DR-192

COO/2748-75/T1

ENERGY STORAGE AND POWER CONDITIONING
ASPECTS OF PHOTOVOLTAIC SOLAR POWER SYSTEMS

Volume I

First Quarterly Report

October 1975

Work Performed Under Contract No. E(11-1)-2748

Bechtel Corporation
San Francisco, California

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

Division of Solar Energy

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161

Price: Paper Copy \$4.50 (domestic)
\$7.00 (foreign)
Microfiche \$2.25 (domestic)
\$3.75 (foreign)

ENERGY STORAGE AND POWER CONDITIONING
ASPECTS OF PHOTOVOLTAIC SOLAR POWER SYSTEMS

Volume I
First Quarterly Report

October 1975

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Work Performed Under Contract No. E(11-1)-2748

PREPARED FOR THE UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

Bechtel Corporation
San Francisco, California

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

24

CONTENTS

<u>Section</u>		<u>Page</u>
1	INTRODUCTION	1-1
2	SUMMARY	2-1
3	CONCLUSIONS AND RECOMMENDATIONS	3-1
	3.1 Conclusions	3-1
	3.2 Recommendations	3-2
4	ENERGY STORAGE	4-1
	4.1 Energy Storage Systems	4-1
	4.2 Battery Terminology	4-2
	4.3 Battery Data Summary	4-3
	4.4 Lead-Acid Batteries	4-4
	4.5 Lithium Batteries	4-15
	4.6 Sodium Batteries	4-23
	4.7 Chlorine Batteries	4-29
5	POWER CONDITIONING	5-1
	5.1 System Requirements	5-1
	5.2 Available Equipment	5-4
	REFERENCES	

ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
2-1	Photovoltaic Solar Power System	2-2
4-1	Typical Discharge Voltage Characteristics	4-7
4-2	Typical Charge Voltage Characteristics	4-8
4-3	Relative Capacity as a Function of Temperature	4-10
4-4	Charge Cutoff Voltage as a Function of Temperature	4-10
4-5	ANL Lithium/Sulfur Test Cell	4-17
4-6	Typical Lithium/Sulfur Test Cell Voltages	4-18
4-7	AI Lithium/Sulfur Test Cell	4-21
4-8	GE Sodium/Sulfur Test Cell	4-25
4-9	Typical Discharge Voltage Characteristics	4-26
4-10	Typical Charge Voltage Characteristics	4-26
4-11	TRW Sodium/Sulfur Test Cell Built for USAECOM	4-28
4-12	Functional Schematic of EDA Zn/Cl System	4-30
5-1	Photovoltaic Solar Power System	5-2
5-2	Simplified Inverter Schematic	5-5
5-3	Basic Graetz Bridge	5-8
5-4	HVDC System	5-9
5-5	Simplified Block Diagram of a UPS System	5-10
5-6	Inverter Cost Versus Power	5-14

<u>Figure</u>		<u>Page</u>
5-7	Cost Versus Quantity	5-15
5-8	Residential Interface A	5-18
5-9	Residential Interface B	5-20
5-10	Residential Interface C	5-22
5-11	Shopping Center Interface A	5-25
5-12	Shopping Center Interface C	5-28

TABLES

<u>Table</u>		<u>Page</u>
4-1	Battery Characteristics	4-4
5-1	Equipment Costs for Residential Interface A	5-19
5-2	Equipment Costs for Residential Interface C	5-23
5-3	Equipment Costs for Shopping Center Interface A	5-26
5-4	Equipment Costs for Shopping Center Interface C	5-29

Section 1

INTRODUCTION.

The rising cost and decreasing availability of fossil fuels have prompted serious consideration of alternative energy sources such as solar energy. While the cost and technology of solar power systems are currently not conducive to large-scale installation, solar power does show promise of being able to replace consumption of appreciable quantities of fossil fuels toward the end of this century. To aid this development, the Division of Solar Energy of the Energy Research and Development Administration (ERDA) is sponsoring programs directed toward furthering the development of solar energy.

Solar energy may be utilized as thermal energy or converted into electricity by solar cells. ERDA's National Photovoltaic Conversion Program is concerned with this latter approach and is currently sponsoring industrial programs for photovoltaic systems and devices. In one such program, Spectrolab, Inc., is charged with performing conceptual design and analysis of three photovoltaic solar power systems. The sizes of these three systems will cover the requirements of residential, commercial and electric utility central station applications. In addition to a solar cell array, photovoltaic power systems must also include an energy storage system to enable operation during periods of low insolation and a power conditioning system to control the dc power from the array and convert it into an ac waveshape compatible with existing electrical equipment.

The Scientific Development Operation of Bechtel Corporation is participating in the Spectrolab program by compiling and studying data on the energy storage and power conditioning aspects of all three photovoltaic solar power systems and by the conceptual design of the system for electric utility central station applications. The results of the energy storage and power conditioning study effort are presented in this report.

Section 2

SUMMARY

Solar power systems include both thermal and photovoltaic systems. This study addresses the electrical energy storage and power conditioning aspects of photovoltaic solar power systems (heavy lines in Figure 2-1).

For purposes of this study, three photovoltaic system applications and power levels were considered:

- Residential — 2.5 kilowatts
- Shopping center — 1 megawatt
- Electric utility central station — 50 to 1000 megawatts

A photovoltaic system consists of a photovoltaic collector, a power conditioning system and an energy storage system. The energy storage system provides dc voltage during periods of low or absent insolation. In order to match the requirements of the ac and dc electrical loads with the dc from the photovoltaic and storage systems, a power conditioning system is necessary. In general, the power conditioning system consists of: a regulator to regulate the dc voltage and current from the solar array; an inverter to convert dc voltage to ac; and an interface to connect the solar power system to a utility or other ac loads. The central station differs from the other two systems (i.e., residential and shopping center) in that its "load" is the utility line itself. The residential and shopping center systems will be interfaced with utility lines and passive loads (e.g., lighting, motors, etc.) and will not be permitted to deliver power into the utility lines.

Of all storage systems, only batteries have technical and economic characteristics compatible with all three system sizes and applications considered.

Figure 2-1. PHOTOVOLTAIC SOLAR POWER SYSTEM -

At present, lead-acid batteries are best suited to serve as the energy storage element in a photovoltaic system. The characteristics of these lead-acid batteries include:

- Energy efficiencies of 70 to 80 percent
- Cycle life of 2000 cycles
- Operating temperature range of 30 to 130°F
- Cost on the order of \$50 per kWh*
- Relatively high salvage value (e.g., 10 to 20 percent of purchase price)

* Unless otherwise specified all costs in this report are in terms of 1975 dollars.

Many advanced types of batteries are currently in various stages of development and will be available as photovoltaic systems come into widespread use. Included among these developmental cells are:

- Sealed, cycle-service-type, lead-acid batteries that will be maintenance free
- Large lead-acid cells at a cost of \$30 per kWh
- Advanced batteries utilizing electrochemical couples such as zinc/chlorine, sodium/sulfur and lithium/sulfur. Such batteries will have higher energy densities than lead-acid cells with projected prices of \$10 to \$25 per kWh.

Although the equipment required for the inverter portion of the power conditioning system is not currently available as "off-the-shelf" hardware, it can be built using present-day technology, but some design effort and associated expense will be required. For the power levels involved, only switching-type, solid state (e.g., SCR) inverters are considered. Many variations of this type of circuit are in use. The cost per kilowatt of commercially available inverter equipment, similar to that required, varies considerably with power level and design; ranging from \$150 to \$1,500 per kW at the 2.5 kW power level, \$75 to \$450 per kW at 1 MW and \$45 to \$105 at 50 MW. Prices, particularly for lower power units where high volume production is likely, also vary with quantity.

Similarly, switching-type, series regulators are most suitable for use at the power levels considered. Again, the exact equipment required is not commercially available. One similar device with an efficiency of 98 percent at its rated power of 625 kW is currently being produced for \$5 per kW.

For the residential and shopping center systems, the electrical interface connections between the utility, inverter and ac loads can be made either by operating the inverter in parallel with the utility or by switching the

load to either source. In these schemes, controls are designed to limit the inverter to its maximum power rating, while still assuring that load demands are met, and also to prevent power flow into the utility line. The central plant interface differs in that its load is the utility itself. All of the proposed interface schemes utilize commercially available components.

Section 3

CONCLUSIONS AND RECOMMENDATIONS

3.1 CONCLUSIONS

- Batteries are best suited to serve as the energy storage element in all three photovoltaic solar power systems considered.
- Immediate and near-term (less than 7 years) installations would use lead-acid batteries. Their cost will be on the order of \$50 per kWh, and they will last 10 to 20 years, depending on the charge/discharge duty cycle that they are subjected to.
- Future installations will likely use any one of the several advanced batteries currently being developed, since their projected cost ranges from \$10 to \$25 per kWh. Use of these batteries will also result in a more compact installation.
- Advanced lead-acid batteries with improved performance characteristics will be developed, but their cost is expected to be \$50 per kWh.
- Although the equipment to meet the specific inverter and regulator requirements is not commercially available, it can be constructed using present day technology. Implicit in this is the requirement for development and design programs and their associated costs.
- The cost per kW for commercially available inverter equipment (similar to that required by photovoltaic systems) decreases with increasing power level, varying over a 100:1 range between 10^2 and 10^9 watts. The cost per kW at any given power level also varies depending on equipment design and manufacturer.
- In general, interfacing the solar power system with the utility line and ac loads may be accomplished either by switching the load between the utility line and inverter or by operating the inverter in parallel with the utility. Both interface designs use standard, commercially available components.

3.2

RECOMMENDATIONS

- The battery voltage for the residential system should be set near 220 volts to facilitate operation of heating elements (in ovens, ranges etc.) on either ac or dc. This permits a reduction in the size of the inverter and results in an increase in system efficiency by having the energy for these heating elements bypass the inefficiency of the inverter. A similar dc load system may determine the optimum battery voltage for the shopping center system.
- As data on transient variations in insolation and loads become better defined, battery manufacturers should be recontacted to assist in evaluating tradeoffs between installed storage capacity, duty cycle, battery life, cell design and cost for the type of service anticipated. With the projected magnitude of the market for photovoltaic systems, battery manufacturers may be willing to design and manufacture cells optimized for this type of energy storage service. This would apply to both lead-acid and developmental batteries.
- Line commutated inverters operating in parallel with the utility should be used in all three systems, since line-commutated inverters have a higher efficiency at partial load and tend to have a lower cost. Also, operating in parallel with the utility would virtually eliminate switching transients and would utilize the energy available from the solar power system more fully.
- Initial evaluations indicate that series switching regulators should be included in the systems. Their use permits the regulation of solar cell output currents at values conducive to extended battery life and, with the addition of control logic and instrumentation, permits tracking of the array's optimum power transfer impedance. These benefits outweigh the relatively small costs estimated for regulators.
- As regulator and inverter specifications become better defined, equipment manufacturers should be recontacted to perform design tradeoff studies for this application and to determine equipment costs with greater accuracy than is possible with present data.

Section 4

ENERGY STORAGE

Due to variations in insolation, some form of energy storage should be incorporated into photovoltaic power systems. In addition to permitting the system to continue supplying load demands during short-term decreases in insolation (e.g., transient cloud cover), an energy storage system can also enable the use of solar derived energy at night or during days when there is insufficient insolation.

4.1 ENERGY STORAGE SYSTEMS

Several schemes to enable storage of electric utility energy have been proposed or are in use. The most successful energy storage system in use today is pumped hydroelectric power. However, it is obvious that the size of these plants prohibits this form of storage from being considered for the residential and commercial applications. Further, pumped hydroelectric plants require a specific site geology which has limited their use and will likely prohibit their use for most photovoltaic central station sites.

Several proposed systems, such as compressed air storage, super conducting magnets, thermal storage, hydrogen storage etc., are similarly excluded from consideration for application in a photovoltaic system due to their projected minimum economic size and other incompatible characteristics.

Flywheel energy storage offers some potential for use in conjunction with a photovoltaic system, but generally economics dictate a minimum system size in excess of one megawatt, and standby losses indicate that this system is best suited to applications with storage times shorter than required for photovoltaic systems.

Of all potential storage systems, only batteries have characteristics and economics that are favorable to all three of the photovoltaic system sizes being evaluated in this study. Therefore, only batteries are considered in subsequent sections of this report.

4.2 BATTERY TERMINOLOGY

The batteries considered for energy storage applications are classified as secondary (rechargeable) batteries. Primary batteries are essentially nonrechargeable. Electric energy applied to the terminals of a secondary battery is electrochemically converted, stored as chemical potential energy and subsequently reconverted to electric energy.

Since electrochemical reactions characteristically result in potentials on the order of a few volts, battery systems for energy storage will require a series connection of cells to attain a practical system voltage. Also, achievable electrode current densities in conjunction with cell construction techniques limit the current per cell and thereby require parallel interconnection of cells to achieve a desired capacity. Paralleling can also result in redundancy and thereby permit continued, limited operation in the event of a cell failure. The optimum series and parallel cell configuration in a battery will vary with cell type and manufacturer's design.

The capacity of a battery refers to the quantity of discharge current obtainable for a specified length of time and is expressed in ampere-hours. Since a battery's capacity can decrease with increasing discharge rates, capacity is usually given for a specified time (e.g., 100 ampere-hours at the five-hour rate). Capacity is also a function of cutoff voltage. The output voltage of a battery decreases during discharge, and eventually the internal chemistry reaches a state such that further discharge will result in a very rapid decrease in output voltage. Manufacturers usually specify a cutoff voltage near the upper bound of this region, and cells may be damaged by discharge beyond this point. Charge and discharge rates are sometimes

referenced to a cell's capacity. With this type of notation, a current's magnitude is inferred by the length of time (in hours) required to completely discharge (or charge) a cell with a given ampere-hour capacity. For example, drawing 20 amperes from a 100-ampere-hour cell would be termed a C/5 discharge rate. Depth of discharge refers to the percentage of a cell's capacity that has been discharged.

The energy capacity of a battery is the time integral of the product of discharge voltage and current from full charge to cutoff voltage. It is given approximately by the product of capacity and average output voltage and is expressed in watt-hours. Comparisons of batteries are often made on the basis of watt-hour per unit weight or per unit volume. This characteristic is particularly important for vehicle propulsion applications, a market being pursued by most battery developers.

A complete discharge and recharge is referred to as a cycle, and the number of cycles which a battery can yield before degrading appreciably (i.e., cycle life) is an important parameter for comparing batteries for use in energy storage applications.

4.3 BATTERY DATA SUMMARY

A brief summary of battery characteristics is presented in Table 4-1. Sections 4.4 through 4.7 discuss these electrochemical systems in detail. The data presented for advanced batteries are tentative and can change as the various research programs proceed.

In addition to currently available lead-acid batteries, any one of several advanced batteries may be suitable in the future for energy storage in a photovoltaic system. There are over 20 major research programs, in the U.S. and abroad directed toward developing and producing new types of secondary batteries. These efforts reflect government, industry and utility sponsorship.

Many of these advanced batteries are in a laboratory prototype stage of development, and commercial systems will not be available before the

Table 4-1
BATTERY CHARACTERISTICS

Parameter	Battery						
Chemistry	Lead-Acid	Li-Al/FeS	Li/FeS _{1.5}	Na/S	Na/S	Zn/Cl	Na/Cl
Manufacturer	several	ANL	AI	GE	TRW	EDA	ESB
Charge Cutoff, (V/cell)	2.5	1.55	2.4	2.75	2.35	2.21	3.7
Discharge Cutoff, (V/cell)	1.75	0.85	1.0	1.83	1.60	1.98	2.3
Operating Temperature (°C)	25	425	400	315	300	32	200
Energy Efficiency (%)	75-80	70	70	85	80	70	80+
Cycle-Life Goal	2000*	1500+	3000	1500+	1500+	2500	2500+
Cost Goal (\$/kWh)	50-90*	15-25	25	10-20	20	10-20	—
Availability	commercial	1983	1983	1983	1983	1981	—

*Currently available batteries suitable for energy storage.

mid-1980's. Notably, demonstrations of kilowatt-size batteries have come about in electric vehicle propulsion programs (e.g., EDA's zinc/chlorine, SOHIO's lithium/chlorine, General Motors' zinc/air.) While these battery configurations are not identical to those required for energy storage systems, the technology is directly applicable and will facilitate the development of megawatt-size test or demonstration battery systems in the early 1980's.

4.4 LEAD-ACID BATTERIES

4.4.1 Available Lead-Acid Batteries

Of the several battery types that may find application in electric energy storage service, only lead-acid batteries are commercially available at present. Nickel-cadmium and silver-zinc are also in commercial use today; however, they are too costly to be considered for large-scale energy storage systems. Several proposals for the construction of a pilot or demonstration battery storage plant utilizing lead-acid cells

have been advanced (Ref. 1). An installation of this type can be built with present day technology and is similar to the storage system required by the photovoltaic central plant. However, the technology for fabricating large cells must be improved to approach that of the highly automated (and very competitive) automobile battery industry in order to reduce costs and make lead-acid battery energy storage installations economically competitive.

Chemistry and Construction. Lead-acid batteries can be grouped into two broad categories by the type of service for which they are intended, i.e., "float" or "cycle" service. In float service, a battery is maintained in a charged state and only discharged occasionally to a low depth of discharge. Emergency power and SLI (automobile starting, lighting, and ignition) batteries are two examples of this category. Float service batteries usually have a low self-discharge rate, low cycle-life (150 to 250 cycles) and low rates of gas evolution (thereby requiring makeup water less often). For batteries in this application, life is often expressed in terms of years instead of the number of cycles.

In cycle service, a battery is charged and discharged on a regular basis. Motive power batteries, such as those used to power electric forklifts, golf carts, etc., typify the cycle service category. Cycle lives of up to 2000 cycles are currently achievable. Motive power cells used on diesel-electric submarines have capacities up to 10,000 ampere-hours (at a six-hour rate), but their life usually does not exceed 500 cycles. It is likely that large cells such as these, with construction modified to improve life, could be the type of lead-acid battery used for electric energy storage in the photovoltaic central plant.

Lead-acid cells are comprised of lead (Pb) negative electrodes and lead dioxide (PbO₂) positive electrodes with a dilute solution of sulfuric acid

(H_2SO_4) as the electrolyte. The equation for this system's reversible electrochemical reaction is:

The active materials of both electrodes are converted to lead sulfate during the discharge cycle. In actual batteries, side reactions occur and are responsible for the evolution of hydrogen and oxygen by a mechanism similar to electrolysis. Also, other side reactions involving alloying constituents or impurities in the electrodes can cause the evolution of gases such as stibine or arsine. The design of a lead-acid battery energy storage installation must take into account the possible presence of these toxic gases (Ref. 2) and provide for the addition of makeup water to the batteries.

Both positive and negative plates for most batteries are fabricated by "pasting" the active electrode materials onto lead alloy grids. These materials are applied as various chemicals and converted to their final chemical composition during a "formation" process. To increase available surface area, a porous sponge form of lead is used for the negative plate. The grids serve to support the active material and conduct electricity. Their construction and alloy composition are governed by the type of service for which the battery is intended. Float service battery grids usually have 0.4- to 0.8-percent calcium alloyed with the lead, while cycle service battery grids are made of a lead alloy with 4- to 8-percent antimony. Plates for cycle service batteries are made two to three times thicker than those intended for float service. Positive plates may be wrapped with cords of fiberglass of similar material to reduce peeling or loss of material caused by operation or mechanical shock. Porous separators made of acid impervious materials such as rubber or plastic keep the assemblies of positive and negative plates from shorting. The number of plates and their size determine the battery's capacity. Electrode assemblies and electrolyte are housed in containers (jars) usually made of hard rubber or plastic.

Characteristics. Figure 4-1 shows the voltage characteristics of a typical lead-acid cell during constant current discharge. Different manufacturing techniques and cell types will cause some variation in the curves for actual cells. As can be seen, the decrease in cell voltage is greater at high rates of discharge. Connector and grid structure resistance contribute to the lowering of the terminal voltage during discharge. Similarly, material type, utilization and construction affect concentration polarization, which decreases the terminal voltage during discharge. These effects also contribute toward increasing the voltage required to recharge a cell. Actual operation of a photovoltaic system will likely entail operation of the battery in a constant power discharge mode for short periods of time. A set of curves for constant power (e.g., voltage as a function of time) can be derived from Figure 4-1. The voltage curves for that mode of operation would drop off faster than those of a constant current mode.

Figure 4-1. TYPICAL DISCHARGE VOLTAGE CHARACTERISTICS

Charging a lead-acid cell can be accomplished by several methods. Generally, any method that does not result in excessive gassing or high temperature is acceptable. Charging at a rate that produces these phenomena will lower efficiency and tend to shorten cell life. Recharge to approximately 80 percent of capacity can be accomplished at high rates (e.g., C/5 or higher). The last portion of the charge should be carried out at a lower rate (e.g., C/20) in order to promote longer cell life and higher efficiency. Figure 4-2 shows the voltages required to recharge a typical lead-acid cell as a function of its state of charge.

Figure 4-2. TYPICAL CHARGE VOLTAGE CHARACTERISTICS

Lead-acid cells typically have coulombic efficiencies of 90 to 95 percent (when recharged in a manner prescribed by the manufacturer). Thus, 111 ampere-hours are required to recharge a 100 ampere-hour cell with a 91-percent coulombic efficiency. These ampere-hours are put back into a battery at voltages higher than the discharge voltage. Therefore, a lead-acid battery's energy (watt-hour) efficiency is on the order of 70 to 80 percent.

Heat produced in a cell due to losses (or any other source) must be removed in order to prevent excessive cell temperature. The majority of the heat is generated during recharge. In addition to resistive loss, the electrochemistry of charging is exothermic. Most manufacturers recommend an operating temperature of 77°F and give data on their cells based on operation at this "standard" temperature. Operating temperature limits vary among manufacturers, but minimum temperatures range from 30 to 50°F. Figure 4-3 shows how the capacity of a typical lead-acid cell decreases with temperature.

Temperature also influences other operating characteristics of a cell. Figure 4-4 indicates the variation in charge cutoff voltage as a function of temperature for an SLI-type cell. This effect must be taken into account when specifying the maximum operating voltage of the dc system.

Although Figure 4-3 indicates that a cell's capacity increases with temperature, high temperature operation is not conducive to long cell life. Manufacturers disagree on the exact amount of reduction in life with temperature, but it is estimated that cell life will be cut in half if the average operating temperature is raised from 77°F to somewhere between 95 and 125°F. Also, internal loss mechanisms, such as electrolyte resistance, show exponential increases with temperature, so that energy efficiency decreases with increasing temperature. Maximum operating temperatures range from 90 to 130°F, with operations at 130°F permitted but not recommended.

Figure 4-3. RELATIVE CAPACITY AS A FUNCTION OF TEMPERATURE

Figure 4-4. CHARGE CUTOFF VOLTAGE AS A FUNCTION OF TEMPERATURE

Lead-acid batteries are cooled mainly by air, either by free or forced convection. In some applications, (e.g., on submarines), batteries are water-cooled by means of channels in the terminal structures. Due to poor thermal conductivity of the case and limited amount of exposed surface area of terminals, water cooling is much more effective than air cooling. However, water cooling is also more costly.

The energy density of lead-acid batteries ranges from 0.5 to 2.5 kWh/ft³. The type of batteries used in photovoltaic energy storage applications will likely resemble high density motive power cells, but since they will not be exposed to the same levels of mechanical shock and vibration, a lighter construction could be used. Energy density for this application will likely be on the order of 1.8 kWh/ft³.

Safety and Maintenance. Several safety aspects must be considered when designing a lead-acid battery system. There is, of course, the potential hazard of dc electrical shock. Unlike other electrical equipment, a battery cannot be switched off or deactivated. Even pumping out the electrolyte could leave enough electrolyte in the porous separator material to have the battery system remain a potential shock hazard. Another potential hazard is the acid electrolyte. Large industrial installations require the presence of eyewash stations, deluge showers and sodium carbonate or similar neutralizing material. Plastic squeeze-bottle eye-wash devices are available for smaller installations. Also, protective clothing (e.g., rubberized aprons, gloves, face shields) are used when servicing lead-acid batteries. Tools used for servicing are usually taped or otherwise insulated to prevent shorting of the terminals. On a bolted short, a battery can deliver currents high enough to melt metal conductors and result in a burn injury.

The size of the residential battery systems is some 100 times larger than the familiar automotive SLI battery and as such can offer a potential safety problem equal to that of the household ac systems in common use today.

Therefore, it is recommended that most battery servicing be carried out by trained personnel. For residential systems, this implies the use of servicemen from either a private company or from the local utility. For the shopping center and central power plant applications, it is likely that the facility's operating engineer would perform most of the maintenance duties.

Operation of the battery system introduces another potential safety problem, the generation of hydrogen. For the most part, hydrogen is generated toward the last part of the charge, at a rate proportional to the current (i.e., 0.0147 cubic feet per ampere-hour of overcharge). Design of the installation must include a ventilation system that will keep the hydrogen concentration well below the 4.1 percent required for combustion; detonation occurs above 8 percent. As mentioned, side reactions with grid alloys can produce trace amounts of stibine (SbH_3) or arsine (AsH_3) gases, but the ventilation system required for hydrogen will likely be adequate for these toxic gases even though they are slightly more dense than air and do not rise as hydrogen does. Use of grids without these alloying elements or use of sealed cells (ref. Section 4.4.2) would eliminate these gases.

One maintenance service that may be required is the addition of makeup water to the cells. It is likely that this maintenance could be performed by an automated or semiautomated water distribution system. The frequency of this service will be determined by the duty cycles to which the cell is exposed, the temperature and the type of cell. Calcium cells in float duty have one-tenth the water loss of a new lead antimony type cell and only one-hundredth that of an old antimony cell.

Antimonial grid battery systems will likely require an occasional equalizing charge. During this period, the charging voltage is raised about 10 percent above the normal end-of-charge value for several hours. The frequency of this type of service will depend on the duty to which a cell is exposed but will be on the order of once per month.

Other maintenance may include occasional (once every several years) cleaning of acid misting deposits from cell tops and tightening of electrical connections.

Cost Data. The cost of a lead-acid battery is affected by the production rate, degree of automation used in production and cell design (e.g., grid thickness). Automotive SLI batteries are the least expensive on a \$ per kWh basis and range in price (OEM) from \$12 to \$25 per kWh. Their production rate is about 5×10^7 units per year, and competitive pressures maintain low prices. It must be remembered that these cells have relatively thin grids and a low cycle life on deep discharge. Motive power cell costs range from \$50 to \$90 per kWh with an annual production of about 10^5 units per year. For this type of cell, about 25 percent of the price is attributable to material cost, compared to about 50 percent for SLI cells. The largest submarine-type cell (10^4 ampere-hours) costs approximately \$80 per kWh. As with any quantity purchasing, the use of large numbers of lead-acid cells for energy storage would tend to lower the cost per cell. Also, extensive use would warrant the development and application of automated production techniques and spawn lower costs per kWh. Additional cost reduction may be realized from the current practice of rebuilding large cells one or more times and from the relatively high salvage value of expended cells. The value of reclaimed lead may represent 10 to 20 percent of the original OEM purchase price of a lead-acid battery. A cost of \$50 per kWh for large cells suitable for use as the storage element in photovoltaic systems could be realized today (with high volume production). A goal for an eventual cost of \$27 to \$30 per kWh has been set by Gould for large energy storage lead-acid cells (Ref. 1).

4.4.2 Advanced Lead-Acid Batteries

Although the lead-acid battery industry is a mature one, research programs are being conducted to improve performance characteristics and lower costs. Several prospects that could affect the use of lead-acid batteries in photovoltaic systems are discussed in this section.

Sealed Cells. Recently, sealed automotive SLI batteries have appeared in the replacement market and will likely be installed as original equipment in the very near future. Small (1 to 40 ampere-hour), sealed lead-acid batteries and cells are also available for other applications that require a secondary battery. These cells use grids fabricated with calcium and other alloying elements. The other alloying elements and exact compositions of the electrodes are proprietary. Basically, the low rates of gas evolution of calcium-type grids allow the cell to be "sealed." Actually, the cells are provided with pressure relief valves and will vent hydrogen if exposed to improper charging. As with most calcium grid designs, the life of these sealed cells is limited to 200 to 300 deep discharge cycles.

At least one manufacturer is in the process of developing a sealed cell designed for cycle service in applications such as forklift motive power. For this type of sealed cell, an antimonial grid is being considered. Again, exact compositions and alloying elements are proprietary. It is expected that this design will yield a cell with a cycle life in excess of 2000 cycles and that the manufacturing techniques can eventually be applied to large (20 kWh) cells. The electrical characteristics of this cell are expected to be nearly identical to those of available cells with the exception that cell voltages rise much faster as full charge is reached.

This type of sealed cell design will be ideally suited for the energy storage element in residential photovoltaic systems. Its use would virtually eliminate routine maintenance requirements (such as adding makeup water) and would offer the potential of having a battery system that need not be accessed by the homeowner. Further, the hydrogen ventilation problem would be mitigated. These features would also be an asset to a shopping center installation, but they are less important in the central plant design.

The projected OEM selling price for the sealed cycle-service-type cell is on the order of \$55 per kWh at a production level of 50,000 units per year.

Distribution and sales costs would double this cost for the purchase of individual units. Salvage value will be 10 to 15 percent of the OEM price.

Material Utilization. Present lead-acid cell designs utilize on the order of one-fourth of the theoretical capacity of the component materials. Since material cost can represent up to one-half of a battery's cost (e.g., for SLI batteries), improvements in utilization can significantly reduce costs and increase energy density. Recognizing this fact, several manufacturers are conducting research in this area. Depending on the outcome of this research, lower cost (based on 1975 prices) lead-acid batteries may be available as photovoltaic systems come into wide use.

Cell Life. In addition to lowering initial cost, it would be desirable to increase the useful life of lead-acid cells. Their prime failure mode is corrosion of the positive electrode. At present, large expensive cells (e.g., submarine batteries) are rebuilt one or more times by replacing the positive electrodes. Research is proceeding to determine the exact mechanism of the failure mode and attempt to extend cell life.

4.5 LITHIUM BATTERIES

4.5.1 Argonne National Laboratory

In 1966, Argonne National Laboratory (ANL), in a continuation of earlier related work, initiated a program to develop a lithium/chalcogen secondary battery. Included among ANL's current programs are efforts directed toward developing lithium/sulfur-type secondary batteries, which will be suitable for use in utility load leveling and motive power applications. A second objective is the dissemination of sufficient knowledge to permit manufacturers to bid on construction of these types of cells. ANL has reported testing 150 ampere-hour engineering test cells and achieving energy efficiencies up to 80 percent (Ref. 3).

Chemistry and Construction. A basic lithium/sulfur cell has a lithium anode, a sulfur cathode and a suitable electrolyte. The electrochemical reaction for this simplified cell is:

The exact composition of the sulfide formed during discharge depends on active materials in the cell and its state of charge (Ref. 4).

For the engineering cells currently being tested, the electrolyte is a lithium chloride/potassium chloride eutectic (59 mol% LiCl, 41 mol% KCl). Use of this salt dictates an operating temperature of approximately 400°C. The life of earlier cells was limited by loss of sulfur from the molten elemental sulfur cathode due to vaporization and formation of compounds with the electrolyte. This effect was mitigated by the addition of arsenic or selenium. Present cells have longer lives due to the use of iron sulfide (FeS or FeS₂) cathodes. Of these two sulfides, FeS₂ results in cathodes with higher performance capability, and recently most cells have been constructed with this type of cathode. However, FeS cathodes can result in longer life, less corrosion and lower cost. The use of FeS cathodes is still under consideration. Current collection in either cathode is provided by the use of various expanded metal screens or the addition of carbon to the active sulfide material.

Two approaches to the construction of the anode are being evaluated. Molten lithium results in a high capacity anode, but this material severely corrodes electrode separators and electrical feedthroughs. Efforts are being directed to develop suitable corrosion-resistant components. Materials such as BN, Y₂O₃ and ZrO₂ are being evaluated. The second approach utilizes a solid lithium aluminum alloy developed by SOHIO for their Li-Al/LiCl-KCl/TeCl₄(C) battery. This less active material is not as corrosive as molten lithium but has the disadvantage of requiring operation at a lower current density. Cells being tested at present utilize porous Li-Al anodes.

A schematic diagram of the type of lithium/sulfur cell currently being tested is presented in Figure 4-5. The FeS_2 is contained in a boron nitride fabric separator. Further research is planned to improve this separator. The cell is housed in a cylindrical stainless steel container. As presently conceived, production batteries for load leveling applications will have vertical electrodes approximately one-foot square and will be packaged with multiple electrodes in a cell, similar to present day lead-acid cells.

Figure 4-5. ANL LITHIUM/SULFUR TEST CELL

Characteristics. Figure 4-6 shows typical test cell voltages during constant current charging and discharging. Utilization in excess of 60 percent of the theoretical capacity for this test cell is also indicated by the curve. The bus voltage of a large battery comprised of such cells would have similar characteristics, and a photovoltaic system incorporating such a battery would then require a power conditioning system to interface with these characteristics. As with other electrochemical systems, a lithium/sulfur cell can be

damaged by applying excessive voltage. When large numbers of cells are connected in series, manufacturing tolerances can result in nonuniformities in capacities and thereby expose a given cell in a series string to an over-voltage. ANL is developing an external, electronic bypass circuit to preclude this possibility. Some design programs will be required to produce a suitable power conditioning system, but there is no basic problem in using a fully developed lithium/sulfur battery as the energy storage element in future photovoltaic systems.

Figure 4-6. TYPICAL LITHIUM/SULFUR TEST CELL VOLTAGES

In order to maintain an operating temperature of 400°C , the cells must be housed in an insulated module. Cell cooling and heating (during standby or startup) can be accomplished by a recirculating air system, with electric heaters used as the heat source. For well defined duty cycles, such as would be seen in electric utility load leveling service, ANL has proposed that cell temperatures be allowed to rise to their maximum values at the

end of charge and discharge cycles and slowly decrease during ensuing standby periods, thus minimizing parasitic heating power. This technique may also be applicable to photovoltaic systems, where load demands and insolation can be predicted to some extent. For large systems, such as a central power plant or shopping center, a lithium/sulfur battery would likely resemble the system that ANL is developing for load leveling applications. At present, ANL is consulting industrial firms regarding cell manufacturability. However, cell and module designs will likely undergo many changes before becoming commercially available.

Safety and Maintenance. Any design for a lithium battery system must consider the safety requirements imposed by the presence of molten lithium, sulfur and electrolyte salts. Cells will be completely sealed, and the use of solid Li-Al anodes serves to further mitigate safety problems. In addition to containing heat, the proposed modules will serve to contain reactive components. ANL's present designs include three walls between the molten components and exterior surfaces. Even in the unlikely event of a cell rupture, ANL tests indicate that ensuing reactions are not necessarily violent. However, cognizant fire fighting departments and operating personnel must be instructed not to use water in the vicinity of lithium cells. Fire extinguishers charged with MET-L-X or similar oxygen barrier agents should be maintained on the premises.

The exterior surfaces of lithium battery modules will be designed to be safe to touch (i.e., 60°C or lower). In addition, the energy storage system design will include provisions to safely vent cooling air with a temperature near 400°C . Although the amount of heat released by the module most likely will be small, it may be possible to incorporate this heat into residential thermal storage systems. An instrumentation package (e.g., thermocouples etc.) in conjunction with control logic would be included as a part of the design in order to ensure safe operation of the battery system.

Since the cells will be completely sealed, the only routine maintenance required would be for ancillary systems (e.g., cooling air intake filters). Qualified service personnel should be utilized for installation or removal of cells. It is also likely that an entire module would be installed or removed as a sealed unit and serviced only at a factory or service center.

Goals. A life cycle of 1500+ cycles, energy density of 120 to 150 Wh/kg and energy efficiency of 70 percent have been given as performance goals for ANL's lithium/sulfur energy storage battery (Ref. 3). The ultimate cost goal has been set at \$15 to \$25 per kWh. These costs are, of course, based on the premise that a battery suitable for mass production has been developed and a mass production facility is available.

4.5.2 Atomics International

Since early 1972, the Atomics International (AI) Division of Rockwell International has been conducting research aimed at producing a lithium/sulfur battery for load leveling and vehicle propulsion applications. Various portions of this work have been sponsored by the Tennessee Valley Authority, the Edison Electric Institute (and the Electric Power Research Institute since April 1973), Argonne National Laboratory and AI's own Independent Research and Development funds.

Chemistry and Construction. The basic reaction for the lithium/sulfur-type battery was given in Section 4.5.1. A 400°C, LiCl-KCl molten salt electrolyte, saturated with Li₂S, has been used by AI in their tests. Initial tests showed a decrease in cell capacity due to the loss of sulfur from the elemental sulfur cathode. Residual activity of sulfides formed with molybdenum cell components led to the testing of a K₂MoS₄ cathode. This cell had a vastly improved life (about 300 cycles).

Thermodynamic analysis of transition metal sulfides and subsequent tests produced two likely candidates (i.e., Cu₂S and FeS) to replace the

elemental sulfur cathode. Copper sulfide (Cu_2S) cathode test cells had the lowest self-discharge rates; but they also resulted in the lowest energy density. Iron sulfide produced the highest energy density and the highest self-discharge rate. Discharge voltage curves of iron sulfide cells have two plateaus, indicating that both FeS and FeS_2 are involved in the reaction. Current research includes efforts to determine an optimum FeS_x compound with $1 < x < 2$ and to improve the self-discharge characteristics of iron sulfide. In most cases, cathodes for test cells were formed by containing the active sulfide material in a dense graphite cavity covered by a porous ceramic, similar to the construction shown in Figure 4-7.

Figure 4-7. LI LITHIUM/SULFUR TEST CELL

AI's approach to producing a viable lithium anode system involves the containment of lithium in a porous metal substrate by capillary forces. Investigations have been conducted to determine the optimum substrate material and interstice size. Research efforts have also been directed toward increasing lithium retention in the substrate by the addition of metals, such as copper, to improve wetting of the substrate by the lithium. Most metals that are resistant to attack by molten lithium are not wetted by the lithium. Test cell anodes are similar to those shown in Figure 4-7, but solid alloy anodes are also under investigation. Li-Al anodes are less corrosive and more readily contained than molten lithium anodes; but this alloy results in a 0.3-volt reduction in potential and thereby results in a lower energy density. Other solid alloy anodes, such as Li-Si, are also under consideration (Ref. 5).

Several ceramic materials are being evaluated for use as separators in the cell. Thus far, it has been found that high purity is essential to resist attack by molten lithium.

Characteristics. The charge/discharge voltage characteristics of AI's cells are similar to those presented for ANL's cells in Section 4.5.1. Presentation of more detailed characteristics must await further determination of cell design by the manufacturer.

Safety and Maintenance. It is likely that production versions of the lithium/sulfur battery will have safety and maintenance requirements essentially as described in Section 4.5.1 for the ANL system.

Goals. AI hopes to ultimately develop a battery with a life of 3000 cycles, an energy density of 170 Wh/kg and a 70-percent energy efficiency. The estimated cost for production-type units is approximately \$25 per kWh. Cells with nominal energy capacities of 100 Wh have been tested with cathode and anode lives of 1200 and 300 cycles, respectively.

4.5.3 Other Lithium Battery Programs

Standard Oil of Ohio (SOHIO) has been developing a lithium/chloride battery that utilizes a solid Li-Al anode. The electrolyte is a LiCl-KCl molten salt. Porous carbon with tungsten or TeCl_4 additives is used for the cathode. Testing of a 2 kW battery has been reported (Ref. 4).

Westinghouse has a program to investigate and develop high temperature batteries. A Li/ Cl_2 system with a molten salt electrolyte is one of the batteries under study (Ref. 4).

In England, Admiralty Materials Laboratory is developing a lithium/sulfur cell similar to that of Argonne National Laboratory.

4.6 SODIUM BATTERIES

4.6.1 General Electric

General Electric has been pursuing the development of a solid electrolyte, high temperature, sodium/sulfur cell. Since 1973, a portion of the work has been sponsored by the Electric Power Research Institute (EPRI).

Chemistry and Construction. Typically, a fully charged sodium/sulfur cell consists of a molten sodium anode, a molten sulfur cathode and a solid electrolyte. During discharge, several sodium polysulfides are formed. The basic electrochemical reaction is:

where x ranges from 2 to 5. The operating temperature is 300°C . Na_2S_5 is formed during the initial portion of the discharge. The cell is usually considered 100-percent discharged when the cathode is principally Na_2S_3 . Further discharge results in the precipitation of Na_2S_2 and an accompanying loss of cell performance.

A unique feature of Na/S batteries is the use of a solid electrolyte, which serves to separate the active materials of the anode and cathode, while at the same time provides for the transport of ionic sodium. This technique can result in a cell with very low self-discharge. General Electric utilizes beta-alumina ($\text{Na}_2\text{O} \cdot 11\text{Al}_2\text{O}_3$) tubes in its cells, as shown in Figure 4-8, because of this material's resistance to attack by liquid sodium and its polysulfides. Although beta-alumina has the external appearance of ordinary alumina (an insulator), its sodium conductivity reaches 0.16 mho/cm at 350°C. The temperature dependence of this electrolyte's conductivity, along with the boiling point of sulfur and the melting point of Na_2S_4 , governs the operating temperature range of this cell. The majority of abrupt test cell failures has been due to cracking or deterioration of the beta-alumina ceramic. The exact failure mechanism is not known, but it is at least partially attributed to local high current densities and impurities. The main thrust of GE's research program has been directed toward studying and improving the solid electrolyte. Several sodium aluminate compounds and additives are being evaluated. Deterioration of seals has also been a major cause of test cell failures. However, GE feels that this area is no longer a problem.

A schematic representation of GE's test cell is presented in Figure 4-8. Due to sulfur's poor electrical conductivity, carbon felt is incorporated into the cathode compartment to act as a current collector. The energy capacity of these test cells has been approximately 300 Wh, and their operating temperature has been in the 300 to 350°C range. As with other high temperature molten salt batteries, production versions will consist of an array of interconnected cells in insulated modules and will be aircooled.

Characteristics. Figures 4-9 and 4-10 indicate typical cell voltage behavior during constant power discharge and charge. The curves shown are for 300°C. Operation at higher temperatures decreases the electrolyte resistance and thereby decreases the spacing between the curves.

Figure 4-8. GE SODIUM/SULFUR TEST CELL

Safety and Maintenance. The safety and maintenance requirements of a sodium battery are similar to those of the lithium system described in Section 4.5.1.

Goals. GE has tested 30 Wh cells with energy efficiencies up to 81 percent and with cycle lives on the order of 100 cycles. GE is projecting the development of load leveling Na/S batteries with a life of 1500 cycles, an energy efficiency of 85 percent and costs in the \$10 to \$20 per kWh range (Ref. 6).

4.6.2 TRW

Over the past six years TRW has had an internally funded program to develop a solid electrolyte battery. Also, the U.S. Army Electronics Command (USAECOM) and EPRI have provided additional sponsorship.

Figure 4-9. TYPICAL DISCHARGE VOLTAGE CHARACTERISTICS

Figure 4-10. TYPICAL CHARGE VOLTAGE CHARACTERISTICS

Chemistry and Construction. The electrochemical reactions for TRW's Na/S cell are as described above in Section 4.6.1. As in the GE program, TRW has concentrated on developing the technology required to produce a suitable beta-alumina solid electrolyte. Various magnesium oxide-enriched beta-aluminas and lithium oxide-stabilized beta"-aluminas have been fabricated and tested. Uniaxial cold pressing followed by sintering and uniaxial hot pressing of these sodium aluminates has been evaluated. After fabrication, blanks are machined and ground to a final shape. Sealing and joining technology for the several ceramic and metal components has been developed (Ref. 7).

Two types of cells have been utilized in the TRW program, laboratory cells and 20 Ah cells for USAECOM. The laboratory cells are rapidly demountable to facilitate testing. Their solid electrolytes are cup shaped slightly over one cubic meter in height and diameter. The solid electrolyte and overall configuration of the 20 Ah cell is shown in Figure 4-11. Both cell types have molten sodium anodes and sulfur impregnated felt graphite cathodes.

Characteristics. Although cell geometry and construction differ, the external electrical characteristics of TRW's cells will generally resemble those presented in Section 4.6.1.

Safety and Maintenance. Safety and maintenance requirements are essentially similar to those of the lithium system described in Section 4.5.1.

Goals. Although one test cell was cycled over 1500 times, other test cell lives were limited to several hundred cycles due to failures in the seal and solid electrolyte. TRW hopes to develop a one-kilowatt battery stack in 1976 (depending on the level of future funding) and ultimately to develop megawatt sized battery systems for load leveling. Current objectives for these large batteries include a 10-year lifetime, a density in excess of 220 Wh/kg, an 80-percent energy efficiency and cost in the region of \$20 per kWh.

Figure 4-11. TRW SODIUM/SULFUR TEST CELL BUILT FOR USAECOM

4.6.3 Other Sodium Battery Programs

The Ford Motor Company has been developing a sodium/sulfur battery for vehicle propulsion. Ford's cells utilize beta-alumina tubes and operate in the 300 to 350°C temperature range. Batteries with powers up to several hundred watts have been tested (Ref. 4).

General Motors has been working on a sodium beta-alumina/sulfur cell and doing research on lithium-chloride and zinc-air batteries (Ref. 4).

Dow Chemical has been conducting research on a sodium/sulfur cell with a solid electrolyte made up of glass tubes sealed into a header on a sodium reservoir. The outer surfaces of the tubes are immersed in a sulfur compartment with aluminum foil current collectors (Ref. 8).

In Japan, Yuasa Battery Company and Toshiba Electric Company are jointly developing a Na/S battery for electric vehicle application.

4.7 CHLORINE BATTERIES

4.7.1 Energy Development Associates

A zinc/chlorine battery for utility load leveling and vehicle propulsion applications is being developed by Energy Development Associates (EDA). EDA is a joint venture of Occidental Petroleum and Gulf & Western.

Chemistry and Construction. The basic reaction of the zinc/chlorine cell is:

This battery is unique among the advanced batteries in that it operates at room temperature. The EDA system has a second unique feature in that an aqueous electrolyte is pumped through an electrode assembly; the system functions as a small chemical plant. A schematic diagram of the EDA system is presented in Figure 4-12. As the battery is charged, zinc is plated onto the anode substrate, and chlorine gas is formed at the cathode. The chlorine gas is carried away by the flowing electrolyte and stored as chlorine hydrate ($\text{Cl}_2 \cdot 6\text{H}_2\text{O}$) in a separate tank. Formation of chlorine hydrate releases

Figure 4-12. FUNCTIONAL SCHEMATIC OF EDA Zn/Cl SYSTEM

18 kcal/mole of heat, which must be removed during discharge. The hydrate can be stored at 9°C and atmospheric pressure. During standby the electrolyte flow is stopped. At present, EDA considers the construction details of its battery to be proprietary.

Characteristics. Due to the nature of the system, the charge and discharge voltage curves (not illustrated) for EDA's zinc/chlorine battery are very flat. Also, the cell's polarization characteristics are such that for anticipated rates, the cell voltages will be within about ± 0.1 volt of the open circuit voltage of 2.12 volts at C/5 rates.

Safety and Maintenance. Design details of EDA's zinc/chlorine system have not been published. However, safety aspects will involve consideration of chlorine handling. Unless there is an upset condition, this battery will essentially be a closed system that does not vent to the atmosphere. EDA has considered venting through an absorbing caustic solution for emergency situations. It is likely that a zinc/chlorine residential system would be a sealed unit with penetrations for dc and control wiring and air ducts for a

heat exchanger . A 24 MWh shopping center storage system would likely consist of a multiplicity of such units.

Maintenance requirements for this system may include servicing pumps and heat exchanger systems. Any servicing of the electrode stacks would likely be carried out at the factory.

Goals. EDA has tested cells configured into batteries with energy capacities of up to 50 kWh, an energy capacity of 154 Wh/kg and coulombic efficiencies up to 90 percent. EDA is striving to develop a load leveling battery system with an energy efficiency of 70 percent, a life of 2500 cycles and an ultimate cost in the range of \$10 to \$20 per kWh. This system is likely the most developed of the advanced batteries for load leveling and may be the first (exclusive of lead-acid batteries) to achieve commercial status.

4.7.2 Other Chlorine Battery Programs

ESB has been developing a sodium/chlorine battery. Several U.S. patents (e.g., #3,877,984) on this system have been issued and others are pending. ESB has not published details of their cell and considers most of its research information as proprietary. Recently, ESB formed a joint venture with ASEA of Sweden to develop and market complete load leveling systems.

The ESB system utilizes a molten sodium anode and operates near 200°C. The electrolyte is a beta-alumina tube. A high surface area carbon is used in the cathode along with additives of aluminum and sodium chlorides (Ref. 9).

Although not stated specifically, the production costs of this system are expected to be similar to other advanced battery systems, i.e., \$10 to \$20 kWh.

Section 5

POWER CONDITIONING

The output from a solar array must be controlled to match the requirements of the energy storage system and the electrical loads. The dc output of a solar cell or a battery energy storage system must be converted into ac in order to be connected to electric utility lines or to most existing electrical equipment. Power conditioning systems needed to perform these functions are discussed in this section.

5.1 SYSTEM REQUIREMENTS

Figure 5-1 presents a block diagram of a solar power system. While the system shown applies mainly to residential or shopping center installations, the basic elements of the power conditioning system are generally included in all three of the system sizes being considered. The power conditioning system consists of a power regulator, an inverter and the system interface with the utility and ac loads. Although not shown specifically in Figure 5-1, control logic and equipment for the solar power system will be required. A portion of this requisite control system will therefore be a part of or interface with the power conditioning system.

As discussed in Section 4, only batteries were considered for use as the energy storage element. Therefore, discussions of the power conditioning system assume operation with a battery storage system. Inverters are emphasized in the following discussion, since they are the major cost factor in the power conditioning system.

Figure 5-1. PHOTOVOLTAIC SOLAR POWER SYSTEM

5.1.1 Inverter:

The primary function of the inverter is to convert the dc output of the photovoltaic array and battery energy storage system into a 60 Hz ac waveform, compatible with the loads it serves. The inverter must be capable of tracking the variable voltage output from a solar cell and battery system, while providing a regulated ac voltage. Transformers within an inverter enable optimization of the dc system voltage level independent of the ac system voltage. Depending on system design, the inverter may supply all or part of the reactive power requirements of the load. Also, inverters can be bidirectional, permitting the storage battery to be charged from the utility lines during off-peak hours if prolonged periods of low insolation are forecast. The design of the inverter (in conjunction with the interface system design) will govern the response of the solar power system to load stimuli.

5.1.2 Regulator.

The output voltage and current of a solar cell varies with insolation, temperature and load impedance. The primary function of the regulator is to control the charging of the battery and maintain voltages and currents from the photovoltaic array within the limits recommended by the battery manufacturer in order to maximize battery life. Similarly, the regulator provides some degree of control for the inputs to the inverter and to the dc loads. Regulators can also be designed to track a solar cell's characteristics and provide the impedance required for maximum power transfer as a function of insolation and solar cell temperature.

5.1.3 Interface.

For residential and shopping center installations, the interface system must provide for switching between utility and solar power. The interface may also be designed to provide load sharing, with the solar power system operating in parallel with the utility. With such designs, the solar power system would supply power (up to its rated maximum), and the utility would supply any demand in excess of this value. Provisions for synchronizing and matching voltage levels would also have to be included in the interface and inverter designs. Inverter efficiency characteristics are such that it may be desirable to have the utility supply power when the load demand is a small fraction (e.g., 5 percent) of the inverter's rated power. The interface system design must also prevent the flow of power into the utility lines for the residential and shopping center installations.

Interface requirements for the central station are somewhat different from those of the other two applications. In this case, the utility grid is the load, and the primary function of the plant is to supply power to the grid. System designs and equipment must provide for controlling voltage level, synchronizing and fault protection. For the most part, the requisite equipment could be considered as a part of the inverter system. A parallel utility interface will be used to supply station power (e.g., lighting, control system power etc.), but its size will be a small fraction of the plant's rating.

5.2 AVAILABLE EQUIPMENT

In general, the power conditioning requirements for the three photovoltaic system applications under consideration cannot be met by "off-the-shelf" equipment. This is particularly true for high power inverters and regulators. However, the equipment can be built using present day technology. Some efforts and associated expenditures will be required to tailor existing design technology to suit the present applications, but similar efforts are required for other types of advanced power systems currently being planned for electric utility application. Systems such as fuel cells, MHD, battery energy storage and magnetic energy storage need inverters to interface their dc power output with ac utility lines. This common need is tending to further the development of the required technology in general, but each system will still require individual design efforts.

5.2.1 Inverter

The term inverter applies to a broad variety of equipment that functions to change dc into ac. Motor-generator sets have been used as inverters, but due to the maintenance problems associated with rotating equipment, this type of device is being replaced by static, solid state inverters. Only solid state inverters are considered here.

Basic Inverter Circuits. Due to their power handling capability and efficiency, switching-type inverter circuits are the most suitable for power conditioning. With this circuit, the main active elements are alternately switched between full on and off conditions. Figure 5-2 presents a simplified schematic of a switching-type inverter circuit. A single-phase, bridge configuration is shown.

Inversion is accomplished as follows. Closing switches 1 and 4 causes a dc current to flow through the transformer winding. After 8.3 milliseconds (for 60 Hz, single-phase devices), switches 1 and 4 are opened, and switches 2 and 3 are closed for 8.3 milliseconds. This cycle is repeated 60 times

Figure 5-2. SIMPLIFIED INVERTER SCHEMATIC

per second. Thus, by this switching action an alternating current flow is produced in the transformer. Also, by proper sequential operation of the switches in synchronism with an ac input, the circuit can be made to function as a rectifier. In actual equipment, the switches are replaced by transistors or silicon controlled rectifiers, and other circuit elements (not shown) are included to provide for proper operation.

Most low power inverters (less than 1 kW) on the market utilize transistors as the switching element. Unfortunately, transistors require relatively high drive power. This effect can be mitigated by the use of Darlington transistor configurations, but these devices are generally rated for lower power levels and tend to be more costly. Development programs are resulting in transistors with ever increasing power levels. However, at present, it appears doubtful that transistors will be utilized for inverters rated above several kilowatts.

Generally, SCR's are used as the switching element in high power inverters and related applications such as controllers for large motors. Multiple SCR bridges in high voltage dc (HVDC) transmission line terminals are currently being operated at hundreds of megawatts. Unlike transistors, SCR's cannot be turned off by a control signal. The current through the SCR must go to zero before these devices are turned off and a blocking ("open switch") condition is established. The energy to accomplish this may be supplied either internally from energy storage circuit elements such as capacitors (self-commutated) or externally by connecting the inverter to a "stiff" ac line (line-commutated). A new type of thyristor, the gate turnoff SCR, is beginning to emerge from the laboratory. Unlike SCR's in common usage today, this device can be turned off by a gate pulse. The power handling capability of devices currently available is less than that of Darlington's, but continued research may lead to the marketing of gate turnoff SCR's with ratings comparable to those available SCR's. This would facilitate the design of high power, self-commutated inverters.

Inverter circuits are broadly categorized as either line or self-commutated. Commutation is the switching of current flow from one branch of a circuit to another. Line-commutated inverters rely on the voltage from a stiff ac bus to provide the energy required to turn off SCR's, and therefore this type of circuit is operated in parallel with a utility line (e.g., HVDC terminal equipment). Line-commutated inverters can be forced to operate in a self-commutating mode by the addition of external capacitors, but then their cost approaches or exceeds that of similar self-commutated equipment. Self-commutated inverters can operate into a passive load. Since transistors can be biased off, transistorized inverters are inherently self-commutating. Internal circuits across SCR bridge legs supply the energy required for commutation. These additional circuit components contribute to the generally higher cost for self-commutated inverters. Further, losses associated with the circulating energy in these commutating circuits cause the efficiency of self-commutated inverters to fall off

more rapidly as output power is reduced. Reversal of power flow in line-commutated inverters is generally accomplished by reversal of voltage polarity, thereby requiring the use of a polarity reversing switch if the energy storage battery is to be charged from the utility line. Self-commutated circuits can be designed to reverse dc current flow, thereby obviating the need for a polarity reversing switch. Also power factor control can be designed into self-commutated inverters. External, switched power factor capacitors are generally used with line-commutated inverters.

HVDC. High voltage dc transmission line terminal inverters represent one type of available equipment. These inverters operate at power levels of several hundred megawatts and dc voltage levels in the hundreds of kilovolts. There are three thyristor (SCR) valve HVDC systems presently operating in the world; similar facilities are under construction. At this time, the trend is toward the use of solid state thyristor valve assemblies as opposed to mercury arc systems, and every HVDC system ordered since 1968 has been designed for solid state inverters (Ref. 10). The Duluth Center project recently awarded to General Electric will be the first domestic thyristor valve installation and will be patterned after the Eel River facility, which has transmitted over two billion kWh during the first year and one-half of operation (Ref. 11). ASEA will also utilize solid state valves on the Underwood/Minneapolis HVDC system. The Caborra Bassa-Apollo system is the largest thyristor valve system planned. It is scheduled for initial operation at 1000 MW in 1976, with an eventual doubling of that power (Ref. 12).

HVDC inverters are comprised of six-pulse, three-phase bridges with line-commutation as typified by the Graetz bridge shown in Figure 5-3. Thyristor valve systems evolved from older mercury arc designs. The "valves" in a HVDC thyristor system are actually several hundred (depending on the voltage) individual thyristors connected in series. Paralleling is used to obtain the desired current rating. Associated with the series configuration are voltage grading circuits to assure a uniform distribution of

Figure 5-3. BASIC GRAETZ BRIDGE

voltage to each thyristor and circuits to provide simultaneous gating for all thyristors in any series string. Present day thyristor valves are limited to about 150 kV. Current designs use a modular approach with several bridges in series to obtain the operating voltage. This is shown in Figure 5-4, which presents a single-line diagram of the Caborra Bassa system. The selection of thyristors and circuit design must include considerations of overvoltages generated by switching or lightning strikes and overcurrents due to system faults. Current design procedures include the use of computer modeling to predict stresses on individual components and circuit behavior. Synthetic testing is also employed for component and system evaluation prior to commencing full-scale construction.

UPS Systems. A second type of available inverter is typified by the uninterruptible power supply (UPS). These systems are used to supply power to critical loads such as computers or process control equipment in the event of an ac line failure. Generally, a UPS will consist of a rectifier (separate from and in addition to an inverter), a secondary battery and a self-commutated inverter. Figure 5-5 presents a functional block diagram of a basic UPS system. Additional equipment (not shown) may include a static

Figure 5-4. HVDC SYSTEM

transfer switch, modularized inverters and control circuitry. The rectifier provides sufficient dc current to simultaneously supply the full-load inverter requirements and (slowly) recharge the battery. Battery system voltages range from 250 to 400 volts, depending on the manufacturer. When the line voltage fails, the inverter is supplied by battery energy. Transfer is so fast that it is seen as a barely perceptible jog on an oscilloscope display of the equipment voltage sine wave. Usually, battery energy is only supplied for a few minutes, until a gas turbine generator set or alternative power source is activated. As an additional benefit, UPS systems also suppress line transients. Standard high power UPS systems are available from about a dozen companies in the U.S. For large installations, systems are made up of modules. The largest modules range

Figure 5-5. SIMPLIFIED BLOCK DIAGRAM OF A UPS SYSTEM

in size from 250 to 400 kVA, depending on the manufacturer. To date the highest power UPS is a 1.8 MVA system installed at the Chase Manhattan Bank in 1971. Systems above several kVA are manufactured on demand with little or no redesign of the component modules. However, manufacturers are working to develop higher power modules.

A UPS is installed to provide a highly reliable source of power. In many instances, extra modules are added in parallel to provide redundancy. Mean times between failure (MTBF) of 20,000 hours are typical for a module, with redundancy used to increase the system MTBF to 200,000 hours (23 years) in some cases.

Since the primary application of this type of unit involves passive loads, the inverters must be self-commutating. Several companies use versions of impulse commutation (a form of self-commutation) for the basic inverter section. Two or more six-pulse bridge circuits are combined with the proper phase difference to give a 12-pulse (24 in one instance) output

waveshape. Relative phase displacement is used by several companies to achieve output voltage control and battery voltage tracking. Two manufacturers utilize a ferroresonant transformer approach. All of these circuits are in use, and each manufacturer believes his design to be the optimum.

Low Power Inverters. Several types of low power inverters are currently available. Included among these are low power, single-phase UPS systems similar to the larger systems discussed. Generally, these are produced by electronics companies different from those manufacturing the higher power (>100 kW) UPS systems.

Small units are also available to convert the 12-volt dc from automobile batteries into 120-volt ac household current to permit operation of standard ac equipment at remote locations. These inverters are usually transistorized. The degree of sophistication of these units varies greatly, with some putting out a 60 Hz square wave. Higher priced units are regulated, filtered, frequency stable and are capable of being operated as rectifiers. Low power inverter prices vary over a 10:1 range at a given power level.

Other low power inverter systems are currently being custom manufactured for various applications including terrestrial and extraterrestrial photovoltaic systems.

Inverter Filtering. All of the available inverter systems described include filters on the ac output, with the possible exception of some of the least expensive, low power equipment. The outputs of the basic circuits discussed (and illustrated in Figures 5-2 and 5-3) are basically rectangular pulses. These waveshapes have a high harmonic content and must be filtered to produce a sine wave compatible with existing ac equipment. Waveforms with a high harmonic content tend to overheat iron core electrical equipment such as motors and transformers.

The symmetry of the waveshape is such that only odd numbered harmonics are present. For single-phase equipment, these odd harmonics must be filtered. This is usually accomplished by series LCR tuned traps across the line for the lowest harmonics and a high pass filter for the remaining harmonics. For higher power inverters, the three-phase interconnection eliminates the third harmonic and its multiples. A wye-delta pair transformer connection, as shown in Figure 5-4, produces a 12-pulse waveform by combining output of two 6-pulse bridges (Ref. Figure 5-3). This theoretically eliminates the fifth and seventh harmonics. In practice, some manufacturer's include filters at these frequencies to compensate for errors in SCR firing angle. This procedure is carried further by several UPS system manufacturers. Four 6-pulse bridges can be combined in a summing transformer to produce a 24-pulse waveshape, where the lowest harmonics present are the 23rd and 25th. All of the multiple bridge approaches require that the SCR firing angles be properly phased in order to compensate for the phase shifts in the different transformer windings. Whatever scheme or combination of schemes is used, the total harmonic content is usually brought down to between three and five percent to comply with telephone interference factor requirements.

In addition to harmonics, an inverter can generate unwanted electromagnetic interference (EMI). This problem can be overcome by packaging the inverter equipment in EMI-proof cabinetry and using suitable filters on cabinet penetrations. Alternatively, the entire room of inverter equipment may be enclosed in a Faraday cage, as is done in HVDC terminals.

Size. The size of available inverter equipment varies from about $0.5 \text{ ft}^3/\text{kW}$ at the 1 kW level to $1.5 \text{ ft}^3/\text{kW}$ at the 1 MW level. Above 1 MW, the units would likely be installed outdoors in switchyard-type construction.

Safety and Maintenance. From the standpoint of safety, inverter equipment is identical to most other electronic or electrical equipment. A

potential hazard exists, in that the operating voltages can deliver an electric shock. Further, the capacitors within the inverter can still deliver a shock when the unit is disconnected. Equipment design will likely include door interlocks. Fusing will be used to protect the equipment and surroundings in the event of an internal fault.

Only qualified service personnel should be allowed access to the interior of the inverter in residential applications. For the shopping center photovoltaic system, the facility's operating staff may be able to perform rudimentary servicing on a defective inverter, but they likely would not have the equipment or training for extensive repairs. Equipment in the central station would be serviced and maintained by utility personnel except for major repairs.

The inverter equipment for photovoltaic systems will be essentially free from routine maintenance, with the possible exception of changing filters in cooling air ducts.

Costs. Since the required inverter equipment is not currently mass produced, determining costs is difficult. However, data are available for similar commercial equipment. Such data are presented in Figure 5-6 in terms of cost per kw as a function of power level. Line segments on the figure denote cost of a single manufacturer's line of inverter equipment as a function of power. Sources of this data are vendor literature, vendor contact, budgetary price quotations and published technical literature. Figure 5-6 is intended to provide a basis for estimating the cost of inverters in photovoltaic power systems by providing cost data on similar, commercially available equipment.

Two important conclusions may be drawn from the data. First, there is an obvious trend indicating that the cost per kW decreases with increasing power level. As may be inferred from the wide range of power levels

Figure 5-6. INVERTER COST VERSUS POWER

encompassed, the cost data are for a variety of inverter types. However, the line segments in the figure show that the cost per kW of a single type of inverter from any one manufacturer decreases with increasing power. Second, there is considerable price spread at any given power level. This reflects both different design approaches by various manufacturers and design alternatives at a given power level. For example, the data points at 40 MW represent budgetary cost estimates by four manufacturers for the same set of equipment specifications. The line segment at 2.5 MW indicates one result of a recent study which found that at a fixed power level, invert

costs decrease with increasing voltage. This fact was confirmed by respondents on the 40 MW equipment. The cost per kW is highest toward the low end of a 10:1 range in voltage, which may be practical at a given power level.

The data presented are for the purchase of single units. At the lower power levels (e.g., 2.5 kW), many units would be manufactured as residential photovoltaic power systems come into widespread use, thereby permitting a price reduction due to quantity purchasing. Components for the inverter (e.g., SCR's, capacitors, transformers etc.) exhibit a characteristic reduction in price of about 20 percent per decade with volume purchasing, as indicated by Figure 5-7. Mass produced products, such as small power supplies similar to the requisite inverter, also exhibit this cost characteristic. Between 10^3 and 10^4 units, the cost per unit levels off as the maximum component discount has been reached and assembly techniques have been optimized. Above these volumes, prices would likely be negotiated. Also, several manufacturers pursuing the same market would cause competitive pricing.

Figure 5-7. COST VERSUS QUANTITY

At the higher power levels, there is less likelihood of multiple purchase, and the price would likely be set by open bidding. At the 40 MW level, price reduction estimates ranged from 10 to 25 percent for the production of 10 units per year.

5.2.2 Regulator

The simplest and least expensive method of power regulation is to rely solely on the characteristics of the cell array and battery. This approach is currently used in low power terrestrial and extraterrestrial applications. With this method, the array must be designed so that its maximum voltage does not exceed the cutoff voltage of the storage battery in order to prevent damage to the battery. Unfortunately, the voltage available from a silicon photovoltaic cell increases with decreasing temperature faster than the cutoff voltage of lead-acid cells (Ref. Figure 4-4). Also, roof-mounted arrays will be exposed to greater temperature variations than the battery, which will likely be in a protected location. As mentioned in Section 4.4.2, the projected cutoff voltage characteristics of one manufacturer's developmental lead-acid battery design may mitigate this effect. In general, the advanced batteries discussed in Sections 4.5 through 4.7 will not tolerate over-voltages. Another factor that must be considered if a regulator is not used is the maximum rate of charging, since a battery may be damaged by high charging rates, particularly toward the end of charge.

Basically, regulators are either in a series or shunt configuration. For low power applications, transistors are used as a controlled dissipative element in both series and shunt regulators. For the power levels of the three sizes of photovoltaic solar power systems being considered, a series, switching-type regulator using SCR's will likely be used. As mentioned in the discussion on inverters in Section 5.2.1, SCR switching circuits generally have a high power handling capability and efficiency. One such applicable device, a time-ratio control dc chopper, is currently being manufactured and sold for about \$5 per kW. It is rated at 625 kW and has an

efficiency of 98 to 99 percent (at full power). It is likely that the cost of similar equipment at other power levels will follow the cost pattern presented by Figure 5-6. The data in Figure 5-6 also indicate that the cost of an inverter at the 625 kW power level ranges from \$80 to \$480 per kW. Thus, the cost of the regulator is between 1 and 6 percent of the inverter cost. With the addition of instrumentation and control logic, this type of equipment could be used to track the peak power of a photovoltaic cell array. Similar systems have been used on the Apollo spacecraft. (Ref. 13).

The safety and maintenance characteristics of the regulator equipment will be essentially the same as those of the inverter equipment.

5.2.3 Interface

The electrical energy derived from solar cell arrays, storage battery and power conditioning system must be connected to loads and a utility line. The central station differs from the other two systems (i.e., residential and shopping center) in that its "load" is the utility line itself. This interface will be considered in detail in Bechtel's central station conceptual design. The residential and shopping center systems are similar to each other in that they both must be interfaced with passive loads and the utility lines. This may be accomplished in several ways by the use of commercially available components.

Residential Interface A. One possible residential interface system is to have the ac loads supplied by either the inverter or the utility but not by both simultaneously. With this scheme, the inverter would supply power to the loads until the load demands exceed the inverter rating. At this point, the loads would be switched to the utility lines, and when the load demand decreases below this value, the load would be switched back to the inverter. This scheme does not fully utilize the energy available from the solar power system and can cause switching transients. No provision was made to charge the storage battery or operate dc loads from the utility line through the inverter.

The hardware required to implement this system is schematically presented in Figure 5-8. Normally, solar derived energy will be supplied by the

Figure 5-8. RESIDENTIAL INTERFACE A

inverter with the control switch HS in the "auto" position. This closes 42I contacts and opens 42U contacts. Interlocks (mechanical and electrical) prevent parallel operation of the inverter and utility. When the load current exceeds a preset value (i.e., corresponding to the maximum rating of the inverter) as sensed by the current-operated meter relay 95, an automatic transfer is made from the inverter to the utility. During the transfer period, the load current is interrupted. To prevent the contactor from reverting back to the previous position and possible hunting, a time delay relay 95X is used to keep the transfer control circuit energized and uninterrupted during the transfer. Future design should consider the use of a meter relay with hysteresis (i.e., dropout current lower than the pull-in current) to assure stable operation when the system is operated very close to the inverter power rating switch point. The control switch also includes a position for direct connection to the utility line and an off position. Since the inverter will be connected to passive loads, it must be self-commutated. Also, this scheme does not allow the inverter to be connected to the utility line to charge the battery or operate dc loads. Therefore, the inverter need not be bidirectional (i.e., operate in a rectifier mode).

It may be desirable to add a second meter or use a dual-contact relay (not presently included) to switch to utility line operation when the load demand is very low and the inverter efficiency is low.

This interface system (as well as all of the others to be discussed) is comprised of standard, proven components and will be free of routine maintenance. Any repair work of defective equipment will require the services of a qualified electrician. Safety will be dictated by existing codes covering electrical wiring and equipment housing.

Typical costs for the hardware utilized with this interface system are presented in Table 5-1. The equipment shown is for a 2.5 kW, 120 volt, single-phase system. Costs for cabinetry are not included, since the hardware

Table 5-1

EQUIPMENT COSTS FOR RESIDENTIAL INTERFACE A

Equipment	Ratings and Description	Typical Manufacturer	Quantity	Unit Price
Reversing Contactor 42	115 V, 25 A, 2-pole with 2 NO contacts, mechanically interlocked, 115 V coil	ITE	1	\$57.00
Circuit Breaker 52	120/240 Vac, 25 A trip, 100 A frame, 2-pole, molded case with face mounting	ITE	2	\$11.10
Meter Relay 95	120V, 5 A, one NO and one NC contacts	GE	1	\$25.00
Time Delay Relay 95X	10A DPDT contacts 120 V coil, time delay to drop out, 0-1 sec.	TimeMark	1	\$20.75
Control Switch HS	2 NO and 2 NC contacts, double-block (miniature)	GE	1	\$19.40

would likely be mounted within the inverter cabinet. Similarly, the equipment cost is not totaled, since a portion of the interface hardware may be included in other systems. For instance, the circuit breaker 52I may be part of the inverter, and circuit breaker 52U may be considered as a normal part of the residence.

Residential Interface B. This system is quite similar to interface A, described above. Figure 5-9 presents a schematic of this system. However, additional relaying is provided to enable operation of dc loads or charging of the battery from the utility. The circuit logic will permit the inverter to be connected to the utility only when an internal contact indicates that the inverter is set to operate as a rectifier. Thus, the inverter (rectifier) is paralleled with the utility only as a passive load. With this scheme, the inverter must be bidirectional and self-commutated.

Figure 5-9. RESIDENTIAL INTERFACE B

The interface has two circuit breakers, a reversing contactor, a charging contactor, a meter relay and a control switch. The basic operation is similar to that of system A. Power is normally taken from the inverter. An automatic transfer to the utility is made when the load power is above the rated inverter power as sensed by a meter relay 95. When battery charging or operation of the dc loads from the utility is desired, as indicated by a contact internal to the inverter S2, contactor 42C connects the inverter to the utility provided that the ac loads have previously been connected to the utility line. If desired, a dc circuit breaker or switch could be added in series with the battery to permit operation of the dc loads without simultaneously charging the battery.

The equipment costs are as presented in Table 5-1 plus \$27.00 for a 115 V, 25 A, two-pole nonreversing contactor (42C). Contact S2 to sense when the inverter is set to operate as a rectifier is considered as part of the inverter and is not included in the cost.

Residential Interface C: With this system, the inverter and utility are operated in parallel. As with large plants that generate a portion of their electricity, load sharing with the utility is accomplished by controlling the phase angle of the inverter (generator). The inverter will supply all power up to its maximum rating with the utility supplying all power in excess of the inverter rating. Circuit controls are provided to ensure that power does not flow into the utility line. In this system, the inverter must be bidirectional (to charge the battery or operate dc loads) and capable of operating in parallel with a utility; and may be either line- or self-commutated.

Figure 5-10 presents a single-line diagram of this system. The interface equipment includes two circuit breakers, two millivolt transducers, a meter relay, a contactor and a hand switch. To utilize the solar power system,

Table 5-2

EQUIPMENT COSTS FOR RESIDENTIAL INTERFACE C

Equipment	Ratings and Description	Typical Manufacturer	Quantity	Unit Price
Contactor 42	115 V, 25 A, 2-pole, non-reversing, 115 Vac coil	ITE	1	\$27.00
Meter Relay 95	120 V, 5 A, 1 NO and 1 NC contact, 25 A input current	GE	1	\$25.00
W-mV Transducer	Dual Element — 125 V 25 A, single-phase, 0-2.5 V dc output into 5000 ohm load	Leeds & Northrup	1	\$50.00
Control Switch HS	1 NO and 1 NC contact, single-block (miniature)	ITE	1	\$13.40
Circuit Breaker 52	120/240 Vac, 25 A trip, 100 A frame, 2-pole, molded case	GE	2	\$11.10

DC Loads. It is technically possible to have a major portion of the electrical loads for a residence served by dc. Lighting, electric ranges, electric heating, motors etc. could all operate on dc. In general, this would require the use of custom manufactured appliances that are not readily available or in common use today. Other devices such as most televisions and clocks require ac. The simplest compromise would be to operate heating elements (for ovens, ranges, clothes dryers, water heaters, etc.) on dc, with a separate ac line to such appliances for timers and controls. At present, most residences already incorporate a separate 220 Vac circuit for this type of load. Similarly, wiring could be dedicated to serving electric heating element loads in a solar power system. It would be desirable to have only heating elements wired to this circuit. Such an arrangement would allow these dc loads to be switched to the ac utility lines when solar derived energy is not available. This switching arrangement would avoid losing energy to the inverter efficiency and also may permit a reduction in the inverter rating.

To be compatible with as many existing element devices as possible, it is recommended that the battery dc system voltage be set near 220 volts. Unfortunately for a 60 kWh residential storage system, the resulting cell size may be too small. Also, consideration should be given to the voltage requirements for motors in the space conditioning system, since this can be an appreciable load.

Shopping Center Interface A. This scheme is similar to the residential system A in that the ac loads are supplied by either the inverter or the utility but not by both simultaneously. The ac loads are supplied by the inverter until the load demands exceed the inverter rating. At this point, the loads would be switched to the utility lines, and when the load demand decreases below this value, the load would be switched back to the inverter. As with the residential switching schemes, this system does not fully utilize the energy available from the solar power system. No provision is made to charge the storage battery or operate dc loads from the utility line.

Figure 5-11 presents a single-line diagram and control logic for this shopping center interface system. The components shown are for a 1 MW, 480 V, three-phase system. To energize the ac load distribution bus, control switch HS is set to the on position, and selector switch HSS is set to either the auto or utility position. With HSS in the utility position, the load bus is tied to the utility line only through circuit breaker 52U. With HSS in the auto position, circuit breaker 52I will close (provided 52U is open), and the inverter will supply power to the ac load bus. If the load current exceeds a preset value, as sensed by meter relay 95 through a current transformer CT2, breaker 52I trips, and breaker 52U closes automatically, thereby transferring the load to the utility when the inverter's power rating is exceeded. During the transfer period, the load current is interrupted. To prevent the control circuit contacts from reverting back to their previous position and possible hunting, a time delay relay 95X is used to keep the transfer control circuit energized and uninterrupted during the transfer. Manual transfer is also possible by use of the selector switch. However, transfer is locked out if the current limit is exceeded. At any time, over-currents will trip a closed breaker by means of a direct-acting trip device.

CONTROL SCHEME

SWITCH DEVELOPMENT

CONTACTS	POSITIONS	
	UTILITY	AUTO
1-2		X
3-4	X	
5-6		X
7-8	X

CONTACTS	POSITIONS	
	ON	OFF
1-2	X	
3-4		X
5-6	X	
7-8		X

Figure 5-11. SHOPPING CENTER INTERFACE A

As with the residential system A, the inverter will be connected to passive loads and must therefore be self-commutated. This system does not allow the inverter to be connected to the utility line to charge the battery or operate dc loads, and therefore the inverter need not be bidirectional. It may be desirable to add a second meter relay (not presently included) to switch to utility line operation when the load demand is very low and the inverter efficiency is low and to devise a load shedding (or transferring) scheme to avoid transferring the entire load to the utility as the inverter's rating is exceeded.

Typical equipment costs are presented in Table 5-3. Equipment such as circuit breaker 52U, current transformer CT1, potential transformer Pt and meters WH and V are normally included as part of a 480 V installation and therefore do not represent an additional cost. Similarly circuit breaker 52I may be included as part of the inverter system. Cabinets are not included in the cost.

Table 5-3

EQUIPMENT COSTS FOR SHOPPING CENTER INTERFACE A

Equipment	Ratings and Description	Typical Manufacturer	Quantity	Unit Price
Switch HS, HSS	2-position, maintained contact 2 NO and 2 NC contacts, double-block (miniature)	GE	2	\$19.40
Current Transformer CT	1500-5 A, accuracy: 0.6-B.2 (ANSI)	W	1	\$42.60
Meter Relay 95	120 V, 5 A, 2 NO and 2 NC contacts, 5 A input	GE	1	\$25.00
Time Delay Relay 95X	10A DPDT Contacts, Time delay to drop out 0-1 sec., 48 Vac coil	TimeMark	1	\$25.00
Circuit Breaker	480 V, 3-phase, 1600 A con- tinuous, 50,000 A interrupting, 48 V dc operating coil, 1 NC auxiliary contact	W	1	\$2,030.00

Shopping Center Interface B. With this system, a permissive contact in the inverter and a normally open contact in the circuit breaker 52I are added to the shopping center interface A. The series connection of the inverter permissive contact and breaker contact 52I/a shunts the contacts in the closed circuit of 52I. This enables operation of dc loads or charging of the battery from the utility line. The inverter must, of course, be bi-directional and self-commutated.

Operation is the same as for shopping center interface A, with the exception that a charge mode is possible. A manual transfer to the utility is first made by the use of switch HSS. When the charge control is set to charge, the inverter permissive contact enables breaker 52I to close with 52U previously closed. This allows the utility to supply both the load and the battery charger.

The costs for interface B equipment are essentially the same as presented in Table 5-3 for interface A.

Shopping Center Interface C. With this interface system, the inverter and utility are operated in parallel in a manner similar to residential interface C. A single-line diagram is presented in Figure 5-12. To supply the ac load bus with power from the solar system, the control switch HSI is turned to inverter. This closes circuit breaker 52I. The inverter is normally synchronized, and the breaker closure will not cause a significant transient. The output of the transducer $\frac{W-mV}{I}$ is subtracted from that of $\frac{W-mV}{L}$. The difference, if positive, results in a phase advance signal to the inverter phase control. This increases the power output of the inverter. If this signal is negative, the phase is retarded. If the signal remains negative, an abnormal condition exists (i.e., the inverter is supplying power to the utility in addition to the load), and breaker 52I will be tripped. The same condition may be attained in case of battery charging mode. Hence, an interlock from the charging control switch

Figure 5-12. SHOPPING CENTER INTERFACE C

is necessary to permit the process. At any time, over-currents will trip a closed breaker by means of a direct acting trip device.

Equipment costs for this interface are presented in Table 5-4. Only the equipment which must be added to that already installed in a normal utility/load interface is costed.

Table 5-4

EQUIPMENT COSTS FOR SHOPPING CENTER INTERFACE C

Equipment	Ratings and Description	Typical Manufacturer	Quantity	Unit Price
Circuit Breaker 52	480 V, 3-phase, 1600 A continuous, 22,000 A symmetrical interrupting, 48 Vdc operating coil	W	1	\$2,030.00
Current Transformer CT	1500-5 A, accuracy: ANSI 0.380.2, 10 kV BIL	W	4	\$42.00
Potential Transformer PT	480-120 V, single-phase, ANSI class 0.6, 10 kV BIL	W	2	\$49.80
W-mW Transducer	208/120 V, 3-phase, 5A	W	2	\$267.00

Central Station Interface. The function of the central station is to deliver power into a utility grid. Therefore, it will be operated in parallel with utility lines. For the power levels involved (i.e., 50 to 1,000 MW), the interface connection to the utility will likely be at 115 kV or above and will be accomplished with standard substation equipment (i.e., isolating switches, breakers, station transformer(s) etc.). A second connection to the utility will serve to provide station power. Details of these interface connections, as well as of the entire plant, will be presented in Bechtel's forthcoming report on the preliminary conceptualization of a photovoltaic central station.

REFERENCES

- (1) Gould Inc, Northern States Power Co. and Bechtel Corporation, "Proposal to the Atomic Energy Commission to Design, Build and Operate an Experimental Storage Battery Load-Leveling Plant," September 1973.
- (2) Bechtel Corporation, "Preliminary Environmental and Safety Assessment for a Battery Energy Storage Test (BEST) Facility," prepared for Argonne National Laboratory, September 1974.
- (3) W. J. Walsh et al., "Development of Prototype Lithium/Sulfur Cells for Application to Load-Leveling Devices in Electric Utilities," presented at the 9th Intersociety Energy Conversion Engineering Conference, San Francisco, August 26-30, 1974.
- (4) M. L. Kyle, E. J. Cairns and D. S. Webster, "Lithium/Sulfur Batteries for Off-Peak Energy Storage: A Preliminary Comparison of Energy Storage and Peak Power Generation Systems," Argonne National Laboratory, Chemical Engineering Division, March 1973.
- (5) Rockwell International, "Development of Lithium-Metal Sulfide Batteries for Load Leveling," Interim Report for EPRI RP116, June 1975.
- (6) S. P. Mitoff and J. B. Bush, "Characteristics of a Sodium-Sulfur Cell for Bulk Energy Storage," presented at the 9th Intersociety Energy Conversion Engineering Conference, San Francisco, August 26-30, 1974.
- (7) TRW, "Development Program for Solid Electrolyte Batteries," Final Report for EPRI RP127, October 1974.
- (8) C. A. Levine et al., "Quarterly Progress Report on Development of the Hollow Fiber Sodium-Sulfur Battery," by Dow Chemical Co., to Naval Underwater Systems Center, U. S. Army ECOM, DOT and EPA, April 1972.
- (9) BEST Battery Workshop, Denver, November 19-22, 1974.
- (10) E. Jeffs, "CIGRE Reveals Mounting Confidence in HVDC," Energy International, Volume II, No. 10, October 1974.
- (11) Energy Info, Volume 9, No. 6, December 1973.
- (12) E. Jeffs and N. Codling, "UHV or HVDC? That is the Question," Energy International, January 1974, p. 10.
- (13) R. Gruber, "High Efficiency Solar Cell Array Peak Power Tracker and Battery Charger," PSCS 1970 Record, pp 128-138.