Energy Storage (I): Using Electricity More Efficiently

"What do you do when the wind dies down?" asks a widely shown television commercial as the inhabitants of a windmill-powered house are left with a suddenly darkened home. One answer not suggested in the commercial might be: Store the energy generated while the wind is blowing for use when it is not.

Energy storage is becoming increasingly important for utilities that face fluctuating demands for power. And solving storage problems is the key to wider use of electrically powered vehicles and intermittent energy sources, such as the sun and wind. There is no shortage of ideas for energy storage, but most storage technologies are in an early stage of development and will not be ready for use in the near term.

Probably the largest existing need for energy storage is related to the way electrical power is generated and consumed. The demand for electrical power depends on the time of day, on the day of the week, and on the season of the year. On a hot and humid summer day in the eastern half of the United States, for example, the peak power demand can be more than twice the minimum demand on the same day, and the trend is toward ever larger costs of peak power relative to the base load. Utilities companies meet this quasi-periodic fluctuation in the demand for power by generating power in three different ways. That part of the total power needed throughout the day, namely, the base load, is generated by large steam turbines powered by fossil fuels, by water turbines (hydroelectric power), and, increasingly, by nuclear-powered steam turbines. The power consumed only during the daylight hours (intermediate power) is generated by older and smaller units powered by fossil fuels. In times of exceptional or peak demand for power, additional steam units or gas turbines are used for the short time they are needed. Brownouts or worse result when even these power generating units are insufficient to meet the peak demand. There is also a reserve capability (spinning reserve) to provide power system stability in the event of power fluctuations (transients).

If electrical energy could be generated during times of low demand (at night, for example) and stored for later use during times of high demand, there could be two beneficial results, points out Fritz Kalhammer of the Electric Power Research Institute, Palo Alto, California. Now, when we have only marginal ability to satisfy peak power demands, storage units could effectively increase the capacity of the power system with energy generated in off-peak hours. In the future, when presumably there will be a sufficiency of generating capacity, storage units could enhance the overall economics of the power plant by allowing the larger and more efficient steam base load units to account for more of the total power generated than is possible in the absence of energy storage. Such a benefit would be especially important if nuclear power generation became widespread. (One utilities' spokesman termed energy storage "the handmaiden of nuclear power.") Primarily because of the high capital cost of nuclear power plants, the economic benefits are realized only when the plants are operated at as high an output as possible. Energy storage could also reduce the requirement for increasingly expensive fossil fuels used for intermediate power generators by coupling storage with nuclear generation. A further benefit for utilities would be that energy storage could form part of the utilities system's spinning reserve, if the stored energy can be delivered at sufficiently high rates.

Pumped Storage Economical

The only economical mode of storage now available to utilities is pumped hydroelectric storage. Pumped hydroelectric storage operates like the hydroelectric power generation common in the northwestern part of the United States, except that the water to operate the turbines must first be pumped uphill (by means of electricity generated during off-peak hours) and stored in a reservoir before it can be used to generate power during periods of high demand. This method of storage is only about 66 percent efficient; that is, it takes 3 watt-hours of energy (1 watt-hour equals 3600 joules) to pump the water to the upper reservoir for 2 watt-hours of energy generated when the water runs back to the lower reservoir. However, the cost of electricity generated in this way is often less than if additional gas turbines or older, fossil-fueled steam turbines were used to meet peak demands.

The first pumped hydroelectric storage facility in the United States was built in western Connecticut in the 1930's and had a power capacity of about 32 megawatts. Now several much larger plants are in operation or are planned. The largest (nearly 1,900 megawatts maximum power and 15,000 megawatt-hours of stored energy) is operated jointly by the Consumers Power Company and Detroit Edison Company at Luddington, Michigan (Fig. 1). The Luddington plant uses Lake Michigan as the lower reservoir, while the upper reservoir is a man-made lake more than 3 kilometers long and nearly 1.5 kilometers wide. The plant was 10 years in the planning stage and it took 4½ years more to complete construction, at a cost of more than $340 million.

While pumped hydroelectric storage is an attractive concept, it is not without its difficulties. There are only a limited number of sites for storage facilities with the elevation difference needed for large storage capacities. Thus pumped hydroelectric storage is not a viable concept for many parts of the country. Even where sites are available, local opposition is often considerable, the objections pointing toward interference with aquatic life and otherwise spoiling the natural environment. The Consolidated Edison plan for a 2000-megawatt pumped hydroelectric storage plant (the Storm King project) on the Hudson River near Cornwall, New York, had been successfully blocked for 10 years by environmentalists, and contracts to begin construction have only recently been signed. Pumped hydroelectric storage facilities are often far from the areas they serve, thus necessitating long-distance power transmission lines, which are becoming more and more costly. Finally, the large size, the long lead time for planning and construction, and the high capital cost involve an inherent inflexibility and inability to respond to changing needs, according to some critics.

A number of new storage technologies that may be more widely applicable than pumped hydroelectric storage are being developed. One such energy storage technique is compressed air storage. In a normal gas turbine, fuel is mixed with air compressed in the compressor stage and combusted to generate mechanical power. About two thirds of the power produced by the turbine is needed to run the compres-

Fig. 1. The upper reservoir of the pumped hydroelectric storage plant near Luddington, Michigan. The reservoir embankment is 110 meters above Lake Michigan (upper right). The reservoir holds up to 102 million cubic meters of water.

sor. In compressed air storage, however, the compressor and the turbine stages can be alternately connected and disconnected from the motor-generator unit. Thus, in off-peak hours when the demand for power is low, the turbine stage can be disengaged, and electrical energy from a base load unit can be used to run the compressor stage with the result that the air is compressed and then pumped into an underground cavern and stored. During hours of peak demand, the compressed air can be used in the combustion stage to run the turbine. All the turbine power can be used for generation of electricity, because the air is already compressed. A considerably enhanced power output per unit of fuel consumed by the turbines results.

The compressed air storage method has some disadvantages. The gas turbines are powered by No. 2 fuel oil, and suitable sites must be found. Although some disagree, many energy storage investigators regard the economics of compressed air storage as unfavorable unless suitable natural caverns can be used. Excavation is considered too expensive. Researchers at United Aircraft Research Laboratories, East Hartford, Connecticut, however, believe that specially mined caverns can enable higher operating efficiencies and overall lower capital costs than is possible with natural caverns. In some cases a water reservoir might be used to maintain a constant pressure in the cavern. Since the air may be compressed to 40 atmospheres, the cavern would have to be more than 300 meters deep. The size of the reservoir would be less than 15 percent of that of an equivalent pumped hydroelectric storage facility.

Although the basic technology exists for compressed air storage, a hard engineering study, beyond exploratory design studies, has yet to be made in the United States. Nor has a demonstration facility yet been built, although Stal-Laval, a Swedish turbine manufacturer, reportedly is much closer to such a plant than anyone in the United States (*1*).

If only because the largest part of the research dollar for energy storage is spent on them, storage batteries may be one of the likeliest energy storage technologies to reach fruition. But so far no battery exists whose performance and costs are adequate to compete with either pumped hydroelectric storage or gas turbines (*2*). If they could be perfected, observers point out, storage batteries would have some desirable features that are absent in pumped hydroelectric storage. Batteries would have minimal siting problems. They make no noise, emit no pollutants, and, being modular in nature, would be rapidly assembled in factories in any desired size. Batteries can also be placed much closer to the power load as compared to pumped hydroelectric facilities, thus reducing the load on power transmission lines.

Although there is no fixed performance goal to be met, it is believed that a battery that delivered a specific energy of 220 watt-hours per kilogram, a specific power of 55 watts per kilogram, a lifetime of 4 years, a cycle life of 1000 (the number of charges and discharges), and a storage efficiency of 70 percent would be attractive for utilities (*3*). A 100–megawatt-hour storage facility, a substation size, made of such batteries might occupy a cube 8 meters on a side.

The lead-acid battery is used to start automobiles and to power industrial and recreational vehicles. In its present state of development, however, the lead-acid battery is not designed for electrical energy storage for utilities. In particular, lead-acid batteries cannot sustain the cycling between fully charged and discharged states which would occur in utility storage facilities. Thus they would have a short life and most investigators discount the use of lead-acid batteries except in circumstances where the high cost of specifically designed heavy-duty batteries can be tolerated. However, scientists at Westinghouse Research Laboratories, Pittsburgh, Pennsylvania, believe economical lead-acid batteries for storage can be developed. And the Atomic Energy Commission is planning a demonstration storage facility that will, at least initially, use lead-acid batteries.

High temperature batteries (that is, batteries that must be heated to a few hundred degrees Celsius in order to operate) promise improved performance, lower cost, and good prospects for the availability of the required raw materials. The two high temperature batteries receiving the most attention are the lithium-sulfur and the sodium-sulfur batteries (*4*). Of the two, the sodium-sulfur battery is thought to be in a somewhat more advanced stage of development, although there is general agreement that it will be 10 years before any high temperature battery is widely available. The earliest work on the sodium-sulfur battery was done at the Ford Motor Company, Dearborn, Michigan, but several laboratories in the United States, England, France, and Japan are now developing them also.

A sodium-sulfur cell operates from

300° to 350°C with molten sodium and sulfur electrodes. The unique feature of these cells is the electrolyte, which is a solid ceramic material called beta alumina ($Na_2O \cdot 11Al_2O_3$). The beta alumina electrolyte is fabricated by proprietary hot pressing and sintering techniques. The high operating temperature is necessary to achieve an appreciable sodium ion conductivity of the electrolyte. The ceramic electrolyte permits a simplicity of design because the electrolyte can also be a container and separator of the electrodes and because its properties prevent battery self-discharge. The beta alumina tends to crack during recharging at a high rate, however, which shortens the battery life. Although on their guard about releasing specific figures, scientists say that the performance of individual cells is approaching that desired for storage applications. Still to be accomplished, however, is the fabrication of individual cells into multicelled, long-lived batteries that can be hermetically sealed. (In the laboratory, cells are often operated in inert atmospheres, but are not sealed.) Identification of component materials that are inexpensive, yet corrosion-resistant, is also required.

Lithium-sulfur batteries differ from sodium-sulfur in that their electrolyte is a molten salt (such as a lithium chloride–potassium chloride eutectic mixture) (Fig. 2). They operate at a slightly higher temperature (375° to 400°C) and theoretically have a higher performance capability. The leading proponent of lithium-sulfur cells has been the Atomic Energy Commission's Argonne National Laboratory, Argonne, Illinois, although there is also ongoing research on these cells in other U.S. laboratories, in England, and in the U.S.S.R. Problems with lithium-sulfur batteries include containment of the electrodes, corrosion, and sealing the high temperature cells.

A battery that does not require high temperatures is being developed at Energy Development Associates, Madison Heights, Michigan. In this battery, the electrodes are zinc and chlorine, and the electrolyte is a zinc chloride solution. The unique feature of this battery is that the chlorine evolved during charging of the battery is stored in a solid chlorine hydrate ($Cl_2 \cdot 6H_2O$), so that the chlorine gas is not a problem. Researchers at Energy Development Associates expect to have a prototype battery in operation within 2 years.

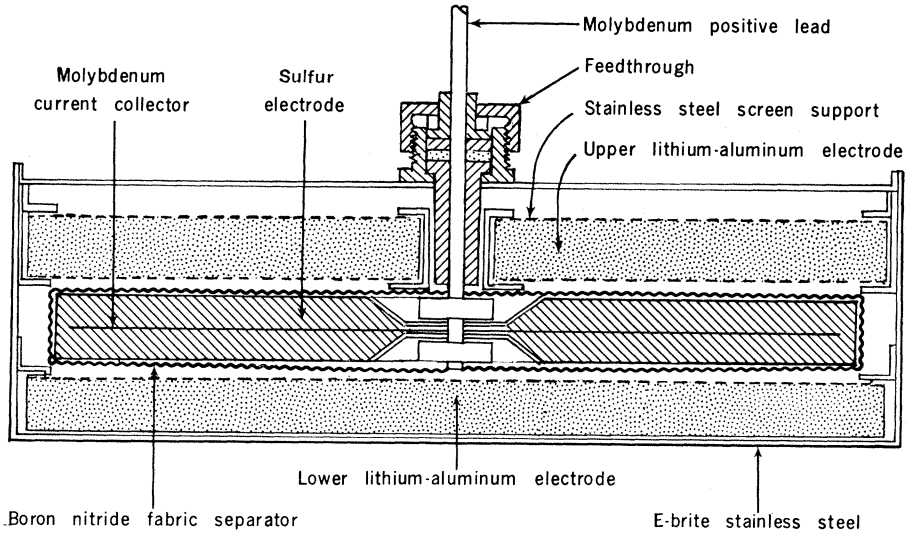

Fig. 2. Diagram of a lithium-sulfur cell. Full-sized cells might be from 12 to 15 centimeters across and 1.6 centimeters high when used in automotive power plants. [Source: Paul Nelson, Argonne National Laboratory]

Vehicles, including cars and buses, also have an energy storage problem. Up to now, this has been solved by carrying energy in the form of liquid fuels, such as gasoline or diesel oil. Although the performance (acceleration, speed, load, range, and refueling convenience) of liquid-fueled vehicles will be hard to match, air pollution resulting from internal combustion engine emissions and the prospect of a decreased availability of fuel (and that at a high price) has stimulated interest in other ways to store energy for vehicles.

Electric vehicles powered by storage batteries could be one solution, but, as with storage for utility load leveling, there is still no adequate battery for powering automobiles. At present, the lead-acid battery is inadequate because of its short lifetime, its weight, and its cost. (Lead-acid battery-powered vans are now being tested by the U.S. Postal Service; and, in Great Britain, a full-sized bus using lead-acid batteries will soon be in operation.) Many of the batteries suitable for load leveling could also power conventional automobiles, provided that the specific power achievable could be increased to 220 watts per kilogram from the lower specific power projected for batteries used in load leveling (*2*). Several hours would still be required each night for recharging the vehicle. Even if batteries with a specific energy of 220 watt-hours per kilogram cannot be achieved, availability of batteries with specific energies of 50 to 100 watt-hours per kilogram would make practical electric vehicles of two to five times greater range than present vehicles powered by lead-acid batteries. This capability would cover a large part of the present use of cars, especially for urban and suburban driving, say proponents of electric vehicles.

Most observers agree that it is much harder to build a good battery to power an automobile than to store power for utilities. So far, the Electricity Council Research Center in England has produced a sodium-sulfur battery to power a van (but the performance is still less than optimum). Scientists at Energy Development Associates have produced a laboratory zinc-chlorine battery to power an experimental 2-ton vehicle. However, this battery could not be recharged while in the vehicle. Workers at Standard Oil of Ohio (Sohio) in Cleveland are developing a high temperature lithium battery that uses tellurium tetrachloride ($TeCl_4$) positive electrodes. Prototype batteries to power fork-lift trucks are expected in 3 years.

Other types of energy storage systems are also being studied, and some are being actively developed, including magnetic energy storage, mechanical storage in flywheels, chemical storage in hydrogen, and thermal storage. A second article will examine some of the many proposed storage technologies—ARTHUR L. ROBINSON

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