessment Guide.⁽⁴⁾ Economic and financial input assumptions utilized in the analysis were also taken from the Technical Assessment Guide. Turbine fuel prices and compression energy cost estimates were developed specifically for this study by a PNL survey effort.^(5,6)

Reference CAES system designs are based on near term (pre-1985) design technology. Estimates reflect expected costs of commercial generating systems existing as part of a mature CAES economy (i.e., tenth plant built of a like technology). Estimates do not reflect costs for prototype or first of a kind systems. CAES systems are assumed to be owned and operated by a regulated electric utility company.

Three sets of input assumptions were used in the analysis. Base case assumptions reflect the most realistic input assumptions. Sensitivity Case 1 assumptions consist of assumptions typical of those used in previous year CAES/thermal energy storage studies. Sensitivity Case 2 input assumptions represent input for a low capacity factor/1000 hour operation per year system. Assumptions are shown in Table 2. In the table, only those sensitivity case inputs that differ from base case inputs are shown.

TABLE 2. Economic Assumptions

	Base Case Most Realistic Assumptions (July 1979)	Sensitivity Case 1 Year 1978 Assumptions	Sensitivity Case 2 Low Capacity Factor Assumption
First Year of Plant Operation	1985		
Plant Capacity Factor	.25 (8 Hr Discharge)		.12
Plant Lifetime	30 Yr		
Cost of Capital	10%/Yr		
Fixed Charge Rate	15%/Yr		
Compression Energy Cost (1979)	15 Mills/kWh	20 Mills/kWh	
Turbine Fuel Cost (1979)	\$5/10 ⁶ Btu	\$3.33/10 ⁶ Btu	
General Inflation Rate	6%/Yr		
Capital Escalation Rate	6%/Yr		
Operating and Maintenance Escalation Rate	6%/Yr		
Compression Energy Escalation Rate	7%/Yr		
Turbine Fuel Escalation Rate	8%/Yr	7%/Yr	
Gas Turbine Technology	Near Term	Advanced	

RESULTS

Estimates of levelized energy cost for the four system concepts are shown in Table 3. Estimates are reported in 1979 price levels for a construction/ operation scenario where CAES systems would begin commercial operation in 1985. Estimates were developed for each of the reference study design cases. A breakdown of levelized energy cost contributor elements for the base case estimates is shown in Figure 5.

TABLE 3. Levelized Energy Cost Estimates (1979 mills/kWh)

	Base Case Most Realistic Assumptions (July 1979)	Sensitivity Case 1 Year 1978 Assumptions	Sensitivity Case 2 Low Capacity Factor Assumption
CAES/One Stage TES/Hybrid	98 108 110	93 94 96	121 136 135
CAES/Two Stage TES/Adiabatic	99 77	116 93	143 102
Conventional CAES	107 108	91 89	127 130
Combustion Gas Turbine	206	103	220

FIGURE 5. Levelized Energy Cost Estimates - Base Case

CONCLUSIONS

A ranking of the economic performance of the four systems is shown in Table 4. Rankings were based on levelized energy cost estimates.

TABLE 4. Ranking of Systems Based on Energy Cost Estimates

	Base Case Most Realistic Assumptions (July 1979)	Sensitivity Case 1 Year 1978 Assumptions	Sensitivity Case 2 Low Capacity Factor Assumption
CAES/One Stage TES/Hybrid	2	2	1
CAES/Two Stage TES/Adiabatic	1	4	1
Conventional CAES	3	1	1
Combustion Gas Turbine	4	3	4

The most significant conclusion that can be made from examination of the rankings is that relative economic performance or ranking is very dependent upon turbine fuel oil and compression energy price. System ranking differs significantly depending upon the set of price assumptions utilized in the analysis. Base assumptions were developed from very current (July 1979) price information. These inputs reflect recent increases and uncertainty in fuel oil prices. Sensitivity Case 1 input assumptions were developed to match assumptions used in reference studies. Recent price increases and uncertainty are not reflected in these earlier year study assumptions. Energy cost estimates for systems that burn fuel oil are very sensitive to input assumptions. Energy cost estimates for systems that burn little or no fuel are relatively insensitive to input assumptions. Relative rankings of systems will vary depending upon the input assumption case utilized due to this difference in assumption sensitivity.

This study makes four conclusions with respect to the economic performance of compressed air energy storage (CAES) systems using thermal energy storage. These conclusions are as follows:

- CAES system energy cost estimates are very sensitive to changes in fuel oil prices and compression energy costs.
- CAES system energy cost estimates are less sensitive to changes in system capital investment cost.
- CAES systems appear less costly than combustion gas turbine systems.
- Previous studies have reported that dramatic fuel oil price increases would make CAES/thermal energy storage systems cheaper than conventional CAES systems. Fuel oil prices have increased dramatically. Adiabatic CAES systems using thermal energy storage now appear slightly less costly than conventional CAES systems.

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