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OFFICE OF ADVANCED
CONSERVATION TECHNOLOGIES
U.S. DEPARTMENT OF ENERGY

COMPILATION OF ENERGY STORAGE ASSESSMENTS

OCTOBER 1981

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A COMPILATION AND SUMMARY OF
TECHNICAL AND ECONOMIC
ASSESSMENTS IN THE FIELD OF
ENERGY STORAGE

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John DeVries

Hittman Associates, Inc.
Columbia, Maryland 21045

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INTRODUCTION

This document provides information extracted from various assessments of energy storage technologies conducted during the past four years, primarily under the auspices of the Office of Energy Systems Research and Development (formerly the Division of Energy Storage Systems).

A thorough search of the relevant literature was conducted using the DOE/RECON computerized data base and other sources. Only tabular or graphic material was abstracted from the documents.

The material has been organized in two ways: by the intended end use, and within each end use, by technology. The summary tables attempt to compare the results of different studies of the same technology or end use. No attempt is made to summarize the conclusions of each individual study, but rather to point out areas of agreement or disagreement between them. The reader should be aware of the risks in making comparisons between studies conducted by researchers with possibly differing purposes and assumptions. Any conclusions based on the summary sections are more indicative than definitive.

All dollar figures have been translated into 1980\$ for the summary tables, using the multipliers in the table below.

CONSTANT DOLLAR MULTIPLIERS

1980	100	1.0
1979	93.3	1.07
1978	85.7	1.17
1977	79.9	1.25
1976	75.4	1.33
1975	71.7	1.39

Source: U.S. Department of Commerce, Bureau of Economic Analysis

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SUMMARY

End Use: Vehicles

Technology: Batteries - General

<u>Energy Density</u> (Wh/kg)		Report		
	1	2	3	4
Lead-Acid	35	-	35-50	40-47
Nickel-Iron	58	-	45-60	55-65
Nickel-Zinc	65	-	70-90	75-85
Lithium-Metal Sulfide	110-120	-	-	-

<u>Power Density</u> (W/kg)		Report		
	1	2	3	4
Lead-Acid	73	-	-	66-98
Nickel-Iron	> 100	-	-	102-130
Nickel-Zinc	125	-	-	125-140
Lithium-Metal Sulfide	115-130	-	-	-

<u>Efficiency</u> (%)		Report		
	1	2	3	4
Lead-Acid	> 60	-	65	
Nickel-Iron	55-70	-	55-60	
Nickel-Zinc	75	-	65	
Lithium-Metal Sulfide	70-75	-	-	

Cycle Life

Report

	1	2	3	4
Lead-Acid	> 250	300-700	500	-
Nickel-Iron	800	1,500	1,500	-
Nickel-Zinc	200	200-300	250	-
Lithium-Metal Sulfide	>1,000	500-1,000	-	-

Cost (\$)

Report

	1	2	3	4
Lead-Acid	53-94	50	56	-
Nickel-Iron	59-70	63-75	94	-
Nickel-Zinc	59-70	63-75	75	-
Lithium-Metal Sulfide	64-94	50	-	-

STORAGE TECHNOLOGY:Electric Vehicle Batteries

SOURCE:TRW Inc. Development of a Data Base
Characterizing Energy Storage Tech-
nologies, Task 2, Characterization of
Storage Technologies in Transportation
Applications. Argonne National Labora-
tory, Contract 31-109-5106, 1979.**INFORMATION:**

Table 5-1. Characteristics of Major Electric Vehicle Batteries

<u>BATTERY CHARACTERISTICS</u>	<u>LEAD</u> <u>ACID</u>	<u>NICKEL</u> <u>IRON</u>	<u>NICKEL</u> <u>ZINC</u>	<u>LITHIUM</u> <u>METAL SULFIDE</u>
Energy Density (WH/kg) [3 hr rate]	35	58	65	110 - 120
Power Density (W/kg) [80% discharge]	73	>100	125	115 - 130
Efficiency (%)	>60	55-70	75	70 - 75
Cycle Life [80% discharge]	>250	800	200	>1000
Operating Temperature (°C)	Ambient	Ambient	Ambient	450
Costs* (1978 \$/kWh)	45-80	50-60	50-60	55 - 80

*Mass production assumed

SOURCES: References 19, 29, 30

Assumptions

Lead Acid - Current Batteries

Nickel Iron - 1980 Batteries (Projected development)

Nickel Zinc - 1980 Batteries (Projected development)

Lithium Metal Sulfide - Probable result of successful development by 1990.

STORAGE TECHNOLOGY:Electric Vehicle Batteries**SOURCE:**

TRW Inc. Development of a Data Base
 Characterizing Energy Storage Technologies, Task 2, Characterization of
 Storage Technologies in Transportation
 Applications. Argonne National Laboratory,
 Contract 31-109-5106, 1979.

INFORMATION:

Table 5-2.
 Characteristics of the Electric Compact Vehicle

<u>Vehicle Characteristics</u>	<u>Lead-Acid</u>	<u>LMS - I</u>	<u>LMS-II</u>
Length, in (cm)	160 (406)	160 (406)	160 (406)
Wheelbase, in (cm)	42 (107)	42 (107)	42 (107)
Curb Weight, lbs (kg)	3315 (1505)	3315 (1505)	2390 (1084)
Payload, lbs (kg) (4 passengers)	600 (270)	600 (270)	600 (270)
Acceleration Time (sec)			
0 to 30 MPH (48 kph)	9.0	4.5	4.5
0 to 60 MPH (96 kpm)	29.5	15.	15.
Peak HP*	25	50	36
Maximum grade (%)	17	17	17
Range, mi (km)**			
(no auxiliaries)	70 (112)	212 (339)	148 (238)
(full auxiliaries)	N/A	118 (189)	70 (113)
Energy use rate, kWh/mi (kWh/km)	0.36 (0.23)	0.36-0.65 ⁺ (0.23-0.41) ⁺	0.26-0.55 ⁺ (.16-.34) ⁺

* Maximum rating of electric motor - LMS vehicles can develop twice the power at 80% depth of discharge compared with lead acid vehicles.

** Based on SAE "D" cycle

⁺ Depends on auxiliary loads

STORAGE TECHNOLOGY:

Electric Vehicle Batteries

SOURCE:

TRW Inc., Development of a Data Base
 Characterizing Energy Storage Technol-
 ogies, Task 2, Characterization of
 Storage Technologies in Transportation
 Applications, Argonne National Labora-
 tory, Contract No. 31-109-5106, 1979.

INFORMATION:

Table 7-1.
 Summary of Characterizations for Urban
 (Commuter) Automobiles - 1990
 [English Units]

<u>Vehicle Characteristics</u>	<u>Baseline - Improved Heat Engine</u>	<u>Electric LMS-I</u>	<u>Electric LMS-II</u>	<u>Heat Engine- Flywheel Hybrid</u>	<u>Heat Engine- Battery Hybrid</u>
Weight (lbs)	2000	3315	2390	2400	3600
Payload (lbs)	600	600	600	600	600
Length (inches)	175	160	160	183	183
Peak HP	61	50	36	--	--
Acceleration Time (sec)					
0 to 30 MPH	3.5	4.5	4.5	3.5	3.5
0 to 60 MPH	15	15	15	14	14
Range (miles)	300	118-212	70-148	300	65 electric 300 total
Energy Use Rate (MPG)	45	--	--	108 heat engine	18.6*
Energy Use Rate (kWh/mi)	--	0.36-0.65	0.26-0.54		0.40** electric
Vehicle Cost (\$)	4,900	4,860	7,400	5,700	6,400

*MPG while operating on gasoline (20% of mileage)

Energy use operating on electricity (80% of mileage)

STORAGE TECHNOLOGY:

Electric Vehicle Batteries

SOURCE:

TRW Inc., Development of a Data Base Characterizing Energy Storage Technologies, Task 2, Characterization of Storage Technologies in Transportation Applications, Argonne National Laboratory, Contract No. 31-109-5106, 1979.

INFORMATION:

Table 7-1.
Summary of Characterizations for Urban
(Commuter) Automobiles - 1990 (cont'd)
[Metric Units]

Vehicle Characteristics	Baseline - Improved Heat Engine	Electric LMS-I	Electric LMS-II	Heat Engine- Flywheel Hybrid	Heat Engine- Battery Hybrid
Weight (kg)	900	1565	1684	1090	1630
Payload (kg)	270	270	270	270	270
Length (m)	4.45	4.06	4.06	4.65	4.65
Peak HP	61	50	36	--	--
Acceleration Time (sec)					
0 to 48 kph	3.5	4.5	4.5	3.5	3.5
0 to 96 kph	15	15	15	14	14
Range (km)	480	264	175	480	105 electric 480 total
Energy Use Rate (km/l)	7.0	--	--	16.8	2.9* heat engine
Energy Use Rate (kWh/km)	--	0.32	0.25	--	0.25** electric
Vehicle Cost (\$)	4,900	4,860	7,400	5,700	6,400

*MPG while operating on gasoline (20% of mileage)

**Energy use operating on electricity (80% of mileage)

ASSUMPTIONS & COMMENTS:

1978 dollars

STORAGE TECHNOLOGY:

Electric Vehicle Batteries

SOURCE:

TRW Inc., Development of a Data Base
 Characterizing Energy Storage Technol-
 ogies, Task 2, Characterization of
 Storage Technologies in Transportation
 Applications, Argonne National Labora-
 tory, Contract No. 31-109-5106, 1979.

INFORMATION:

Table 7-3.
 Summary of Characterizations for
 Urban Bus - 1990
 [English Units]

<u>Vehicle Characteristics</u>	<u>Baseline Bus (RTS-2)</u>	<u>Electric LMS Battery</u>
Weight (lbs)	24,500	22,050
Payload (Passengers)	50 seats 80 total	60 total
Length (ft)	40	33
Peak HP	270	105*
Acceleration Time (sec)		
0 to 30 MPH	14	22
Range (miles)	120 ⁺	155
Energy Use Rate		
(MPG)	3.9	--
(kWh/mi)	--	1.5
Vehicle Cost (\$)	72,000	85,500

* Could be increased to improve acceleration time
⁺ Typical Daily Range

STORAGE TECHNOLOGY:Electric Vehicle Batteries**SOURCE:**

TRW Inc., Development of a Data Base
 Characterizing Energy Storage Technol-
 ogies, Task 2, Characterization of
 Storage Technologies in Transportation
 Applications. Argonne National Labora-
 tory, Contract No. 31-109-5106, 1979.

INFORMATION:

Table 7-3.
 Summary of Characterizations for
 Urban Bus - 1990 (cont'd)
 [Metric Units]

<u>Vehicle Characteristics</u>	<u>Baseline Bus (RTS-2)</u>	<u>Electric LMS Battery</u>
Weight (kg)	(11,100)	1,000
Payload (Passengers)	50 seats 80 total	60 total
Length (m)	12	10
Peak HP	270	105*
Acceleration Time (sec)		
0 to 48 kph	14	22
Range (km)	75	250
Energy Use Rate		
(Km/l)	2.4	--
(kWh/km)	--	1.5
Vehicle Cost (\$)	72,000	85,500

* Could be increased to improve acceleration time.

ASSUMPTIONS & COMMENTS:

1978 dollars

STORAGE TECHNOLOGY:Batteries

SOURCE:Heiter, Kenneth and Paul Skartvedt.
Battery Technology An Assessment of the
State of the Art, TRW Energy Systems
Group DOE Contract EX-76-C-10-3885
Task Order 23, 1978.**INFORMATION:**

Table 3-2. Summary of Battery Cycle Life Data

Stage of Development	Current (Cycles)	Capacity Level
Near-Term		
Lead Acid	300-700	Full Battery
Nickel Iron	1500	Full Battery
Nickel Zinc	200-300	Full Battery
Advanced Development		
Advanced Lead Acid	2000	Projected for Full Battery
Lithium Metal Sulfide	500-1000	100-300 Wh Cell
Sodium Sulfur (B-Alumina)	>250	200 Wh Cell
Zinc Chlorine	200-300	1.4 kWh Cell
Exploratory Development		
Iron Air Zinc Air	150	No Data
Lithium Organic	250	20 Wh Cell
Sodium Ant. Trichloride	500-900	20 Wh Cell
Sodium Sulfur (Glass)	250	10 Wh Cells

STORAGE TECHNOLOGY:

Batteries

SOURCE:

Helter, Kenneth and Paul Skartvedt.

Battery Technology An Assessment of the
State of the Art, TRW Energy Systems

Group DOE Contract EX-76-C-10-3885

Task Order 23., 1978.

INFORMATION:

Table 3-3. Summary of Battery Costs

STAGE OF DEVELOPMENT	CURRENT (\$/kWh)	PROJECTED PILOT PROD. (\$/kWh)	PROJECTED MASS PROD. (\$/kWh)
Near-Term			
Lead Acid	45-80	80-100	40
Nickel-Iron	120-400	100-200	50-60
Nickel-Zinc	150	100-120	50-60 ¹
Advanced Development			
Advanced Lead Acid ²	70-80	--	40-50
Lithium Metal Sulfide	>2000	100	40 ²
Sodium Sulfur	>2000	100	40 ²
Zinc Chlorine	>2000	--	50
Exploratory Development			
Hydrogen Halogen			40-60
Iron Air/Zinc Air	>2000		30-60
Lithium Organic			42
Redox			27-38
Sodium Ant. Trichloride			40
Zinc Bromine			21-42

¹Long-term.²Includes balance of plant.**ASSUMPTIONS & COMMENTS:**

1977 dollars.

STORAGE TECHNOLOGY:

Electric Vehicle Batteries

SOURCE:

Behrin, E., et al., Energy Storage
Systems for Automobile Propulsion,
Vol. 2, UCRL-52303, Lawrence Livermore
Laboratories, 1977.

INFORMATION:

Table 2-3. Characteristics of engineering batteries.

	State-of- the-art Pb/acid	State-of- the-art Ni/Zn	State-of- the-art Ni/Fe	Improved Pb/acid (goals)	Improved Ni/Zn (goals)	Improved Ni/Fe (goals)
Specific energy, W·h/kg ^a	35	70	45	50	90	60
Volumetric energy density, W·h/l	60	115	85	90	150	110
Energy efficiency, %	65	65	55	65	65	60
Cycle life	500	250	1500	1000	750	2000
Cost, \$/kW·h	45	100-200	100-300	45	60	75

^a Assumes discharge at the 3-h rate.

STORAGE TECHNOLOGY:

Electric Vehicle Batteries

SOURCE:

Behrin, E., et al., Energy Storage
Systems for Automobile Propulsion,
Vol. 2, UCRL-52303, Lawrence Livermore
Laboratories, 1977.

INFORMATION:

Table 5-23. Projected cycle life for batteries (in years).

Battery type	1980-1982	Time period	
		1985-1990	1990-2000
Pb/acid	2-3	2-5	5
Ni/Zn	2	4-5	5
Ni/Fe	>100,000 mi (life of car)		
Zn/Cl ₂	2-3	2-5	5
Li-Al/FeS _x	X	3-5	5
Na/S (ceramic)			
ICE-equivalent cycle	X	2-5	5
Intermediate performance cycle		2	
Na/S (glass)	No meaningful estimate		

STORAGE TECHNOLOGY:Electric Vehicle Batteries

SOURCE:Behrin, E., et al., Energy Storage
Systems for Automobile Propulsion,
Vol. 2, UCRL-52303, Lawrence Livermore
Laboratories, 1977.

INFORMATION:

Fig. 5-18. Comparison of the projected characteristics of various batteries for the time period 1980-1982. The range of values shown for each battery encompasses the 25% through 75% confidence interval.

STORAGE TECHNOLOGY:Electric Vehicle Batteries**SOURCE:**Behrin, E. et al., Energy Storage
Systems for Automobile Propulsion,
Vol. 2, UCRL-52303, Livermore
Laboratories, 1977.**INFORMATION:**

Fig. 5-19. Comparison of the projected characteristics of various batteries for the time period 1985-1990. The range of values shown for each battery encompasses the 25% through 75% confidence interval.

STORAGE TECHNOLOGY:

Electric Vehicle Batteries

SOURCE:

Behrin, E., et al., Energy Storage
Systems for Automobile Propulsion,
Vol. 2, UCRL-52303, Lawrence Livermore
Laboratories, 1977.

INFORMATION:

Fig. 5-20. Comparison of the projected characteristics of various batteries for the time period 1990-2000. The range of values shown for each battery encompasses the 25% through 75% confidence interval.

STORAGE TECHNOLOGY:

Electric Vehicle Batteries

SOURCE:

Behrin, E. et al "Energy Storage Systems
for Automobile Propulsion, 1978 study"
Vol. 2, Lawrence Livermore Laboratory,
UCRL-52553, 1978.

INFORMATION:

TABLE 1-1. Battery forecasts for engineering batteries.

Battery type	Time period ^a	Conf. level, ^b %	Limits					Density, kg/l
			E _{C/3'} W·h/kg	E _{C/5'} W·h/kg	P _{M80'} W/kg	E _{C/3'} W·h/kg	P _{M80'} W/kg	
Pb/acid	1	10	45	52	75	57	130	2.05
		50	40	46	66	57	130	2.05
	2	10	50	57.5	100	57	130	2.05
		50	44	51	95	57	130	2.05
	3	10	55	63	110	57	130	2.05
		50	47	54	98	57	130	2.05
Ni/Fe	1	10	60	64	130	85	200	1.70
		50	55	59	102	85	200	1.73
	2	10	70	75	143	85	200	1.50
		50	60	64	112	85	200	1.70
	3	10	80	85	157	85	200	1.38
		50	65	70	130	85	200	1.62
Ni/Zn	1	10	81	86	140	115	310	1.88
		50	75	79	125	115	310	1.88
	2	10	90	95	160	115	310	1.88
		50	81	85	135	115	310	1.88
	3	10	98	102	175	115	310	1.88
		50	85	91	140	115	310	1.88

^a1--1980-1982, 2--1985-1990, 3--1990-2000.

^b10%--highly optimistic, 50%--most probable.

STORAGE TECHNOLOGY:

Vehicle Energy Storage Systems

SOURCE:

Behrin, E. et al., Energy Storage Systems for Automobile Propulsion, 1978 Study, Vol. 2, UCRL-52553,
Lawrence Livermore Laboratory, 1978.

INFORMATION:

FIG. 3-4. Ranges of specific energy and specific peak power for the storage devices evaluated. Thermal values have been converted at a 30% efficiency; battery energies are for a 3-h discharge rate; ranges are for 50% and 10% confidence levels, and all time periods.

STORAGE TECHNOLOGY:

Electric Vehicle Batteries

SOURCE:

Behrin, E. et al., Energy Storage Systems
for Automobile Propulsion, 1978 Study,
Vol. 2, UCRL-52553, Lawrence Livermore
Laboratory, 1978.

INFORMATION:

TABLE 3-11. Battery service-life forecasts (years) for three time periods and the 50% (most probable) and 10% (highly optimistic) confidence levels.

Battery	<u>1980-1982</u>		<u>1985-1990</u>		<u>1990-2000</u>	
	50%	10%	50%	10%	50%	10%
Pb/acid	3	4	4	6	5	10
Ni/Fe	10	10	10	10	10	10
Ni/Zn	2	4	4	8	5	10
Na/S (cer)	-	-	2	5	3	10
Li-Al/FeS _x	-	3	4	8	5	10
Zn/Cl ₂	3	4	4	6	5	10

STORAGE TECHNOLOGY:

Metal Air Cells

SOURCE:

Behrin, E., et al., Energy Storage
Systems for Automobile Propulsion,
Vol. 2, UCRL-52303, Lawrence Liver-
more Laboratories, 1977.

INFORMATION:

Table 2-8. Theoretical energies of metal/air systems.

Fuel	Net cell reaction (basic electrolyte)	Standard cell voltage, V	Theoretical specific energy, ^a kW·h/kg
H ₂	$1/2 \text{ H}_2 + 1/4 \text{ O}_2 \rightarrow 1/2 \text{ H}_2\text{O}$	1.23	33.0
Li	$\text{Li} + 1/2 \text{ H}_2\text{O} + 1/4 \text{ O}_2 \rightarrow \text{LiOH}$	3.45	13.3
Al	$\text{Al} + 3/2 \text{ H}_2\text{O} + 3/4 \text{ O}_2 \rightarrow \text{Al(OH)}_3$	2.70	8.1
Mg	$\text{Mg} + \text{H}_2\text{O} + 1/2 \text{ O}_2 \rightarrow \text{Mg(OH)}_2$	3.09	6.8
Ca	$\text{Ca} + \text{H}_2\text{O} + 1/2 \text{ O}_2 \rightarrow \text{Ca(OH)}_2$	3.42	4.6
Na	$\text{Na} + 1/2 \text{ H}_2\text{O} + 1/4 \text{ O}_2 \rightarrow \text{NaOH}$	3.11	3.6
Gasoline ^b		—	2.3 ^b
K	$\text{K} + 1/2 \text{ H}_2\text{O} + 1/4 \text{ O}_2 \rightarrow \text{KOH}$	3.33	2.3
Zn	$\text{Zn} + \text{H}_2\text{O} + 1/2 \text{ O}_2 \rightarrow \text{Zn(OH)}_2$	1.65	1.3
Fe	$\text{Fe} + \text{H}_2\text{O} + 1/2 \text{ O}_2 \rightarrow \text{Fe(OH)}_2$	1.28	1.2

^aEnergy is based on the weight of the metal fuel.

^bSpecific energy based on the weight of gasoline at 18% engine efficiency over SAE J227a(D) test cycle.

ASSUMPTIONS & COMMENTS:

Theoretical Specific Energy - Actual cells will achieve lower performance

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE: O'Connell, C. G. Role of Energy
Storage Power Systems in Transportation.

UCID-17274. Lawrence Livermore Laboratory,
October 1976.

INFORMATION:

TABLE IV

MAJOR TECHNICAL PROBLEMS FOR ADVANCED BATTERY SYSTEMS

Li-Al/FeS_x

{ Separator Cost and Durability
Li-Al Electrode Lifetime

Na/S (ceramic separator)

{ Lifetime and Reliability
β-Al₂O₃ Cost
Materials Compatibility, Sulfur Electrode

Zn/Cl₂

{ System Complexity and Bulk
Lifetime and Safety for Transportation Application

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE: O'Connell, C. G. Role of Energy Storage Power Systems in Transportation, UCID-17274. Lawrence Livermore Laboratory, October 1976.

INFORMATION:

TABLE III

CHARACTERISTICS (GOALS) OF ADVANCED BATTERIES

	<u>Lithium Iron Sulfide</u>	<u>Sodium Sulfur (β-Al₂O₃ Electrolyte)</u>	<u>Zinc Chlorine</u>
Specific Energy, W-hr/kg	150	100	130
Peak Power, W/kg	200	280*	150
Energy Efficiency, %	80	80	80
Cycle Life	1000	1000	500
Cost, \$/kW-hr*	30	30	30

*Difficult to achieve

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE: Escher, W. and R. W. Foster. An

Assessment of the Status of Fuel Cell/
Battery Vehicle Power Systems, BNL 51210.

Prepared for U. S. Department of Energy by
Escher - Foster Technology Associates, Inc.,
February 1980.

INFORMATION:

Table 1-2. BATTERY FUNDING SHOWING PORTION ALLOCATED TO EV BATTERIES (\$10⁶)

	FY 1979			FY 1980		
	Total Batteries	Near-Term Batteries	Advanced EV Batteries	Total Batteries	Near-Term Batteries	Advanced EV Batteries
Near-Term Batteries	6.33	6.33	--	9.95	9.95	--
Advanced Batteries	11.50	--	8.53	14.40	--	10.75
Solar Applications	0.80	--	--	5.00	--	--
Electrochemical System Research	2.50	--	1.63	2.60	--	1.63
Supporting Research	2.14	0.38	0.42	3.00	0.83	0.59
Electrolytic Technology	1.32	--	--	1.50	--	--
Dispersed Battery Applications	5.90	--	--	4.50	--	--
	30.49	6.71	10.58	40.95	10.78	12.97

Note: "Total Batteries" column include program elements, e.g., component technologies efforts, other than what is represented; hence the columns do not add up horizontally.

Source: Reference 2.

STORAGE TECHNOLOGY:

Flywheel Energy Storage for Vehicles

SOURCE: Schwartz, M. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 3, Battery/Flywheel Electric Vehicles Using Advanced Batteries, UCRL-52841, Vol. 3. Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, Dec. 15, 1979.

INFORMATION:

Table 6. Break-even specific energy of flywheel energy-storage device, Wh/lb.

Perf. level	Time frame — 1980 to 1985											
	Prob.						Opt.					
	Pb/acid	Ni/Fe	Ni/Zn	Na/S (cer)	LiAl/FeS ₂	Zn/Cl ₂	Pb/acid	Ni/Fe	Ni/Zn	Na/S (cer)	LiAl/FeS ₂	Zn/Cl ₂
Min.	0.315	0.785		N.A.	N.A.	1.58	0.942			N.A.	0.894 ^a	
Lim.			3.62	N.A.	N.A.	0.772	0.572	1.81	8.16	N.A.	0.634 ^a	1.39
Inter.				N.A.	N.A.				1.33	N.A.		0.765
Equiv.				N.A.	N.A.					N.A.		

^a LiAl/FeS

STORAGE TECHNOLOGY:

Flywheel Energy Storage for Vehicles

SOURCE: Schwartz, M. Energy Storage Systems
for Automobile Propulsion: 1979 Study,
Volume 3, Battery/Flywheel Electric Vehicles
Using Advanced Batteries, UCRL-52841, Vol. 3.
Prepared for U.S. Department of Energy by
Lawrence Livermore Laboratory, Dec. 15, 1979.

INFORMATION:

Table 7. Break-even specific energy of flywheel energy-storage device, Wh/lb.

[illegible]

STORAGE TECHNOLOGY:

Flywheel Energy Storage for Vehicles

SOURCE: Schwartz, M. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 3, Battery/Flywheel Electric Vehicles Using Advanced Batteries, UCRL-52841, Vol. 3. Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, Dec. 15, 1979.

INFORMATION:

Table 8. Break-even specific energy of flywheel energy-storage device, Wh/lb.

Perf. level	Time frame — 1990 to 2000											
	Prob.						Opt.					
	Pb/acid	Ni/Fe	Ni/Zn	Na/S (cer)	LiAl/FeS ₂	Zn/Cl ₂	Pb/acid	Ni/Fe	Ni/Zn	Na/S (cer)	LiAl/FeS ₂	Zn/Cl ₂
Min.				22.6								
Lim.				1.28	1.66	2.84						
Inter.		13.3	2.95	0.923	0.820	1.37				8.61		
Equiv.										0.941	1.23	

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE: Escher, W. and R. W. Foster. AnAssessment of the Status of Fuel Cell/Battery Vehicle Power Systems, BNL 51210.

Prepared for U. S. Department of Energy by

Escher - Foster Technology Associates, Inc.,

February 1980.

INFORMATION:

Table 1-2, Cont. PERFORMANCE PROJECTIONS FOR NEAR-TERM BATTERY PROGRAM

	Lead-Acid				Nickel/Iron				Nickel/Zinc			
	1979*	1980	1982	1984	1979*	1980	1982	1984	1979*	1980	1982	1984
Specific Energy (Wh/kg)	34	42	50	50	48	54	58	60	60	64	67	70
Specific Power (Wh/kg)												
-- Peak (20 seconds @ 50% State of Charge)	80	90	95	100	100	110	120	120	110	140	140	140
--Sustained (1/2 hour rate)	35	40	45	50	70	80	90	95	80	80	90	95
Cells/Modules Cycle Anticipated Life Capa- bility (No. Cycles)	300	300	500	750	800	1500	1800	2000	100	200	300	500
Production Capacity Per Contractor (Batteries/ Year)	200	400	1100	2000	50	100	300	500	40	100	100	500
Battery Price @ the Above Production Level (\$/kWhr)(1979\$)	100	100	80	60	1200	500	350	300	550	500	500	250

* Only cell data will be obtained in 1979. Table values are estimates for batteries if assembled with these cells.

Source: Reference 2.

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE: Schwartz, M. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 3, Battery/Flywheel Electric Vehicles Using Advanced Batteries, UCRL-52841, Vol. 3. Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, Dec. 15, 1979.

INFORMATION:

FIG. 25. Probable results of mass analysis for five-passenger vehicles--minimum performance. All-battery vehicles: minimum acceleration capability, minimum range.

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE: Schwartz, M. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 3, Battery/Flywheel Electric Vehicles Using Advanced Batteries, UCRL-52841, Vol. 3. Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, Dec. 15, 1979.

INFORMATION:

FIG. 26. Optimistic results of mass analysis for five-passenger vehicles--minimum performance. All-battery vehicles: minimum acceleration capability, minimum range. Battery/flywheel vehicles: equivalent acceleration capability, minimum range.

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE: Schwartz, M. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 3, Battery/Flywheel Electric Vehicles Using Advanced Batteries, UCRL-52841, Vol. 3. Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, Dec. 15, 1979.

INFORMATION:

FIG. 27. Probable results of mass analysis for five-passenger vehicles--limited performance. All-battery vehicle: limited acceleration capability, limited range. Battery/flywheel vehicles: equivalent acceleration capability, limited range.

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE: Schwartz, M. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 3, Battery/Flywheel Electric Vehicles Using Advanced Batteries, UCRL-52841, Vol. 3. Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, Dec. 15, 1979.

INFORMATION:

FIG. 28. Optimistic results of mass analysis for five-passenger vehicles--limited performance. All-battery vehicles: limited acceleration capability, limited range. Battery/flywheel vehicles: equivalent acceleration capability, limited range.

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE: Schwartz, M. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 3, Battery/Flywheel Electric Vehicles Using Advanced Batteries, UCRL-52841, Vol. 3. Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, Dec. 15, 1979.

INFORMATION:

FIG. 29. Probable results of mass analysis for five-passenger vehicles--intermediate performance. All-battery vehicle: intermediate acceleration capability, intermediate range. Battery/flywheel vehicle: equivalent acceleration capability, intermediate range.

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE: Schwartz, M. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 3, Battery/Flywheel Electric Vehicles Using Advanced Batteries, UCRL-52841, Vol. 3. Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, Dec. 15, 1979.

INFORMATION:

FIG. 30. Optimistic results of mass analysis for five-passenger vehicles--intermediate performance. All-battery vehicles: intermediate acceleration capability, intermediate range. Battery/flywheel vehicles: equivalent acceleration capability, intermediate range.

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE: Schwartz, M. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 3, Battery/Flywheel Electric Vehicles Using Advanced Batteries, UCRL-52841, Vol. 3. Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, Dec. 15, 1979.

INFORMATION:

FIG. 31. Probable results of mass analysis for five-passenger vehicles--equivalent performance. All-battery vehicles: equivalent acceleration capability, equivalent range. Battery/flywheel vehicles: equivalent acceleration capability, equivalent range.

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE: Schwartz, M. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 3, Battery/Flywheel Electric Vehicles Using Advanced Batteries, UCRL-52841, Vol. 3. Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, Dec. 15, 1979.

INFORMATION:

FIG. 32. Optimistic results of mass analysis for five-passenger vehicles--equivalent performance. All-battery vehicles: equivalent acceleration capability, equivalent range. Battery/flywheel vehicles: equivalent acceleration capability, equivalent range.

STORAGE TECHNOLOGY:

Vehicle Storage Systems

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

FIG. 20. Minimum performance.

* MgHx is combined with FeTi in the dual-hydride system.

† All-battery/flywheel systems exhibit equivalent-level acceleration.

STORAGE TECHNOLOGY:

Vehicle Storage Systems

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

FIG. 21. Limited performance.

* MgHx is combined with FeTi in the dual-hydride system.

† All-battery/flywheel systems exhibit equivalent-level acceleration.

STORAGE TECHNOLOGY:

Vehicle Storage Systems

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

FIG. 22. Intermediate performance.

* MgHx is combined with FeTi in the dual-hydride system.

† All-battery/flywheel systems exhibit equivalent-level acceleration.

STORAGE TECHNOLOGY:

Vehicle Storage Systems

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

FIG. 23. Equivalent performance.

* MgHx is combined with FeTi in the dual-hydride system.

† All-battery/flywheel systems exhibit equivalent-level acceleration.

STORAGE TECHNOLOGY:

Vehicle Storage Systems

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

FIG. 24. Minimum performance.

* MgHx is combined with FeTi in the dual-hydride system.

† All-battery/flywheel systems exhibit equivalent-level acceleration.

STORAGE TECHNOLOGY:

Vehicle Storage Systems

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

FIG. 25. Limited performance.

* MgHx is combined with FeTi in the dual-hydride system.

† All-battery/flywheel systems exhibit equivalent-level acceleration.

STORAGE TECHNOLOGY:

Vehicle Storage Systems

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1), Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

FIG. 26. Intermediate performance.

* MgHx is combined with FeTi in the dual-hydride system.

† All-battery/flywheel systems exhibit equivalent-level acceleration.

STORAGE TECHNOLOGY:

Vehicle Storage Systems

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

FIG. 27. Equivalent performance.

* MgHx is combined with FeTi in the dual-hydride system.

† All-battery/flywheel systems exhibit equivalent-level acceleration.

STORAGE TECHNOLOGY:

Hydrogen Storage for Vehicles

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

TABLE 6. Current hydrogen-storage-device projections. Note: Heat content values have been converted to their mechanical equivalent using 30% efficiency.

Storage devices	Probability	Specific energy Wh/kg			Specific peak power (80% discharge) W/kg		
		1980- 1985	1985- 1990	1990- 2000	1980- 1985	1985- 1990	1990- 2000
Liquid H ₂	Prob.	675	1080	1680	a	a	a
	Opt.	1080	1680	1680	a	a	a
FeTiH _x	Prob.	84	90	96	1100	1230	1320
	Opt.	99	105	114	1320	1440	1560
MgH _x	Prob.	105	144	165	870	1230	1380
	Opt.	195	201	207	1650	1680	1740
Microcavity	Opt.	--	381	--	--	570	--

^a In this case the peak-power capacity is determined by the design of the heat engine.

STORAGE TECHNOLOGY:

Thermal Energy Storage for Vehicles

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

TABLE 12. Highly optimistic thermal-storage analysis assumptions.

Storage projections^a

Energy density (gravimetric), Wh/kg	244
Energy density (volumetric), Wh/liter	263
Short duration (15-30 s) peak power, W/kg	460
Maximum continuous peak power, W/kg	192
Average power loss, W/kg	1.42
Lifetime, y	10

Engine assumptions

Average efficiency, %	40
Engine mass (lb) = 4.4 (hp) + 40	

Cost projections

Storage system (1990-2000), \$/kg	4.80
Residual value, \$/kg	1.20
Refueling cost (electric), \$/kWh	0.03
Engine cost (\$) = 3.8 (hp) + 196	

^a Projections are for total system without engine.

STORAGE TECHNOLOGY:

Vehicle Storage Systems

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

TABLE 13. Matrix of propulsion systems evaluated for performance and cost.

	Time period			Performance levels ^a				Vehicle ^b types	Prob. level	No. of vehicles
	1980- 1985	1985- 1990	1990- 2000	Min.	Lim.	Int.	Equiv.			
<u>All-battery system</u>										
Pb/acid	x	x	x	x	x	x	x	2P, 4P 5P,MPV	Prob.& Opt.	96
Ni/Fe	x	x	x	x	x	x	x	2P, 4P 5P,MPV	Prob.& Opt.	96
Ni/Zn	x	x	x	x	x	x	x	2P, 4P 5P,MPV	Prob.& Opt.	96
LiAl/FeS ₂		x	x	x	x	x	x	2P, 4P 5P,MPV	Prob.& Opt.	66
Zn/Cl ₂	x	x	x	x	x	x	x	2P, 4P 5P,MPV	Prob.& Opt.	96
Na/S(cer)		x	x	x	x	x	x	2P, 4P 5P,MPV	Prob.& Opt.	64
Na/S(glass)		x	x	x	x	x	x	2P, 4P 5P,MPV	Prob.& Opt.	64
<u>H₂ Storage systems</u>										
FeTiH _x /fuel cell	x	x	x	x	x	x	x	2P, 4P 5P,MPV	Prob.& Opt.	96
Microspheres/ ICE		x		x	x	x	x	2P, 4P 5P,MPV	Opt.	16
Dual hydride/ ICE	x	x	x	x	x	x	x	2P, 4P 5P,MPV	Prob.& Opt.	96
FeTi hydride/ ICE	x	x	x	x	x	x	x	2P, 4P 5P,MPV	Opt.	96
Liquid H ₂		x	x	x	x	x		2P, 4P 5P,MPV	Prob.	9
<u>Battery/flywheel electric systems</u>										
Pb/acid	x	x	x	x	x	x	x	5P	Prob.& Opt.	24
Ni/Fe	x	x	x	x	x	x	x	5P	Prob.& Opt.	24
Ni/Zn	x	x	x	x	x	x	x	5P	Prob.& Opt.	24
LiAl/FeS ₂		x	x	x	x	x	x	5P	Prob.& Opt.	16
Zn/Cl ₂	x	x	x	x	x	x	x	5P	Prob.& Opt.	24

STORAGE TECHNOLOGY:

Vehicle Storage Systems

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

TABLE 13. (Cont.)

	Time period			Performance levels ^a				Vehicle ^b types	Prob. & level	No. of vehicles
	1980- 1985	1985- 1990	1990- 2000	Min.	Lim.	Int.	Equiv.			
Na/S(cer)		x	x	x	x	x	x	5P	Prob. & Opt.	16
Na/S(glass)		x	x	x	x	x	x	5P	Prob. & Opt.	16
<u>Dual-fueled hybrids</u>										
Pb/acid/ fly/ICE	x	x	x				x	5P	Prob. & Opt.	6
NiFe/ fly/ICE	x	x	x				x	5P	Prob. & Opt.	6
NiZn/ fly/ICE	x	x	x				x	5P	Prob. & Opt.	6
LiAl/FeS ₂ / fly/ICE		x	x				x	5P	Prob. & Opt.	4
ZnCL ₂ / fly/ICE	x	x	x				x	5P	Prob. & Opt.	6
NaS(cer)/ fly/ICE		x	x				x	5P	Prob. & Opt.	4
NaS(Glass)/ fly/ICE		x	x				x	5P	Prob. & Opt.	4
<u>Power-leveling hybrids</u>										
Compressed air	x	x	x	Type 1 and Type 2				5P	Prob.	6
Hydraulic accumulator	x	x	x	Type 1 and Type 2				5P	Prob.	6
Composite isotropic rotor flywheel	x	x	x	Type 1 and Type 2				5P	Prob.	6
Battery	x	x	x	Type 1 and Type 2				5P	Prob.	6

^a Performance level refers primarily to vehicle power/mass ratio. Vehicle masses are determined as a function of range to include all combinations of power and range.

^b The abbreviations 2P, 4P, 5P and MPV stand for two-passenger, four-passenger, five-passenger, and multipurpose vehicle, respectively.

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

TABLE 14. Battery constants and limiting values.

Battery type	Time period	Confidence level	Limits		Battery Constants		
			$E_{C/3}$, Wh/kg	P_{M80} , Wh/kg	M_1	C_1	M
Pb/acid	1980-85	Optimistic	56	130	-2.2	178	-0.70
		Probable	50	130		154	-0.73
	1985-90	Optimistic	61	130		214	-0.72
		Probable	55	130		196	-0.68
	1990-2000	Optimistic	68	130		235	-0.75
		Probable	60	130		206	-0.73
Ni/Fe	1980-85	Optimistic	69	200	-3.0	310	-1.80
		Probable	64	200		267	-1.63
	1985-90	Optimistic	78	200		353	-1.67
		Probable	67	200		292	-1.80
	1990-2000	Optimistic	89	200		397	-1.93
		Probable	74	200		325	-1.53
Ni/Zn	1980-85	Optimistic	85	310	-4.51	483	-1.83
		Probable	78	310		441	-2.13
	1985-90	Optimistic	95	310		543	-1.69
		Probable	85	310		478	-2.33
	1990-2000	Optimistic	100	310		590	-2.87
		Probable	92	310		501	-1.58
Na/S(ceramic)	1985-90	Optimistic	130	200	-1.8	309	-0.62
		Probable	110	200		262	-0.60
	1990-2000	Optimistic	150	200		356	-0.60
		Probable	135	200		314	-0.65
Na/S (glass)	1985-90	Optimistic	124	250	0.1	212	-7.67
		Probable	118	230		191	-7.27
	1990-2000	Optimistic	130	300		263	-8.13
		Probable	123	250		212	-7.67
Zn/Cl ₂	1980-85	Optimistic	115	175	-2.2	340	-2.47
		Probable	105	175		293	-2.20
	1985-90	Optimistic	125	175		381	-2.29
		Probable	112	175		331	-1.98
	1990-2000	Optimistic	135	175		414	-2.13
		Probable	115	175		351	-1.80
LiAl/FeS ₂	1985-90	Optimistic	145	210	-2.1	377	-1.00
		Probable	135	210		346	-0.61
	1990-2000	Optimistic	160	210		444	-0.80
		Probable	145	210		382	-0.60

STORAGE TECHNOLOGY:

Vehicle Storage Systems

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

FIG. 28. Minimum performance.

* MgHx is combined with FeTi in the dual-hydride system.

† All-battery/flywheel systems exhibit equivalent-level acceleration.

STORAGE TECHNOLOGY:

Vehicle Storage Systems

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

FIG. 29. Limited performance.

* MgHx is combined with FeTi in the dual-hydride system.

† All-battery/flywheel systems exhibit equivalent-level acceleration.

STORAGE TECHNOLOGY:

Vehicle Storage Systems

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

FIG. 30. Intermediate performance.

* MgHx is combined with FeTi in the dual-hydride system.

† All-battery/flywheel systems exhibit equivalent-level acceleration.

STORAGE TECHNOLOGY:

Vehicle Storage Systems

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

FIG. 31. Equivalent performance.

* MgHx is combined with FeTi in the dual-hydride system.

† All-battery/flywheel systems exhibit equivalent-level acceleration.

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

TABLE 2. Battery forecasts for engineering batteries.

Battery type	Time period ^a	Prob. level ^b	$E_{C/3}$ ^c Wh/kg	$E_{C/5}$ ^c Wh/kg	P_{M80} ^d W/kg
Pb/acid	1	Opt.	47	54	75
		Prob.	42	48	66
	2	Opt.	52	59	100
		Prob.	46	53	95
	3	Opt.	57	65	110
		Prob.	49	56	98
Ni/Fe	1	Opt.	60	64	130
		Prob.	55	59	102
	2	Opt.	70	75	143
		Prob.	60	64	112
	3	Opt.	80	85	157
		Prob.	65	70	130
Ni/Zn	1	Opt.	76	81	140
		Prob.	70	74	125
	2	Opt.	85	91	160
		Prob.	76	80	135
	3	Opt.	92	96	175
		Prob.	80	86	140

^a 1--1980-1985, 2--1985-1990, 3--1990-2000.

^b Optimistic or Probable.

^c Specific energy at 3-h (5-h) discharge rate.

^d Specific peak power when 80% discharged.

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

TABLE 3, Battery forecasts for advanced batteries.

Battery type	Time period ^a	Prob. ^b level	E _{C/3'} Wh/kg	E _{C/5'} Wh/kg	P _{M80'} W/kg
Na/S(cer)	2	Opt.	105	122	120
		Prob.	90	105	100
	3	Opt.	120	140	140
		Prob.	108	125	120
Zn/Cl ₂	1	Opt.	100	105	120
		Prob.	90	95	95
	2	Opt.	112	118	135
		Prob.	98	104	115
	3	Opt.	120	130	150
		Prob.	105	111	120
Li/FeS ₂	2	Opt.	120	140	125
		Prob.	110	128	115
	3	Opt.	140	155	150
		Prob.	120	140	130

^a 1--1980-1985, 2--1985-1990, 3--1990-2000.

^b Optimistic or Probable.

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE: Forsberg, H. C., et al. Energy Storage Systems for Automobile Propulsion: 1979 Study, Volume 1. Overview and Findings. UCRL-52841 (Vol. 1). Prepared for U.S. Department of Energy by Lawrence Livermore Laboratory, December 15, 1979.

INFORMATION:

TABLE 4. Key technical Barriers.^a

Advanced Pb/acid	Ni/Fe	Ni/Zn	Zn/Cl ₂	LiAl/FeS _x	Na/S(cer)
Specific- energy	Cost ^b	Lifetime ^b Cost	Volumetric energy Cost	Specific energy	Specific energy Volumetric energy
Peak-power			Lifetime	Cost	Lifetime
lifetime			Safety ^b	Lifetime ^b	Materials
			System complexity	Materials corrosion	corrosion
				Battery eng.	Safety ^b
				Separator	Peak power
					Battery eng.
Probability of ^c overcoming all key barriers (estimated)					
0.25	0.5	0.35	0.25	0.25	0.15

^a Only technical barriers with serious development difficulty are included.

^b Denotes especially difficult technical barrier.

^c Assumes intensive development until 1990.

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE:

Webster, W. H. Battery Development for
Electric Vehicles in the United States.

U. S. Department of Energy, 1980.

INFORMATION:

Table 4 - Projected* Performance of An Advanced Electric Vehicle

	<u>Comm'l Pb/A</u>	<u>Improved Pb/A</u>	<u>Ni/Fe</u>	<u>Ni/Zn</u>	<u>Zn/Cl</u>	<u>Li/FeS</u>
<u>CURRENT (1981)</u>						
RANGE (mi.)	54	74	86	123	117	146
BATTERY LIFE (mi X 1000)	13	44	67	22	2	53
<u>PROGRAM SUCCESS</u>						
RANGE (mi.)	54	90	108	126	144	225
BATTERY LIFE (mi. X 1000) .	13	72	130	101	216	180

*1981 is present state of technology in cells; Program success assume goals realized.

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE:

Walsh, W. J. "Advanced Batteries for Electric Vehicles - A Look at the Future"

Physics Today, June 1980.

INFORMATION:

Relationship between the technical barriers to developing new battery systems and their desirability. Difficulty and desirability were measured with a Bayesian interrogation method.

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE:

Walsh, W. J. "Advanced Batteries for Electric Vehicles - A Look at the Future"

Physics Today, June 1980.

INFORMATION:

Relative desirability of battery systems

	Lead-acid	Ni/Zn	Ni/Fe	Zn/Cl ₂	Li-Al/ FeS ₂	Na/S (ceramic)	Na/S (glass)
Specific energy	3	5	4	6	8	8	8
Volumetric energy density	3	6	4	4	8	5	5
Peak power ^a	2	8	4	4	5	5	9
Sustained power	3	7	5	8	5	5	9
Cost	7	(5)	3	(5)	(5)	(5)	(8)
Cycle life	(5)	(5)	10	(5)	(5)	(5)	(5)
Safety	7	7	7	2	8	2	3
Resource availability	4	3	3	9	(4)	9	9
Overall desirability rating ^c	3.5	7.5	4.5	6.0	8.0	6.0	8.5

^aAt 80% state-of-discharge.

^bParentheses denote relatively uncertain assessment.

^cThe values have no meaning except to illustrate the "overall relative desirability" for the automobile application on a linear scale (obtained using Bayesian interrogation).

STORAGE TECHNOLOGY:

Electric-Vehicle Batteries

SOURCE: O'Connell, C. G. Role of Energy Storage Power Systems in Transportation, UCID-17274. Lawrence Livermore Laboratory, October 1976.

INFORMATION:

Fig. 4 Mini car GVW comparisons using projected properties of various forms of non-hybrid power systems.

STORAGE TECHNOLOGY:

Sodium-Sulfur Batteries for
Electric Vehicles

SOURCE: Meyer, C. F. Potential Benefits
of Thermal Energy Storage in the Proposed
Twin Cities District Heating - Cogeneration
System, Final Report, ORNL/Sub-7604/2.
Prepared for U.S. Department of Energy by
General Electric Company-TEMPO, October 1979.

INFORMATION:

TABLE 5. Battery forecasts for Na/S batteries (glass).

Battery type	Time period ^a	Prob. level	E _{C/3'} WH/kg	E _{C/5'} Wh/kg	P _{M80'} W/kg
Na/S (glass)	2	Opt.	118	120	200
		Prob.	112	114	180
	3	Opt.	125	127	250
		Prob.	118	120	200

^a1--1980-1985, 2--1985-1990, 3--1990-2000.

SUMMARY

End Use: Vehicles

Technology: Nickel-Zinc Battery

No useful comparisons possible.

STORAGE TECHNOLOGY:

Nickel-Zinc Batteries

SOURCE:

Gould, Inc. Develop Nickel Zinc Battery
Suitable for Electric Vehicle Propulsion
Design and Cost Study ANL Contract No.
31-109-38-3558, Gould Report No. 762-003-1,
1977.

INFORMATION:

TABLE 1-8

PERFORMANCE SPECIFICATIONS FOR PROPOSED CELL
(1.15 VOLT CUT-OFF)

CELL ENERGY

Hr. RATE	LOW ENERGY CELLS				HIGH ENERGY CELL			
	AMPS	MID VOLTAGE	CAPACITY		AMPS	MID VOLTAGE	CAPACITY	
			Ah	Wh			Ah	Wh
6	80	1.63	501	817	110	1.62	658	1066
5	100	1.615	500	808	130	1.595	656	1050
3	165	1.575	500	788	220	1.545	651	1008
1	600	1.38	471	650	650	1.32	569	751

ENERGY DENSITY

Hr. RATE	LOW ENERGY CELLS		HIGH ENERGY CELLS	
	Wh/Lb.	Wh/in. ³	Wh/Lb.	Wh/in. ³
6	32.5	2.38	42.6	3.11
5	32.2	2.36	42.0	3.06
3	31.4	2.30	40.2	2.93
1	25.9	1.90	30.0	2.19

SPECIFIC POWER ⁽¹⁾

Hr. RATE	LOW ENERGY CELLS		HIGH ENERGY CELLS	
	AMPS	W/Lb.	AMPS	W/Lb.
6	80	5.2	110	7.1
5	100	6.4	130	8.3
3	165	10.4	220	13.6
1	500	27.5	650	34.3
0.5	1000	49.0 ⁽²⁾	1300	61.4 ⁽²⁾
0.33	1500	69.3 ⁽²⁾	1950	89.7 ⁽²⁾

⁽¹⁾Based on Midpoint Voltages at the Specified Rates.

⁽²⁾Estimated

ASSUMPTIONS & COMMENTS:

Data for individual cells.

STORAGE TECHNOLOGY:

Nickel Zinc Batteries

SOURCE:

Gould Inc., Develop Nickel Zinc Battery
Suitable for Electric Vehicle Propulsion
Design and Cost Study, ANL Contract No.
31-109-38-3558 Gould Report No. 762-003-1,
1977.

INFORMATION:

TABLE 1-9

PERFORMANCE SPECIFICATIONS FOR PROPOSED BATTERY
(1.15 VOLT / CELL CUT-OFF)

ENERGY

LOW ENERGY CELLS					HIGH ENERGY CELLS			
HL. RATE	AMPS	MID VOLTAGE	CAPACITY		AMPS	MID VOLTAGE	CAPACITY	
			Ah	kWh			Ah	kWh
6	80	52.16	501	26.13	110	51.84	658	34.11
5	100	51.68	500	25.84	130	51.04	658	33.58
3	165	50.40	500	25.20	220	49.44	651	32.19
1	500	44.16	471	20.80	650	42.24	569	24.03

ENERGY DENSITY

HL. RATE	LOW ENERGY CELLS		HIGH ENERGY CELLS	
	Wh/Lb.	Wh/in. ³	Wh/Lb.	Wh/in. ³
6	31.9	2.05	41.9	2.67
5	31.6	2.02	41.2	2.63
3	30.8	1.97	39.5	2.52
1	25.4	1.63	29.5	1.88

SPECIFIC POWER ⁽¹⁾

HL. RATE	LOW ENERGY CELLS		HIGH ENERGY CELLS	
	AMPS	W/Lb.	AMPS	W/Lb.
6	80	5.1	110	7.0
5	100	6.3	130	8.1
3	165	10.0	220	13.3
1	500	27.0	650	33.7
0.5	1000 ⁽²⁾	48.1	1300 ⁽²⁾	60.2
0.33	1500 ⁽²⁾	68.1	1950 ⁽²⁾	88.0

(1) Based on Midpoint Voltages at the Specified Rates.

(2) Estimated

ASSUMPTIONS & COMMENTS:

Data for E.V. Battery (32 cells).

STORAGE TECHNOLOGY:

Nickel Zinc Batteries

SOURCE:

Behrin, E. Et al., Energy Storage Systems for Automobile Propulsion, 1978 Study, Vol. 2, UCRL-52553, Lawrence Livermore Laboratory, 1978.

INFORMATION:

FIG. 3-3. Most probable values for the changes in specific power vs specific energy as a function of short-term, specific peak power for three Ni/Zn batteries in the 1980-1982 time period.

SUMMARY

End Use: Vehicles

Technology: Zinc-Chlorine Battery

No useful comparisons possible.

STORAGE TECHNOLOGY:

Zinc Chlorine Battery

SOURCE:

Heiter, Kenneth and Paul Skarttredt.
 Battery Technology An Assessment of
 the State of the Art, TRW Energy
 Systems Group DOE Contract EX-76-C-10-3885
 Task Order 23., 1978

INFORMATION:

Table A-8. Zinc Chlorine Battery Characterization

CHARACTERISTIC	CURRENT	PROJECTED-1982
Energy Density	66-95 Wh/kg	80-100 Wh/kg
Volumetric	90 Wh/L	115 Wh/L
Peak Power Density	100 W/kg	150 W/kg
Sustaining Power Density	70 W/kg	-
Efficiency	55%	65%
Cycle Life	200-300 Cycles ¹	1000 Cycles
Operating Temperature	Ambient to 50°C	Ambient to 50°C
Pilot Costs	\$2000/kWh	-
Mass Production Costs	-	\$50/kWh

¹1.4 kWh cell

Source: References 1-1, 2-1, 2-2, 2-7

ASSUMPTIONS & COMMENTS:

1977 dollars.

STORAGE TECHNOLOGY:

Hydrogen-Halogen Batteries

SOURCE: |

Heiter, Kenneth and Paul Skartredt.

Battery Technology An Assessment of
the State of the Art, TRW Energy

Systems Group DOE Contract EX-76-C-10-3885 Task Order 23., 1978.

INFORMATION:

Table A-9. Hydrogen Halogen Storage Battery Characterization

CHARACTERISTIC	PROJECTION
Efficiency	70%
Operating Temperature	Ambient to 100°C
Cost	\$40-60/kWh for 5-10 hour storage

Source: Reference 2-8

STORAGE TECHNOLOGY:Iron-Air and Zinc-Air Batteries

SOURCE:Heiter, Kenneth and Paul Skartvedt.
Battery Technology An Assessment of
the State of the Art, TRW Energy Systems
Group DOE Contract EX-76-C-10-3885
Task Order 23., 1978.**INFORMATION:**

Table A-10. Iron Air/Zinc Air Battery Characterization
Exploratory Development

CHARACTERISTIC	CURRENT	PROJECTED
Energy Density	80-120 Wh/kg	110 Wh/kg
Peak Power Density	40 W/kg	90 W/kg
Sustaining Power Density	No Data	No Data
Efficiency	40%	40-50%
Cycle Life	150 Cycles	1000 Cycles
Operating Temperature	Ambient	Ambient
Pilot Costs	>\$2000/kWh	-
Mass Production Costs	-	\$30-60/kWh

Sources: References 2-9, 2-10

ASSUMPTIONS & COMMENTS:

1977 dollars

STORAGE TECHNOLOGY:Zinc Bromine Battery

SOURCE:Helter, Kenneth and Paul Skartvedt.
Battery Technology. An Assessment of
the State of the Art. TRW Energy
Systems Group. DOE Contract EX-76-C-10-
3885 Task Order 23. 1978**INFORMATION:**

Table A-15. Zinc Bromine Battery Characterization

CHARACTERISTIC	PROJECTION
Energy Density	60 Wh/kg
Power Density	20-25 W/kg
Efficiency	75-80 Percent
Mass Prod. Cost	\$21-42/kWh
Operating Temperature	Ambient

Source: Reference 2-16

ASSUMPTIONS & COMMENTS:

1977 dollars

STORAGE TECHNOLOGY:Lithium-Water Air Battery

SOURCE:Heiter, Kenneth and Paul Skartvedt.
Battery Technology An Assessment of
the State of the Art, TRW Energy Systems
Group DOE Contract EX-76-C-10-3885
Task Order 23., 1978.**INFORMATION:**

Table A-12. Lithium Water Air Battery Characterization

CHARACTERISTIC	CURRENT LI-WATER	PROJECTION
Energy Density	160 Wh/kg	300-400 Wh/kg
Peak Power Density	18 W/kg	100 W/kg
Efficiency (System)	Primary Cell	25 %
Operating Temperature	Ambient	Ambient

Sources: References 2-12, 2-13

ASSUMPTIONS & COMMENTS:

1977 dollars.

SUMMARY

End Use: Vehicles

Technology: Lead-Acid Battery

No useful comparisons possible.

STORAGE TECHNOLOGY:Lead Acid Batteries

SOURCE:

Heiter, Kenneth and Paul Skartvedt.

Battery Technology An Assessment of
the State of the Art, TRW Energy Systems
Group DOE Contract EX-76-C-10-3885 Task
Order 23., 1978.**INFORMATION:**Table A-1. Lead Acid Battery Characterization
(for Transportation Application)

CHARACTERISTIC	CURRENT ¹	PROJECTED-1980
Energy Density	25-30 Wh/kg	50 Wh/kg
Volumetric	60 Wh/L	90 Wh/l
Peak Power Density	50-80 W/kg	150 W/kg
Sustaining Power Density	15 W/kg	25 W/kg
Efficiency	65-70%	> 60%
Cycle Life	300-700 Cycles	1000 Cycles
Operating Temperature	Ambient	Ambient
Low Temp. Capacity	Poor	-
Pilot Costs	\$100/kWh	\$80-100/kWh
Mass Production Costs	\$45-80/kWh	\$40/kWh

¹Golf Cart-Traction

Sources: References 3 and 4

ASSUMPTIONS & COMMENTS:

1977 dollars.

SUMMARY

End Use: Vehicles

Technology: Lithium-Metal Sulfide Batteries

Number of Reports: 6

Parameter	Report					
	1	2	3	4	5	6
Specific Energy (Wh/kg)	100	99.2	-	110-180	80-160	135
Peak Specific Power (W/kg)	100	54.4	-	-	80-200	-
Cost, \$ (Mass Production Quantities)	-	-	35-59	31-38	-	53

STORAGE TECHNOLOGY:

Lithium-Metal Sulfide Batteries

SOURCE:

Chilenskas, A. A. Lithium/Iron Sulfide
Batteries for Electric Vehicles.
Prepared for Fifth International Electric
Vehicle Symposium, 1978. Conf. 781006

INFORMATION:

Fig. 4. Peak Specific Power Achieved by Li-Al/FeS Cells

STORAGE TECHNOLOGY:Lithium-Metal Sulfide Batteries**SOURCE:**

Chilenskas, A. A. Lithium/Iron Sulfide
Batteries for Electric Vehicles. Prepared
for Fifth International Electric Vehicle
Symposium, 1978. Conf. 781006.

INFORMATION:

Fig. 3. Specific Energies of Li-Al/FeS Cells at the Four-Hour Discharge Rate

STORAGE TECHNOLOGY:

Lithium-Metal Sulfide Batteries

SOURCE:

Chilenskas, A. A. Lithium/Iron Sulfide
Batteries for Electric Vehicles. Prepared
for Fifth International Electric Vehicle
Symposium, 1978. Conf. 781006

INFORMATION:

Fig. 5. Cycle Life of Li-Al/FeS Cells

STORAGE TECHNOLOGY:Lithium Metal Sulfide Batteries

_____**SOURCE:**Argonne National Laboratory. High-
Performance Batteries for Electric Vehicle
Propulsion and Stationary Energy Storage.
ANL79-94. DOE Contract W-31-109-Eng-38.
March 1980.**INFORMATION:**

Table IV-3. Performance of Six Multiplate Li-Al/FeS Cells (Mark IA)

	Six-Cell Average	EPMP-7 -062	EPMP-7 -096	EPMP-7 -089	EPMP-7 -046	EPMP-7 -055	EPMP-7 -095
Specific Energy, ^a W-hr/kg	101.3	106.8	104.6	106.8	100.8	100.8	87.8
Specific Power, ^b W/kg	54.4	58	-	58	52	46	58
Percent Decline in Energy	30	32	40	38	25	12	21
Percent Decline in Energy per Cycle	0.12	0.17 ^c	0.14 ^d	0.12 ^d	0.13 ^c	0.04 ^e	0.10 ^c
Cycle Life	258	190	289	330	200	320	218

^a Measured at the 4-hr rate.^b Measured at 50% depth of discharge.^c Cell still operating as of the end of September 1979.^d Cell operation voluntarily terminated.^e Cell failure due to short circuit.

STORAGE TECHNOLOGY:Lithium Metal Sulfide Batteries

SOURCE:Argonne National Laboratory. High-
Performance Batteries for Electric Vehicle
Propulsion and Stationary Energy Storage.
ANL79-94. DOE Contract W-31-109-Eng-38.
March 1980.**INFORMATION:**

Table IV-2. Performance Summary for Li-Al/FeS Multiplate Cells (Mark IA)

Cell Designation	No. of Cells	Average Specific Energy, ^a W-hr/kg	Average Discharge Rate, hr	Average No. of Cycles Operated ^b	Percent Decline in Specific Energy	Percent Decline in Specific Energy Per Cycle
A-series	7	95.4	5	97	20	0.21
B-series	18	100.5	4	100	23	0.23
C-series	13	102.4	4	111	36	0.32
D-series	24	97.2	4	119	28	0.24
Mark IA Production Cells	21	100.7	4	122	26	0.24
Total	83 ^c	99.2	4	110	27	0.25

^aTypical value within the first 25 cycles; 4-hr rate.^bReasons for termination include cell failure (short circuit or declining coulombic efficiency) as well as the end of scheduled testing.^c65 cells tested at Eagle-Picher; 18 at ANL.

STORAGE TECHNOLOGY:

Lithium Metal Sulfide Batteries

SOURCE:

Argonne National Laboratory. High-
Performance Batteries for Electric Vehicle
Propulsion and Stationary Energy Storage.
ANL79-94. DOE Contract W-31-109-Eng-38.
March 1980.

INFORMATION:

Table IV-1. Performance of Li-Al/FeS Bicells

Cell Designation	No. of Cells	Average Specific Energy, ^a W-hr/kg	Average Discharge Rate, hr	Average No. of Cycles Operated ^b	Percent Decline in Specific Energy	Percent Decline in Specific Energy Per Cycle
M-series ^c	6	54.3	3.5	252	24	0.09
R-series ^c	14	52.9	4.0	235	12	0.05
PW-series ^c	8	47.2	7.0	328	18	0.05
G-series ^d	7	55.8	7.6	107	5	0.05
Total	35	54.2	5.3	250	14	0.06

^aTypical value determined within the first 20 cycles.

^bReasons for termination include cell failure (short circuit or declining coulombic efficiency) as well as the end of scheduled testing.

^cFabricated at ANL.

^dFabricated at Gould Inc.

STORAGE TECHNOLOGY:

Lithium-Metal Sulfide Batteries

SOURCE:

Chilenskas, A.A. A Preliminary Estimate of the Manufacturing Cost for Lithium/Metal Sulfide Cells for Stationary and Mobile Applications. ANL-79-59, 1979.

INFORMATION:

Table 7 Cell Manufacturing Cost Summary

Assumptions

Costing Basis: ANL-76-12
Plant Production Rate: 1.15×10^6 kWh/yr

Scaling Factors

Inflation @ 10%/yr, $(1.1)^4 = 1.46$
Cell Size Factor, SES = 1, EV = 1.51
Process Complexity Factor, 1976 Plant = 1, 1979 Range 0.75-1.25

	1976 Dollars			1979 Dollars			
	ANL-76-12	SES	REF	EV (FeS)	REF	EV (FeS ₂)	REF
<u>Scaling Factors</u>		<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>
Inflation, 10%/yr	1.0	1.46	1.46	1.46	1.46	1.46	1.46
Cell Size	1.0	1.0	1.0	1.51	1.51	1.51	1.51
Process Complexity	1.0	0.75	1.25	0.75	1.25	0.75	1.25
<u>Cost Item</u>							
Equipment, \$/MM	3.20	3.51	5.85	5.28	8.81	5.28	8.81
Land, Bldgs., Inst., \$/MM	6.40	7.01	11.69	10.57	17.62	10.57	17.62
Labor (Dir. & Ind.) \$/MM	3.56	3.90	6.50	5.88	9.80	5.88	9.80
Total Investment, \$/MM	12.53	13.82	21.69	19.55	31.62	19.44	31.53
Materials Cost, \$/kWh	19.02	14.76	25.05	17.24	29.63	16.14	28.64
Factory Cost, \$/kWh	26.27	20.88	35.30	27.81	46.86	26.47	45.65
Profit, \$/kWh	2.89	3.46	5.42	4.88	7.91	4.86	7.88
Selling Price, \$/kWh	29.16	24.34	40.72	32.69	54.77	31.33	53.53

STORAGE TECHNOLOGY:

Lithium Metal Sulfide Battery

SOURCE:

Chilenskas, A.A. et al., A Preliminary
Estimate of the Manufacturing Cost
for Lithium/Metal Sulfide Cells for
Stationary and Mobile Applications.
ANL-79-59, 1979.

INFORMATION:

Table 10. Cell Manufacturing Cost Summary

	<u>1976 Estimate^a of SES Cell</u>	<u>Present Estimate</u>					
		<u>SES Cell</u>		<u>EV (FeS) Cell</u>		<u>EV (FeS₂) Cell</u>	
		<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>
Equipment, \$ x 10 ⁶	3.20	3.51	5.85	5.28	8.81	5.28	8.81
Land, bldgs., inst., \$ x 10 ⁶	6.40	7.01	11.69	10.57	17.62	10.57	17.62
Labor, \$ x 10 ⁶	3.56	3.90	6.50	5.88	9.80	5.88	9.80
Total Investment, \$ x 10 ⁶	12.53	13.82	21.69	19.55	31.62	19.44	31.53
Materials Cost, \$/kW-hr	19.02	14.76	25.05	17.24	29.63	16.14	28.64
Factory Cost, \$/kW-hr	26.27	20.88	35.30	27.81	46.86	26.47	45.65
ROI, \$/kW-hr	2.89	3.46	5.42	4.88	7.91	4.86	7.88
Selling Price, \$/kW-hr	29.16	24.34	40.72	32.69	54.77	31.33	53.53

^aManufacturing cost from ANL-76-12.

ASSUMPTIONS & COMMENTS:

1979 dollars.

STORAGE TECHNOLOGY:Lithium-Metal Sulfide Batteries**SOURCE:**

Chilenskas, A.A. A Preliminary Estimate of the Manufacturing Cost for Lithium/Metal Sulfide Cells for Stationary and Mobile Applications. ANL-79-59, 1979.

INFORMATION:

Fig. 2. Cost Estimates for SES and EV Cells (for each cell type, the column on the left represents the low estimate and that on the right represents the high estimate).

STORAGE TECHNOLOGY:Lithium-Aluminum/Metal SulfideBatteries**SOURCE:**High Performance Batteries for Stationary
Storage and Electric Vehicle Propulsion.
ANL-77-17.**INFORMATION:**

Table 1-1. Performance Goals for Lithium-Aluminum/Metal Sulfide Batteries

Battery Goals	Electric Vehicle Propulsion		Stationary Energy Storage	
	Mark I 1978	Prototype 1985	BEST 1981	Prototype 1985
Power				
Peak	30 kW	60 kW	1.5 MW	25 MW
Sustained Discharge	12 kW	25 kW	1 MW	10 MW
Energy Output	30 kW-hr	45 kW-hr	5 MW-hr	100 MW-hr
Specific Energy, ^a W-hr/kg	110	180	60-80	60-150
Discharge Time, hr	4	4	5	5-10
Charge Time, hr	8	5-8	8	10
Cycle Life	300	1000	1000	3000
Cost of Cells, \$/kW-hr	-	35	25-30 ^b	20

^aIncludes cell weight only; insulation and supporting structure is approximately 25% of total weight for the Mark I electric vehicle battery and 15 to 20% for the 1985 prototype vehicle battery.

^bProjected cost at a production rate of 2000 MW-hr/yr.

STORAGE TECHNOLOGY:

Electric Vehicle Batteries

SOURCE:

High Performance Batteries for
Stationary Storage and Electric
Vehicle Propulsion ANL-77-17.

INFORMATION:

Table 11-2. Calculated Ranges for a Light Delivery Van (1500 kg) Powered by a 430-kg Battery with Selected Motor/Control Systems Using a J227 Driving Profile

Type of Motor	Range, km (miles)							
	Electronic Chopper				Resistance Control			
	3-Speed Drive		Direct Drive		3-Speed Drive		Direct Drive	
	PB220 ^a	Li/MS ^b	PB220 ^a	Li/MS ^b	PB220 ^a	Li/MS ^b	PB220 ^a	Li/MS ^b
Series ^c	32 (20)	119 (74)	27 (17)	108 (67)	24 (15)	74 (46)	18 (11)	55 (34)
Compound ^d	29 (18)	113 (70)	29 (18)	114 (71)	29 (18)	97 (60)	21 (13)	71 (44)
Shunt ^c	34 (21)	113 (70)	26 (16)	64 (40)	34 (21)	105 (65)	24 (15)	56 (35)

^aCommercially available lead-acid battery weighing 436 kg (960 lb).

^bLi/FeS₂ battery weighing 432 kg (950 lb); output based on 1976 cell performance.

^cMotor parameters obtained from a theoretical model.

^dMotor parameters obtained from an actual motor.

STORAGE TECHNOLOGY:Lithium Metal Sulfide Batteries**SOURCE:**

Chilenskas, A.A. Commercialization
 Planning for the Lithium/Metal Sulfide
 Battery. Prepared for LI 77 Symposium on
 Lithium Needs and Resources, Corning, NY.
 Argonne National Laboratory. 1977

INFORMATION: Table I-1. Program Goals for the Lithium/Metal Sulfide
 Electric-Vehicle Battery

Goal	Mark IA	Mark II	Mark III
Specific Energy, ^a W-hr/kg			
Cell (Average)	80	125	160
Battery	60	100	130
Energy Density, W-hr/liter			
Cell (Average)	240	400	525
Battery	100	200	300
Peak Power, ^b W/kg			
Cell (Average)	80	125	200
Battery	60	100	160
Battery Heat Loss, ^c W	400	150	125
Lifetime			
Deep Discharges	200	500	1,000
Equivalent Kilometers	32,000	95,000	240,000
Equivalent Miles	20,000	60,000	150,000

^a Calculated at the 4-hr discharge rate.

^b Peak power sustainable for 15 sec at 0 to 50% state of discharge;
 at 80% discharge, the peak power is 70% of the values shown.

^c The values shown represent the heat loss of the battery through
 the insulated case; under some operating conditions, additional
 heat removal may be required.

ASSUMPTIONS & COMMENTS:

1976 dollars

STORAGE TECHNOLOGY:

Lithium Metal Sulfide Batteries

SOURCE:

Heiter, Kenneth and Paul Skartvedt.
Battery Technology An Assessment of
the State of the Art, TRW Energy Systems
Group DOE Contract EX-76-C-10-3885
Task Order 23., 1978.

INFORMATION:

Table A-11. Lithium Organic Battery
Characterization (Projected on Basis
of Li/TiS₂ Cells)

CHARACTERISTIC	PROJECTION
Energy Density	135 Wh/kg
Volumetric	324 Wh/L
Peak Power Density	110 WL/kg
Sustaining Power Density	22 W/kg
Operating Temperature	Ambient
Mass Production Cost	\$42/kWh

Source: Reference 2-11

¹Also known as the lithium sulfide ambient temperature battery.

ASSUMPTIONS & COMMENTS:

1977 dollars.

SUMMARY

End Use: Vehicles

Technology: Thermal Storage

No useful comparisons possible.

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE:

Behrin, E. et al., Energy Storage Systems
for Automobile Propulsion, 1978 Study,
Vol. 2, UCRL-52553, Lawrence Livermore
Laboratory, 1978.

INFORMATION:

	LiF		NaF/MgF ₂	
	Rect. ^a	Cyl. ^b	Rect. ^a	Cyl. ^b
Total energy storage, kW•h(thermal)	172	134	127	99
Energy density, W•h/l	397	396	293	293
Specific energy, W•h/kg	303	275	199	185
Specific power, 80% depleted	352	411	313	375
15 s, W/kg				
Energy loss rate, kW	0.55	0.57	0.55	0.57
Production cost including all accessories. 1978 dollars (200,000 units/yr), \$/kW•h	39	44	47	53

^aRectangular design.^bCylindrical design.

STORAGE TECHNOLOGY:Thermal Energy Storage

SOURCE:Behrin, E., et al., Energy Storage Systems
for Automobile Propulsion, Vol. 2,
UCRL-52303, Lawrence Livermore Labora-
tories, 1977.

INFORMATION:

Table 5-22. Projected characteristics of a thermal energy storage device.

Confidence level, %	Peak power at 80% discharge, W/lb (W/kg)	Specific energy per unit volume, W·h/ft ³ (W·h/l)	Energy density, W·h/lb (W·h/kg)
			Period 3 (1990-2000)
75	48.6 (107)	13,926 (492)	110 (241)
50		14,433 (510)	114 (250)
25		14,686 (519)	116 (254)

SUMMARY

End Use: Vehicles

Technology: Hydrogen

<u>Energy Density</u> (Wh/kg)	<u>Report</u>		
	1	2	3
Liquid Hydrogen	3,600	2,250	3,600
TiFe Hydride	240	300	-
Mg Hydride	390	421	390

<u>Peak Power At 80% Charge</u> (W/kg)	<u>Report</u>		
	1	2	3
Liquid Hydrogen	(Engine Limited)	4,800	-
TiFe Hydride	3,300	284-640	-
Mg Hydride	3,300	284-640	-

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

Hydrogen Storage Devices for

Automobiles. G. Strickland.

BNL - 25263

INFORMATION:

TABLE I

ENERGY AND PEAK-POWER RATINGS OF HYDROGEN STORAGE SYSTEMS FOR 1985-90^A

	ENERGY DENSITY				PEAK POWER			
	Wh/kg		Wh/ft ³		W/kg		W/kg	
	GRAVIMETRIC		VOLUMETRIC		80%, 0.5min ^B		50%, 15min ^C	
Confid. Level	50%	10%	50%	10%	50%	10%	50%	10%
Ni-Zn Battery	81	90	--	--	135	160	--	--
Liq. Hydrogen	3600	5600	40,000	42,000	LIMITED BY ENGINE SIZE			
TiFe Hydride ^B	240	320	16,000	21,000	3300	4400	550	830
Mg Hydride ^C	390	570	15,000	22,000	3300	4800	550	910

^A Ratings (thermal) are based on weight of storage device and all system components for fuel delivery, and on volume of the device, except for the battery.

^B 80% discharge at 5-h rate, then peak power sustained for 0.5 min with no intervening recovery period.

^C 50% discharge at 5-h rate, then peak power sustained for 15 min with no intervening recovery period.

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

Hydrogen Storage Devices for Automobiles,

G. Strikland. BNL-25263.

INFORMATION:

TABLE II

PASSENGER VEHICLE WEIGHTS AND COST FACTORS FOR 1985-1990

A

PERFORMANCE:	<u>EQUIVALENT</u>		<u>INTERMED.</u>		<u>LIMITED</u>		<u>MINIMUM</u>	
Part A: Curb Weights (lb) and Factors Relative to ICE Values								
Confid. Level	50%	10%	50%	10%	50%	10%	50%	10%
Baseline ICE	2500	2400	2180	2090	2050	1970	1920	1840
Ni-Zn Battery	--	--	2.54	1.90	1.55	1.39	1.21	1.14
Liq. Hydrogen	0.99	0.93	0.95	0.93	0.94	0.94	0.93	0.95
Dual Hydride	--	1.79	1.61	1.29	1.16	1.10	1.06	1.04
TiFe Hydride	--	--	1.92	1.49	1.26	1.15	1.14	1.09

Part B: Initial User Costs (1977\$) and Factors Relative to ICE Values

Confid. Level	50%	10%	50%	10%	50%	10%	50%	10%
Baseline ICE	3550	3530	3400	3380	3350	3330	3260	3240
Ni-Zn Battery	--	--	3.53	2.51	1.78	1.53	1.22	1.18
Liq. Hydrogen	1.10	1.03	1.05	1.05	1.02	1.02	1.02	1.02
Dual Hydride	--	2.50	1.93	1.36	1.14	1.09	1.07	1.04
TiFe Hydride	--	--	2.03	1.48	1.15	1.09	1.09	1.06

Part C: Life-Cycle Costs (cents/mi) and Factors Relative to ICE Values

Confid. Level	50%	10%	50%	10%	50%	10%	50%	10%
Baseline ICE	13.8	13.7	13.2	13.1	13.0	12.9	12.7	12.6
Ni-Zn Battery	--	--	2.86	1.68	1.55	1.17	1.14	0.98
Liq. Hydrogen	1.25	1.20	1.14	1.12	1.12	1.12	1.11	1.11
Dual Hydride	--	1.78	1.67	1.31	1.17	1.16	1.13	1.11
TiFe Hydride	--	--	1.76	1.42	1.19	1.13	1.14	1.13

A Partial requirements in terms of range in miles and power-to-weight ratio in hp/lb: Equivalent, 250 and 0.03; Intermediate, 150 and 0.02; Limited, 75 and 0.016; and Minimum, 50 and 0.01.

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

Behrin, E., et al., Energy Storage
Systems for Automobile Propulsion, Vol.
2, UCRL-52303, Lawrence Livermore
Laboratories, 1977.

INFORMATION:

Table 5-19. Projected characteristics of an FeTiH_x energy storage device
(including all system components for delivering fuel to the
engine).

Confidence level, %	Peak power at 80% discharge, W/lb (W·h/kg)		Specific energy per unit volume, (W·h/ft ³ (W·h/l)	Energy density, W·h/lb (W/kg)	
	3-in.-diam	2-in.-diam		Period 2 (1985-1990)	Period 3 (1990-2000)
75	129	291	16,480	132	132
	(284)	(640)	(580)	(291)	(291)
50			16,980	136	136
			(600)	(300)	(300)
25			17,354	139	139
			(610)	(306)	(306)

STORAGE TECHNOLOGY:Hydrogen

SOURCE:Behrin, E., et al., Energy Storage
Systems for Automobile Propulsion, Vol.
2, UCRL-52303, Lawrence Livermore
Laboratories, 1977.

INFORMATION:

Table 5-20. Projected characteristics of a MgH_x (10% Ni) energy storage (including all system components for delivering fuel to the engine).

Confidence level, %	Peak power at 80% discharge, W/lb (W·h/kg)		Specific energy per unit volume, (W·h/ft ³) (W·h/l)	Energy density, W·h/lb (W/kg)	
	3-in.-diam	2-in.-diam		Period 2 (1985-1990)	Period 3 (1990-2000)
75	129	291	16,090	181	181
	(284)	(640)	(570)	(398)	(398)
50			16,980	191	191
			(600)	(421)	(421)
25			17,956	202	202
			(630)	(444)	(444)

STORAGE TECHNOLOGY:Liquid Hydrogen

 SOURCE:Behrin, E., et al., Energy Storage
Systems for Automobile Propulsion, Vol.
2, UCRL-52303, Lawrence Livermore
Laboratories, 1977.
 INFORMATION:

Table 5-21. Projected characteristics of a liquid hydrogen energy storage device.

Confidence level, %	Peak power at 80% discharge, W/lb (W/kg)	Specific energy per unit volume, W·h/ft ³ (W·h/l)	Energy density, W·h/lb (W·h/kg)	
			Period 2 (1985-1990)	Period 3 (1990-2000)
25	2,180	33,102	920	920
	(4,800)	(1,170)	(2,024)	(2,024)
50		36,790	1,023	1,023
		(1,300)	(2,250)	(2,250)
25		40,469	1,125	1,125
		(1,430)	(2,475)	(2,475)

STORAGE TECHNOLOGY:

Thermal and Chemical Storage

SOURCE:

Behrin, E., et al., Energy Storage
Systems for Automobile Propulsion,
Vol. 2, UCRL-52303, Lawrence Livermore
Laboratories, 1977.

INFORMATION:

Table 8-1. Data on chemical and thermal storage systems with 150 kW·h of stored energy available for conversion.

System	Gravimetric energy density, W·h/kg	Volumetric energy density, W·h/cm ³	Power density, W/kg	Tank wt, kg	Reactor, kg	Piping and control, kg	Total ^a nonfuel wt, kg	Fuel material wt, kg	H ₂ wt in fuel material, kg
Liquid H ₂	2250	1.3	4800	32	12	18	62	4.4	4.4
FeTiH _x	300	0.6	284 @ 80% ^b 640 @ 80% ^c	150	—	6	156	352	4.4
MgH _x (10 wt% Ni)	421	0.6	Same as FeTiH _x (assumed)	156	—	37	193	163	8.3
NH ₃	756	0.75	441.5 + 490 $\frac{\Delta W}{W}$	29	104	26	159.5	38.7	6.8
Methanol-water	642	0.85	375 + 190 $\frac{\Delta W}{W}$	5	160	25	190	43	5.2
MCH-toluene	482	0.54	281 + 377 $\frac{\Delta W}{W}$	27	144	19	190	121.5	7.4
LiH	1500	2.28	No limits probably	55	—	26.25	81.25	18.75	4.75
Thermal storage	250	0.51	107 @ 80%	240	—	—	240	240	—

^aFuel not included.

^bThree-inch-diam tubes in tank bundle (22 tubes 4 ft long).

^cTwo-inch-diam tubes in tank bundle.

ASSUMPTIONS & COMMENTS:

All systems except thermal storage involve hydrogen storage.

STORAGE TECHNOLOGY:

Thermal and Chemical Storage

SOURCE:

Behrin, E., et al., Energy Storage Systems for Automobile Propulsion, Vol. 2, UCRL-52303, Lawrence Livermore Laboratories, 1977.

INFORMATION:

Table 8-2. Costs of chemical and thermal storage systems with 150 kW·h of stored energy available for conversion.

System	Tank cost, \$	Tank material	Piping, reactor, etc. cost, \$	Quantity priced	Storage material cost
Liquid H ₂	475	Al + SS	780	Commercial limited quantity	
FeTiH	2300	304 SS ^a	200	1 ^c	\$5/kg = 1760
MgH _x (10 wt% Ni)	2300	304 SS	500	1 ^c	\$2.50/kg = 410
NH ₃ → H ₂	450	Al + SS	1150	Commercial limited quantity	\$100/ton
Methanol-water	Same as gasoline	Steel	1200	Commercial limited quantity	
MCH-toluene	Gasoline + 25	Steel	1300	Commercial limited quantity	\$1/gal
Thermal storage	5000 ^b	321 SS	250	1 ^c	\$1.60/kg

^a Aluminum and carbon steel possible depending on heating medium.

^b Estimated cost is strongly dependent on handling needs for lithium fluoride.

^c Experimental.

ASSUMPTIONS & COMMENTS:

1975 dollars

STORAGE TECHNOLOGY:

Liquid Hydrogen

SOURCE:

Behrin, E. et al. Energy Storage
Systems for Automobile Propulsion,
1978 Study Vol. 2, Lawrence Liver-
more Laboratory, UCRL-52553, 1978.

INFORMATION:

TABLE 1-13. Liquid-hydrogen tank gravimetric and volumetric energy-density ratings.^a

Time period	<u>50% confidence</u>		<u>10% confidence</u>	
	Energy density,		Energy density,	
	W•h/kg	W•h/cm ³	W•h/kg	W•h/cm ³
1980-1982	2250	1.3	3600	1.4
1985-1990	3600	1.4	5600	1.5
1990-2000	5600	1.5	5600	1.5

^aRatings are based on mass of tank and all system components for fuel delivery, and on volume of the tank, for a 150-k•Wh (thermal) storage system.

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

Behrin, E. et al. Energy Storage
Systems for Automobile Propulsion,
1978 Study Vol. 2, Lawrence Liver-
more Laboratory UCRL-52553, 1978.

INFORMATION:

Table 1-18. Mg-based hydride storage system^a gravimetric and volumetric energy-density ratings.^b

Time period	50% confidence level		10% confidence level	
	Energy density,		Energy density,	
	W•h/kg	W•h/cm ³	W•h/kg	W•h/cm ³
1980-1982	250	0.33	530	0.71
1985-1990	390	0.53	570	0.78
1990-2000	480	0.64	600	0.81

^aHydride is Mg(10 wt% Ni)H_x.

^bRatings are thermal based on: 10-min charge; mass of the hydride reservoir and all the system components for fuel delivery; and volume of the reservoir.

SUMMARY

End Use: Vehicles

Technology: Mechanical Storage

No useful comparisons possible.

STORAGE TECHNOLOGY:

Mechanical Storage

SOURCE:

Behrin, E., et al., Energy Storage
Systems for Automobile Propulsion,
Vol. 2, UCRL-52303, Lawrence Livermore
Laboratories, 1977.

INFORMATION:

Table 3-6. Gravimetric specific energies projected
for mechanical energy storage devices
through 2000.

Storage system	Specific energy, W•h/lb
Composite rotor flywheel ^a	10-20
Hydraulic accumulator	2.5-6
Compressed-air ^b	10-20
Linear elastic solids	<1
Elastomers	
Compressed fluids	

^a Includes rotor, shaft, and housing.

^b Assumes use of waste heat.

ASSUMPTIONS & COMMENTS:

1975 dollars

STORAGE TECHNOLOGY:

Mechanical Storage

SOURCE:

Behrin, E., et al., Energy Storage
Systems for Automobile Propulsion,
Vol. 2, UCRL-52303, Lawrence Livermore
Laboratories, 1977.

INFORMATION:

Fig. 3-26. Comparative costs of energy storage devices based upon available energy.

ASSUMPTIONS & COMMENTS:

1975 dollars

SUMMARY

End Use: Vehicles

Technology: Flywheels

No useful comparisons possible.

STORAGE TECHNOLOGY:

Flywheels

SOURCE:

Behrin, E. et. al. Energy Storage Systems for Automobile Propulsion, 1978 Study. Vol. 2, Lawrence Livermore Laboratory, UCRL-52553, 1978.

INFORMATION:

TABLE 1-5. Characteristics of kinergy automobiles.

	71 Camaro	73 Cadillac	77 Volvo	70 VW Beetle
Curb mass, kg	1600	2500	943	
Engine type	4-cyl. Subaru	4-cyl. Subaru	4-cyl. Renault	El. Motor
Engine hp, max	60 at 5200 rpm	60 at 5200 rpm	70 at 5500 rpm	8 hp
Engine mass, kg	70	70	132	300 (for batteries and motor)
Flywheel type	Pierced disk (steel)	Pierced disk (steel)	Pierced disk (steel)	Steel disk
Flywheel mass, kg	70	90	82	60
Diam, cm x thickness, cm	46 x 5	52.5 x 5	55 x 4	46 x 4.2
Housing and pressure	None, atmospheric	None, atmospheric	Lexan, 0.25 psia He	Aluminum, 0.5 psia air
Operating range, rpm	2250 to 9000	2000 to 7500	3000 to 8000	4000 to 8000
Energy at max speed, kW*h	0.25	0.31	0.29	0.2
Specific energy, Wh/kg	3.4	3.5	3.5	3.3
Quoted peak power, kW, at speed, rpm	120 at 9000	40 at 3000	75 at 8000	Not given
Transmissions	4-speed manual (Borg-Werner) to be exchanged for a Lemmons CVT	4-speed manual (Dodge Colt) plus traction drive CVT	Standard belt-drive DAF/Volvo CVT	Standard VW 4-speed plus CVT

STORAGE TECHNOLOGY:

Flywheels

SOURCE:

Behrin, E., et al., Energy Storage Systems for Automobile Propulsion, Vol. 2, UCRL-52303, Lawrence Livermore Laboratories, 1977.

INFORMATION:

	Laminated rotor	Shaped disk	Multirim

Material	Steel	Steel	E-glass	S-glass	Kevlar
Shape factor K	0.30	0.85	0.30	0.30	0.30
Max stress/density — in.-lb/lb	0.49	0.49	1.25	1.90	2.40
Peripheral speed — fps	1260.00	2300.00	1950.00	2200.00	2500.00
Rotational speed (relative)	1.00	1.00	1.00	1.00	1.00
Rotor specific energy — W-h/lb	5.60	13.10	11.80	17.90	22.60
Rotor energy/swept vol — W-h/in. ³	1.30	2.20	0.50	0.75	0.68
Approx containment weight relative to corresponding rotor	0.40	5.00	0.80	1.30	1.60
Flywheel assembly specific energy — W-h/lb	4.00	2.30	6.50	8.00	9.00
Flywheel assembly energy/sweep vol — W-h/in. ³	1.00	1.60	0.39	0.58	0.52

Fig. 3-22. Comparisons of equal-life designs of various flywheels.

STORAGE TECHNOLOGY:

Flywheels

SOURCE:

Behrin, E., et al., Energy Storage
Systems for Automobile Propulsion,
Vol. 2, UCRL-52303, Lawrence Livermore
Laboratories, 1977.

INFORMATION:

Table 5-16. Projected characteristics of a flywheel energy storage device
(including housing and vacuum pump).

Confidence level, %	Energy density, ^a W•h/lb (W•h/kg)		
	Period 1 (1980-1982)	Period 2 (1985-1990)	Period 3 (1990-2000)
75	13 (28.6)	17 (37.4)	19 (41.8)
50	13.5 (29.7)	18.5 (40.7)	20 (44.0)
25	14.5 (31.9)	20 (44.0)	21 (46.2)

^a Available energy.

SUMMARY

End Use: Vehicles

Technology: Compressed Air

No useful comparisons possible.

STORAGE TECHNOLOGY:

Compressed Air

SOURCE:

Behrin, E., et al., Energy Storage
Systems for Automobile Propulsion, Vol.
2, UCRL-52303, Lawrence Livermore
Laboratories, 1977.

INFORMATION:

Table 5-17. Projected characteristics of a compressed-air energy storage device (including the pressure vessel) at an air pressure of 1500 psi (isothermal process).

Confidence level, %	Energy density, ^a W·h/lb (W·h/kg)		
	Period 1 (1980-1982)	Period 2 (1985-1990)	Period 3 (1990-2000)
75	10.4 (22.9)	17.3 (38.1)	19.2 (42.2)
50	12.0 (26.4)	20.0 (44.0)	25.0 (55.0)
25	13.0 (28.6)	21.7 (47.7)	27.8 (61.2)

^aAvailable energy.

STORAGE TECHNOLOGY:

Compressed Air

SOURCE:

Behrin, E., et al., Energy Storage
Systems for Automobile Propulsion,
Vol. 2, UCRL-52303, Lawrence Livermore
Laboratories, 1977.

INFORMATION:

Table 5-18. Projected characteristics of a hydraulic accumulator energy storage device (including the pressure vessel with compressed gas).

Confidence level, %	Energy density, ^a W·h/lb (W·h/kg)		
	Period 1 (1980-1982)	Period 2 (1985-1990)	Period 3 (1990-2000)
75	1.6	1.9	2.3
	(3.5)	(4.2)	(5.1)
50	1.6	2.2	2.4
	(3.5)	(4.8)	(5.3)
25	1.7	2.4	2.5
	(3.7)	(5.3)	(5.5)

^a Available energy.

STORAGE TECHNOLOGY:

Energy Storage Systems Comparison

SOURCE:

Aerospace Corporation "Survey of Energy Storage Assessments for Solar Applications" 1980. Prepared for U.S. Department of Energy, 1980.

INFORMATION:

Table 8. Summary of Cost Parameters - Utility Application (GE Report 1)

ENERGY STORAGE CONCEPT	NOMINAL EXPECTED LIFE(YRS)	NOMINAL EFFICIENCY (%)	Construction Cost CCF ^a	Fixed Charge Rate FCR ^a	CAPITAL COSTS ^b		O&M COSTS ^b	
					I _P (\$/kW) <small>per kW of capacity installed</small>	I _E (\$/kWh) <small>per kWh of capacity installed</small>	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 Report³ 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).

ASSUMPTIONS & COMMENTS:

Table from: Applied Research on Energy Storage and Conversion for Photovoltaic and Wind Energy Systems, General Electric Company, 77SDS4245, 1977.

STORAGE TECHNOLOGY:

Energy Storage Systems Comparison

SOURCE:

General Electric Space Division.

Applied Research on Energy Storage and
Conversion for Photovoltaic and WindEnergy Systems. National Science
Foundation. NSF C-75-22221-01**INFORMATION:**

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

ENERGY STORAGE CONCEPT	NOMINAL EXPECTED LIFE(YRS)	NOMINAL EFFICIENCY (%)	CCF ³	FCR ⁴	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 Report³ 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).

STORAGE TECHNOLOGY:

Energy Storage Systems Comparison

SOURCE:

Fischer, W., et al. Economic Prospects
for the Application of New Electric
Energy Storage Devices. Journal of
Power Sources. 3(1978) 331-345.
Lausanne, Switzerland

INFORMATION:**TABLE 5**

Data for peak power plants for the calculation of energy costs

	Power related price (DM/kW)	Energy related price (DM/kWh)	Efficiency	Lifetime (years)
1 Pumped hydro storage plant	550	25	0.75	30
2 Gas turbine	400	—	0.26 - 0.3	20
3 Compressed air power plant	240	25	0.7	20
4 Battery (Na/S)	190 - 300	135 - 170	0.7	10
5 Battery (Redox)	300 - 655	75 - 95	0.7	10
6 Hydrogen storage (solid electrolyte H ₂ O-electrolysis-gas turbine)	1090 - 1415	15	0.2	10
7 Hydrogen storage (solid electrolyte cells used for the electrolysis and as fuel cells alternately)	790 - 1115	15	0.45	10
8 Hydrogen storage (high pressure-H ₂ O-electrolysis-gas turbine)	1390 - 1915	15	0.2	10
9 Steam storage	215 - 285	70 - 100	0.7	20
10 Flywheel	370 - 420	500 - 800	0.7	20

ASSUMPTIONS & COMMENTS:

Costs in German Marks

STORAGE TECHNOLOGY:Energy Storage Systems Comparison**SOURCE:**

TRW Inc., Development of a Data Base
 Characterizing Energy Storage Technol-
 ogies, Task 1, Characterization of
 Storage Technologies in Utility Load
 Leveling Applications. Argonne National
 Laboratory, Contract No. 31-109-38-5106,
 1979.

INFORMATION:

Table 6-5. Range of Values for Baseline
 Storage Technologies

CHARACTERISTICS	CURRENT PUMPED HYDRO	TES HEATING (BRICKS)	TES COOLING (WATER)
Typical Facility Size	50 - 2000 MW	15 - 250 kWh	250 kWh & up
Capital Cost (1978 \$): Storage (\$/kWh) Power (\$/kW)	2.5 - 12 120 - 190	8 - 14 0 - 4	15 - 25 *
O & M Cost (1978 mills/kWh)	1 - 14	nil	nil
Energy Storage Capacity (hours)	5.6 - 94	4 - 16	4 - 16
Storage System Efficiency	.66 - .78	.70 - .95	.90 and up
Expected Lifetime (years)	50 or more	10 - 15	25
Construction Lead Time	4 - 10 yrs	1 - 7 days	.25 -1 yr

*Capital cost expressed in \$/kWh only.

STORAGE TECHNOLOGY:Energy Storage Systems Comparison

SOURCE:TRW Inc., Development of a Data Base
Characterizing Energy Storage Technol-
ogies, Task 1, Characterization of
Storage Technologies in Utility Load
Leveling Applications. Argonne National
Laboratory, Contract 31-109-38-5106, 1979.**INFORMATION:**Table 6-6. Expected Values for Baseline
Storage Technologies

CHARACTERISTIC	CURRENT PUMPED HYDRO	TES HEATING (BRICKS)	TES COOLING (WATER)
Typical Facility Size	350 MW	150 kWh	1000 kWh
Capital Cost (1978 \$): Storage (\$/kWh) Power (\$/kW)	8 175	10 3.4	18
O & M Cost (1978 mills/kWh)	2.5	nil	nil
Energy Storage Capacity (hours)	9	8	8
Storage System Efficiency	.72	1.0	.90
Expected Lifetime (years)	50	15	25
Construction Lead Time	8 yrs	2 days	10 months

STORAGE TECHNOLOGY:

Energy Storage Systems Comparison

SOURCE:

TRW Inc., Development of a Data Base
Characterizing Energy Storage Technol-
ogies, Task 1 Characterization of
Storage Technologies in Utility Load-
Leveling Applications. Argonne National
Laboratory, Contract 31-109-38-5106, 1979.

INFORMATION:

Table 6-7. Range of Values for Storage Technologies

CHARACTERISTIC	UPHS	CAES	ADVANCED UTILITY BATTERIES	SMES	TES HEATING (PCM)	TES COOLING (PCM)
Typical Facility Size	1000-3000 MW	290-2000 MW	200-500 MW	no data	50-500 kWh	15-500 kWh
Capital Cost (1978 \$):						
Storage (\$/kWh)	3.5 - 16	3 - 16	24 - 75	40 - 90	10 - 12	24
Power (\$/kW)	150 - 300	120 - 250	60 - 85	70 - 90	*	*
O & M Cost (1978 mills/kWh)	1 - 2	2.4 - 6.3	0.5 - 4.0	no data	nil	nil
Energy Storage Capacity (hours)	6 - 10	2 - 20	2 - 10	3 - 20	4 - 16	4 - 16
Heat Rate (Btu/kWh)	NA	4200 - 5800	NA	NA	NA	NA
Storage System Efficiency	.67 - .78	.69 - .86	.70 - .80	.93 - .97	.80 & up	.90 & up
Expected Lifetime (years)	50 or more	25 - 35	10 - 25	30 or more	unknown	unknown
Construction Lead Time	7 - 12 yrs	4 - 8 yrs	0.5 - 2 yrs	no data	1 - 7 days	1 - 26 weeks

*Capital cost expressed in \$/kWh only.

NA = Not Applicable

STORAGE TECHNOLOGY:

Energy Storage Systems Comparison

SOURCE:

TRW Energy Systems Planning Division,
 Development of a Data Base Characterizing
 Energy Storage Technologies, Task 1,
 Characterization of Storage Technologies
 in Utility Load Leveling Applications.
 Argonne National Laboratory, Contract
 31-109-38-5106, 1979.

INFORMATION:

Table 6-8. Expected Values for Storage Technologies

CHARACTERISTIC	UPHS	CAES	ADVANCED UTILITY BATTERIES	SMES	TES HEATING (PCM)	TES COOLING (PCM)
Typical Facility Size	2000 MW	700 MW	350 MW	1000 MW	150 kWh	150 kWh
Capital Cost (1978 \$):						
Storage (\$/kWh)	14	4 - 14*	49 - 55	45	11	24
Power (\$/kW)	200	200	70	75	**	**
O & M Cost (1978 mills/kWh)	1.5	3	3.2	1.8	nil	nil
Energy Storage Capacity (hours)	10	10	4	10	8	8
Heat Rate (Btu/kWh)	NA	4800	NA	NA	NA	NA
Storage System Efficiency	.725	.77	.70	.95	.90	.90
Expected Lifetime (years)	50	30	20	30	unknown	unknown
Construction Lead Time	8 yrs	7 yrs	1 yr	no data	2 days	2 weeks

*Depends on storage type and mode.

**Capital cost given in \$/kWh only.

NA = Not Applicable

STORAGE TECHNOLOGY:

Energy Storage Systems Comparison

SOURCE:

Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
Prepared for Electric Power Research
Institute. 1976

INFORMATION:

Table 4-1 COST SUMMARY FOR SELECTED STORAGE SYSTEMS
1975 DOLLARS - NO CCIF INCLUDED

	<u>Cp (\$/kW) *</u>	<u>Cs (\$/kWh)</u>
Hydro Pumped Storage Conventional and Underground	90-160	2-12
Compressed Air Storage with Combustion Turbines	100-210	4-30
Thermal Storage - Water	150-250	30-70
Thermal Storage - Oil	150-250	10-15
Near-Term Lead Acid Batteries	70-80	65-110
Advanced Batteries	60-70	20-60
Flywheels	65-75	100-300
Hydrogen	500-860	6-15
SMES	50-60	30-140

*Equal charge and discharge times.

Caveat: These estimates only apply to the specific
design considered in this chapter

ASSUMPTIONS & COMMENTS:

1975 dollars

STORAGE TECHNOLOGY:Energy Storage Systems Comparison

SOURCE:Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
Prepared for Electric Power Research
Institute. 1976**INFORMATION:**

Table 4-39 RECOMMENDED OPERATING AND MAINTENANCE
EXPENSES TO BE USED IN COMPARISONS
OF ENERGY STORAGE TECHNOLOGIES

	<u>OPERATING AND MAINTENANCE EXPENSE</u>	
	<u>FIXED</u>	<u>VARIABLE</u>
	\$/kW/yr	mills/kWh
Hydro Pumped Storage	1.6	-
Compressed Air Storage with Combustion Turbines	-	5.3
Thermal Energy Storage	3.2	.2
Battery Storage	-	2.7
Flywheels	-	5.3
Hydrogen Storage	-	2.7
Superconducting Magnetic Energy Storage	1.6	.2

ASSUMPTIONS & COMMENTS:

1975 dollars - Operating and Maintenance Costs only

STORAGE TECHNOLOGY:

Energy Storage Systems Comparison

SOURCE:

Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities
Prepared for Electric Power Research
Institute. 1976

INFORMATION:

Table 5-1 ASSUMPTIONS FOR ENERGY STORAGE SYSTEMS AND CONVENTIONAL GENERATION
USED IN BREAK-EVEN ECONOMIC ANALYSIS CALCULATIONS

Generation Technology	Expected Life (Years)	Annual Carrying Charges (a) Percent	Overall Efficiency Percent	1975 Operation and Maintenance Costs		1975 Installed Capital Cost (\$/kW)
				Fixed Costs (\$/kW/Year)	Variable Costs (mills/kWh)	
ENERGY STORAGE SYSTEMS:						
NEAR-TERM (Present to 1985):						
Hydro Pumped Storage	50	21	70-75	1.6 (g)	-	-
Compressed Air	25	18	5,400 to 4,200 (b)	-	5.3 (h)	-
Thermal, steam	25	16	65-75	3.2 (i)	0.2 (i)	-
Thermal, oil	25	16	65-75	3.2 (i)	0.2 (i)	-
Batteries, lead-acid	5-10 (c)	27-19	60-75	-	2.7 (j)	-
INTERMEDIATE-TERM (1985-2000):						
Advanced Batteries	25 (c)	15	70-80	-	2.7 (j)	-
Chemical (H ₂) Storage	25	15	40-50	-	2.7 (j)	-
Flywheels	25	15	70-85	-	5.3 (h)	-
LONG-TERM (Beyond 2000):						
Superconducting Magnetic Energy Storage (SMES)	25	22	70-85	1.6 (k)	-	-
CONVENTIONAL GENERATION:						
Gas turbine (b)	25	15	12,100 to 11,000 (f)	-	5.3	100 (l)
Combined Cycle (e)	25	15	8,900 to 8,100 (f)	-	4.1	225 (m)

- (a) Expressed as a percent of total capital (power and storage) cost and includes rate of return, depreciation and taxes. This also includes adjustment for interest accumulated construction. (See Appendix B5) No salvage value was assumed except for salvage of 25% of storage costs for lead-acid batteries.
- (b) Heat rate, Btu/kWh. Corresponding compressed air pumping requirements from 80 to 58 kWh (in) per 100 kWh (out).
- (c) Assuming approximately 200 cycles per year, or 1,000 to 2,000 cycles for near-term and 5,000 cycles for advanced batteries.
- (d) Unit size of 100 to 300 megawatts.
- (e) Based on 255 MW unit with gas turbine 175 MW and fossil steam turbine 80 MW.
- (f) Heat rate, Btu/kWh. Near-term to intermediate-term heat rates.
- (g) Based on typical data from existing operational installations.
- (h) Costs assumed similar to conventional simple cycle gas turbines.
- (i) Costs assumed similar to conventional steam peaking units.
- (j) Costs assumed to be about half of conventional simple cycle gas turbine installations.
- (k) Costs assumed to be similar to hydro pumped storage installations.
- (m) Average industry 1975 capital costs are about \$225/kW for the combined cycle unit. Costs include equipment and installation. If cooling towers are required, the capital costs would increase by about \$20/kW.

SUMMARY

End Use: Utility Load Leveling

Technology: Batteries - General

<u>Cost</u> (\$/kWh)	<u>Report</u>		
Battery	1	2	3
Lead-Acid	50		49-90
Nickel-Iron	63-75		
Nickel-Zinc	63-75		
Advanced Lead-Acid	50-63		
Lithium-Metal Sulfide	50	53	42-49
Sodium-Sulfur	50	46	21-35
Zinc-Chlorine	63	50	17-42
Hydrogen-Halogen	50-75		
Iron Air-Zinc Air	38-75		
Lithium Organic	53		
Redox	34-48		42-49
Sodium Antimony Trichloride	50		
Zinc-Bromine	26-53		

STORAGE TECHNOLOGY:Iron-Air and Zinc-Air Batteries**SOURCE:**

Heiter, Kenneth and Paul Skartvedt.
Battery Technology An Assessment of
the State of the Art, TRW Energy Systems
Group DOE Contract EX-76-C-10-3885
Task Order 23., 1978.

INFORMATION:

Table A-10. Iron Air/Zinc Air Battery Characterization
Exploratory Development

CHARACTERISTIC	CURRENT	PROJECTED
Energy Density	80-120 Wh/kg	110 Wh/kg
Peak Power Density	40 W/kg	90 W/kg
Sustaining Power Density	No Data	No Data
Efficiency	40%	40-50%
Cycle Life	150 Cycles	1000 Cycles
Operating Temperature	Ambient	Ambient
Pilot Costs	>\$2000/kWh	-
Mass Production Costs	-	\$30-60/kWh

Sources: References 2-9, 2-10

ASSUMPTIONS & COMMENTS:

1977 dollars

STORAGE TECHNOLOGY:Zinc Bromine Battery

SOURCE:Heiter, Kenneth and Paul Skartvedt.Battery Technology. An Assessment of
the State of the Art. TRW Energy
Systems Group. DOE Contract EX-76-C-10-
3885 Task Order 23. 1978**INFORMATION:**

Table A-15. Zinc Bromine Battery Characterization

CHARACTERISTIC	PROJECTION
Energy Density	60 Wh/kg
Power Density	20-25 W/kg
Efficiency	75-80 Percent
Mass Prod. Cost	\$21-42/kWh
Operating Temperature	Ambient

Source: Reference 2-16

ASSUMPTIONS & COMMENTS:

1977 dollars

STORAGE TECHNOLOGY:Lithium-Water Air Battery

SOURCE:Heiter, Kenneth and Paul Skartvedt.
Battery Technology An Assessment of
the State of the Art, TRW Energy Systems
Group DOE Contract EX-76-C-10-3885
Task Order 23., 1978.**INFORMATION:**

Table A-12. Lithium Water Air Battery Characterization

CHARACTERISTIC	CURRENT LI-WATER	PROJECTION
Energy Density	160 Wh/kg	300-400 Wh/kg
Peak Power Density	18 W/kg	100 W/kg
Efficiency (System)	Primary Cell	25 %
Operating Temperature	Ambient	Ambient

Sources: References 2-12, 2-13

ASSUMPTIONS & COMMENTS:

1977 dollars.

STORAGE TECHNOLOGY:

Batteries

SOURCE:

Redox Bulk Energy Storage System Study,
Final Report. V.II. Exxon Research and
Engineering Co. Jan. 30, 1977

INFORMATION:

Summary of Performance Characteristics of Various Batteries

Battery System ^(a)	Open Circuit Voltage, V	Average Operating Voltage, V	Maximum Reported Ahr Capacity	Maximum practical Power Level	Operating Temperature Range, °C	Life in Years	Depth of Discharge, percent	Reported Cycle Efficiency, percent	Reported Ahr Efficiency, percent
PbO ₂ /Pb	2.02	1.70	5000	2.5 kw	0 - 100	≥2000	50	83 - 91	68 - 75
NiOOH/Cd	1.29	1.10	1245	1 kw	0 - 100	≤5000	50	70 - 85	60 - 75
NiOOH/Fe	1.37	1.20	750	--	0 - 100	≤3000	80	80	60
NiOOH/Zn	1.71	≥1.30	140	--	0 - 100	1200	90	~ 85	~ 70
NiOOH/H ₂	1.36	1.25	55	--	0 - 100	≤8000	≥50	~ 95	--
Ag ₂ O/Cd	1.40	1.16	--	--	0 - 100	2500	45	50 - 95	70 - 75
Ag ₂ O/Pb	1.60	1.50	300	1 kw	0 - 100	300	45	90 - 95	70 - 75
Ag ₂ O/Zn	--	0.90	--	--	0 - 100	20	--	--	--
Ag ₂ O/H ₂	1.50	1.10	500	--	0 - 100	1000	"deep"	--	--
Zn/H ₂	1.80	--	--	20 kw	0 - 100	>150	50	~ 95	~ 80
Zn/Cl ₂ (H ₂ O)	2.12	≥1.93	30,000	12.5 kw	0 - 100	(b)	≤100	--	--
Zn/Sr ₂	1.80	--	--	--	0 - 100	poor	--	--	--
Na/(Na)Cl ⁺	(24.00)	~3.00	5	1 kw	150 - 240	72	"deep"	--	67
Li(Al)/(Na)Cl ₂	3.46	--	30	--	400 - 680	200	≥50	--	--
Zn/O ₂	1.65	1.30	25	27 kw	0 - 100	200	50	~ 70	--
Fe/O ₂	2.60	--	--	15 kw	100 - 250	--	--	--	--
Fe/O ₂	1.25	--	--	--	0 - 100	--	--	--	--
Ca/O ₂	1.21	±0.85	12	--	0 - 100	≤500	"deep"	--	--
Na/S	2.03	1.64	700	1 kw	285 - 400	≥100	50	≤100	≤50
Li/S	2.25	--	--	30 kw	300 - 450	≥100	--	80 - 100	80 - 85
Li/Se	2.10	--	--	--	350 - 400	>100	--	--	--
Li/Fe	≥1.70	≥1.55	--	≤170 kw	400 - 470	>200	--	--	--
Li-Al/FeCl ₂	≤1.77	≤1.50	150	≤118 w	300 - 400	250	--	80	≤74
Median	0.74 - 1.74	--	0.38	--	0 - 100	(b)	90	≤59	70

(a) Alloying additions or other principal components are sometimes used. These are given in parenthesis.

(b) Indefinite cycle life with proper maintenance of solution compositions.

Note: Na represents a metal.

STORAGE TECHNOLOGY:

Batteries

SOURCE:

Redox Bulk Energy Storage System Study,
Final Report. V.II. Exxon Research &
Engineering Co. Jan. 30, 1977

INFORMATION:

Table 1.1.1 (Cont'd)
Primary Assessment of Candidate Electrochemical Energy Storage Systems

Battery System Characteristics	Lead-Acid				Zn-Air	Ni-Zn	Ni-H ₂	Zn-Cl ₂ (Hydrate)	Na-Cl (CC)	Na-S (TBE)	Li-FeS ₂	Li/Al-FeS	Organic Electrolyte
	ESB	Present C+B	Could	Advanced									
Environmental Impact of System													
Normal Operation	Low	Low	Low	Low	Low	Low	Low	Low	Medium	Medium	Medium	Medium	Medium
Unusual Upset	Low	Low	Low	Low	Low	Low	Medium	Medium High	High	High	High	High	Medium
Constant Power Charge ⁽¹⁾													
Low Rates	+	+	+	+	+	+	+	+	+/-	+/-	+/-	+/-	-
High Rates	-	-	-	-	++	+	+	+	-	+	-	-	-
Salvage ⁽¹⁾	++	++	++	++	++	++	+	++	+/-	+/-	+/-	+/-	-
Auxiliaries	Air Pump Cooling	Air Pump Cooling	Air Pump Cooling	Air Pump Cooling	Pumps Compressors CO ₂ Scrub Pumps	Cooling ?	Cooling ?	Pump Refrigerator	Heaters Exchangers	Heaters Exchangers	Heaters Exchangers	Heaters Exchangers	None
Maintenance Requirements	H ₂ O Addition Cell Balancing Coolant Loops	H ₂ O Addition Cell Balancing Coolant Loops	H ₂ O Addition Cell Balancing Coolant Loops	H ₂ O Addition Cell Balancing Coolant Loops	CO ₂ Scrubbers Pumps	Possible Air Pump H ₂ O Addition Cell Balancing	Pressure Water Addition Cell Balancing	Pumps Vents Refrigerator Plating Additives	Cooling Gas Circulator	Cooling Gas Circulator	Cooling Gas Circulator	Cooling Gas Circulator	(None)
Replacement Possibilities	Electrode Replacement	Electrode Replacement	Electrode Replacement	Electrode Replacement	Oxygen Electrode Replacement Retain ZnO	Renewal	Renewal	Cell Replacement Retain ZnCl ₂	Cell Replacement	Cell Replacement	Cell Replacement	Cell Replacement	Cell Replacement
Problem Areas	Gassing Utilization Excess Pb Addn Weight	Gassing Utilization Excess Pb Addn Weight	Gassing Utilization Excess Pb Addn Weight	Gas Recombiners	Shunt Currents Zinc Plating O ₂ Electrode	Shape Change Zn Temperature Rise Gassing	Pressure Cost Of H ₂ Electrode Water Redistribution	Shunt Currents Zn Plating Ti Cost Ru Cost	Seals High Temp Materials Life	Seals High Temp Materials Life	Seals High Temp Materials Life	Seals High Temp Materials Life	Life

(1) Exp = explosion, + = favorable, - = unfavorable
NA = not available

STORAGE TECHNOLOGY:

Batteries

SOURCE:

Redox Bulk Energy Storage System Study,
Final Report. V.II. Exxon Research &
Engineering Co. Jan. 30, 1977

INFORMATION:

TABLE 1. Comparison of Selected Batteries and Low and Medium Density

Battery System	Lead-Acid				Zn-Air	Ni-Cd	Ni-Ni	Zn-Cl ₂ (LiClO ₄)	Fe-S (LiClO ₄)	Na-S (Thi)	Li-PeS ₂	Li/Al-PeS ₂	Organic Polymer
	Present	Present	Present	Advanced									
Characteristics	Ed	C+D	Gould	Advanced									
Temperature, °C	10-60	10-60	10-60	10-60	4-40	1-45	0	0	0	0	0	0	Ambient
Open Circuit Voltage	2.09	2.09	2.09	2.09	1.60	1.71	1.50	2.00	2.00	2.00	2.00	2.00	2
Charge Voltage	2.3	2.3	2.3	2.3	2.4	1.9	1.5	2.23	2.35	2.75	2.4	1.55	NA
Maximum Charge Voltage	2.65	2.45	2.6	2.4	2.4	2.0	15	2.4(T)	2.50	2.75	2.7(T)	1.62	NA
Discharge Cutoff Voltage	1.7	1.7	1.7	1.7	0.9-1.0	>1.3	>1.25	1.90	1.60	1.60	1.0	0.85	NA
Minimum Voltage	1.3	1.3	1.3	1.3	0.8	1.0	1.0	1.5+0	1.00	1.0	0.1	0.65	NA
V _c /V _{od}	1.58	1.44	1.58	1.4	2.67-2.4	1.46	1.20	1.17	1.47	1.53	2.4	1.82	--
Turn-around Efficiency	85-75	85-75	80-70	85-75	50-40	85	~0	90-70	~80	80	95-75	85-75	High
Energy Density, kWh/m ³	5.5	51	50	120-60	160-110	90	60-30	175-95	270-90	270-90	280	140	NA
Power Density, kW/m ³ (10 hr rate)	55	5.1	5.0	12-6	16-11	9	6-5	17.5-8.5	27-9	27-9	28	14	NA
Life, yrs.	~10	~10	~7	~10	5	10-5	10-5	10-5	10-5	10-5	10-5	10-5	NA
Open Circuit Losses, %/day	1	1	1	1	Nil	1-2	0.1-1	~0	~0	~0	~0	~0	NA
Essential Materials	Pb Sb H ₂ SO ₄	Pb Sb H ₂ SO ₄	Pb Sb H ₂ SO ₄	Pb Sb H ₂ SO ₄	Zn KOH Catalysts?	Na Zn KOH	Na H ₂ Container	ZnCl ₂ Ti Catalysts	Na C BaI ₂ O ₃	Na C BaI ₂ O ₃ Glass	Li C Separators	Li BN Separators	Cathodes Li Organic Solvent
Essential Material Cost, \$/KWH	20	22	13	10-15	1	8	8-15	2-8	1.50-2	10-20	10-20	10-20	NA
Material Availability (E/Excellent, G/Good, F/Fair)	Pb G Sb F	Pb G Sb F	Pb G Sb F	Pb G Sb F	Zn G/E Cat O	Na F Zn G/E	Na F Catalysts F	ZnCl ₂ G/E Ti F Mobile Metals F	Na G/E C F/C	Na G/E C F/C	Li P C F/C	Li P BN F	NA
Hazards (1)	Low H ₂ Acid	Low H ₂ Acid	Low H ₂ Acid	Low H ₂ Acid	Low KOH H ₂	Low KOH H ₂	Medium H ₂ Pressure	Medium High Cl ₂ Acid	High Na (2) S (2) Temp Fire Exp	High Na (2) S (2) Temp Fire Exp	High Li (4) Temp Fire Exp	Medium Li/Al Temp Fire Exp	Medium Li (4) Organics

(1) Exp = explosion, + = favorable, - = unfavorable
NA = not available.

STORAGE TECHNOLOGY:

Load Leveling Batteries

SOURCE:

TRW Inc., Development of a Data Base
 Characterizing Energy Storage Technolo-
 gies, Task 1, Characterization of Storage
 Technologies in Utility Load Leveling
 Applications, Argonne National Labora-
 tory, Contract No. 31-109-38-5106, 1979.

INFORMATION:

Table 5-5. Advanced Utility Batteries

Characteristic	Range of Values	Expected
Typical Facility Size (MWh)	200 - 500	350
Capital Cost (1978 \$/kWh)		
Sodium-Sulfur	18 - 40	39
Labor		5
Materials & Components		28
Other		6
Lithium-Metal Sulfide	35 - 45	45
Cell Only		37
Labor		3
Materials		29
Other		5
Zinc-Chlorine	35 - 50	43
Labor		4
Materials		32
Other		7
Installation & Foundation (78 \$/kWh)	6 - 25	10
AC/DC Converter (78 \$/kW)	60 - 85	70
O & M Cost (1978 mills/kWh)	.5 - 4.0	3.2
Energy Storage Capacity (hrs/day)	2 - 10	4
Efficiency	.70 - .80	.70
Expected Lifetime (Goal in years)	10 - 25	20
Construction Lead Time (years)	.5 - 2.0	1.0
Annual Operating Profile (hrs/years)	<1500	1000

Sources: References 10, 18, 19, 50, 51, 52, 53

STORAGE TECHNOLOGY:

Batteries

SOURCE:

Fischer, W., et al. Economic Prospects
for the Application of New Electric Energy
Storage Devices. Journal of Power Sources
3(1978) 331-345. Lausanne, Switzerland

INFORMATION:

TABLE 1

Data for battery systems^a

Type	Pb/PbO ₂ (advanced) ^b		Na/S		LiAl/FeS _x		Redox systems (Cr ⁶⁺ /Cr ³⁺ or Ti ³⁺ /Fe ²⁺)	
Operating temperature	20 - 40 °C		300 - 350 °C		400 - 450 °C		20 - 50 °C	
Literature references	[2 - 5]		[6 - 11]		[12]		[13, 14]	
Investment costs (estimated) ^c	DM/kW	DM/kWh	DM/kW	DM/kWh	DM/kW	DM/kWh	DM/kW	DM/kWh
battery	140 - 190	160 - 230	105 - 190	90	} >Na/S		215 - 550	30
assembly	—	20 - 25	—	30 - 55			—	20 - 25
converter, transformer	85 - 110	—	85 - 110	—			85 - 110	—
cos φ-compensation	—	15 - 25	—	15 - 25			—	25 - 40
buildings	—	—	—	—			—	—
	225 - 300	195 - 280	190 - 300	135 - 170			300 - 655	75 - 95
Charge-discharge cycles attained in laboratory	~1500		10,000 ^d		700		—	
Availability of reactants (years) ^e	Pb 26 ^f		Na: 6000 S: > 10,000		Li: 400 ^g Al: 160 Fe: 400		Cr: 550	

^aExpectation for other batteries (e.g. Zn/Cl₂ [15] or Na/SbCl₃ [16]) are similar to those of this Table. Investment costs are split up into energy related and power related costs.

^bSLI batteries: 100 - 500 cycles. Stationary batteries: >1000 cycles, ≥500 DM/kWh [23].

^c1977 costs for mass production, in some cases due to our own estimates.

^dAt partial recharge.

^eResources divided by present annual consumption [17 - 19].

^fLead can be recovered and recycled.

^gMore than 95% of resources in U.S.A. and Canada.

ASSUMPTIONS & COMMENTS:

Costs in German Marks

STORAGE TECHNOLOGY:

Energy Storage Systems Comparison

SOURCE:

Public Service Gas & Electric Company.

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

Prepared for Electric Power Research
Institute. 1976

INFORMATION:

Figure 4-6 RELATIONSHIP BETWEEN BATTERY
SYSTEM COSTS AND MATERIAL COSTS

ASSUMPTIONS & COMMENTS:

1975 dollars

STORAGE TECHNOLOGY:

Batteries for Utility Load Leveling

SOURCE:

Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
Prepared for Electric Power Research
Institute. 1976

INFORMATION:

Table 4-18 RESULTS OF REVIEW OF MANUFACTURER
ESTIMATES OF SELECTED BATTERIES

Type	Operating Temperatures	Suggested ¹ Approximate Module Cost (\$/kWh)
Lead-Acid	20°-50°C	35 ² -65
Sodium-Sulfur	300°-350°C	15-25
Lithium-Metal Sulfide	400°-450°C	30-35
Sodium-Chloride	180°-210°C	15-25
Zinc-Chlorine	0°-80°C	12-30
Redox	20°-50°C	30-35 ³

1. Further studies are required before the differences in the advanced systems can be used to distinguish between them. Assumes success in R&D for advanced batteries.
2. Lower value estimate for an advanced battery module.
3. These estimates may be low and include a portion of power related costs. Highly suspect.

ASSUMPTIONS & COMMENTS:

1975 dollars

STORAGE TECHNOLOGY:

Batteries

SOURCE:

Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
 Prepared for Electric Power Research
 Institute. 1976

INFORMATION:

Table 4-22 RECOMMENDED RANGE OF COSTS
 FOR BATTERY STORAGE SYSTEMS

<u>Storage Costs¹</u>	<u>Near Term Lead Acid</u>	<u>Advanced⁶ Batteries</u>
Battery Modules	\$40-\$65/kWh ²	\$15-\$40/kWh ⁴
Installation and Foundations	-	\$ 5-\$20/kWh ⁵
Buildings, Installation, and Foundations	\$20-\$35/kWh ³	-
Cooling	\$ 5-\$10/kWh	-
	\$65-\$110/kWh	\$20-\$60/kWh
<u>Power Costs¹</u>		
Converter and Transformer	\$70-\$80/kW	\$60-\$70/kW

1 Contingencies and overheads included in individual cost elements.

2 From cost estimates of ESB, C&D and Gould; Battery life of 1750 to 2500 cycles.

3 J. R. Birk, Lead Acid Workshop, November 14, 1976; from estimates by Bechtel.

4 Includes cooling systems.

5 Assumes 500 MWh or more of battery modulation; weather-proof battery, no building.

6 Includes an advanced lead acid module which is suitable for outdoor installation without extensive cooling auxiliaries and site engineering.

ASSUMPTIONS & COMMENTS:

1975 dollars

SUMMARY

End Use: Utility Load Leveling

Technology: Lithium-Metal Sulfide Battery

	Report					
	1	2	3	4	5	6
Specific Energy (Wh/kg)	60-150	160	150	-	-	-
Specific Power (W/kg)	-	200	300	-	-	-
Cycle Life	3,000	1,000	1,000	-	-	-
Cost (\$/kWh)	25	26	50	39	63	26-44

STORAGE TECHNOLOGY:Lithium-Aluminum/Metal SulfideBatteries**SOURCE:**High Performance Batteries for Stationary
Storage and Electric Vehicle Propulsion.
ANL-77-17.**INFORMATION:**

Table 1-1. Performance Goals for Lithium-Aluminum/Metal Sulfide Batteries

Battery Goals	Electric Vehicle Propulsion		Stationary Energy Storage	
	Mark I 1978	Prototype 1985	BEST 1981	Prototype 1985
Power				
Peak	30 kW	60 kW	1.5 MW	25 MW
Sustained Discharge	12 kW	25 kW	1 MW	10 MW
Energy Output	30 kW-hr	45 kW-hr	5 MW-hr	100 MW-hr
Specific Energy, ^a W-hr/kg	110	180	60-80	60-150
Discharge Time, hr	4	4	5	5-10
Charge Time, hr	8	5-8	8	10
Cycle Life	300	1000	1000	3000
Cost of Cells, \$/kW-hr	-	35	25-30 ^b	20

^aIncludes cell weight only; insulation and supporting structure is approximately 25% of total weight for the Mark I electric vehicle battery and 15 to 20% for the 1985 prototype vehicle battery.

^bProjected cost at a production rate of 2000 MW-hr/yr.

STORAGE TECHNOLOGY:Lithium Metal Sulfide Batteries**SOURCE:**

Chilenskas, A.A. Commercialization
 Planning for the Lithium/Metal Sulfide
 Battery. Prepared for LI 77 Symposium on
 Lithium Needs and Resources, Corning, NY.
 Argonne National Laboratory. 1977

INFORMATION:

Table I-1. Program Goals for the Lithium/Metal Sulfide
 Electric-Vehicle Battery

Goal	Mark IA	Mark II	Mark III
Specific Energy, ^a W-hr/kg			
Cell (Average)	80	125	160
Battery	60	100	130
Energy Density, W-hr/liter			
Cell (Average)	240	400	525
Battery	100	200	300
Peak Power, ^b W/kg			
Cell (Average)	80	125	200
Battery	60	100	160
Battery Heat Loss, ^c W	400	150	125
Lifetime			
Deep Discharges	200	500	1,000
Equivalent Kilometers	32,000	95,000	240,000
Equivalent Miles	20,000	60,000	150,000

^a Calculated at the 4-hr discharge rate.

^b Peak power sustainable for 15 sec at 0 to 50% state of discharge;
 at 80% discharge, the peak power is 70% of the values shown.

^c The values shown represent the heat loss of the battery through
 the insulated case; under some operating conditions, additional
 heat removal may be required.

ASSUMPTIONS & COMMENTS:

· 1976 dollars

STORAGE TECHNOLOGY:

Lithium Metal Sulfide Batteries

SOURCE:

Chilenskas, A.A. Commercialization Plan-
ning for the Lithium/Metal Sulfide Battery.

CONF 7710171-1. DOE Contract W-31-109-

Eng-38. October 1977.

INFORMATION:

Table III.. Sales Price of Stationary Energy Storage (SES) Cells and Batteries

	SES Design I	SES Design II
Materials Cost, \$kW-hr	16.89	13.55
Materials Losses, %	0.84	0.68
Labor and Overhead	3.70	3.70
Factory Cost, \$/kW-hr	21.43	17.93
General Administration, @11%	2.36	1.97
Subtotal	23.79	19.90
Profit, 25% R.O.I.	2.89	2.89
Subtotal	26.68	22.79
Recycle Credit, 25% of Li Values	1.83	1.83
Cell Price, \$/kW-hr	24.85	20.96
Battery Auxiliaries @7/kW-hr	7.00	7.00
Battery Selling Price, \$/kW-hr	31.85	27.96
(Truckable 5 MW-hr Module)		

STORAGE TECHNOLOGY:

Lithium Metal Sulfide Batteries

SOURCE:

Chilenskas, A.A. Commercialization Planning for the Lithium/Metal Sulfide Battery.

CONF 7710171-1. DOE Contract W-31-109-

Eng-38. October 1977.

INFORMATION:

Table II. A Comparison of Materials Costs for Stationary Energy Storage (SES) Cells.

	SES Design I ^a			SES Design II ^b		
	lb/kW-hr	\$/lb	\$/kW-hr	lb/kW-hr	\$/lb	\$/kW-hr
Negative Electrode						
Lithium	0.62	7.75	4.81	-	-	-
Aluminum	2.42	0.50	1.21	2.74	0.50	1.37
Steel Wool	0.42	1.00	0.42	-	-	-
Iron Screen	-	(0.50/ft ²)	1.08	-	-	-
Positive Electrode						
FeS	3.62	0.097	0.35	-	-	-
Cu ₂ S	0.91	0.58	0.53	0.91	0.58	0.53
Steel Wool	0.36	1.00	0.36	-	-	-
Li ₂ S	-	-	-	2.42	1.68	4.06 ^d
Fe Powder	-	-	-	2.94	0.20	0.59 ^c
Electrolyte						
LiCl	2.20	1.13	2.49	4.06	1.13	4.59
KCl	2.70	0.10	0.27	5.01	0.10	0.50
Separator						
BN Paper	0.17	(\$1.00/ft ²)	2.72	-	-	-
MgO Powder	-	-	-	2.01	0.25	0.50 ^c
Feedthrough	-	(\$1.00 ea)	1.08	-	-	0.45
Structure						
Steel Sheet	4.48	0.33	1.48	-	-	-
Steel Sheet	-	-	-	7.25	0.12 ^c	0.87
Steel Rod	0.16	0.54	0.09	0.16	0.54	0.09
Totals	18.06		16.89	27.50		13.55

^aBased on 1975 cell design. See W. Towle et al., ANL-76-12, p. 10.

^bBased on 1977 cell design described in this paper.

^cJ. Battles

^dA. A. Chilenskas, manufactured from Li₂CO₃.

STORAGE TECHNOLOGY:Lithium-Metal Sulfide Battery**SOURCE:**Heiter, Kenneth and Paul Skartredt.Battery Technology An Assessment of
the State of the Art, TRW EnergySystems Group DOE Contract EX-76-C-10-3885
Task Order 23.**INFORMATION:**

Table A-5. Lithium Metal Sulfide Battery Characterization

Source: References 1-1, 2-1, 2-2

CHARACTERISTIC	CURRENT	PROJECTED-1981-85
Energy Density ¹	80-100 Wh/kg	150 Wh/kg
Volumetric	200 Wh/L	250 Wh/L
Peak Power Density	100-120 W/kg	300 W/kg
Sustaining Power Density	No Data	No Data
Efficiency	70%	75%
Cycle Life	500-1000 Cycles ²	>1000 Cycles
Operating Temperature	450°C	450°C
Pilot Costs	\$2000/kWh	\$100/kWh
Mass Production Costs	-	\$40/kWh ³

¹Based on cell data; battery densities likely to be lower by
20-25 percent.

²100-130 Wh cells.

³1990 cost.

ASSUMPTIONS & COMMENTS:

1977 dollars.

STORAGE TECHNOLOGY:

Lithium Metal Sulfide Batteries

SOURCE:

Towle, W.L. et al., Cost Estimate for the
Commercial Manufacture of Lithium/Iron
Sulfide Cells for Load Leveling, Argonne
National Laboratory ANL-76-12, 1976.

INFORMATION:

Table 3. Summary of Manufacturing Cost

Labor and Overhead Cost (Basis: Annual)

Direct Labor	\$1,080,000
Overhead	
Fringe Benefits (30%)	324,000
Supervision, Indirect Labor, and Indirect Operating Costs (2 x Direct Labor)	2,160,000
Depreciation	692,000
Total Labor and Overhead	\$4,256,000

Factory Cost (Basis: 1 kW-hr)

Labor and Overhead	\$ 3.70
Materials	19.02
Material Losses, 5% of Materials	0.95
Total Factory Cost	\$ 23.67

Battery Price (Basis: 1 kW-hr)

Factory Cost	\$ 23.67
General and Administrative, 11%	2.60
Subtotal	\$ 26.27
Profit, 11%	2.89
Battery Price	\$ 29.16 ^a

^a Where appropriate, credit for recycle of lithium values would give a net figure of \$27.33/kW-hr (see text).

ASSUMPTIONS & COMMENTS:

1976 dollars.

STORAGE TECHNOLOGY:

Lithium Metal Sulfide Batteries

SOURCE:

Sudar, S. et. al. Development of Lithium Metal Sulfide Batteries for Load Leveling
Atomics International, EPRI EM-460, 1977.

INFORMATION:

TABLE 9-7
PROJECTED COST BREAKDOWN FOR THE ADVANCED 2.5 kWh CELL

Components	Production Volume					
	5 MWh		100 MWh		1000 MWh	
	\$	%	\$	%	\$	%
Positive Electrodes						
Steel Collectors	8.1	1.8	7.1	3.9	5.9	5.0
Graphite Matrices	15.5	3.5	13.8	7.7	10.5	8.9
Active FeS ₂	1.5	0.3	0.2	0.1	0.2	0.2
Separators						
Boron Nitride	261.5	58.4	52.3	29.0	16.7	14.2
Negative Electrodes						
Grid Structures	31.0	6.9	20.9	11.6	15.8	13.4
Screens	7.7	1.7	7.5	4.2	4.7	4.0
Active Li ₅ Si	26.7	6.0	20.3	11.2	16.7	14.2
Electrolyte						
LiCl-KCl Eutectic	34.2	7.6	27.3	15.1	20.9	17.7
Conductors	0.4	0.1	0.3	0.2	0.2	0.2
Feedthrough	2.0	0.5	1.0	0.6	1.0	0.8
Case	6.8	1.5	5.9	3.3	5.3	4.5
Assembly	52.3	11.7	23.6	13.1	19.9	16.9
Total	447.7	100.0	180.2	100.0	117.8	100.0
\$/kWh	179.2		72.1		47.1	

ASSUMPTIONS & COMMENTS:

1976 dollars

STORAGE TECHNOLOGY:

Lithium-Metal Sulfide Batteries

SOURCE:

Chilenskas, A.A. A Preliminary Estimate of the Manufacturing Cost for Lithium/Metal Sulfide Cells for Stationary and Mobile Applications. ANL-79-59, 1979.

INFORMATION:

Fig. 2. Cost Estimates for SES and EV Cells (for each cell type, the column on the left represents the low estimate and that on the right represents the high estimate).

STORAGE TECHNOLOGY:

Lithium-Metal Sulfide Batteries

SOURCE:

Chilenskas, A.A. A Preliminary Estimate of the Manufacturing Cost for Lithium/Metal Sulfide Cells for Stationary and Mobile Applications. ANL-79-59, 1979.

INFORMATION:

Table 7 Cell Manufacturing Cost Summary

Assumptions

Costing Basis: ANL-76-12

Plant Production Rate: 1.15×10^6 kW-h/yr

Scaling Factors

Inflation @ 10%/yr, $(1.1)^4 = 1.46$

Cell Size Factor, SES = 1, EV = 1.51

Process Complexity Factor, 1976 Plant = 1, 1979 Range 0.75-1.25

	<u>1976 Dollars</u>	<u>1979 Dollars</u>					
	<u>ANL-76-12</u>	<u>SES REF</u>		<u>EV (FeS) REF</u>		<u>EV (FeS₂) REF</u>	
<u>Scaling Factors</u>		<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>
Inflation, 10%/yr	1.0	1.46	1.46	1.46	1.46	1.46	1.46
Cell Size	1.0	1.0	1.0	1.51	1.51	1.51	1.51
Process Complexity	1.0	0.75	1.25	0.75	1.25	0.75	1.25
<u>Cost Item</u>							
Equipment, \$/MM	3.20	3.51	5.85	5.28	8.81	5.28	8.81
Land, Bldgs., Inst., \$/MM	6.40	7.01	11.69	10.57	17.62	10.57	17.62
Labor (Dir. & Ind.) \$/MM	3.56	3.90	6.50	5.88	9.80	5.88	9.80
Total Investment, \$/MM	12.53	13.82	21.69	19.55	31.62	19.44	31.53
Materials Cost, \$/kWh	19.02	14.76	25.05	17.24	29.63	16.14	28.64
Factory Cost, \$/kWh	26.27	20.88	35.30	27.81	46.86	26.47	45.65
Profit, \$/kWh	2.89	3.46	5.42	4.88	7.91	4.86	7.88
Selling Price, \$/kWh	29.16	24.34	40.72	32.69	54.77	31.33	53.53

STORAGE TECHNOLOGY:

Lithium Metal Sulfide Battery

SOURCE:

Chilenskas, A.A. et al., A Preliminary
Estimate of the Manufacturing Cost
for Lithium/Metal Sulfide Cells for
Stationary and Mobile Applications.
ANL-79-59, 1979.

INFORMATION:

Table 10. Cell Manufacturing Cost Summary

	1976 Estimate ^a of SES Cell	Present Estimate					
		SES Cell		EV (FeS) Cell		EV (FeS ₂) Cell	
		<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>
Equipment, \$ x 10 ⁶	3.20	3.51	5.85	5.28	8.81	5.28	8.81
Land, bldgs., inst., \$ x 10 ⁶	6.40	7.01	11.69	10.57	17.62	10.57	17.62
Labor, \$ x 10 ⁶	3.56	3.90	6.50	5.88	9.80	5.88	9.80
Total Investment, \$ x 10 ⁶	12.53	13.82	21.69	19.55	31.62	19.44	31.53
Materials Cost, \$/kW-hr	19.02	14.76	25.05	17.24	29.63	16.14	28.64
Factory Cost, \$/kW-hr	26.27	20.88	35.30	27.81	46.86	26.47	45.65
ROI, \$/kW-hr	2.89	3.46	5.42	4.88	7.91	4.86	7.88
Selling Price, \$/kW-hr	29.16	24.34	40.72	32.69	54.77	31.33	53.53

^aManufacturing cost from ANL-76-12.

ASSUMPTIONS & COMMENTS:

1979 dollars.

SUMMARY

End Use: Utility Load Leveling

Technology: Lead-Acid Battery

	1	2	3	4	5
Cost (\$/kWh)	60-97	76-93	-	-	50-63

STORAGE TECHNOLOGY:Lead Acid Batteries

SOURCE:

Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
Prepared for Electric Power Research
Institute. 1976

INFORMATION:

Table 4-19 LEAD-ACID BATTERY COST ESTIMATES

	<u>MANUFACTURER</u>		
	<u>C. & D.</u>	<u>ESB</u>	<u>GOULD</u>
Lead Cost (\$/kWh)	22.10	19.80	13.00
Other Materials Cost (\$/kWh)	11.70	14.40	10.70
Price (\$/kWh)	62.90	65-70	43.30
Price/Cycle (\$/kWh/Cycle)	2.51	2.60	2.47

From summary at Lead-Acid Workshop, EPRI, Palo Alto,
CA, J. R. Birk. November 19, 1975 [28]

ASSUMPTIONS & COMMENTS:

1975 dollars.

STORAGE TECHNOLOGY:

Lead Acid Batteries

SOURCE:

Redox Bulk Energy Storage System,

Final Report. V.II. Exxon Research &

Engineering Co. Jan. 30, 1977

INFORMATION:

Table A-14. Storage Plant Costs

<u>Item</u>	<u>Cost</u>	PLANT COST (\$/kW of nominal output)		
		<u>3 Hour⁽¹⁾</u>	<u>5 Hour⁽¹⁾</u>	<u>10 Hour</u>
Battery	\$57-70/kWh ⁽²⁾	220-270	320-400	570-700
Convertors	\$70/kW	70	70	140 ⁽³⁾
Cooling ⁽⁴⁾	\$5-8/kWh	20-30	30-45	50-80
Site/Engineering	\$20-35/kWh ⁽⁵⁾	80-140	110-200	200-350
TOTAL ⁽⁶⁾		390-510	530-715	960-1270

- (1) The energy-related costs for the 3- and 5-hour battery are 1.30 and 1.15 times those of the 10-hour battery. However, these factors might approach 1.15 and 1.0, respectively, if the battery were specifically designed for this application and if the battery were used fewer than 250 cycles/year.
- (2) Gould's battery price of \$43.30/kWh (see Table IV) is increased to include "up-front" money for refurbishments, making it a 21-year battery (as compared to a 10-year battery for the other manufacturers).
- (3) Power is controlled by the 7-hour charge, not the 10-hour discharge.
- (4) Optional for Gould battery as presently conceived.
- (5) Lower limit is a rough estimate; and upper value is from a study by Bechtel for ERDA. Gould has estimated \$27/kWh. Estimates as low as \$10/kWh has been projected by others.
- (6) Total has to be divided by the one-way efficiency of the convertors (c.a. 94-95%).

ASSUMPTIONS & COMMENTS:

1976 dollars

STORAGE TECHNOLOGY:Lead Acid Batteries**SOURCE:**

Redox Bulk Energy Storage System Study,
Final Report. V.II. Exxon Research &
Engineering Co. Jan. 30, 1980

INFORMATION:

Table 1-2

Capital Costs And Specifications
 For Utility Lead-Acid Batteries
 (Ten-Hour Capacity)

COST/SPECIFICATION ⁽¹⁾	BATTERY SYSTEM			
	C&D	ESB	GOULD	SLI ⁽²⁾
Lead Cost (\$/kWh)	22.10	19.80	13.00	9.60
Other Materials Costs (\$/kWh)	11.70	14.40	10.70	4.40
Price (\$/kWh) ⁽³⁾	62.90	65-70	43.30	28.10
Cycle Life (cycles) (years)	2500 10	2500 10	1750 7	100-150 ⁽⁵⁾ --
Price/Cycle (\$/kWh/cycles)	2.51	2.60	2.47	2.3
Depth of Discharge (10-hr rate)	72	80	80	80
Plate Design	pasted	tubular	pasted	pasted
Efficiency (%) ⁽⁴⁾	83	82	80	--
Cell Capacity (kWh)	20	19	125 ⁽⁶⁾	--
Energy Density (Wh/lb)	7.5	8.6	8.9	--
Footprint (kWh/ft ²)	4.6	5.0	4.0	--

(1) Costs are based upon rated or end-of-life capacity.

(2) Based upon discussions with Warren Towle of Globe Union, Dec. 1975.

(3) Assumes 1000 MWh/year of sales.

(4) Ten-hour discharge and 7-hour charge with additional 3-hr taper charge.

(5) Can be improved with little additional cost to achieve 250-300 cycles.

(6) Open-tank concept.

STORAGE TECHNOLOGY:

Lead Acid Batteries

SOURCE:

Smith, J. Charles. Battery Requirements for Electric Utilities As Seen Through a Utility Economic Assessment. PSE&G. In First Annual ERDA Battery Contractors Coordination Meeting. 1977

INFORMATION:

TABLE ES-7

**Capital Costs and Operating Characteristics
of Lead/Acid Storage Batteries**

CAPITAL COSTS

<u>Initial Investment</u>	<u>10 Hour Battery</u>	<u>5 Hour Battery</u>	<u>3 Hour Battery</u>
Installed Cost (\$/kW)			
Battery Costs	350	202	138
Other Energy Related Costs	300	173	117
Converter Costs	70	70	70
Total	720	445	325
Lead Time (years)	2	2	2
	1.05	1.05	1.05
Estimated Life (years) (exclusive of Batteries)	30	30	30
Carrying Charges (exclusive of Batteries)	18	18	18
<u>Battery Replacement</u>			
(\$/kW)	175	101	69
Estimated Life	1750 cycles up to 14 years		
Carrying Charges	Determined as a function of life in Section 5.		

OPERATING CHARACTERISTICS

Efficiency (%)	75	70	65
Charging Time (hours)	10/13	5/7/10	3/5/10
Charging Capacity (% of rated load)	133/100	143/100/- 71	154/100/- 46
Fixed O&M		None	
Variable O&M (mills/kWhr)	0.5	0.5	0.5
Forced Outage Rate (%)	4	4	4

STORAGE TECHNOLOGY:

Batteries

SOURCE:

Smith, J. C. "Battery Plant Design
and Cost Studies," in First Annual
Battery Contractor's Coordination
Meeting. 1977.

INFORMATION:

Table 6

BATTERY PLANT DELIVERED ENERGY COST (mils/kwh) AT 200 CYCLES PER YEAR

	3 HR			4 HR			5 HR		
	L	M	H	L	M	H	L	M	H
CONVERTER	20	20	20	15	15	15	12	12	12
BOP	29	37	58	25	32	44	24	29	37
BATTERY 1	39	60	62	36	58	56	34	55	53
BATTERY 2	12	13	11	11	12	10	11	12	10
O & M	.5	.5	.5	.5	.5	.5	.5	.5	.5
CHARGING	7	20	44	7	20	43	7	20	43
SUBTOTAL ₁	103	150	196	95	138	168	88	128	155
\$75/kw CREDIT	23	23	23	17	17	17	14	14	14
SUBTOTAL ₂	85	127	173	78	121	151	74	114	141
\$150/kw CREDIT	46	46	46	35	35	35	28	28	28
SUBTOTAL ₃	62	104	150	60	103	133	60	100	127

ASSUMPTIONS & COMMENTS:

1977 Dollars.

STORAGE TECHNOLOGY:

Batteries

SOURCE:

Smith, J. C. "Battery Plant Design and
Cost Studies," in First Annual Battery
Contractor's Coordination Meeting. 1977.

INFORMATION:

Table 3

BATTERY PLANT CAPITAL COST

	3 HR			4 HR			5 HR		
	L	M	H	L	M	H	L	M	H
CYCLE LIFE	2000	2000	2000	2000	2000	2000	2000	2000	2000
EFF. (AC Rd Trip)	67	73	68	68	75	69	69	76	70
1st PRICE (\$1 kwh)	40	61	64	37	58	57	35	56	54
REBUILD (% of 1st Price)	79	57	46	79	57	46	79	57	45
PRESENT WORTH OF CAPITAL (x 1st Price)	1.31	1.22	1.18	1.31	1.22	1.18	1.31	1.22	1.18
FOR 20 YR BATTERY (\$1 kwh)	52	74	75	48	71	67	46	68	64
CONVERTER (no conting.) (\$1 kwh)	60	60	60	60	60	60	60	60	60
BOP (\$1 kwh)	38	38	59	33	33	45	30	30	38
BOP (w/o conting.) (\$1 kwh)	30	30	47	26	26	36	24	24	30
TPC _{DC} (with) (\$1kw)	330	396	462	384	476	508	440	550	570
TPC _{AC} (with) (\$1 kw)	348	418	487	404	500	534	462	578	600
TPC _{DC} (w/o) (\$1 kw)	306	372	426	356	448	472	410	520	530
TPC _{AC} (w/o) (\$1 kw)	322	392	440	375	472	496	431	547	557

STORAGE TECHNOLOGY:

Lead Acid Batteries

SOURCE:

Bechtel Power Corp. Engineering Study
of a 20 MW Lead-Acid Battery Energy
Storage Demonstration Plant. 1976.

CON/1205-1

INFORMATION:

Figure 4-40. PLANT OPERATING COSTS - WITH \$60/kW CREDITS

STORAGE TECHNOLOGY:

Lead Acid Batteries

SOURCE:

Bechtel Power Corp. Engineering Study
of a 20 MW Lead Acid Battery Energy
Storage Demonstration Plant. 1976.

CONS./1205-1

INFORMATION:

Figure 4-41. PLANT OPERATING COSTS - WITH \$120/kW CREDITS

STORAGE TECHNOLOGY:

Lead Acid Batteries

SOURCE:

Bechtel Power Corp. Engineering Study
of a 20 MW Lead-Acid Battery Energy
Storage Demonstration Plant. 1976.

CONS/1205-1

INFORMATION:

Figure 4-39. PLANT OPERATING COSTS

STORAGE TECHNOLOGY:Lead Acid Batteries

SOURCE:

Heiter, Kenneth and Paul Skartredt.
Battery Technology An Assessment of
the State of the Art, TRW Energy Systems
Group DOE Contract EX-76-C-10-3385
Task Order 23., 1978.

INFORMATION:

Table A-4. Advanced Lead Acid Battery Characterization
(for Utility Load Leveling Application)

Source: Reference 2-5

CHARACTERISTIC	CURRENT	PROJECTED
Efficiency	70%	70%
Cycle Life	2000 Cycles	2000-5000 Cycles ¹
Mass Production Costs	\$70-80/kWh ²	\$40-50/kWh

¹Westinghouse estimate.

²Includes \$25-30/kWh for balance of plant.

ASSUMPTIONS & COMMENTS:

1977 dollars.

SUMMARY

End Use: Utility Load Leveling

Technology: Redox Battery

No useful comparisons possible.

STORAGE TECHNOLOGY:

Redox Batteries

SOURCE:

Ciprios, G., W. Erskine and P.G. Grimes
Redox Bulk Energy System Storage Study
Vol. I, Exxon Research and Engineering
Co. Prepared for NASA Lewis Research
Center, 1977.

INFORMATION:

Table 2-22

Projected Cost Reduction for Daily Cycle Redox Battery System

Case No. (1)	1			2			3			4		
Redox Couple Energy Density kWh/L	5.65(4)			35.5			57.2			116.7		
Sub-System Installed Cost at Indicated Factor Reduction Level, k\$	Base- line	Moderate	Substan- tial	Base- line	Moderate	Substan- tial	Base- line	Moderate	Substan- tial	Base- line	Moderate	Substan- tial
Tankage	2010	1809	1407	870	783	609	663	597	464	445	400	312
Pumps	535	482	428	205	184	164	166	149	133	131	118	105
Filters	8153	4076	2446	1999	1000	600	1249	624	375	626	313	188
Heat Exchangers	2429	2429	1943	2320	2320	2016	2261	2261	1809	2477	2477	1932
Redox Trailers	4163	3330	2914	4163	3330	2914	3437	2766	2419	3437	2766	2419
Power Conditioning	2694	1885	1885	2693	1885	1885	2582	1807	1807	2582	1807	1807
Reactants	904	904	904	401	401	401	377	377	377	287	287	287
Total, k\$	20388	14916	11927	12831	11181	8589	10953	8781	7384	10005	8162	7100
\$/kW (2)	1044	746	596	643	559	429	548	439	379	500	408	355
\$/kWh (3)	261	186	149	161	140	107	137	110	95	125	102	89

(1) Daily cycle; Discharge power = 20 MW; Discharge time = 4 hrs.; Charge time = 5 hrs.; Typical cases with various combinations of Z (1,2); C (1, 2, 5); V_R (0.8, 1.0).

(2) Based on discharge power level.

(3) Based on discharge time

(4) Base-line parameter value

ASSUMPTIONS & COMMENTS:

1976 dollars.

STORAGE TECHNOLOGY:

Redox Batteries

SOURCE:

Ciprios, G., W. Erskine and P. G. Grimes
Redox Bulk Energy System Storage Study,
Vol. I, Exxon Research and Engineering
Co. Prepared for NASA Lewis Research
Center, 1977.

INFORMATION:

Figure 3-36

**Improved Redox Couples Help, But Additional
System Cost Reduction Is Needed To Meet Daily Cycle Targets**

ASSUMPTIONS & COMMENTS:

P_d = discharge power t_d = discharge time t_c = charge time V_r = cell voltage
 2^d = electrons transferred per mole of reactant C = concentration of reactants
1976 dollars.

STORAGE TECHNOLOGY:

Redox Batteries

SOURCE:

Ciprios, G., W. Erskine and P.G. Grimes
Redox Bulk Energy System Storage Study,
Vol. 1, Exxon Research and Engineering
Co. Prepared for NASA Lewis Research
Center, 1977.

INFORMATION:

Figure 3-20

Effect of Charge/Discharge Time on Daily
Cycle Redox System Investment Costs

ASSUMPTIONS & COMMENTS:

P_d = discharge power, 1976 dollars

STORAGE TECHNOLOGY:

Redox Batteries

SOURCE:

Ciprios, G., W. Erskine and P. G. Grimes
Redox Bulk Energy System Storage Study,
Vol. I, Exxon Research and Engineering
Co. Prepared for NASA Lewis Research
Center, 1977.

INFORMATION:

Figure 3-37

**Weekly Cycle Targets Are Closer, Especially
With Improved Redox Couples**

ASSUMPTIONS & COMMENTS:

P_d, P_c = power output and charging rate T_d = discharge time T_c = charging time
 V_r = cell voltage z = electrons transferred per mole of reactant C = reactant concentration, 1976 dollars.

STORAGE TECHNOLOGY:

Redox Batteries

SOURCE:

Ciprios, G., W. Erskine and P.G.
Grimes, Redox Bulk Energy System
Storage Study Vol. 1, Exxon Research
and Engineering Co. Prepared for
NASA Lewis Research Center, 1977.

INFORMATION:

Figure 3-21

Energy Investment Costs Look Good
For Redox Case Using Optimistic Parameters

ASSUMPTIONS & COMMENTS:

P_d = discharge power t_c = discharge time, 1976 dollars

STORAGE TECHNOLOGY:

Redox Batteries

SOURCE:

Ciprios, G., W. Erskine and P.G. Grimes
 Redox Bulk Energy System Storage Study
 Vol. 1, Exxon Research and Engineering
 Co. Prepared for NASA Lewis Research
 Center, 1977.

INFORMATION:Figure 3-32

Considerable Opportunity Exists For Optimizing
 Daily and Weekly Redox Systems

$P_D = 20 \text{ MW}$ $P_c = 10\text{-}30 \text{ MW}$ $t_c = 5\text{-}9 \text{ HRS DAILY} + \text{SUNDAY}$

ASSUMPTIONS & COMMENTS:

P_d = discharge power P_c = charge power t_c = charge time, 1976 dollars

STORAGE TECHNOLOGY:

Redox Batteries

SOURCE:

Ciprios, G., W. Erskine and P.G. Grimes
Redox Bulk Energy System Storage Study,
Vol. 1, Exxon Research and Engineering
Co. Prepared for NASA Lewis Research
Center, 1977.

INFORMATION:

Figure 3-19

Stage 1 Model Power Ratio Predictions As
a Function of Energy Storage Efficiency

STORAGE TECHNOLOGY:

Redox Batteries

SOURCE:

Ciprios, G., W. Erskine and P.G. Grimes
Redox Bulk Energy System Storage Study,
Vol. 1. Exxon Research and Engineering
Co. Prepared for NASA Lewis Research
Center, 1977.

INFORMATION:**Figure 3-33****Energy Investment Costs for Batteries in Weekly Storage Cycles** **ASSUMPTIONS & COMMENTS:**

P_d = discharge power P_c = charge power t_c = charging time, 1976 dollars.

STORAGE TECHNOLOGY::Redox Batteries

SOURCE:

Heiter, Kenneth and Paul Skartvedt.
Battery Technology An Assessment of
the State of the Art, TRW Energy Systems
Group DOE Contract EX-76-C-10-3885
Task Order 23., 1978.

INFORMATION:

Table A-13. Redox Battery Characterization

CHARACTERISTIC	PROJECTION
Energy Density	55 Wh/kg
Operating Temperature	Ambient
Costs	\$27-38/kWh

ASSUMPTIONS & COMMENTS:

1977 dollars.

SUMMARY

End Use: Utility Load Leveling

Technology: Sodium-Sulfur Battery

No useful comparisons possible.

STORAGE TECHNOLOGY:Sodium Sulfur Batteries

SOURCE:Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
Prepared for Electric Power Research
Institute. 1976**INFORMATION:**

Table 4-20 SODIUM-SULFUR MATERIALS COST

<u>Cell Costs</u>	<u>\$ Per kWh</u>	
Sodium (22.5¢/lb)	0.28	
Sulfur (8¢/lb)	0.21	
Beta-Alumina (25¢/lb)	0.44	
Graphite (\$10/lb)	0.44	
Aluminum Sheet (63¢/lb)	0.93	
Insulating Header Material	<u>0.18</u>	2.48
 <u>Module Costs</u>		
(Based on 62.5 kWh units)		
Steel Sheet	0.80	
Thermal Controls	0.56	
Insulation	<u>0.24</u>	<u>1.60</u>
TOTAL		4.08

ASSUMPTIONS & COMMENTS:

1975 dollars

STORAGE TECHNOLOGY:

Sodium Sulfur Batteries

SOURCE:

Redox Bulk Energy Storage System Study,
Final Report. V.11. Exxon Research &
Engineering Co. February 18, 1976

INFORMATION:**CELL COSTS****\$ Per KWh**

Sodium (22.5¢/lb)	0.28	
Sulfur (8¢/lb)	0.21	
beta-Alumina (25¢/lb)	0.44	
Graphite (\$10/lb)	0.44	
Aluminum Sheet (63¢/lb)	0.93	
Insulating Header Material	<u>0.18</u>	2.48

MODULE COSTS (Based on 62.5 KWh units)

Steel Sheet	0.80	
Thermal Controls	0.56	
Insulation	<u>0.24</u>	<u>1.60</u>
<u>TOTAL</u>		<u>4.08</u>

ASSUMPTIONS & COMMENTS:

1976 dollars. Part 2 of Appendix

STORAGE TECHNOLOGY:

Sodium Sulfur Batteries

SOURCE:

Redox Bulk Energy Storage System Study,

Final Report. Exxon Research and

Engineering Co. Jan. 30, 1977.

INFORMATION:Major Materials Costs for Laboratory Cells

<u>Material</u>	<u>Cost (\$/lb)</u>	<u>Amount (gm/cm² of β''-Alumina)</u>	<u>Cost (\$/kWh)</u>
Graphite felt	75	0.091	6.57
Stainless Steel	2	2.53	4.86
α -Alumina Header	10	0.35	3.18
β -Alumina	--	0.32	50.46
Sodium	0.4	2.06	0.79
Sulfur	0.1	3.71	0.36
Total			62.22

SUMMARY

End Use: Utility Load Leveling

Technology: Compressed Air

Reports

	1	2	3	4	5
<u>Near Term</u>					
Specific Heat Rate (Btu/kWh)	-	3,808-4,195	-	4,800	3,793-4,000
Efficiency (%)	-	54.7-57.2	-	.77	54.4-56.7
Cost (\$/kW)	-	-	146-260	351	403

STORAGE TECHNOLOGY:

Compressed Air

SOURCE:

E.S. Loan and J.F. McConnel. CAES,
A Utility Point of View, in: 1978
Compressed Air Energy Storage Sympo-
sium Proceedings. U.S. Department
of Energy, 1979.

INFORMATION:

**TABLE 3. 1981 Generation Costs for 600 MW Plant
Operating 8 hrs/day**

<u>Configuration</u>	<u>Total Generation Cost (mills/kWh)</u>	<u>Cost Elements (mills/kWh)</u>			
		<u>Invest- ment</u>	<u>Fuel</u>	<u>Comp. Energy</u>	<u>O & M Expense</u>
*1 Simple cycle gas turbine plant	56.2	14.5	38.9	-	2.8
CAES: Conventional cavern, compensated, atm.					
2 12	72.5	45.3	18.1	6.3	2.8
3 40	65.1	34.5	18.1	9.7	2.8
4 40 EXP ^(a)	63.1	33.4	17.2	9.7	2.8
5 80	68.6	36.6	18.1	11.1	2.8

a) High pressure recuperator/expander system with generation rating 788 MW.

Recomputation, with compression energy cost of \$10/MWh (as above)

6 Low pressure plant (12 atm.)	72.5	45.3	18.1	6.3	2.8
7 High pressure (40 EXP)	70.7	39.1	17.2	9.7	4.7

Recomputation, with compression energy cost of \$20/MWh

8 Low pressure plant (12 atm.)	78.8	45.3	18.1	12.6	2.8
9 High pressure (40 EXP)	80.4	39.1	17.2	19.4	4.7

*Lines 1 to 5 are copied from Table 4-10 of reference 1; the compression energy cost is there assumed to be \$10/MWh.)

ASSUMPTIONS & COMMENTS:

1981 dollars

STORAGE TECHNOLOGY:Compressed Air**SOURCE:**

Kartsounes, G.T. and J.G. Daley. The Use of Reciprocating Engines in Compressed Air Energy Storage Power Plants, in: 1978 Compressed Air Energy Storage Symposium Proceedings U.S. Department of Energy, 1978.

INFORMATION:**TABLE 1. CAES Plant Performance Comparisons**

	Huntorf Plant [4]	Near-term Turbine System (1000,1600°F)* [5]	Advanced Turbine System (2400,2400°F)* [5]	Constant- Pressure Combustion Engine	Pressure- Limited Combustion Engine
Reservoir pressure, MPa	4.48	4.48	4.48	4.48	4.48
(psia)	(650)	(650)	(650)	(650)	(650)
Specific air flow rate, kg/MJ	1.46	1.38	.976	.656	.659
(lb _m /kWh)	(11.59)	(10.92)	(7.75)	(5.21)	(5.23)
Specific heat rate, J/J	1.61	1.12	1.23	1.46	1.46
(Btu/kWh)	(5500)	(3808)	(4195)	(4972)	(4994)
Expansion power/compression power	1.24	1.405	1.93	3.30	3.29
Overall efficiency, %	41.5	54.7	57.2	56.8	56.6
Storage effectiveness	.569	.848	1.09	1.59	1.58

Engine Characteristics:

Max. temp, K	2136	2552
(°F)	(3385)	(4134)
Max. pressure, MPa	4.48	13.8
(psia)	(650)	(2000)
Air/fuel ratio	20	20

*Inlet temperature to high-pressure and low-pressure turbines, respectively.

STORAGE TECHNOLOGY:

Compressed Air

SOURCE:

Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
 Prepared for Electric Power Research
 Institute. 1976

INFORMATION:

Table 4-7 SUMMARY OF TOTAL SYSTEM COSTS
 REPORTED IN PREVIOUS STUDIES
 OF COMPRESSED AIR

Reference	Type of Air Storage Facility	MW, MWh	Capital Cost \$/kW	Year
Giramonti [5]	Mined cavern, 14 atm	(140, 140) (140, 420)	52.1 69.1	1968
	Mined cavern, 50 atm	(140, 140) (140, 420)	50.7 59.8	
	Mined cavern, 14 atm	(700, 700) (700, 2100)	46.0 56.3	
Pratt & Whitney Aircraft [6]	Mined cavern			1968
	4 atm compensated	(37, 185)	140-330	
	13.8 atm compensated	(225, 1125)	80-115	
	30 atm compensated	(300, 1500)	70-90	
Kalapasev [7]	Mined cavern Compensated	(250, 2125)	50	1970
Olsson [8]	Mined cavern 640 psia compensated	(220, 1100)	50	1971
Harboe [9]	Mined cavern 40 atm compensated	(200-250, 1600-2000)	85	1971
	Salt cavern 45 atm		75	1971
Fryer [10]	Nuclear explosive chimney	(175, 875)	65.7	1973
		(542, 4336)	42.2	1973
Richert [11]	Mined cavern	(190-1900)	129	
	Mined cavern Uncompensated Compensated			

ASSUMPTIONS & COMMENTS:

1975 dollars unless noted.

STORAGE TECHNOLOGY:

Compressed Air

SOURCE:

Public Service Gas & Electric Company.

An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.Prepared for Electric Power Research
Institute. 1976**INFORMATION:**

Table 4-7 SUMMARY OF TOTAL SYSTEM COSTS
(Con't) REPORTED IN PREVIOUS STUDIES
OF COMPRESSED AIR

<u>Reference</u>	<u>Type of Air Storage Facility</u>	<u>MW,MWh</u>	<u>Capital Cost \$/kw</u>	<u>Year</u>
Harza Engineering[12]	Mined cavern	(190,1900)	136	1973
Harza Engineering[13]	Mined cavern	(970,9700)		
	240 psi uncompensated		167	
	415 psi uncompensated		150	
	500 psi uncompensated		145	
	415 psi compensated		202-223	
	580 psi compensated		175	
Ayers & Hoover [14]	Aquifer @ 520-ft depth	(168,00)	63	
Rogers & Larson [15]	Mined cavern	(1000,10000)		
	240 psi compensated		155	
	415 psi compensated		148	
Giramonti & Leasard [16]	Mined cavern, 40 atm	(1000,10000)	75-95	
Rudisel	Mined cavern	(--,1000)	191	
Day et al [18]	Mined cavern	(135, 350)		
	300 psi uncompensated		85	
	600 psi uncompensated		93	
	600 psi compensated		85	
Glendenning[19]	Mined cavern	(1000,8000)	99-135	1974

ASSUMPTIONS & COMMENTS:

1975 dollars unless noted.

STORAGE TECHNOLOGY:Compressed Air

SOURCE:

Public Service Gas & Electric Company.

An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.Prepared for Electric Power Research
Institute. 1976**INFORMATION:**

Table 4-8 COSTS OF COMPRESSED AIR
STORAGE MAJOR SUBSYSTEMS

<u>Subsystem</u>	<u>Cost Range</u> \$/kW
Compressor (High Pressure)	\$50 - \$85
Combustion- Turbine	\$10 - \$30
Motor - Generator	\$35 - \$50
Clutch	\$ 5 - \$12
Substation	\$ 5 - \$10

Includes installation and overheads.

ASSUMPTIONS & COMMENTS:

1975 dollars - Component Costs

STORAGE TECHNOLOGY:Compressed Air**SOURCE:**

TRW Inc., Development of a Data Base
 Characterizing Energy Storage Technol-
 ogies, Task 1, Characterization of
 Storage Technologies in Utility Load
 Leveling Applications. Argonne National
 Laboratory, Contract No. 31-109-38-5106,
 1979.

INFORMATION:

Table 5-2. Compressed Air Energy Storage

Characteristic	Range of Values	Expected
Typical Facility Size (MW)	290 - 2000	700
Capital Cost		
Total (1978 \$/kW)	170 - 600	300
Storage Cost (1978 \$/kWh):		
Uncompensated		
Excavated Caverns	11 - 16	14
Solution Mined	3.8 - 7	5
Compensated		
Excavated Caverns	3 - 12	4
Aquifers	9 - 10	9.7
Balance of Plant (1978 \$/kW)	120 - 250	200
Percentage Breakdown:		
Land and Land Rights	0 - 1%	4%
Structures & Improvements	1 - 2%	1.7%
Plant Equipment	1 - 12%	4%
Storage Facilities	11 - 46%	21%
Turbomachinery	37 - 56%	46%
Electrical	2 - 7%	4%
Engineering & Management	6 - 11%	10%
Contingencies	3 - 15%	13%
O & M Costs (1978 mills/kWh)	2.4 - 6.3	3
Heat Rate (Btu/kWh)	4200 - 5800	4800
Storage System Efficiency	.69 - .86	.77
Electric Energy Ratio (kWh in/kWh out)	0.6 - 0.9	0.8
Storage Capacity (hours)	2 - 20	10
Expected Lifetime (years)	25 - 35	30
Construction Lead Time (years)	4 - 8	7

Sources: References 18, 19, 41, 43, 44, 45, 46, 47

STORAGE TECHNOLOGY:Compressed Air**SOURCE:**

TRW Inc., Development of a Data Base
 Characterizing Energy Storage Technol-
 ogies, Task 1, Characterization of
 Storage Technologies in Utility Load
 Leveling Applications, Argonne National
 Laboratory, Contract No. 31-109-38-5106,
 1979.

INFORMATION:

Table 5-4. Methods of Storing Compressed Air

	¹ Energy Storage Density kWh/ft. ³	1978 Approximate Capital Cost \$/kWh ⁷
Excavated caverns		
- Constant pressure ⁴	0.28	3.1
- Constant volume ³	0.08	11.1
Abandoned mines		
- Constant pressure ⁴	0.28	"site specific"
- Constant volume ³	0.08	"site specific"
Solution-mined cavities ³	0.08	3.8
Depleted oil and gas ² fields	0.017	6.5
Aquifers ²	0.017	9.5
Cryogenic liquid ⁵	6.1	0.6
Pressure storage vessels		
- Constant pressure ^{4,6}	0.11	59.9
- Constant volume	0.056	11.9
Nuclear explosive ³ formed cavities	≤.08	17.9

NOTES:

- 1 - Stored at 40 atm. Turbines fired at 1800°F (982°C)
- 2 - 20% porosity assumed
- 3 - 51 atm to 40 atm pressure variation. Turbines fired at 1600°F (982°C)
- 4 - Hydrostatically compensated with atmospheric reservoir and water column.
- 5 - Cryogenic equipment not included.
- 6 - For pressure of 18 atm.
- 7 - Costs based on eastern central site with satisfactory geology, available water, construction labor and access facilities.

Source: Reference 46

STORAGE TECHNOLOGY:Compressed Air

SOURCE:TRW Inc., Development of a Data Base
Characterizing Energy Storage Technol-
ogies, Task 1, Characterization of
Storage Technologies in Utility Load
Leveling Applications. Argonne National
Laboratory, Contract No. 31-109-38-5106,
1979.**INFORMATION:**

Table 5-3. Compressed Air Energy Storage Data Samples

Ref. No.	Capital Cost (1978 \$/kW)	O & M Cost (1978 mills/kWh)	Daily Generation Time (hrs)	Heat Rate (Btu/kWh)	Const. Lead Time (yrs)	Electric Energy Ratio	Power Output (MW)
18**	210 - 295	6.3	4	4000-5200	-	.58 - .74	-
19	180 - 670	6.3	12	4200-5800	-	.7 - .8	200-1000
41*	370 - 532	-	10	-	-	-	2000
42*	342	-	10	-	-	-	280
45	182	3.0	10	4628	8	.566	2000
46**	322	2.4	10	5252	8	-	600
43	220	-	2	5500	4	.81	290
44	310	-	20	4397	7	.9	705
44	266	-	20	4383	7	.9	750

*Escalation and interest during construction may have been included

**Escalation and interest during construction is included

NOTE: "-" indicates data not given.

STORAGE TECHNOLOGY:

Compressed Air

SOURCE:

Loscutoff, W. V. Compressed Air Energy
Storage. Pacific Northwest Laboratories.
1979. PNL-2935. UC-94-b

INFORMATION:

TABLE 4.1 Capital Cost Comparison (\$1000)

	Reference CAES System	Hybrid System	Double-Stage Adiabatic System
Land, Structures, and Plant Equipment	\$ 5,538	\$ 5,538	\$ 5,228
Turbo Machinery			
Intercoolers	1,664	1,241	449
Aftercoolers	780	-	-
Compressor Recuperator	-	22,000	-
Compressors	24,972	24,972	37,458
Compressor Motors	17,304	19,207	31,946
Turbines	18,354	18,354	27,531
Turbine Exhaust Recuperator	8,501	8,501	-
Other Turbo Machinery	27,735	27,735	26,199
Storage Facilities			
Air Storage & Associated Costs	34,509	34,509	51,764
Thermal Storage	-	2,030	6,090
Fuel Storage	428	428	-
Electrical and Miscellaneous	10,625	10,625	10,625
	\$150,410	\$175,140	\$197,290
Engineering and Construction Management	22,562	26,271	29,594
	\$172,972	\$201,411	\$226,884
Contingency	25,946	30,212	34,033
Escalation	50,387	58,672	66,092
Interest During Construction	31,436	36,604	41,234
July 1984 \$	\$280,741	\$326,899	\$368,243
January 1985 \$	287,759	338,071	377,449
Plant Capacity	750 MW	750 MW	750 MW
Cost/kW 1985 \$	\$384/kW	\$447/kW	\$503/kW

STORAGE TECHNOLOGY:

Compressed Air

SOURCE:

Loscutoff, W. V. Compressed Air Energy
Storage. Pacific Northwest Laboratories.
1979. PNL-2935. UC-94-b

INFORMATION:

TABLE 8.3. Comparison of Cost Estimates for Compressed Air Energy Storage Plants
Using Various Types of Expansion and Compression Equipment(a,b)

	Turbine Systems		Compound-Engine Systems	
	Near-Term	Advanced	Using Conventional Turbocompressors	Using Reversible High-Pressure Expanders/Compressors
Capital Cost, \$kW				
Expansion/Compression Equipment(c)	35.5	43.4	49.0	38.6
Storage Cavern	65.8	58.4	41.6	41.6
Surface Reservoir	5.5	4.7	3.4	3.4
Balance of Plant	80.0	80.0	70.8	71.8
Indirect Costs(d)	116.8	116.5	103.0	96.5
Total	303.6	303.0	267.8	250.9
Difference(h)		- 0.2%	-11.8%	-17.4
Operating Cost, \$/kWh				
Capital Charge(e)	25.0	24.9	22.0	20.6
Fuel(f)	9.5	10.0	11.8	11.8
Electricity(g)	10.9	8.9	6.3	6.3
Operating and Maintenance	2.0	2.0	2.0	2.0
Total	47.4	45.8	42.1	40.7
Difference(h)		- 3.4%	-11.2%	-14.1%

(a) Costs are expressed in 1976 dollar values.

(b) The storage cavern was assumed to be a water-compensated mined type with storage pressure - 7.09 MPa (70 atm) and storage temperature = 322 K (120°F). Nominal storage capacity was assumed to be 20 h yielding a generation time of 2190 h/yr.

(c) Turbines, reciprocating engines, and/or compressors (including ducting, mountings, and installation).

(d) Indirect costs consist of engineering and administration (10% of direct costs), contingency (15% of direct costs), and escalation and interest during construction (30% of direct costs plus engineering, administration, and contingency).

(e) The capital charge was 18% per year for a generation time of 2190 h/year.

(f) The fuel cost used was \$8.53/10³ kWh (\$2.50/10⁶ Btu).

(g) The electricity cost used was 15 mil/kWh.

(h) As compared to the near-term turbine system.

STORAGE TECHNOLOGY:Compressed Air

SOURCE:Loscutoff, W. V. Compressed Air Energy
Storage. Pacific Northwest Laboratories.
1979. PNL-2935. UC-94-b**INFORMATION:**

TABLE 8.1. Comparison of Performance Parameters for Compressed Air Energy Storage Plants Using Various Types of Expansion/Compression Equipment

	Huntorf Plant (1)	Plant Using Near-Term Turbine System	Plant Using Advanced Turbine System	Plant Using Compound- Engine System
Reservoir Pressure, MPa	6.89	7.09	7.09	7.09
(atm)	(68)	(70)	(70)	(70)
(psia)	(1000)	(1029)	(1029)	(1029)
Specific Air Flow Rate, kg/MJ	1.46	1.41	1.20	0.86
(lb _m /kWh)	(11.59)	(11.18)	(9.55)	(6.80)
Specific Heat Rate, J/J	1.61	1.11	1.17	1.38
(Btu/kWh)	(5500)	(3793)	(4000)	(4726)
Expansion Power/Compression Power	1.24	1.27	1.68	2.36
Overall Efficiency, %	41.5	54.4	56.7	55.4

SUMMARY

End Use: Utility Load Leveling

Technology: Underground Pumped Hydro

No useful comparisons possible.

STORAGE TECHNOLOGY:Pumped Hydro

SOURCE:TRW Inc., Development of a Data Base
Characterizing Energy Storage Technol-
ogies, Task 1, Characterization of
Storage Technologies in Utility Load
Leveling Applications. Argonne National
Laboratory, Contract No. 31-109-38-5106,
1979.**INFORMATION:**

Table 4-13. Current Pumped Storage Plants

Characteristic	Range of Values	Expected
Typical Facility Size (MW)	50 - 2000	350
Capital Cost		
Total (1978 \$/kW)	145 - 485	255
Storage Cost (1978\$/kWh)	2.5 - 12	8
Balance of Plant (1978 \$/kW)	120 - 190	175
Percent Breakdown:		
Land & land rights	0 - 15%	2%
Structures	10 - 30%	15%
Reservoirs, dams, & waterways	25 - 66%	49%
Equipment	5 - 55%	32%
Roads, RR, & bridges	0 - 15%	2%
O & M Cost (1978 mills/kWh)	1 - 14	2.5
(1978 \$/kW)	.5 - 6	3
Head (feet)	100 - 1200	300
(meters)	30 - 360	90
Energy Storage Capacity (kWh/kW of plant capacity =hours)	5.6 - 94	9
Efficiency	.66 - .78	.72
Expected Lifetime (years)	50 or more	50
Construction Lead Time (years)	4 - 10	8
Annual Operating Profile (hrs/yr)	300 - 4000	2300

Sources: References 14, 19, 26, 27, 29, 30

STORAGE TECHNOLOGY:

Pumped Hydro

SOURCE:

TRW Inc., Development of a Data Base
Characterizing Energy Storage Technol-
ogies, Task 1, Characterization of
Storage Technologies in Utility Load
Leveling Applications, Argonne National
Laboratory, Contract No. 31-109-38-5106,
1979.

INFORMATION:

Table 5-1. Underground Pumped Storage Plants

Characteristic	Range of Values	Expected
Typical Facility Size (MW)	1000 - 3000	2000
Capital Cost		
Total (1978 \$/kW)	170 - 450*	350
Storage Cost (1978 \$/kWh)	3.5 - 16	14
Balance of Plant (1978 \$/kW)	150 - 300	200
Percentage Breakdown (Direct Costs):		
Land & Land Rights	.3 - 1%	1%
Structures & Improvements	11 - 17%	14%
Reservoirs, Dams, & Waterways	47 - 59%	53%
Equipment	27 - 37%	31%
Roads & RR	.8 - 1.4%	1%
O & M Costs		
1978 mills/kWh or	1 - 2	1.5
1978 \$/kW	1.4 - 3.1	2.0
Efficiency	.67 - .78	.725
Head (feet)	1500 - 4500	3500
(meters)	450 - 1350	1070
Energy Storage Capacity (kWh/kW of plant capacity = hours)	6 - 10	10
Expected Lifetime (years)	50 or more	50
Construction Lead Time (years)	7 - 12	8

* Lower values are for underground voids (unexcavated)

Sources: References 16, 18, 19, 40, 41, 42

ASSUMPTIONS & COMMENTS:

1975 dollars - upper bound on costs-residential application.

STORAGE TECHNOLOGY:Pumped Hydro

SOURCE:Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
Prepared for Electric Power Research
Institute. 1976**INFORMATION:**

Table 3-2 HYDRO PUMPED STORAGE COMPONENT EFFICIENCIES

	<u>Representative Ranges, %</u>	
	<u>Low</u>	<u>High*</u>
<u>Pumping</u> - Motor & Transformer	97.5	98.5
Pump	91.5	92.5
Water Passages	96.5	98.5
<u>Generating</u> - Water Passages	95.5	97.5
Turbine	89	92.5
Generator & Transformer	97.5	98.5
<u>Allowance for Operation Under</u>		
Other Than Optimum Conditions	92	98
<u>Over-all cycle efficiency</u>	66%	78%

*Not yet confirmed by experience.

STORAGE TECHNOLOGY:

Pumped Hydro

SOURCE:

Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
Prepared for Electric Power Research
Institute. 1976

INFORMATION:

*Costs for Plants are Adjusted to 1/1/74

Figure 4-1 ENERGY STORAGE COSTS
(DAMS AND RESERVOIRS)

ASSUMPTIONS & COMMENTS:

1974 dollars. Reservoir Costs Only

STORAGE TECHNOLOGY:

Pumped Hydro

SOURCE:

Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
Prepared for Electric Power Research
Institute. 1976.

INFORMATION:

Table 4-3 PUMPED STORAGE COST DATA*

Plant Name	Year of Initial Operation	Capacity in MW	Hours	Storage Cost \$/KWH	Power Cost \$/KW	Total Costs \$/KW
Taum Sauk	1963	350	7.7	9.87	158	234
Yards Creek	1965	330	8.75	3.54	136	167
Muddy Run	1967	855	14.25	11.89	129	156
Cabin Creek	1967	280	5.85	11.45	124	191
Seneca	1969	380	11.2	6.34	186**	257
Northfield Mtn.	1972	1000	8.5	1.71	132	146.5
Blenheim-Gilboa	1973	1030	11.6	3.45	100	140
Ludington	1973	1675	9	8.44	125	201
Jocassee	1973	625	94	.69	117.5	182.5
Bear Swamp	1974	540	5.6	12.86	141	213
Raccoon Mountain	1975	1370	24	1.25	87	117

* 1974 Dollars

** Adjusted to \$175/kW to Eliminate Costs Associated with Downstream
Discharge which Permits the Plant to Utilize the Head Created by
the Lower Reservoir Dam for Generation.

ASSUMPTIONS & COMMENTS:

1974 dollars

STORAGE TECHNOLOGY:

Pumped Hydro

SOURCE:

Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
Prepared for Electric Power Research
Institute. 1976

INFORMATION:

Table 4-40 OPERATING COST EXPERIENCE OF
HYDRO PUMPED STORAGE PLANTS

Plant	Years Of Operation	Capacity MW	Adjusted Annual Expenses, \$kW/Year		
			Operation	Maintenance	Total
Yards Creek	9	330	0.36	0.78	1.14
Cabin Creek	7	280	0.97	0.41	1.38
Taum Sauk	11	350	0.28	1.25	1.53
Smith Mt.	9	440	0.56	1.00	1.56
Muddy Run	7	856	0.66	1.15	1.81
Kinzua (Seneca)	4	380	1.09	1.43	2.52
Average (6 plants, unweighted)			0.67	1.00	1.67
Average (without Kinzua)			0.59	0.92	1.51
Blenheim-Gilboa	1	1,030	0.19	0.12	0.31
Jocassee	1	312	0.52	0.07	0.59
Luddington	1	1,675	0.35	0.46	0.81
Northfield	2	1,000	0.86	0.32	1.18

ASSUMPTIONS & COMMENTS:

1975 dollars

STORAGE TECHNOLOGY:

Underground Pumped Hydro for Utility
Load Leveling

SOURCE: Chas. T. Main, Inc. Underground

Hydroelectric Pumped Storage, an Evaluation
of the Concept, Final Report. Prepared for
U. S. Department of Energy and U. S. Department
of the Interior, November, 1978.

INFORMATION:

Table II-1

UNITED STATES DEPARTMENT OF THE INTERIOR, BUREAU OF RECLAMATION (USBR)
UNITED STATES DEPARTMENT OF ENERGY (DOE)

Number	Title	Date	Prepared By	Sponsored By	Preferred Scheme
1	Underground Pumped Storage Research Priorities	4/76	Acres American, Inc.	Electric Power Research Institute (EPRI)	Indirectly suggested one or two drops approx. 900m (3000 ft) head
2	An Assessment of Energy Storage Systems Suitable for use by Electric Institutes	7/76	Public Service Electric & Gas Co., Newark, NJ	EPRI, Energy Research & Development Administration (now DOE)	Considered: Up to 765m (2500 ft) for single stage reversible units about 1070m (3500 ft) for two plants in series
3	Siting Opportunities in the U.S. for Compressed Air and Underground Pumped Hydro Energy Storage Facilities	12/76	Acres American, Inc.	Argonne Nat'l. Lab (ANL) DOE	In economic computations assumed 200 mW plant, 10 hr. storage 1070m (3500 ft) head
4	Underground Pumped Hydro Storage and Compressed Air Energy Storage An Analysis of Regional Markets and Development Potential	3/77	Harza Engineering Company	(ANL) DOE	Two drop scheme. Total head 1340m (4400 ft) 2000 mW, 6 to 10 hr storage

STORAGE TECHNOLOGY:

Underground Pumped Hydro for Utility
Load Leveling

INFORMATION:

UNDERGROUND HYDROELECTRIC PUMPED STORAGE (UHPS) COMPARATIVE REVIEW OF RECENT STUDIES

Preferred Type of Equipment	Estimated Cost \$/kW	Lower Reservoir Excavation Cost \$/m (\$/cy)	Excavation Cost (\$/cy)	Allowance for Civil Works Contingencies	Const. Schedule Remarks	Major Geologic Criteria	Minimum Geologic Data Required	Pumping Cycle Efficiency	Principal Purpose
200 mW units: at 700 m (2300 ft) single stage runner reversible & at 1000 m (3300 ft) multistage runner, reversible	300 For 1000 mW at 900 m (3000 ft) and 10 hr storage	19.7 ⁽¹⁾ (15) to 23.6 (18) (1)		Amount not known	Total const. schedule increases approx. 2 years as the depth increases from 610 m (2000 ft) to 1220 m (4000 ft)	Competent stratum approx. 60 m (200 ft) thick	-Confirmation of stratigraphic projections -Water levels -Jointing, discontinuities	-	To identify particular aspects requiring detailed examination during a subsequent comprehensive preliminary design phase.
Single stage reversible units of about 300 mW	<290 For 10 hr storage	18.3 ⁽¹⁾ (14) to 22.3 (17) (2)		About 12.5%	Suggested speedy lower reservoir excavation to reduce the interest during const.	Determine first top of Precambrian rock. Preferred rocks: Undeformed granite -No residual tectonic stresses	-	70 to 75%	To provide the required data to establish research and development priorities for energy storage technology.
-	Approx 230	-Approx 19.7 (15) in competent rock up to 66 (50) under adverse conditions		Amount not known	-	Chamber stability based on Barton's criteria (Q)	Rock mineability & stability Rock mass permeability. Existing groundwater regime. Local & regional rock structure. In-situ stresses.	-	To categorize the geology of the continental United States in accordance with the potential for the siting of compressed air energy storage (CAES) and UHPS.
250 mW single stage reversible units at 670 m (2200 ft) head	252 to 308 (2000 mW 10 hr storage)	24.1(2) (18.4) to 27.6(2) (21.1)		20%	Total time 12 years of which 6-1/2 years are const. time -No additional const. time for Region IV with poor geologic conditions for shafts	-Massive crystalline igneous or metamorphic rocks -Massive limestone or dolomite	Unfavorable areas: -Unsuitable sedimentary rocks -Complex geologic structures -High seismic risk -Extensive faulting -Volcanic rocks	About 78%	To identify and describe regional markets for UHPS and CAES and perform geologic analysis to determine regional development potential.
<p>All costs updated to July 1, 1976. Includes contingencies but neither interest during const. nor substation.</p> <p>All costs updated to July 1, 1976. (1) Includes contingencies (2) Includes contingencies, rock support, & disposal on site.</p> <p>General Notes: This exhibit highlights the listed studies. Costs have been indexed as required for purposes of comparison.</p>									

SOURCE: Chas. T. Main, Inc. Underground

Hydroelectric Pumped Storage, an Evaluation of the Concept, Final Report. Prepared for U. S. Department of Energy and U. S. Department of the Interior, November, 1978.

STORAGE TECHNOLOGY:

Underground Pumped Hydro for Utility
Load Leveling

SOURCE: Chas. T. Main, Inc. Underground
Hydroelectric Pumped Storage, an Evaluation
of the Concept, Final Report. Prepared for
U. S. Department of Energy and U. S. Department
of the Interior, November, 1978.

INFORMATION:

NOTE: Table II-1 is intended to present a summary of major studies prior to this report. For this reason the findings of this report were not included thereon. Should readers so desire the following could be added:

Title	-	Underground Hydroelectric Pumped Storage. An Evaluation of the Concept.
Date	-	June 1978
Prepared by	-	Chas. T. Main, Inc.
Sponsored by	-	Department of the Interior, Bureau of Reclamation and Department of Energy, Division of Energy Storage Systems
Preferred Scheme	-	One drop arrangement with multi-stage reversible units Total head 1200 m (4000 ft) 2000 MW, 10 hour storage
Preferred Type of Equipment	-	333 MW multistage reversible units at 1200 m (4000 ft) head
Estimated Cost, \$/kW	-	\$318
Lower Reservoir Excavation Cost (1977) \$m ³ (\$c.y.)	-	\$24.84/m ³ , \$19.00 c.y.
Allowance for Civil Works Contingency	-	25%
Construction Schedule Remarks	-	7-1/2 yrs. construction
Geologic Criteria	-	See Plate III-2
Pumping Cycle Efficiency	-	67-75%
Principal Purpose	-	An Evaluation of the Concept

STORAGE TECHNOLOGY:

Underground Pumped Hydro for Utility Load Leveling

SOURCE: Chas. T. Main, Inc. Underground Hydroelectric Pumped Storage, an Evaluation of the Concept, Final Report. Prepared for U. S. Department of Energy and U. S. Department of the Interior, November, 1978.

INFORMATION:

TABLE IV-1. INVESTMENT COST AND CONSTRUCTION TIME OF UHPS SCHEMES

No.	Scheme	Total Cost (\$x10 ⁶)	\$ /kW (Incl. Storage)	% of Scheme I	Construction Time	
					First Unit Com. Oper.	Last Unit Com. Oper.
I	2000 mW (6x33) 1200 m; 10 hrs.	636	318	100	6 yr + 9 mo	7 yr + 7 mo
II	2000 mW (8x250) 2x600m; 10 hrs	658	329	103	7 yr + 1 mo	7 yr + 6 mo
III	2000 mW (6x333) 1200m; 10 hrs tandem	693	347	109	6 yr + 9 mo	7 yr + 7 mo
IV	2000 mW (6x333) 500m; 10 hrs	623	311	98	7 yr + 2 mo	8 yr
V	2000 mW (6x333) 900m; 10 hrs	704	352	111	7 yr + 6 mo	8 yr + 4 mo
VI	2700 mW (8x337) 1200m; 10 hrs	815	302	95	7 yr + 11 mo	9 yr + 3 mo
VII	1300 mW (4x325) 1200m; 10 hrs	454	350	110	6 yr + 5 mo	6 yr + 11 mo

NOTE: Based on unit prices as of January 1977
Time counted from the award of the Civil Contract
Interest during construction (AFDC) and escalation not included

STORAGE TECHNOLOGY:

Underground Pumped Hydro for Utility Load Leveling

INFORMATION:

TABLE VI-2. COMPARISON OF GENERAL CHARACTERISTICS

Modes of Generation	Land Requirements (Hectares)	Capital Cost (\$/kW)	Fuel Costs (cents/10 ⁶ Btu)	Major Environmental Impacts	Construction Schedule (months from initiation)		Number of Existing Plants 1000 MW or Greater	Potential Siting of Plants (1000 MW or Greater)
					Finish ¹	Commercial Operation		
UHPS (2000 mw)	40-120	\$325	During pumping cycle Oil: 180-230	Water	93	96	0	High
Conventional Hydro	4000-32,000	\$500-700	---	Water & land	48	52	5(FPC-74)	Low
Conventional Pumped Storage (1000 mw)	300-4000	\$300-350	Pumping cycle Oil: 180-230	Water & land	48	57	3(FPC-74)	Low
Nuclear	40-80	\$800-1000	45-55	Water & air Health & safety	60	66	9(FPC-74)	Med
Fossil	50-150 (On-site coal storage)	\$640-coal	Coal: 70-110 Oil: 180-230 Gas: 80-120	Water & air Health & safety	42	42	97(FPC-74)	Med
Internal Combustion	Usually used as a peaking unit in conjunction with a base loaded facility	\$450-oil	Oil: 180-230 Gas: 80-120	Noise & air (NO _x)	18	18	0(FPC-73)	High

1 - Does not include time delays for regulatory licensing process.

Source: Ref. 5, 6, 8, 9

SOURCE: Chas. T. Main, Inc. Underground

Hydroelectric Pumped Storage, an Evaluation of the Concept, Final Report. Prepared for U. S. Department of Energy and U. S. Department of the Interior, November, 1978.

SUMMARY

End Use: Utility Load Leveling

Technology: Thermal Storage

No useful comparisons possible.

STORAGE TECHNOLOGY:Thermal Energy Storage**SOURCE:**

Dooley, James L. et. al. A Feasibility Study of Underground Energy Storage Using High-Pressure, High Temperature Water." R&D Associates Martina Del Rey, California, CONS-1243-1, RDA-TR-7100-001, 1977.

INFORMATION:**III. Complete Peaking Plant Costs**

ALL COSTS ARE IN 1976 DOLLARS ($\times 10^6$) AND INCLUDE 20 PERCENT MINIMUM FOR UNCERTAINTIES, 25 PERCENT FOR ADMINISTRATION PLUS 20 PERCENT ON ALL COSTS FOR FINANCE CHARGES. COST RANGE SHOWN.

CAVITIES ARE SIZED FOR 10 hr OF PEAKING OUTPUT IN THESE EXAMPLES.

A. LOW PRESSURE PEAKING POWER SYSTEM (1000 lb/in.²)

PEAKING OUTPUT (MW)	200	500	1000
CAVITY SPHERE DIAMETER (ft)	192	260	325
- GENERATING PLANT COMPLETE (\$)	46-55	83-92	139-145
- COOLING TOWER (\$)	3-3	6-6	13-13
- UNDERGROUND SHAFT COSTS AND PIPING (EXCEPT CAVITY) (\$)	12-21	16-25	20-31
TOTAL POWER RELATED COSTS (\$)	61-79	105-123	172-189
TOTAL CAVITY COST RANGE (\$)	25-31	54-62	81-99
COMPLETE PEAKING PLANT COST RANGE (\$)	86-110	158-185	253-288

B. HIGH PRESSURE PEAKING POWER SYSTEM (2000 lb/in.²)

PEAKING OUTPUT (MW)	200	500	1000
CAVITY SPHERE DIAMETER (ft)	181	248	310
- GENERATING PLANT COMPLETE RANGE (\$)	46-55	84-93	141-145
- COOLING TOWER (\$)	2-3	5-6	11-13
- UNDERGROUND SHAFT COST AND PIPING RANGE (EXCEPT CAVITY) (\$)	16-29	20-34	29-43
TOTAL POWER RELATED COSTS (\$)	64-87	109-133	181-202
TOTAL CAVITY COST RANGE (\$)	22-29	47-56	77-94
COMPLETE PEAKING PLANT COST RANGE (\$)	86-115	156-189	258-296

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE: Meyer, C. F. Potential Benefits

of Thermal Energy Storage in the Proposed

Twin Cities District Heating - CogenerationSystem, Final Report, ORNL/Sub-7604/2.

Prepared for U.S. Department of Energy by

General Electric Company-TEMPO, October 1979.

INFORMATION:

Table 5-3. Combined savings and resultant breakeven annual cost of TES (1978 dollars).

	Capital Costs Saved Due to TES		Fuel Cost Savings Due to TES	Breakeven Annual Cost of TES*			
	Municipal Financing [†]	Private Financing [‡]	\$M/yr	Municipal Financing		Private Financing	
	\$M/yr	\$M/yr		\$M/yr	\$/yr per kW of TES Capacity	\$M/yr	\$/yr per kW of TES capacity
Case A-1	7.9	11.9	16	23.9	15.7	27.9	18.3
Case A-2	11.0	16.6	14	25.0	13.4	30.6	16.4
Case A-3	13.2	19.8	14	27.2	14.5	33.8	18.1
Case A-4	14.6	22.0	14	28.6	12.7	36.0	16.0
Case B-1	13.1	19.6	27	40.1	15.8	46.6	18.4
Case B-2	17.5	26.3	26	43.5	15.1	52.3	18.1
Case B-3	27.1	40.7	26	53.1	17.8	66.7	22.3
Case B-4	31.0	46.4	25	56.0	15.1	71.4	19.3

* For a recovery fraction of 0.75

[†] Fixed charge rate = 0.12[‡] Fixed charge rate = 0.18

Notes on Table 5-3.

BASIS. The reference for comparing performance and cost is the system described for the Twin Cities area by Studsvik Energiteknik AB, under contract to the U.S. Department of Energy via Oak Ridge National Laboratory.

Studies of aquifer TES by TEMPO and others, since 1972, and limited field testing, provide estimates of the performance of Heat Storage Wells for large-scale storage. More than three-fourths of the heat stored is expected to be recoverable after several months of storage. While novel as an energy-system component, the Heat Storage Well technology draws upon experience gained from millions of water and oil wells and from ongoing geothermal investigations.

Only the mature system is considered. The assumption is that TES devices would have been incorporated into the system during the 20 years from inception to maturity, not that it would be retrofitted. Details of when, where, and how TES would have been incorporated may be considered in a later study.

For this study, the availability of suitable aquifers for TES is assumed.

APPROACH. For the Scenario A and the Scenario B versions of the system as proposed by Studsvik, four study cases were developed to describe potential modifications of the mature system to incorporate TES. Heat loads for the study cases are those described by Studsvik in interim reports on their Scenario A and Scenario B reference cases. The load factor is 0.28; the load duration, 2465 hours.

	<u>Scenario A</u>		<u>Scenario B</u>	
Peak demand in megawatts thermal	2704	MW	4405	MW
Delivered to consumers	2621	MW	4266	MW
Pipeline losses	83		139	
Annual load in terawatt hours thermal	6.994	TWH	11.016	TWH
Delivered to consumers	6.298	TWH	9.798	TWH
Pipeline losses	0.695		1.218	

STORAGE TECHNOLOGY:Thermal Energy Storage

SOURCE:

Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
Prepared for Electric Power Research
Institute. 1976

INFORMATION:

Table 3-6 THERMAL ENERGY STORAGE DENSITIES

<u>Concept</u>	<u>Thermal Energy Storage Density (Btu/ft³)</u>	<u>Temperature Swing (°F)</u>
Steam Storage	10,600	420-250
Feedwater Storage	15,850	422-168
Liquid Sodium	11,690	1,000-300
Fused Salt	26,030	950-750
Fuel Oils	10,700	530-250
Metal Hydride	1,820	200
Thermal Well	2,450	340-180

STORAGE TECHNOLOGY:Thermal Energy Storage

SOURCE:

Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
Prepared for Electric Power Research
Institute. 1976.

INFORMATION:

Table 4-15 THERMAL OIL SYSTEM, COST ESTIMATES

I. <u>Plant Net Output</u>		MW
(a)	Conventional Nuclear, Base Case	1,000
(b)	Nuclear + storage, Normal Operation	1,023
(c)	Nuclear + storage, Maximum Operation	1,282
(d)	Nuclear + storage, Minimum Operation	670
II. <u>Incremental Investment over Base Case</u>		
(1) <u>kW-Dependent Facilities (259 MW)</u>		
		<u>\$M</u> <u>\$/kW</u>
	Powerhouse-related	23.8
	kW-related oil facilities	37.4
	Total, kW-dependent	61.2
	Less credit for 23 MW @ \$625/kW	14.4
	Net, kW-dependent	46.8
(2) <u>kWh-Dependent Facilities over Base Case (2593 MWh)</u>		
		<u>\$M</u> <u>\$/kWh</u>
	Oil Tankage, etc.	12.1
	670,000 Bbl Oil at 69¢/gal	19.4
	50¢/gal to \$1/gal (\$M 14-28)	31.5
		12.15
(3) <u>Total Cost, 10-hr storage</u>		
	Incl. oil	78.3 302
	Excl. oil	58.9 227

ASSUMPTIONS & COMMENTS:

1975 dollars

STORAGE TECHNOLOGY:Thermal Energy Storage

SOURCE:

Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
Prepared for Electric Power Research
Institute. 1976

INFORMATION:

Table 4-16 SUMMARY OF COST CHARACTERISTICS
FOR MOLTEN SALT STORAGE

Power (MW)	Storage Capacity (MWh)	Power Related Capital Costs (\$/kW)		Energy Storage Related Capital Costs (\$/kWh)	
		Turbine and Balance of Plant	Heat Exchanger	Salt Mixture	Concrete Container
100	1,000	\$190/kW	370-740	18-56	25-30
100	10,000	\$190/kW	370-749	17-53	20-25
1000	10,000	\$100/kW	340-680	17-53	20-25

ASSUMPTIONS & COMMENTS:

1975 dollars

SUMMARY

End Use: Utility Load Leveling

Technology: Hydrogen

No useful comparisons possible.

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

Fischer, W., et al. Economic Prospects
for the Application of New Electric
Energy Storage Devices. Journal of
Power Sources. 3(1978) 331-345.
Lausanne, Switzerland

INFORMATION:

TABLE 2

Data for hydrogen storage systems

Characterization of electrolyzer	Atmospheric pressure (conventional)	High pressure (30 bar)	Solid electrolyte	
Hydrogen generation:				
Type of electrolyte	aqueous KOH	aqueous KOH	solid polymer electrolyte (Nafion)	zirconia
Operating temperature	70 - 90 °C	100 - 150 °C	80 - 150 °C	800 - 1000 °C
References	[18, 24, 25]	[18, 26 - 28]	[18, 29]	[18, 30 - 32]
Price ^a , DM/kW _{input}	530 - 600 ^b	360 ^c	240 - 290 ^c	260 - 320 ^c
Lifetime achieved (years)	30 - 40	10	4	1
Efficiency	0.7 ^b	0.8 - 0.85 ^c	0.8 - 0.85 ^c	0.9 ^c
Availability of materials (years) ^d	Ni: 120	Ni: 120	Pt: 130	Zr, Y, La: > 50 Ni: 120
Electric energy generation:				
Characterization of generator	Low temp. fuel cell (electrolyte KOH or acid)	Solid electrolyte fuel cell (electrolyte Nafion or zirconia)	Gas turbine	
References	[18, 37, 38]	[29, 30, 32]	[39, 40]	
Price DM/kW	700 - 1200 ^c	700 - 1100 ^c	390 - 420 ^b	
Efficiency	0.45 - 0.6 ^c	0.45 - 0.6 ^c	0.25 - 0.35 ^c	
Lifetime achieved (years)	2 - 4	4	20	

^a1977 prices including auxiliary equipment.

^bAchieved.

^cExpected for mass production.

^dResources divided by present annual consumption [36].

ASSUMPTIONS & COMMENTS:

Costs in German Marks

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
 Prepared for Electric Power Research
 Institute. 1976

INFORMATION:

Table 3-9

PERFORMANCE DATA FOR WATER ELECTROLYZERS

	<u>Electrolyzer Type</u>	<u>Approximate Capacity</u> <u>kg/hr of H₂</u>	<u>Electrical Efficiency,</u> <u>Percent</u>	<u>Electrical Requirements</u> <u>kWhr/kg of H₂</u>	<u>Capital Cost,</u> <u>\$/KW (c)</u>
	Ideal (NTP)	--	100	40.1	--
1966	Hypothetical	(20,000)	---	---	40
1971	Hypothetical	---	68-95	---	<50
1972	Hypothetical	(66,000)	63-70	53-64	~40
1973	Teledyne, Bipolar	(4,750)	---	---	88-109
1974	G.E. SPE Cells(a)	~2,000	92.5	---	~335(b)
1974	Lurgi, High Pressure	~ 800	---	---	~345(b)
1975	Brown Boveri, Bipolar	60-950	---	(53)	145-215

Data in parentheses are projected or calculated.

(a) SPE = Solid Polymer Electrolyte

(b) Installation, freight, and insurance costs included

(c) Hydrogen output equivalent

ASSUMPTIONS & COMMENTS:

Electrolysers only

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

Public Service Gas & Electric Company.

An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.Prepared for Electric Power Research
Institute. 1976**INFORMATION:**

Table 3-10

TECHNICAL CHARACTERISTICS OF HYDROGEN ENERGY STORAGE SYBSYSTEMS

Subsystem Alternative	Power, MW	Storage Capacity, MWhr	Efficiency %		Energy Density Kwh/m ³	
			High	Low	High	Low
(a) Compressed Gas Storage	10	100	99	75	20	14
(b) Metal Hydride	10	100	95	75	53	35

ASSUMPTIONS & COMMENTS:

Hydrogen storage subsystem only

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
 Prepared for Electric Power Research
 Institute. 1976

INFORMATION:

Table 3-11

TECHNICAL CHARACTERISTICS OF HYDROGEN ENERGY STORAGE CONCEPTS

Hydrogen Energy Storage Concept (a)	Power, MW	Storage Capacity, MWhr	Efficiency %		Energy Density kWh/M ³	
			High	Low	High	Low
(A)	10	100	58	28	25	17
(B)	10	100	56	28	41	27
(C)	10	100	45	23	25	17
(D)	10	100	43	23	41	27

(a) See text for concept identification details

A = electrolyzer + gas storage + fuel cell

B = electrolyzer + hydride storage + fuel cell

N_t = overall thermal efficiency, percent

D_E = energy storage density,

D_p = power density, kW/m³

A daily duty cycle with 10 hours of discharge is assumed.

C = electrolyzer + gas storage = gas turbine

D = electrolyzer + hydride storage + gas turbine

R_C = maximum charging rate, MWhr/hr

R_d = maximum discharging rate, MWhr/hr

L = useful life, years

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
 Prepared for Electric Power Research
 Institute. 1976

INFORMATION:

Table 4-23 BIPOLAR ELECTROLYZER COST ESTIMATES

Manufacturer	Current Technology			Advanced Technology		
	Cost \$/kWh _t of H ₂	Efficiency %	Life Years	Cost \$/kWh _t of H ₂	Efficiency %	Life Years
Lurgi [37]	310(a)	73	10	150 to 175	75	10
Brown Boveri (Oerlikon) [38]	400(b)	73 to 67	25			
Teledyne Isotopes [39] (1 ton/day plant)	500(c)	-	-	50(d)	94	20

No Large Systems Operating

General Electric [40]	325(d)	94	-	\$40-85(d)	94	20
--------------------------	--------	----	---	------------	----	----

No Large Systems Operating

- (a) 750Nm³/h plant (140 lb/hr); equipment 1.825 x 10⁶ DM, installation 0.398 x 10⁶ DM; 4.6 kWh/Nm³H₂ (DM = Deutsch Mark)
- (b) Estimate for 452 Electrolyzers (EBK 385-70); 113,000 Nm³/h total; \$150 x 10⁶ for equipment
- (c) Projected cost for 1 ton/day, one-of-a-kind plant.
- (d) Electrolyzer excluding rectifier and balance of plant.

ASSUMPTIONS & COMMENTS:

1975 dollars. Hydrogen Electrolyzer only

SUMMARY

End Use: Utility Load Leveling

Technology: Superconducting Magnetic Storage

No useful comparisons possible.

STORAGE TECHNOLOGY:

Superconducting Magnetic Energy

Storage

SOURCE:

Public Service Gas & Electric Company.
An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
Prepared for Electric Power Research
Institute. 1976

INFORMATION:

Table 4-36 SUMMARY OF ADJUSTED COST DATA
OF PREVIOUS INVESTIGATIONS OF
SUPERCONDUCTING MAGNETS

Gross Storage Capacity MWh	Estimated Gross Cost \$ Millions	Adjusted (1) Net Capacity MWh	Adjusted Storage (1) Cost \$/kWh
10,000 [58]	505	7210 - 8640	\$58-70
10,587 [59]	300	7630 - 9150	\$32-38
10,833 [62]	641	7820 - 9360	\$68-82

Notes: (1) Adjusted to account for depth of discharge and efficiency

ASSUMPTIONS & COMMENTS:

1975 dollars

STORAGE TECHNOLOGY:

Superconducting Magnetic Energy

Storage

SOURCE:

Public Service Gas & Electric Company.
 An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.
 Prepared for Electric Power Research
 Institute. 1976

INFORMATION:

Table 4-37 MODIFIED COST ESTIMATE FOR
 10,000 MWh (GROSS) SUPERCONDUCTING MAGNET

	(\$) Millions	
Material Costs		
Al 36 x 10 ⁶ kg at \$2.2/kg	79.2	
(For Conductor)		
Ti N6 .71 x 10 ⁶ kg at \$33 /kg	23.4	
Al 20 x 10 ⁶ kg at \$2.2/kg	59.5	
(For Structures)		
Epoxy Fiberglass		
20 x 10 ⁶ kg at \$2.2/kg	48.4	
Subtotal		210.5
Insulation Electrical		
Thermal	Unknown	
Fabrication Costs		
Conductor 36 x 10 ⁶ kg at \$2.2/kg	79.2	
Epoxy Fiberglass Support Struts		
20 x 10 ⁶ kg at \$2.2/kg	48.4	
Subtotal		127.6
Refrigeration	13.0	13.0
Labor for Assembly at 50% of above costs (not including Dewar assembly)	145.0	145.0
Supervision at 30% of Direct Labor	43.5	43.5
Assembly of Dewar (from Al) includes supervision 36 x 10 ⁶ kg at \$4.4/kg	160.0	160.0
Rock Excavation and Wall Preparation	25.0	25.0
Helium	8.0	8.0
Subtotal		732.6
Engineering at 12% of 732.6	87.9	87.9
Contingency - Unknown - 20%	164.0	164.0
TOTAL Materials, Assembly, Labor and Engineering		984.5

Storage Cost \$/kWh

<u>Gross Storage Capacity</u>	<u>Estimated Gross Cost</u>	<u>Adjusted Net Capacity</u>	<u>Adjusted Storage Cost</u>
10,000 MWh	984.5	7,210-8,640	114-136

ASSUMPTIONS & COMMENTS:

1975 dollars

STORAGE TECHNOLOGY:

Superconducting Magnetic Energy

Storage

SOURCE:

TRW Inc. Development of a Data Base
 Characterizing Energy Storage Technologies, Task 1, Characterization of
 Storage Technologies in Utility Load
 Leveling Applications. Argonne National
 Laboratory, Contract No. 31-109-38-5106,
 1979.

INFORMATION: Table 5-6. Superconducting Magnetic Energy Storage

Characteristic	Range of Values	Expected
Typical Facility Size (MW)	no data	1000
Capital Cost		
Total (1978 \$/kW)	460 - 830	500
Storage Cost (1978 \$/kWh)	40 - 90	45
Power Cost (1978 \$/kW)	70 - 90	75
Percentage Breakdown		
Conductor NbTi	11 - 15	11%
Conductor Al	15 - 21	18%
Structure - Rock	22 - 53	25%
Struts	3 - 4	3%
Cryogenic Container	16 - 26	19%
Refrigerator	5 - 7	6%
Helium	4 - 8	4%
Power Conversion	9 - 24	14%
O & M Costs		
(1978 \$/kW/yr)	no data	3.6
(1978 mills/kWh)*	no data	1.8
Storage System Efficiency	.93 - .97	.95
Storage Capacity (hours)	3 - 20	10
Expected Lifetime (yrs)	30 or more	30
Construction Lead Time (years)	no data	no data
Annual Operating Profile (hrs/yr)	1000 - 3500	2000

*Assumes 2000 hours of operation per year.

Source: Reference 48.

SUMMARY

End Use: Utility Load Leveling

Technology: Flywheels

No useful comparisons possible.

STORAGE TECHNOLOGY:

Flywheels

SOURCE:

Public Service Gas & Electric Company.
 An Assessment of Energy Storage Systems
 Suitable for Use by Electric Utilities.
 Prepared for Electric Power Research
 Institute. 1976

INFORMATION:**TABLE 3-16 ENERGY DENSITIES**

Material Properties and Energy Characteristics	FLYWHEEL CONCEPT AND MATERIAL TYPE					
	Brush Boron Fibers	Single-Ring Graphite/Epoxy (Thornel 300)	MultiRing Steel	Disk Steel	Constant Stress Steel	MultiDisk Graphite/Epoxy with Interleaves
Ultimate Tensile Strength, F_{tu} , ksi	400	150	150	150	150	220
Material Density, lb/in ³	0.10	0.056	0.30	0.30	0.30	0.072
Energy Density, W-H/lb	40-50	60-65	6.75-7.25	5-7	12-13	40-50
Energy/Unit Swept Volume, W-H/in ³	0.0006- 0.0010	0.10-0.4	2.0-2.2	1.5-2.0	4-4.5	3

STORAGE TECHNOLOGY:

Flywheels

SOURCE:

Public Service Gas & Electric Company.

An Assessment of Energy Storage Systems
Suitable for Use by Electric Utilities.Prepared for Electric Power Research
Institute. 1976.**INFORMATION:**Table 4-34 SUMMARY OF STORAGE RELATED COST COMPONENTS
FOR FLYWHEEL SYSTEMS

	Conservative			Optimistic		
	E-Glass	S-Glass	Kelvar	E-Glass	S-Glass	Kelvar
Wheel Cost \$/kWh	1200-1900	700-1400	450-600	65-100 @X = 1 130-200 @X = 2	75-130	70-90
Vacuum Housing \$/kWh	230-390	140-280	90-120	65-100	40-65	25-30
Vault Foundation \$/kWh	13-25	10-13	8-13	8-11	6-10	6-8
Assumptions:						
Working Stress Load, , ksi	75-125	100-200	150-200	100-150	150-250	200-250
Mass Ratio, MR	1	1	1	1	1	1
Vacuum Housing Cost, VH, \$/lb	2	2	1-2	1	1	1
Shape Factor, K	.33	.33	.33	.5	.5	.5
Wheel Cost, X _w , \$/lb	10	10	10	1-2	2	3
Bearing Weight Limit, lb	80,000	80,000	80,000	160,000	160,000	160,000
Efficiency		70%			70%	
Depth of Discharge		75%			75%	

ASSUMPTIONS & COMMENTS:

1975 dollars

SUMMARY

End Use: Residential Load Leveling

Technology: Thermal Storage

No useful comparisons possible.

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE:

B&A Engineers Inc. An Assessment of the
Technoeconomic Feasibility of Seasonal
Thermal Energy Storage Systems STES.
Prepared for Argonne National Laboratory
ANL/EES-TM-35, 1978.

INFORMATION:

ASSUMPTIONS & COMMENTS:

1978 dollars.

STORAGE TECHNOLOGY:Thermal Energy Storage

_____**SOURCE:**Consumer Thermal Energy Storage Costs
for Residential Hot Water, Space Heating,
and Space Cooling Systems. TRW Energy
Systems Group for ANL. Nov. 30, 1976**INFORMATION:**

TABLE 2-1. COOL STORAGE SYSTEM PARAMETERS

STORAGE SYSTEM PARAMETERS	ICE MAKING	COOL WATER	GLYCOL- WATER (50/50)	EUTECTIC
Operating Range, °F	32-55	35-55	0-55	55
Btu/Pound	~144	20	42.5	80
Pounds/Gallon	8	8	~8	13.3
Storage Material Cost (\$/Pound)	0	0	.10	.016
Pounds/KWH	23.8	171	80.6	42.7
KWH/FT ³	2.6	.361	.77	2.34

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE:

TRW Energy Systems Group. Consumer
Thermal Energy Storage Costs for
Residential Hot Water, Space Heating
and Space Cooling System. Prepared
for Argonne National Laboratory, Con-
tract No. 31-109-38-3364, 1976.

INFORMATION:

FIGURE 2-2. HOT WATER STORAGE SYSTEM COSTS

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE:

Consumer Thermal Energy Storage Costs
for Residential Hot Water, Space Heating,
and Space Cooling Systems. TRW Energy
Systems Group for ANL. Nov. 30, 1976

INFORMATION:

FIGURE 2-7. TANK UNIT STORAGE COSTS (INSTALLED) VS TANK STORAGE CAPACITY

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE:

Consumer Thermal Energy Storage Costs
for Residential Hot Water, Space Heating,
and Space Cooling Systems. TRW Energy
Systems Group for ANL. Nov. 30, 1976

INFORMATION:

FIGURE 2-8. COOLING STORAGE UNIT COSTS STAINLESS STEEL TANKS (UPPER BOUND)

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE:

Consumer Thermal Energy Storage Costs
for Residential Hot Water, Space Heating,
and Space Cooling Systems. TRW Energy
Systems Group for ANL. Nov. 30, 1976

INFORMATION:

FIGURE 2-9. COOLING STORAGE UNIT COSTS PLASTIC-CONCRETE TANKS (LOWER BOUND)

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE:

Consumer Thermal Energy Storage Costs
for Residential Hot Water, Space Heating,
and Space Cooling Systems. TRW Energy
Systems Group for ANL. Nov. 30, 1976

INFORMATION:

FIGURE 2-5. SUMMARY OF THERMAL ENERGY STORAGE PRICES

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE:

Consumer Thermal Energy Storage Costs
for Residential Hot Water, Space Heating,
and Space Cooling Systems. TRW Energy
Systems Group for ANL. Nov. 30, 1976

INFORMATION:

TABLE 4-1. HOUSEHOLD STORAGE REQUIREMENTS

SERVICE AREA	DESIGN DAILY LOAD (kWh _e)			INSTALLED STORAGE (kWh _e)								
				4 Hour Storage Use Time			8 Hour Storage Use Time			16 Hour Storage Use Time		
	H ₂ O WITH 10% INSULATION LOSS	HEAT	COOL WITH 5% INSULATION LOSS	H ₂ O	HEAT	COOL	H ₂ O	HEAT	COOL	H ₂ O	HEAT	COOL
C	15.0	257	96	11.8	42.8	16.8	14.2	85.6	33.7	23.6	171.3	67.4
D	15.0	NA	113	8.8	NA	19.8	9.4	NA	39.7	15.6	NA	79.2
A	11.6	259	NA	11.8	43.2	NA	14.2	86.3	NA	23.6	172.6	NA
B	15.0	288	NA	11.8	48	NA	14.2	96	NA	23.6	192	NA

NA = Not Analyzed

STORAGE TECHNOLOGY:Thermal Energy Storage

SOURCE:

Consumer Thermal Energy Storage Costs
for Residential Hot Water, Space Heating,
and Space Cooling Systems. TRW Energy
Systems Group for ANL. Nov. 30, 1976

INFORMATION:

TABLE 4-2. CUSTOMER INCREMENTAL COST FOR INSTALLED STORAGE

SERVICE AREA	CUSTOMER INCREMENTAL COST FOR INSTALLED STORAGE SYSTEMS (\$)								
	4 HOURS STORAGE USE			8 HOURS STORAGE USE			16 HOURS STORAGE USE		
	H ₂ O *	HEAT (CENTRAL)	COOL	H ₂ O *	HEAT (CENTRAL)	COOL	H ₂ O *	HEAT (CENTRAL)	COOL
C	111	276	788	140	791	1093	256	1820	2090
D	105	NA	924	114	NA	1382	214	NA	2597
A	111	279	NA	140	799	NA	256	1839	NA
B	111	311	NA	140	887	NA	256	2039	NA

NA = Not Analyzed

STORAGE TECHNOLOGY:Thermal Energy Storage

SOURCE:

Consumer Thermal Energy Storage Costs
for Residential Hot Water, Space Heating,
and Space Cooling Systems. TRW Energy
Systems Group for ANL. Nov. 30, 1976

INFORMATION:

TABLE 4-3. ALTERNATE STORAGE SYSTEM SUMMARY COMPARISON

STORAGE SYSTEM TYPE	RANGE OF SYSTEM COSTS (\$/kWhe)		
	<u>4 HOUR STORAGE</u>	<u>8 HOUR STORAGE</u>	<u>16 HOUR STORAGE</u>
HOT WATER	9.4-11.9	9.8-12.1	10.8-13.7
SPACE HEAT	6.4-6.5	9.2	10.6
SPACE COOLING	46.7-46.9	32.4-34.8	31.0-32.8

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE:

TRW Inc., Development of a Data Base
Characterizing Energy Storage Technol-
ogies, Task 1, Characterization of
Storage Technologies in Utility Load
Leveling Applications. Argonne National
Laboratory, Contract No. 31-109-38-5106,
1979.

INFORMATION:

Figure 4-1. Summary of European Thermal
Energy Storage Heater Prices
(8-Hour Charge Time)

SOURCE: Reference 33

STORAGE TECHNOLOGY:Thermal Energy Storage

SOURCE:TRW Inc., Development of a Data Base
Characterizing Energy Storage Technol-
ogies, Task 1, Characterization of
Storage Technologies in Utility Load
Leveling Applications. Argonne National
Laboratory, Contract No. 31-109-38-5106,
1979.**INFORMATION:**

Table 4-15. Customer TES Space Heating, Ceramic Brick Storage

Characteristic	Range of Values	Expected
Typical Size (kWh)	15 - 250	150
Capital Cost		
Storage (1978 \$/kWh)	8 - 14	10
Power (1978 \$/kW)	0 - 4	3.4
Controls and Fixed Cost (1978 \$/unit)		200
O & M Costs	negligible	nil
Efficiency (turn around)		1.0
Utilization Factor for Heat Supplied	.70 - .95	.90
Storage Capacity (kWh)	15 - 250	150
Storage Duration (hrs/day)	4 - 16	8
Expected System Lifetime (yrs)	10 - 15*	15
Installation or Construction Lead Time (days)	1 - 7	2
Annual Operating Profile (hrs/yr)	1000 - 4000**	1500

* May be longer

** Depends on climate

Sources: References 31, 32, 33, 34, 35, 36

STORAGE TECHNOLOGY:Thermal Energy Storage**SOURCE:**

TRW Inc., Development of a Data Base
 Characterizing Energy Storage Technol-
 ogies, Task 1, Characterization of
 Storage Technologies in Utility Load
 Leveling Applications. Argonne National
 Laboratory, Contract No. 31-109-38-5106,
 1979.

INFORMATION:

Table 4-16. Customer TES Cooling, Chilled Water Storage

CHARACTERISTIC	RANGE OF VALUES	EXPECTED
Typical Size (kWh)	250 and up	1000
Capital Cost		
Total (1978 \$/kWh)	15 - 25*	18
Percentage Breakdown		
Tank Cost		70
Valves and Pumps		12
Piping and Trench		8
Contingency		10
O & M Costs	negligible	nil
Efficiency (turn around)	0.90 or greater	.90
Storage Capacity (kWh)	250 and up	1000
Expected System Lifetime (yrs)	20 - 25	25
Installation or Construction Lead Time (years)	.25 - 1	.8
Annual Operating Profile (hrs/year)	1000 - 4000	2000

* Depends on system size

Sources: References 37, 38, 39

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE:

TRW Inc., Development of a Data Base
Characterizing Energy Storage Technol-
ogies, Task 1, Characterization of
Storage Technologies in Utility Load
Leveling Applications. Argonne National
Laboratory, Contract No. 31-109-38-5106,
1979.

INFORMATION:

Table 5-8. PCM Properties, TES System Costs

Material Factors	Sodium Sulfate Decahydrate	Sodium Thiosulfate Pentahydrate	Disodium Phosphate Dodecahydrate	Sodium Acetate Trihydrate
Temp Range, °F	(70-180)	(70-180)	(70-180)	(70-180)
H _f , Btu/lb	108	90	114	100
Melting Point, °F	90	120	97	135
C _p , Btu/lb-°F	.5	.5	.5	.5
Density, lb/ft ³	91	101	104	95
Void Factor	.37	.37	.37	.37
Heat Extraction Factor	1.0	1.0	1.0	1.0
Cost, \$/lb	.01	.072	.045	.035
Material Cost, \$	33	268	144	122
Container Cost, \$	256	297	255	279
Area Cost, \$	60	59	56	64
Insulation Cost, \$	66	67	64	69
Blower Cost, \$	367	173	283	143
System Cost, \$ (Uninstalled)	782	864	802	398

1978 \$

System Size = 500,000 Btu (146.5 kWh)
Heat Rate = 50,000 Btu/hr (14.6 kW)

Source: Reference 54

STORAGE TECHNOLOGY:Thermal Energy Storage

SOURCE:TRW Inc., Development of a Data Base
Characterizing Energy Storage Techno-
logies, Task 1, Characterization of
Storage Technologies in Utility Load
Leveling Applications. Argonne National
Laboratory, Contract No. 31-109-38-5106,
1979.**INFORMATION:**

Table 5-9. Customer TES Cooling, PCM Storage

Characteristic	Range of Values	Expected
Typical Size (kWh)	15 - 500	150
Capital Cost		
Total (1978 \$/kWh)		24
Percentage Breakdown:		
Materials		17%
Fabrication		14%
Shipping		6%
Installation		38%
Profit		25%
O & M Costs	negligible	0
Efficiency (turn around)	.90 and up	.90
Storage Capacity (kWh)	15 - 500	150
(hrs/day)	4 - 16	8
Installation or Construction		
Lead Time (weeks)	1 - 26	2
Expected System Lifetime	unknown	
Annual Operating Profile		
(hrs/year)	500 - 4000	1000

* Long-term degradation of PCM materials unknown.

PCM Material: sodium sulfate decahydrate

Sources: Reference 57

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE:

Segaser, C.L. and Jeffrey E. Christian
 Low Temperature Thermal Energy Storage,
 Argonne National Laboratory ANL/CES/TE
 79-3, 1979.

INFORMATION:

Table 8.3 Estimated Costs per Therm of Thermal Energy Storage
 Devices Using Sodium Thiosulfate Pentahydrate (STP)
 as Storage Medium at Costs of 10¢ and 40¢/lb, Re-
 spectively.

Capacity		Cost (\$/Therm)	
Therms	Btu	10¢/lb	40¢/lb
1	10 ⁵	2,400	4,960
10	10 ⁶	955	1,975
100	10 ⁷	380	786
1,000	10 ⁸	151	313

ASSUMPTIONS & COMMENTS:

1975 dollars.

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE:

Segaser, C.L. and Jeffrey E. Christian
Low Temperature Thermal Energy Storage,
Argonne National Laboratory ANL/CES/TE
79-3, 1979.

INFORMATION:

Fig. 8.4 Cost of Latent Heat Storage Vs Storage Capacity (for Two Different Materials and a Range of Material Costs)

ASSUMPTIONS & COMMENTS:

STP is Sodium Thiosulfate Pentahydrate. P116 is paraffin wax, 1975 dollars.

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE:

Segaser, C.L. and Jeffrey E. Christian
Low Temperature Thermal Energy Storage,
Argonne National Laboratory ANL/CES/TE
79-3, 1979.

INFORMATION:

Fig. 8.6 Comparative Costs per Therm (10^5 Btu) of Thermal Energy Storage Devices Using Water Vs Phase-Change Material (PCM) for Storage

ASSUMPTIONS & COMMENTS:

1975 dollars.

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE:

Brunton, G.D., et al., Low Temperature Thermal Energy Storage Program Annual Report for Period October 1977-September 1978. ORNL/TM-6701, Oak Ridge National Laboratory, 1979.

INFORMATION:

Fig. 3.18. Economic characteristics of regenerated desiccant drying system with 6000 lb/hr moisture-removal capacity. ($kg = 2.204 \text{ lb}$; $J = 9.48 \times 10^{-4} \text{ Btu.}$)

ASSUMPTIONS & COMMENTS:

1977 dollars

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE:

Brunton, G.D., et al., Low Temperature Thermal Energy Storage Program Annual Progress Report for Period October 1977-September 1978, ORNL/TM-6701, Oak Ridge National Laboratory, 1979.

INFORMATION:

FIGURE 2-8. COOLING STORAGE UNIT COSTS STAINLESS STEEL TANKS (UPPER BOUND)

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE:

Lane, George. A. "Micro-Encapsulation
of Heat Storage Phase Change Materials."
Dow Chemical Company. ERDA Contract
E(40-1)-5217. In Thermal Energy Storage
Contractor's Information Exchange
Meeting. 1977.

INFORMATION:

TABLE VII
 PREDICTED EFFICIENCIES OF MODEL SYSTEMS

MATERIAL	MELTING TEMPERATURE °F	EXCHANGER CAPACITY 10 ⁵ Btu	CONTAINER	PERCENT DISCHARGED
Mg(NO ₃) ₂ ·6H ₂ O	192	3	Cylinder 2.5 in. dia.	87 ¹
Napthalene- Benzoic Acid Eutectic	152	3	Cylinder 3 in. dia.	95
			Pillow 8 X 5.5 X 1.25 in.	95
Stearic Acid - Palmitic Acid	146	8.4	Cylinder 4.25 in. dia.	96
		3	Cylinder 4.25 in. dia.	87
		3	Cylinder 3 in. dia.	93
		3	Tetrahedron 4 X 4 in.	95
		3	Tetrahedron 4 X 4 in.	93 ²
Mg(NO ₃) ₂ ·6H ₂ O - NH ₄ NO ₃ Eutectic	125	3	Cylinder 3 in. dia.	75
		3	Cylinder 2.5 in. dia.	85
		3	Tetrahedron 4 X 4 in.	91
		3	Pillow 8 X 5.5 X 12.5 in.	82
CaCl ₂ ·6H ₂ O	80	3	Cylinder 2.5 in. dia.	97 ³

¹Water as heat transfer fluid

²Air film heat transfer coefficient arbitrarily reduced 45%

³Exhaust air at 35°F, heat pump output 3000 Btu/hr.

STORAGE TECHNOLOGY:Thermal Energy Storage

SOURCE:Kauffman, K.W. Lorsch and Kyllonen.
Thermal Energy Storage by Means of
Saturated Aqueous Solutions. Frank-
lin Institute Research Laboratories.
DOE Contract EY-76-C-05-5158, 1977.**INFORMATION:**

Table 4-5. Expected Characteristics of Storage Devices for Air Conditioning

<u>Storage Medium</u>	<u>Temperature Range, °C</u>	<u>Weighted¹ Average Charging Temperature, °C</u>	<u>Storage Capacity, kJ/kg</u>	<u>Additional² Compressor Energy Requirement, %</u>	<u>Storage Volume for 58.6 kWh(th), m³</u>
21.8 weight % Trimethylamine	12.8 to 2	2	2.53	43	0.83
Water	12.8 to 2	2.4	45.2	41	4.67
Ice	12.8 to -1	-5	386	99	0.60

¹The average temperature of the storage medium during charging is determined by weighting each temperature in the indicated range by the heat capacity of the medium at that temperature, and then subtracting 5°C for heat transfer.

²The compressor electrical energy required to charge the storage device at its average charging temperature compared to the energy required to deliver the same thermal capacity without storage at 12.8°C, for the machine whose performance is indicated by Figure 4-16 (see also Sections 2.2 and 4.3.4).

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE: Rust, C. L. et al. Preliminary

Market Analysis for Customer-Side-of-the-Meter

Thermal Energy Storage. Prepared for U. S.

Department of Energy by Booz, Allen &

Hamilton, Inc., December 31, 1979.

INFORMATION:

EXHIBIT III-5
Cumulative Demand By End Use:
United States

UNITED STATES

SPACE HEATING & WATER HEATING	—	9.7	20.9	33.4	47.1
AIR CONDITIONING & WATER HEATING	—	28.4	59.4	92.9	130.0

* ASSUMES 50% DIVERSITY, I.E. TWO 8-HOUR CHARGING PERIODS FOR SPACE HEATING AND AIR CONDITIONING AND 33% DIVERSITY, I.E. THREE 4-HOUR CHARGING PERIODS FOR WATER HEATING.

LEGEND:

MAX: MAXIMUM TES SUPPORTABLE BY UTILITY CAPACITY
SH & WH: SPACE HEATING AND WATER HEATING, 5% OF NEW INSTALLATIONS
AC & WH: AIR CONDITIONING AND WATER HEATING, 5% OF NEW INSTALLATIONS

STORAGE TECHNOLOGY:

Thermal Energy StorageSOURCE: Rust, C. L. et al. PreliminaryMarket Analysis for Customer-Side-of-the-MeterThermal Energy Storage. Prepared for U. S.

Department of Energy by Booz, Allen &

Hamilton, Inc., December 31, 1979.

INFORMATION:

EXHIBIT III-4
Cumulative Demand for Residential
and Commercial TES
(Gigawatts)

DOE REGION/END USE	Cumulative Demand Per Percent Penetration*				
	1980	1985	1990	1995	2000
No. 1--New England					
Space & Water Heat	-	0.16	0.34	0.51	0.68
Air Conditioning & Water Heat	-	0.13	0.26	0.40	0.56
No. 2--New York/New Jersey					
Space & Water Heat	-	0.06	0.12	0.20	0.29
Air Conditioning & Water Heat	-	0.22	0.46	0.72	1.00
No. 3--Mid Atlantic					
Space & Water Heat	-	0.25	0.51	0.79	1.06
Air Conditioning & Water Heat	-	0.85	1.79	2.78	3.85
No. 4--South Atlantic					
Space & Water Heat	-	0.59	1.21	1.86	2.55
Air Conditioning & Water Heat	-	1.29	2.69	4.20	5.83
No. 5--Midwest					
Space & Water Heat	-	0.32	0.69	1.10	1.58
Air Conditioning & Water Heat	-	0.61	1.27	1.99	2.79
No. 6--Southwest					
Space & Water Heat	-	0.21	0.49	0.86	1.32
Air Conditioning & Water Heat	-	1.34	2.80	4.37	6.08
No. 7--Central					
Space & Water Heat	-	0.06	0.14	0.24	0.33
Air Conditioning & Water Heat	-	0.23	0.48	0.74	1.02
No. 8--North Central					
Space & Water Heat	-	0.05	0.12	0.20	0.31
Air Conditioning & Water Heat	-	0.15	0.32	0.50	0.69
No. 9--West					
Space & Water Heat	-	0.16	0.40	0.67	0.93
Air Conditioning & Water Heat	-	0.62	1.32	2.08	2.91
No. 10--Northwest					
Space & Water Heat	-	0.08	0.16	0.25	0.35
Air Conditioning & Water Heat	-	0.24	0.51	0.79	1.10
United States					
Space & Water Heat	-	1.94	4.18	6.68	9.43
Air Conditioning & Water Heat	-	5.68	11.88	18.50	25.85

* Assumes 50% diversity, i.e., two 8-hour charging periods, for space heating and air conditioning and 33% diversity, i.e., three 4-hour charging periods, for water heating.

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE: Rust, C. L. et al. Preliminary

Market Analysis for Customer-Side-of-the-Meter

Thermal Energy Storage. Prepared for U. S.

Department of Energy by Booz, Allen &

Hamilton, Inc., December 31, 1979.

INFORMATION:

EXHIBIT III-3
Annual Market for Residential
and Commercial TES
(Megawatts)

DOE REGION/SECTOR/END USE	ANNUAL DEMAND PER PERCENT PENETRATION				
	1980	1985	1990	1995	2000
No. 1 - New England					
Residential					
Space Heating	39.0	44.2	46.2	42.0	37.4
Water Heating	10.1	11.1	11.7	13.0	12.8
Air Conditioning	0	0	0	0	0
Commercial					
Water Heating	7.0	7.0	9.0	9.0	9.0
Air Conditioning	29.0	31.0	33.0	35.0	39.0
No. 2 - New York/New Jersey					
Residential					
Space Heating	4.8	5.7	6.0	8.3	11.9
Water Heating	8.1	9.0	10.4	12.8	15.4
Air Conditioning	0	0	0	0	0
Commercial					
Water Heating	12.0	13.0	14.0	15.0	17.0
Air Conditioning	57.0	62.0	66.0	71.0	80.0
No. 3 - Mid Atlantic					
Residential					
Space Heating	60.7	65.1	67.6	66.5	66.8
Water Heating	16.3	18.1	19.5	20.2	20.8
Air Conditioning	42.5	46.3	49.3	51.1	52.4
Commercial					
Water Heating	13.0	13.0	15.0	16.0	16.0
Air Conditioning	212.0	230.0	250.0	265.8	298.0
No. 4 - South Atlantic					
Residential					
Space Heating	153.7	164.2	172.9	180.6	188.6
Water Heating	39.9	41.5	43.7	45.6	47.5
Air Conditioning	31.2	36.1	42.5	107.9	103.2
Commercial					
Water Heating	14.0	15.0	16.0	18.0	20.0
Air Conditioning	297.0	323.0	351.0	375.0	416.0
No. 5 - Midwest					
Residential					
Space Heating	73.6	88.4	98.4	111.5	131.2
Water Heating	22.1	28.7	32.7	38.2	44.4
Air Conditioning	0	0	0	0	0
Commercial					
Water Heating	12.0	13.0	14.0	16.0	19.0
Air Conditioning	169.0	184.0	200.0	214.0	239.0
No. 6 - Southwest					
Residential					
Space Heating	45.1	58.5	92.6	109.7	133.9
Water Heating	13.9	22.1	29.7	33.7	35.9
Air Conditioning	62.1	71.5	75.6	79.1	82.7
Commercial					
Water Heating	7.0	9.0	10.0	11.0	12.0
Air Conditioning	345.0	373.0	405.0	434.0	483.0
No. 7 - Central					
Residential					
Space Heating	12.0	14.0	17.5	23.9	36.1
Water Heating	5.5	7.0	9.7	12.4	14.6
Air Conditioning	22.3	23.1	23.3	23.3	23.4
Commercial					
Water Heating	5.0	6.0	6.0	7.0	8.0
Air Conditioning	45.0	48.0	51.0	54.0	60.0
No. 8 - North Central					
Residential					
Space Heating	8.3	13.7	16.8	22.2	29.5
Water Heating	4.6	6.2	7.9	9.8	11.6
Air Conditioning	0	3	0	0	0
Commercial					
Water Heating	3.0	3.0	3.0	3.0	4.0
Air Conditioning	43.0	46.0	50.0	54.0	59.0
No. 9 - West					
Residential					
Space Heating	23.2	44.1	54.2	54.7	57.8
Water Heating	13.4	13.8	39.5	41.4	42.5
Air Conditioning	0	0	0	0	0
Commercial					
Water Heating	8.0	8.0	9.0	10.0	11.0
Air Conditioning	178.0	195.0	212.0	227.0	253.0
No. 10 - Northwest					
Residential					
Space Heating	24.5	25.2	26.3	26.5	26.5
Water Heating	0	0	0	0	0
Air Conditioning	0	0	0	0	0
Commercial					
Water Heating	3.0	4.0	4.0	5.0	6.0
Air Conditioning	75.0	82.0	88.0	95.0	104.0
United States					
Residential					
Space Heating	445.0	524.0	589.7	645.9	715.1
Water Heating	134.4	177.3	204.9	227.1	246.8
Air Conditioning	214.1	227.0	240.7	261.4	261.7
Commercial					
Water Heating	83.0	91.0	101.0	110.0	122.0
Air Conditioning	1,435.0	1,574.0	1,706.0	1,827.0	2,035.0

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE: Rust, C. L. et al. Preliminary
Market Analysis for Customer-Side-of-the-Meter
Thermal Energy Storage. Prepared for U. S.
 Department of Energy by Booz, Allen &
 Hamilton, Inc., December 31, 1979.

INFORMATION:

EXHIBIT II-3

Economic Competitiveness of TES
 and Conventional Systems
 in the Commercial Sector

Building Type/End Use	Rate for 4-Year Customer Payback (¢/kWh)	Economically Competitive With Conventional Electric System*
Office Building		
Water Heating	0.4	X
Air Conditioning	1.5	X
Educational Building		
Water Heating	1.0	X
Air Conditioning	1.4	X
Retail Store		
Water Heating	NC**	X
Air Conditioning	1.9	X

* Based on comparative life-cycle costs

** Not calculated

STORAGE TECHNOLOGY:

Thermal Energy StorageSOURCE: Rust, C. L. et al. PreliminaryMarket Analysis for Customer-Side-of-the-MeterThermal Energy Storage. Prepared for U. S.

Department of Energy by Booz, Allen &

Hamilton, Inc., December 31, 1979.

INFORMATION:

EXHIBIT II-1
Economic Competitiveness of
TES and Conventional Systems
in the Residential Sector

DOE Region/End Use	Rate Difference for 4-Year Customer Payback (¢/kWh)	Economically Competitive With:*		
		Oil	Gas	Electric
No. 1 - New England				
Space Heating	4.2	X	X	X
Water Heating	2.0			X
Air Conditioning	>30.0			
No. 2 - New York/New Jersey				
Space Heating	4.4			X**
Water Heating	2.0			X
Air Conditioning	>30.0			
No. 3 - Mid Atlantic				
Space Heating	5.8	X	X	X
Water Heating	2.0	X		X
Air Conditioning	28.7			X
No. 4 - South Atlantic				
Space Heating	9.3	X	X	X
Water Heating	2.0			X
Air Conditioning	12.5			X
No. 5 - Midwest				
Space Heating	4.1	X		X
Water Heating	2.0			X
Air Conditioning	>30.0			
No. 6 - Southwest				
Space Heating	8.5		X	X
Water Heating	2.0			X
Air Conditioning	11.4			X
No. 7 - Central				
Space Heating	3.3	X		X
Water Heating	2.0			X
Air Conditioning	22.9			X
No. 8 - North Central				
Space Heating	4.0	X	X	X
Water Heating	2.0			X
Air Conditioning	>30.0			
No. 9 - West				
Space Heating	8.6		X	X
Water Heating	2.0			X
Air Conditioning	>30.0			
No. 10 - Northwest				
Space Heating	5.9	X	X	X
Water Heating	2.0			
Air Conditioning	>30.0			

* Based on comparative life-cycle costs

** Electric Resistance Heating Only

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE: Rust, C. L. et al. Preliminary
Market Analysis for Customer-Side-of-the-Meter
Thermal Energy Storage. Prepared for U. S.
Department of Energy by Booz, Allen &
Hamilton, Inc., December 31, 1979.

INFORMATION:

EXHIBIT I-1
Projected Maximum TES Potential

SUMMARY

End Use: Industrial

Technology: Hydrogen

No useful comparisons possible.

STORAGE TECHNOLOGY:

Hydrogen

SOURCE: Ekman, K. R. Cost of Hydrogen
Production from Fossil and Nuclear Fuels.
Prepared for U.S. Department of Energy by
Jet Propulsion Laboratory, July 15, 1980.

INFORMATION:

Hydrogen Production Costs (1979\$/MBtu)*

	1980	1985	1990	2000	2020
Natural gas	3.2	5.0	6.3	7.8	8.5
Petroleum	6.3	7.7	8.4	9.1	9.7
Coal	6.1	7.0	7.6	8.2	8.8
Advanced electrolysis	9.0	10.4	11.4	10.4	10.8
Nuclear (HTR) thermo- chemical	12.0	10.3	9.5	8.9	8.5
Solar thermochemical	-	-	11.6	7.8	6.0

*The abbreviation "M", as used throughout this report, is meant to signify 'million' or 1×10^6 . Example - \$6/MBTU is \$6 per million BTU.

STORAGE TECHNOLOGY:

Hydrogen

SOURCE: Ekman, K. R. Cost of Hydrogen Production from Fossil and Nuclear Fuels.
Prepared for U.S. Department of Energy by
Jet Propulsion Laboratory, July 15, 1980.

INFORMATION:

Hydrogen Production Costs (1979\$)

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

General Atomic Company. Hydrogen Production Using Coal and Nuclear Heat, presented at NASA Meeting. Washington, D.C., November 13, 1975.

INFORMATION:

**HYDROGEN PRICE ESTIMATE, CASE II, 1400°F,
HYDROGEN PRODUCED 610 MMSCFD AT 0.9 PLANT
CAPACITY FACTOR**

	TOTAL	
PLANT INVESTMENT (\$10⁶)		
PROCESS UNITS & HTGR	687.6	
OFF-SITE FACILITIES & HTGR (BOP)	306.7	
INTEREST DURING CONSTRUCTION	192.4	
TOTAL INVESTMENT	1,186.7	
WORKING CAPITAL	18.1	
TOTAL CAPITAL REQUIRED	1,204.8	
	<hr/> ¢/MSCF	
COST OF COAL CHARGE = \$10/TON	23	
COST OF NUCLEAR FUEL = \$0.425/10⁶ BTU	15	
OPERATION AND MAINTENANCE	13	
BYPRODUCT CREDITS		
AROMATICS = \$11/BBL	(15)	
AMMONIA & SULFUR	(2)	
HYDROGEN PRICE (UTILITY BASIS) (¢/MSCF)	15%	25%
CAPITAL CHARGE	72	120
HYDROGEN PRICE	106	154

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

General Atomic Company. Hydrogen Production Using Coal and Nuclear Heat, presented at NASA meeting. Washington, D.C., November 13, 1975.

INFORMATION:

HYDROGEN PRICE AS A FUNCTION OF COAL COST (JULY 1974) NUCLEAR FUEL COST 42.5 TO 83 ¢/10⁶ BTU

STORAGE TECHNOLOGY:

Hydrogen

SOURCE: U.S. Energy Research and Development Administration. An Evaluation of the Use of Hydrogen as a Supplement to Natural Gas, TID-27747. Prepared by the Ad Hoc Committee, Washington, D.C., June 1977.

INFORMATION:

TABLE 3

Comparison of Present and Projected Advanced State-of-the-Art in Electrolysis Technology

	<u>Present</u>	<u>Advanced</u>
Installed Capital Costs \$/kW	300.00	150.00
Operating Efficiency %	65.0	90.0
Space Requirements Amps/sq.ft.	250.0	1000.00
Output H ₂ pressure psig	14.7	450.0
Time to come on line	Minutes	Seconds
Time to drop off line	Minutes	Seconds
Operation Mode	Manned	Unmanned
Maintenance Costs	Medium	Low
Minimum Life	10-15 Years	20 Years

STORAGE TECHNOLOGY:

Hydrogen

SOURCE: U.S. Energy Research and Development Administration. An Evaluation of the Use of Hydrogen as a Supplement to Natural Gas, TID-27747. Prepared by the Ad Hoc Committee, Washington, D.C., June 1977.

INFORMATION:

TABLE 5

Production Cost for Electrolytic Hydrogen
GE-SPE Process

Column Number	1	2	3	4
Annual Capacity Factor	0.90	0.45	0.45	0.45
Electricity Cost (¢/kWh)	1.0	0.6	0.8	1.1
Hydrogen Cost (\$/MBtu)	4.93	4.59	5.27	6.27

STORAGE TECHNOLOGY:

Hydrogen

SOURCE: Salzano, F. J., et al. Electrolysis Based Hydrogen Storage Systems, Annual Report January 1, 1976 to December 31, 1976, BNL-50714. Brookhaven National Laboratory. January 1977.

INFORMATION:

Table 5.1

COMPUTATION OF HYDROGEN PRODUCTION COSTS BY VARIOUS TECHNOLOGIES IN THE YEARS 1985 AND 2000
1975 Dollars

Performance and Cost Items	Methane Steam Reforming (1) (5)	Resid Partial Oxidation (1) (5)	Coal Gasification		Lurgi Water Electrolyzer Using Off-Peak Power (2) (4)	SPE New Water Electrolysis		
			Koppers Totzek (1) (5)	Improved K-T (1) (5)		Off-Peak Power (3) (4)	Spinning Reserve (3) (4)	Dedicated Plant (3) (4)
Plant Cost (10^6 \$)	40.7	103.5	160.1	130.0	17.1	0.75	0.75	0.75
Plant Production	100 $\frac{\text{MSCF}}{\text{Day}}$	100 $\frac{\text{MSCF}}{\text{Day}}$	100 $\frac{\text{MSCF}}{\text{Day}}$	100 $\frac{\text{MSCF}}{\text{Day}}$	53.3 MWth	5 MWth	5 MWth	5 MWth
Annual Operation	330 $\frac{\text{Days}}{\text{Yr}}$	330 $\frac{\text{Days}}{\text{Yr}}$	330 $\frac{\text{Days}}{\text{Yr}}$	330 $\frac{\text{Days}}{\text{Yr}}$	55 $\frac{\text{Hours}}{\text{Week}}$	55 $\frac{\text{Hours}}{\text{Week}}$	7920 $\frac{\text{Hours}}{\text{Year}}$	109 $\frac{\text{Hours}}{\text{Week}}$
Annual Average Load Factor	0.904	0.904	0.904	0.904	0.33	0.33	0.904	0.65
Conversion Efficiency (%)	70.2	82.7	59.6	64.2	74.7	90.0	90.0	90.0
Unit Capital Cost $\frac{\$}{\text{kW(th)}}$	-	-	-	-	320	150	150	150
<u>Basic Fuel Cost</u>								
Year 1985 (\$/M Btu)	2.15	2.52	0.74	0.74	0.76	0.76	0.76	2.53
Year 2000 (\$/M Btu)	2.41	3.15	0.82	0.82	0.88	0.88	0.88	2.65
<u>Unit Production Costs - 1985</u>								
Capital Cost (7) (\$/M Btu)	0.65	1.64	2.54	2.06	5.50	2.58	0.94	1.31
Fuel Cost (\$/M Btu)	3.06	3.05	1.24	1.15	3.08	2.56	2.56	8.53
O and M Cost (6) (\$/M Btu)	0.50	0.50	1.34	1.25	0.47	0.47	0.47	0.47
<u>Total Unit Cost (\$/M Btu)</u>	4.21	5.19	5.12	4.46	9.05	5.61	3.97	10.31
<u>Unit Production Costs - 2000</u>								
Capital Cost (7) (\$/M Btu)	0.65	1.64	2.54	2.06	5.50	2.58	0.94	1.31
Fuel Cost (\$/M Btu)	3.43	3.81	1.38	1.28	3.46	2.88	2.88	8.66
O and M Cost (6) (\$/M Btu)	0.50	0.50	1.34	1.25	0.47	0.47	0.47	0.47
<u>Total Unit Cost (\$/M Btu)</u>	4.58	5.95	5.26	4.59	9.43	5.93	4.29	10.44

Footnotes for Table 5-1.

1. Plant capacity, capital cost, conversion efficiency and annual load factor are from the Exxon study [11]. The investment cost figures are converted from 1980 to 1975 dollars using a nine percent annual discount factor, based on a private communication from H. G. Corneil (Exxon Research and Engineering Company) to C. Braun, BNL, November 15, 1976.
2. Lurgi Electrolyzer capacity, capital cost and conversion efficiency data obtained from the EPRI/IGT report on Utilization of Off-Peak Electric Power [12], Table III-1 and III-2.
3. Plant capacity, capital cost and conversion efficiency of solid-polymer-electrolyte, water-electrolysis equipment based on communication from R. Fernandes (Niagara Mohawk Power Corp.) to the Ad Hoc Committee on Hydrogen as a Natural Gas Supplement, November 12, 1976 [13].
4. Electricity supplied to the water electrolysis plant is assumed to be provided by a LWR nuclear power plant having the following economic parameters:
 - (a) Capital cost of \$585/kW(e) in 1974 dollars [14], escalated to 1975 dollars assuming 5%/year escalation rate according to [15].
 - (b) Nuclear fuel cycle cost - \$0.65/M Btu and \$0.77/M Btu in 1985 and 2000, respectively, according to [14].
 - (c) Operating and maintenance costs of 1.2 mills/kWh according to [14], or the equivalent of \$0.11/M Btu.
 - (d) Thermal efficiency of 0.33 and 0.34 in 1985 and 2000, respectively, according to [14].

Footnotes for Table 5-1. (Continued)

(e) Base-load, annual-average load factor of 0.65 according to [14].

Spinning reserve is assumed available on a year-round basis (7920 hr/year) at nuclear-fuel price. Off-peak and spinning-reserve operation are charged only the variable, i.e., fuel and O and M nuclear costs which amount to 7.86 and 9.10 (mills/kWh) in 1985 and 2000, respectively. The water electrolysis plant operated in conjunction with a dedicated nuclear plant is charged the full nuclear electricity cost which amounts to 26.2 and 27.1 (mills/kWh) in the years 1985 and 2000, respectively.

5. Fossil fuels costs, including raw fuel cost and incremental fuel processing expenses were obtained from [14].
6. Operating and maintenance costs of fossil-fuel-based hydrogen production plants were obtained from [14]. Water-electrolysis plants O and M costs were obtained from [13].
7. Annual fixed charges on capital are assumed at 17% of investment per year according to [16].

STORAGE TECHNOLOGY:

Hydrogen

SOURCE: U.S. Energy Research and Development Administration. An Evaluation of the Use of Hydrogen as a Supplement to Natural Gas, TID-27747. Prepared by the Ad Hoc Committee, Washington, D.C., June 1977.

INFORMATION:

TABLE 4

Electrolytic Hydrogen Cost by GE-SPE Process

Operation by a utility using off-peak electricity
1985 operation, 1975 \$

Plant - SPE electrolysis with forced commutated converter interface

Location - Northeast U.S.

Utilization factor for converter = 0.90

Utilization factor for electrolyzer = 0.45

Electrolyzer capacity = 5.0 MW hydrogen product = 17.075 MBtu/hr hydrogen product
= 52,538 SCF/hr of hydrogen or 26,269 SCF/hr of oxygen

Thermal efficiency = 90.0%

Electrical input for capacity operation = 5.556 MW

Hydrogen product pressure - 450 psig

<u>Investment</u>	<u>\$/kW out</u>	<u>\$ thousands</u>
Power conversion and switchgear	45	225
Electrolysis modules	20	100
Other process equipment	23	115
Installation costs	22	110
Offsites	15	75
Contingency	<u>25</u>	<u>125</u>
Total	150	750

STORAGE TECHNOLOGY:

Hydrogen

SOURCE: U.S. Energy Research and Development Administration. An Evaluation of the Use of Hydrogen as a Supplement to Natural Gas, TID-27747. Prepared by the Ad Hoc Committee, Washington, D.C., June 1977.

INFORMATION:

TABLE 4 (cont'd)

Column No.	1	2	3	4
Converter capacity factor	0.90	0.90	0.90	0.90
Electrolyzer capacity factor	0.90	0.45	0.45	0.45
Electrolyzer operating hours per year	7884	3942	3942	3942
Hydrogen production MBtu/yr x 10 ³	134.6	67.3	67.3	67.3
Electricity input kWhr/yr x 10 ⁶	43.8	21.9	21.9	21.9
Electricity cost, c/kWhr	1.0	0.6	0.8	1.1
Working capital, \$ x 10 ³ (Note 1)	78	26	33	44
<u>Annual Costs, \$ Thousands</u>				
Electricity	438	131	175	240
Water and chemicals (Note 2)	7	4	4	4
Labor and supervision (Note 3)	25	18	18	18
Maintenance and general overhead (Note 4)				
o Power conversion (Note 5)	15	8	8	8
o All other	35	35	35	35
Capital charges (Note 6)				
o Power conversion (Note 5)	38	19	19	19
o All other	89	89	89	89
Working capital charges (Note 7)	16	5	7	9
Total	663	309	355	422

STORAGE TECHNOLOGY:

Hydrogen

SOURCE: U.S. Energy Research and Development Administration. An Evaluation of the Use of Hydrogen as a Supplement to Natural Gas, TID-27747. Prepared by the Ad Hoc Committee, Washington, D.C., June 1977.

INFORMATION:

TABLE 4 (cont'd)

Column No.	1	2	3	4
Electrolyzer capacity factor	0.90	0.45	0.45	0.45
Electricity cost, ¢/kWhr	1.0	0.6	0.8	1.1
<u>Costs, \$/MBtu of hydrogen product</u>				
Electricity	3.25	1.95	2.60	3.57
Water and chemicals	0.05	0.05	0.05	0.05
Labor and supervision	0.19	0.27	0.27	0.27
Maintenance and general overhead	0.37	0.64	0.64	0.64
Capital charges	0.95	1.61	1.61	1.61
Working capital charges	<u>0.12</u>	<u>0.07</u>	<u>0.10</u>	<u>0.13</u>
Total	4.93	4.59	5.27	6.27

Oxygen credit (Note 8)

Note 1 - Working capital = 2 months costs of electricity, water + chemicals, and labor and supervision.

Note 2 - Charges for water and chemicals are \$0.054/MBtu hydrogen product.

Note 3 - Labor and supervision for 1.0 man/shift would be \$236,000/yr.

Note 4 - Maintenance and general overhead are 6.6% of investment each year.

Note 5 - Maintenance and general overhead and capital charges for the power conversion and switchgear equipment is charged in proportion to its use for electrolysis since when not used for electrolysis it provides credits to the utility for power factor correction.

Note 6 - Capital charges are 17.0% of investment per year.

Note 7 - Working capital charges are 21.0% of working capital per year.

Note 8 - If oxygen production could be marketed at \$24/ton, the credit would correspond to \$1.53/MBtu of hydrogen.

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

Salzano, F.J. and C. Braun. Hydrogen
Energy Assessment. Brookhaven National
Laboratories, 1977.

INFORMATION:

HYDROGEN PRODUCTION COSTS 1975 DOLLARS

Operating Mode

Off-Peak or Spinning Reserve

	1985		1990			
Electrolyzer Capacity (MW)	696	1,392	1,044	1,820	2,275	910
Electrolyzer Capacity Factor	0.4	0.45	0.5	0.4	0.45	0.5
Converter Capacity Factor	0.9	0.9	0.9	0.9	0.9	0.9
Cost of Electricity (ϕ /kWh-1975)	0.35	1.18	1.41	0.35	0.85	1.02
<u>Production Costs (ϕ/kWh_{th} Output)</u>						
Electricity	0.39	1.31	1.57	0.39	0.94	1.13
Water & Chemicals	0.02	0.02	0.02	0.02	0.02	0.02
Labor & Supervision	0.06	0.06	0.06	0.06	0.06	0.06
Maintenance & Overhead	0.08	0.08	0.08	0.08	0.08	0.08
Capital Charges (17% of Investment)						
- Electrolyzer (100\$/kw)	0.49	0.44	0.39	0.49	0.44	0.39
- Converter & Switchgear (50\$/kw)	0.11	0.11	0.11	0.11	0.11	0.11
Total Costs: (ϕ /kWh)	1.15	2.02	2.23	1.15	1.65	1.79
Without Oxygen Credit ($\$/10^6$ BTU)	3.37	5.92	6.54	3.37	4.84	5.25
With Oxygen Credit ($\$/10^6$ BTU)	2.00	4.65	5.17	2.00	3.47	3.88

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

Salzano, F.J. and C. Braun. Hydrogen
Energy Assessment. Brookhaven National
Laboratories, 1977.

INFORMATION:

GENERAL ELECTRIC SPE ELECTROLYSIS SYSTEM
HYDROGEN PRODUCT COST FOR VARIOUS OPERATING MODES

Utility Financing, 1985 Operation, 1975 \$

Investment	\$ /kW Out		M\$	M\$	
Electrolysis Modules	9		0.460	On-Sites	5.093
Power Conversion and Switchgear	46		2.351	Off-Sites	1.355
Other Process Equipment	19		0.571	Total	6.448
Installation	9		0.460		
Off-Sites	20		1.022		
Contingency	31		1.584		
Total	134		6.448		

Operating Mode	Off-Peak or Spinning Reserve				Dedicated
Cost of Electricity, \$/kWhr	0.010	0.010	0.010	0.010	0.021
Operating hours per day	24	18	12	6	24
Operation hours per year	7920	5940	3960	1980	7920
MBtu product per year x 10 ⁶	1.378	1.034	0.689	0.345	1.378
Working Capital, M\$	0.920	0.700	0.480	0.260	1.876

Annual Production Costs, M\$					
Electricity	5.211	3.908	2.606	1.303	10.944
Water and Chemicals	0.075	0.056	0.038	0.019	0.075
Labor and Supervision	0.236	0.236	0.236	0.236	0.236
Annual Production Costs	5.522	4.200	2.880	1.558	11.255

Maintenance (4% of on-sites)	0.204	0.204	0.204	0.204	0.204
General Overhead (2.6% of on-sites)	0.132	0.132	0.132	0.132	0.132
Capital Charges (17% of total Invest.)	1.096	1.096	1.096	1.096	1.096
Working Capital Charges (21% of work cap.)	0.193	0.147	0.101	0.055	0.394
Total Annual Costs	7.147	5.779	4.413	3.045	13.081

Total Cost, \$/MBtu					
Without Oxygen Credit	5.19	5.59	6.41	8.83	9.49
With Oxygen Credit	3.62	--	--	--	7.92

Plant - GE SPE Electrolysis

Plant Capacity - 51.1 MW Hydrogen Output = 0.5417×10^6 SCF/hr = 174×10^6 Btu/hr

Thermal Efficiency - 77.6% Operating Days per year - 330

Electrical Requirement - 65.8 MW

Note: The contingency is 30% of the estimate for on-sites + off-sites. These investments include cost of funds during construction.

ASSUMPTIONS & COMMENTS:

1975 dollars

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

Salzano, F.J. and C. Braun. Hydrogen Energy Assessment. Brookhaven National Laboratories, 1977.

INFORMATION:

Table 1
COMPARISON OF HYDROGEN PRODUCTION COSTS BY VARIOUS TECHNOLOGIES IN THE YEARS 1985 AND 2000
1975 Dollars

Performance and Cost Items	Methane Steam Reforming	Resid Partial Oxidation	Coal Gasification		Lurgi Water Electrolyzer Using Off-Peak Power	SPE New	Water Electrolysis	
	(1) (5)	(1) (5)	Koppers Totzek	Improved K-T	(2) (4)	Off-Peak Power	Spinning Reserve	Dedicated Plant
			(1) (5)	(1) (5)		(3) (4)	(3) (4)	(3) (4)
Plant Cost (10 ⁶ \$)	40.7	103.5	160.1	130.0	17.1	0.75	0.75	0.75
Plant Production	100 $\frac{\text{MScf}}{\text{Day}}$	100 $\frac{\text{MScf}}{\text{Day}}$	100 $\frac{\text{MScf}}{\text{Day}}$	100 $\frac{\text{MScf}}{\text{Day}}$	53.3 MWh	5 MWh	5 MWh	5 MWh
Annual Operation	330 $\frac{\text{Days}}{\text{Yr}}$	330 $\frac{\text{Days}}{\text{Yr}}$	330 $\frac{\text{Days}}{\text{Yr}}$	330 $\frac{\text{Days}}{\text{Yr}}$	55 $\frac{\text{Hours}}{\text{Week}}$	55 $\frac{\text{Hours}}{\text{Week}}$	7920 $\frac{\text{Hours}}{\text{Year}}$	109 $\frac{\text{Hours}}{\text{Week}}$
Annual Average Load Factor	0.904	0.904	0.904	0.904	0.33	0.33	0.904	0.65
Conversion Efficiency (%)	70.2	82.7	59.6	64.2	74.7	90.0	90.0	90.0
Unit Capital Cost $\frac{\$}{\text{kW(th)}}$	-	-	-	-	320	150	150	150
<u>Basic Fuel Cost</u>								
Year 1985 (\$/M Btu)	2.15	2.52	0.74	0.74	0.76	0.76	0.76	2.53
Year 2000 (\$/M Btu)	2.41	3.15	0.82	0.82	0.88	0.88	0.88	2.65
<u>Unit Production Costs - 1985</u>								
Capital Cost (7) (\$/M Btu)	0.65	1.64	2.54	2.06	5.50	2.58	0.94	1.31
Fuel Cost (\$/M Btu)	3.06	3.05	1.24	1.15	3.08	2.56	2.56	8.53
O and M Cost (6) (\$/M Btu)	0.50	0.50	1.34	1.25	0.47	0.47	0.47	0.47
<u>Total Unit Cost (\$/M Btu)</u>	4.21	5.19	5.12	4.46	9.05	5.61	3.97	10.31
<u>Unit Production Costs - 2000</u>								
Capital Cost (7) (\$/M Btu)	0.65	1.64	2.54	2.06	5.50	2.58	0.94	1.31
Fuel Cost (\$/M Btu)	3.43	3.81	1.38	1.28	3.46	2.88	2.88	8.66
O and M Cost (6) (\$/M Btu)	0.50	0.50	1.34	1.25	0.47	0.47	0.47	0.47
<u>Total Unit Cost (\$/M Btu)</u>	4.58	5.95	5.26	4.59	9.43	5.93	4.29	10.44

ASSUMPTIONS & COMMENTS:

1975 dollars

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

Salzano, F.J. and C. Braun. Hydrogen Energy Assessment. Brookhaven National Laboratories, 1977.

INFORMATION:

ASSUMPTIONS & COMMENTS:

1980 dollars

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

Salzano, F.J. and C. Braun. Hydrogen Energy Assessment. Brookhaven National Laboratories, 1977.

INFORMATION:

Figure 9

Hydrogen Manufacturing Costs - Electrolysis

\$/MBtu - 1980 \$

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

Salzano, F.J. and C. Braun. Hydrogen
Energy Assessment. Brookhaven National
Laboratories, 1977.

INFORMATION:

Table 9

ELECTROLYTIC HYDROGEN PRODUCTION COSTS
1975 DOLLARS

I. General Assumptions

Plant: Solid Polymer Electrolyzer With Forced Commutated
Converter Interface

Location: Northeast USA

Mode of Operation: Using Spinning Reserve/Off-Peak Energy

Utilization Factor: Electrolyzer 0.4, 0.45, 0.5
Converter 0.9

Plant Size: 5MW_{th} (Output)

Production Efficiency: 90% (Hydrogen Thermal Output)

Hydrogen Pressure: 450 psig

Construction Period: 1 year

II. Investment Costs:

	<u>\$/KWout</u>	<u>10³\$(Plant)</u>
Electrolysis Modules	20	100
Plant Auxiliaries	23	115
Power Conversion & Switchgear	45	225
Installation	22	110
Offsites	15	75
Contingency	<u>25</u>	<u>125</u>
TOTAL	150	750

ASSUMPTIONS & COMMENTS:

1975 dollars

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

Salzano, F.J. and C. Braun. Hydrogen
Energy Assessment. Brookhaven National
Laboratories, 1977.

INFORMATION:

Figure 12

COMPARISON OF THE COST OF OFF-
PEAK ELECTRIC, COAL DERIVED AND THERMOCHEMICAL
HYDROGEN, AS A FUNCTION OF HYDROGEN PRODUCTION
PROCESS COST AND CONVERSION EFFICIENCY HYDROGEN
YEAR 2000
1975 Dollars

ASSUMPTIONS & COMMENTS:

1975 dollars

STORAGE TECHNOLOGY:

Hydrogen

SOURCE:

Mezzina, Alessio, Electrolysis-Based
Hydrogen Storage Systems, BNL 51060,
Brookhaven National Laboratory, 1978.

INFORMATION:

Figure 5.2. Hydrogen production cost estimates

SUMMARY

End Use: Solar

Technology: All

No useful comparisons possible.

STORAGE TECHNOLOGY:

Energy Storage Systems Comparison

SOURCE:

General Electric Space Division. Applied Research on Energy Storage and Conversion for Photovoltaic and Wind Energy Systems. National Science Foundation. NSF C-75-22221-01

INFORMATION:

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

ENERGY STORAGE CONCEPT	KEY CHARACTERISTICS							AVAILABILITY		APPLICABILITY			NOTES
	SYSTEM EFFIC. %	USEFUL LIFE YEARS	NOMINAL RANGE OF PLANT SIZES		RELIABILITY	SPECIAL HAZARD POTENTIAL	MAJOR LIMITATIONS	DEVELOPMENT STATUS	DEVELOPMENT REQUIREMENTS	U	R	I	
			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
UNDERGROUND PUMPED HYDRO	70-75	50	200-2000	1000-20,000	HIGH	FLOODING	SITING, ENVIRONMENTAL	BASIC TECHNOLOGY AVAILABLE	HIGHER HEAD EQUIPMENT	H	NO	L	MECS/PVCS SOURCE VARIABILITY LIMITS DEDICATED APPLICATIONS
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	MECS/PVCS SOURCE VARIABILITY LIMITS DEDICATED APPLICATIONS
PNEUMATIC STORAGE	55-65	20-30	UP TO ~25 MW	UP TO ~100 MWh	UNKNOWN-EXPECTED TO BE MODERATE	RUPTURE OF HIGH PRESSURE TANKS, HIGH TEMP. DISCHARGE	SMALL SCALE	PROOF OF CONCEPT STAGE	SYSTEM & COMPONENT DEVELOPMENT	NO	H	L	
LEAD-ACID BATTERIES	70-75	10 ~ 10	<10 MW 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 MW 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	H	L/M	HIGH COST IS A MAJOR BARRIER TO IMPLEMENTATION
HYDROGEN STORAGE	40-50	10-25	<10 MW 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	H	NO	H	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

STORAGE TECHNOLOGY:

Energy Storage Systems Comparison

SOURCE:

General Electric Space Division.

Applied Research on Energy Storage and
Conversion for Photovoltaic and Wind
Energy Systems. National Science
Foundation. NSF C-75-22221-01**INFORMATION:**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.

ASSUMPTIONS & COMMENTS:

Intermediate-sized system

STORAGE TECHNOLOGY:

Energy Storage Systems Comparison

SOURCE:

General Electric Space Division.

Applied Research on Energy Storage
and Conversion for Photovoltaic and
Wind Energy Systems. National Science
Foundation. NSF C-75-22221-01

**INFORMATION: | 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	1000 MWh
Underground Pumped Hydro	301	364	190	230	
Underground Compressed Air	264	308	250	340	
Lead-Acid Batteries	354	415	495	840	1985 START 6% FUEL ESCALATION
Advanced Batteries, 10,20 Yr	340,364	396,431	220	370	
Inertial Storage	287	339	1120	2170	
Hydrogen Storage	235	268	870	940	

* 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.

ASSUMPTIONS & COMMENTS:

Assumes storage is shared between general utility system and wind/photovoltaic system

STORAGE TECHNOLOGY:Energy Storage Systems Comparison**SOURCE:**General Electric Space Division.Applied Research on Energy Storage and
Conversion for Photovoltaic and Wind
Energy Systems. National Science
Foundation, NSF C-75-22221-01**INFORMATION:**

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.

STORAGE TECHNOLOGY:

Energy Storage Systems Comparison

SOURCE: i

General Electric Space Division.

Applied Research on Energy Storage and Conversion for Photovoltaic and Wind Energy Systems. National Science Foundation, NSF C-75-22221-01

INFORMATION: /

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.

STORAGE TECHNOLOGY:

Batteries

SOURCE:

General Electric Space Division.

Applied Research on Energy Storage and
Conversion for Photovoltaic and Wind
Energy Systems. National Science
Foundation. NSF C-75-22221-01

INFORMATION:

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 ⁵⁸ Chloride	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.

STORAGE TECHNOLOGY:

Energy Storage Systems Comparison

SOURCE:

General Electric Space Division.

Applied Research on Energy Storage and
Conversion for Photovoltaic and Wind
Energy Systems. National Science
Foundation. NSF C-75-22221-01

INFORMATION: 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).

STORAGE TECHNOLOGY:

Batteries for Photovoltaic Systems

SOURCE: [REDACTED]

Feduska, W. Energy Storage for Photo-
voltaic Conversion. Volume I.
Westinghouse R&D Center 1977. Prepared
for National Science Foundation,
Contract NSF C-7522180

INFORMATION:

TABLE 1

**Total Battery Plant Bus Bar Energy Costs
(mills/kWh)**

<u>Battery Type</u>	<u>Battery Fixed Charges + O&M Costs</u>	<u>Fixed Charge for Conversion Equipment</u>	<u>Charging Energy Costs</u>	<u>Bus Bar Energy Costs (BBEC)</u>
State-of-the-Art Lead-Acid	48.5	4.2	21.7	74.4
Advanced Technology Lead-Acid	26.4	4.1	20.3	50.8
Zinc-Chlorine	49.8	4.3	23.2	77.3

STORAGE TECHNOLOGY:Batteries for PhotovoltaicSystems**SOURCE:**Feduska, W., et.al. Energy Storage for
Photovoltaic Conversion Final Report -
Utility Systems. Vol. II. Westinghouse
R&D Center. 1977. NSF Contract NSF C-
7522180**INFORMATION:**

<u>Battery Type</u>	<u>Battery Fixed Charges + O&M Costs</u>	<u>Fixed Charge for Conversion Equipment</u>	<u>Charging Energy Costs</u>	<u>Total Battery Plant Bus Bar Energy Costs (BBEC)</u>
State-of-the-Art Lead-Acid	48.5	4.2	21.7	74.4
Advanced Technology Lead-Acid	26.4	4.1	20.3	50.7
Zinc-Chlorine	49.8	4.3	23.2	77.3

STORAGE TECHNOLOGY:

Batteries

SOURCE:

Feduska, W., et.al. Energy Storage for
Photovoltaic Conversion Final Report -
Utility Systems. Vol. II. Westinghouse
R&D Center. 1977. NSF Contract NSF C-
7522180

INFORMATION:

TABLE 3.5
UTILITY BATTERY CHARACTERISTICS

System	Energy Efficiency (%)	Life (Cycles)	Volts		(kWh) (4-hr-rate)	Cell	Module					Modules/ String	Strings/ Battery	310 MWh Plant		Reference
			(Min. Disc)	(Max. Charge)		(Height- ft)	(no.)	(Cells/ Module)	(Area, ft ²)	(Height- ft)	(Weight, lbs)			(Area, ft ²)	(Lbs/ ft ²)	
Lead-acid (SDA)	75	2000	4210	7100	5.0	2.75	102,570	5	5.75	2.75	2500	526	39	150,000 (100,000)	684	9
Lead-acid (Advanced Tech)	80	3000	4880	6680	35.9	5.0	13,050	1	6.0	5.0	3750	2610	5	206,800 (155,000)	482	9
LiSi-FeS	75	2500	3940	8760	5.2	0.9	96,400	7	0.6	6.3	800	626	22	25,000	441	11,12,13,21
LiAl-FeS	85	3000	4030	6050	4.4	0.8	113,000	8	0.7	7.0	1000	504	28	40,000	353	11,22
Na/S(I)	84	2000	4400	6460	0.73	0.9	684,750	25	3.0	1.1	300	110	250	100,000	83	20
Na/S(II)	80	2000	4500	7000	2.5	1.5	200,000	20	4.5	8.5	400	125	80	50,000	80	14,15,16
Na/SbCl ₃	75	2500	4640	8260	1.1	1.5	460,000	23	5.5	2.0	540	101	198	110,000	100	17,18,23
Zn/Cl ₂	70	2500	4650	5700	1.61	n.a.	360,000	2220	168	10.0	100,000	36	4	157,000 ² (101,000)	325	19,24

¹ Battery + auxiliaries, incl. refrigeration.

² Battery only, not incl. refrigerator.

() = battery area

STORAGE TECHNOLOGY:

Batteries

SOURCE:

Feduska, W., et.al. Energy Storage for
Photovoltaic Conversion Final Report -
Utility Systems. Vol. II. Westinghouse
R&D Center. 1977. NSF Contract NSF C-
7522180

INFORMATION:

TABLE 5.8

BATTERY SYSTEM ECONOMIC FACTORS

	Present Operating Temperature	Cell Size	Battery Cost \$/kWh	Aux. Cost \$/kWh	Annual O&M \$/kWh	Salvage Value \$/kWh	Life Disch. Cycles	Life Time Confidence	Life Yrs.	Energy Effic.
1. Lead-Acid (SOA)	20-30°C	5.0 kWh	\$36.90	21.70	0.37	7.03	2000	100%	6.4	72%
2. Lead-Acid (Advanced)	20-50	38.9	31.62	16.30	0.18	5.77	5000	90%	16.0	76.8
3. LiSi-FeS	390-450	5.2	30.00	16.00	0.73	2.00	2500	50%	8.0	72.0
4. LiAl-FeS	400-450	4.4	28.75	18.00	0.73	2.05	3000	50%	8.0	81.6
5. Na-S(I)	290-300	0.73	31.70	58.00	0.73	0	2000	65%	6.4	80.6
6. Na-S(II)	300-350	2.5	30.00	25.00	0.55	0	2000	65%	6.4	76.8
7. Na-SbCl ₃	200-220	1.1	30.00	45.00	0.73	2.00	2500	65%	8.0	72.0
8. Zn-Cl ₂	20-50	1.61	30.00	36.00	0.73	0	2500	80%	8.0	67.2
9. Li-TiS ₂	20-40	1.00	45.00	45.00	0.73	5.00	1000	80%	3.2	86.4

ASSUMPTIONS & COMMENTS:

1975 dollars

STORAGE TECHNOLOGY:

Batteries

SOURCE:

Feduska, W., et.al. Energy Storage for Photovoltaic Conversion Final Report - Utility Systems. Vol. II. Westinghouse R&D Center. 1977. NSF Contract NSF C-7522180

INFORMATION:

TABLE 5.11
BATTERY ENERGY COSTS OF CANDIDATE BATTERY SYSTEMS

	First Cost \$/kWhr	Present Worth of Replacement	Total of First and Replace Cost	Annual Fixed Charges	Other O&M	Total Ann. Costs \$/kWhr	Capacity Factor	BEC Mills kWhr	Relative Rank	FOM
1. Pb-Acid (SOA)	\$58.60	\$39.78	\$98.38	\$12.00	\$0.37	\$12.37	0.7128	48.52	5	4
2. Pb-Acid (Advanced)	47.92	7.06	54.98	6.71	0.18	6.89	0.7291	26.42	1	10
3. LiS ₁ -FeS	46.00	27.55	73.55	8.97	0.73	9.70	0.7128	38.04	3	7
4. LiAl-FeS	46.75	26.26	73.01	8.91	0.73	9.64	0.7454	36.16	2	8
5. Na-S(I)	89.70	41.98	131.69	16.07	0.73	16.80	0.7420	63.30	8	1
6. Na-S(II)	55.00	39.71	94.71	11.55	0.55	12.10	0.7291	46.40	4	5
7. Na-SbCl ₃	75.00	27.55	102.55	12.51	0.73	13.24	0.7128	51.93	7	3
8. Zn-Cl ₂	66.00	29.70	95.70	11.68	0.73	12.41	0.6965	49.81	6	4
9. Li-TiS ₂	90.00	127.21	217.21	26.50	0.73	27.73	0.7618	99.93	9	0

ASSUMPTIONS & COMMENTS:

1975 dollars

STORAGE TECHNOLOGY:

Batteries for Photovoltaic

Systems

SOURCE:

Feduska, W., et.al. Energy Storage
for Photovoltaic Conversion Final Report -
Utility Systems. Vol. II. Westinghouse
R&D Center. 1977. NSF Contract NSF C-
7522180

INFORMATION:

TABLE 5.14
BUS BAR ENERGY COSTS (BBEC)
FOR SELECTED BATTERY SYSTEMS

Component of Cost	State of Art Lead Acid	Advanced Lead Acid	Zinc Chlorine
Battery Capital and O&M	48.5 Mills/kWh	26.4 Mills/kWh	49.8 Mills/kWh
Conversion Capital	4.2	4.1	4.3
Charging	<u>21.7</u>	<u>20.3</u>	<u>23.2</u>
Total	74.4	50.8	77.3

ASSUMPTIONS & COMMENTS:

Assumes charging electricity costs 1.558¢/kWh. 1975 dollars

STORAGE TECHNOLOGY:

Batteries

SOURCE:

Feduska, W., et.al. Energy Storage for
Photovoltaic Conversion Residential
Systems Final Report. Vol.III.
Westinghouse R&D Center. 1977. NSF
Contract NSF C-7522180

INFORMATION:

Table 2.8

Battery Characteristics, 50V. System

System	Storage (KWh)	Energy Efficiency %	Life (cycles)	Volts		Cell		Battery			Tray or Container (Weight lbs)	Reference
				(min. disch.)	(max. chg.)	(no.)	(Weight ft.)	(Area ft ²)	(Height ft.)	(Weight lbs)		
Lead-Acid (SGA)	15	75	2000	42	70	26	1.5	2.5	5.5	2200	120	4
	20	75	2000	42	70	26	1.5	3.0	5.5	2800	135	
	25	75	2000	42	70	26	1.5	3.6	5.5	3300	150	
Lead-Acid (Advanced Tech.)	15	80	5000	48	65	25	1.5	3.0	5.5	2200	120	4
	20	80	5000	48	65	25	1.5	3.6	5.5	2800	135	
	25	80	5000	48	65	25	1.5	6.2	5.5	3300	150	
LiSi/LiCl-KCl/FeS	15	75	2500	40	70	44	0.9	2.75	1.25	320	40	5, 6, 7
	20	75	2500	40	70	44	0.9	3.5	1.25	420	45	
	25	75	2500	40	70	44	0.9	4.4	1.25	520	50	
LiAl/LiCl-KCl/FeS	15	75	3000	32	66	40	0.7	5.7	1.4	440	180	5
	20	75	3000	32	66	40	0.7	7.3	1.4	590	200	
	25	75	3000	32	66	40	0.7	9.1	1.4	730	220	
Na/S	15	80	2000	47	73	26	1.5	5.0	2.0	150	30	8, 9, 10
	20	80	2000	47	73	26	1.5	6.3	2.0	200	40	
	25	80	2000	47	73	26	1.5	7.4	2.0	250	50	
Na/SbCl ₃	15	75	2500	46	82	23	1.5	3.5	2	360	T.B.D.*	11, 12
	20	75	2500	46	82	23	1.5	4.5	2	450		
	25	75	2500	46	82	23	1.5	5.5	2	540		
Zn/Cl ₂	15	70	2500	50	56	25	0.5	3.6	1	215	T.B.D.*	13
	20	70	2500	50	56	25	0.5	4.5	1	270		
	25	70	2500	50	56	25	0.5	5.5	1	360		

*To be determined.

STORAGE TECHNOLOGY:

Batteries

SOURCE:

Feduska, W., et.al. Energy Storage for
Photovoltaic Conversion Residential
Systems Final Report. Vol. III.
Westinghouse R&D Center. 1977. NSF
Contract NSF C-7522180

INFORMATION:

Table 2.9

Battery Characteristics, 200V System

System	Storage (kWh)	Energy Efficiency %	Life (cycles)	Volts		Cell		Battery			Tray or Container (Weight lbs)	Reference
				(min. disch.)	(max. chg.)	(no.)	(Height ft.)	(Area ft ²)	(Height ft.)	(Weight lbs)		
Lead-Acid (SOA)	15	75	2000	165	275	102	1.5	3.0	5.5	2400	130	4
	20	75	2000	165	275	102	1.5	1.5	5.5	3000	145	
	25	75	2000	165	275	102	1.5	4.0	5.5	3500	160	
Lead-Acid (Advanced Tech.)	15	80	5000	180	250	96	1.5	3.6	5.5	2400	130	4
	20	80	5000	180	250	96	1.5	4.2	5.5	3000	145	
	25	80	5000	180	250	96	1.5	4.8	5.5	3500	160	
LiSi/LiCl-KCl/FeS	15	75	2500	155	280	174	0.55	2.10	1.60	350	35	5, 6, 7
	20	75	2500	155	280	174	0.64	2.30	1.75	440	40	
	25	75	2500	155	280	174	0.71	2.50	1.90	540	45	
LiAl/LiCl-KCl/FeS	15	75	3000	128	264	160	0.3	5.7	1.4	500	180	5
	20	75	3000	128	264	160	0.3	7.3	1.4	650	200	
	25	75	3000	128	264	160	0.3	9.1	1.4	790	240	
Na/S	15	80	2000	188	292	104	0.4	5.0	2.0	170	40	8, 9, 10
	20	80	2000	188	292	104	0.4	6.5	2.0	225	50	
	25	80	2000	188	292	104	0.4	7.4	2.0	280	60	
Na/SbCl ₃	15	75	2500	180	320	90	1.5	3.	2.	400	T.B.D.*	11, 12
	20	75	2500	180	320	90	1.5	4.	2.	500		
	25	75	2500	180	320	90	1.5	5.	2.	600		
Zn/Cl ₂	15	70	2500	200	223	101	0.5	4.	1.	240	T.B.D.*	13
	20	70	2500	200	223	101	0.5	5.	1.	300		
	25	70	2500	200	223	101	0.5	6.3	1.	400		

*To be determined.

STORAGE TECHNOLOGY:

Batteries

SOURCE:

Feduska, W., et.al. Energy Storage for
Photovoltaic Conversion Residential
Systems Final Report. Vol. III.
Westinghouse R&D Center. 1977. NSF
Contract NSF C-7522180

INFORMATION:

Table 2.10
Battery Characteristics, 400V System

System	Storage (kWh)	Energy Efficiency %	Life (cycles)	Voltage		Cell		Battery			Tray or Container (Weight lbs)	Reference
				(min. disch.)	(max. chg.)	(no.)	(Height ft.)	(Area ft ²)	(Height ft.)	(Weight lbs)		
Lead-Acid (SOA)	15	75	2000	330	550	204	1.	3.0	8.5	2600	200	4
	20	75	2000	330	550	204	1.	3.5	8.5	3250	225	
	25	75	2000	330	550	204	1.	4.0	8.5	3800	250	
Lead-Acid (Advanced Tech.)	15	80	5000	360	500	192	1.	3.6	8.5	2600	200	4
	20	80	5000	360	500	192	1.	4.2	8.5	3250	225	
	25	80	5000	360	500	192	1.	4.8	8.5	3800	250	
LiSA/LiCl-KCl/FeS	15	75	2500	315	560	348	0.39	3.7	1.25	380	47	5, 6, 7
	20	75	2500	315	560	348	0.45	4.0	1.35	480	50	
	25	75	2500	315	560	348	0.50	4.3	1.45	580	56	
LiAl/LiCl-KCl/FeS	15	75	3000	256	528	320	0.3	5.7	1.4	550	180	5
	20	75	3000	256	528	320	0.3	7.3	1.4	700	200	
	25	75	3000	256	528	320	0.3	9.1	1.4	840	220	
Na/S	15	80	2000	376	584	208	0.4	2.6	4.0	190	50	8, 9, 10
	20	80	2000	376	584	208	0.4	3.3	4.0	250	60	
	25	80	2000	376	584	208	0.4	3.8	4.0	310	70	
Na/SbCl ₃	15	75	2500	360	640	180	1.5	3.3	2.	440	T.B.D.*	11, 12
	20	75	2500	360	640	180	1.5	4.4	2.	550		
	25	75	2500	360	640	180	1.5	5.5	2.	660		
Zn/Cl ₂	15	70	2500	400	446	202	0.5	4.5	1.	265	T.B.D.*	13
	20	70	2500	400	446	202	0.5	5.5	1.	330		
	25	70	2500	400	446	202	0.5	7.0	1.	440		

*To be determined.

STORAGE TECHNOLOGY:Batteries

SOURCE:Feduska, W., et.al. Energy Storage for
Photovoltaic Conversion Residential
Systems Final Report. Vol. III.
Westinghouse R&D Center. 1977. NSF
Contract NSF C-7522180**INFORMATION:**

TABLE 2.13
Residential Battery Characteristics*

<u>System</u>	<u>\$/KWh Delivered</u>	<u>Auxiliary \$/KWh</u>	<u>Replacement Cost</u>	<u>Predicted Cycle Life</u>	<u>Estimated Efficiency</u>
Lead Acid (SOA)	46.00	22.00	0.82	2000	75
Lead Acid (Advanced Tech)	39.50	16.50	0.82	5000	80
LiSi-FeS	39.00	16.00	0.93	2500	75
LiAl-FeS	37.50	18.00	0.93	3000	75
NaS (I)	44.50	29.00	1.0	2000	80
NaS (II)	42.00	25.00	1.0	2000	80
Na-SbCl ₃	42.00	22.50	0.93	2500	75
Zn-Cl ₂	45.00	36.00	1	2500	70
Li-TiS ₂	67.50	22.50	0.89	1000	90

*Nominal 200 V, 20 kWh Battery System.

STORAGE TECHNOLOGY:Lead Acid Batteries

SOURCE:Feduska, W., et.al. Energy Storage for
Photovoltaic Conversion Residential
Systems Final Report. Vol.III.
Westinghouse R&D Center. 1977. NSF
Contract NSF C-7522180**INFORMATION:**

TABLE 2.17

Advanced Technology Lead-Acid Subsystem Costs

<u>Capacity</u> <u>(kWh)</u>	<u>Year</u> <u>1985 - 1990</u>		<u>Year</u> <u>2000</u>	
	<u>This Study</u>	<u>PVEPS*</u>	<u>This Study</u>	<u>PVEPS*</u>
15	\$1550	\$1500	\$1300	\$1150
20	1900	1750	1600	1350
25	2250	2000	1900	1550

All values in 1975 dollars.

*Estimate of battery portion of total system cost as determined for the ERDA "Conceptual Design and Systems Analysis of Photovoltaic Power Systems" (PVEPS) as performed by Westinghouse.

STORAGE TECHNOLOGY:

Batteries for Residential Solar
Photovoltaic Energy Storage

SOURCE: Leigh, R. W. Storage in Residential
Solar Total Energy Systems, BNL-51230.

Prepared for U.S. Department of Energy by
Brookhaven National Laboratory, December 1980.

INFORMATION:

Table I-3
Breakeven Capital Costs for Batteries in
Optimized Photovoltaic Systems (\$/kWh)

Collector Costs	Boston, SF = 0.50			Albuquerque, SF = 0.50		
	LPP	MPP	HPP	LPP	MPP	HPP
DOE Targets	-	-	44	-	43	108
DOE Targets + 50%	-	-	-	-	-	63

STORAGE TECHNOLOGY:

Batteries for Residential Energy Storage

SOURCE: Leigh, R. W. Storage in Residential

Solar Total Energy Systems, BNL-51230.

Prepared for U.S. Department of Energy by

Brookhaven National Laboratory, December 1980.

INFORMATION:

Table I-2
Breakeven Capital Costs for Batteries in
Optimized Stirling Cycle Systems (\$/kWh)

Collector Costs	Boston, SF = 0.50			Albuquerque, SF = 0.70		
	LPP	MPP	HPP	LPP	MPP	HPP
DOE Targets	-	-	75	-	43	80
DOE Targets + 50%	-	-	-	-	23	65

STORAGE TECHNOLOGY:

Residential Thermal Energy Storage

SOURCE: Leigh, R. W. Storage in Residential

Solar Total Energy Systems, BNL-51230.

Prepared for U.S. Department of Energy by

Brookhaven National Laboratory, December 1980.

INFORMATION:

Table I-1
Breakeven Capital Costs of Thermal Storage in
Optimized Rankine Cycle Systems (\$/GJ)

Collector Costs	Boston, SF = 0.50			Albuquerque, SF = 0.70		
	LPP	MPP	HPP	LPP	MPP	HPP
Cost Targets	-	-	2980	4200	15200	33000
Cost Targets + 50%	-	-	1580	-	9800	27100

STORAGE TECHNOLOGY:

Solar Thermal Energy Storage

SOURCE: Copeland, R. J. Preliminary Requirements for Thermal Storage Subsystems in Solar Thermal Application, SERI/PR-731-364. Prepared for U.S. Department of Energy by SERI, April 1980.

INFORMATION:

TABLE 3-5. TOTAL THERMAL STORAGE VALUE FOR LONG-DURATION STORAGE^c

Location	Hours Storage ^d	AF _{ST} ^a	Total Thermal Storage Value \$/kW (1977\$)		
			1.00 ^b	0.62 ^b	0.41 ^b
Albuquerque		.50	765	252	-31
Madison		.37	587	207	-2
Miami		.44	683	231	-18
New York		.35	566	200	2

^aAvailability factors from Iannucci (1978) with the critical solar multiple (Note: what is identified here as AF is called "percent solar" by Iannucci).

^bEfficiency of long-term storage; the ratio of the electrical energy delivered in Case 1 to Case 2 from the solar thermal system.

^cFor application in the 1990s.

^dAll short-duration storage capacities have 3.0 hours of storage in Case 2.

STORAGE TECHNOLOGY:

Solar Thermal Energy Storage

SOURCE: Copeland, R. J. Preliminary

Requirements for Thermal Storage Subsystems
in Solar Thermal Application, SERI/PR-731-364.Prepared for U.S. Department of Energy by
SERI, April 1980.

INFORMATION:

TABLE 3-4. RECOMMENDED VALUE DATA FOR THERMAL STORAGE

Storage Capacity	Appropriate Collector Area (km ²)		Average Thermal Storage Value (1976 \$/kWh _e)				
	Westing- house (W)	Aero- space (A)	High Insolation W ^a Inyokern	Medium Insolation		Low Insolation	
				W ^a Mid- land	A ^b Ft. Worth	W ^a Ster- ling	A ^b Seattle
3 Hours	0.7	1.0	>83	>30	48	>18	24
6 Hours	0.8	1.0 ^c	>45	>15	29	>11	14
		1.5	--	--	36	--	18
9 Hours	ND ^d	1.5	ND	ND	32	ND	15

^aBased on Westinghouse data for 0.6 km² collector area, value is probably higher than these data.^bBased on Aerospace data, converted to 1976 money assuming 10% inflation.^cThe appropriate area is between 1.0 km² and 1.5 km², but insufficient data exists at this time to determine the areas and the thermal storage value.^dND = No Data Available.

STORAGE TECHNOLOGY:

Solar Thermal Energy Storage

SOURCE: Copeland, R. J. PreliminaryRequirements for Thermal Storage Subsystemsin Solar Thermal Application, SERI/PR-731-364.Prepared for U.S. Department of Energy by
SERI, April 1980.**INFORMATION:**

RECOMMENDED PRELIMINARY COST GOALS FOR THERMAL
STORAGE IN SOLAR THERMAL ELECTRIC PLANTS
(1976 \$/KW_e)

<u>Quantity of Storage</u>	<u>High Insolation</u>	<u>Medium Insolation</u>	<u>Low Insolation</u>
Buffer	established by obtainable cost		
Diurnal			
3 Hours	255	120	60
6 Hours	300	180	90
9 Hours	-	225	110
Long Duration			
62% Efficiency	230	210	180
100% Efficiency	695	620	515

STORAGE TECHNOLOGY:

Thermal Energy Storage

SOURCE:

Chub, T.A., Nemecek and Simmons. Energy Storage As Heat-of-Fusion in Containerized Salts. Naval Research Laboratory NRL Memorandum Report 4267, 1980.

INFORMATION:

TABLE 2
Cost Estimate for Energy Storage Based on MgCl_2 , NaCl ,
 KCl Eutectic Costs per kWh⁽¹⁾ (s 1979)⁽¹⁾⁽²⁾

Item	Proof-of-Concept Tank	At Build-up Rate 1200 MWh ⁽¹⁾ per year
Anhydrous Eutectic	16.48	1.37 ⁽²⁾
Containers	9.41	2.20 ⁽³⁾
Heat Transfer Fluid	23.04	3.70 ⁽⁴⁾
Salt Transportation	1.65	0.49 ⁽⁵⁾
Containment Vessel	27.50	1.20 ⁽⁶⁾
Foundation	0.58	0.76 ⁽⁷⁾
Load Bearing Insulation	0.23	0.04 ⁽⁸⁾
Loose Insulation	1.23	0.15 ⁽⁹⁾
Piping—Including Boiler, Superheater	5.49	0.24 ⁽¹⁰⁾
Pump for Heat Transfer Fluid	2.03	0.05 ⁽¹¹⁾
Feedwater Pump	0.46	0.02 ⁽¹²⁾
TOTAL of Big Items	88.10	10.22
Allowance for Misc. and Construction, (30% of above)	26.43	3.07
TOTAL	114.53 \$ kWh ⁻¹ ⁽¹²⁾	13.29 \$ kWh ⁻¹

(1) All costs based on eutectic heat-of-fusion measurement 240 kJ kg^{-1} (Appendix C).

(2) Based on quotes for raw salts with processing costs estimated as per Appendix B. Rossborough estimate is 6.1 \$ kWh⁻¹.

(3) Based on 1975 can prices of the Freund Can Co., inflated 10% per year. See Appendix G.

(4) Based on m-terphenyl fractionated within tank from a starting fluid of thermal 88, Appendix F. Initial cost only.

(5) 1500 miles. Cost inflated 10% per year from 1976 quote.

(6) Based on use of 66' tanks providing 444 MWh⁽¹⁾ storage and weighing 241 tons. Cost of steel and fabrication estimated at 1200 \$ ton⁻¹.

(7) 7324 tons of salt + 241 tons steel $\Rightarrow$ 4422 lbs. ft^{-2} based on slab 2 feet thick of sufficient area to reduce ground loading to 1000 lb ft^{-2} . Cost of doubly reinforced concrete taken at \$300 per cu. yd.

(8) Based on 24" of Foamglas.

(9) Based on 40" of Dacotherm sodium silicate insulation.

(10) Ratio of piping cost to tank cost assumed same as for proof-of-concept tank.

(11) Three pumps (500 gpm each @ 100' head) with 20 hp motors, Lawrence Pump and Engine Co., Lawrence, MA.

(12) Two triplex pumps plus relief valve including motors, F.E. Meyers, Ashland, OH.

(13) Actual cost several times this value due to expensive site preparations, development costs and costs associated with electrical heater input system.

ASSUMPTIONS & COMMENTS:

1979 dollars