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Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
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A REVIEW OF STORAGE BATTERY SYSTEM COST ESTIMATES

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SUMMARY

The purpose of the work described in this report was to identify the current status of battery system cost analyses and make recommendations for future work in this area. Cost analyses for zinc bromine, sodium sulfur, and lead acid batteries were reviewed. Zinc bromine and sodium sulfur batteries were selected because of their advanced design nature and the high level of interest in these two technologies. Lead acid batteries were included to establish a baseline representative of a more mature technology.

The most recent and thorough cost analyses of zinc bromine, sodium sulfur and lead acid battery systems were sought for the review. Zinc bromine and sodium sulfur battery developers were contacted to ensure that the latest and/or most detailed analyses were being considered. Current manufacturers of lead acid batteries were not contacted since interest was primarily oriented toward lead acid battery cost analyses that were completed during the earlier development stages of that technology. The lead acid battery cost analyses served as a bench mark for comparison with zinc bromine and sodium sulfur battery cost analyses. The time frame of the analysis process limited PNL's review to publications available by the end of 1984.

An essential part of the review process was the development of a list of cost characterizing information relevant to battery systems. The list defines the type of information and level of detail that should be available to fully and adequately evaluate the costs of a battery system. Following a standard set of estimating guidelines would benefit the cost analysis process by providing more consistency between estimates, more complete estimates, more accurate estimates, and better reproducibility by independent parties. All of these factors would give greater credence to the estimated costs and enhance their usefulness to the R&D planning process.

The list of cost characterizing information is headed by six categories: system description summary, design specifications, performance specifications, manufacturing cost, installed system cost, and life-cycle cost. System description and design/performance specifications define the system being

costed and serve to identify cost differences among systems stemming from differences in system boundary, design type, and performance characteristics. Cost estimating ground rules and assumptions are defined within each of the cost categories. Each category addresses the costing premises and emphasized the inclusion of all cost components pertinent to manufacturing, installed system, and life-cycle costs, respectively.

Each of the battery system cost analyses reviewed was evaluated with regard to the system completeness and level of detail associated with the cost characterizing information described above. The emphasis of the evaluation was oriented toward determining whether the information presented would allow an independent reconstruction of the estimate and/or reconciliation of estimates from different sources. No attempt was made in this study to validate any single estimate or reconcile two or more estimates to common assumptions.

In general, cost analyses for mature lead acid batteries have been more numerous, more complete, and have greater detail than for either zinc bromine or sodium sulfur batteries. Several cost analyses completed for lead acid batteries could, with minor modifications, serve as examples of expected levels of detail and completeness for other batteries. The quality of the economic analyses combined with the greater commercial experience has created less uncertainty in estimated costs for lead acid battery systems.

The lack of maturity in zinc bromine and sodium sulfur battery cost analyses, when compared to lead acid batteries, can be partly attributed to the differences in design maturity. The level of design detail available provides an upper limit to the level of cost detail possible. Still, improvements could be made even at the current level of design maturity. Problems currently facing zinc bromine and sodium sulfur battery cost analyses are briefly discussed below:

- Cost information is fragmented. No single report addresses each of the six major categories of cost characterizing information. Rapidly changing designs make it difficult to trace costs presented in one report to design information presented in another report.

- Completeness of estimates varies significantly. Incomplete estimates inevitably lead to underestimated costs. Differences in completeness also makes direct comparison of cost estimates impossible.
- May estimates lack supporting details. Lack of detail makes an independent reproduction of the estimate impossible, thus lowering credibility. For example, descriptions of manufacturing operations, floor space requirements, and equipment were often limited, if they existed at all.
- Very few installed system or life-cycle cost estimates. Estimates of installed system and life-cycle costs were limited to three sources for zinc bromine batteries and two sources for sodium sulfur batteries.

The following observations apply to all battery systems. Converter costs were found to vary widely with assumptions made regarding power level, design, and production volume. Converters for large battery systems are currently in their own developmental phase and suffer from cost uncertainty that is comparable with that for the batteries themselves. Finally, it is important to remember that the technical feasibility, the probability a battery will work as advertised, may be significantly different for two batteries that are estimated to have similar installed-system and life-cycle costs. Two systems must provide a similar service in order for cost comparisons to be meaningful.

In view of the observations summarized above, the following recommendations are offered as a means to improve battery cost analyses:

1. Develop standard guidelines which establish the system components to be included, the appropriate level of detail in description, and ground rules and assumptions for estimating manufacturing, installation, and life-cycle costs. The implementation of guidelines would serve to standardize the economic analysis procedure and focus on cost differences attributable to differences in battery type or design.

2. Spend more effort characterizing installed system and life-cycle costs. Balance-of-plant, battery replacement, and O&M costs are just as important as manufacturing costs to the total battery system cost. Additional balance-of-plant and life-cycle cost studies are needed to develop a balanced set of cost characterizing information.

3. Complete cost analyses in more detail and more frequently. More frequent cost analyses will minimize the problem of cost analyses becoming outdated by changes in technology.

Each of the recommendations cited above represents a part of an overall plan to enhance the state of battery cost analysis. The availability of quality cost data is seen as a first step in this plan. Consistent cost analyses completed for the entire battery system will lay the groundwork for the development of cost goals and R&D plans, market assessments, and cost/performance tradeoffs.

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TABLES

1.0 INTRODUCTION

This report summarizes work completed within the Technology and Economic Analysis (TEA) Program at the Pacific Northwest Laboratory. The long-term objectives of the TEA Program's Battery Cost Analysis Task are to: 1) enhance coordination of battery cost analysis activities, 2) improve the quality of battery system cost estimates, and 3) perform cost-oriented analyses that help the Department of Energy establish goals, develop R&D plans, and make decisions on R&D emphasis. Task objectives for FY 1985, and the focus of this report, were to identify the current status of battery system cost analyses and make recommendations for future work in this area.

Cost analyses for zinc bromine, sodium sulfur, and lead acid batteries were reviewed. Zinc bromine and sodium sulfur batteries were selected because of their advanced design nature and the high level of interest in these two technologies. Lead acid batteries were included to establish a baseline representative of a more mature technology.

Estimates prepared by individual developers were critiqued to identify global problems that existed and to suggest possible remedies. The quality of any single estimate provided by a developer reflects their resources and research focus, among other factors, and the level of quality may vary for reasons beyond the control of any individual developer.

2.0 APPROACH

The most recent and thorough cost analyses of zinc bromine, sodium sulfur, and lead acid battery systems were sought for review. Zinc bromine and sodium sulfur battery developers were contacted to ensure that we were working with the latest and/or most detailed analyses. A list of the developers and other organizations contacted is shown in Table 2.1. Current manufacturers of lead acid batteries were not contacted because we were primarily interested in lead acid cost analyses that were completed during its earlier development phase. The lead acid cost analyses served as a benchmark for comparison with zinc bromine and sodium sulfur cost analyses. The time frame of the analysis process limited the review to publications available by the end of 1984. A complete list of the articles and reports reviewed is presented in Appendix D.

TABLE 2.1. Battery Research Organizations Contacted

Firm	Contact	Technology
Dow Chemical	Charles Levine	Sodium Sulfur
EPRI	Jim Birk	Several
ERC	Marty Klein	Zinc Bromine
Exxon	Dick Bellows	Zinc Bromine
Ford Aerospace	Bob Minck	Sodium Sulfur
General Electric	Bill Auxer	Sodium Sulfur
Public Service Electric & Gas	John DelMonaco	Several
Sandia National Laboratory	Kevin Murphy	Several

An essential part of the review process was the development of a list of cost characterizing information relevant to battery systems (see Table 2.2). The list outlines the type of information and level of detail that should be available to fully and adequately evaluate the costs of a battery system. Following a more standard set of estimating guidelines would benefit the cost analysis process by providing more consistency between estimates, more complete estimates, more accurate estimates, and better reproducibility by independent parties. All of these factors would give greater credence to the estimated costs and enhance their usefulness to the R&D process.

TABLE 2.2. Cost Characterizing Information for Battery Systems

System Description Summary

- System Operational Description
- General Features
- Materials of Construction
- System Completeness

Design Specifications

- Power Rating
- Capacity
- Submodule, Module Size
- Series/Parallel Connections
- Electrode Size
- Electrolyte Volume
- Battery Weight and Dimensions
- Interface Requirements

Performance Specifications

- Energy Efficiency (voltaic, coulombic, net)
- Charge and Discharge Rates
- Current Density
- Effective Capacity
- Current and Voltage Ratings
- Cycle Life
- Depth of Discharge
- Peak Power
- Duration of Peak Power

Manufacturing (Factory) Cost

- Assembly Procedure/Unit Operations
- Manufacturing Equipment
- General Plant Facilities
- Plant Floor Space
- Direct Materials and Labor
- Overheads
- Profit
- Taxes
- Unit Costs for Material, Labor, Overhead
- Plant Throughput; Operating Schedule

Installed System Cost

- FOB Purchase Price
- Shipping
- Field Materials
- Field Labor Hours
- Auxiliary Equipment/Structures
- Field Indirect Cost Factor
- Field Labor Rate

Life-Cycle Cost

- Installed System (initial capital cost)
- Battery Replacement
- Salvage Value/Disposal Costs
- Maintenance
- Auxiliary Power
- Unit Labor Costs
- Economic Life
- Discount Rate
- Component Escalation Rates

The list of cost characterizing information is headed by six categories: system description summary, design specifications, performance specifications, manufacturing cost, installed cost, and life-cycle cost. System description and design/performance specifications define the system being costed and serve to identify cost differences among systems stemming from differences in system boundary, design type, and performance characteristics. Cost estimating ground rules and assumptions are defined within each of the cost categories. Each category addresses the costing premises and emphasizes the inclusion of all components pertinent to manufacturing, installed system, and life-cycle costs, respectively.

The battery description provides a qualitative discussion of cell chemistry and battery features and operation. The design specifications describe the battery in a more quantitative way leading to a physical description of the system. Included here is information such as submodule/module size, power rating, capacity, and system configuration (series, parallel, both). The system description summary lists the battery features and discusses the completeness of the system design information. Performance specifications include energy efficiency (voltaic, coulombic, net), charge and discharge rates, battery life, and depth of discharge.

The manufacturing cost estimate includes overheads, taxes, and profit as well as direct materials and labor. The manufacturing characterization also includes a description of the assembly procedure and unit operations. Plant facilities, including specialized equipment, are specified as well. Critical assumptions include labor rates, material costs, plant capacity, and facility life.

Installed system costs include all expenditures necessary to place a battery system in operation at a specific site. Cost components in this category include battery FOB price, transportation, field materials and labor, auxiliary equipment, and design and engineering. Two important assumptions for this category are the field labor rate and field indirect cost factor.

Life-cycle cost components include initial (installed) battery system cost, battery replacement, salvage value or disposal, maintenance, and auxiliary power. Estimation of maintenance costs involves decisions on the time allotted for specific tasks as well as the unit labor rate. Important economic assumptions include system economic life, discount rate, and cost component escalation rates.

Each of the battery system cost analyses reviewed was evaluated with regard to the system completeness and level of detail associated with the cost characterizing information described above and presented in Table 2.2. The emphasis of the evaluation was oriented toward determining whether the information presented would allow an independent reconstruction of the estimate and/or reconciliation of estimates from different sources. No attempt was made in this study to validate any single estimate or reconcile two or more estimates to common assumptions. Cost figures presented in the sections that follow have not been normalized to standard assumptions other than the price year. Otherwise, the estimates are as presented in the original sources. The index of GNP price deflators was used to adjust costs from one price year to another. Index values corresponding to calendar years 1975 through 1984 are shown in Table 2.3.

The evaluation of zinc bromine, sodium sulfur, and lead acid batteries follows in Sections 3.0, 4.0, and 5.0, respectively. Each section includes a description of the cells, batteries, and cost analyses that have been developed. Summary cost estimates ($/kWh) extracted from the original sources are presented in these sections. Additional cost data supporting the individual estimates are presented in Appendices A, B, and C. Observations and recommendations are discussed in Section 6.0.

TABLE 2.3. GNP Implicit Price Deflators

Year	Index
1975	125.79
1976	132.34
1977	140.05
1978	150.42
1979	163.42
1980	178.42
1981	195.60
1982	207.38
1983	215.34
1984	223.38

3.0 THE ZINC BROMINE BATTERY

Zinc bromine battery system cost analyses are described and discussed in this section. Battery cost analyses were reviewed with regard to the completeness and level of detail of their system descriptions and design and performance specifications, as well as manufacturing, installed system, and life-cycle cost estimates. A brief description of zinc bromine cells and batteries is also provided.

3.1 BATTERY DESCRIPTION

This section provides a general description of zinc bromine battery technology. The fundamentals of the zinc bromine cell are presented, followed by a discussion of the general design features of the two zinc bromine batteries now being developed.

3.1.1 The Zinc Bromine Cell

The cells that compose a zinc bromine battery are based on the reversible reaction between zinc and bromine to form zinc bromide.

$$Zn + Br_2 \rightleftarrows Zn\,Br_2$$

In its simplest form, the cell consists of an anode and a cathode, an aqueous electrolyte solution of zinc bromide, a conductor connecting the anode and cathode, and a power source. During the charge cycle, the zinc bromide in the electrolyte separates into elemental zinc, which plates out on the anode, and elemental bromine, which forms around the cathode. When the cell is discharged, the elemental zinc and bromine recombine to form the zinc bromide salt. Electricity is generated during discharge by the flow of electrons from the anode to the cathode as elemental zinc is converted to zinc ions. Zinc bromine batteries are appealing for energy storage applications because of their electrochemical simplicity and reversibility.

There are two designs for zinc bromine batteries that are currently being developed. One design originated with Gould Laboratories and was further developed by Fluor Engineers and Energy Research Corporation (Gould battery).

The other design originated with Exxon Research and Engineering Company (Exxon battery). Although the two battery designs are generally similar, there are some differences that affect the cost estimates. The following two subsections will discuss the similarities and differences between the Exxon and Gould batteries. The adequacy of the design information is discussed in Section 3.2.

3.1.2 The Gould Design

When work on the Gould battery was taken over by Fluor and ERC, design emphasis changed from an 80 kWh module developed for photovoltaic applications to a 500 kWh battery system that could be tested at the Battery Energy Storage Test (BEST) facility. The 500 kWh battery is composed of 30 submodules (3.33 kW ea) submodules with a discharge voltage of 83.3V each (Monn 1983). The cell stacks use the same design as the 80 kWh battery. However, the most recent cell design described in an unpublished report substituted carbon-plastic composite electrodes, in order to save costs. The stacks can be held together either by compression with strongback assemblies, or by heat sealing of the plastic components.

The submodules are hydraulically connected in 10 parallel sets, with three parallel submodules per set. The anolyte system includes a heat exchanger and a hydrogen bromine recombiner made of a coiled bed of catalyst. The catholyte system includes a static mixer and a bromine storage facility. These systems also include pumps, piping, storage tanks, and controls. The electrolyte feeder lines contain rotating vanes used to momentarily interrupt the electrolyte flow. This has the effect of increasing the resistance through the electrolyte, so that shunt current losses through the electrolyte manifolds will be reduced.

The 30 submodules are electrically connected in series and parallel. Three submodules are connected in parallel per group, five groups are linked in series per string, and the two strings are parallel-connected. The resulting 500 kWh battery can deliver 240 amps at 416.7 volts for five hours. The electrical system includes cabling, temperature switches, fuses, ammeters, and a control panel.

3.1.3 The Exxon Design

The Exxon zinc bromine battery chemistry is similar to the Gould battery and many design principles are also currently similar. However, there are specific engineering differences between them, which affect their cost and lifetime estimates.

A 20 kWh battery was used as the basis for Exxon's cost estimate (Bellows 1983a, 1983b). This battery has two stacks of 78 bipolar cells each, connected in parallel. Each electrode has an area of 1200 cm^2. The nominal discharge is 120 volts. The cells are manufactured by a co-extrusion process for the electrode, the separator material is extruded, and the separator frame is injected molded. The carbon plastic electrodes are less expensive than those made of pure carbon used by Gould, but they may have a shorter lifetime (Bechtel 1982).

As with the Gould design, the electrolyte is divided into separate anolyte and catholyte circulation systems. The anolyte system includes heat rejection via plastic coils carrying forced cooled air, and a hydrogen bromine recombiner. The catholyte system includes a reservoir for the polybromide complex, but does not need a static mixer; dispersal of the bromine complex in the electrolyte is achieved through normal pumping action. Centrifugal pumps are used, and piping and reservoirs are also included.

Shunt currents from the cells through the electrolyte manifold are prevented by using "tunnel" shunt current protection. This method uses connections (tunnels) between the channels which connect the manifolds to the cells. A protective current is passed through the common electrolyte network from the first channel/tunnel to the last channel/tunnel. The voltage drop through each tunnel, which results from this current, is equal to the voltage of the cell. The electrical system for the Exxon battery also includes instrumentation, controls, busbars, tie rods, and miscellaneous hardware.

3.2 EVALUATION OF COST ANALYSES

This section evaluates the adequacy of previous cost data and cost analyses developed for zinc bromine batteries. The structure of this section closely follows the list of cost characterizing information presented in Table 2.2. The adequacy of information is captured in the system completeness and level of detail associated with the cost analyses reviewed.

3.2.1 System Descriptions

Design information for the two zinc bromine battery types should exist in sufficient detail to determine specific similarities and differences, if accurate cost comparisons are to be possible. The designs should include not only the battery itself, but should also describe the system in which the battery will be used so that the installation arrangements and auxiliary equipment can be compared. This section will discuss the system descriptions for the Gould and the Exxon batteries.

The design specifications for the 500 kWh battery system intended for the BEST facility (Gould battery) are comprehensive for that facility. The report describes the construction of the cells in the submodule stacks and the stack assembly, and presents the following information: 1) diagrams of process flow, piping, and mechanical flow for the electrolyte systems, 2) a photograph of a 3-D model of the completed battery system, 3) wiring diagrams, 4) lists of instruments, controls, and equipment, and 5) startup and shutdown procedures (Monn 1983). These design specifications are for a conceptual facility only; the largest battery size that had actually been constructed at the time of this review was 80 kWh.

Some of the auxiliary equipment required by the battery system was available at the BEST facility, and was therefore excluded from the design specifications for the BEST battery. Excluded items were power conditioning equipment, foundations, cranes for battery unloading, fire protection systems, and sewer drainage connections for cooling water and power. The battery could not be considered to be a stand-alone unit without these items. If the 500 kWh Gould battery system were used in any other application besides the BEST facility, the excluded items would need to be included in the design specifications.

Publicly available design specifications for the Gould battery do not include the most recent changes in cell construction. An unpublished ERC report indicates that carbon plastic is now being used for the electrode. This could alter the cell construction, might alter the hydraulic and electrical connections, and would definitely affect the cost estimate.

The design information for the Exxon two-stack battery describes the manufacture of the two-piece unit cell with co-extruded electrodes and extruded separators, discusses shunt current protection design factors, describes the flow frame design selected for the cells, lists the dimensions of electrodes, frames, channels and manifolds, and includes a schematic drawing of the cell construction. Hydraulic components such as pumps, reservoirs, and electrolyte are the same as the ones used for their earlier six-stack battery design. However, no design information was presented for the system that would use the 20 kWh battery module. No system configurations have been suggested, so the interbattery hydraulic and electrical connections that would be necessary for battery installation have not been described. Information about the auxiliary equipment and the structural supports needed for a battery installation are also needed in order to allow a complete design comparison between the two zinc bromine batteries.

3.2.2 Performance Specifications

The performance specifications define the functions of the battery systems and include ratings of capacity, output, efficiencies, loading, and charge/discharge time. Performance specifications are needed, along with design specifications, to ensure cost comparability between different battery systems. The performance specifications are listed in Table 3.1 for the Exxon and the Gould batteries.

The designers of the Gould 500 kWh battery system, Fluor and ERC, could have intended the energy efficiency, electrode size, depth of discharge, and expected lifetime to be the same as the 80 kWh battery developed by Gould. If this is the case, the performance specification information needed that will allow a system comparison would be current density, zinc loading, and peak power for the Gould battery.

3.2.3 Manufacturing Costs

Each of the reports reviewed included an estimate of the factory (manufactured) cost of the battery. The quality of the estimates varied, but some

TABLE 3.1. Performance Specifications for the Exxon and Gould Batteries

Specification	Gould	Exxon
Nominal Capacity	500 kWh	20 kWh
Voltage Delivered	916.7 V	120 V
Current Delivered	240 amps	55.5 amps[(a)]
Charge/Discharge Rate	5 hours	3 hours
Overall Energy Efficiency[(b)]	65-70%[(c)]	65-70%
Electrode Size	929 cm^2[(c)]	1200 cm^2
Zinc Loading	--	94 mAh/cm^2
Peak Power	--	26 kW
Depth of Discharge	80%[(c)]	80%
Expected Lifetime	2500 + cycles[(c)]	1000 + cycles

(a) Calculated from data available.
(b) Obtained by multiplying voltaic and coulombic efficiencies.
(c) Performance specifications for the Gould 80 kWh battery.

general observations can be made. The assembly process is usually not described in enough detail to substantiate labor and floor space estimates and/or allow for an independent analysis of the estimate. An exception would be the description of manufacturing operations in Monn (1983). Manufacturing plant equipment descriptions were lacking in all of the reports evaluated. Several reports contained estimates for incomplete systems; however, the most recent estimates for both the Exxon and Gould batteries include the majority of direct and indirect cost components that might be included.

Most of the reports used the A. D. Little (ADL) guidelines (George 1979) for estimating factory FOB costs from estimates of direct material and labor, factory floor space, and factory equipment costs. The ADL method provides a standardized approach to developing factory FOB costs and is relatively simple to apply, but should probably be modified to reflect changes in depreciation laws that have occurred since the model was first developed. It may be better to develop a new approach based on levelized production cost. This would allow a more accurate treatment of capital and expense cash flows over the life of a manufacturing facility.

Estimates of factory costs for $ZnBr_2$ batteries are presented in Table 3.2. These estimates are as published in each of the reports, except for adjustment to 1984 dollars. No attempt has been made to reconcile the estimates to a standard set of assumptions. Supporting details for the manufacturing cost estimates are presented in Appendix A.

3.2.4 Installed System Costs

Only three of the reports reviewed contained a complete estimate of installed system cost. Installed costs were estimated by Bechtel (1982) for both the Gould and Exxon batteries. Their estimates were extremely detailed and addressed all of the major cost components associated with field installation for a battery except power conditioning. Gould estimated installed system costs for their battery (Ramsay 1982), but several components (such as power conditioning, shipping, and field labor) were not included. Fluor/ERC (Monn 1983) estimated an installed system cost for the Gould battery based on a 500 kWh module designed for the BEST facility. Their estimate also lacked power conditioning equipment and other auxiliaries. Table 3.3 presents the estimates for installed system costs as prepared by Bechtel, Gould, and Fluor/ERC with

TABLE 3.2. Non-Normalized Factory Cost Estimates for Zinc Bromine Batteries

Source	Battery Design	1984$/kWh
Bechtel 1982	Gould	120-172
Bechtel 1982	Exxon	44-67
Bellows 1983b	Exxon	50
Monn 1983	Gould	106
Ramsay 1982	Gould	86
Bellows 1983a	Exxon	35

TABLE 3.3. Non-Normalized Installed System Cost Estimates for Zinc Bromine Batteries

Source	Battery Design	1984$/kWh
Bechtel 1982	Exxon	121-216
Bechtel 1982	Gould	237-379
Ramsay 1982	Gould	117
Monn 1983	Gould	524

adjustment to 1984 dollars. No attempt was made to reconcile the estimates to a standard set of assumptions. Supporting details for the installed cost estimates are presented in Appendix A.

3.2.5 Life-Cycle Costs

Bechtel (1982) and Ramsay (1982) were the only two reports which included estimates of life-cycle cost. Both sources included all of the major life-cycle components in their estimates. Bechtel explicitly included the cost of energy losses due to system inefficiencies at 5¢/kWh. A real discount rate of 2% was employed by Bechtel. The Ramsay analysis used real discount rates of 6% and 8% in his calculations.

The life-cycle costs estimated by Bechtel and Ramsay are presented in Table 3.4. These estimates are as published in the two reports, with adjustment to 1984 dollars. No attempt has been made to reconcile the estimates to a standard set of assumptions. Supporting details for the life-cycle cost estimates are presented in Appendix A.

TABLE 3.4. Non-Normalized Life-Cycle Cost Estimates for Zinc Bromine Batteries

Source	Battery Design	1984$/kWh
Bechtel 1982	Exxon	348-634
Bechtel 1982	Gould	420-738
Ramsay 1982	Gould	188-193

4.0 THE SODIUM SULFUR BATTERY

Sodium sulfur battery system cost analyses are described and discussed in this section. Battery cost analyses were reviewed with regard to the completeness and level of detail of their system descriptions and design and performance specifications, as well as manufacturing, installed system, and life-cycle cost estimates. A brief description of sodium sulfur cells and batteries is also provided.

4.1 BATTERY DESCRIPTION

This section provides a general description of sodium sulfur battery technology. The fundamentals of the sodium sulfur cell are presented. This is followed by a comparison of general design features of different cells and a description of batteries now being developed.

4.1.1 The Sodium Sulfur Cell

The cells that compose a sodium sulfur battery are based on the reversible reaction between liquid sodium and liquid sulfur to form liquid sodium polysulfide.

$$2\ Na + y\ S \rightleftarrows Na_2S_y$$

Sodium is the anode for this cell, sulfur is the cathode, and the electrolyte is usually beta"-alumina. During charging, the sodium polysulfide is broken down into sodium and sulfur; during discharge, the reaction is reversed. The exact proportion of recombinant sodium and sulfur in the sodium polysulfide will vary, ranging from Na_2S_5 to Na_2S_2, depending on the depth of discharge. The potential advantages of the sodium sulfur cell are that raw materials are abundant and inexpensive and that the cell has high energy efficiency and energy density.

Sodium sulfur cell designs differ to a much greater extent than zinc bromine cell designs. Three NaS cell designs will be described in more detail: one developed by General Electric, one developed by Ford Aerospace, and one developed by Dow Chemical. Each company has tested several cell designs. The designs described in this report were those that served as the basis for their battery cost estimates.

4.1.1.1 The General Electric Cell

General Electric, in conjunction with Chloride Silent Power, Ltd., has developed two different types of NaS cells. The first type, referred to as the NaS7, is intended primarily for electric vehicle use. This design features the sulfur electrode on the inside of the electrolyte, and the sodium on the outside. The NaS7 cell features good reliability and a long lifetime, mostly because there are fewer corrosion problems if the sulfur is in the center (Roberts 1984). However, since cell capacity is related to the amount of sulfur, the central sulfur cell has a lower capacity and, therefore, is a more expensive way to store power (Wicker 1979). The central sulfur configuration might be preferred for applications where safety is emphasized more than cost.

The second cell type, referred to as the FII cell, is intended primarily for load-leveling applications. The FII cell has an upper sodium reservoir, an inner core of sodium, a beta"-alumina electrolyte, an outer well of sulfur, and a chromized steel outer container. The sulfur electrode contains carbon fibers to act as a wick. The seal between the electrolyte and the reservoir is made of alpha-alumina ceramic and a borosilicate glass to bond the alpha-alumina to the beta"-alumina. There is also a sleeve around the sodium container to help reduce stress on the seal. The FII cell has twice the current density of the NaS7 cell, and has a lower projected cost.

4.1.1.2 The Ford Cell

Ford Aerospace has also developed sodium sulfur cells for electric vehicles and load-leveling applications. The cells for both uses are of similar design, with the main difference being that the electric vehicle cells have a smaller capacity and a shorter charge/discharge cycle. The cell that has received the most testing and cost analysis is called the Mark-II, developed for load-leveling applications (Harlow 1984).

The Mark-II cell configuration is similar to the GE FII cell in many respects. The arrangement of sodium, wick, sulfur, and electrolyte is the same. The main differences are in engineering design of safety components, methods of production, and materials for seal construction. The sulfur electrode is made up of twelve wedge-shaped electrode strips, which contain graphite felt and a carbon mat for wicking. A metering-bulkhead/safety tube is inserted on the inside of the sodium wick to prevent uncontrolled reaction of the sodium and sulfur. The radial compression seal used to assemble the upper and lower containers of the cell uses metallic aluminum gaskets between the alpha-alumina header and the electrolyte tube, rather than borosilicate glass. Another difference between the Mark II and the FII cells is in the manufacture of electrolyte. The electrolytes used by Ford Aerospace were produced by isostatic pressing of the dry powder to form the desired shape before sintering, rather than using electrophoretic deposition. Ford Aerospace considers the isostatic pressing method to be more economical.

4.1.1.3 The Dow Cell

The sodium sulfur cell being developed at Dow Chemical is completely different from either the Ford or the GE cell. Its description is included here because it illustrates the range of possible designs for the NaS cells. The Dow Chemical design does not use a beta"-alumina electrolyte. A specially developed borate glass, shaped into fine hollow fibers, is used instead. Sodium anolyte is on the interior of the fibers, and sulfur catholyte is on the exterior. Cell resistance is low because the ion path is short, and the thousands of fibers act as parallel resistances. The glass fibers are interspersed with coated aluminum foil, which acts as a cathode current collector. The cell assembly consists of a foil-fiber assembly immersed in the sulfur-polysulfide melt with the sodium reservoir at the top. The upper and lower containers can be made of aluminum rather than coated steel.

The potential advantages of this cell design include: 1) cell operation at very low current density, 2) less expensive hollow glass fibers, 3) greater design flexibility with regard to the desired energy and power levels, and 4) greater cell reliability (Levine 1981).

4.1.2 Battery Design

This section will qualitatively describe battery designs that use the Ford and General Electric cells. The designs selected were the ones used as the basis for the cost analyses that were reviewed. Quantitative performance specifications are listed and compared in Section 4.2.2.

4.1.2.1 The Ford Battery

The conceptual design for the Ford battery has a nominal rating of 20 MW or 100 MWh. An installed capacity of 132 MWh allows for cell failures and performance degradation over the battery lifetime. Typical charge time is 7 to 10 hours, with a 5-hour discharge time. The battery design was evaluated with two different options: 1) using smaller 211 Wh cells, or 2) using larger, 402 Wh cells. The smaller cell has a rated capacity of 130.2 Ah, a discharge current of A26, and a discharge voltage of 1.6 V. The larger cell has a rated capacity of 249.2 Ah, a discharge current of A49.8, and a discharge voltage of V1.6. Details of the cell configurations were discussed in Section 4.1.1.2.

The smaller-cell battery is assembled in the following way: 96 cells are arranged in parallel to form a submodule. Five submodules are arranged on a tray, and there are two trays per module. One hundred twelve modules are connected in a series to make a unit battery string. This string has a discharge current of A2600, an average discharge voltage of V1850, and an end-of-charge voltage of V2600. Five unit battery strings are connected in parallel for the 100 MWh stationary energy storage (SES) battery. The larger-cell battery also has 96 cells per submodule, but there is only one tray with five submodules per module. The larger-cell battery thus has half the number of cells per module as the smaller-cell battery. Extra modules are added to allow for the lower reliability that a smaller number of larger tubes would have.

The SES facility includes a power converter to provide an interface with the utility power grid. Electrical connections within the battery are provided by spider busbars made of aluminum. Forced-air cooling is used for temperature control. Modules are removed from the unit battery structure for maintenance or replacement. Preliminary data indicate that the cells could tolerate cooling to room temperature before removal and repair, which would improve the ease of maintenance.

4.1.2.2 The General Electric Batteries

General Electric has published a cost estimate for a 100 MWh rated utility load leveling battery that uses their FII cell. This cell is described in Section 4.1.1.1. Unfortunately, relatively little information about the design configuration of this battery system was presented (Roberts 1984). Therefore, this section will also discuss the design developed by Compagnie Generale D'Electricite (CGDE) of Marcoussis, France (Wicker 1981). This design includes a more complete set of cost and technical information. The CGDE design is based on a cell of optimized size that uses a beta"-alumina electrolyte. This cell had a smaller capacity than the FII cell, but the energy density and volumetric density were higher.

The 100 MWh battery designed for the FII cell was made from approximately 132,000 cells. Each cell has a design capacity of Ah447 with a theoretical capacity of Ah658, a discharge current of A89, a discharge voltage of V1.7, power rating of W152, and an energy rating of 765 Wh. The rated capacity includes a 15% excess for loss of capacity due to cell failure. Charge time is 7 hours and discharge time is 5 hours. The cells are arranged in the following way: 36 cells are assembled into a module, 363 modules are arranged in series to form a string, and 10 strings in parallel are connected to form the battery. Further details of the battery configuration had not been determined.

The battery system designed by CGDE is a 100 MWh system requiring 2.27×10^5 cells that use a beta"-alumina electrolyte. The number of cells includes the theoretical requirement, plus an excess to allow for cell failure and for capacity losses associated with connecting large numbers of cells in parallel. Each cell has a useful energy of 523 Wh, a charge time of seven hours, a discharge time of 10 hours, a maximum capacity of Ah309, and an energy efficiency of 80.3%. The cells are arranged as follows: 26 cells are connected in parallel to make a submodule, four submodules are connected to make a module, 436 modules are connected in a series to make a string, and five strings are connected in parallel to make a battery.

Thermal management for the battery is provided with nitrogen and with a minimal amount of foamed concrete insulation. The parallel nitrogen channels have a large cross section, and are made of refractory concrete. This arrangement allows lower pumping energy, although it requires a lot of space. Each string contains an independent nitrogen circulation system, which is located at the far end of the unit. A separate loop is incorporated for startup, and encloses the heat exchangers needed for the initial heating period. Thermal energy recovery is not used because the high battery efficiency reduces the economic value of a recovery system. The busbars used for current collection are made of aluminum.

4.2 EVALUATION OF SODIUM SULFUR COST ANALYSES

This section evaluates the adequacy of previous cost data and cost analyses developed for sodium sulfur batteries. The structure of this section closely follows the list of cost characterizing information presented in Table 2.2. The adequacy of information is captured in the system completeness and level of detail associated with the cost analyses reviewed.

4.2.1 System Descriptions

Design information for the batteries developed by Ford and General Electric should exist in sufficient detail to determine specific similarities and differences, if accurate cost comparisons are to be possible. The designs should include not only the battery itself, but should also describe the system in which the battery will be used so that the installation arrangements and auxiliary equipment can be compared. This section will discuss the system descriptions developed by Ford and General Electric.

Design information for the Ford load-leveling battery module is developed in detail. Flow charts thoroughly describe the process steps needed to prepare the electrolyte, the alpha-alumina header, the alpha-alumina seal, and the cell assembly. These flow charts provide a good idea of the design and manufacturing techniques used for the cells that make up the battery. A very clear exploded diagram of an assembled cell is included, which is a useful way to quickly demonstrate cell configuration. There is a diagram that shows how the cells are connected to form a submodule and how the submodules are stacked in a module. Another drawing shows the arrangement of the modules, the air cooling manifold, the insulation, the enclosure cover, and the module controller within the unit battery. The battery design also includes thorough discussions of the rationales for various design choices, such as a discussion of the advantages of aluminum busbars, various cooling options, design optimization for minimum cost and energy loss, and requirements for module controls.

The design information describing the incorporation of the units into a utility load leveling system, however, is less detailed. Site-specific information describing the power conditioning equipment, foundations, fire protection equipment, power connections, and construction requirements is not included. Little information is presented regarding maintenance requirements. Site assembly of a complete system from a 20 MWh unit battery should also be described to allow a complete cost analysis of the battery system.

The General Electric report on the FII cell battery system includes a comprehensive discussion of individual cell components, cell performance testing, safety, and cell failure, but very little discussion of utility cell assembly. Battery design information includes an evaluation of maintenance and cell efficiency requirements. However, the series-parallel arrangement of cells in the battery had not been determined, nor had the cooling system or the electrical connections. There is a diagram showing how unit batteries might be assembled into a load-leveling system, but no details were included.

Battery design for the FII cell was not complete for the battery or the load-leveling system, therefore we also reviewed information about the battery design developed by Compagnie Generale D'Electricite (CGDE). The CGDE report provides a thorough discussion of the manufacturing options for the electrolyte, and describes the process steps very clearly and in great detail. Design information for the cells even includes the dimensions of the busbars and the thermal insulation requirements. For the unit battery, there is a description of the complete thermal management system, including cooling, heat exchangers, fan, and startup heat requirements. The load-leveling battery system description also includes yardwork, engineering and construction planning, control room equipment, and installation requirements.

The report by CGDE provided comprehensive information about the electrolyte, but the descriptions of the cells, modules, and batteries lacked information about assembly and assembly methods. Descriptions of the arrangement of cells in the module or of modules in the unit battery were limited. Power conversion equipment was not included in the design nor was a rationale for estimated labor hours included.

4.2.2 Performance Specifications

The performance specifications define the functions of the battery systems and include ratings of capacity (both theoretical and nominal), discharge energy, voltage and current, efficiencies, charge/discharge time, and energy density. Performance specifications are needed, along with design specifications, to ensure cost comparability between different battery systems. The performance specifications are listed in Table 4.1 for the small and large-cell Ford battery, the GE FII cell battery, and the CDGE battery.

The performance specifications are complete, except for the following:

1. Theoretical capacity of the GE and CGDE batteries for the rated 100 MWh battery. This would be higher than the rated value, depending on the assumptions made for the number of additional cells that would be needed to ensure that battery capacity does not fall below the rated value. The assumptions would include information such as expected failure rate and resistance rise.
2. Energy footprint information for the GE and CGDE batteries which indicates the efficiency of a battery system in relation to its size.
3. Theoretical capacity of the CGDE cell, which would normally be higher than the rated capacity to allow for resistance losses.
4. CGDE battery discharge current.

4.2.3 Manufacturing Costs

Several manufacturing cost estimates have been completed by the sodium sulfur battery developers and their subcontractors. The estimates vary significantly in their level of detail, completeness, date of publication, and their bottom line cost per kilowatt-hour. Each of the more significant reports reviewed is discussed below.

TABLE 4.1. Performance Specifications for Sodium Sulfur Batteries

Specification	Ford Small Cell	Ford Large Cell	GE	CGDE
Cell Discharge Energy	211 Wh	402 Wh	765 Wh	523 Wh
Cell Theoretical Capacity	186 Ah	356 Ah	658 Ah	--
Cell Rated Capacity	130 Ah	249 Ah	447 Ah	309 Ah
Cell Discharge Voltage	1.6 V	1.6 V	1.7 V	1.7 V
Cells/Battery	537,600	288,000	131,000	227,000
Cell Efficiency	80% max 75% min	80% max 75% min	75-80%	80%
Rated Battery Discharge	100 MWh	100 MWh	100 MWh	100 MWh
Theoretical Battery Capacity	131 MWh	134 MWh	--	--
Battery Discharge Current	15,100 A[a]	15,200 A[a]	32,150 A	--
Battery Discharge Voltage	1000 V	1000 V	636 V	1000 V
Charge Time	7-10 hr	7-10 hr	7 hr	5 hr
Discharge Time	5 hr	5 hr	5 hr	5 hr
Energy Footprint	8 kWh/ft^2	8 kWh/ft^2	--	--
Energy Efficiency	75%	75%	75%	75%
Nominal Lifetime	10 yr	10 yr	30 yr	10 yr

(a) Calculated from available data.

A report prepared by Ford Aerospace (1980) contained one of the more detailed manufacturing analyses that we reviewed. The Ford report contains very detailed process flow diagrams, along with material unit cost data, equipment lists, and a manufacturing facility that was explicitly sized based on equipment floor space requirements. Unfortunately, several design changes have occurred since the estimate was made in 1980.

General Electric (Bast 1982, Roberts 1984) has published more recent reports with manufacturing cost estimates for their sodium sulfur battery. Unfortunately, their reports only provide summary cost information. Little substantiation or basis is given for the equipment, labor, and materials figures presented.

The most detailed battery cost estimate for a GE design was included in a report completed by Compagnie Generale D'Electricite (CGDE) (Wicker 1981). The CGDE report was primarily focused on the cost of producing beta"-alumina electrolyte tubes. The evaluation investigated alternative tube sizes and processing routes and compared tube costs manufactured from beta and beta"-alumina. The report included detailed descriptions of the manufacturing processes and itemized labor and material lists, but limited description of the equipment requirements.

A detailed analysis of beta"-alumina electrolyte tube costs was completed for Ford by Ceramatec (1980). The Ceramatec study was similar to that performed by CGDE for General Electric. Ceramatec's analysis included an examination of different tube sizes, different processing routes, and the availability of low cost raw materials.

The most recent estimate of the sodium sulfur cell developed by Dow Chemical was completed in 1981. The report by Levine (1981) provides detailed descriptions of unit operations and material, labor, and equipment requirements at the unit operation level. The report includes the cost of manufacturing the cells but not the cost of a complete battery system.

All of the reports mentioned above used the A. D. Little guidelines for estimating factory FOB costs. Using the guidelines facilitates the evaluation of the estimates by normalizing many of the economic assumptions and grouping costs in consistently defined categories. Factory FOB costs are presented in Table 4.2. These estimates have all been adjusted to 1984 dollars, however, no attempt has been made to reconcile any other differences in assumptions. Supporting details for the manufacturing cost estimates are presented in Appendix B.

4.2.4 Installed System Costs

Only two of the reports evaluated included an estimate of installed system cost for a sodium sulfur battery. Bechtel (1982) estimated the cost for a battery system installed in a photovoltaic power application. The Bechtel estimate selected the Ford Aerospace design as their baseline. Battery prices (FOB

TABLE 4.2. Non-Normalized Factory Cost Estimates for Sodium Sulfur Batteries

Source	Battery Design	1984$/kWh
Roberts 1984a	General Electric	71
Wicker 1981	General Electric	87
Bechtel 1982	Ford Aerospace	126 - 159
Sernka 1984	Ford Aerospace	89 - 94
Ford 1980	Ford Aerospace	105
Levine 1981	Dow Chemical	45[a]

(a) Cost estimate is for the cell only

factory) were based on information in Ford (1980) and studies from other sodium sulfur battery developers. Bechtel modified the developer's estimates based on their assessment of design completeness, material costs, manufacturing and assembly, operations, and cost of manufacturing facilities.

Bechtel's installed battery cost estimate was aggregated from material and labor costs for installation components. Major components included shipping, building, thermal management, instrumentation and electrical. The basis for each of the component estimates was substantiated by a detailed design description. The total installed cost was estimated to range from $199 to 272/kWh in 1984 dollars. CGDE developed the other installed sodium sulfur battery cost estimate that we reviewed. The CGDE estimate included major system components such as yardwork, civil and structural work, cooling and heating equipment, and control room equipment, but lacked detailed descriptions of the plant facilities or other cost bases and did not include converter costs. Their installed system cost estimate was $105/kWh in 1984 dollars. Supporting details for the installed system cost estimates are presented in Appendix B.

4.2.5 Life-Cycle Costs

Bechtel (1982) was the only report evaluated that estimated life-cycle costs for a sodium sulfur battery. The Bechtel estimate included all the major contributors to a life-cycle cost such as installed costs, salvage, maintenance, and energy losses. Battery replacement was assumed to be all at once for all of the modules. An initial redundancy of 16% was built into the battery to allow for a 10-year life before complete replacement. The total life-cycle cost was estimated by Bechtel to range from $404 - $602/kWh in 1984 dollars. Supporting details for the life-cycle cost estimate are presented in Appendix B.

5.0 THE LEAD ACID BATTERY

Lead acid battery system cost analyses are described and discussed in this section. Battery cost analyses were reviewed with regard to the completeness and level of detail of their system descriptions and design and performance specifications, as well as manufacturing, installed system, and life-cycle cost estimates. A brief description of lead acid cells and batteries is also provided.

5.1 BATTERY DESCRIPTION

This section provides a general description of lead acid battery technology. The fundamentals of the cell chemistry are presented, along with trade-offs in cell design, differences in cell types, and the general design features of different hatteries that have been developed from the lead acid cells.

5.1.1 The Lead Acid Cell

The electrochemical reaction that drives the so-called lead acid cell is between sponge lead, which functions as the negative electrode, and lead dioxide, which functions as the positive electrode. In an aqueous solution of sulfuric acid, the lead and lead dioxide are reversibly converted to lead sulfate and lead oxide. The overall chemical reaction is as follows:

$2\ Pb$ +	$2PbO_2$ +	$2H_2SO_4$ +	H_2O	$2PbSO_4$ +	$2PbO$ +	$3\ H_2O$
lead	lead dioxide	sulfuric acid	water	lead sulfate	lead oxide	water

The sponge lead and the lead dioxide are supported on grids made from lead alloys. The alloy materials may be a combination of antimony and arsenic, to increase grid strength and cell life, or calcium for safer operation. The positive and negative electrodes are usually separated by a microporous material. The plates of the cell are immersed in aqueous sulfuric acid electrolyte, which is contained in a plastic case. The cells are usually closed, except for ventilation requirements, and require the periodic addition of water. However, the recently developed "starved electrolyte" cell has an immobilized electrolyte that requires much less maintenance.

There are many manufacturers of lead acid batteries. Rather than discuss the cell design of each individual manufacturer, three categories of cell design will be described. These categories will include: 1) closed flooded electrolyte cell, 2) open flooded electrolyte cell, and 3) starved electrolyte cell. Following the cell descriptions, some representative batteries that use the flooded electrolyte cell will be described.

5.1.1.1 Closed Flooded Electrolyte Cell

The closed flooded electrolyte cell could be considered to be the most traditional category for lead acid cell design. The generic cell has several flat plate electrodes per cell. The plates are made of lead alloy grids with a coating of the active material. Positive and negative plates are alternated with a porous separator in between. Ventilation is provided from the cover to allow the escape of hydrogen, arsine, and stibine. The electrolyte is usually stirred by airlift pumps to ensure even distribution. Cooling requirements are usually met with a water system. Maintenance requirements include adding water, tightening connections, cleaning cell vents and cover, checking temperature, and checking electrolyte composition.

5.1.1.2 Open Flooded Electrolyte Cell

The open flooded electrolyte cell uses the same materials as the more traditional closed version, but its configuration is substantially different. A typical open cell would be a large, uncovered tank containing dozens of plates. Evaporation is reduced by floating a layer of glass or plastic beads on the top of the electrolyte. This cell design is intended to be used for large, stationary installations. These open cells can be effectively cooled with air, but ventilation systems would still be needed to inhibit the development of explosive mixtures. The cooling and ventilation auxiliary systems costs would be saved, along with the cost of the cover. However, water addition is required more frequently. Because the cells are large, heavy, and difficult to stack, the land requirements for an open-cell battery are higher. The open cells are also more susceptible to contamination.

5.1.1.3 The Starved-Electrolyte Cell

The starved electrolyte lead acid cell is currently in the developmental stage, and there is limited data available. These cells absorb the electrolyte with a highly porous separator, such as a combination of fiberglass and polyethylene. The cells can be operated in any position because the electrolyte is immobilized. The separator has sufficient void space to allow passage of oxygen from the positive to the negative electrode, where it recombines with hydrogen to form water. The recombination theoretically eliminates the need to add water. The grid alloys contain no antimony, usually they are made of lead-calcium alloys instead. This eliminates the generation of toxic gases during the equalization charge cycle. Ventilation requirements are reduced when hydrogen is recombined and toxic gases are eliminated. The battery operates at a positive pressure, with a safety vent for release of gas if the rate of overcharge exceeds the rate of recombination of hydrogen and oxygen. External corrosion is eliminated, because acid mist is no longer released.

5.1.2 Battery Design

This section will qualitatively describe only those battery designs that use the closed flooded electrolyte cell. Battery descriptions were limited to this type of cell for the following reasons:

1. There is a wealth of information about batteries based on this cell type. Many manufacturers have published comprehensive descriptions of battery design, manufacturing procedures, installation, auxiliaries, and costs.

2. Conversely, there is not much information about batteries based on either open flooded or starved electrolyte cells.

3. Battery design incorporating flooded electrolyte cells could be modified for the starved cell by removing some auxiliary systems, such as

the airlift pump, the ventilation exhaust, sloped floor, and acid resistant paint, and reducing or eliminating the maintenance requirements (Bechtel 1982).

5.1.2.1 The ESB Batteries

ESB has completed detailed design and cost studies on three different battery sizes: a 10 MW-100 MWh battery, a 20 MW-60 MWh battery, and a 20 MW-100 MWh battery (Ferrell 1977, Ferrell et al. 1977). The 100-MWh batteries are based on two VLL 45 cell assemblies (one with high specific gravity electrolyte and one with low specific gravity electrolyte), and the 60 MWh system uses a similar VLL 43 cell. Bechtel also used one of the VLL 45 cell designs as the basis for their own cost estimates for a 6.2 MWh (6200 kWh) energy storage system. Two representative battery sizes will be discussed in this section: the 20 MW-100 MWh system for utility storage, and the much smaller 6200 kWh system intended for applications such as shopping centers.

The 20 MW-100 MWh ESB battery has an actual energy output of 120 MWh at the beginning of its lifetime. It is constructed from 5484 VLL 45 (HSG) tubular positive cells with high specific gravity electrolyte. These cells are divided into six parallel strings, with each string containing 914 cells in series. The cells have only half an inch of space between them, except for safety aisles dividing the strings. This minimizes intercell connections and accessory systems, thereby reducing materials costs and increasing efficiency, but cell maintenance is more difficult. The cells are designed to meet the minimum output requirements (100 MWh) after a 2000 cycle lifetime.

The auxiliary systems for this battery design include:

1. A cooling water system to remove the heat generated by reaction thermodynamics, resistive losses, and polarization.
2. An airlift stirrer to circulate the electrolyte and maintain uniform acid concentration.
3. Electrical monitors for cells and batteries.
4. Connections between cells, rows, and sections of the battery.

Maintenance for this battery includes adding water to the cells to maintain electrolyte levels and specific gravity, cleanup of leakages, and tightening intercell connectors. Most of the water loss is expected to occur during the equalizing charge period. The battery is expected to require the addition of about 4.5 liters/month per cell of water. Intercell tightening would be needed shortly after installation, and the connections are expected to remain tight for the lifetime of the battery. Leakage is expected to occur randomly.

The 775 kW, 6200 kWh battery was designed by Bechtel, based on information supplied by ESB about their VLL 45 LSG cell (Bechtel 1982). This battery is intended for smaller applications, such as energy storage for a shopping center. The battery has an eight-hour discharge period, a newly installed capacity of 7750 kWh, and an end-of-life capacity of 6210 kWh. It is made up of 340 tubular positive cells with low specific gravity electrolyte, arranged in a single series string. Spacing between the cells is one half inch, as with the 100 MWh battery. The cells are arranged in two groups of four columns, and each column has 42 or 43 cells. There are aisles between the two groups and between the cells and the walls. The cell is expected to have a minimum lifetime of 2000 cycles, and a maximum lifetime of 2500 cycles. The lifetime is longer for this system, partly because the discharge period is longer, and partly because the electrolyte specific gravity is lower.

The auxiliary systems included in this design are:

1. A cooling water system.
2. A ventilation system for the battery room.
3. Monitors for detecting fires, hydrogen levels, and toxic gas levels.
4. An air lift pump system for electrolyte stirring.
5. Connections between cells, plus DC busses, disconnects, circuit breakers, power cables, and lighting.

Maintenance for this system is essentially the same as for the larger 100 MWh ESB system. Water is added annually, and periodic checks for leakage and/or loose connections are expected to be needed.

5.1.2.2 The Westinghouse Battery

Westinghouse has prepared detailed plans for a 10 MW, 40 MWh battery storage system, including a comprehensive discussion of the auxiliaries (Long 1977, Vaill 1977). This battery is based on their kW 160-45 cell. The cell has a nominal capacity of 3.2 KAh, or 6.2 kWh, at the beginning of its lifetime, when discharged over a 4-hour period. At the end of its lifetime, the cell has a capacity of 2.6 KAh, or 4.9 kWh for a 4-hour discharge period. The 40 MWh battery contains 8085 of these cells, arranged in 21 parallel strings of 385 cells connected in series. The strings are further subdivided into 11 units; each unit contains 5 modules of 7 cells each. The module is designed to be the unit of assembly at the site, rather than the cell. Each module has a structural foam base and a cover, which includes water cooling coils, an automatic watering mechanism, and vent plugs. Each module has a nominal capacity of 2600 Ah, or 34.6 kWh.

There have been extensive design studies made of the auxiliary systems needed to support the kW 160-45 - based battery. These include the electrical connections, the cooling water and automatic water addition systems, ventilation, monitoring and control, and power conversion.

All cables, wire ducts, and piping are routed underground. At the end of each string, there is an enclosure for the string contactor, fuse, and disconnect, which connects to the main bus work beneath the floor. The main bus connects underground to the converter.

The ventilation system uses a manifold for more efficient removal of gases and more flexible operation. Each cell in a module is connected through a flash arrestor to a module manifold. The module manifolds connect to the main underground ductwork at the end of each string. A fan is used to blow the gases out the exit stack.

Temperature control is provided with a water cooling system using an evaporative cooling tower and a coiled tube heat exchanger immersed in the cell electrolyte. Each module has a series of intercell water tubes that supply the cooling water to the surfaces of individual cell walls. A thin layer of open cell foam is applied to the cell walls to aid uniform wetting. The evaporative cooling system is designed to reduce water requirements and capital costs.

Automatic water addition is expected to be required at weekly intervals. Deionized water is piped to distribution manifolds at each 5 module unit. The manifolds are overflow-controlled to provide a fixed head to the gravity feed fill valve in each cell. A water level detector triggers the necessary water addition.

Monitoring and control systems for fire protection, acid containment, cell ventilation, temperature control, battery charge/discharge control, and system maintenance are included in the design. Different types of alarms, monitors, and controls were selected for all of these operations.

Maintenance is performed with a powered gantry crane used for overhead module handling. Disconnect fuses at the end of each unit provide safety for the personnel. Because an automatic watering system is used, maintenance requirements would be primarily module replacements, and repair of leakages or faulty connections.

5.2. EVALUATION OF LEAD ACID COST ANALYSES

This section evaluates the adequacy of previous cost data and cost analyses developed for conventional lead acid batteries. The structure of this section closely follows the list of cost characterizing information presented in Table 2.2. The adequacy of information is captured in the system completeness and level of detail associated with the cost analyses reviewed.

5.2.1. System Descriptions

Information on the batteries designed by ESB and Westinghouse should exist in sufficient detail to determine specific similarities and differences, if accurate cost comparisons are to be possible. The designs should include not only the battery itself, but should also describe the system in which the battery will be used so that the installation arrangements and auxiliary equipment can be compared. This section will discuss the battery system descriptions published by ESB and Westinghouse.

ESB's report on their 20 MW-100 MWh battery includes comprehensive system descriptions for everything except the tubular positive plates of the cells, the converter, and requirements for site installation. The description of the cells includes a listing of the quantity of lead, active materials, and electrolyte used to manufacture a cell; performance specifications at various discharge rates, and blueprints for the assembly of the cell. However, there are no descriptions of the configuration of the tubular positive plates, or of how they are produced.

The description of the auxiliary systems includes:

1. Oesigns and equipment lists for the cooling water system.
2. Equipment lists for the air lift stirrer.
3. Equipment lists for the electrical connections between cells, rows, and sections, and for the electrical monitoring of cells and batteries.
4. Calculations of the ventilation requirements based on the amount of each type of gas that would be generated by various battery operational modes.

The operating and maintenance requirements include instructions for performing daily charging, equalizing charging, and for operating the water cooling system. Recommendations for water addition include quantity and frequency requirements. There is a checklist for the inspection of cell connections, cell covers, and cooling systems. Safety precautions for working with acid electrolyte, electrical charge, and flammable and toxic gases are also included.

The Bechtel design of a 6200 kWh battery based on ESB cells does not include as much information about the cells or the battery system, but does include information about installation requirements, except for power conversion. Bechtel's battery layout, performance specifications, and electrical connections are briefly described. The various auxiliary systems are essentially the same as the system described by ESB. The Bechtel report, when combined with the information already published by ESB, presents a well-defined battery system.

The Westinghouse 40 MWh battery, based on their kW 160-45 cell, also has comprehensive system descriptions. Cell design information includes a diagram showing its configuration and dimensions, a flow chart describing its assembly, and a diagram of a seven-cell module. The description of the battery includes the layout diagrams, dimensions, and electrical connections, along with diagrams and designs for auxiliaries such as automatic watering, cooling, ventilation, monitoring, maintenance, safety systems, and power conversion. Instructions are given on how to charge and discharge the battery, how to maintain adequate ventilation, and how to repair or replace faulty modules.

The Westinghouse design for a lead acid battery also includes information about a state-of-the-art converter that a utility would need to transfer the stored energy. The technical information presented is adequate for accurate cost comparisons to be made between battery systems. The information is consistent, complete, and has the detail necessary to back the design decisions.

5.2.2 Performance Specifications

The performance specifications define the functions of the battery systems and include ratings of capacity, output, efficiencies, loading, and charge/discharge time. Performance specifications are needed, along with design specifications, to ensure cost comparability between different battery systems. The performance specifications are listed in Table 5.1 for the 100 MWh ESB Battery, the 40 MWh Westinghouse battery, and the 6200 kWhr Bechtel battery based on ESB cells. The performance specifications for the three designs for lead acid batteries evaluated in this section are adequate for accurate cost comparisons.

5.2.3 Manufacturing Costs

Manufacturing cost estimates reviewed for lead acid batteries are similar to zinc bromine and sodium sulfur in that the level of detail and completeness varied significantly among the battery developers. The principal difference between the manufacturing cost analyses for lead acid and the other two technologies is the greater detail provided by two of the lead acid developers. Each of the reports reviewed are discussed below.

TABLE 5.1. Performance Specifications for Lead Acid Batteries

Specification	ESB	Westinghouse	Bechtel
Nominal Energy Capacity	100 MWh	40 MWh	6.2 MWh
Average Discharge Voltage	1700 V	162 V	700 V
Charge Voltage	2150 V	1700 V[a]	800 V[a]
Equalization Voltage	2400 V	1900 V[a]	900 V[a]
Discharge Current	14 kA	6.5 kA[a]	--
Power Rating	20 MW	10 MW	0.8 MW
Discharge Time	5 h	4 h	8 h
Charge Time	9 h	10 h	9 h
Energy/Area	2.6 kWh/ft^2	1.7 kWh/ft^2	2.1 kWh/ft^2
Energy Efficiency	85%	76%	82%
Expected Lifetime	2000 cycles	1750 cycles	2500 cycles

(a) Calculated from available data for individual cells

Westinghouse completed manufacturing cost estimates for both "state-of-the-art" (Long 1977) and "advanced technology" (Pittman 1977) batteries. Both estimates included a comprehensive bill of materials. Equipment cost, labor requirements, and factory floor space were all itemized per unit operation. Overhead costs were also estimated on an itemized basis. The only shortcomings found were the lack of a process flow diagram in Pittman (1977) and the need for greater explanation of how profit and taxes were incorporated into the factory selling price.

Another detailed manufacturing cost analysis was completed by ESB, Inc., (Ferrell 1977) for their battery. The level of detail and completeness is similar to the Westinghouse studies described above. Materials, equipment, floor space, and manpower requirements are all itemized, the latter three per unit operation. ESB also includes a process flow diagram. Overhead costs are not well defined, however, and the inclusion of profit and taxes in the selling price could be explained better. Neither Westinghouse nor ESB used the subsequently published A. D. Little guidelines, which would remove the uncertainty surrounding the estimates of overheads, profit, and taxes.

Manufacturing cost estimates for three other lead acid battery developers, Gould, Globe Union, and C&D, were not as detailed as for Westinghouse or ESB. Only summary estimates were presented in papers presented at the Second Workshop on Lead Acid Batteries for Utility Applications. No detailed design report was found for C&D. A design report prepared by Globe Union (Weinlein 1977) did not include any cost information. Gould has more recently completed a comparison of several advanced storage batteries in residential, commercial, and utility applications (Ramsay 1982). The Ramsay report identifies the inputs to the A. D. Little manufacturing cost model for both low maintenance and maintenance-free lead acid batteries, but does not give any backup for how these inputs were estimated. Lead acid battery manufactured cost estimates are summarized in Table 5.2. Supporting details for the manufacturing cost estimates are presented in Appendix C.

5.2.4 Installed System Costs

Much more has been done to define balance-of-plant (BOP) and installed system costs for lead acid batteries than for either zinc bromine or sodium sulfur batteries. The most detailed work in this area has been completed by Westinghouse and Bechtel.

TABLE 5.2. Manufactured Cost Estimates for Lead Acid Batteries

Source		Battery Design	1984$/kWh
Boden	1977	C&D	82
Ferrell	1977	ESB	77 - 88
Towle	1977	Globe-Union	97
Hellman	1977	Gould	86
Ramsay	1982	Gould - Low Maintenance	116
Ramsay	1982	Gould - Maintenance Free	126
Long	1977	Westinghouse - State of the Art	81
Pittman	1977	Westinghouse - Advanced	70

Westinghouse (1976) completed a detailed definition of BOP requirements and a conceptual design and cost estimate for lead acid battery systems. Auxiliary components specifically addressed by Westinghouse are identified in Table 5.3. Westinghouse developed a conceptual design and cost estimate for a baseline 40 MWh, 1620 VDC system and then evaluated the cost/performance trade-offs under different assumptions for system voltage, cell reliability, level of monitoring, type of thermal management system, power rating, and larger cells. Costs were itemized per individual equipment item, and included an estimate for the converter. The estimates did not identity the breakdown between equipment, labor, and materials, however, or discuss the unit labor and material rates that went into the estimates.

Bechtel has completed several studies (Stolte 1977; Stolte 1982; Bechtel 1982) that address balance-of-plant costs for lead acid and other batteries. The 1977 study developed designs and costs for ten different battery systems built around the cells of the five lead acid battery developers (identified in Table 5.2). Costs were estimated for a complete system, including converters, thermal management, ventilation, controls, site, and building costs. Costs were broken down into direct and indirect field costs, engineering, and contingency. The 1982 report by Stolte developed BOP costs as part of a customer-side-of-the-meter assessment. Balance-of-plant components included battery

TABLE 5.3. Westinghouse BOP Components

Operational	Safety and Protection
Ventilation	Electrical Protection
Temperature Control	Acid Containment
Water Addition	Fire Equipment
Monitoring and Control	Hydrogen Detection
Charge/Discharge Control	Stibine Detection
Bus Work	Arsine Detection
Maintenance Requirements	
Layout	
Enclosure	

and power conditioning structures, control and monitoring, stibine and arsine detectors, direct current wiring and switchgear, fire protection, and makeup water system. Converters were specifically characterized and costed separately. Power conditioning (converter) costs were estimated as a function of rated power for both state-of-the-art and advanced designs. Balance-of-plant costs were estimated as a function of system capacity and duration deviation. These cost estimates were then used in a parametric investigation of customer-side-of-the-meter applications. The other Bechtel report (Bechtel 1982) estimated installed costs for conventional and sealed lead acid batteries in photovoltaic applications. Detailed BOP cost estimates were developed for eleven different battery/application combinations. The basis for BOP cost estimates is explained explicitly and costs are broken down into direct, indirect, and contingency components. No converter costs were included, however.

Other estimates of lead acid BOP costs include those by Ferrell (1977), Ramsay (1982) and Birk (1977). Each of these are of less detail and/or based on estimates developed by Westinghouse and Bechtel. Lead acid battery BOP and converter costs estimated by Westinghouse (1976) and Bechtel (Stolte 1977) have been inflated to 1984 dollars and are summarized in Table 5.4. Supporting details for the installed cost estimates are presented in Appendix C.

5.2.5 Life-Cycle Costs

The life-cycle costs of lead acid battery systems have been well defined compared to zinc bromine and sodium sulfur batteries. Several reports were reviewed that included estimates of O&M, salvage and other life-cycle cost components. Bechtel (Bechtel 1982, Stolte 1982) and Gould (Ramsay 1982) have completed the most detailed analyses of life-cycle costs. Each of these reports is discussed briefly below.

TABLE 5.4. Lead Acid BOP Costs

Source	Energy Related Costs	Power Related (Converter) Costs
Stolte (1977)	47 - 94 $/kWh	127-139 $/kW @ 20 MW
Westinghouse (1976)	$53/kWh	$131/kW @ 10 MW

Bechtel has defined O&M and other life-cycle cost components for lead acid batteries. Bechtel estimates O&M, salvage, battery replacement, and auxiliary power costs for state-of-the-art lead acid batteries in Stolte (1982). Costs were estimated based on consultation with battery manufacturers and Bechtel's engineering judgment. Expectations of maintenance requirements and net salvage credit varied widely among manufacturers, which points out the need to verify estimates with field tests. In a parallel study Bechtel (1982) estimated installed and life-cycle costs for conventional and sealed lead acid batteries in several different photovoltaic applications. Both of the Bechtel reports consider all the principal life-cycle cost components and provide a description of how the costs were estimated.

Ramsay (1982) has also estimated life-cycle costs for low maintenance and maintenance-free lead acid batteries in photovoltaic applications. Estimates were developed for battery replacement, O&M costs, and salvage credit. Auxiliary power requirements and efficiency losses were not characterized. Battery cell replacement was based on the continuous (rather than periodic) replacement of cells. This would enhance system reliability, but increases this aspect of life-cycle costs. Estimates for a 2000 kWh system are shown in Table 5.5. Costs have been adjusted to 1984 dollars, but otherwise have not been normalized to common assumptions. Supporting details for the life-cycle cost estimates are presented in Appendix C.

TABLE 5.5. Non-Normalized Life-Cycle Cost Estimates for Lead Acid Batteries

Source	Battery Type	$1984/kWh
Ramsay (1982)	"low maintenance"	586 - 625
Ramsay (1982)	"maintenance-free"	344 - 371
Bechtel (1982)	"conventional"	447 - 761
Bechtel (1982)	"sealed"	477 - 800

6.0 OBSERVATIONS AND RECOMMENDATIONS

In general, cost analyses for mature lead acid batteries have been more numerous, more complete, and have greater detail than for either zinc bromine or sodium sulfur batteries. Several cost analyses completed for lead acid batteries could, with minor modifications, serve as examples of expected levels of detail and completeness for other batteries. The quality of the economic analyses combined with greater commercial experience has created a lower level of uncertainty in costs for lead acid battery systems.

The lack of maturity in zinc bromine and sodium sulfur cost analyses compared to lead acid can be partly attributed to the differences in design maturity. The level of design detail available provides an upper limit to the level of cost detail possible. Still, improvements could be made even at the current level of design maturity. Problems currently facing zinc bromine and sodium sulfur cost analyses are presented and briefly discussed below:

Cost Information is Fragmented. No single report addresses each of the six major categories of cost characterizing information. Rapidly changing designs make it difficult to trace costs presented in one report to design information presented in another report.

Completeness of Estimates Varies Significantly. Incomplete estimates inevitably lead to underestimated costs. Differences in the level of completeness also makes direct comparison of cost estimates impossible.

Many Estimates Lack Supporting Details. Lack of detail makes an independent reproduction of the estimate impossible, thus lowering believability. For example, descriptions of manufacturing operations, floor space requirements, and equipment were often limited, if they existed at all.

Very Few Installed System or Life-Cycle Cost Estimates. Estimates of installed system and life-cycle costs were limited to three sources for zinc bromine and two sources for sodium sulfur.

The above comments apply to both zinc bromine and sodium sulfur cost analyses. Table 6.1 lists some additional observations that identify differences in the status of zinc bromine and sodium sulfur cost analyses.

TABLE 6.1. Zinc Bromine/Sodium Sulfur Status Comparison

1. Detailed sodium sulfur manufacturing cost studies are several years old.

2. Detailed zinc bromine manufacturing cost studies are fairly recent.

3. Design and material specification detail is generally less for sodium sulfur than for zinc bromine.

4. Performance specification detail is generally greater for sodium sulfur than zinc bromine.

The following observations apply to all battery systems. Converter costs were found to vary widely with assumptions regarding power level, design, and production volume. Converters for large battery systems are currently in their own developmental phase and suffer from cost uncertainty that is comparable to the batteries themselves. Finally, it's important to remember that the technical feasibility, the probability a battery will work as advertised, may be significantly different for two batteries that are estimated to have similar initial and operating costs. Two systems must provide a similar service in order for cost comparisons to be meaningful.

In view of the observations summarized above, the following recommendations are offered as a means to improve battery cost analyses:

1. Develop standard guidelines which establish the system components to be included, the appropriate level of detail in description, and ground rules and assumptions for estimating manufacturing, installed system, and life-cycle costs. The implementation of guidelines would serve to standardize the economic analysis procedure and focus on cost differences attributable to differences in battery type or design.

2. Spend more effort characterizing installed system and life-cycle costs. Balance-of-plant, battery replacement, and O&M costs are just as important as manufacturing costs to the total battery system cost. Additional balance-of-plant and life-cycle cost studies are needed to develop a balanced set of cost characterizing information.

3. Complete cost analyses in more detail and more frequently. More frequent cost analyses will minimize the problem of cost analyses becoming outdated by changes in technology.

Each of the recommendations cited above represents a part of an overall plan to enhance the quality of battery cost analysis. The availability of quality cost data is seen as a first step in this plan. Consistent cost analyses completed for the entire battery system will lay the groundwork for the development of cost goals, R&D plans, market assessments, and cost/performance tradeoffs.

APPENDIX A

ZINC BROMINE COST DETAILS

The following pages present cost estimating details extracted from the sources reviewed for this study. The tables have been reproduced to match the figures and notes presented in the original sources except for some minor modification to the format or style. Additional clarifying comments, if any, are designated as PNL Notes.

The data provide an indication of the completeness and level of detail found among the various estimates and also serve as a rudimentary data base of battery cost information. The supporting details presented in this appendix correspond to the cost estimates referenced in Tables 3.2, 3.3, and 3.4.

TABLE A.1. Bechtel (1982) Manufacturing Cost Estimate

Factory Price Estimate - Zinc-Bromine Battery (Gould)

	1980 $/kWh	
	Low	High
Labor (Direct + 150% Overhead)	--	--
Materials (Materials + 10% Overhead)	68.10	83.00
Energy	--	--
Depreciation	--	--
Rent	--	--
Factory Cost[a]	68.10	83.00
After Tax ROI (15%)	3.06	3.74
Taxes (15% of Investment)	3.06	3.74
Marketing, Warranty, and Miscellaneous	5.00	5.00
FOB Factory Price[a]	79.22	95.48

Manufacturing Plant Assumptions[a]

	1980 $ x 10^3	
	Low	High
Equipment (Including 25% Installation)	--	--
Working Capital (30% of Factory Cost)	51,075	62,250
Total Plant Investment	51,075	62,250

Unit Capacity, kWh	80
Production Volume, MWh/yr	2,500
Factory Floor Space, ft^2	--

(a) Estimate does not include costs for labor, and manufacturing facility and equipment. Preliminary results from a more recent study (by Gould), which includes labor and manufacturing facility costs, indicate a FOB price of $96/kWh to $138/kWh. These more recent numbers were used in the installed cost estimate presented in later sections of this report.

PNL Note: FOB prices of $96-138/kWh (1980 $) were inflated to $120-172/kWh (1984 $).

TABLE A.2. Bechtel (1982) Balance of System Cost Estimate

BOS Installed Cost Estimate

Battery: Zinc-Bromine (Gould) Application: Shopping Center

System/Component	Hours	Costs (1980 $) Labor	Material	Subtotal	Cost Distribution $	$/kW	$/kWh
Battery							
Shipping (500 miles)	--	--	--	26,640	--	--	4.27
Installation	1,638	29,480	--	29,480	--	--	4.72
Other	--	--	3,120	3,120	--	--	0.50
Building							
Land	--	--	--	1,800	--	--	0.29
Building	--	--	--	126,000	--	--	20.19
Structural	380	6,840	3,200	10,040	2,680	--	1.18
Thermal Management							
Heat Rejection	50	900	25,000	25,900	--	--	4.15
Piping, Pumps, Valves	307	5,530	14,960	20,490	--	--	3.28
Other	56	1,010	3,280	4,290	--	--	0.69
Instrumentation							
Fire Detection	10	180	130	310	310	--	--
Electrical							
DC Wiring	600	10,800	99,000	109,800	--	--	17.60
DC Equipment	32	580	10,660	11,240	--	--	1.80
AC Wiring	618	11,120	4,980	16,100	--	--	2.58
AC Panel Requirements	24	430	600	1,030	--	--	0.17
Lighting	191	3,440	1,850	5,290	--	--	0.85
Other	6	110	750	860	--	--	0.14
Subtotals	3,912	70,420	167,530	392,390	2,990	0	62.41
Total Direct Field Cost				392,390	2,990	0	62.40
Indirect Field Cost				35,210	270	0	5.60
BOS Field Cost				427,600	3,260	0	68.00

TABLE A.3. Bechtel (1982) Installed System Cost Estimate
Total Installed Costs
(1980 $)

Battery: Zinc-Bromine (Gould)

Application: Shopping Center

Item	Low Estimate Total Cost $	Low Estimate Cost Distribution $	Low Estimate Cost Distribution $/kW	Low Estimate Cost Distribution $/kWh	High Estimate Total Cost $	High Estimate Cost Distribution $	High Estimate Cost Distribution $/kW	High Estimate Cost Distribution $/kWh
Battery, FOB[a]	599,040	0	0	96	861,120	0	0	138
BOS, Field Cost[b]	256,560	1,960	0	41	513,120	3,910	0	82
Total Field Cost	855,600	1,960	0	137	1,374,240	3,910	0	220
Engineering Costs (15%)	128,340	290	0	21	206,140	590	0	33
Subtotal	983,940	2,250	0	158	1,580,380	4,500	0	253
Contingency (20%)	196,790	450	0	32	316,080	900	0	51
Total Installed Cost	1,180,730	2,700	0	190	1,896,460	5,400	0	304

(a) From Table A.1
(b) From Table A.2. High = 1.2 x Field Cost; Low = 0.6 x Field Cost.

PNL Note: Installed system costs of $190-304/kWh (1980 $) were inflated to $237-379/kWh (1984 $).

TABLE A.4. Bechtel (1982) Frequent Maintenance for the Gould Zinc-Bromine Battery in the Shopping Center

Activity	Frequency	Labor, Manhours Per Event	Material $ Per Event	Annual Cost Low $	Annual Cost High $
Battery Maintenance	Annual	20	--	220	308
Cooling System Maintenance	Annual	9	200	299	418

TABLE A.5. Bechtel (1982) Infrequent Maintenance for the Gould Zinc-Bromine Battery in the Shopping Center

Activity	Frequency Years	Labor, Manhours Per Event	Material $ Per Event	Annual Cost Low $	Annual Cost High $
Coolant Pump	8	25	1,500	2,300	3,220
Refrigerator System	12	30	9,000	9,960	13,944

TABLE A.6. Bechtel (1982) Low Life-Cycle Cost Estimate

Battery Type: Zinc-Bromine (Gould)
Application Type: Shopping Center

Low Estimate Input Parameters

Energy Rating	6240.0	kWh per cycle	Power cost ($/kWh)	0.050
Power Rating	900	kW	Resale/new value	1
Battery Life	2500	cycles		
Cycles Per Year	250		Discount rate	10
Efficiency	74%		Escalation rates	
Auxiliary Losses	0	kWh/cycle (fixed)	Capital	8
	0	kWh/cycle (kW)	Maintenance	8
	96	kWh/cycle (kWh)	Energy	10.2

Cost Data

Item	Fixed Costs ($)	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	2700	0	190
Replacement 1	0	0	105
Salvage 1	0	0	8.73
Annual Maintenance	0	0	0.08
Infrequent Maintenance			
8 year	0	0	0.37
12 year	0	0	1.60

Output (Net Present Value)

Item	Fixed Costs ($)	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	2700	0	190
Periodic Replacements Less Sal, Unused Life	0	0	74.08
Annual Maintenance	0	0	1.33
Infrequent Maintenance	0	0	1.88
Energy Losses	0	0	69.91
Total	2700	0	337.20

Total System Life-cycle cost: $2107 thousand

PNL Note: Life-cycle cost of $337.20/kWh (1980 $) was inflated to $420/kWh (1984 $).

TABLE A.7. Bechtel (1982) Life-Cycle Cost Analysis (1980 $)

Battery Type: Zinc-Bromine (Gould)
Application Type: Shopping Center

High Estimate Input Parameters

Energy Rating	6240.0	kWh per cycle	Power cost ($/kWh)	0.050
Power Rating	900	kW	Resale/new value	1
Battery Life	2000	cycles		
Cycles Per Year	250		Discount rate	10
Efficiency	64%		Escalation rates	
Auxiliary Losses	0	kWh/cycle (fixed)	Capital	8
	0	kWh/cycle (kW)	Maintenance	8
	96	kWh/cycle (kWh)	Energy	10.2

Cost Data

Item	Fixed Costs ($)	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	5400	0	304
Replacement 1	0	0	156
Salvage 1	0	0	4.85
Annual Maintenance	0	0	0.17
Infrequent Maintenance			
8 year	0	0	0.52
12 year	0	0	2.23

Output (Net Present Value)

Item	Fixed Costs ($)	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	5400	0	304
Periodic Replacements			
Less Sal, Unused Life	0	0	187.49
Annual Maintenance	0	0	2.82
Infrequent Maintenance	0	0	2.63
Energy Losses	0	0	95.29
Total	5400	0	592.23

Total System Life-cycle cost: $3701 thousand

PNL Note: Life-cycle cost of $592.23/kWh (1980 $) was inflated to $738/kWh (1984 $).

TABLE A.8. Bechtel (1982) Manufacturing Cost Estimate

Factory Price Estimate--Zinc-Bromine Battery (Exxon)

	1980 $/kWh Low	1980 $/kWh High[a]
Labor (Direct + 150% Overhead)	3.52	7.04
Materials (Materials + 10% Overhead)	26.65	39.98
Energy	--	--
Depreciation	0.50	0.50
Rent	0.20	0.20
Factory Cost[b]	30.87	47.72
After Tax ROI (15%)	2.14	2.90
Taxes (15% of Investment)	2.14	2.90
Marketing, Warranty, and Miscellaneous	5.00	5.00
FOB Factory Price[c]	40.15	58.52

Manufacturing Plant Assumptions

	1980 $ x 10^3 Low	1980 $ x 10^3 High
Equipment (Including 25% Installation)	12,500	12,500
Working Capital (30% of Factory Cost)	23,153	35,790
Total Plant Investment	35,653	48,290

Unit Capacity, kWh	20
Production Volume, MWh/yr	2,500
Factory Floor Space, ft^2	100,000

Notes:

(a) The high estimate presented here is based on projected uncertainties in labor and materials costs. Other components of the estimate were not adjusted.

(b) Factor cost included no contribution from energy costs since these were projected to be less than 5% of materials costs.

(c) The factory price does not include a required heat exchanger nor intermodule electrical connectors.

TABLE A.9. Bechtel (1982) Adjusted Manufacturing Cost Estimate

Exxon Zinc-Bromine Battery Adjusted Factory Prices

Application Type	System Capacity kWh	Adjusted Factory Price,[a] FOB, 1980 $/kWh	
		Low	High
Baseline Module	20	40	59
Multiple Residence	640	35	54
Remote Residence[b]	160	40	59
Single Residence	16	56	80

Notes: (a) Baseline battery price plus applicable credits or less applicable penalties.
(b) The remote residence uses the baseline module without change.

PNL Note: The multiple residence prices of $35-54/kWh (1980 $) were inflated to $44-67/kWh (1984 $).

TABLE A.10. Bechtel (1982) Balance of System Cost Estimate

BOS Installed Cost Estimate

Battery: Zinc-Bromine (Exxon) Application: Multiple Residence

System/Component	Hours	Costs (1980 $) Labor	Material	Subtotal	Cost Distribution $	$/kW	$/kWh
Battery							
Shipping (500 miles)	--	--	--	1,020	--	--	1.59
Installation	76	1,370	--	1,370	--	--	2.14
Other	--	--	320	320	--	--	0.50
Building							
Building	--	--	--	15,000	--	--	23.44
Structural	249	4,480	3,160	7,640	2,680	--	7.75
Thermal Management							
Heat Rejection	32	580	2,320	2,900	--	--	4.53
Piping, Pumps, Valves	13	230	380	610	--	--	0.95
Instrumentation							
Fire Detection	10	180	130	310	310	--	--
Other	15	270	230	500	500	--	--
Electrical							
DC Wiring	10	180	260	440	--	--	0.69
DC Equipment	18	320	1,280	1,600	--	--	2.50
AC Wiring	76	1,370	640	2,010	--	--	3.14
AC Panel Requirements	14	250	340	590	--	--	0.92
Lighting	59	1,060	620	1,680	--	--	2.63
Other	1	20	60	80	--	--	0.13
Subtotals	573	10,310	9,740	36,070	3,490	0	50.93
			Total Direct Field Cost	36,070	3,490	0	50.90
			Indirect Field Cost	5,670	550	0	8.00
			BOS Field Cost	41,740	4,040	0	58.90

TABLE A.11. Bechtel (1982) Installed System Cost Estimate

Total Installed Costs
(1980 $)

Battery: Zinc-Bromine (Exxon)

Application: Multiple Residence

Item	Low Estimate: Total Cost $	Low Estimate: Cost Distribution $	Low Estimate: Cost Distribution $/kW	Low Estimate: Cost Distribution $/kWh	High Estimate: Total Cost $	High Estimate: Cost Distribution $	High Estimate: Cost Distribution $/kW	High Estimate: Cost Distribution $/kWh
Battery, FOB[a]	22,400	0	0	35	34,560	0	0	54
BOS, Field Cost[b]	25,040	2,420	0	35	50,090	4,850	0	71
Total Field Cost	47,440	2,420	0	70	84,650	4,850	0	125
Engineering Costs (15%)	7,120	360	0	11	12,700	730	0	19
Subtotal	54,560	2,780	0	81	97,350	5,580	0	144
Contingency (20%)	10,910	560	0	16	19,470	1,120	0	29
Total Installed Cost	65,470	3,340	0	97	116,820	6,700	0	173

Notes: (a) From Table A.9.
(b) From Table A.10. High = 1.2 x Field Cost; Low = 0.6 x Field Cost.

PNL Note: Installed System Costs of $97-173/kWh (1980 $) were inflated to $121-216/kWh (1984 $).

TABLE A.12. Bechtel (1982) Frequent Maintenance for the Exxon Zinc-Bromine Battery in the Multiple Residence

Activity	Frequency	Labor, Manhours Per Event	Material $ Per Event	Annual Cost Low $	Annual Cost High $
Battery Maintenance	Semi-Annual	4	--	256	358
Cooling System Maintenance	Annual	1	--	32	45

TABLE A.13. Bechtel (1982) Low Life-Cycle Cost Estimate

Life-Cycle Cost Analysis (1980 $)

Battery Type: Zinc-Bromine (Exxon)
Application Type: Multiple Residence

Low Estimate Input Parameters

Energy Rating	640.0	kWh per cycle	Power cost ($/kWh)	0.050
Power Rating	72	kW	Resale/new value	1
Battery Life	1250	cycles		
Cycles Per Year	250		Discount rate	10
Efficiency	70%		Escalation rates	
Auxiliary Losses	0	kWh/cycle (fixed)	Capital	8
	0	kWh/cycle (kW)	Maintenance	8
	49	kWh/cycle (kWh)	Energy	10.2

Cost Data

Item	Fixed Costs ($)	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	3340	0	97
Replacement 1	0	0	35
Salvage 1	0	0	4
Annual Maintenance	0	0	0.45
Infrequent Maintenance			
10 year	0	0	5.23

Output (Net Present Value)

Item	Fixed Costs ($)	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	3340	0	97
Periodic Replacements			
Less Sal, Unused Life	0	0	74.86
Annual Maintenance	0	0	7.46
Infrequent Maintenance	0	0	4.35
Energy Losses	0	0	95.59
Total	3340	0	279.26

Total system life-cycle cost: $182 thousand

PNL Note: Life-cycle cost of $279.26/kWh (1980 $) was inflated to $348/kWh (1984 $).

TABLE A.14. Bechtel (1982) High Life-Cycle Cost Estimate

Life-Cycle Cost Analysis (1980 $)

Battery Type: Zinc-Bromine (Exxon)
Application Type: Multiple Residence

High Estimate Input Parameters

Energy Rating	640.0	kWh per cycle	Power cost ($/kWh)	0.050
Power Rating	72	kW	Resale/new value	1
Battery Life	1000	cycles		
Cycles Per Year	250		Discount rate	10
Efficiency	60%		Escalation rates	
Auxiliary Losses	0	kWh/cycle (fixed)	Capital	8
	0	kWh/cycle (kW)	Maintenance	8
	49	kWh/cycle (kWh)	Energy	10.2

Cost Data

Item	Fixed Costs ($)	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	6700	0	173
Replacement 1	0	0	61
Salvage 1	0	0	2.25
Annual Maintenance	0	0	0.63
Infrequent Maintenance 10 year	0	0	7.32

Output (Net Present Value)

Item	Fixed Costs ($)	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	6700	0	173
Periodic Replacements Less Sal, Unused Life	0	0	197.71
Annual Maintenance	0	0	10.45
Infrequent Maintenance	0	0	6.09
Energy Losses	0	0	120.98
Total	6700	0	508.23

Total system life-cycle cost: $332 thousand

PNL Note: Life-cycle cost of $508.23/kWh (1980 $) was inflated to $634/kWh (1984 $).

TABLE A.15. Ramsay (1982) Manufacturing Cost Estimate

Zinc-Bromine: Capital Cost and Salvage Value

			$/kWh
Initial Capital Cost of Battery			68.73
a)	Labor (excluding overhead) 180 people		1.50
b)	Purchased Components and Materials		48
	Electrodes	$10.75	
	Polybromide	7.80	
	Electrolyte	3.60	
	All else	25.85	
c)	Rent 150,000 ft^2		0.30
d)	Installed Equipment Costs $10.8 Million		4.32
e)	Marketing, Warranty, and Miscellaneous		5
Salvage Value			15.75
	Electrolyte (90% of Material) (60% Cost/lb)	$1.95	
	Electrodes (100% of Material) (80% Cost/lb)	8.60	
	All else (50% of Material) (40% Cost/lb)	5.20	

PNL Note: Battery cost of $68.73/kWh (1980 $) was inflated to $86/kWh (1984 $).

TABLE A.16. Ramsay (1982) Balance of System Cost Estimate

Zinc-Bromine: Other Costs of Utility System

Utility System (100 MWh and 20MW)	$/kWh
• Ancillary Equipment	
- Reservoir cooling equipment	9.00
- Racks	1.50
- Controls and sensors	5.00
- Prefabricated enclosure	3.00
- Electrolyte spill containment	4.00
- Electrical connections and protectors	2.50
	$25.00

• Operation and Maintenance Scenario

- Replacement of pumps during years 7 and 14; pump cost: $150 per module, labor: 1 man-hour per module
- Replacement of one cell per module during years 3, 6, 10, 13, and 16; cell cost: $650 per cell, labor: 4 man-hours per cell
- Scheduled maintenance: 16 man-days/month
- Unscheduled maintenance: 24 man-days/year

Present worth of O&M over system lifetime
6% discount rate: $1,383,000
8% discount rate: $1,185,000

PNL Note: Balance of system cost of $25/kWh (1980 $) was inflated to $31/kWh (1984 $) and added to the battery cost of $86/kWh (1984 $) to yield an installed system cost estimate of $117/kWh (1984 $).

TABLE A.17. Ramsay (1982) Life-Cycle Cost Estimates

Zinc-Bromine: Utility System Summary Costs

Nominal System Rating	100 MWh and 20 MW
Output Voltage	1000 V_{OC}
Battery Depth of Discharge	80%
Initial Battery Capacity	125 MWh
Battery Cutoff Voltage	1.40 V_{DC}/Cell
System Configuration:	62 parallel rows of 25 modules in series (40 V_{DC} each) Total: 1550 modules
Module Capacity	80.7 kWh

	Discount Rate	
	6%	8%
Initial Capital Cost of Battery	$8,591,000	$8,591,000
Initial Capital Cost of Ancillary Equipment	3,125,000	3,125,000
Present Worth of Battery Replacement Costs	3,245,000	2,781,000
Present Worth of Annual Operation and Maintenance Costs	1,383,000	1,185,000
Present Worth of Battery at End of System Life	(614,000)	(422,000)
Present Worth of Ancillary Equipment at End of System Life	(195,000)	(134,000)
Life-Cycle Cost	$15,535,000	$15,126,000
Life-Cycle Cost/kWh of Battery Capacity	$155/kWh	$151/kWh

PNL Note: Life-cycle costs of $151-155/kWh (1980 $) were inflated to $188-193/kWh (1984 $).

TABLE A.18. Monn (1983) Manufacturing Cost Estimate

Total Cost Estimate for Production of Submodules for 500 kWh System

Production Level:	One 500 kWh Module			100 Modules/Year		
	$/kWh	$/Submodule	$/Module	$/kWh	$/Submodule	$/Module
Materials	300	4,980	149,400	40	664	19,920
Labor at 10 $/hr	13	219	6,573	4	66	1,992
Overhead, G&A, and Profit	154	2,581	77,427	57	960	28,788
Total Cost	467	7,780	233,400	101	1,690	50,700

PNL Note: Manufactured cost of $101/kWh (1983 $) was inflated to $106/kWh (1984 $).

TABLE A.19. Monn (1983) Battery Material Costs

Component Cost Breakdown for 16.6 kWh Submodules

	One 500 kWh Unit Produced			100 Units/Year Produced		
Component	Unit Cost	Cost/ kWh	Cost/ 500 kWh	Unit Cost	Cost/ kWh	Cost/ 500 kWh
Frames	3.15 ea	9.86	4,930	0.80 ea	2.50	1,250
Electrodes	7.15 ea	22.38	11,190	1.52 ea	4.76	2,380
Separator--2.1 ft^2 gasket type[a] DARAMIC	3.75 ea	11.74	5,869	2.70 ea	6.89	3,443
Separator--1 ft^2 sealed[b] DARAMIC	1.30 ea	4.07	2,035	0.65 ea	2.03	1,017
Felt	2.40/ft^2	7.50	3,756	1.25/ft^2	3.91	1,956
Anode Grid	1.50 ea	4.70	2,348	0.35 ea	1.10	547
End Electrode	200 ea	24.00	12,048	150 ea	18.07	9,036
End Plate--thick[a]	350 ea	42.17	21,084	100 ea	12.05	6,024
Strongback Assembly[a]	3000 submod	180.72	90,361	1000/submod	60.24	30,120
Thin End Plate[b]	300 ea	36.14	18,072	50 ea	6.02	3,012

(a) Used in calculation of compressed stack construction cost.
(b) Used in calculation of heat-sealed stack construction cost.

TABLE A.20. Monn (1983) Battery Labor Costs

Time and Labor Requirements for Production of Submodules for 500 kWh System

No.	Operation	Rate	Total Man Hour	No. Men	Time Hr	Calendar Time, Hr	Critical Path
1	Acquire Purchased Parts and Raw Materials	6 weeks	--	--	--	1000	1000
2	Compression Mold Bipolar Plate[a]	2 plates/hr + 1 hr setup; 14 plates/day	890	1	890	1250	1250
3	Cut Felt to Size[a]	200 felts/day	60	1	60	84	
4	Cut Separator to Size[a]	200 sep/day	60	1	60	84	
5	Fabricate End Electrode[a]	6 hr/electrode	300	1	300	420	
6	Fabricate End Plate[a]	5 hr/plate	300	1	300	420	
7	Fabricate and Coat Strongback Assembly[a]	2 hr/assembly	60	1	60	84	
8	Bond Electrode to Frame	10 sets/hr	160	1	160	224	224
9	Bond Spacer to Frame	10 sets/hr	160	1	160	224	224
10	Coat Separator[a]	10 pieces/hr	160	1	160	224	
11	Bond Felt to Electrode	10 sets/hr	160	1	160	224	224
12	Assemble Submodule	2 hr/submodule	60	2	30	42	42
13	Qualification Testing	4 hr/submodule	120	2	60	84	84
	Total Man-Hour Requirement		2490				3050 = 4.24 months

(a) Man-hour requirement included in component cost estimate: 1830.
Man-hour requirement not included in component cost estimate: 660 = 1.32 man-hours/kWh.

TABLE A.21. Monn (1983) Cost Comparison of Heat Sealing and Compression Sealing

Materials and Components Cost Estimate

Stack Construction		One 500 kWh Unit Produced Cost $/kWh	One 500 kWh Unit Produced Cost $/500 kWh	100 Units/Year Produced Cost $/kWh	100 Units/Year Produced Cost $/500 kWh
Compressed	DARAMIC	303.07	151,535	109.52	54,760
Heat Sealed[a]	DARAMIC	108.65	54,325	38.39	19,195

(a) Does not include tooling cost for heat sealing equipment.

Heat Sealed Tooling Cost--$100,000 Installed
Amortized over 1 system $200/kWh
Amortized over 100 systems $2.00/kWh
Amortized over 10 years $0.20/kWh

TABLE A.22. Monn (1983) Installed System Cost Estimate

Capital Cost Estimate 100 kW-500 kWh Zinc Bromine Battery Based on Order of 100 Units (January 1983 $)

Structural Steel	$28,400
Battery Submodules	50,700
Equipment	22,100
Piping	49,900
Electrical	21,400
Instruments	34,400
Painting and Scaffolding	1,000
Subtotal--Fabrication Costs	$207,900
Office Costs	10,000
Subtotal--Fabrication and Office Costs	217,900
Contingency (15%)	32,700
Total Project Cost	250,600 or $501.20/kWh

Notes: 1. FOB East Coast shop.
2. Power conditioning equipment and certain other auxiliaries not included.

PNL Note: The installed system cost of $501.20/kWh (1983 $) was inflated to $524/kWh (1984 $).

TABLE A.23. Bellows (1983a) Manufacturing Cost Estimate

Total Factory Cost--20 kWh Zinc-Bromine Battery

Bipolar Electrodes	38.30
Current Collectors	28.20
Separator Assembly (inc. outside labor)	77.44
End-Support Block Assembly	10.52
Center-Support Blocks Inc. outside labor)	10.36
Reservoir	8.59
Reservoir Tray	2.95
Battery stacks--Total	176.36
Electrolyte Pump	24.00
Electrolyte Pump Motor	16.00
Isolating Drive System	10.00
Protective Electrode System	10.00
Pump Pressure Sensor	4.00
Electronic Control Board	12.00
Electrolyte Level Sensor	2.00
State-of-Charge Sensor	4.00
Voltage Cut-Out	1.50
Temperature Probes (3)	3.00
Hydrogen Recombination	2.00
Plumbing and Fittings	10.00
Bus Bars--Tie Rods and Hardware	20.00
Batt. Access., Controls, Etc.--Total	118.50
Electrolyte	200.00
Packaging and External Case	18.49
Materials--Total	513.35
In-House Labor	47.75
Factory Cost Total, $/Unit	561.10
Factory Cost Total, $/kWh	28.05

PNL Note: The factory cost of $28.05/kWh (1980 $) was inflated to $35/kWh (1985 $).

TABLE A.24. Bellows (1983b) Manufacturing Cost Estimate

Total Factory and Capital Costs

Material (Includes electrolyte at $220/Module)	$321.36
Purchased Components (Includes outside molding costs and accessories)	211.71
In-House Labor Costs	68.74
Total Material, Components and Labor Cost/20 kWh Module	601.81
Total Material, Components and Labor Cost/kWh	30.09
1. At 2500 MWh Material, Components and Labor Cost Per Year	$75,225,000.00
2. Marked-up Equipment Costs (10% of estimated $12,500,000)	1,250,000.00
3. Rent (100,000 sq ft plant at 5.00/ft^2)	500,000.00
4. Total Factor Costs (Lines 1 + 2 + 3)	76,975,000.00
5. Working Capital Requirement (30% line 4)	23,092,500.00
6. Total Investment ($12,500,000 + line 5)	35,592,500.00
7. Return on Investment and Taxes (30% line 6)	10,677,750.00
8. Additional at $5.00/kWh	12,500,000.00
9. Total Capital Cost Lines 4, 7 and 8)	100,152,750.00
Capital Cost per 20 kWh Module	801.22
Capital Cost per kWh	40.06

PNL Note: Manufactured cost of $40.06/kWh (1980 $) was inflated to $50/kWh (1984 $).

TABLE A.25. Bellows (1983b) Salvage Value and Net Costs

Electrolyte Salvage Value 225 lb Zn/Br_2 at 0.30/lb	$67.50
50 lb Quaternary Ammonium Bromide at 0.70/lb	35.00
$16.31 Silver at 50% Recovery Value (Includes disassembly costs)	8.15
Copper--Est. $9.00 at 50% Value	4.50
Total per 20 kWh Salvage Value/kWh	115.15 5.76
From Table A.24	
Capital Cost per kWh	40.06
- Salvage Value	-5.76
Net Capital Cost/kWh	$34.30

Notes:
- Additional salvage possible but minimal (motors, controls, etc.).
- Indicated costs are based on 80% coulombic efficiency and 10% auxiliary power (present battery design and parameters). Further cost reductions are possible in future batteries. Larger battery modules consisting of 8 to 12 battery stacks with single pumps and reservoirs serving all stacks in comparison to only two stacks in this analysis would obviously reduce cost appreciably.

TABLE A.26. Bellows (1983b) Purchased Materials and Components and Fabrication Labor

Unit	Material Cost[(a)]	Factory In-House Labor[(b)]	Purchased Components[(c)]	Total Cost Per Module	Description
Bipolar Electrode	0.196/ea 30.15/Module (154 pcs)	--	0.0695 ea 10.70 Module (154 pcs)	40.85	Co-extruded conductive plastic strip with nonconductive border. A layer of increased surface area material applied continuously. One side part is pierced, blanked, cleaned, and stacked continuously
Current Collector, Consisting of:					'Sandwich' structure of bipolar electrode, silver-plated expanded lead-foil and plastic backing. Cycle time-in house labor at 30 pcs/h
Silver at $12.00/troy oz	3.597 ea				
Lead Foil	0.165 ea				
Expanding Foil	--		0.088 ea		
Silver Plating	0.165 ea				
Plastic Backing	0.150 ea				
Laminating	--	0.83 ea			
	16.31 Module (4 units)	3.33/Module	0.35 (4 pcs)	19.99	
Separator Assembly, Consisting of:					Consists of an injection molded frame around a separator sheet. Frame contains manifold holes and electrolyte flow channels. Separator is extruded, cleaned, pierced and blanked continuously. Molding cycle 60 s. Two per mold yields 120 pcs/h
Separator	0.126 ea		0.179 ea		
Injection Molded Frame			0.211 ea		
			0.39 ea		
	19.66 (156 pcs)		60.84 (156 pcs)	80.50	
End Support Block	4.114 ea 8.2 (2 pcs)	0.833 ea 1.67 (2 pcs)	0.847 ea 1.69 (2 pcs)	11.59	Injection-molded, glass-filled polypropylene. In-house secondary operations--tapping and deflashing
End Support Block Assembly					In-House Assembly of Components 30 pcs/hr
Assembly Blocks	--	--	--	--	
Electrodes (4 pcs)			0.18		
Seals (4 pcs)			0.10		
Plugs (4 pcs)		Total	0.18		
Contacts (4 pcs)		0.83	0.18	1.47	
Center Support Block Assembly		--		--	*Injection Molding Costs (outside)
Center Block	8.64		1.69*		In-House Tapping 30 pcs/h
Electrodes (8)			0.35		
Seals (8)			0.18		In-House Assembly 20 pcs/h
Plugs (8)	Total		0.35	13.47	
Contacts (8)		1.08	0.18		
Reservoir	6.81	--	2.28*	9.09	*Injection Molded 4 min cycle (outside vendor)
Reservoir Tray	1.56		1.61*	3.17	*Injection Molded 3 min cycle (outside vendor)
Totals	91.36	7.91	80.86	180.13	

(a) Base material cost at 95% yield plus 10% overhead.
(b) Based at $10.00/h + 150% overhead.
(c) Base cost at 95% yield plus 10% overhead--includes outside machine time and labor. Factory cost (1980 $).

TABLE A.27. Bellows (1983b) Purchased Component Cost

Accessories	Purchased Component Cost[a]
Electrolyte Pump	$26.40
Electrolyte Pump Motor	17.60
Drive System	11.00
Bromine Pump Head	4.40
Bromine Pump Motor	6.60
Pump Pressure Sensor	4.40
Electrolyte Level Sensor	2.20
State-of-Charge Sensor	4.40
Voltage Cutout	1.65
Temperature Probes (3)	3.30
Electronic Control Board	13.70
Hydrogen Recombination	2.20
Plumbing Fittings	11.00
Bus Bars--Tie Rods and Miscellaneous Hardware	22.00
Total (Accessories)	$130.85
Electrolyte	$220.00

(a) Base cost at 95% yield plus 10% overhead includes outside machine time and labor.

TABLE A.28. Bellows (1983b) Assembly Costs

Operation		Cost Per Module[a]
Stack Assembly--End Blocks, 77 Electrodes Alternating with Separators--Collectors Center Block Assembly--77 Electrodes Alternating with Separators Collector End Block--Estimated at 6 s per part (Includes handling and visual inspection)		
Assemble 4 Tie Rods, etc. 4 min Heat Seal and Inspect 4 min		
	Total time 38 min	\$15.83
Final Assembly		
Assemble Stack Assembly to Tray and Tray to Reservoir--Assembly Pumps--Controls Bus Bars, Hardware Probes--Gaskets Inspect		
	Total time 38 min	15.83
Final Test and Inspection		
Inspect and Test--A percentage of Batteries to Undergo Complete Test Including Several Cycles		
	Average time 60 min	25.00
Packaging-Shipping--10 min		\$ 4.17
	Total Labor (In-House)	\$60.83
	Packing Materials Est.	\$10.00

(a) Based at \$10.00/h + 150% overhead.

APPENDIX B

SODIUM SULFUR COST DETAILS

APPENDIX B

SODIUM SULFUR COST DETAILS

The following pages present cost estimating details extracted from the sources reviewed for this study. The tables have been reproduced to match the figures and notes presented in the original sources except for some minor modification to the format or style. Additional clarifying comments, if any, are designated as PNL Notes.

The data provide an indication of the completeness and level of detail found among the various estimates and also serve as a rudimentary data base of battery cost information. The supporting details presented in this appendix correspond to the cost estimates referenced in Table 4.2 and Sections 4.2.4 and 4.2.5.

TABLE B.1. Ford (1980) Manufacturing Cost Estimates

Factory Cost and Selling Price of Sodium-Sulfur Cells (1980 $)

Cell Size, Wh	62 at C/3	211 at C/5	402 at C/5
Production Rate, Units/Year			
Electrolyte Subassembly	52,632,000	14,000,000	7,474,000
Cell Assembly	50,000,000	13,300,000	7,100,000
Electrolyte Subassembly			
Factory Cost, $	1.32	2.57	3.41
Selling Price, $	1.79	3.67	4.97
Cell Assembly			
Factory Cost, $	5.63	10.55	14.78
Selling Price, $	7.03	13.20	18.53

Sodium-Sulfur SES Battery Selling Price

	Per Detailed Cost Study		Projected
Cell Size, Wh	211	402	500
Selling Price (1980 $)	10,612,600	8,816,800	8,400,000
Normalized Selling Price			
$/kWh	106.1	88.2	84
$/kW	530.6	440.8	420

PNL Note: The projected battery selling price of $84/kWh (1980 $) was inflated to $105/kWh (1984 $).

TABLE B.2. Ford (1980) Sodium-Sulfur Cell Materials, Labor and Energy Costs (1980 $)

	A. 62 Wh at C/3				B. 211 Wh at C/5				C. 402 Wh at C/5			
	Materials	Labor	Energy	Total	Materials	Labor	Energy	Total	Materials	Labor	Energy	Total
Direct Operations												
Electrolyte	0.19	0.35	0.16	0.70	0.70	0.47	0.37	1.54	1.00	0.56	0.54	2.10
Lower Container	0.15	0.15	0.06	0.37	0.30	0.20	0.11	0.62	0.51	0.34	0.23	1.07
Upper Container	0.15	0.01	--	0.15	0.32	0.01	--	0.32	0.38	0.01	--	0.39
Seal Gaskets and Rings	0.12	0.10	--	0.22	0.24	0.12	--	0.36	0.24	0.13	--	0.37
Safety Tube	0.03	0.04	--	0.07	0.05	0.04	--	0.09	0.08	0.04	--	0.13
Sodium Fill	0.13	0.01	--	0.14	0.45	0.02	--	0.46	0.85	0.03	--	0.88
Metering Bulkhead	0.45	0.03	--	0.49	0.80	0.04	--	0.83	0.80	0.04	--	0.84
Sulfur Electrode	0.50	0.02	--	0.52	1.75	0.03	--	1.78	3.25	0.04	--	3.29
Sodium Wick	0.03	0.00	--	0.03	0.09	0.00	--	0.09	0.11	0.01	--	0.12
Assembly of Cells	0.06	0.30	--	0.36	0.12	0.31	--	0.43	0.15	0.34	--	0.49
Support Operations												
Tubing Mill		0.01	--	0.01		0.01	--	0.01		0.03	--	0.03
Press Shop		0.04	--	0.04		0.05	--	0.05		0.05	--	0.05
Paint Shop	0.02	0.04	--	0.06	0.04	0.15	--	0.19	0.08	0.15	--	0.23
Cleaning Area	0.01	0.04	--	0.05	0.01	0.05	--	0.07	0.01	0.05	--	0.07
Nonsynchronous Labor		0.05	--	0.05		0.07	--	0.07		0.07	--	0.07
Unburdened Total Costs	1.85	1.19	0.22	3.26	4.86	1.58	0.48	6.92	7.46	1.89	0.77	10.12
Overhead Costs	0.19	1.78	0.02	1.99	0.49	2.36	0.05	2.90	0.75	2.84	0.07	3.66
Burdened Total Costs	2.04	2.97	0.24	5.25	5.35	3.94	0.53	9.81	8.21	4.73	0.84	13.78

TABLE B.3. Ford (1980) Sodium-Sulfur Cell Electrolyte Materials, Labor and Energy Costs (1980 $)

	A. 62-Wh Cell[a]				B. 211-Wh Cell[b]				C. 402-Wh Cell[c]			
	Materials	Labor	Energy	Total	Materials	Labor	Energy	Total	Materials	Labor	Energy	Total
Electrolyte Tube	0.13	0.16	0.13	0.42	0.48	0.27	0.29	1.04	0.77	0.32	0.44	1.53
Seal Header	0.05	0.12	0.02	0.19	0.17	0.13	0.06	0.36	0.18	0.15	0.06	0.39
Electrolyte Assembly	0.01	0.05	0.00	0.06	0.01	0.05	0.00	0.06	0.01	0.06	0.00	0.07
Unburdened Total Cost	0.19	0.33	0.15	0.67	0.66	0.45	0.35	1.46	0.96	0.53	0.51	2.00
Overhead Costs	0.02	0.49	0.02	0.53	0.07	0.68	0.03	0.78	0.09	0.80	0.05	0.94
Burdened Total Costs	0.21	0.82	0.17	1.20	0.73	1.13	0.38	2.24	1.05	1.33	0.56	2.94

(a) 16-mm O.D. x 300-mm length x 1.0-mm wall.
(b) 34-mm O.D. x 259-mm length x 2.5-mm wall.
(c) 34-mm O.D. x 460-mm length x 2.5-mm wall.

TABLE B.4. Ford (1980) Sodium-Sulfur Cell Manufacturing Plant Equipment Cost

	Installed Equipment Cost ($ millions)		
Cell Size, Wh	62 at C/3	211 at C/5	402 at C/5
Production Rate, Units/Year	50,000,000	13,300,000	7,100,000
Direct Operations			
Electrolyte	58.4	39.0	29.1
Lower Container	22.9	7.4	7.3
Upper Container	14.7	4.7	3.1
Seal Gaskets and Rings	13.1	4.7	2.5
Safety Tube	4.9	1.8	1.5
Sodium Fill	2.6	1.8	1.4
Metering Bulkhead	4.2	1.6	1.3
Sulfur Electrode	3.1	1.5	1.3
Sodium Wick	0.3	0.2	0.1
Assembly of Cells	3.4	1.1	0.6
Supporting Operations			
Tubing Mill	5.3	3.2	3.2
Press Shop	5.6	1.9	1.2
Paint Shop	1.1	0.6	0.3
Cleaning Area	1.5	0.6	0.3
Other	8.0	5.1	4.0
Total Cost	149.1	75.2	57.2

TABLE B.5. Ford (1980) Sodium-Sulfur Cell Manufacturing Plant Size (1000 ft^2)

	Cell Size, Wh		
	62 at C/3	211 at C/5	402 at C/5
Production Plant			
Cell Assembly	643	257	139
Electrolyte	177	122	97
Total	820	379	236
Manufacturing Support			
Cell Assembly	69	28	15
Electrolyte	37	27	21
Total	106	55	36
Administration			
Cell Assembly	46	18	10
Electrolyte	6	6	6
Total	52	24	16
Total Plant Size			
Cell Assembly	758	303	164
Electrolyte	220	155	124
Total	978	458	288
Production Rate, Cells/Year	50,000,000	13,000,000	7,100,000

TABLE B.6. Ford (1980) Sodium-Sulfur Cell Manufacturing Plant Direct Labor Force (persons)

	Cell Size, Wh		
	62 at C/3	211 at C/5	402 at C/5
Cell Assembly	2,296	823	479
Electrolyte	868	315	199
Total	3,164	1,138	678
Production Rate, Cells/Year	50,000,000	13,300,000	7,100,000

TABLE B.7. Ford (1980) Sodium-Sulfur SES Battery Assembly Plant

Plant Size, ft^2	128,000
Direct Labor Force, Persons	340
Equipment Costs, 1980 $	
Welding	5,608,000
Overhead Conveyors	3,500,000
Parts Handling	2,650,000
Painting	619,000
Heat Treating	550,000
Tooling	331,000
Metal Working	221,000
Other	1,250,000
Total Equipment Cost	14,729,000

TABLE B.8. Levine (1981) Manufacturing Cost Estimate

Summary of Costs ... Stainless Steel Case Cell

	1981 $/Year	1981 $/Cell
Raw Materials	20,257,903	15.446
Labor (75% of est.)	2,816,842	2.141
Overhead		
150% of Labor	4,225,263	3.211
10% of Materials	2,025,790	1.620
Depreciation (10% of Capital)	989,196	0.791
Tax (15% of required Capital)	2,886,859	2.309
After Tax ROI (15% of required Capital)	2,886,859	2.309
		$27.827

	or $34.784/kWh
Marketing Costs	2.00
Replacement, returns, service	2.00
Miscellaneous	1.00
Total	$39.78/kWh

PNL Note: Manufactured cell cost of $39.78/kWh (1981 $) was inflated to $45/kWh (1984 $).

TABLE B.9. Levine (1981) Raw Material Cost - Stainless Steel Case Cell

Material	$/Unit	Amount/Cell	$/Cell
Sodium, lb	1.00	1.0435	1.044
Sulfur, lb	0.10	2.5735	0.257
Glass for fibers, lb	3.30	0.1629	0.537
Al lay-down tape, lb	3.84	0.0645	0.248
Mo coated foil, ea	1.494	1.05	1.567
Al spacer tape, lb	3.72	0.2325	0.865
Glass for tube sheet, lb	3.85	0.3944	1.519
Al mandrel, lb	2.50	0.0239	0.060
Al anode cup, ea	0.24	1.05	0.252
Al anode lead, lb	2.70	0.0198	0.053
Al flow restrictor, ea	0.33	1.05	0.347
Stainless steel case, ft	5.87	0.883	5.183
Stainless steel case, top, lb	1.74	0.616	1.072
Stainless case, bottom, lb	1.74	0.5527	0.962
Al sulfur fill tube, lb	2.50	0.0032	0.010
Feed-through, ea	1.00	1.05	1.05
Cup dip glass, lb	3.85	0.0573	0.221
Cumene, lb	0.25	0.0404	0.010
Zn alloy, g	0.18	1.05	0.189
			$15.446/cell

TABLE B.10. Levine (1981) Labor and Capital Cost Summary Stainless Steel Case Cell

Operation		Labor $/Year	Labor $/Cell	Capital
1.	Spinning	1,434,000	1.09	1,725,022
2.	Store glass fibers	--	--	--
3.	Mix tube sheet paste	28,680	0.0217	50,000
4.	Bundle rolling	956,000	0.726	200,000
5.	Dry tube sheet	95,600	0.0726	21,200
6.	Curing tube sheet	95,600	0.0726	377,360
7.	Weld Al anode lead to formed cup	47,800	0.0363	24,000
8.	Glass lip of anode cup	95,600	0.0726	100,000
9.	Insert flow resistor	47,800	0.0363	--
10.	Fuse anode cup on tube sheet	143,400	0.109	216,000
11.	Form outer case	28,680	0.0218	10,000
12.	Weld feed through and S° fill tube to plate	28,680	0.0218	80,000
13.	Weld top on case	28,680	0.0218	80,000
14.	Insert bundle, weld at feed through	95,600	0.0726	40,000
15.	Weld foil lead to case	23,680	0.0218	30,000
16.	Weld bottom plate to case	95,600	0.0726	40,000
17.	Leak test	124,280	0.0944	162,200
18.	Store good cells	95,600	0.0726	--
19.	Load Na and S, crimp	191,200	0.1453	800,000
20.	Test for shorts	95,600	0.0726	1,000
	Total		2.8544	3,956,782
	(times 2.5 for installation and buildings) =			9,891,955

TABLE B.11. Levine (1981) Manufacturing Cost Estimate

Summary of Costs - Double Al Can Cell

	1981 $/Year	$/Cell
Raw Materials	11,023,687	8.399
Labor (75% of estimate)	2,839,320	2.157
Overhead		
150% of Labor	4,258,980	3.236
10% of Materials	1,102,369	0.840
Depreciation (10% of Capital)	955,145	0.728
Tax (15% of required Capital)	2,550,243	1.943
After Tax R.O.I. (15% of required Capital)	2,550,243	1.943
		$19.246/cell

	= $24.058/kWh
Marketing Costs	2.00
Replacement, returns, service	2.00
Miscellaneous	1.00
Total	$29.058/kWh

TABLE B.12. Levine (1981) Raw Material Costs ... Double Al Can Cell

Material	$/Unit	Amount/Cell	$/Cell
Sodium, lb	1.00	1.0435	1.044
Sulfur, lb	0.10	2.5735	0.257
Glass for fibers, lb	3.30	0.1629	0.537
Al lay-down tape, lb	3.84	0.0645	0.248
Mo coated foil, ea	1.493	1.05	1.567
Al spacer tape, lb	3.72	0.2325	0.865
Glass for tube sheet, lb	3.85	0.3944	1.519
Al mandrel, lb	2.50	0.0239	0.060
Al anode cup, ea	0.24	1.05	0.252
Al anode lead, lb	2.70	0.0198	0.053
Al flow restrictor, ea	0.33	1.05	0.347
Al cathode cup, ea	0.765	1.05	0.803
Cumene, lb	0.25	0.0404	0.010
Zn alloy, g	0.18	1.05	0.189
Cup dip glass, lb	3.85	0.1146	0.442
Cathode bottom cap, ea	0.181	1.05	0.190
Mandrel extension, ea	0.015	1.05	0.016
			$8.399

TABLE B.13. Levine (1981) Labor and Capital Breakdown ... Double Al Can Cell

	Operation	Labor $/Year	Labor $/Cell	Capital
1.	Spinning	1,434,000	1.09	1,725,022
2.	Store	--	--	--
3.	Mix tube sheet paste	28,680	0.0217	50,000
4.	Bundle roller	956,000	0.726	200,000
5.	Dry tube sheet	95,600	0.0726	21,200
6.	Cure tube sheet	95,600	0.0726	377,360
7.	Weld anode lead to cup	47,800	0.0363	24,000
8.	Insert flow restrictor	47,800	0.0363	--
9.	Glass lips of cups	95,600	0.0726	150,000
10.	Bundle into cathode cup	95,600	0.0726	--
11.	Induction seal	191,200	0.1453	216,000
12.	Weld, foil to case	95,600	0.0726	25,000
13.	Weld, bottom on cathode cup	47,800	0.0326	45,000
14.	Weld, bottom to mandrel	47,800	0.0326	24,000
15.	Leak test	124,280	0.0944	162,200
16.	Store good cells	95,600	0.0726	--
17.	Na and S fill, crimp	191,200	0.1453	800,000
18.	Electrical test	95,600	0.0726	1,000
19.	Assemble battery	--	--	--
	Total	3,785,760	2.876	3,820,582
	(times 2.5 for installation and buildings) =			9,551,455

TABLE B.14. Wicker (1981) Raw Materials Required for Production of 100 Tubes by Isostatic Pressing

	β-Alumina	β"-Alumina
α-Alumina	21.07 kg	21.03 kg
Sodium carbonate	3.65 kg	3.45 kg
Lithium carbonate	--	0.40 kg

TABLE B.15. Wicker (1981) Raw Materials Required for Production of 100 Tubes by Electrophoretic Deposition Followed by isostatic Pressing

	β-Alumina
Alpha alumina	16.00 kg
Sodium carbonate	2.78 kg
Methlpropylketone[(a)] (MPK)	1.60 L

(a) Assuming that 95% of the MPK is recovered.

TABLE B.16. Wicker (1981) Labor for the Alternative Routes Studied

Route	Labor (man-hours)	Powder Preparation (%)	Shaping (%)	Sintering (%)	Control (%)	Miscellaneous (%)
H11 J1 M1	6.842	14.6	12.7	29.6	31.6	11.4
H11 J1 L1	8.902	11.2	9.8	45.9	24.2	8.8
H12 K1 M1	7.898	13.7	23.4	25.7	27.3	9.8
H12 K1 L1	9.958	10.9	18.5	41.1	21.7	7.8

TABLE B.17. Wicker (1981) Cost of Materials for 100 β-Alumina Tubes by Production Route

Route	Raw Materials $	Other Materials $
H11 J1 M1	13.2	147.7
H11 J1 L1	13.2	292.7
H12 K1 M1	18.5	147.7
H12 K1 L1	18.5	292.7

TABLE B.18. Wicker (1981) Equipment Costs and Floor Area for β-Alumina by Production Route

Routes	Floor Area: Square Meter	Floor Area: Square Feet	Investments $ Million
H11 J1 M1	13,200	142,000	31.5
H11 J1 L1	19,600	211,000	63.2
H12 K1 M1	15,000	162,000	30.5
H12 K1 L1	21,300	230,000	62.4

TABLE B.19. Wicker (1981) Factory Cost for β-Alumina in U.S. $ by Production Route

Route	Labor	Materials and Purchased Components	Overhead on Labor	Overhead on Materials	Equipment Depreciation	Rent	Factory Cost
H11 J1 M1	91.30	214.5	136.95	21.45	49.22	8.88	522.30
H11 J1 L1	118.70	407.9	178.05	40.79	98.75	13.19	857.38
H12 K1 M1	105.30	221.6	157.95	22.16	47.66	10.13	564.80
H12 K1 L1	132.80	415.0	199.20	41.50	97.50	14.38	900.38

TABLE B.20. Wicker (1981) Selling Prices of 100 β-Alumina Tubes by Production Route

Route	Selling Price $
H11 J1 M1	717
H11 J1 L1	1,231
H12 K1 M1	759
H12 K1 L1	1,274

TABLE B.21. Wicker (1981) Cell Weight Characteristics

	β-Alumina	β"-Alumina Nonoptimized	β"-Alumina Optimized
Sulfur weight	691 g	691 g	1,072 g
Sodium weight	420 g	420 g	477 g
β-Alumina weight	180 g	180 g	180 g
Steel container weight	303 g	303 g	356 g
Aluminum container weight	63 g	63 g	69 g
Carbon felt weight	57 g	57 g	89 g
α-Alumina weight	21 g	21 g	34 g
Total weight	1,735 g	1,735 g	2,278 g

TABLE B.22. Wicker (1981) Raw Material Purchase prices ($/kg)

Sodium	1.84
Sulfur	0.3
α-Alumina powder	1.10
Carbon mat	35.6
Aluminium (ingot)	4.0
C12 Steel (ingot)	0.58
Glass	4.3
Chromium	10.5

TABLE B.23. Wicker (1981) Factory Cost Comparison Between β and β"-Alumina Tubes

	β-Alumina	β"-Alumina
Labor	1.123	1.253
Material and purchased components	2.678	2.790
Overhead on labor	1.684	1.880
Overhead on materials	0.268	0.279
Equipment depreciation	0.66	0.75
Rent	0.123	0.135
Factory cost ($)	6.536	7.087

TABLE B.24. Wicker (1981) Cell Factory Cost Comparison - by Components

Labor Cost + Materials Cost + Overhead on Labor and Materials	β-Alumina Cell	Nonoptimized β"-Alumina Cell	Optimized β"-Alumina Cell
α-Alumina	0.267	0.267	0.343
Glass seal	0.260	0.260	0.261
Sodium and filling	1.034	1.034	1.163
Sulfur and fillng	0.382	0.382	0.523
Graphite and electrode fabrication	2.463	2.520	3.822
Steel container + chrome plating	1.489	1.489	1.689
Aluminium container	0.336	0.336	0.367
Thermo-compression	0.438	0.511	0.511
Quality control and tests	0.540	0.581	0.589
Others	0.175	0.177	0.212
Total ($)	7.384	7.557	9.48
Equipment depreciation	0.57	0.58	0.73
Rental cost	0.57	0.58	0.73
Factory cost for cell assembly and tests	8.52	8.72	10.9
Factory cost of β or β"-alumina	6.863	7.44	7.44
Cell factory cost ($)	15.38	16.16	18.3
Cell factory cost ($/kWh)	37.7	37.5	35.0

TABLE B.25. Wicker (1981) Cell Factory Cost Comparison by Financial Category

	β-Alumina Cell	Nonoptimized β"-Alumina Cell	Optimized β"-Alumina Cell
Labor	2.133	2.338	2.375
Materials	7.358	7.476	9.137
Overhead on labor	3.199	3.506	3.562
Overhead on materials	0.736	0.748	0.914
Equipment depreciation	1.263	1.367	1.516
Rental cost	0.699	0.722	0.859
Cell factory cost ($)	15.38	16.16	18.33
Cell factory cost ($/kWh)	37.7	37.5	35.0

TABLE B.26. Wicker (1981) Module Factory Cost Comparison - by Components

	β-Alumina	β"-Alumina Nonoptimized	β"-Alumina Optimized
Materials Costs (cells not included)			
Busbars (internal)	51.24	43.92	58.56
Concrete (jacket and cover)	5.29	3.97	4.87
Concrete (outer module cover plate)	1.45	1.00	1.29
Concrete (gas flow connection piping)	0.64	0.77	0.87
Intermodule busbar	42.09	36.79	46.72
Insulator	68.3	50.0	53.75
Total ($)	169	136.5	166
Labor (cells not included)			
Rank busbars	1.36	1.21	1.06
Terminal busbars	0.67	0.67	0.67
Rank busbars weld	2.38	1.59	1.59
Terminal busbars weld	0.91	0.91	0.91
Concrete mixing	0.63	0.47	0.58
Concrete casting	5.55	5.35	5.50
Connecting busbar	1.52	1.52	1.52
Assembly	2.54	2.54	2.54
Quality control	0.67	0.67	0.67
Total ($)	16.23	14.93	15.04
Overhead on materials	16.9	13.66	16.6
Overhead on labor	24.34	22.42	22.56
Rental costs	78	73	71
Equipment depreciation	20	17	19
Module factory cost	324.5	277.5	310.2
Cells	2,214.7	2,068.5	1,906.3
Total module factory cost ($)	2,540	2,340	2,220

TABLE B.27. Wicker (1981) Module Factory Costs Comparison - by Financial Category

	β-Alumina	β"-Alumina	
		Nonoptimized	Optimized
Material costs	1,228.5	1,093.4	1,116.2
Labor	323.4	314.2	262.0
Overhead on materials	122.8	109.3	111.6
Overhead on labor	485.1	471.3	393.1
Rental costs	178.7	161.3	161.5
Equipment depreciation	202	192	177
Module factory cost ($)	2,540	2,340	2,220
Nominal energy	50 kWh	47.06 kWh	45.87 kWh
Module factory cost ($/kWh)	50.8	49.7	48.4

TABLE B.28. Wicker (1981) Balance of System Cost Estimate

	β-Alumina	β"-Alumina
Yardwork	90,000	90,000
Civil and structural	190,000	185,000
Cost of planning and construction supervision (15%)	42,000	41,000
Cooling and heating equipment	675,000	425,000
Control room equipment	150,000	150,000
Installation cost, equipment (10%)	82,000	50,000
Installation cost, modules	210,000	210,000
Total ($)	1,439,000	1,151,000

TABLE B.29. Wicker (1981) Total Battery Cost ($ million)

	β-Alumina	β"-Alumina Nonoptimized	β"-Alumina Optimized
100 MWh modules factory cost	5.12	5.25	4.89
Taxes	0.84	0.88	0.80
After taxes return on investment	0.84	0.88	0.80
Battery selling price	6.80	7.01	6.49
Plant cost	1.44	1.15	1.15
Contingency on plan cost (20%)	0.29	0.23	0.23
Marketing, Warranty, Miscellaneous cost	0.50	0.50	0.50
Total	9.03	8.89	8.37
$/kWh	90.3	88.9	83.7

PNL Note: The battery selling price and marketing, warranty, and miscellaneous expenses were added to estimate a total manufactured cost estimate. The cost for the optimized beta"-alumina battery of $69.90/kWh (1980 $) was inflated to $87/kWh (1984 $). The total installed system cost of $83.71 kWh (1980 $) was inflated to $104/kWh (1984 $).

TABLE B.30. Wicker (1981) Detailed Comparison Between β and β"-Alumina

Cell Weight Parameters	β-Alumina kg	β-Alumina kg/kWh	β"-Alumina kg	β"-Alumina kg/kWh
Sulfur	0.691	1.693	1.072	2.050
Sodium	0.420	1.029	0.477	0.912
β-Alumina	0.180	0.441	0.180	0.344
Steel container	0.303	0.743	0.356	0.681
Aluminum container	0.063	0.154	0.069	0.132
Carbon felt	0.057	0.140	0.089	0.170
Other	0.027	0.051	0.035	0.067
Total	1.735	4.252	2.278	4.356
Cell Cost Parameters	**$**	**$/kWh**	**$**	**$/kWh**
Alumina (material and labor)	6.040	14.80	6.512	12.45
Equipment depreciation on alumina	0.693	1.70	1.434	2.74
Rental costs on alumina	0.129	0.32	0.129	0.25
β-Alumina factory cost	6.862	16.82	8.075	15.44
Sulfur	0.382	0.936	0.523	1.000
Sodium	1.034	2.534	1.163	2.224
Steel container	1.489	3.649	1.689	3.229
Aluminum container	0.336	0.824	0.367	0.702
Carbon felt	2.463	6.037	3.822	7.308
Thermo-compression	0.438	1.073	0.511	0.977
Quality control and tests	0.540	1.324	0.589	1.126
Other	0.702	1.720	0.816	1.560
Equipment depreciation on cell fabrication	0.57	1.40	0.73	1.40
Rental costs on cell fabrication	0.57	1.40	0.73	1.40
Cell factory cost	15.38	37.7	18.33	35.0

TABLE B.30. Wicker (1981) Detailed Comparison Between β and β"-Alumina (contd)

Module Weight Parameters	β-Alumina kg	β-Alumina kg/kWh	β"-Alumina kg	β"-Alumina kg/kWh
Cells	250.0	5.0	237.0	5.17
Busbars	28.0	0.56	32.0	0.70
Concrete and other	228.0	4.56	210.0	4.58
Total	506.0	10.1	479.0	10.4
Module Cost Parameters	**$**	**$/kWh**	**$**	**$/kWh**
Cell factory cost	2,215.0	44.3	1,906.0	41.6
Busbar material and labor	116.0	2.3	126.0	2.7
Concrete	24.0	0.5	23.0	0.5
Assembly, control, other	87.0	1.7	71.0	1.5
Rental costs	78.0	1.6	71.0	1.5
Equipment depreciation	20.0	0.4	19.0	0.4
Module factory cost	2,540.0	50.8	2,220.0	48.4
Taxes and return	832.0	16.6	730.0	16.0
Module selling price	3,372.0	67.4	2,950.0	64.4
100-MWh Unit	**$ Million**	**$/kWh**	**$ Million**	**$/kWh**
Battery selling price	6.80	68.0	6.49	64.9
Plant cost and contingency	1.73	17.3	1.38	13.8
Marketing, warranty, ...	0.50	5.0	0.50	5.0
Total 100-MWh unit price	9.03	90.3	8.37	83.7

TABLE B.31. Roberts (1984a) Factory Cost Per Year (mid-1982 $)

		Cost/Year
Capital Equipment		
Total Investment	$34,319,010	
Yearly Amortization at 10%/Year		$3,432,000
Installation and Freight Charges		
Total Charges at 25% of Capital Equipment	$8,580,000	
Yearly Charges at 10%/Year		$858,000
Materials		
Direct		$85,542,000
Overhead at 10% of Direct		$8,554,000
Labor		
Direct at $10/man-hour		$11,042,000
Overhead at 150% of Direct		$16,563,000
Rent		
Charge at $5/ft^2$-year		$1,100,000
Factory Cost/Year		$127,091,000
Factory Cost/Battery at 25 Batteries/Year		$5,084,000

TABLE B.32. Roberts (1984a) Selling Price Per Battery (mid-1982 $)

Factory Cost/Battery		$5,084,000
Return on Investment (ROI) Base		
Working Capital/Battery at 30% of Factory Cost	$1,525,000	
Investment/Battery (Captital Cost plus Installation Charges)	$1,716,000	
Base for ROI	$3,241,000	
ROE (after tax) at 15% of Base		$486,000
Taxes at 15% of Base		$486,000
Marketing, Engineering, Warranty, Service		$500,000
Selling Price/Battery		$6,556,000
Selling Price/kWh		$66
Selling Price/kW		$330

PNL Note: The manufactured selling price of $66/kWh (1982 $) was inflated to $71/kWh (1984 $).

TABLE B.33. Bechtel (1982) Manufacturing Cost Estimate

Factory Price Estimate - Sodium-Sulfur Battery	1980 \$/kWh[a]	
	Low	High[b]
Labor (Direct + 150% Overhead)	27.49	--
Materials (Materials + 10% Overhead)	43.24	--
Energy	2.82	--
Depreciation	3.60	--
Rent	1.17	--
Factory Cost	78.32	--
After Tax ROI (15%)	8.92	--
Taxes (15% of Investment)	8.92	--
Marketing, Warranty, and Miscellaneous	5.00	--
FOB Factory Price	101.16	127.46

Manufacturing Plant Assumptions	1980 \$ x 10^3	
	Low	High[b]
Equipment (Including 25% Installation)	89,929	--
Working Capital (30% of Factory Cost)	58,740	--
Total Plant Investment	148,669	--

Unit Capacity, kWh	100,000
Production Volume, MWh/yr	2,500
Factory Floor Space, ft^2	586,000

(a) The kWh base is for end-of-life energy capacity.
(b) Data for high estimate was not available. A high value of \$127.46/kWh was obtained by multiplying the low estimate by 1.26, as explained in the text.

PNL Note: The manufactured cost estimates of \$101.16 to \$127.46/kWh (1980 \$) were inflated to \$126 to \$159/kWh (1984 \$).

TABLE B.34. Bechtel (1982) Balance of System Installed Cost Estimate

Battery: Sodium-Sulfur | Application: Multiple Residence

System/Component	Hours	Costs (1980 $) Labor	Material	Subtotal	Cost Distribution $	$/kW	$/kWh
Battery							
Shipping (500 miles)	--	--	--	680	--	--	1.06
Installation	74	1,330	--	1,330	860	--	0.73
Building							
Land	--	--	--	720	--	--	1.13
Thermal Management							
Heating Subsystem	100	1,800	--	1,800	--	--	2.81
Thermal Housing	42	760	1,240	2,000	--	--	3.13
Other	23	410	840	1,250	--	--	1.95
Instrumentation							
Smoke Detection	10	180	400	580	580	--	--
Other	15	270	230	500	500	--	--
Electrical							
DC Wiring	28	500	2,240	2,740	--	--	4.28
DC Equipment	14	250	2,580	2,830	--	--	4.42
AC Wiring	25	450	310	760	--	--	1.19
AC Panel Requirements	6	110	80	190	--	--	0.30
Other	3	50	100	150	--	--	0.23
Auxiliaries							
Fire Extinguisher	--	--	330	330	330	--	--
Subtotals	340	6,110	8,350	15,860	2,270	0	21.23
Total Direct Field Cost				15,860	2,270	0	21.20
Indirect Field Cost				3,360	480	0	4.50
BOS Field Cost				19,220	2,750	0	25.70

TABLE B.35. Bechtel (1982) Total Installed System Costs

Battery: Sodium-Sulfur | Application: Multiple Residence

Item	Low Estimate Total Cost $	Low Estimate Cost Distribution $	$/kW	$/kWh	High Estimate Total Cost $	High Estimate Cost Distribution $	$/kW	$/kWh
Battery, FOB[a]	64,640	0	0	101	81,280	0	0	127
BOS, Field Cost[b]	11,530	1,650	0	15	23,060	3,300	0	31
Total Field Cost	76,170	1,650	0	116	104,340	3,300	0	158
Engineering Costs (15%)	11,430	250	0	17	15,650	500	0	24
Subtotal	87,600	1,900	0	133	119,990	3,800	0	182
Contingency (20%)	17,520	380	0	27	24,000	760	0	36
Total Installed Cost	105,120	2,280	0	160	143,990	4,560	0	218

(a) From Table B.33 using end-of-life (rated) capacity.
(b) From Table B.34. High = 1.2 x Field Cost; Low = 0.6 x Field Cost.

PNL Note: Installed system cost estimates of $160 to 218/kWh (1980 $) were inflated to $199 to 272/kWh (1984 $).

TABLE B.36. Bechtel (1982) Low Life-Cycle Cost Estimate

Life-Cycle Cost Analysis (1980 $)

Battery Type: Sodium-Sulfur (Ford) Application Type: Multiple Residence

Low Estimate Input Parameters

Energy Rating	640.0 kWh per cycle	Power Cost ($/kWh)	0.050
Power Rating	72.0 kW	Resale/New Value	1.00
Battery Life	2500 cycles		
Cycles per Year	250	Discount Rate	10.0
Efficiency	72.0%	Escalation Rates	
Auxiliary Losses	0.0 kWh/cycle (fixed)	Capital	8.0
	0.0 kWh/cycle (kW)	Maintenance	8.0
	0.0 kWh/cycle (kWh)	Energy	10.2

Cost Data

Item	Fixed Costs $	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	2280.00	0	160.00
Replacement 1	0	0	105.00
Salvage 1	0	0	-1.15
Annual Maintenance	0	0	0.10
Infrequent Maintenance	0	0	0

Output (Net Present Value)

Item	Fixed Costs $	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	2280.00	0	160.00
Periodic Replacements Less Sal, Unused Life	0	0	89.15
Annual Maintenance	0	0	1.66
Infrequent Maintenance	0	0	0
Energy Losses	0	0	73.62
Total	2280.00	0	324.43

Total System Life-Cycle Cost: $210,000

PNL Note: The life-cycle cost of $324.43/kWh (1980 $) was inflated to $404/kWh (1984 $).

TABLE B.37. Bechtel (1982) High Life-Cycle Cost Estimate

Life-Cycle Cost Analysis (1980 $)

Battery Type: Sodium-Sulfur (Ford) Application Type: Multiple Residence

High Estimate Input Parameters

Energy Rating	640.0 kWh per cycle	Power Cost ($/kWh)	0.050
Power Rating	72.0 kW	Resale/New Value	1.00
Battery Life	2000 cycles		
Cycles per Year	250	Discount Rate	10.0
Efficiency	66.0%	Escalation Rates	
Auxiliary Losses	0.0 kWh/cycle (fixed)	Capital	8.0
	0.0 kWh/cycle (kW)	Maintenance	8.0
	0.0 kWh/cycle (kWh)	Energy	10.2

Cost Data

Item	Fixed Costs $	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	4560.00	0	218.00
Replacement 1	0	0	136.00
Salvage 1	0	0	-2.31
Annual Maintenance	0	0	0.14
Infrequent Maintenance	0	0	0

Output (Net Present Value)

Item	Fixed Costs $	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	4560.00	0	218.00
Periodic Replacements Less Sal, Unused Life	0	0	176.24
Annual Maintenance	0	0	2.32
Infrequent Maintenance	0	0	0
Energy Losses	0	0	86.31
Total	4560.00	0	482.87

Total System Life-Cycle Cost: $314,000

PNL Note: The life-cycle cost of $482.87/kWh (1980 $) was inflated to $602/kWh (1984 $).

APPENDIX C

LEAD ACID BATTERY COST DETAILS

APPENDIX C

LEAD ACID BATTERY COST DETAILS

The following pages present cost estimating details extracted from the sources reviewed for this study. The tables have been reproduced to match the figures and notes presented in the original sources except for some minor modification to the format or style. Additional clarifying comments, if any, are designated as PNL Notes.

The data provide an indication of the completeness and level of detail found among the various estimates and also serve as a rudimentary data base of battery cost information. The supporting details presented in this appendix correspond to the cost estimates referenced in Tables 5.2, 5.4, and 5.5.

TABLE C.1. Ferrell (1977) Manufacturing Cost Estimates

Manufacturing Price Estimates for the VLL43 and VLL45 Cells Produced at 1000 MWh per Year

Item	20 MW 60 MWh Battery Cell (VLL43 HSG) $/cell	20 MW 60 MWh Battery Cell (VLL43 HSG) $/kWh	20 MW 100 MWh Battery Cell (VLL45 HSG) $/cell	20 MW 100 MWh Battery Cell (VLL45 HSG) $/kWh	10 MW 100 MWh Battery Cell (VLL45 LSG) $/cell	10 MW 100 MWh Battery Cell (VLL45 LSG) $/kWh
Purchased Parts						
Separators	36.08	2.26	37.80	2.07	37.80	1.98
Jar and Cover Assembly	101.00	6.32	101.00	5.54	101.00	5.30
Copper Inserts	19.61	1.23	19.61	1.08	19.61	1.03
Other Parts	108.18	6.77	112.30	6.16	112.30	5.90
Total	264.87	16.58	270.71	14.85	270.21	14.21
Scrap and Freight on Parts	13.21	.83	13.50	.74	13.50	.71
Total Purchased Parts	278.08	17.41	284.21	15.59	284.21	14.92
Plate Grid and Active Materials and Terminals	309.15	19.36	330.57	18.14	329.50	17.30
Direct Labor	45.12	2.83	47.22	2.59	47.22	2.48
Overhead, G&A, Profit	256.35	16.05	268.31	14.72	268.09	14.07
Selling Price	888.70	55.65	930.31	51.03	929.02	48.77
Rated Energy (kWh) (h)	15.97 (3 h)		18.23 (3 h)		19.05 (10 h)	
Rated Depth of Discharge, %	90		85		80	

Notes: 1. Lead at $0.20 per lb; antimony at $2.00 per lb.
2. Scrap on purchased parts at 1.93%.
3. Freight on purchased parts and scrap at 3.03.

PNL Note: Manufactured cost estimates of $48.77-55.65/kWh (1977 $) were inflated to $77-88/kWh (1984 $).

TABLE C.2. Ferrell (1977) Salvage and Reuse Credits (20¢/lb lead)

Cell Component	Reuse Rate	20 MW 60 MWh Battery Cell $/cell	20 MW 60 MWh Battery Cell $/kWh	20 MW 100 MWh Battery Cell $/cell	20 MW 100 MWh Battery Cell $/kWh	10 MW 100 MWh Battery Cell $/cell	10 MW 100 MWh Battery Cell $/kWh
Plate and Terminal Pb, Sb	(0.8)	243	15.22	260	14.26	260	13.65
Jar, Cover, Hoops	(0.95)	96	6.01	96	5.27	96	5.04
Terminal Copper	(0.8)	16	1.00	16	0.88	16	0.84
Other Cell Parts		10	0.62	10	0.55	10	0.53
Totals		365	22.85	382	20.96	382	20.06
Rated Output Energy, kWh		15.97		18.23		19.05	
Original Parts and Material Cost		587		615		624	
Recovery of Original Parts and Material Cost, %		62		62		62	

Similarly, salvage and reuse credits were calculated for the case of 25- and 30-cent lead. These credits are summarized below:

Battery Type	Lead Price ¢/lb	Salvage and Reuse Credit $/Cell	Salvage and Reuse Credit $/kWh
20 MW 60 MWh	20	365	22.86
	25	418	26.17
	30	470	29.43
20 MW 100 MWh	20	382	20.95
	25	438	24.03
	30	494	27.10
10 MW 100 MWh	20	382	20.05
	25	438	22.99
	30	494	25.93

TABLE C.3. Ferrell (1977) Plant and Equipment Cost and Manning Estimates - VLL-45 Cell Produced at 54,840 Per Year Three Shift Operation

Operation	Number of Pieces of Equipment	Estimated Total Cost of Equipment	Manning Required	Floor Space Required Sq Ft
Oxide Manufacturing and Handling	3	1,500,000	4	15,000
Negative Grid Casting	2	300,000	6	7,500
Negative Pasting:				
Mixers	2	270,000	6	2,000
Pasting Machine	1	125,000	12	2,000
Miscellaneous	1	105,000	--	4,500
Positive Grid Casting	4	500,000	9	8,000
Positive Tubing Manufacturing	1	200,000	5	5,000
Positive Filling Machines	4	600,000	9	12,000
Plate Finishing	1	500,000	26	20,000
Strap Casting and Finishing	2	200,000	28	10,000
Assembly	5	550,000	105	20,000
Finish, pack and ship	1	300,000	38	15,000
Total - Direct		5,150,000	248	121,000
Plant Support		750,000	92	39,000
Services and Office		100,000	50	10,000
Total		6,000,000	390	170,000
Inflation and Contingency at 20%		1,200,000	--	30,000
Total		7,200,000	390	200,000
Building, all Improvements		7,000,000	--	--
Land, 10 Acres		200,000	--	--
Grand Total		$14,400,000	390	200,000

TABLE C.4. Ferrell (1977) Plate Grid, Terminal and Active Material Price Estimates for VLL45 and VLL43 Cells

Item	20 MW 60 MWh Battery 3756 Cells			20 MW 100 MWh Battery 5484 Cells			10 MW 100 MWh Battery 5250 Cells		
	$/cell	$/kWh	lb/kWh (Rated)	$/cell	$/kWh	lb/kWh (Rated)	$/cell	$/kWh	lb/kWh (Rated)
Positive Grid: Pb	67.20	4.21	21.0	71.60	3.93	19.6	71.60	3.76	18.8
Sb	43.00	2.69	1.4	45.60	2.50	1.3	45.60	2.39	1.2
Positive Active Material	78.00	4.88	24.4	84.54	4.64	23.2	84.54	4.44	22.2
Negative Grid	41.60	2.60	13.0	43.42	2.38	11.9	43.42	2.28	11.4
Negative Active Material	62.40	3.91	19.5	67.64	3.71	18.0	67.64	3.55	17.7
Post Terminal Pb	11.94	0.75	3.7	12.50	0.69	3.4	12.50	0.66	3.3
Electrolyte	5.01	0.31	31.0	5.21	0.29	28.3	4.20	0.22	26.4
Total Price	309.15	19.36	114.0	330.57	18.14	100.3	329.50	17.30	101.0
Cell Type	VLL43 (HSG)			VLL45 (HSG)			VLL45 (LSG)		
Rated kWh (H^2)	15.97 (3 h)			18.23 (5 h)			19.05 (1 h)		
Depth of Discharge %	90			85			80		

Note: 1. Lead at $0.20 per lb; Sb at $2.00 per lb.

TABLE C.5. Ferrell (1977) Battery Shipping Costs

Battery			Shipping	No.				
Power MW	Energy MWh	Cells Each	Weight MM lb	Loads Each	Projected Shipping Cost, $/kWhr 100	200	300	500 miles
10	100	5250	9.64	241	1.11	1.19	1.64	1.88
20	60	3756	7.74	194	1.48	1.59	2.19	2.52
20	100	5484	11.97	299	1.38	1.17	2.03	2.33

TABLE C.6. Ferrell (1977) Battery Transportation and Installation

Power	MW	10		20		20	
Energy Output	MWh	100		60		100	
Price		$	$/kWh	$	$/kWh	$	$/kWh
Transportation 500 miles		188,000	1.88	151,200	2.52	233,000	2.33
Installation, Formation Charge and First Cycle		72,670	0.73	52,430	0.87	75,835	0.76
Total Transportation and Installation		260,670	2.61	203,630	3.39	308,835	3.09

TABLE C.7. Ferrell (1977) Battery Cooling System Costs

Cooling System	20 MW 60 MWh Battery K$	20 MW 60 MWh Battery $/kWh	20 MW 100 MWh Battery K$	20 MW 100 MWh Battery $/kWh
Without Back-Up Components				
Ion exchanger	24	0.40	24	0.24
Cooling Towers	225	3.75	275	2.75
Pumps, valves, piping	69	1.15	103	1.03
Assembly labor	56	0.93	75	0.75
OH, G&A, Profit	163	2.72	217	2.17
Price	537	8.95	694	6.94
With Back-Up Equipment				
Ion exchanger	24	0.40	24	0.24
Cooling towers	250	4.17	300	3.00
Pumps, valves, piping	92	1.53	141	1.41
Assembly labor	57	0.95	82	0.82
OH, G&A, Profit	172	2.87	241	2.41
Price	595	9.92	788	7.88

TABLE C.8. Ferrell (1977) Air-Lift Stirrer Costs

Component	20 MW 60 MWh Battery K$	20 MW 60 MWh Battery $/kWh	20 MW 100 MWh Battery K$	20 MW 100 MWh Battery $/kWh
Rotary vane compressor	2.0	0.10	3.0	0.03
Piping, valves, flowmeters, filters	2.0	0.10	3.0	0.03
Assembly labor	10.0	0.17	13.7	0.14
OH, G&A, Profit	24.6	0.41	33.9	0.34
Price	38.6	0.64	53.6	0.54

TABLE C.9. Ferrell (1977) Electrical Monitoring Costs

Electrical System Cost Element	20 MW 60 MWh Battery K$	$/kWh	20 MW 100 MWh Battery K$	$/kWh
Hardware, parts, etc.	31.7	0.53	40.2	0.40
Computer	16.5	0.28	16.5	0.17
Assembly labor	13.3	0.22	13.7	0.14
OH, G&A, and Profit	37.0	0.62	39.4	0.39
Price	98.5	1.65	109.8	1.10

TABLE C.10. Ramsay (1982) Manufacturing Cost Estimate

Low-Maintenance Lead Acid: Capital Cost and Salvage Value

		$/kWh
Initial Capital Cost of Battery		93.12
a) Labor (excluding overhead) 375 people		3.12
b) Purchased Components and Materials		
Plates and Grids ($0.40/lb lead)	$37.49	
All else	26.09	
c) Rent 375,000 ft^2		0.75
d) Installed Equipment Costs $15.7 million		6.28
e) Marketing, Warranty, Miscellaneous		5.00
Salvage Value		23.20
Plates and Grids	$18.00	
(80% of Material) (60% Cost/lb)		
All else		
(50% of Material) (40% Cost/lb)	5.20	

PNL Note: Manufactured cost estimate of $93.12/kWh (1980 $) was inflated to $116/kWh (1984 $).

TABLE C.11. Ramsay (1982) Balance of System Costs

Low-Maintenance Lead Acid: Other Costs of Commercial System	
Commercial System (2 MWh and 400 kW)	$/kWh
• Ancillary Equipment	
- Automatic water system	25.00
- Ventilation and cooling equipment	6.00
- Racks	1.50
- Controls and sensors	5.00
- Electrolyte spill containment	4.00
- Prefabricated enclosure	5.00
- Electrical connections and protectors	2.50
	$49.00

- Operation and Maintenance Scenario
  - 2-1/2% annual cell failure rate
  - Individual cell replacement: 4 man-hours
  - Bulk cell replacements: 0.4 man-hours
  - Scheduled maintenance: 2 man-days/month
  - Unscheduled maintenance: 6 man-days/year

  Present worth of O&M over system lifetime

  6% discount rate: $137,700

  8% discount rate: $116,800

TABLE C.12. Ramsay (1982) Life-Cycle Cost Estimates

Low-Maintenance Lead Acid: Commercial System Summary Costs

Nominal System Rating: 2 MWh and 400 kW

Output Voltage: $110V_{AC}$

Battery Depth of Discharge: 50%

Initial Battery Capacity: 4 MWh

Battery Cutoff Voltage: 1.75 V_{DC}/Cell

Converter Efficiency: 95%

System Configuration: 8 parallel rows of 66 cells in series. Total: 528 Cells

Cell Capacity: 7.58 kWh

	Discount Rate	
	6%	8%
Initial Capital Cost of Battery	$ 372,500	$372,500
Initial Capital Cost of Ancillary Equipment	196,000	196,000
Present Worth of Battery Replacement Costs	352,800	293,400
Present Worth of Annual Operation and Maintenance Costs	137,700	116,800
Present Worth of Battery at End of System Life	(44,900)	(30,900)
Present Worth of Ancillary Equipment at End of System Life	(12,200)	(8,400)
Life Cycle Cost	$1,002,000	$939,500
Life Cycle Cost/kWh of Battery Capacity	$501/kWh	$470/kWh

PNL Note: Life-cycle costs of $470-501/kWh (1980 $) were inflated to $586-625/kWh (1984 $).

TABLE C.13. Ramsay (1982) Manufacturing Cost Estimate

Low-Maintenance Lead Acid: Capital Cost and Salvage Value		$/kWh
Initial Capital Cost of Battery		100.72
a) Labor (excluding overhead) 375 people		3.12
b) Purchased Components and Materials		69.92
Plates and Grids ($0.40/lb lead)	$35.60	
All else	34.32	
c) Rent 375,000 ft^2		0.75
d) Installed Equipment Costs $15.7 million		6.28
e) Marketing, Warranty, Miscellaneous		5.00
Salvage Value		23.95
· Plates and Grids	$17.10	
(80% of Material) (60% Cost/lb)		
All else		
(50% of Material) (40% Cost/lb)	6.85	

PNL Note: Manufactured cost of $100.72/kWh (1980 $) was inflated to $126/kWh (1984 $).

TABLE C.14. Ramsay (1982) Balance of System Costs

Maintenance-Free Lead Acid MFX: Other Costs of Commercial System	
Commercial System (2 MWh and 400 kW)	$/kWh
• Ancillary Equipment	
- Cooling equipment	6.00
- Racks	1.50
- Controls and sensors	5.00
- Prefabricated enclosure	5.00
- Electrical connections and protectors	2.50
	$20.00

• Operation and Maintenance Scenario

- 2-1/2% annual cell failure rate
- Individual cell replacement: 4 man-hours
- Bulk cell replacements: 0.4 man-hours
- Scheduled maintenance: 1 man-day/month
- Unscheduled maintenance: 2 man-days/year

Present worth of O&M over system lifetime

6% discount rate: $84,650

8% discount rate: $71,400

TABLE C.15. Ramsay (1982) Life-Cycle Cost Estimates

Maintenance-Free Lead Acid: Commercial System Summary Costs

Nominal System Rating: 2 MWh and 400 kW

Output Voltage: $110V_{AC}$

Battery Depth of Discharge: 80%

Initial Battery Capacity: 2.5 MWh

Battery Cutoff Voltage: 1.75 V_{DC}/Cell

Converter Efficiency: 95%

System Configuration: 8 parallel rows of 66 cells in series. Total: 528 Cells

Cell Capacity: 4.74 kWh

	Discount Rate	
	6%	8%
Initial Capital Cost of Battery	$251,800	$251,800
Initial Capital Cost of Ancillary Equipment	50,000	50,000
Present Worth of Battery Replacement Costs	242,100	201,400
Present Worth of Annual Operation and Maintenance Costs	84,650	71,400
Present Worth of Battery at End of System Life	(29,600)	(20,400)
Present Worth of Ancillary Equipment at End of System Life	(3,750)	(2,600)
Life Cycle Cost	$595,200	$551,600
Life Cycle Cost/kWh of Battery Capacity	$298/kWh	$276/kWh

PNL Note: Life-Cycle costs of $276-298/kWh (1980 $) were inflated to $344-371/kWh (1984 $).

TABLE C.16. Long (1977) Manufacturing Cost Estimates

Summary of Results

State-Of-The-Art	Direct Product Costs ($/kWh)	Projected Selling Price ($/kWh) With Moderate Risk	Projected Selling Price ($kWh) With Low Risk
1) 25¢/lb, lead	$36.81	$48.25	$44.24
2) Manufacturing plant vertical integration and 25¢/lb lead	34.30	45.48	41.68
3) Effective lead cost 19¢/lb with manufacturing plant vertical integration	29.73	40.50	36.90
4) Recycled batteries 10¢/lb lead	22.96	32.65	29.87

PNL Note: The manufactured cost estimate of $48.25/kWh (1976 $) was inflated to $81/kWh (1984 $).

TABLE C.17. Long (1977) kW 160-45 Material Cost Estimate

Assumptions

1. At $0.25/lb lead
   a. 4% antimonial grid lead costs $0.315/lb
   b. Negative oxide cost (litharge) $0.276/lb
   c. Positive oxide (red lead) $0.286/lb
2. Plate yield = 97.5% (80% of loss recoverable)

Item	Quantity Per Cell	Cost Per Cell	Cost per kWh (4-hour rate)
Negative and Positive Grids	143.70 lb	$ 45.26	$ 9.17
Negative and Positive Oxide	222.96 lb	62.71	12.70
Straps and Cell Connector	20.97 lb	6.32	1.28
Reclaimed Lead	7.33 lb	-.73	-0.15
Positive Plate Wrap	5.00 lb	14.83	3.00
Separator and Protectors	44 pcs	14.94	3.03
Case	1 pc	4.33	0.88
Cover	1/7 pc	1.01	0.21
Base	1/7 pc	5.14	1.04
Side Plates	2/7 pc	1.47	0.30
Auxiliaries		1.39	0.28
Electrolyte	101 lb	1.11	0.22
		$157.78	$31.96

	Per Cell	Per kWh
Lead Costs	$113.56	$23.00
Non-Lead	44.22	8.96
Total	$157.78	$31.96

TABLE C.18. Long (1977) Plant, Equipment and Labor Estimates kW 160-45 40 MWh Battery 25 Batteries/Year Three Shift Operation

Operation	Number of Pieces of Equipment	Estimated Total Cost of Equipment	Operation Required	Floor Space Required Sq Ft
Oxide Handling and Mixing	18	$ 224,000	6.0	11,000
Alloying Furnaces	3	90,000	6.0	750
Grid and Parts Casting	11	471,000	27.0	12,500
Plate Pasting	3	136,000	27.0	2,250
Plate Drying and Curing	11	600,000	7.5	6,300
Pos. Plate Wrapping	17	200,000	24.0	3,400
Assembly Plates and Cast Straps	1	200,000	15.0	1,250
Place Cells in Jar, Place on Base	3	145,000	6.0	3,250
Jar, Cover and Base Molds	3	112,000		
Burn Intercell Connection	Misc	20,000	4.5	3,100
Continued Test and Repair	Misc	45,000	3.0	2,250
Prepare Cover	Misc	50,000	4.5	1,000
Attach Cover and Complete Module	Misc	20,000	1.5	2,250
Shipping and Receiving	Misc	120,000	12.0	20,000
Machine Shop and Laboratories	Misc	195,000	O.H.	1,750
Spare Parts Inventory	Misc	160,000	O.H.	500
Waste and Stack				
Gas Treatment		In Bldg Cost	O.H.	4,000
Medical Health	Misc	20,000		200
Aisle and Laydown Space				40,250
Plant Service				4,000
Office		71,000		10,000
Total		$2,879,000	144.0	130,000
			+ 6.0 Relief	
			150.0	

TABLE C.19. Long (1977) Administrative and General Functions

	Salary Rate	Quantity	Total Cost
Plant Manager	45K	1	$ 45K
Secretary	12K	1	12K
Controller	30K	1	30K
Payroll Clerk	10K	1	10K
A/P, A/R and General Accounting Clerks	10K	2	20K
Cost Accountant	12K	1	12K
Materials Manager	25K	1	25K
Buyers	15K	1	15K
Purchasing Clerk	10K	1	10K
Personnel Relations Manager	30K	1	30K
Benefits Clerk	10K	1	10K
Medical	15K	1	15K
Total A&G Salaries		13	$234K
Benefits			47K
Computer Costs			50K
Telephone Costs			10K
Travel Costs			10K
Supplies, Copies and Miscellaneous			24K
Total A&G Management Cost			$375K

TABLE C.20. Long (1977) Engineering and Service Functions

	Salary Rate	Quantity	Total Cost
Engineering and Service Manager	30K	1	$ 30K
Customer Service Engineer	18K	2	36K
Drafters	13K	1	13K
Installation Engineers	18K	2	36K
Order Correspondent	15K	1	15K
Secretary	8K	1	8K
Total Engineering and Service Salaries		8	$138K
Benefits			27K
Telephone Costs			15K
Travel Costs			55K
Supplies Copies and Miscellaneous			25K
Total Engineering and Service Costs			$260K

TABLE C.21. Long (1977) Manufacturing Functions

	Salary Rate	Quantity	Total Cost
Manufacturing Manager	35K	1	$ 35K
Scheduler and Planners	12K	2	24K
Secretary	10K	1	10K
First Line Supervisor	17K	6	102K
Receiving Clerks	10K	2	20K
Manufacturing Services Manager	25K	1	25K
Factory Engineers	18K	2	36K
Plant and Tool Maintenance	15K	12	180K
Janitors	8K	2	16K
QA Manager	25K	1	25K
Quality Engineers	18K	1	18K
Inspectors	12K	3	36K
Lab Technicians	15K	2	30K
Waste Treatment Operator	8K	1	8K
Total Manufacturing Overhead Salaries		37	$ 565K
Benefits			113K
Telephone Costs			5K
Travel Costs			10K
Total Plant Fuel Costs			285K
Medical Supplies and Exams			25K
Water and Sewage Costs			80K
Waste Treatment Supplies			40K
Office Supplies etc.			20K
Total Manufacturing Managed Overhead			$1143K
Miscellaneous Shop Supplies Excluding Waste Treatment			50K
Electric Power Costs			300K
Unapplied Materials			200K
Employee Benefits on Direct Hourly Personnel			326K
Maintenance Materials			150K
Total Direct Overhead			$1026K

TABLE C.22. Long (1977) Other Costs

Transportation Costs - Truck ($1.60/kWh)	$1,600K
Product Warranty Costs ($0.35/kWh)	350K
Selling Costs	700K
Insurance and Taxes	175K
Total Other Costs	$2,825K

TABLE C.23. Long (1977) Summary of Cost Data (Lead at 25¢/lb)

Land (50 acres)	$ 250K
Building (130,000 sq ft)	3,800K
Machinery and Equipment	2,200K
Total Capital Investment	$ 6,250K
Factory Tooling	$ 679K
Initial Stock of Factory Supplies and Expense Items for Start-up	51K
Manufacturing Planning (135 man-months)	270K
Training and Start-up Costs	2000K
Total Strategic Expense	$ 3,000K
Accounts Receivable (45 days)	$ 5,210K
Inventories	4,637K
Less: Accounts Payable and Warranty Reserve	-3,056K
Total Working Capital	$ 6,791K
Direct Labor	$ 1,650K/year
Direct Material	31,960K/year
Transportation	1,600K/year
Direct Overhead	1,026K/year
Warranty	350K/year
Installation Labor	255K/year
Subtotal Direct Cost	$36,811K/year
Less: Potential Improvement From Vertical Integration	-2,510K/year
Total Direct Cost	$34,301K/year
Administrative and General	$ 375K/year
Engineering and Service	260K/year
Manufacturing Managed Overhead	1,143K/year
Marketing	700K/year
Insurance and Taxes	175K/year
Total Indirect Overhead	$ 2,653K/year

TABLE C.24. Pittman (1977) Manufacturing Cost Estimates

Summary of Results

Advance Technology	Direct Product Costs ($/kWh)	Projected Selling Price ($/kWh) With Moderate Risk	Projected Selling Price ($kWh) With Low Risk
1) 25¢/lb, lead	$32.36	$41.77	$38.53
2) Manufacturing plant vertical integration and 25¢/lb lead	34.30	38.80	35.50
3) Effective lead cost 19¢/lb with manufacturing plant vertical integration	25.44	34.50	31.62
4) Replacement batteries 10¢/lb lead	20.17	28.75	25.85

PNL Note: The manufacturing cost estimate of $41.77/kWh (1976 $) was inflated to $70/kWh (1984 $).

TABLE C.25. Pittman (1977) WE 67 Material Cost Estimate

Assumptions

1. At $0.25/lb lead
   a. Grid lead costs $0.292/lb
   b. Negative oxide cost (litharge) $0.275/lb
   c. Positive oxide (red lead) $0.286/lb
2. Plate yield = 97.5% (80% of loss recoverable)

Item	Qty. Per Cell	Cost Per Cell	Cost per kWh (4-hour rate)
Negative and Positive Grids	1194 lb	$420.29	$ 8.57
Negative and Positive Oxide	1671 lb	470.28	9.59
Straps and Posts	227 lb	70.99	1.45
Reclaimed Lead	60 lb	-6.00	-0.12
Glass Mats	1068 ft^2	39.52	0.81
Positive Plate Wrap	1000 ft^2	59.39	1.21
Separators	528 ft^2	129.36	2.64
Case	1 pc	36.52	0.75
Cover	1 pc	7.20	0.15
Base	1 pc	28.20	0.58
Side Plates	2 pc	53.28	1.09
Tensioning Device	6 pc	30.00	0.61
Auxiliaries		3D.36	0.62
Electrolyte	1350 lb	14.84	0.30
		$1384.23	$28.25

	Per Cell	Per kWh
Lead Costs	$ 939.06	$19.16
Non-Lead Costs	445.17	9.09
Total	$1384.23	$28.25

TABLE C.26. Pittman (1977) Plant, Equipment and Labor Estimates WE-67 40 MWh Battery 25 Batteries/Year Three-Shift Operation

Operation	Number of Pieces of Equipment	Estimated Total Cost of Equipment	Oper. Required	Floor Space Required Sq Ft
Oxide Mixing and Handling	16	$196,000	18	9,000
Plate Processing	3	340,000	7	2,300
Small Parts Casting	1	71,000	1	500
Plate Wrapping	3	111,000	9	550
Terminal Welding	1	170,000	9	500
Automatic Stacking	1	140,000	6	2,000
Cast on Posts and Straps	1	250,000	12	1,500
Mold Jar	1	91,000	6	2,000
Assemble Cell in Jar	1	185,000	6	700
Base Cover and Side Plate Molds	3	109,000	--	--
Attach Side Plates and Base to Cell and Place on Conveyer	1	100,000	3	3,000
Continuity Test and Repair	1	75,000	4	2,000
Prepare Cover and Attach to Cell	2	130,000	12	3,500
Shipping and Receiving	Misc	220,000	12	20,000
Machine Shop and Laboratories	Misc	195,000	O.H.	1,750
Spare Parts Inventory	Misc	120,000	--	500
Medical Health	Misc	20,000	O.H.	200
Aisle and Laydown Space				26,000
Plant Service	Misc	5,000	O.H.	4,000
Office	Misc	71,000	O.H.	10,000
		$2,599,000	105	90,000
			+ 4 Relief	
			109	

TABLE C.27. Pittman (1977) Administrative and General Functions

	Salary Rate	Quantity	Total Cost
Plant Manager	45K	1	$ 45K
Secretary	12K	1	12K
Controller	30K	1	30K
Payroll Clerk	10K	1	10K
A/P, A/R and General Accounting Clerks	10K	2	20K
Cost Accountant	12K	1	12K
Materials Manager	25K	1	25K
Buyers	15K	1	15K
Purchasing Clerk	10K	1	10K
Personnel Relations Manager	30K	1	30K
Benefits Clerk	10K	1	10K
Medical	15K	1	15K
Total A&G Salaries		13	$234K
Benefits			47K
Computer Costs			50K
Telephone Costs			10K
Travel Costs			10K
Supplies, Copies and Miscellaneous			24K
Total A&G Mgd. Cost			$375K

TABLE C.28. Pittman (1977) Engineering and Service Functions

	Salary Rate	Quantity	Total Cost
Engineering and Service Manager	30K	1	$ 30K
Customer Service Engineer	18K	2	36K
Drafters	13K	1	13K
Installation Engineers	18K	2	36K
Order Correspondent	15K	1	15K
Secretary	8K	1	8K
Total Engineering and Service Salaries		8	$138K
Benefits			27K
Telephone Costs			15K
Travel Costs			55K
Supplies Copies and Miscellaneous			25K
Total Engineering and Service Costs			$260K

TABLE C.29. Pittman (1977) Manufacturing Functions

	Salary Rate	Quantity	Total Cost
Manufacturing Manager	35K	1	$ 35K
Scheduler and Planners	12K	2	24K
Secretary	10K	1	10K
First Line Supervisor	17K	6	102K
Receiving Clerks	10K	2	20K
Manufacturing Services Manager	25K	1	25K
Factory Engineers	18K	2	36K
Plant and Tool Maintenance	15K	12	180K
Janitors	8K	2	16K
QA Manager	25K	1	25K
Quality Engineers	18K	1	18K
Inspectors	12K	3	36K
Lab Technicians	15K	2	30K
Waste Treatment Operator	8K	1	8K
Total Manufacturing Overhead Salaries		37	$565K
Benefits			113K
Telephone Costs			5K
Travel Costs			10K
Total Plant Fuel Costs			50K
Medical Supplies and Exams			25K
Water and Sewage Costs			80K
Waste Treatment Supplies			40K
Office Supplies etc.			20K
Total Manufacturing Managed Overhead			$908K
Miscellaneous Shop Supplies Excluding Waste Treatment			50K
Electric Power Costs			250K
Unapplied Materials			200K
Employee Benefits on Direct Hourly Personnel			238K
Maintenance Materials			200K
Total Direct Overhead			$938K

TABLE C.30. Pittman (1977) Other Costs

Transportation Costs - Truck ($1.40/kWh)	$1,400K
Product Warranty Costs ($0.35/kWh)	350K
Selling Costs	700K
Insurance and Taxes	150K
Total Other Costs	$2,600K

TABLE C.31. Pittman (1977) Summary of Cost Data (Lead at 25¢/lb)

Land (50 acres)	$ 250K
Building (90,000 sq ft)	2,700K
Machinery and Equipment	2,040K
Total Capital Investment	$ 4,990K
Factory Tooling	$ 559K
Initial Stock of Factory Supplies and Expense Items for Start-up	46K
Manufacturing Planning (135 man-months)	270K
Training and Start-up Costs	1,855K
Total Strategic Expense	$ 2,730K
Accounts Receivable (45 days)	$ 4,410K
Inventories	4,010K
Less: Accounts Payable and Warranty Reserve	-2,710K
Total Working Capital	$ 5,710K
Direct Labor	$ 1,200K/year
Direct Material	28,250K/year
Transportation	1,400K/year
Direct Overhead	938K/year
Warranty	350K/year
Installation Labor	225K/year
Subtotal Direct Cost	$32,363K/year
Less: Potential Improvement From Vertical Integration	-2,940K/year
Total Direct Cost	$29,423K/year
Administrative and General	$ 375K/year
Engineering and Service	260K/year
Manufacturing Operations	908K/year
Marketing	700K/year
Insurance and Taxes	150K/year
Total Indirect Overhead	$ 2,393K/year

TABLE C.32. Boden (1977) Manufacturing Cost Estimates

Typical User Costs - C&D Battery Design for Utility Peaking Energy Storage

	User Costs (at 5 Hour Rate)		Facility Cost	Tooling Cost
Production at:				
500/MWh/Yr. (Pb = 25¢/lb)	$50.67/kWh	FOB Factory	$ 1,670,000	$ 3,000,000
1000/MWh/Yr.	$48.72/kWh	FOB Factory	$ 2,500,000	$ 4,000,000
4000/MWh/Yr.	$47.72/MWh	FOB Factory	$10,000,000	$16,000,000
Trucking to Site	$ 2.10/kWh			
Price of Replacement Battery[a]	$36.13/kWh			

(a) Replacement Price = Price of second battery less value or use of first battery materials and components.

PNL Note: Median manufactured cost estimate of $48.72/kWh (1976 $) was inflated to $82/kWh (1984 $).

TABLE C.33. Hellman (1977) Manufacturing Cost Estimates

Discharge Rate	Price
3 Hour	$61 per kWh
5 Hour	$51 per kWh
10 Hour	$44 per kWh

PNL Note: The median manufacturing cost estimate of $51/kWh (1976 $) was inflated to $86/kWh (1984 $).

TABLE C.34. Bechtel (1982) Balance of System Installed Costs

Battery: Lead Acid (Antimony)
Application: Shopping Center

System/Component	Hours	Costs (1980 $) Labor	Material	Subtotal	Cost Distribution $	$/kW	$/kWh
Battery							
Shipping (500 miles)	--	--	--	32,000	--	--	5.15
Installation	4,760	85,680	--	85,680	--	--	13.80
Building							
Land	--	--	--	1,800	--	--	0.29
Building	--	--	--	63,000	--	--	10.14
Structural	398	7,160	4,320	11,480	4,120	--	1.19
Paint (Acid-resistant)	60	1,080	3,000	4,080	--	--	0.66
Other	20	360	400	760	760	--	--
Thermal Management							
Heat Rejection	50	900	21,000	21,900	--	--	3.53
Piping, Pumps, Valves	118	2,120	6,660	8,780	--	--	1.41
Other	56	1,010	1,880	2,890	--	--	0.47
Ventilation							
Fans	25	450	1,500	1,950	--	--	0.31
Ducts	212	3,820	13,850	17,670	--	--	2.85
Instrumentation							
Fire Detection	10	180	130	310	310	--	--
Gas Detection	65	1,170	3,200	4,370	4,370	--	--
Electrical							
DC Wiring	200	3,600	30,500	34,100	--	--	5.49
DC Equipment	27	490	9,160	9,650	--	--	1.55
AC Wiring	336	6,050	2,490	8,540	--	--	1.38
AC Panel Requirements	14	250	250	500	--	--	0.08
Lighting	188	3,380	5,120	8,500	--	--	1.37
Other	5	90	750	840	--	--	0.13
Auxiliaries							
Make-up Water System	26	470	1,280	1,750	200	--	0.25
Air-Lift System	83	1,490	3,080	4,570	--	--	0.74
Plumbing Support Trays	125	2,250	2,050	4,300	--	--	0.69
Fire Extinguisher	--	--	50	50	50	--	--
Subtotals	6,779	122,000	110,670	329,470	9,810	0	51.48
Total Direct Field Cost				329,470	9,810	0	51.50
Indirect Field Cost				61,000	1,820	0	9.50
Balance of System Field Cost				390,470	11,630	0	61.00

TABLE C.35. Bechtel (1982) Total Installed System Costs (1980 $)

Battery: Lead Acid (Antimony)
Application: Shopping Center

Item	Low Estimate				High Estimate			
		Cost Distribution				Cost Distribution		
	Total Cost $	$	$/kW	$/kWh	Total Cost $	$	$/kW	$/kWh
Battery, FOB	533,910	0	0	86	821,400	0	0	132
BOS, Field Cost (1)	331,900	9,890	0	52	429,520	12,790	0	67
Total Field Cost	865,810	9,980	0	138	1,250,920	12,790	0	199
Engineering Costs (15%)	129,870	1,480	0	21	187,640	1,920	0	30
Subtotal	995,680	11,370	0	159	1,438,560	14,710	0	229
Contingency (20%)	199,140	2,270	0	32	287,710	2,940	0	46
Total Installed Cost	1,194,820	13,640	0	191	1,726,270	17,650	0	275

Note: From Table C.34. High = 1.1 x Field Cost; Low = 0.85 x Field Cost.

TABLE C.36. Bechtel (1982) Frequent Maintenance for the Lead Acid Battery in the Shopping Center

Activity	Frequency	Labor, Manhours per Event	Material, $ per Event	Annual Cost Low $	Annual Cost High $
Cell Maintenance	Monthly	11	74	2,340	2,808
Cooling System	Annual	9	200	300	360
Ventilation System Exhaust Fan	Annual	1	--	11	13
Air Lift System Compressor	Annual	4	50	94	113

TABLE C.37. Bechtel (1982) Infrequent Maintenance for the Lead Acid Battery in the Shopping Center

Activity	Frequency, Years	Labor, Manhours per Event	Material, $ per Event	Event Cost Low $	Event Cost High $
Cooling System Water Pump	8	25	1,500	2,300	2,760
Refrigeration System	12	30	9,000	9,960	11,950
Ventilation System Exhaust Fan	8	10	200	520	624
Air Lift System Compressor	6	30	2,000	2,960	3,552

TABLE C.38. Bechtel (1982) Low Life-Cycle Cost Estimate (1980 $)

Battery Type: Lead Acid (Antimony)
Application Type: Shopping Center

Low Estimate Input Parameters

Energy Rating	6210.0 kWh/cycle	Power Cost ($/kWh)	0.0050
Power Rating	900.0 kW	Resale/New Value	1.00
Battery Life	2500 cycles		
Cycles per Year	250	Discount Rate	10.0
Efficiency	79.0 percent	Escalation Rates	
Auxiliary Losses	.0 kWh/cycle (fixed)	Capital	8.0
	.0 kWh/cycle (kW)	Maintenance	8.0
	410.0 kWh/cycle (kWh)	Energy	10.2

Cost Data

Item	Fixed Costs ($)	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	13,640.00	.00	191.00
Replacement 1	.00	.00	117.00
2	.00	.00	117.00
Salvage 1	.00	.00	14.00
2	.00	.00	-1.41
Annual Maintenance	.00	.00	0.44
Infrequent Maintenance 6.0 Year	.00	.00	0.48
8.0 Year	.00	.00	0.45
12.0 Year	.00	.00	1.60

Output (Net Present Value)

Item	Fixed Costs ($)	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	13,640.00	.00	191.00
Periodic Replacements Less Salvage, Unused Life	.00	.00	86.71
Annual Maintenance	.00	.00	7.30
Infrequent Maintenance	.00	.00	3.17
Energy Losses	.00	.00	70.07
Total	13,640.00	.00	358.25

Total System Life-Cycle Cost: $2238 thousand.

PNL Note: The life-cycle cost estimate of $358.25/kWh (1980 $) was inflated to $447/kWh (1984 $).

TABLE C.39. Bechtel (1982) High Life-Cycle Cost Estimate (1980 $)

Battery Type: Lead Acid (Antimony)
Application Type: Shopping Center

High Estimate Input Parameters

Energy Rating	6210.0 kWh/cycle	Power Cost ($/kWh)	0.050
Power Rating	900.0 kW	Resale/New Value	1.00
Battery Life	2000 cycles		
Cycles per Year	250	Discount Rate	10.0
Efficiency	70.0 percent	Escalation Rates	
Auxiliary Losses	.0 kWh/cycle (fixed)	Capital	8.0
	.0 kWh/cycle (kW)	Maintenance	8.0
	410.0 kWh/cycle (kWh)	Energy	10.2

Cost Data

Item	Fixed Costs ($)	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	17,650.00	.00	275.00
Replacement 1	.00	.00	172.00
2	.00	.00	172.00
Salvage 1	.00	.00	-2.60
2	.00	.00	-12.80
Annual Maintenance	.00	.00	0.53
Infrequent Maintenance 6.0 Year	.00	.00	0.57
8.0 Year	.00	.00	0.54
12.0 Year	.00	.00	1.92

Output (Net Present Value)

Item	Fixed Costs ($)	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	17,650.00	.00	275.00
Periodic Replacements Less Salvage, Unused Life	.00	.00	229.86
Annual Maintenance	.00	.00	8.79
Infrequent Maintenance	.00	.00	3.79
Energy Losses	.00	.00	92.92
Total	17,650.00	.00	610.36

Total System Life-Cycle Cost: $3808 thousand.

PNL Note: The life-cycle cost estimate of $610.36/kWh (1980 $) was inflated to $761/kWh (1984 $).

TABLE C.40. Bechtel (1982) Balance of System Installed Costs

Battery: Sealed Lead Acid
Application: High School

System/Component	Hours	Costs (1980$) Labor	Material	Subtotal	Cost Distribution $	$/kW	$/kWh
Battery							
Shipping (500 miles)	--	--	--	10,000	--	--	4.98
Installation	1,540	27,720	--	27,720	--	--	13.79
Building							
Land	--	--	--	850	--	--	0.42
Building	--	--	--	45,900	--	--	22.84
Structural	333	5,990	3,440	9,430	3,310	--	3.04
Thermal Management							
Heat Rejection	40	720	9,330	10,050	--	--	5.00
Piping, Pumps, Valves	78	1,400	3,520	4,920	--	--	2.45
Other	40	720	1,120	1,840	--	--	0.92
Instrumentation							
Fire Detection	10	180	130	310	310	--	--
Electrical							
DC Wiring	80	1,440	9,400	10,840	--	--	5.39
DC Equipment	28	500	9,160	9,660	--	--	4.80
AC Wiring	233	4,190	1,740	5,930	--	--	2.95
AC Panel Requirements	14	250	250	500	--	--	0.25
Lighting	114	2,050	1,180	3,230	--	--	1.61
Other	8	140	720	860	--	--	0.43
Auxiliaries							
Plumbing Support Trays	64	1,150	1,050	2,200	--	--	1.09
Subtotals	2,582	46,450	41,040	144,240	3,620	0	69.96
Total Direct Field Cost				144,240	3,620	0	70.00
Indirect Field Cost				25,550	640	0	12.40
Balance of System Field Cost				169,790	4,260	0	82.40

TABLE C.41. Bechtel (1982) Total Installed System Costs (1980 $)

Battery: Sealed Lead Acid
Application: High School

Item	Low Estimate				High Estimate			
		Cost Distribution				Cost Distribution		
	Total Cost $	$	$/kW	$/kWh	Total Cost $	$	$/kW	$/kWh
Battery, FOB	172,740	0	0	86	265,750	0	0	132
BOS, Field Cost (1)	144,320	3,620	0	70	186,770	4,690	0	91
Total Field Cost	317,060	3,620	0	156	452,520	4,690	0	223
Engineering Costs (15%)	47,560	540	0	23	67,880	700	0	33
Subtotal	364,620	4,160	0	179	520,400	5,390	0	256
Contingency (20%)	72,920	830	0	36	104,080	1,080	0	51
Total Installed Cost	437,540	4,990	0	215	624,480	6,470	0	307

Note: From Table C.40. High = 1.1 x Field Cost; Low = 0.85 x Field Cost.

TABLE C.42. Bechtel (1982) Frequent Maintenance for the Sealed Lead Acid Battery in the High School

Activity	Frequency	Labor, Manhours per Event	Material, $ per Event	Annual Cost Low $	Annual Cost High $
Cell Maintenance	Annual	1	0	11	13
Cooling System	Annual	7	140	217	260

TABLE C.43. Infrequent Maintenance for the Sealed Lead Acid Battery in the High School

Activity	Frequency, Years	Labor, Manhours per Event	Material, $ per Event	Event Cost Low $	Event Cost High $
Cooling System Water Pump	8	25	1,180	1,980	2,376
Cooling System Refrigerator	12	30	3,730	4,690	5,628

TABLE C.44. Bechtel (1982) Low Life-Cycle Cost Estimate (1980 $)

Battery Type: Sealed Lead Acid
Application Type: High School

Low Estimate Input Parameters

Energy Rating	2010.0 kWh/cycle	Power Cost ($/kWh)	0.050
Power Rating	315.0 kW	Resale/New Value	1.00
Battery Life	2500 cycles		
Cycles per Year	250	Discount Rate	10.0
Efficiency	79.0 percent	Escalation Rates	
Auxiliary Losses	.0 kWh/cycle (fixed)	Capital	8.0
	.0 kWh/cycle (kW)	Maintenance	8.0
	176.0 kWh/cycle (kWh)	Energy	10.2

Cost Data

Item	Fixed Costs ($)	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	4,990.00	.00	215.00
Replacement 1	.00	.00	117.00
2	.00	.00	117.00
Salvage 1	.00	.00	14.00
2	.00	.00	-1.39
Annual Maintenance	.00	.00	0.11
Infrequent Maintenance 8.0 Year	.00	.00	0.99
12.0 Year	.00	.00	2.33

Output (Net Present Value)

Item	Fixed Costs ($)	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	4,990.00	.00	215.00
Periodic Replacements Less Salvage, Unused Life	.00	.00	86.53
Annual Maintenance	.00	.00	1.82
Infrequent Maintenance	.00	.00	3.46
Energy Losses	.00	.00	75.54
Total	4,990.00	.00	382.35

Total System Life-Cycle Cost: $774 thousand.

PNL Note: The life-cycle cost estimate of $382.35/kWh (1980 $) was inflated to $477/kWh (1984 $).

TABLE C.45. Bechtel (1982) High Life-Cycle Cost Estimate (1980 $)

Battery Type: Sealed Lead Acid
Application Type: High School

High Estimate Input Parameters

Energy Rating	2010.0 kWh/cycle	Power Cost ($/kWh)	0.050
Power Rating	315.0 kW	Resale/New Value	1.00
Battery Life	2000 cycles		
Cycles per Year	250	Discount Rate	10.0
Efficiency	70.0 percent	Escalation Rates	
Auxiliary Losses	.0 kWh/cycle (fixed)	Capital	8.0
	.0 kWh/cycle (kW)	Maintenance	8.0
	176.0 kWh/cycle (kWh)	Energy	10.2

Cost Data

Item	Fixed Costs ($)	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	6,470.00	.00	307.00
Replacement 1	.00	.00	172.00
2	.00	.00	172.00
Salvage 1	.0D	.00	-2.39
2	.00	.00	-12.80
Annual Maintenance	.00	.D0	0.14
Infrequent Maintenance 8.0 Year	.00	.00	1.18
12.0 Year	.00	.00	2.80

Output (Net Present Value)

Item	Fixed Costs ($)	Power-Related Costs ($/kW)	Energy-Related Costs ($/kWh)
Initial Investment	6,470.00	.00	307.00
Periodic Replacements Less Salvage, Unused Life	.00	.00	229.61
Annual Maintenance	.00	.00	2.32
Infrequent Maintenance	.00	.00	4.15
Energy Losses	.00	.00	98.38
Total	6,470.00	.00	641.46

Total System Life-Cycle Cost: $1296 thousand.

PNL Note: The life-cycle cost estimate of $641.46/kWh (1980 $) was inflated to $800/kWh (1984 $).

TABLE C.46. Stolte (1977) Cost Estimate Summary Three Hour Lead Acid Battery Systems Mature Plants

	Open-Tank Cell			Sealed Cells: Single Layer			Sealed Cells: Tiered Configuration			Sealed Cells: Outdoor Configuration		
Major Cost Components	Cost ($1000's)	Specific Cost $/kW +	$/kWh	Cost ($1000's)	Specific Cost $/kW +	$/kWh	Cost ($1000's)	Specific Cost $/kW +	$/kWh	Cost ($1000's)	Specific Cost $/kW +	$/kWh
Battery	370		6.20	360		6.00	360		6.00	360		6.00
Converter	1,180	59.00		1,180	59.00		1,180	59.00		1,180	59.00	
Civil-Structural	770	1.00 +	12.50	290	1.00 +	4.50	300	1.00 +	4.70	550	1.00 +	8.80
Mechanical, Piping and HVAC	510		8.50	380		6.30	3.20		5.30	310		5.20
Electrical	250	0.80 +	3.80	170	1.00 +	2.50	110	0.50 +	1.70	120	0.50 +	1.90
Instrumentation	180	2.50 +	2.20	200	2.50 +	2.50	200	2.50 +	2.50	170	1.00 +	2.50
Yardwork and Utilities	130	1.50 +	1.70	80	1.00 +	1.00	70	0.70 +	0.90	60	0.50 +	0.80
Total Direct Field Cost	3,390	64.80 +	34.90	2,660	64.50 +	22.80	2,540	63.70 +	21.10	2,750	62.00 +	25.20
Distributables (@ 60% of Direct Field Labor)	310	3.90 +	3.90	220	3.30 +	2.60	230	3.40 +	2.70	240	3.60 +	2.80
Total Field Cost	3,700	68.70 +	38.80	2,880	67.80 +	25.40	2,770	67.10 +	23.80	2,990	65.60 +	28.00
Engineering Services												
Title I @ 3% of Total Field Cost	110	1.10 +	1.40	90	0.90 +	1.20	80	0.80 +	1.10	90	0.90 +	1.20
Title II @ 8% of Total Field Cost	300	3.00 +	4.00	230	2.30 +	3.10	220	2.20 +	2.90	240	2.40 +	3.20
Title III @ 10% of Field Labor	50	0.50 +	0.70	40	0.40 +	0.50	40	0.40 +	0.50	40	0.40 +	0.50
Subtotal	4,160	73.30 +	44.90	3,240	71.40 +	30.20	3,110	70.50 +	28.30	3,360	69.30 +	32.90
Contingency	840	8.40 +	11.20	660	6.60 +	8.80	590	5.90 +	7.90	640	6.40 +	8.50
Subtotal	5,000	81.70 +	56.10	3,900	78.00 +	39.00	3,700	76.40 +	36.20	4,000	75.70 +	41.40
Battery Cells	3,790		63.20	3,538		59.00	3,538		59.00	3,538		59.00
Total Construction Cost	8,790	81.70 +	119.30	7,438	78.00 +	98.00	7,238	76.40 +	95.20	7,538	75.70 +	100.40

PNL Notes: Total power-related balance of plant costs ranging from $75.70 to $82.80/kW (1976 $) in Tables C-46 and C-47 were inflated to $127 to $139/kW (1984 $).
Total energy-related balance of plant costs ranging from $28.00 to $56.10/kWh (1976 $) in Tables C-46 and C-47 were inflated to $47 to $94/kWh (1984 $).

TABLE C.47. Stolte (1977) Cost Estimate Summary Five Hour Lead Acid Battery Systems Mature Plants

					Sealed Cells							
	Open-Tank Cell								Outdoor Configuration			
	Air-Cooled		Water-Cooled		Single Layer		Tiered Configuration		Single Layer		Stacked	
Major Cost Components	Cost ($1000's)	Specific Cost $/kW + $/kWh	Cost ($1000's)	Specific Cost $/kW + $/kWh	Cost ($1000's)	Specific Cost $/kW + $/kWh	Cost ($1000's)	Specific Cost $/kW + $/kWh	Cost ($1000's)	Specific Cost $/kW + $/kWh	Cost ($1000's)	Specific Cost $/kW + $/kWh
Battery	460	4.60	600	6.00	520	5.20	520	5.20	520	5.20	560	5.60
Converter	1,180	59.00	1,180	59.00	1,190	59.50	1,190	59.50	1,190	59.50	1,190	59.50
Civil-Structural	820	1.00 + 8.00	620	1.00 + 6.00	400	1.00 + 3.80	440	1.00 + 4.20	750	1.00 + 7.30	1,060	1.00 + 10.40
Mechanical, Piping and HVAC	490	4.90	610	6.10	450	4.50	380	3.80	390	3.90	380	3.80
Electrical	280	1.50 + 2.50	290	1.50 + 2.60	220	1.50 + 2.90	130	1.00 + 1.10	130	1.00 + 1.10	120	1.50 + 0.90
Instrumentation	190	2.50 + 1.40	190	2.50 + 1.40	250	2.40 + 2.00	240	2.50 + 1.90	210	1.00 + 1.90	210	1.00 + 1.90
Yardwork and Utilities	150	1.50 + 1.20	130	1.00 + 1.10	130	1.50 + 1.00	80	1.00 + 0.60	60	0.50 + 0.50	40	0.50 + 0.30
Total Direct Field Cost	3,570	65.50 + 22.60	3,620	65.00 + 23.20	3,160	65.90 + 18.40	2,980	65.00 + 16.80	3,250	63.00 + 19.90	3,560	63.50 + 22.90
Distributables (@ 60% of Direct Field Labor)	350	3.50 + 2.80	300	3.00 + 2.40	300	3.80 + 2.20	300	4.00 + 2.20	300	3.80 + 2.20	350	3.50 + 2.80
Total Field Cost	3,920	69.00 + 25.40	3,920	68.00 + 25.60	3,460	69.70 + 20.70	3,280	69.00 + 19.00	3,550	66.80 + 22.10	3,910	67.00 + 25.70
Engineering Services												
Title I @ 3% of Total Field Cost	120	1.20 + 0.90	120	1.20 + 1.00	100	1.00 + 0.80	100	1.00 + 0.80	100	1.10 + 0.90	110	1.10 + 0.90
Title II @ 8% of Total Field Cost	310	3.10 + 2.50	310	3.10 + 2.40	280	2.80 + 2.20	260	2.60 + 2.10	280	2.80 + 2.20	310	3.10 + 2.40
Title III @ 10% of Field Labor	60	0.60 + 0.50	50	0.50 + 0.40	50	0.50 + 0.40	50	0.50 + 0.40	50	0.50 + 0.40	60	0.60 + 0.50
Subtotal	4,410	73.90 + 29.30	4,400	72.80 + 29.40	3,890	74.00 + 24.10	3,690	73.10 + 22.30	3,990	71.20 + 25.60	1,390	71.80 + 29.50
Contingency	890	8.90 + 7.10	900	9.00 + 7.20	810	8.10 + 6.50	710	7.10 + 5.70	810	8.10 + 6.50	910	9.10 + 7.30
Subtotal	5,300	82.80 + 36.40	5,300	81.80 + 36.60	4,700	82.10 + 30.60	4,400	80.20 + 28.00	4,800	79.30 + 32.10	5,300	80.90 + 36.80
Battery Cells	5,120	51.20	5,120	51.20	5,406	54.10	5,406	54.10	5,406	54.10	5,406	54.10
Total Construction Cost	10,420	82.80 + 87.60	10,420	81.80 + 87.80	10,106	82.10 + 84.70	9,806	80.20 + 82.10	10,206	79.30 + 86.20	10,706	80.90 + 90.90

TABLE C.48. Westinghouse (1976) Battery Auxiliaries Costs

		Total	$/kWh
Building and Slab		$ 350,000	8.75
23,100 ft^2 at $15.15/$ft^2$			
Monitoring and Control		442,000	11.05
Computer with input/output	175,000		
Computer startup and software	20,000		
Isolation	86,000		
Cabling	67,000		
Input Devices	16,000		
Static Contactors	78,000		
Ventilation System		48,000	1.20
Ductwork	24,500		
Fans and Stack	23,500		
Acid Containment		110,000	2.75
Concrete Work	100,000		
Excavation and Backfill	10,000		
Buswork and Protection		81,500	2.04
Intermodule Cabling	11,500		
Main Buswork	40,000		
Fuse Disconnects	23,000		
String Disconnects	7,000		
Water Cooling		117,000	2.93
Cooling Tower	54,500		
Piping	47,500		
Pumps, Miscellaneous	5,000		
Deionized Loop	10,000		
Maintenance		49,000	1.23
Room and Equipment	34,000		
Gantry	15,000		
Fire System		25,000	0.63
23,100 ft^2 at ~$1.08/$ft^2$			

TABLE C.48. Westinghouse (1976) Battery Auxiliaries Costs (contd)

		Total	$/kWh
Water Addition		33,000	.83
Demineralizer and Controls	5,000		
Piping	22,000		
Reservoirs and Hookups	6,000		
Auxiliaries Total		$1,255,500	31.39
Battery Costs		1,476,000	36.90
Power Conversion (Estimated)		780,000	($78.00/kW)
System Total		$3,511,500	$68.29/kWh + $78.00/kW
			($351.15/kW Total)

PNL Notes: The auxiliaries cost of $31.39/kWh (1976 $) was inflated to $53/kWh (1984 $).
The power conversion cost of $78/kW (1976 $) was inflated to $131/kW (1984 $).

APPENDIX D

PUBLICATIONS REVIEWED

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