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Lead–acid battery energy-storage systems for electricity supply networks

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Abstract

This paper examines the development of lead–acid battery energy-storage systems (BESSs) for utility applications in terms of their design, purpose, benefits and performance. For the most part, the information is derived from published reports and presentations at conferences. Many of the systems are familiar within the energy-storage community; others have appeared in numerous tabulations of such systems, but little is known about them beyond the basic descriptive parameters such as energy and power ratings. As a consequence, some are simply cited without comment while others are described in appreciable detail. It is found that a progression in the maturity and applications of battery energy-storage is evident in these systems. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Lead–acid batteries; Valve-regulated; Energy storage; Peak-shaving; Spinning reserve; Power quality

1. Introduction

From a historical perspective, small battery energy-storage systems (BESSs) were relatively prevalent at the turn of the 20th century when low-voltage, dc distribution of electrical power in small, densely populated areas was the common practice. The emergence and maturing of ac systems allowed the transmission and distribution of high-voltage electrical power, which enabled delivery of more electricity over ever-larger areas and redefined upward the meaning of utility-scale. These circumstances tended to limit the wide spread growth of BESS. More recently, beginning in the 1980s, several factors have led to a renewed interest in BESSs. These factors include: (i) the evolution of power electronic systems capable of rapidly and seamlessly transferring high-quality electrical power between ac and dc power systems; (ii) the concurrent emergence of electrical loads that both contribute to and are relatively intolerant of power-line anomalies. A BESS with the former capabilities can be used to mitigate a host of ac power distribution issues that arise from the latter power-line anomalies.

Since the early 1980s, large BESSs have been increasingly placed in routine, daily service to the benefit of either a host electrical utility or consumers with large, sensitive, critical electrical loads. These BESSs have served numerous purposes, which include rapid (spinning) reserve, load leveling, peak shaving, voltage–frequency stabilization, volt–ampere reactive (VAR) control, and facility upgrade deferrals (many of these terms are defined in Section 3). These encompass a host of interventions such as the economic dispatch of stored energy and power quality and power reliability enhancements. In these roles, BESSs are enormously valuable, but they are also expensive. On the basis of a benefit-to-cost ratio, however, present trends favor greater numbers of utility-scale BESSs in the future. (The term ‘utility-scale’ used herein refers to relatively large BESSs with minimum power and energy ratings of hundreds of kW and kWh.) The battery and power electronics technologies are increasingly capable, and the need for reliable, high-quality electrical power is increasingly urgent.

The objective of this paper is to review historical (dating from the early 1980s), existing, and planned utility-scale lead–acid BESSs. A summary is given of large BESSs that have been described in the literature and for which some descriptive information is available. Unfortunately, the extent of this information varies dramatically — some systems are defined by the most basic of parameters, i.e. energy and power capacities, and others are described in much detail with the inclusion of performance data. The systems are classified as first generation, transitional or second generation BESSs. Although it cannot be asserted that the BESSs under discussion constitute an exhaustive list, it is thought to be reasonably complete and certainly representative.

2. Other options for utility-scale storage of electricity

In addition to lead–acid batteries, there are other energy storage technologies which are suitable for utility-scale applications. These include other batteries (e.g. redox-flow,

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sodium–sulfur, zinc–bromine), electromechanical flywheels, superconducting magnetic energy storage (SMES), supercapacitors, pumped-hydroelectric (hydro) energy storage, and compressed-air energy storage (CAES). Among these, hydro and CAES typically differ significantly in scale (capacity) and response time from others. Whereas hydro is a mature technology, CAES is much less mature (there are perhaps only two examples in operation). Both are capable of high-power discharges of hours duration, but their response times from a standby status are longer (min) than those of other storage technologies. If hydro and CAES are to function as rapid (spinning) reserve or in other power quality roles, they must do so as a 'spinning' resource rather than as a standby or reserve resource, which is an operational mode that continuously depletes the store of energy. Hydro and CAES require special geologic formations for implementation, i.e. upper and lower reservoirs for hydro, and aquifers or salt caverns for CAES. Although this restriction can be circumvented in some instances, there are likely to be some compromises, e.g. in capacity, environmental impact, and/or costs. In general, hydro and CAES are more suitable for bulk, large-scale storage applications where response time is not an issue.

Batteries, SMES, flywheels, and supercapacitors have rapid response capabilities (<5 ms) and are therefore well suited for power–quality-related responses. From a power capacity perspective, they can be ranked, in descending order, as follows: batteries, SMES, flywheels, capacitors. From an energy capacity perspective, the descending-order ranking would be batteries (hours duration), flywheels, capacitors, SMES (seconds to minutes duration). These rankings are not absolute and are subject to change because the technologies are still at an evolutionary stage. Among these latter four storage technologies, flooded lead–acid batteries are the most mature, and are followed closely by valve-regulated lead–acid (VRLA) batteries. Although VRLA batteries are still the subject of much research and development, they are compiling an enviable record of performance in some utility-scale BESSs. SMES systems have performed well in a dozen or so demonstration installations and some are operating in permanent installations.

3. Applications of energy storage

There are many applications for electrical energy storage in large-scale systems. These have been described in numerous publications that often used descriptive but somewhat imprecise terminology. In 1999, Sandia National Laboratories (SNL) published a study that categorized, defined and summarized the requirements for electrical energy-storage systems [1]. Contributors to that study included an appreciable number of experts on energy-storage systems and the results are summarized in this section. High-value, utility-scale applications for energy-storage systems are defined below and are categorized as either generation, transmission and distribution (T&D), or customer service applications. BESSs are suitable for, and have been applied in each of these applications. More recent BESSs, however, typically serve multiple applications.

3.1. Rapid reserve (generation)

This is generation capacity that a utility holds in reserve to prevent interruption in the service to customers in the event of a failure of an operating generation station [1]. This application is frequently referred to as 'spinning reserve'. Before the advent of rapid-response energy-storage systems (e.g. BESSs), generation meeting this requirement had to be 'spinning' and available when the demand occurred. Typically, BESSs meeting this requirement detect the onset of an anomaly in the power supply and respond within about one-quarter of a 60 Hz cycle (i.e. 4.2 ms).

3.2. Area control and frequency responsive reserve (generation)

This is the ability for grid-connected utilities to prevent unplanned transfers of power between themselves and neighboring utilities (area control), and the ability of isolated utilities to instantaneously respond to frequency deviations (frequency responsive reserve) [1]. Interconnected utilities must operate at the same frequency ('frequency control'), and power transfers between them if one begins to deviate. The remedy is for the offending utility to generate additional power. (Transfers of power among utilities can, however, be planned for and accommodated.) In the case of an isolated utility, e.g. an island utility, frequency deviations are the first indication of insufficient generation (excessive load). Remedies are either additional generation, perhaps from a BESS, or load shedding.

3.3. Commodity storage (generation)

This refers to the storage of inexpensive off-peak power for (economic) dispatch during relatively expensive on-peak hours [1]. From the generation perspective, commodity storage can also encompasses 'systems management' applications such as 'load leveling' (energy–cost savings), 'peak shaving' (demand–cost savings) and 'generation capacity deferral' [2].

3.4. Transmission system stability (T&D)

This is the ability to keep all components on a transmission line in synchronization with each other and thus prevent system collapse [1].

3.5. Transmission voltage regulation (T&D)

This refers to the ability to maintain the voltages at the generation and load ends of a transmission line within 5% of each other [1]. It encompasses supplying watts, and perhaps VARs, at selected locations to meet load demands. In dc systems, voltage (V) and current (A) are in-phase ($\mathrm{VAR} = 0$) and power is defined as the product of voltage and current. In ac systems, voltage and current are not necessarily in-phase, i.e. current can either lead or lag the voltage. When viewed as a phasor diagram, power (W) is the in-phase component of volt–ampere and reactive power (VAR) is the quadrature component of volt–amperes.

3.6. Transmission facility deferral (T&D)

This refers to the ability of a utility to postpone installation of new transmission lines and transformers by supplementing the existing facilities with another resource [1], e.g. a BESS. In this application, BESSs function as fast-response sources of generation at selected locations.

3.7. Distribution facility deferral (T&D)

This refers to the ability of a utility to postpone installation of new distribution lines and transformers by supplementing the existing facilities with another resource [1], e.g. a BESS. This application differs from transmission facility deferral only in that the storage resource is utilized along a distribution line rather that a transmission line.

3.8. Renewable energy management (customer service)

This refers to energy-storage applications through which renewable energy is made available during periods of peak utility demand (coincident peak) and available at a consistent level or rate [1].

3.9. Customer energy management (customer service)

This refers to the dispatch of energy stored during off-peak or low-cost time periods to manage demand on utility-sourced power [1]. This also encompasses ‘peak shaving’ and ‘load leveling’ (see Section 3.3), but from a customer perspective.

3.10. Power quality and reliability (customer service)

This refers to the use of energy storage to prevent voltage spikes, voltage sags, and power outages that last for a few cycles (>1 s to minutes) from causing data and production loss for customers with demands of less than 1 MW [1]. (In practice, there are BESSs that meet these requirements for demands much greater that 1 MW, e.g. the BESS at Vernon (see Section 4).)

4. Battery energy-storage systems

Many, probably most, of the recent (since 1980), utility-scale BESSs are presented in Table 1. For each BESS, details are given of the location, rated capacity, principle applications, and the date of installation. The more familiar systems, i.e. those for which descriptive information is reasonable available, are discussed individually in subsequent paragraphs. In recent years, the lead–acid battery, energy-storage and related industries have often been involved in acquisitions and other corporate structure changes that have resulted in name changes. The following discussion uses names that were appropriate when these BESSs came to public attention.

4.1. Elektrizitätswerk, Hammermuehle, Germany

Hammermuehle is a small electric energy distributor with a single customer that accounts for about 70% of its total load. It purchases over 99% of its energy from a bulk power supplier and produces the remaining 1% through hydroelectric generation. The 400 kW, 400 kWh BESS was used for peak shaving and the attendant reduction in demand charges. After 20 years of service (since 1980), this BESS was shut down in 2000 when the battery reached the end of its service life. The battery was not replaced and the BESS returned to service because the current utility rate structure reduced the potential for realizing cost savings. The system is of particular interest because of its longevity.

The battery consisted of 114, tubular-positive cells, each with a $C/4$ capacity of 3200 Ah. In 1993, and again in 1995, the battery was capacity tested and exhibited a $C/4$ capacity of 98.8 and 94.8%, respectively. Thus, after 15 years of service, the battery appeared to be in very good condition and was expected to provide several additional years of peak-shaving service. Its longevity was likely due to the fact that the total energy throughput was relatively low, e.g. approximately 384 cycles after 12 years of operation [3].

4.2. BEWAG AG, Berlin, Germany

The BEWAG BESS facility was installed in 1986 to provide spinning reserve and frequency regulation for the isolated, ‘island’ utility which served West Berlin. When placed in service, it was the largest lead–acid BESS in the world. It functioned for 7 years, from the beginning of 1987 to 1993. In December of 1993, BEWAG was connected to the West European grid; this resolved the frequency deviation problem. Subsequently, the BESS continued to provide a spinning reserve until the end of the battery’s service life, an additional 2 years. The battery’s 9-year service life (1987 through most of 1995) was remarkably successful with virtually no problems. During the 7-year period that it provided both frequency regulation and spinning reserve, the battery had a capacity or turnover of about 7000 times its nominal 14 MWh energy capacity, i.e. about 98 GWh.

The BEWAG battery consisted of 12 parallel strings, each with 590 cells (7080 cells). The cells were configured in 1416 modules, five cells per module. Each cell had a capacity of 1000 Ah at the $C/5$ rate; thus, the nominal

Table 1
Historic, operating and pending BESSs

BESS	Location	System capacity[a]	Applications[a]	Date[b]
Elektrizitätswerk	Hammermuehle, Germany	400 kW, 400 kWh	Peak shaving	1980
BEWAG AG	Berlin, Germany	17 MW, 14 MWh	Frequency control Spinning reserve	1986
Kansai Power Co.	Tatsurni, Japan	1 MW, 4 MWh	Multipurpose demonstration	1986
Hagen Batterie AG	Soest, Germany	500 kW,7 MWh	Load leveling	1986
Crescent EMC	Statesville, NC, USA	500 kW, 500 kWh	Peak shaving	1987
Delco Remy Division, GM	Muncie, IN, USA	300 kW, 600 kWh	Peak shaving	1987
SCE	Chino, CA, USA	10 MW, 40 MWh	Multipurpose demonstration	1988
Vaal Reefs Exploration and Mining Co.	South Africa	4 MW, 7 MWh	Peak shaving Emergency power	1989
Johnson Controls, Inc.	Humboldt Foundry, Milwaukee, WI, USA	300 kW, 600 kWh	Peak shaving Load leveling	1989
SDG&E	San Diego, CA, USA	200 kW, 400 kWh	Peak shaving	1992
PG&E (PM250)	San Ramon, CA, USA	250 kW, 167 kWh	Power management	1993
PREPA	San Juan, Puerto Rico	20 MW, 14 MWh	Spinning reserve Frequency control Voltage regulation	1994
GNB Technologies	Vernon, CA, USA	3.5 MW, 3.5 MWh 2.45 MW, 4.9 MWh 1.8 MW, 5.5 MWh	Peak shaving Spinning reserve Environmental	1996
MP&L	Metlakatla, AK, USA	1.3 MW, 1.3 MWh 915 kW, 1.83 MWh 700 kW, 2.1 MWh	Utility stabilization Power quality Environmental	1997
PQ2000	Hornerville, GA (first commercial)	2 MW, 10 s	Power quality Standby power	1997
Golden Valley	Golden Valley, AK, USA	40 MW, 14 MWh	Spinning reserve Voltage regulation Frequency control	Pending

[a] Multiple entries under system capacity and applications for a BESS do not imply a correspondence between side-by-side entries.

[b] It is not always clear whether the reported date is for completion or commissioning of the BESS. Most are thought to be the commissioning dates. The discussions that follow are more definitive about the dates of events, when possible.

battery capacity was 12,000 Ah or about 14 MWh (at 1180 V). The cells were made by Hagen and used flooded, copper-stretch-metal (CSM) technology which featured enhanced negative-plate conductivity [4]. The battery was connected to a 30 kV distribution line via four paralleled converters. When providing frequency control, the converters were programmed to limit power flow to 8.5 MW. When providing spinning reserve, the power limit was increased to supply 17 MW [5].

4.3. Hagen Batterie AG, Soest, Germany

This 500 kW, 7 MWh BESS was placed in service at a Hagen industrial battery plant in Soest in 1986 to reduce energy cost by lowering the energy demand and attendant demand charges via peak-shaving. The system was well instrumented and computer controlled such that utility-supplied power could be limited to a selected value. If the load exceeded the selected limit, the BESS supplied the excess demand. When the load demand fell below the selected limit, the system functioned to recharge the battery while continuing to limit the utility demand to the selected value. Typically, the battery began the week in a full state-of-charge (SOC). Each weekday, load demand would exceed the selected power limit, and the battery would supply the additional demand. When the load demand decreased below the selected utility-power limit, utility power was used to recharge the battery, but within the constraint of the utility-power limit. Thus, there was a daily, weekday cycle that would typically, but not necessarily, recharge the battery, but not always to a full SOC. Each weekend, when the load demand was typically low, the system would fully recharge the battery to 100% SOC. The computer control tracked the SOC of the battery and would, perhaps, alter the utility-power limit to prevent excessive battery discharges and, thus, optimize the performance of the system. Hagen used the BESS to maximize the energy purchased during off-peak periods and minimize the energy purchased during on-peak hours, to achieve appreciable savings in energy costs.

The 7 MWh battery consisted of two parallel strings, each with 200 cells with an individual capacity of 9000 Ah. The cells had tubular positive plates and copper negative grids (which suggest that they are Hagen CSM technology cells [4]). An electrolyte agitation system prevented, or limited, acid stratification. The 400 V battery connected to a 380 V bus within the plant via two parallel, 250 kW converters [5].

4.4. Crescent Electric Membership Corporation (EMC), Statesville, NC, USA

Crescent EMC has used this 500 kW, 500 kWh BESS as a peak-shaving facility since July 1987 to reduce demand charges paid to their supplying utility, Duke Energy. There were two interruptions early on due to converter malfunctions. Subsequently, it has performed to expectations. This BESS was originally installed for test purposes at the Battery Energy Storage Test (BEST) facility in New Jersey and underwent some cycling there, perhaps the equivalent of 200 cycles. At Crescent, it is cycled to reduce Crescent's demand whenever there is a possibility that Duke Energy will experience their monthly peak load. The peak load establishes Crescent's (and other EMC's) demand–charge rate for that entire month. Thus, the BESS system is typically discharged 1 h (at 500 kW) on selected cold winter mornings and 3 h (at 200 kW) on selected hot summer afternoons, i.e. periods likely to correspond to Duke Energy's monthly peak. This strategy does not necessarily require daily discharges. For example, an exceptionally cold winter morning early in the month followed by days with mild temperatures can provide a respite, days when one can be confident that Duke Energy's load will not surpass the earlier monthly peak. On hot summer days, Duke Energy's peak-load is not as predictable and a 3 h discharge is selected to enhance the likelihood that Crescent will reduce their demand during Duke Energy's monthly peak load. (The purchasing and rate setting process is somewhat more complex than described herein. EMCs in North Carolina purchase power through a statewide organization, but it is Duke Energy's monthly peak that establishes the demand–charge rate.) In the spring and fall, the peak-load can occur in mornings or afternoons, and predicting the peak-load hour is more difficult. The net result of this strategy is that the Crescent BESS is discharged about 100 times annually.

The battery consists of a single string of 324 cells with six cells per module. These are flooded, deep-cycle cells with lead–antimony grids and are manufactured by GNB Inc. The cells are rated at 500, 300 and 200 kW at the *C*/1, *C*/2 and *C*/3 rates, respectively. When the battery was transferred to Crescent, its measured capacity was in excess of 2200 Ah. It was warranted at that time for 2000 cycles, or 8 years, and has far exceeded that expectation. (Note, in October 1998, Crescent EMC and Davidson EMC merged to become UnitedEnergy EMC. Nevertheless, the BESS has long been identified with Crescent, is recognized by this name and, consequently, the practice is continued here).

The converter is a 12-pulse, line-commutated system rated at 500 kW with a three-phase, 480 V ac output. When charging the battery, current is initially limited to about 475 A. Subsequently, charging continues at a nominal, constant 755 V dc until current decreases to 30 A. At this point, a separate float charger continues the charging process. At full charge, the float current is about 3 A. Once fully charged, the battery remains on float charge for 48 h unless interrupted for a discharge cycle. If the fully charged battery is inactive for 2 weeks, the float charge for 48 h is repeated [6].

After 14 years of service at Crescent, the BESS continues its peak-shaving duty although the battery capacity is somewhat diminished. Crescent EMC is uncertain as to the number of battery cycles that has been performed. The automated system functions so routinely that Crescent tends 'to forget it is there'.

4.5. Southern California Edison (SCE), Chino, CA, USA

The Chino BESS is, to date, the largest BESS ever assembled. It was built at SCE's Chino 230/69/12.5 kV substation, about 80 km east of Los Angeles. The project was initiated in August 1986, and the 10 MW, 40 MWh facility became operational in July 1988. SCE initiated the project, and the Electric Power Research Institute and the International Lead Zinc Research Organization participated by supplying the power conditioning system and the lead for the batteries, respectively. The BESS was developed as a multi-purpose demonstration project and was used in a host of applications during its 9 years as an experimental facility. It was decommissioned in 1997 when planned experimentation and demonstrations had been completed. The batteries were subsequently recycled. The following BESS capabilities were demonstrated: peak shaving, load leveling, load following, spinning reserve, T&D facilities deferrals, frequency control (see below), voltage and VAR control, and black-start operations. The output of the BESS fed a 12.5 kV Chino distribution line which, in turn, fed a 69 kV line at the 230 kV substation. The interconnecting 69/12.5 kV transformer operated at near rated capacity during peak hours at the time. In the early stages of service, a 2-year test period established the following round-trip (ac to ac) efficiencies: plant (BESS) efficiency, 72%; battery efficiency, 81%; and power-conditioner efficiency, 97%.

A somewhat unusual test project at Chino demonstrated the capacity of the BESS to damp low frequency oscillations which can affect the stability and limit the capacity of long transmission lines. SCE is part of the Western States Coordinating Council (WSCC), which consists of 14 western US states, British Columbia and part of northwestern Mexico. These regions are interconnected by a large power transmission system (the 'big O ring') that is generally heavily loaded (SCE imports about 40% of its power from the northwest and Arizona). Low frequency oscillations (0.3–0.7 Hz) limited the power that could be transmitted through this system. Traditional power system stabilizers damp these oscillations by changing reactive power (VAR) output. The Chino BESS provided low-frequency damping and enhanced system stability by modulating its power output. The effectiveness of this service was restricted, however, by the limited power output of the BESS (10 MW).

The battery consisted of 8256 cells (six cells per module) configured in eight paralleled strings of 1032 cells each. The nominal battery voltage rating was 2000 V. The cells were Exide, GL-35 cells and featured compressed-air electrolyte agitation, flame arrestors, acid sampling tubes, thermocouple wells, stibine-arsine traps, and acid-level indicators. The cell capacity was 2600 Ah at the *C*/4 rate to 80% depth-of-discharge. The battery rating is nominally 40 MWh. Cycle-life was warranted to be a minimum of 2000 cycles, which translated to a life of about 8 years.

The power conditioner was an 18-pulse, stepped-wave, voltage-sourced, gate-turn-off thyristor (GTO) converter which was capable of four-quadrant operation (i.e. bi-directional and VAR capable) and was manufactured by General Electric (GE). It was configured with three six-pulse converters connected in series on the ac side and in parallel on the dc side. It was rated 10 MW with a 1750–2800 V dc input window. A monitoring and control system produced by Westinghouse provided highly automated supervisory control and data acquisition [7,8].

4.6. Johnson Controls, Inc., Milwaukee, WI, USA

This 300 kW, 600 kWh BESS was developed by Johnson Controls as a turn-key, customer-side-of-the-meter demonstration project. It was placed in service at an in-house brass foundry with a base load of about 1.1 MW with four or five daily peaks to 1.5–1.6 MW. The peak loads corresponded to the melt cycles of two, inductively heated furnaces that were operated at the foundry. The BESS was used for peak shaving and energy-usage redistribution. In the former service, the BESS reduced daily peak-demand charges. In the latter service, however, the associated cost savings were a more complex issue. Johnson Controls employed a control strategy, the prevailing rate structure and on-peak charging, while still avoiding the higher peaks which corresponded to the furnace melt cycles, to converge to an optimum battery capacity. Thus, the peak demands of the foundry were reduced and the battery capacity was less than the capacity requirement when using off-peak charging. The net result also produced savings in energy costs. The battery depth-of-discharge was limited to 80%. Of necessity, the operation of this BESS required an interactive, 'smart' controller.

The battery was assembled from VRLA modules of a gelled-electrolyte design which had excellent deep-discharge capabilities. The 6 V, 180 Ah modules were assembled in parallel to produce 6 V, 1500 Ah units. The modules had lead-coated copper terminals and bus-bars, a status indicator that warned if the SOC dropped below 20%, and an internal air manifold for thermal management. The facility contained 64 modules connected in series to produce a 384 V, 1500 Ah battery.

The power conditioning system was a self-commutated, dual-bridge, six-pulse design. The ac output was three-phase, 480 V ac. The BESS typically operated in a constant power output mode. Charging of the battery was conducted initially at constant power and then finished at constant voltage [9].

4.7. Puerto Rico Electric Power Authority (PREPA)

In November 1994, a 20 MW, 14 MWh BESS began commercial operation at PREPA, an isolated island utility. The system provided spinning reserve, frequency control, and voltage regulation. The successes of the Chino and BEWAG BESSs influenced the decision to build the PREPA BESS, and with the closure of the Chino facility, it became the largest in the world. In October 1999, the BESS ceased operation because of numerous cell failures. Nevertheless, because the BESS was otherwise successful and was highly valued by the system operators during its 5 years of service, PREPA intends to replace the battery, using different cells, and return the BESS to service in 2001. Subsequently, PREPA plans to begin construction of a similar BESS in the period 2002–2003.

It is reasonable to consider the PREPA facility to be a transitional system between two generations of BESSs. It is a large system selected by a public utility as the 'best' solution to a costly operating problem, i.e. insufficient spinning reserve and an attendant necessity to resort to load shedding to maintain system stability. The specifications and design were intended to meet the requirements of a commercial plant. No incentive funds or apparatus were involved in its construction. For the most part, it featured proven technology and equipment, and it provided a valuable benefit. Except for the premature cell failures, perhaps an anomaly, the PREPA BESS exhibits evidence of technological maturity. It was built as the first of several units that will eventually provide up to 100 MW of spinning reserve to the PREPA system.

PREPA is the only electric utility serving the island of Puerto Rico. Its generation capacity is about 4.4 GW, which is produced at five power plants from distillate and residual fuel oil and distributed over about 3600 km of transmission lines. Like many 'island' utilities, the generation facilities of PREPA could not respond rapidly enough to system anomalies to prevent frequency instabilities. Consequently, the operators had to resort to automatic load shedding (reduce load by temporarily ceasing to serve some customers, i.e. rolling blackouts), a practice that affected all classes of customers and threatened the industry and commerce of the island. By contrast, the PREPA BESS responds almost instantly to such anomalies and minimizes load shedding.

The initial battery consisted of 6000 flooded cells arranged in six parallel strings of 1000 cells each. The rated cell capacities were 1280, 1680 and 2088 Ah at the *C*/0.5, *C*/1 and *C*/3 rates, respectively. The cells had the following features: flat, wrapped positive plates; flat negative plates; lead–calcium grids; automatic watering and air-lift electrolyte agitation. The power condition system was comprised of two paralleled converters, which were manufactured by GE. Each converter was rated at 10 MVA and had three, six-pulse GTO bridges (18-pulses) and a capacitor bank for harmonic filtering [10]. It is likely that this power conditioner will be retained in the refurbished BESS.

4.8. GNB Technologies, Vernon, CA, USA

The BESS at the GNB lead smelting and recycling center in Vernon is foremost an uninterruptable power supply (UPS) that serves an essential purpose at an environmentally sensitive facility. The recycling center is located about 16 km southeast of downtown Los Angeles, and it recycles about 10 million lead–acid batteries annually. A critically important part of the process is a recovery facility that prevents the escape of lead dust to the environment, which otherwise would be unacceptable both environmentally and economically. The area around the plant is closely monitored and the owner, GNB, is likely to face penalties and punitive fines in the event of a single lead-emissions episode. The BESS also has sufficient capacity to be used daily in a peak-shaving role to reduce the power demand and the attendant demand charges of the center.

Construction on the Vernon BESS began in January 1995 and commissioning tests were completed in November 1995. The BESS took up its UPS role in January 1996. In April 1996, the BESS also began operating periodically, 3–6 h daily, in a peak-shaving role to reduce the demand charges. By design, the BESS is depleted of about 50% of its capacity when peak shaving and the remaining 50% capacity is held in reserve for the UPS role, i.e. to continue plant operations in the event of a power outage.

Like PREPA, this BESS was built as a reasonable, cost-effective solution to an urgent problem. Unlike PREPA, the Vernon BESS was built as a turnkey facility by an established, credible, industrial alliance (GNB–GE) which, apparently, will quote, build, and warrant large-scale BESS facilities in the future. These circumstances are indicative of an increasing commercial maturity of BESSs. The Vernon BESS is a demand-side facility and provides an essential benefit on the consumer-side of the revenue meter.

The Vernon lead-recycling center is powered via a three-phase, 4.16 kV feeder from the local utility. The total plant load is typically about 3.5 MVA, but it can peak to maximum of 5 MVA. The critical loads, i.e. the loads that prevent lead-dust emissions, are about 2.1 MVA. Because of the utility energy-supply configuration, i.e. the critical loads are not isolated, the BESS is designed to carry the entire plant. In the event of an outage or other supply anomalies, the BESS will open the utility supply and carry the entire plant at up to 5 MVA for up to 10 s. During that period, it will shed all but the critical loads and then carry these at up to 3 MVA for about 1 h. Only about 20 min are needed for an orderly, emissions-free shutdown of the critical loads. Subsequently, the BESS will either initiate an orderly, controlled plant shutdown or, if utility excitation returns, will synchronize with the utility and transition back to normal power. All of these operations can occur automatically. In its peak-shaving role, the BESS battery, by design, has an additional reserve capacity to supply 500 kW for 3 h or 1.5 MWh.

The battery consists of two parallel strings of GNB Absolyte IIP, type 100A99 VRLA modules of the absorptive glass-mat (AGM) design. These are configured as three parallel cells per module (5000 Ah) with 378 modules per series string to give a nominal battery voltage of 756 V. The capacity is 3.5, 4.9 and 5.5 MWh at the *C*/1, *C*/2 and *C*/3 rates, respectively.

The GE power-conditioning system consists of paired, six-pulse converters which form a 12-pulse converter module, and three of these are paralleled to achieve the required power rating. The switches are GTO thyristors. The power conditioner incorporates harmonic filtering and provides for four-quadrant operation (i.e. it is bi-directional and provides VAR control) [11,12].

4.9. Metlakatla Power and Light, AK, USA

Metlakatla is a small community on Annette Island, which is located about 40 km from Ketchikan, Alaska. The island is relatively inaccessible, especially in the winter, and is usually reached by boat or float airplane. Metlakatla Power and Light (MP&L), a small, isolated utility, supplies the electricity needs of the island. The MP&L load consisted of the Metlakatla community, several relatively small commercial loads and, until recently, a large sawmill. The load peaked at about 3.5 MW, and the sawmill load, which was about one-third of the total, varied dramatically. The resources of MP&L consist of about 4.0 MVA of hydroelectric generation and a large, 5.0 MVA/3.3 MW diesel generator. Typically, the hydroelectric units could supply the load, but they could not respond rapidly enough to follow load fluctuations. As a consequence, MP&L operated the diesel generator, which was oversized to provide an adequate load-following rate, at about 1.0 MW to provide a suitable power dynamic range. Thus, the diesel supplied much of the required energy even though the hydro reservoirs frequently had to spill water. Moreover, the diesel operation was less efficient and required more maintenance than would have been the case with more favorable loading. Transporting and storing fuel for the diesel and the threat of fuel spills were also issues of concern, especially during the long Alaskan winters.

Studies showed that a BESS on the MP&L system could: (i) help stabilize and improve the power quality of the system, i.e. reduce voltage and frequency deviations; (ii) reduce reliance on the diesel generator, and thus realize an attendant savings in fuel-related costs. Subsequently, the GNB–GE alliance provided a suitable, 1.6 MVA (10 s)/ 1.0 MW (continuous) BESS which was interconnected at a 12.47 kV substation. Construction began in April 1996, was completed in December 1996, and the BESS has been operational since 3 February 1997. It provides a rapid (spinning) reserve, i.e. supplies instantaneous power when demand exceeds generation, and it accepts charge when there is excess power available from the hydroelectric generators. In this role, the BESS battery operates for long periods in a partial SOC. By design, it tends to oscillate or 'dither' between about 70 and 90% SOC, and equalization charges are scheduled only semi-annually. Moreover, the diesel generator typically stands idle for long periods of time.

The Metlakatla battery consists of a single string of GNB, Absolyte IIP, model 100A75 modules of the AGM design of VRLA technology. Each module consists of three paralleled cells, and 378 modules are connected in series to form the 756 V battery. The modules have capacities of 3600 and 2000 Ah at the *C*/8 and *C*/1.5 discharge rates, respectively. The battery is rated at 1.4, 1.8 and 2.1 MWh at the *C*/1, *C*/2 and *C*/3 rates, respectively. The battery has performed remarkably well. In September 2000, it was reported [13] that the total battery output had been 745,735 Ah or the equivalent of 295 cycles to 80% of the *C*/8 capacity, and the total charge returned was 751,468 Ah, which corresponds to only 0.77% overcharge.

In October 1999, GNB and SNL conducted a planned assessment of the battery. Four cells were removed for evaluation with the BESS monitoring system indicating that the battery was at about 78 to 81% SOC. The measured open-circuit voltages of the cells indicated they were at approximately 78.5% SOC. One cell was maintained in this status for subsequent chemical analysis, while others were subjected to a series of cycling tests, which included a range of discharge rates, overcharging and equalization charging. The results of these tests were very encouraging and suggested that the cells had not been harmed by operating at a partial SOC for extended periods. Subsequent physical and chemical examinations of the electrodes, active materials and other internal components of the cells were also encouraging. In summary, there were no anomalies, no sign of oxidation corrosion, positive grid corrosion was lower than expected and there were no indicators of early degradation. It was concluded that the battery will exceed its projected design lifetime in this application. The battery is warranted for 8 years.

The GE power conditioning system is based on GTO thyristor technology and features rapid (4.2 ms) response, bi-directional four-quadrant operation (charge, discharge and VAR capable), 12-pulse wave-form (low distortion), and is self-commutating. It is rated at 1.6 MVA peak (10 s) and at 1 MW continuous power [13].

The sawmill on Annette Island ceased operation around June 2000 because of concern for the loss of trees. However, the Metlakatla BESS remains in operation and is serving the same purposes, i.e. stabilizing an isolated, island utility. It is reasonable to assume that the BESS battery will last even longer than anticipated and at the end of its life will be replaced with a smaller battery.

4.10. PQ2000

The PQ2000 is a BESS designed to meet the growing market demand for high-quality, reliable power for industrial and utility applications. It is primarily a rapid or 'spinning' reserve resource that temporarily substitutes for the utility supply in the event of a power-line anomaly and, subsequently, returns the load to utility service excitation when the service returns to normal. Its capacity is scaleable, in 250 kVA increments, up to 2 MVA and 10 s duration. This capacity was selected because it can protect a load from a majority of anomalies that defined the Computer and Business Equipment Manufacturers' Association (CBEMA) profile. (Note, the CBEMA profile is a historic plot of episodes of voltage deviations from normal that resulted in computer equipment failures versus their duration. These data create a profile of voltage anomalies likely to disrupt the microprocessor- or computer-controlled equipment. Recent studies have indicated that 95% of all power problems occur when the power is disrupted for 5 s or less [14].) In the event of an extended outage, steps would need to be taken to effect an orderly shutdown of the load or, alternatively, to transfer to a standby generator. It is notable that the developers of the PQ2000 (SNL, USDOE, AC Battery, Ominion Power Engineering Corporation, Electric Power Research Institute (EPRI), Pacific Gas and Electric (PG&E), and Oglethorpe Power Corporation) were recognized for its development with a 1997 R&D 100 Award from R&D magazine [15].

The PQ2000 was designed as a modular BESS. It is housed in three containers that can be transported on a lowboy, flatbed trailer without requiring special permits and can be pad-mounted in an outdoor setting. The three containers house the PQ2000 module, the static switch (i.e. the interface module) and the isolation transformer. The PQ2000 module, which houses the battery modules and power conditioners, features a roof-mounted ventilating and air-conditioning system for temperature control, and its modularity is designed to simplify maintenance. The PQ2000 is factory assembled and tested prior to transporting to an installation site.

Modularity is taken a step further in that the battery is configured with up to eight, 250 kW battery modules. Each of the modules contains its own inverter and charger, and each contains 48, 12 V batteries (nominally 576 V). When configured with a full complement of eight, 250 kW battery modules, there are 384, 12 V batteries in the PQ2000 unit. The full-scale PQ2000 switches from standby to full operation in about one-quarter of a 60 Hz cycle (4.2 ms) and can supply 2 MW/2 MVA for 10 s. When the utility supply normalizes, load excitation is transferred back to the utility supply. If the disturbance is due to a utility distribution-line recloser operation, for example, the entire PQ2000 cycle will be completed in about 3 s. (Note, utilities use reclosers to momentarily open a feeder-line in the event of a fault on the line. Typically, the recloser is programmed to cycle about three times before it latches opens and requires operator intervention.)

The batteries are Delco, model 1150, 12 V units. These are flooded, maintenance-free batteries, and Delco produces more than 400,000 annually. In the PQ2000 application, they are typically subjected to many, very shallow discharges and quickly recharged using a proprietary algorithm. The power conditioning inverters, one 250 kVA unit for each 250 kW battery module, feature insulated gate bipolar transistor (IGBT) switching technology. The utility interface is three-phase, 480 V ac [14].

The PQ2000 is commercially available. The first commercial installation was at a lithography plant in Homerville, GA. That plant is served by the Slash Pine EMC, which, in turn, is supplied by Oglethorpe Power Corporation. The lithography plant was fed via a long transmission line in a region that experiences numerous lightening strikes, and the resulting power line disturbances plagued the plant's operations. This PQ2000 has been in service since about 1996. Since installation of the facility, downtime and spoilage have been reduced, productivity has increased and efficiency has improved. There have been many additional installations in a host of other locations.

There are two transportable versions of the PQ2000. An EPRI version, the TBESS, is a significantly modified version, which is nominally designed to provide 250 kW for about 40 min. An SNL version, the Transportable PQ2000, is essentially the PQ2000 permanently mounted and interconnected on a lowboy trailer, which can be coupled to a tractor and readily transported to most locations. The trailer remains with the PQ2000, and transportation to a different location involves disconnecting the wiring and coupling to a tractor. The SNL version was initially located in a Virginia Power Facility in Richmond for about 2 years. Currently, it is located at a facility at the S&C Electric Company in Chicago.

4.11. Golden Valley Electric Association, AK, USA

The Golden Valley Electric Association (GVEA) is one of several electric utility cooperatives that make up the Alaskan Railbelt system. The Railbelt defines a relatively narrow corridor that extends from just north of Fairbanks in the north to the coast south of Anchorage. It consists of three main areas, referred to as the southern, central and northern areas. Each area has its own load centers and generation facilities and are interconnected via radial, 138 kV transmission lines that run from Healy (central area) to Fairbanks in the north (300 km) and from Healy to Anchorage in the south (170 km). This small and low inertia system is susceptible to minor system disturbances, which result in voltage and frequency fluctuations that constrain the capacity of the system.

GVEA is planning the addition of a second transmission line from Healy to Fairbanks and also the installation of a 40 MW, 14 MWh BESS, which will greatly enhance the stability of the entire system and minimize load shedding. Specifications for the BESS were issued in November 1999 and bids were received in February 2000. Subsequently, vendors were asked to revise their proposals and these are currently being evaluated. An award, which was anticipated in the Fall of 2000, is still pending [16].

5. Cost considerations

Perhaps the best available cost estimates for the BESSs discussed in this paper are documented in two Sandia reports [17,18]. These data, categorized in a standardized format, were requested from the appropriate utilities and suppliers. Because some suppliers were reluctant to reveal the detailed costs and wished to maintain a degree of confidentiality, the costs were aggregated into three categories: the storage subsystem; power-conversion subsystem (PCS); and the

Table 2
Costs of BESSs[a,b]

BESS	Capacities	Cost of Subsystems			Total costs		
		Storage	PCS	BOP (%)	US$ (kW)$^{-1}$	US$ (kWh)$^{-1}$	USK$
Crescent[c]	500 kW, 500 kWh	41%, US$ 518 (kWh)$^{-1}$	40%, US$ 506 (kW)$^{-1}$	19	1272	1272	636
Chino[d]	10 MW, 40 kWh	44%, US$ 201 (kWh)$^{-1}$	14%, US$ 258 (kW)$^{-1}$	42	1823	456	18.234
SDG&E[e]	200 kW, 400 kWh	16%, US$ 658 (kWh)$^{-1}$	23%, US$ 1855 (kW)$^{-1}$	61	8150	4075	1630
PREPA[f]	20 MW, 14 MWh	22%, US$ 341 (kWh)$^{-1}$	27%, US$ 294 (kW)$^{-1}$	51	1102	1574	22042
Vernon	3 MW, 4.5 MWh	32%, US$ 305 (kWh)$^{-1}$	19%, US$ 275 (kW)$^{-1}$	49	1416	944	4250
MP&L	1 MW, 1.2 MWh	–	–	–	–	–	1200
PQ2000[g]	2 MW, 10 s	9%	65%, US$ 316 (kW)$^{-1}$	26	495	–	899

[a] These data is taken from Sandia reports [16,17]. Additional cost details for Crescent, Chino, SDG&E, PREPA and Vernon are included in Appendix C of [16].

[b] Costs are in constant 1995 US$.

[c] Crescent BOP cost is exclusively the cost of a building (US$ 81,000) to house the BESS, the only cost incurred by Crescent.

[d] Chino BOP cost includes US$ 150,000 for load interface, US$ 3.8 million for facility, and US$ 1.7 million for the services.

[e] The SDG&E BESS was a demonstration project that was over-engineered in many respects.

[f] PREPA is comparable to Chino, but was built 6 years later. The PREPA PCS is an improved version of the Chino PCS, and both were built by GE. BOP cost includes US$ 600,000 for load interface, US$ 1 million for finance charges, US$ 4.7 million for building the facility, and US$ 1.8 million for the services.

[g] The high discharge rate of the PQ2000 distorts the battery cost when specified in US$ kWh^{-1}. The PCS cost include the converter and the static switch. The BOP cost includes delivery, installation and start-up. Commercial maturity and economy of the scale may have reduced the total cost below the given value.

balance-of-plant (BOP). Some of the data were supplied in a percentage form and are discussed here.

Cost estimates for prototype, one-of-a-kind systems such as most of the BESSs considered in this paper are often estimates that are not well documented. Demonstration projects, e.g. may be funded by multiple sources and the cost estimates assembled somewhat after the fact. Peripheral costs such as site preparations, permitting, installations, etc. are sometimes overlooked. In other instances, unique circumstances not likely to reoccur, can result in cost estimates that are not realistic. On the other hand, experience gained from similar systems (e.g. Vernon and Metlakatla) and especially systems that are replicated (e.g. the PQ2000) will eventually benefit from the economies of familiarity and scale. As a consequence, the costs listed in Table 2 should be taken only as estimates.

6. Conclusions

The 16 BESSs, from 1980 to the present day, are listed in Table 1. These systems encompass a wide range of capacities and a multitude of applications. They also reflect the maturing of BESS technology. Of the 10 systems, dating from 1980 to 1992, two are multipurpose demonstrations systems (Chino and Kansai Power). Three of these 10 systems were operated by supply-side interest (Chino, Kansai Power and BEWAG), and remaining seven by demand-side interest (including distributing utilities Crescent and Hammermuehle). Nine of the 10 systems list a subset of multipurpose demonstration, peak shaving and load leveling as applications. Only BEWAG, an ‘island’ utility, lists spinning reserve and frequency control as applications; these are typical, often urgent needs for such isolated utilities. The San Diego Gas and Electric (SDG&E) BESS provided peak shaving for a specific load, a light-rail transportation system. This BESS too, was a demonstration system and featured more recent technologies, e.g. VRLA (gel) battery modules and IGBT technology power conditioning. It demonstrated the technical viability of peak shaving the demand of the light-rail system, but it was not economically viable (at least partly because economic viability was not the original goal) and was shut down after a 2-year demonstration period. Crescent has benefited from the peak shaving of its BESS, but the facility was acquired under somewhat unique economic circumstances that are not likely to be available again.

The PG&E system is also somewhat unique in that the PM250 was a prototype, power management system and, perhaps, the forerunner of the PQ2000. PG&E was also a test site for the subsequent PQ2000 prototype.

The PREPA BESS can be viewed as a transitional system. The applications are those characteristic of isolated or island utilities (note the similarities with BEWAG) and do not include peak shaving or load leveling. Its benefits have been highly valued by PREPA and, in spite of problems with the battery, it is anticipated that the BESS will be returned to service with new batteries. This is evidence of both economic and technical justification.

The BESSs at Vernon and Metlakatla, and the PQ2000 can be viewed as second-generation systems, or at least more mature systems. They are much smaller than BEWAG, Chino and PREPA, and they tend to serve multiple, demand-side, power-quality related purposes. All three were produced by entities who assumed responsibility for the entire system, quoted a price, warranted system performance and delivered a turnkey product. The Vernon BESS provides spinning reserve, which initially continues the uninterrupted operation of the entire plant in the event of a power outage or disruption. Subsequently, if necessary, the Vernon BESS will continue to power critical and environmentally-sensitive loads until the outage or disruption goes away or a controlled shutdown is completed. Peak shaving at the Vernon site is a secondary application undertaken because the BESS has adequate capacity to provide an added benefit via peak shaving without compromising its primary purpose.

A final comment about the Vernon BESS is in the order. In response to the rolling blackouts now plaguing California, the Los Angeles Department of Water and Power (DWP) recently initiated a 5-year effort to help its largest customers lower the costs by installing energy-storage systems. Participating customers are eligible for an incentive of US\$ 400 kWh^{-1} of demand reduced from on-peak hours. Additionally, DWP will provide up to US\$ 10,000 for engineering services and half the actual cost of commissioning [19]. The Vernon BESS and similar systems elsewhere on the DWP system should be eligible to benefit from this initiative.

Metlakatla is another small, island utility in need of spinning reserve for utility stabilization and power quality purposes. There are also environmental issues involved, i.e. fuel delivery and the stand down of a diesel generator that would otherwise operate under difficult and inadvisable circumstances.

The PQ2000 is a commercially available BESS. Following its commercial introduction at Homerville, many additional units have been sold and placed in service. This is evidence of commercial maturity and economic viability. Note that its primary application is standby power (spinning reserve) for interventions in the interest of assuring power quality. In one sense, it is an industrial-scale UPS.

The cost data presented in Table 2 are interesting, but comparisons are difficult. Most of these systems are one-of-kind systems built for demonstration purposes and, in some instances, costs may have been a secondary issue. Chino and PREPA were large systems assembled from individual components. PREPA is the more expensive but was built 6 years later. The costs on a dollar per kW and per kWh basis reflect the differences in their respective capacities. PREPA’s BOP costs were much higher. Taking capacities into consideration, the SDG&E BESS was very expensive, perhaps unnecessarily so. The Metlakatla and Vernon systems differ in capacities, but are similar in many ways, e.g. similar components and built by the same entity. The costs of the Metlakatla BESS may reflect an economy based on experience and familiarity. The PQ2000 differs dramatically from the others; its future costs will likely reflect its growing market and commercial status.

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