# BATTERY STORAGE FOR SUPPLEMENTING RENEWABLE ENERGY SYSTEMS

## 1.0 System Description

Battery energy storage can be integrated with renewable energy generation systems in either grid-connected or stand-alone applications. For stand-alone systems, batteries are essential to store electricity for use when the sun is not shining or when the wind is not blowing. For grid-connected systems, batteries add value to intermittent renewable resources by facilitating a better match between the demand and supply.

The system characterized in this appendix consists of a 30 kWh battery energy storage system operating with a 30 kW PV array to shave peak load on the utility side of the meter. This system is sized for commercial or small industrial applications (low-rise buildings where PV arrays are mounted on the roof and the battery system is installed indoors) as opposed to residential (1-4 kW) or utility (multi-MW) applications. Although batteries can be charged either by the PV array when PV output exceeds on-site requirements, or by the grid during off-peak hours for use during peak periods when rates are higher, only the latter case is considered in this appendix based on the data available. This data is from the first-of-a-kind-product.

As indicated in Figure 1, the system components include a "max power tracker", the battery subsystem, a power conditioning subsystem (PCS), switchgear and structural/mechanical items. The PV array consists of fixed PV modules that use large-area, solid-state semiconductor devices to convert sunlight into DC power. The PV subsystem is characterized elsewhere in this document.

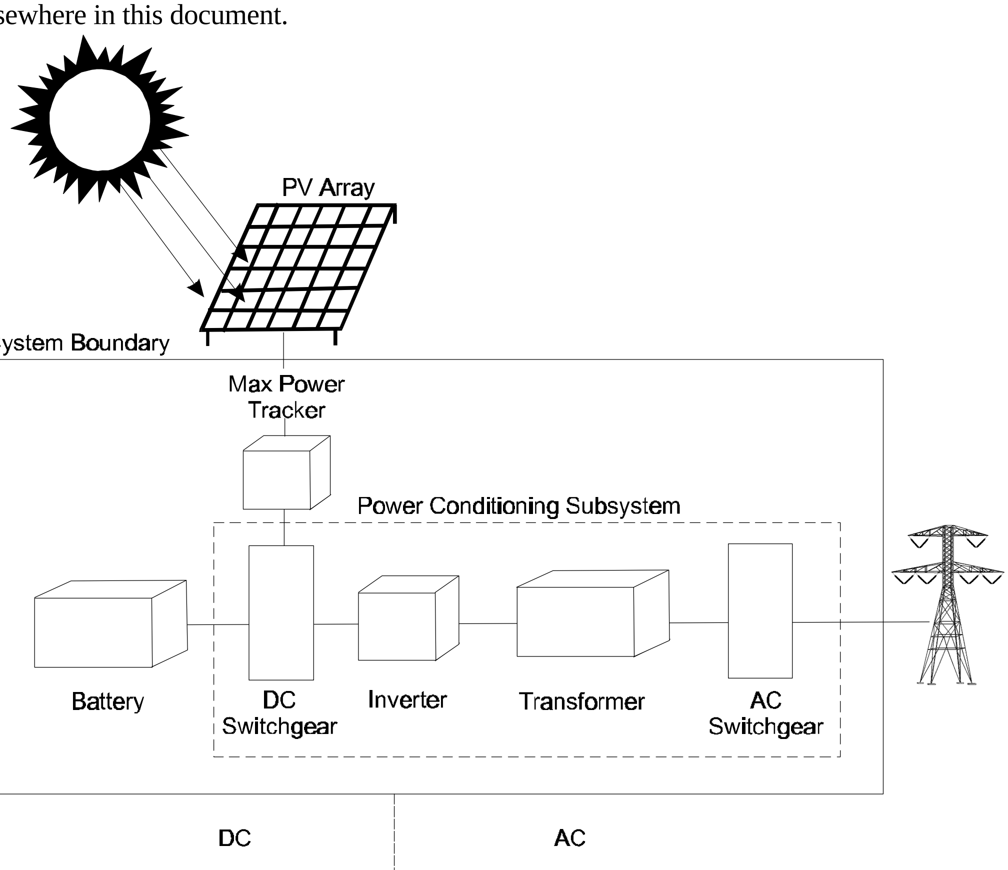


Figure 1. Battery storage system schematic.

## BATTERY STORAGE FOR SUPPLEMENTING RENEWABLE ENERGY SYSTEMS

Like PV cells, batteries are direct-current (DC) devices and are compatible with DC loads. Batteries not only store electrical energy -- in combination with a PCS, they can also enhance the quality of the power in the system. The battery can be discharged as required and therefore supply a variable electrical load. The PV array can then be designed to operate closer to its optimum power output [1].

Batteries are not specifically designed for PV systems. Most of the batteries used in current small PV systems were actually designed for use in deep-cycle electric vehicle or recreational vehicle applications where the recharge is carefully controlled and complete for every cycle. Insufficient battery recharge due to the diurnal limitations of PV output and poor charge control results in long periods of low state-of-charge which can be detrimental to some batteries, depending on design [2]. Lead-acid batteries are mostly used in integrated PV systems.

The PCS processes the electricity from the PV array and battery and makes it suitable for alternating-current (AC) loads. This includes (a) adjusting current and voltage to maximize power output, (b) converting DC power to AC power, (c) matching the converted AC electricity to a utility's AC electrical network, and (d) halting current flow from the system into the grid during utility outages to safeguard utility personnel. The conversion from DC to AC power in the PCS is achieved by an inverter, which is a set of electronic switches that change DC voltage from the solar array and/or battery to AC voltage in order to serve an AC load [1].

The PCS also maintains the DC voltage of the integrated PV system. It protects the batteries from excessive overcharge and discharge, either of which can cause permanent damage. The PCS usually includes a solid-state device, such as a blocking diode, that prevents current from flowing from the battery to the PV array and damaging it.

The max power tracker (also known as an auto power tracker) interfaces between the PV array and the storage system. Like the PCS, it also performs some power conditioning functions. It converts the DC energy from the PV array into a higher DC voltage to match the existing load or storage system. The max power tracker is needed in addition to the PCS to handle the voltage variability of the PV array and maximize its power output. The max power tracker monitors DC amperage and voltage from the PV array and employs an iterative method to match DC voltage of the PV array and the battery.

The key differences between the max power tracker and the PCS are:

| **Max Power Tracker** | **Power Conditioning System** |
|---|---|
| Single channel | Three channels |
| DC components exclusively | DC and AC components |
| Accommodate high-voltage and current | Accommodate lower voltage which is less costly |
| Dedicated to PV | Not technology-specific |

**Battery subsystem:** Most PV storage subsystems today consist of flooded lead-acid batteries. Improved valve-regulated lead-acid (VRLA) batteries are now emerging in utility systems. Advanced batteries (such as lithium ion and zinc/bromine) are being developed and are at different levels of size and readiness for utility operation. Other electric storage subsystems are addressed briefly in the Overview of Energy Storage Technologies, including flywheels, superconducting magnetic energy storage (SMES) and supercapacitors.

Batteries store chemical energy during electrical charging from a DC source, such as a PV array, or AC power from the electric grid can be converted to DC to charge the battery subsystem. For this technology characterization, it is assumed the battery is recharged from the grid during off-peak hours. The battery storage subsystem complements the PV array, whose output is delivered to a commercial building load.

Batteries are complex devices whose performance is a function of many variables, including rate and depth of charge and discharge, temperature, and previous operating history [3]. The basic building block of the battery module is the electrochemical cell. Cells are packaged together into modules which are connected in a matrix of parallel-series combinations to form a string. Lead-acid batteries consist of two-volt (at open circuit) cells which are connected in series and parallel arrays as needed to match the desired electrical characteristics of the application. Extremely high discharges (thousands of amperes) are possible, and batteries can be switched very rapidly between open circuit, charge, or discharge.

**Power Conditioning Subsystem:** The PCS rectifies AC line power to DC to charge the battery, and inverts the DC power back to AC during discharge. It controls the rate of discharge and the switching time of the system. The power switches in a PCS are typically either GTO (gate turn off) or the newer, more flexible IGBT (insulated gate bipolar transistor) semiconductors. IGBT semiconductors have fewer requirements for driver circuitry, making inverters more compact and modular. IGBTs are used to overcome problems of poor power factor and high current harmonics [4].

The PCS functionally acts as a combination rectifier and inverter and may include a transformer. When the battery is being charged, the converter behaves like a rectifier, changing the AC into DC. When the battery is being discharged (supplying power to the system), the converter operates as an inverter. In the rectifier mode, the converter controls the voltage across the battery or the charging current. The PCS converts AC voltage to DC by firing power semiconductors so that the voltage in each of the transformer windings sums to that needed to cause the desired charge current to flow into the battery [5].

Additional PCS components include switchgear, both AC and DC; transformers as needed for voltage matching and isolation; and a controller for operating the system and interfacing with the host supervisory system. The control system has three main functions: (a) the storage subsystem control monitors charge level, charge/discharge requirements, and related operations, (b) the PCS control monitors the utility power supply and switches the system on- and off-line, and (c) the facility control monitors temperature, ventilation, and lighting in the structure housing the battery.

**Balance of plant:** Structural and mechanical equipment such as the protective enclosure, heating/ventilation/air conditioning (HVAC), and maintenance/auxiliary devices are non-trivial parts of the balance of plant. Other balance-of-plant features and costs include the foundation, structure (if needed), siting and permits, electrical protection and safety equipment, metering equipment, data monitoring equipment, communications and control equipment, and project management and training.

## 2.0 System Application, Benefits, and Impacts

**Application:** This document describes the use of a battery storage system in conjunction with a PV system to avoid or reduce the purchase of more costly on-peak power. However, energy storage systems can also play a flexible, multi-function role in an electric supply network to manage resources effectively. Battery energy storage systems are used for a variety of applications, such as: power quality assurance, transmission and distribution (T&D) facility deferral, voltage regulation, spinning reserve, load leveling, peak shaving, and integration with renewable energy generation plants [6]. Battery systems appear to offer the most benefits for utilities when providing power management support (i.e., voltage regulation, spinning reserve, customer peak shaving, integration with renewables, and T&D facility deferral) and when responding to instant voltage spikes or sags and outages.

## BATTERY STORAGE FOR SUPPLEMENTING RENEWABLE ENERGY SYSTEMS

**Benefits:** Specific studies at electric utilities considering battery energy storage systems revealed a number of generation, T&D, and customer-based benefits that are generally site-specific [5,6]. A number of factors determine the benefits of installing energy storage systems, such as storage size, location, system load profiles, and load profiles at individual substations and T&D lines.

A few battery energy storage systems are currently being demonstrated, some with U.S. DOE Energy Storage Systems (ESS) Program funding. Crescent Electric Membership Cooperative (CEMC) has been using a 500 kW lead-acid battery energy storage system for peak shaving purposes since 1987. CEMC has been able to significantly reduce the demand charges paid to its generation and transmission cooperative, North Carolina Electric Membership Cooperative [7].

Niagara Mohawk funded an investigation into peak load reduction with PV and buffer battery storage. The utility and the Empire State Electric Energy Research Corporation installed a 13 kW (AC) PV system on an energy-efficient office building in Albany, NY in 1990. The PV system operated as designed, but because afternoon clouds were reducing the PV system's effect on peak demand somewhat, Niagara Mohawk added a 21 kW/1-hour battery storage system in July 1993 [8]. The PV/battery prototype had the two systems operate in parallel, with off-peak grid power used to recharge the battery. It acted as a "quasi-dispatchable" unit, protecting against local load excesses and, thus, guaranteeing T&D benefits [9].

The manufacturer has since improved on this PV/battery system, by creating a compact system that can be installed on rooftops. Delmarva Power & Light is testing these units to determine whether, after PV generation cuts back at 4 P.M., the battery can provide three more hours of output to help shave peak loads in the summer. The prototypes were installed July 1996-April 1997 [10]. The unit can be operated locally or remotely; the batteries are charged from the grid overnight. Delmarva has successfully obtained peak shaving benefits from their operation. This quantity of storage is being evaluated to determine if the benefits of multiple hours of storage capacity justify the additional costs.

EPRI, Sandia National Laboratories, and the Salt River Project electric utility installed a 2.4 kW PV array and 25.2 kWh battery in an experimental residence owned by the utility. The system was designed to discharge the PV generated electricity stored in the batteries to match specific three-hour peak loads. The PV/battery system has operated continually and reliably since its installation in August 1995. No repairs or homeowner involvement has been needed. The only maintenance performed was periodic watering of the battery cells and manually changing the dispatch schedule each season [11].

There are many examples of battery energy storage integrated with PV facilities at national parks and military installations. For example, Dangling Rope Marina on Lake Powell in Utah is the largest PV system ever installed at a national park. The Dangling Rope PV system replaced an existing diesel generator and consists of a 115 kW PV array, a 250 kW power conditioning unit and a 2.4 MWh battery bank. The Yuma Proving Ground in Arizona has a grid-tied 441 kW PV system with 5.6 MWh of lead-acid batteries. During the summer peak season, the system can deliver 825 kW to the grid to help reduce peak demand. The system can also operate stand-alone in the event of an extended outage.

A number of studies have examined the contribution of storage coupled with renewable generation [9-15]. A recent study examined the benefits and costs of installing an integrated MW-scale windfarm with battery storage to defer the upgrade of a 25 kV circuit to 69 kV for Orcas Power and Light Company. Although sufficient wind potential was identified, the high winds did not generally occur coincidentally with peak loads on the distribution line. A transportable 500 kW/2-hour battery was considered for use during low wind periods to defer the upgrade in the distribution line until the year 2000 [15]. The study concluded that extremely high winds and high utility costs appear to economically justify the addition of MW-scale windfarms and battery storage.

**Impacts:** There are no emissions, solid wastes, or effluent produced during the operation of PV/battery energy storage systems. Flooded lead-acid batteries are closed, and VRLA and advanced batteries are essentially sealed. Electrolyte leakage from batteries is a rare occurrence because each lead-acid cell is surrounded by a double container. In the rare event of a leak, the fluid is captured by a containment system, neutralized and cleaned up as a chemical spill. The volume of leakage is typically small as each cell contains little liquid and there is very low likelihood that a large number of cells would break open simultaneously.

When the battery subsystems are replaced, essentially all battery materials (e.g., lead, acid, plastic casing) are captured and recycled. According to the Battery Council International, 95% of all lead available in scrapped batteries was recycled on average during 1990-1995. Batteries used in stationary applications represent less than 4% of the total tonnage of lead available for recycling during that period [16].

## 3.0 Technology Assumptions and Issues

Currently, there are a variety of PV array materials and battery energy storage technologies in use and under development. This document assumes off-the-shelf silicon-based PV panels are used, although the specific choice is not an issue. PV technology descriptions are provided elsewhere.

### Battery Technologies

This appendix assumes that current R&D activities will lead to significant improvements in the cost and performance of battery storage systems. As these improvements take place, battery storage systems will compete with conventional sources of peak electric power generation, such as gas turbines, diesel generators, or uninterruptible power supply units. Flooded lead-acid and VRLA batteries are commercially available today, although not in designs wholly suited to utility applications. Zinc/bromine and lithium batteries are two advanced batteries under development. Each of these technologies has particular strengths and weaknesses.

**Lead-Acid Batteries:** Basically, flooded lead-acid battery technology for renewable energy storage systems is the large-scale application of a technology similar to that found in automobile batteries. Flooded lead-acid batteries are manufactured in large numbers for many uses and their operating characteristics and technology are well understood by manufacturers. However, they have several key limitations: (a) they require relatively frequent maintenance to replace water lost in operation, (b) they are relatively expensive compared to conventional options with limited reduction in cost expected, and (c) because of their use of lead, they are heavy, reducing their portability and increasing construction costs. The strengths of flooded lead-acid batteries center around their relatively long life span, durability, and the commercial availability of the technology. This allows flooded lead-acid battery customers to better justify their acquisitions and to amortize the cost of their systems over a longer period. Flooded lead-acid batteries are the most common batteries found in PV applications.

**VRLAs:** VRLAs use the same basic electrochemical technology as flooded lead-acid batteries, but these batteries are closed with a pressure regulating valve, so that they are essentially sealed. In addition, the acid electrolyte is immobilized. This eliminates the need to add water to the cells to keep the electrolyte functioning properly, or to mix the electrolyte to prevent stratification. The oxygen recombination and the valves of VRLAs prevent the venting of hydrogen and oxygen gases and the ingress of air into the cells. The battery subsystem may need to be replaced more frequently than with the flooded lead-acid battery, increasing the levelized cost of the system. The major advantages of VRLAs over flooded lead-acid cells are: a) the dramatic reduction in the maintenance that is necessary to keep the battery in operation, and b) the battery cells can be packaged more tightly because of the sealed construction and immobilized electrolyte, reducing the footprint and weight of the battery [17]. The disadvantages of VRLAs are that they are less robust than flooded lead-acid batteries, and they are more costly and shorter-lived. VRLAs are perceived as being maintenance-free and safe and have become popular for standby power supplies in telecommunications applications, and for uninterruptible power supplies in situations where special rooms cannot be set aside for the batteries [7].

**Advanced Batteries:** Among the advanced batteries which may support renewable energy applications is the zinc/bromine system. It uses a flowing aqueous zinc bromide electrolyte, with metallic zinc being deposited on the negative electrode, while the bromine produced at the positive is stored in external tanks. The advantages of zinc/bromine battery technology are low cost, modularity, transportability, low weight, and flexible operation. Because of the chemical nature of the reactants and room-temperature operating conditions, the casing and components can be constructed from low-cost and light-weight molded plastic and carbon materials. The major disadvantages of zinc/bromine batteries center around the maintenance requirements, including upkeep of pumps needed to circulate the electrolyte, and the somewhat lower electrical efficiency. Also, the zinc deposited during the charging process must be completely removed periodically [17].

Other advanced batteries include the lithium-ion and lithium-polymer batteries which operate at or near ambient temperatures and may become appropriate for renewable energy applications. Rechargeable lithium batteries have already been introduced into the market for consumer electronics and other portable equipment in small button and prismatic cylindrical sizes [3]. The advantages of lithium batteries include their high specific energy (four times that of lead-acid batteries) and charge retention. However, scaling up to the sizes, power levels and cycle life required for large applications remains an exacting challenge.

Technology development currently underway (with assistance from the DOE-SNL-ESS program among others) is expected to significantly improve the performance and reduce the operation and maintenance (O&M) costs of energy storage systems. Engineering development is proceeding on VRLA battery systems, which are nearly commercial, and advanced battery systems, which may be near-commercial within 10 years. Government and private industry are currently developing a variety of advanced batteries for electricity, transportation, and defense applications: lithium ion, lithium polymer, nickel metal hydride, sodium metal chloride, sodium sulfur, and zinc bromine. The large cost of development of these new technologies is being shared by many organizations world-wide.

**Battery Operation**

The life of a battery and its energy delivery capability are highly dependent on the manner in which it is operated. Many deep discharges (above 70-80%) reduce the life of lead-acid batteries. High rates of discharge reduce the energy delivery potential of lead-acid batteries. Batteries also have shelf-life limitations.

Poor charging practices are responsible for short battery life more than any other cause. A number of methods exist for charging batteries used in stationary utility applications. Optimum life and energy output from batteries, but not efficiency, are best achieved when depth of discharge (low, e.g., 40%) and time for recharge are predetermined and repetitive, a condition not always achievable in PV applications. Modified constant-potential charging is common for deep-cycling batteries and preferred for PV batteries designed for optimum life [3].

PV system manufacturers have incorporated battery storage into their off-grid installations for many years. Customers are beginning to request storage for grid-connected PV systems as well. The two systems have not been totally integrated; redundant PCS and balance of plant exist since both the PV modules and battery systems generally come with their own total package. The 1997 baseline system is derived from an existing 31 kW PV/21 kWh (40 minutes) flooded lead-acid battery system that is currently being demonstrated at five different utility sites. The systems are located in Newark and Wilmington, DE; Northeast, MD; Green Bay, WI; and Aberdeen, NC [10]. Although none of the sites have excellent solar insolation, there is good coincidence between peak solar generation and peak demand of the host facility.

For this technology characterization, we assume a 30 kW system with one hour of storage available in the initial year and all outyears. The system is based on one module of a larger, commercially available (250 kW) power management battery system comprised of eight equally-sized modules. The 1997 system cost, benefits, and performance presented in Section 4.0 are based upon batteries and power electronics that are near-commercial today.

### 4.0 Performance and Cost

Table 1 summarizes the performance and cost indicators for the storage portion of the system being characterized in this report.

### 4.1 Evolution Overview

The 1997 30 kW baseline system is based on a commercially-available 31 kW PV/flooded lead-acid battery system. The battery subsystem is assumed to improve and transition in technology type, changing from flooded lead-acid in 1997 and 2000 to VRLA beyond 2005. Advanced batteries are anticipated in 2020. These technology changes slow the cost reduction path for the battery subsystem. The PCS and max power tracker are expected to be integrated, so significant cost reductions are expected as modular design and factory-assembly become the norm and production volumes increase substantially. The balance of plant subsystems are expected to decline in cost as one-of-a-kind engineering and site-specific installations become less common.

### 4.2 Performance and Cost Discussion

The most productive hours of sunlight for PV systems are from 9 AM to 3 PM. Before and after these times, electricity is generated, but at much lower levels [8]. In addition, an afternoon thunderstorm will severely reduce local PV output before it will indirectly reduce the load by cooling ambient temperatures and suppressing solar heat gains. This has profound technical impacts that can negate some of the benefits associated with distributed, grid-connected PV. An hour of energy storage can alleviate this problem [9].

Table 1. Performance and cost indicators.

| INDICATOR NAME | UNITS | Base Case 1997 | +/- % | 2000 | +/- % | 2005 | +/- % | 2010 | +/- % | 2020 | +/- % | 2030 | +/- % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Plant Size | kW | 30 | | 30 | | 30 | | 30 | | 30 | | 30 | |
| Battery Subsystem | Type | Lead-acid | | Lead-acid | | VRLA | | VRLA | | Adv. Battery | | Adv. Battery | |
| Units Per Year | Each | 5 | | 50 | | 200 | | 200 | | 200 | | 200 | |
| Performance | | | | | | | | | | | | | |
| Battery Replacement | Years | 3 | | 5 | | 5 | | 10 | | 10 | | 10 | |
| AC-to-AC Efficiency | % | 76 | | 78 | | 78 | | 80 | | 80 | | 80 | |
| Discharge | kWh/day | 30 | | 30 | | 30 | | 30 | | 30 | | 30 | |
| Availability | % | 90 | | 90 | | 90 | | 90 | | 90 | | 90 | |
| Annual Energy Delivery | MWh | 2.7 | | 2.7 | | 2.7 | | 2.7 | | 2.7 | | 2.7 | |
| Energy Footprint | $kWh/m^2$ | 13 | | 13 | | 15 | | 15 | | 26 | | 26 | |
| Selling Price | | | | | | | | | | | | | |
| Battery | $/kW | 350 | | 200 | 10 | 300 | 15 | 275 | 20 | 300 | 30 | 275 | 30 |
| Power Conditioning | | 650 | | 600 | 10 | 550 | 15 | 500 | 20 | 400 | 30 | 300 | 30 |
| Max Power Tracker | | 700 | | 675 | 10 | 650 | 15 | 625 | 20 | 575 | 30 | 500 | 50 |
| Balance of Plant | | 350 | | 325 | 10 | 300 | 15 | 275 | 20 | 225 | 30 | 200 | 30 |
| Total Capital Requirement | | 2,050 | | 1,800 | | 1,800 | | 1,675 | | 1,500 | | 1,275 | |
| Unit Operations and Maintenance Cost | | | | | | | | | | | | | |
| Fixed Costs | $/kW | | | | | | | | | | | | |
| Cooling | | 18 | | 18 | | 18 | | 18 | | 18 | | 18 | |
| General Maintenance | | 33 | | 33 | | 25 | | 25 | | 17 | | 17 | |
| Variable Costs | ¢/kWh | | | | | | | | | | | | |
| Charging | (delivered) | 2.1 | | 2.0 | | 2.0 | | 2.0 | | 2.0 | | 2.0 | |
| Battery Replacement | | 52 | | 44 | | 67 | | 30 | | 33 | | 30 | |
| Operations and Maintenance Cost | | | | | | | | | | | | | |
| Fixed Costs | $/yr | | | | | | | | | | | | |
| Cooling | | 548 | | 548 | | 548 | | 548 | | 548 | | 548 | |
| General Maintenance | | 1,000 | | 1,000 | | 750 | | 750 | | 500 | | 500 | |
| Variable Costs | $/yr | | | | | | | | | | | | |
| Charging | | 56 | | 55 | | 55 | | 54 | | 54 | | 54 | |
| Battery Replacement | | 3,500 | | 1,200 | 10 | 1,800 | 15 | 825 | 20 | 900 | 30 | 825 | 30 |
| Annual Operating Costs | $/yr | 4,600 | | 2,800 | | 3,200 | | 2,200 | | 2,000 | | 1,900 | |

Notes:

1. The columns for "+/- %" refer to the uncertainty associated with a given estimate.
2. Battery system installation requires several hours.

# BATTERY STORAGE FOR SUPPLEMENTING RENEWABLE ENERGY SYSTEMS

## PV/Battery Sizing

There are different approaches to sizing batteries for PV applications. For stand-alone applications, some system developers have sized batteries to provide up to seven days of back-up. Examples include the following military installations:

- Navy facilities at China Lake (334 kW PV/3,500 kWh battery) and San Clemente Island (94 kW PV/2,500 kWh battery) in California
- Air Force facilities in Idaho (78 kW PV/700 kWh battery)
- Army training areas in Hawaii (5 kW PV/600 kWh battery)
- Marine tank target range in California (69 kW PV/2,000 kWh battery)

Sizing strategy for grid-connected PV installations depends on the uses of the system and the tariffs available from the local utility. For example, power quality applications require batteries sized to provide nearly instantaneous full-power discharges for only 15 minutes of back-up. A peak shaving application for a PV system may require the battery to boost the output of the array to meet peak loads for 1-2 hours a day. If the differential between peak and off-peak electric rates is not significant, then the battery can be sized for one hour of operation and the facility owner can purchase power from the grid when the PV array is not available. However, if the differential between peak and off-peak rates is significant, then an economic analysis should be undertaken to determine the optimum size of the battery system. For example, the 2.4 kW PV/25.2 kWh battery Salt River Project offered 17¢/kWh peak, 10¢/kWh shoulder, and 3¢/kWh off-peak experimental rates to the PV/battery demonstration it sponsored with EPRI and Sandia National Laboratories. The battery was sized to match the peak electric demand of the home (5 kW) or double the PV output (2.4 kW), in 3-hour load-shifting operations [11]. A number of PV developers optimize the PV installation, but not the battery system, opting for 7-10 hours of battery back-up power in the event of outages. In many cases, PV installations require only minimal battery back-up to add value to PV-generated electricity. If the transmission system is heavily loaded, batteries can store solar energy which would be lost during hours when transmission service is constrained, delivering the electricity later [14].

## Performance Indicators

The assumed economic life of the battery system is 30 years, requiring battery component replacements at appropriate intervals. The structure and power conditioning system are expected to last 30 years [18]. Battery replacement charges vary by the type of the battery and the number of years until replacement. One manufacturer claims that the type of flooded lead-acid batteries they use should be replaced every three years [25]. When VRLA batteries are used more widely for renewable applications in 2005, they initially are replaced at 5-year intervals, improving to 10-year intervals in 2010. Advanced batteries are assumed to require replacement once every 10 years when incorporated into the PV-battery system in 2020 [3,19]. This is an engineering estimate based on lifetime expectations for fundamental materials used in these battery systems and expectations for battery operation (charging and discharging).

The charging profile for the battery, which is pivotal in determining battery life, is controlled by the PCS for a grid-connected system. Continually undercharging a flooded lead-acid battery will cause it to sulfate, thereby greatly reducing battery life. Overcharging a VRLA battery at moderately high rates and above will cause it to dry out, thereby reducing its life. Thus, the design and operation of the PCS is a major determinant of the system life cycle costs [20].

Battery energy storage systems operate at an AC-to-AC efficiency of about 75%, and, therefore, consume some energy. However, storage systems can accumulate energy during periods when efficient base load or renewable generation are available, and discharge during peak load times, thereby reducing the use of less efficient peaking generators. AC-to-AC efficiency is the ratio of AC energy removed from a storage system to the AC energy used to charge the system. This efficiency measure includes all losses in the storage system from the battery, PCS, switchgear, etc. The AC-to-AC efficiency values are based on the existing performance of installed storage systems in the field. In the future, systems are expected to become more efficient through the use of improved storage devices and better power electronics. The storage device will become more efficient due to the use of improved technologies. The power electronics will be enhanced through improved high-power switches that reduce losses [21]. As shown in Table 1, AC-to-AC efficiency increases from 76% in 1997 to 80% in 2010 and there after.

The annual energy delivery is calculated from the unit size and estimated operating time. Battery energy storage systems are assumed to be available 90% of the time. Annual energy delivered is the projected amount from the utilization of energy storage systems operated on average one hour per day for 100 days/year at 90% availability [22]. Heavy-duty batteries of the type that should be used in solar plants can cycle daily up to 250 days per year [14].

The system energy footprint, measured in kWh/$m^2$, is an important characteristic of storage systems, many of which will be installed in facilities with fixed and/or small areas available. The example 1997 baseline system is very compact: 1.5 x 1.5 m deep (2.3 $m^2$) and 1.3 m high. The unit weighs 1,724 kg and can be located in service bay areas, warehouses or storerooms [4]. The projected improvements in unit energy footprint are attributable to the expected increases in the energy density for VRLA and certain advanced battery technologies. The energy density of the VRLA, for example, is 15% greater than that of flooded lead-acid, hence the 15% increase in energy footprint.

The construction period is expected to be two months for PV array set-up; battery storage can be installed in a day or less [10]. The PV array is the only subsystem needed to be erected; all other components are contained in the modular, factory-assembled housing.

**System Capital Costs**

The cost of an energy storage system is affected primarily by four drivers: (a) the initial cost of the storage subsystem, (b) the cost of the power converter, (c) the cost of the balance of system, and (d) the need to design, engineer, procure, and construct one-of-a-kind systems. The capacity of the plant as well as the discharging profile impact both capital and O&M costs. At present, flooded lead-acid batteries are the dominant choice for many utility applications. Flooded lead-acid batteries have been in widespread production and use for so long that further reductions in costs are unlikely [7]. Industry and government have been working to develop improved VRLA batteries and advanced batteries that offer potentially lower costs and longer cycle lives.

The 1997 cost estimates for the system are based on a turnkey price of $65,800 for the baseline/PV battery system in limited production (based on the manufacturer's estimate). Sandia National Laboratories calculated the component costs based on experience in the field and products already under development [18,19,21]. Estimates done for this study for the 2005-2030 time frame are best-judgement engineering estimates based on expected increases in production; potential reductions in the costs of batteries, PCS, and balance of plant; and greatly reduced engineering costs for modular, factory-integrated systems.

An annual production volume of 160 system units (compared to production of 5 in 1997) has been identified by one battery manufacturer as necessary for costs to decline by 50%. Since the lead-acid battery is a mature technology, automating production and assembly is assumed to result in cost reductions of at least 10-15% over the next five years [19]. It is anticipated that this device will have a stable niche market of about 200 units a year in 2005 and beyond.

The battery portion of the system will be available for $350/kW, with great potential for volume production savings. Sized for commercial use at 30 kW PV/30 kWh storage, the batteries account for less than 20% of the total cost of these systems. The introduction of VRLA technology in 2005 [19] will be about $300/kW. As advanced batteries enter the market in 2020, battery costs are estimated at $300/kW, with further reductions as production capability increases.

The PCS costs approximately $650/kW (based on the estimate of $65,800 for the entire system) and includes the converters, controls, AC/DC switchgear, filters, etc. According to a 1997 survey of manufacturers, PCS costs are expected to decrease by only 10% by 2000 since IGBT semiconductors are already in the design [19]. Subsequent reductions in PCS costs are substantial, bottoming out at $300/kW in 2030. This reduction is expected to be due to further integration of the functions of the max power tracker and PCS, new advances in switch components, replacement of magnetics with less expensive materials, and high volume production.

Several organizations are also investigating ways to reduce power converter costs by encouraging more productive and efficient manufacturing processes and the utilization of the latest advances in power conversion technology. Manufacturers and system integrators are working to reduce or eliminate the need for one-of-a-kind engineering in all aspects of PV and storage system implementation. Failures of inverters are the number one cause of PV system problems. Cooperative R&D contracts support the development of quieter, more reliable inverters that can be mass-produced for the PV industry.

The max power tracker is an expensive customized component in this system ($700/kW). One manufacturer sells 31 kW power trackers for $22,000 [4]. Improvement in the max power tracker depends on advances in the PV power electronics industry and in increased production volumes. Max power tracker costs are projected to decrease to $500/kW by 2030.

Balance of plant includes the facility to house the equipment, HVAC, the interface between the system and the utility, and the provision of services such as data gathering, project management, transportation, permitting, and financing. Balance of plant costs are low for this PV/storage system because compact design enables the entire system to be housed in a container. The balance of plant costs are reduced during the forecast period from $350/kW to $200/kW as lightweight, modular, factory-assembled systems become the norm [18,19,21].

**System O&M Costs**

Operation & maintenance costs consist of fixed and variable costs. Fixed costs include cooling and general maintenance at the site. Variable costs include recharging the batteries and periodically replacing the batteries. These O&M costs are presented as annual expenses in the prior table. The cooling charge is based on a power management system which consists of eight modules, each one of which is the same size as the system being characterized here [18]. The unit must be installed in an air-conditioned room [4], and thus, the parasitic load for the cooling fans is quite small at 1.25 kW. At a peak or shoulder rate of 5¢/kWh, the annual cost of the cooling load for the 30 kW system is $548. The general maintenance cost of $1,000/year is based on the experience of CEMC with a larger flooded lead-acid battery.

The recharging cost is calculated as the kW rating * discharge time * ( (1 - AC-to-AC efficiency) + 1) * off-peak ¢/kWh rate * 100 days/year. The 30 kW unit requires a 37.2 kWh charge (given 76% efficiency [4]), at a 1.5¢/kWh off-peak rate, costs $56 annually in 1997.

The cost of battery replacement is based on an expected battery life of three years. Thus, on average, the annual cost of battery replacement is one third the cost of the batteries. Expanded battery life increases to five years in 2000 and ten years in 2010 and later, so replacement costs improve accordingly.

## 5.0 Land, Water, and Critical Materials Requirements

There are no water requirements for PV-battery energy storage systems. Land requirements are insignificant for the battery system which occupies less than 2.3 $m^2$.

The 1997 baseline system contains a lead-acid battery; 50% of the system weight (excluding the PV array) is lead. Battery system weight will decrease significantly when the advanced battery subsystem is introduced in 2020.

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