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ENERGY STORAGE

by

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June 1989

INTRODUCTION

Energy storage systems have long been recognized for their ability to decouple energy supply from energy demand, an important feature that offers valuable flexibility in the choice of fuels and primary energy sources. Early cultures stored thermal energy in water and rocks for later use, and flywheels have been used in pottery making for thousands of years. More advanced forms of energy storage were not practiced until the advent of the Industrial Revolution. As our society has grown more and more dependent on the ready availability of inexpensive and clean energy, ways of storing it have become more and more important. There are now numerous technologies for storage, conversion, and use of thermal, mechanical, chemical, electrical, and magnetic energy. The scale of energy storage systems ranges from micron-sized elements on integrated circuits to pumped hydroelectric reservoirs that store the equivalent of 20 GWh of electrical energy.

Applications of Energy Storage Systems

The applications of modern energy storage systems reach into numerous aspects of daily life. The chemical energy stored in batteries provides electric power to start our automobiles, operate flashlights and other portable hand-held devices, run implantable medical equipment such as heart pacemakers, drive motors in electrically powered vehicles, operate weapons systems, and furnish standby and emergency power for telephones, computers, and other widely used products. Thermal energy can be stored in a variety of materials for time intervals ranging from minutes to months, thereby permitting the optimal design of building energy systems to maximize their energy conservation potential. Mechanical energy is stored in flywheels to improve the performance of motors and other devices. All of these energy storage applications have important roles in today's society, and we can expect greater opportunities for energy storage applications in the future. This chapter focuses, however, on energy storage applications that may have a significant impact on the U.S. energy economy within the next one or two decades. These applications are described in the following paragraphs.

Figure 1 is a diagram of the quantities of energy converted and utilized in the U.S. during 1987 (1); the total energy converted was about 76 quadrillion Btu (76 quads). The sizes of the "pipes" show the relative importance of the major primary energy sources, as well as the roles of the major end-use sectors in consuming energy. The cross-hatched areas of the "utilization" boxes on the right-hand side of Figure 1 represent the potential use of stored energy in the year 2010, about 8.5 quads per year (equivalent to 1.4 billion barrels of oil).

Energy storage technologies can provide a vital link between the primary source of energy and its actual use. Owing to the number of primary energy sources and the great variety of energy uses, there are numerous forms of energy storage. Figure 2 shows possible links among "converted" energy sources (thermal or electrical), energy storage systems, conversion back to thermal or electrical energy, and final energy use. The sizes of the "pipes" show the potential use of stored energy in the U.S. by the year 2010, *i.e.*, about 8.5 quads. The relative sizes of the pipes showing four major types of energy storage systems (electrical, thermal, mechanical, and chemical) provide an approximate measure of the possible annual energy throughput for each system. The right-hand side of the figure shows the three major sectors of the U.S. energy economy that could use stored energy.

A very attractive feature of energy storage is its compatibility with various energy conversion processes. This feature can be illustrated by following the various energy paths shown in Figure 2.

1.　Thermal energy, from combustion of fossil fuels or from solar-powered devices, can be stored directly as sensible heat or in a suitable phase-change material, stored as electrochemical energy using a thermally driven electrochemical cell, or stored as chemical energy via reversible chemical reactions.

2.　Electrical energy, the most versatile and easily converted form of energy, can be stored thermally (resistance heating — *note* that an electrical-to-thermal storage path is not shown on Figure 2), electrically (rechargeable batteries, capacitors, magnetic fields), mechanically (pumped hydro, compressed air, flywheels), or chemically (hydrogen, metals).
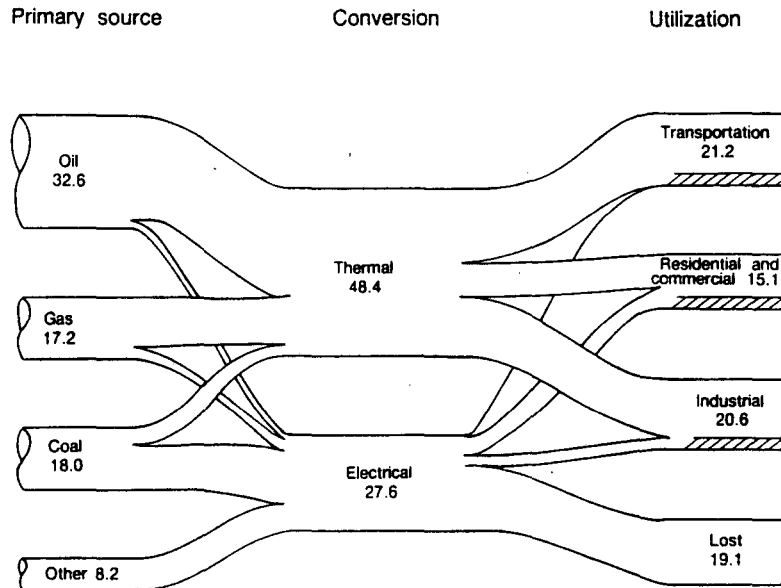
Figure 1. Relative importance of primary energy sources and end-use sectors to the U.S. energy economy during 1987 (1). The numbers shown are in quadrillion Btu (quads), and the sizes of the pipes are scaled accordingly. The primary energy source identified as "other" includes nuclear (4.9 quads), hydroelectric (3.0 quads), geothermal (0.2 quads), and solar (<0.1 quad), but does not include sources such as wood used in wood-burning stoves, passive solar, etc. The utilization pipe labeled as "lost" represents electrical energy conversion and distribution losses. The electric-transportation pipe appears as a line because of the small quantity of energy used in this fashion (<0.1 quad). The cross-hatched areas in the pipes at the right-hand side of the figure represent the potential use of stored energy in the year 2010 (about 8.5 quads).
(XBL 8811-9800)
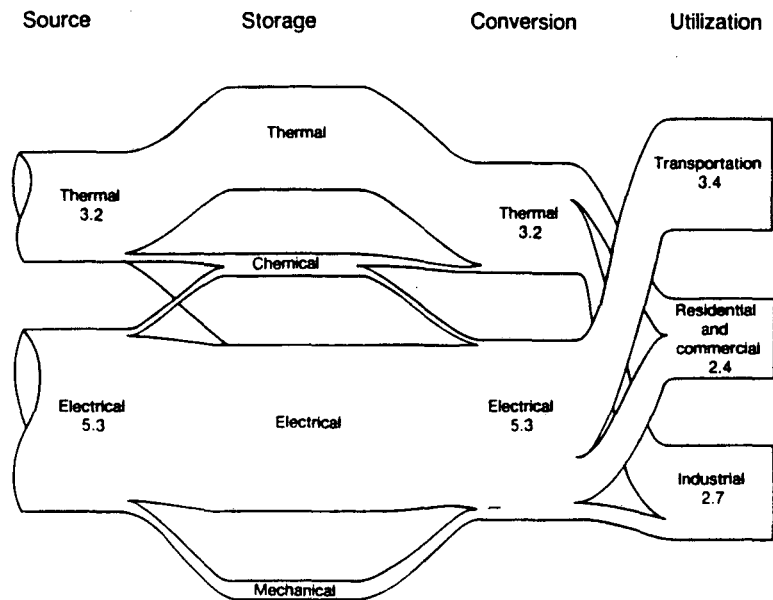
Figure 2. Role of energy storage systems in energy conversion and utilization. The relative sizes of the "pipes" on the left-hand side of the figure indicate possible use of stored energy in the year 2010. The numbers are in quadrillion Btu (quads) of equivalent thermal energy. The sizes of the pipes representing the four major types of energy storage systems indicate the quantity of stored energy used by the end-use sectors shown on the right-hand side of the figure. The thermal-to-electric pipe appears as a line because of the small quantity of energy likely to be stored in this manner.
(XBL 8811-9799)

3. Chemical energy, thermally or electrically derived as methane or other energy-rich fuels from fossil or biomass feedstocks, can be stored and used in electro-chemical (fuel cell) or combustion devices.

Energy storage is critically important to intermittent energy systems, *i.e.*, solar and wind, because it allows supply to be matched with demand. Energy storage is also important to large utility genera-tion systems, *e.g.*, nuclear power plants, that must operate near full capacity for economic reasons; again, energy storage allows supply to satisfy demand more effectively.

Table 1 lists several key energy storage applications that represent important means of shifting primary energy demand away from petroleum fuels, and toward fuels that are more abundant, less expensive, and/or more environmentally benign. Electric vehicles can be charged at night using baseload-generated off-peak electricity, derived from coal or nuclear fuel. The energy is recovered when the vehicle is driven, so electric vehicles serve to transfer demand away from petroleum toward coal or nuclear fuels. Electric utilities (or industries that provide their own electricity) can store less-expensive baseload energy during off-peak times and use the stored energy to provide electric power during peak demand periods (load leveling). Customer-side-of-the-meter (CSOM) electric energy storage offers the equivalent economic benefits to consumers, provided that favorable time-of-day electricity rates are in effect. Thermal energy storage (TES) offers a means for building and com-munity heating and cooling systems to increase the overall efficiency of energy use. Both diurnal and seasonal TES technologies can have a major impact on the practicality of building energy systems that depend on the use of solar irradiance.

Potential Impacts on Energy Conservation and Environmental Quality

Electric vehicles are a good example of the potential national benefits of widespread application of energy storage technologies. The present U.S. domestic fleet is about 1.8×10^8 vehicles, which consume 2900 million barrels of oil (Mboe) equivalent per year, at 15 mpg average fuel economy and 10,000 miles per year per vehicle (1). Anticipated improvements in the fleet-average vehicle fuel-economy will be roughly offset by the projected growth in the size of the fleet, so transportation

energy demand is not likely to change dramatically in the near future. If 10% of U.S. vehicles were electrically powered, however, petroleum consumption would be cut by 290 million barrels per year. This reduction corresponds to $5.8 billion per year, at $20 per barrel.

Table 1. Applications of energy storage technologies

Application	Candidate energy storage technologies
Electric vehicles	Rechargeable batteries Hydrogen[a] Flywheels
Load leveling	Rechargeable batteries Pumped hydro Compressed air Hydrogen Flywheels Superconducting magnets
Customer-side electric	Rechargeable batteries Hydrogen
Building thermal storage	Phase-change materials Sensible-heat materials

[a] storage as a H_2-rich compound (*e.g.*, CH_3OH, NH_3, etc.) is also feasible.

Electric vehicles emit no pollutants, so emissions are shifted away from the vehicle tailpipe, where they are very difficult to control and regulate, to utility central generating stations, where they are much easier to control and regulate. Present-day U.S. vehicles emit several million tons of sulfur oxides, nitrogen oxides, and hydrocarbons per year (2). Electrification of vehicles could eliminate all these pollutants if nuclear, solar and/or hydroelectric power were used as the primary energy sources, and a significant portion of these pollutants would be eliminated if coal were used as the primary energy source.

The 580 Mboe associated with a 20% electric domestic vehicle fleet corresponds to about 2×10^8 tons of domestic CO_2 production that would be avoided each year, provided that

noncarbonaceous primary fuels (nuclear, solar, hydroelectric) generate the electricity used to charge the batteries. The corresponding worldwide value is about 5×10^8 tons of CO_2 avoided each year, assuming a comparable penetration of the global vehicle fleet by electrics.

Electric vehicles would be most useful in urban areas owing to their limited ranges, and would thus have an even greater environmental impact there. Electric vehicles are also very quiet, and would help reduce urban noise levels.

Both utility load leveling and CSOM storage have fuel-shifting and environmental benefits that are comparable to those of electric vehicles. Installed (pumped hydroelectric) load leveling capacity is now about 3% of the total U.S. electric generating capacity. The potential annual use of load leveling in the U.S. has been estimated to provide as much as 2×10^5 GWh (3), or 330 Mboe. The potential annual use of stored energy storage capacity (20% electric vehicle fleet and 2×10^5 GWh load leveling) is 910 Mboe, or about 5.3 quads. This is the size of the electrical energy storage pipe on Figure 2.

The potential installed thermal energy storage capacity in the residential, commercial, and industrial sectors has been estimated at 550 Mboe (3), or about 3.2 quads. This is the size of the thermal energy storage pipe on Figure 2.

TECHNOLOGY STATUS

Table 2 lists some of the important features of various energy storage technologies. High specific energy is important for electric vehicle applications, whereas a high energy/land area ratio and high efficiency are important for utility load-leveling applications. Of particular interest to electric utilities are the costs of energy storage systems. Figure 3 shows how these costs vary with the time interval over which the energy storage system is discharged; this time interval is a function of the utility load profile. It is clear that different energy storage systems may have economic advantages or disadvantages, depending on the discharge time for the intended application.

Table 2. Features of energy storage systems

Energy storage system	Specific energy (Wh/kg)	Energy/area ratio (kWh/m²)	Efficiency (%)	Cost[a] ($/kW)
Batteries	40-100	40-80	70-85	600-1100
Thermal	—	—	60-90	600-700
Pumped Hydro	—	—	70	700-900
Compressed Air	—	—	70-85	500-600
Flywheels	10-20	—	70	1600-3200
Hydrogen	80	—	50-60	>1000
Magnetic	—	—	90	1000-1800

[a] 5-10 hour discharge duration
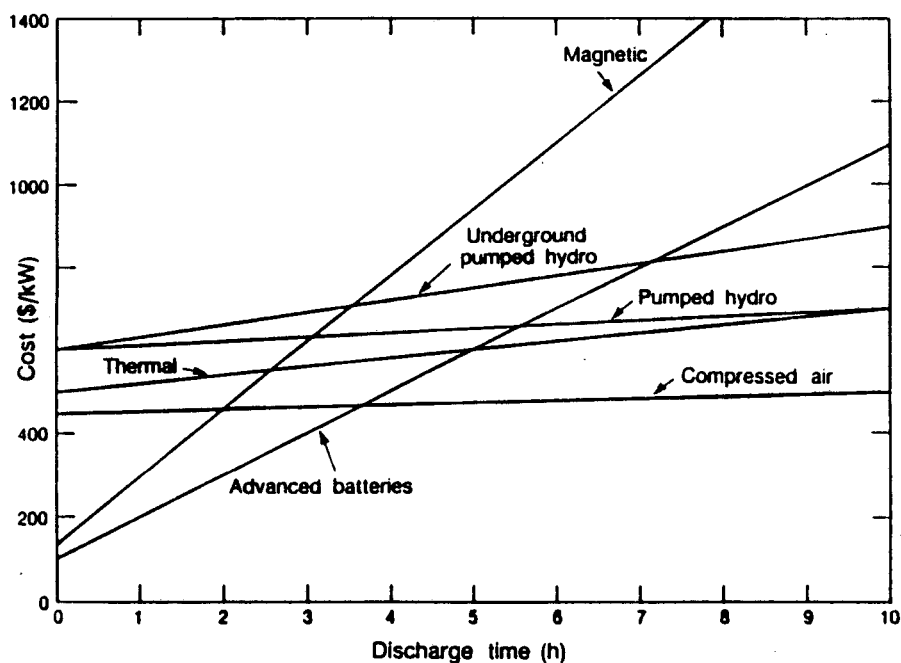
Figure 3. Costs of energy storage systems. The ordinate represents the sum of the power-related costs ($/kW) and the energy-related capital costs ($/kWh) multiplied by the storage system discharge time. (XBL 8811-9801)

This section reviews and summarizes the technical and economic status of various energy storage technologies, particularly those that could have a significant impact on the U.S. energy economy within the next one or two decades. The status of promising new systems that offer improved performance, durability, and/or costs compared to near-term energy storage technologies are also presented.

Electrochemical Energy Storage

Secondary (rechargeable) batteries are ideally suited for storing energy and serving as power sources for electric vehicles. Advanced batteries with high specific energy, high specific power, durability, and low cost must be developed to provide electric vehicles with the range, acceleration, and low life-cycle costs necessary to penetrate commercial markets. Spurred by oil embargos during the 1970s, an international race to develop battery-powered vehicles has produced major advances in this technology. Commercial electric vans are now in the proof-of-concept stage in the U.S. following years of support by the Department of Energy's (DOE) Electric and Hybrid Vehicle Program (4) and the Electric Power Research Institute's (EPRI) Electric Vehicle Program (5, 6).

Secondary batteries are also ideally suited for electric utility load leveling applications. Batteries not only provide the fuel flexibility and environmental benefits described earlier, but also offer a number of important operating benefits to an electric utility. They respond very rapidly to load changes, thus enabling the utility to better manage peak loads, follow load changes, provide spinning reserve (quick-response replacements for failed generating units), accept cogenerated and/or third-party power, and enhance system stability. Utility planning is facilitated by the short lead time, convenient siting, and modular construction of battery systems.

Many battery systems have been considered for energy storage applications such as electric vehicles and load leveling. Particularly challenging is the requirement that the battery exhibit attractive energy and power characteristics, be very durable, *and* also be low in cost. Table 3 lists some of the performance and cost goals that have been proposed for energy storage batteries. While some batteries exhibit some of these characteristics, none at this time meets all of the demanding

requirements for commercial energy storage applications. Significant advances in battery technology have occurred in recent years, however, and some batteries are now in a position to capture a large portion of the energy storage market during the next 20 years. Particularly noteworthy are the DOE (4, 6-8) and EPRI (5, 6, 9) R&D programs to develop advanced energy storage batteries. These batteries are briefly reviewed in the paragraphs that follow.

Table 3. Requirements for energy storage batteries

Requirement	Electric vehicles	Load leveling
Specific energy (Wh/kg)	>70	—
Energy density (Wh/l)	>140	>13
Energy/area (kWh/m^2)	—	>80
Specific power (W/kg)	>130	—
Energy efficiency (%)	>60	>70
Cycle life	>800	>2000
Calendar life (years)	>5	>10
Cost ($/kWh)	<100	<100

AMBIENT-TEMPERATURE BATTERIES Batteries that operate near room temperature have received the most attention for energy storage applications.

Lead-acid batteries The $Pb/H_2SO_4/PbO_2$ (lead-acid) battery is the most widely used rechargeable electrochemical device. It is a relatively mature technology, discovered a century ago. A recent Electrochemical Society symposium described numerous advances in this system (10). Optimized Pb and PbO_2 active-material formulations have resulted in improved electrode efficiencies and led to the development of maintenance-free or low-maintenance batteries. Cell designs that afford electrolyte circulation have reduced electrolyte concentration gradients, promoting more even utilization of

reactant species. Novel electrode structures and current-collector designs have led to a more uniform current density distribution and lighter weight electrodes. Better electrode materials have reduced corrosion problems and improved electrode cohesion, although these remain life-limiting problems. All these advances have combined to produce lead-acid batteries with improved performance and durability.

Lead-acid batteries designed for transportation applications can now deliver more than 40 Wh/kg, (a 30% improvement over the performance available a decade ago), with peak (30-sec) specific power values of 70 to 100 W/kg, depending on the battery's state of charge. Electric vans, powered by advanced lead-acid batteries such as these, exhibit a 60-mile driving range per charge in simulated city driving, more than 52 mph top speed, and 0-30 mph acceleration in less than 30 seconds (9). Figure 4 shows an electric van that has achieved this performance. Even better performance will be obtained with advanced batteries.

Lead-acid batteries designed for stationary energy storage applications are capable of withstanding more than 2000 deep-discharge cycles and exhibit energy efficiencies of more than 80%. These characteristics led a consortium [EPRI, Southern California Edison (SCE), and the International Lead Zinc Research Organization] to contract with the Exide Corporation to build a 10-MW, 40-MWh lead-acid battery (the world's largest), which has been installed at the SCE Chino facility and is shown in Figure 5 (11). The cost of this one-of-a-kind energy storage system was $340/kWh (half of which was the cost of the battery), about three times higher than the goal listed in Table 3. Its energy/area ratio is about 42 kWh/m^2, half the goal listed in Table 3. Particularly noteworthy is the short (two-year) construction time. This experience is very encouraging, considering that it represents the first precommercial large electrochemical energy storage facility in the U.S. Tests at the Chino facility will provide valuable information on the battery's potential operating benefits to the utility, its performance and lifetime under realistic operating conditions, and its need for periodic maintenance. The Chino battery is a low-maintenance vented design, which requires regular water additions, electrolyte specific gravity measurements, and terminal cleaning. More advanced battery designs will result in less frequent maintenance; however, a totally maintenance-free lead-acid load leveling battery is not available at this time.

Figure 4. The G-van proof-of-concept electric vehicle. (CBB 8811-11141)
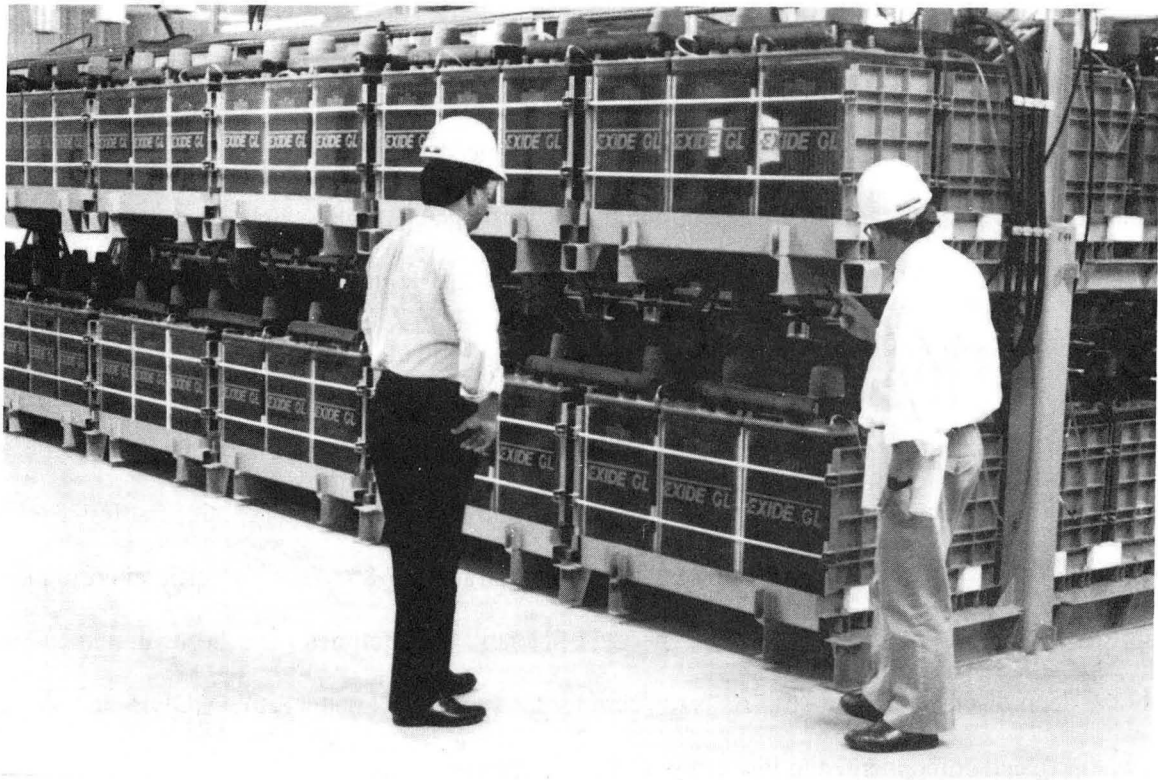

Figure 5. The Chino 10-MW/40-MWh battery energy storage facility. (CBB 8811-11139)

A number of organizations are evaluating lead-acid batteries for CSOM applications (12). Depending on utility time-of-day pricing schedules and the customer's daily and weekly load profile, it appears that CSOM lead-acid battery storage plants could save enough in electricity demand charges to provide a 3-5 year payback.

Iron/nickel oxide batteries The Fe/KOH/NiOOH battery is also known as the nickel-iron battery or Edison cell. It exhibits somewhat greater specific energy and power than the lead-acid battery, and is known for its long life and ruggedness. Modules using sintered electrodes have demonstrated 48-57 Wh/kg, 90-120 W/kg, lifetimes in excess of 1100 cycles, and the ability to withstand extended overcharge and overdischarge (4-7). A Fe/NiOOH battery developed for use in an electric van has demonstrated 55 Wh/kg and 79 W/kg. These characteristics will provide an electric van with a range of more than 110 miles between recharges, 7-second acceleration from 0 to 30 mph, and a sustained top speed of 65 mph (5).

Both the Fe and NiOOH electrodes are inherently inefficient, and the Fe/NiOOH battery's energy efficiency is typically about 60%. This characteristic has precluded serious consideration of the Fe/NiOOH battery for load leveling, for which energy efficiency is important consideration. For electric-vehicle applications, this inefficiency leads to the need for rather frequent water additions to the battery. The H_2 evolved at the Fe electrode during recharge can cause safety problems. Also, the NiOOH electrode is an expensive cell component; designs are being evaluated for a fiber-substrate electrode, potentially a cost-effective substitute.

Zinc/nickel oxide batteries The Zn/KOH/NiOOH battery (also known as the nickel-zinc battery) exhibits better performance than either the lead-acid or the Fe/NiOOH battery, but it suffers from a short cycle life. Zinc/nickel oxide batteries have demonstrated 55-80 Wh/kg specific energy, more than 200 W/kg specific power, and 70% energy efficiency, but lifetimes have been limited to less than 200 deep-discharge cycles (6). As is the case for the Fe/NiOOH battery, the NiOOH electrode is an expensive cell component, and lower-cost electrode designs are needed.

The short cycle life of the Zn/NiOOH battery can be traced to the relatively high solubility of Zn species in the alkaline battery electrolyte. The resulting transport of Zn active material to different regions of the cell compartment leads to capacity loss and/or cell shorting, eventually causing premature cell and battery failure. New cell components, such as Zn-Ca negative electrodes and modified alkaline electrolyte compositions with reduced Zn species solubility, have led to Zn/NiOOH cells with lifetimes of more than 500 cycles (13, 14). These advances have not yet been demonstrated in full-size modules or batteries, however. If extended Zn electrode lifetimes can be realized in full-size, sealed modules, the Zn/NiOOH battery would be very attractive for electric-vehicle applications.

Zinc/chlorine batteries The $Zn/ZnCl_2/Cl_2$ battery employs a flowing electrolyte that serves to transport Cl_2 to and from the cell, and to help control the morphology of the Zn metal as it is electrodeposited onto the negative-electrode substrate. The Cl_2 gas generated on charge may be stored as a chilled hydrate (15) or in an organic solvent (16); a complex Cl_2-sensing and scrubbing system is necessary for safety reasons. This system may be attractive for load leveling applications, due to its inherent low materials cost and potential for long lifetime. A 60-kW, 480-kWh Zn/Cl_2 battery has demonstrated about 78% dc-dc energy efficiency early in life, and its energy/area ratio is about 64 kWh/m^2 (16, 17); these values are near the design goals listed in Table 3. This large system is being tested at the Furukawa Battery Company.

Tests of other smaller Zn/Cl_2 batteries have demonstrated up to 1400 cycles, although energy efficiencies have generally been less than the figure reported above. This system tends to require rather frequent maintenance, due to its complexity, sensitivity to trace amounts of impurities in the electrolyte, and tendency to form nonuniform Zn deposits. Further R&D is necessary to reduce system complexity, identify cell designs that guarantee dense, uniform Zn deposits, and engineer a low-maintenance system.

Zinc/bromine batteries The $Zn/ZnBr_2/Br_2$ battery is very similar to the Zn/Cl_2 battery. The major difference is that the Br_2 evolved on charge is stored in a separate "oil" phase. Also, bipolar cell stack designs, using carbon-plastic electrode substrates and advanced electrolyte flow channel

configurations to minimize shunt currents in the common-electrolyte manifold, have been developed (18, 19). A 50-kW, 400-kWh Zn/Br_2 battery has shown 75% efficiency and an energy/area ratio of about 71 kWh/m^2, and it is being tested at the Meidensha Corporation (17, 19). Tests of other Zn/Br_2 batteries of various sizes (80 Wh to 80 kWh) have shown energy efficiencies (early in life) up to 75% and lifetimes up to 2030 cycles (6, 7). However, modules and batteries have often shown very short lifetimes, typically less than 200 cycles. Failures are often attributed to warping of electrode substrates, cell shorting caused by nonuniform Zn deposits, chemical degradation of plastic parts, and/or pump failures.

Additional R&D on Zn/Br_2 batteries is needed, particularly to identify cell materials that are chemically and dimensionally stable for extended periods. Other needs are similar to those of the Zn/Cl_2 battery.

Redox batteries The $CrCl_3/HCl/FeCl_2$ cell forms the basis for the so-called redox battery, in which the active Cr and Fe salts are fully soluble in the anolyte and catholyte, respectively. The anolyte and catholyte may be stored in tanks remote from the cell stack, permitting independent sizing of system energy (proportional to tank size) and power (proportional to stack size). This attractive feature, coupled with the potential for long lifetime (no electrode morphology changes, owing to the fully soluble active materials) make this system attractive for load-leveling applications.

Tests of an advanced 10-kW, 80-kWh redox flow battery showed more than 65% energy efficiency for 400 cycles (20). A 60-kW, 480-kWh battery has also been constructed (17); however, its energy/area ratio is only 5 kWh/m^2, which is significantly less than the goal listed in Table 3. It is the inherent low energy content associated with soluble active materials that results in such a bulky energy storage system.

The $Zn/NaOH/Na_3Fe(CN)_6$ system is a hybrid redox energy storage system, in that the ZnO oxidation product of the negative Zn electrode may be stored as a solid phase, whereas the ferricyanide and ferrocyanide species formed at the positive electrode are fully soluble (6). Cell tests have demonstrated more than 80% dc-dc energy efficiency, with lifetimes up to 2165 cycles. Large

Zn/Na$_3$Fe(CN)$_6$ batteries have not been constructed.

Hydrogen/nickel oxide batteries   The H$_2$/NiOOH battery (also known as nickel-hydrogen) is favored for space energy storage applications, because of its very long lifetime and ability to withstand extended overcharge and overdischarge, but it is very costly (more than $20,000/kWh). Recent design changes, however, have led to an advanced H$_2$/NiOOH battery for terrestrial applications that should cost less than $1000/kWh at multi-MWh/yr production rates (7). Tests of a 7-kWh H$_2$/NiOOH battery of this design have shown more than 70% dc-dc energy efficiency and lifetimes of more than 700 cycles (test on-going), and cell tests have shown more than 2000 cycles. This battery appears to be ideally suited for a remote, stand-alone energy storage application. If its cost can be reduced to less than $375/kWh, its cycle life cost ($/kWh-cycle) could be competitive with other battery energy storage systems.

Metal/air batteries   Fe/air, Zn/air and Al/air batteries have all been considered as power sources for electric vehicles, due to their high theoretical specific energies. The inherent irreversibility of air electrodes leads to low-to-moderate energy efficiencies for metal/air batteries, with the best values (about 60%) projected for the Zn/air system. Electrically rechargeable metal/air batteries rely on a either a bifunctional air electrode, which must reduce O$_2$ on discharge and generate O$_2$ on charge, or a three-electrode system that includes an O$_2$-reduction electrode and an O$_2$-evolution electrode. Electrically rechargeable metal/air batteries using bifunctional air electrodes have been favored, partly because of the cost, weight, and volume penalties associated with a three-electrode system. A fundamental problem with bifunctional air electrodes, however, is their short lifetimes. This problem has been linked to the corrosion of the carbon substrate, particularly under oxygen-evolution conditions. Small (32 Wh) electrically rechargeable Fe/air cells have demonstrated 30 Wh/kg, 40 W/kg and more than 120 cycles (4). Still smaller (2 Wh) electrically rechargeable Zn/air cells have been operated (6), and projected performance is very attractive: 110 Wh/kg, 140 W/kg, 60% energy efficiency, materials cost under $20/kW, and more than 600 cycles. Large Fe/air and Zn/air cells have not been operated for extended periods.

A number of organizations have developed Zn/air and Al/air batteries that are configured to accept replacement metal electrodes, that is, the battery is operated by adding metal plates, slurries, or powders in order to supply the active metal, and removing the metal oxide (or hydroxide) reaction product as a highly-concentrated electrolyte phase or as a precipitated solid phase. This type of battery is called "mechanically rechargeable." Because reactant air is extracted from the atmosphere during battery discharge, and because there is no need to generate O_2 during recharge, there is the possibility of rapid refueling, *e.g.*, in less than 10 minutes, which may be compared to the 1-10 hours typically required to electrically recharge a secondary battery. However, methods to mechanically recharge either Al/air or Zn/air batteries have not, so far, been successful. Mechanically rechargeable Zn/air batteries up to 35 kWh have been built and tested, with battery-specific energies as high as 121 Wh/kg. Al/air batteries have been constructed (21), although neither the electrodes nor the system to separate the $Al(OH)_3$ reaction product have operated well.

The unifunctional air electrode, which must reduce O_2 in a mechanically rechargeable metal/air battery, is an expensive component of the battery. Recent work, however, has indicated that certain metal-organic complexes (*e.g.*, cobalt tetramethoxyphenylporphyrin) may be used as a substitute for precious-metal electrocatalysts, but the stability of these compounds has not been demonstrated in extended metal/air cell tests.

HIGH-TEMPERATURE BATTERIES Batteries that operate at elevated temperatures exhibit improved performance, compared to ambient-temperature batteries. However, it is necessary to insulate them to prevent rapid heat loss to the environment.

Sodium/sulfur batteries The Na/S battery, also known as the beta battery, has been under development for more than 20 years. It uses a molten Na negative electrode, a solid Na^+-ion conducting electrolyte, and a molten sulfur-sodium polysulfide mixture as the positive electrode. Elevated temperatures, typically 300-350°C, are required to achieve sufficiently high ionic conductivity of the solid electrolyte, and Na/S cells must be sealed from the atmosphere to prevent reaction with water or air.

Cylindrical cell designs have been favored to provide adequate strength of the solid electrolyte, and to simplify sealing. The solid electrolyte of choice is Na/β''-Al_2O_3, and methods for its manufacture have improved significantly in recent years. High-quality, fine-grained materials are now routinely produced, and it has been found that the addition of ZrO_2 helps refine the grain size and toughens the ceramic. Also, special sulfur electrode designs, including the use of graded-resistivity shaped graphite felt current collectors, have improved rechargeability of the sulfur electrode. A number of cell sizes and configurations have been considered, but 10-50 Ah, inside-Na cell designs have become common in recent years. Efforts are under way in a number of countries to develop this very promising battery for both electric-vehicle and load-leveling applications.

Sodium/sulfur cells being developed for electric vehicles have demonstrated specific energies as high as 165 Wh/kg and specific powers as high as 220 W/kg (4, 6, 7, 22). Battery performance is more modest, owing in part to the need to provide a thermally-insulating enclosure, and values around 100 Wh/kg and 130 W/kg are typical for a 50-kWh battery (4). Such a battery should result in a range of about 125 miles for an electric vehicle under an urban driving schedule. Cell lifetimes of more than 2000 cycles have been demonstrated, although premature cell failures are a problem. Such failures greatly complicate cell interconnection strategies, because cells may fail either shorted or open circuit, and because individual cells will fail if subjected to overcharge or overdischarge. A number of Na/S modules have been constructed and tested, and individual module lifetimes have ranged up to about 600 cycles.

A 50-kW, 400-kWh Na/S load-leveling battery has been constructed (23), and it has demonstrated 85% dc-dc energy efficiency (8-h charge and 8-h discharge) and a 48.5 kWh/m^2 energy/area ratio. It is now being tested at Yuasa Battery Company; a 100-kWh battery of a similar design demonstrated comparable performance and a lifetime of more than 400 cycles with little capacity degradation.

The Na/S battery is truly a leading candidate for advanced, high-performance energy storage applications. An important goal is to reduce its cost to less than $100/kWh, and some projections for high-volume battery production rates indicate that this may be possible. Another important goal is

the demonstration of extended (more than 5 years) calendar lifetimes (as distinguished from cycle lifetimes) for Na/S batteries. R&D issues include the identification of corrosion-resistant cell containers and sealing materials, further optimization of the sulfur electrode structure, development of strategies for cells to withstand overcharge and overdischarge, strengthening of the solid electrolyte to avoid premature failures and better resist freeze-thaw cycles, and the development of a low-cost manufacturing process.

Sodium/metal chloride batteries A new high-temperature battery that resembles the Na/S battery has been developed (24). The major differences between the two systems are the positive electrode, which is an insoluble metal chloride in molten $NaAlCl_4$, and the temperature of operation, which is about 250°C. The cell configuration is $Na/\beta''-Al_2O_3/NaAlCl_4/MCl_2$, where M can be Fe, Ni, or possibly other transition metals. Both the $Na/FeCl_2$ and $Na/NiCl_2$ cells have been shown to be electrochemically reversible, and they exhibit a number of features that may be considered improvements over those of Na/S cells. These features include lower operating temperature, ability to withstand limited overcharge and overdischarge, cell failures in short-circuit conditions, better safety characteristics, and higher cell voltage. Disadvantages include a slightly lower specific energy, lower specific power (due to the reduced ionic conductivity of $\beta''-Al_2O_3$ at the lower temperature of operation), high impedance of the positive electrode, and poor wetting of the $\beta''-Al_2O_3$ by Na at the lower temperature. On balance, Na/MCl_2 batteries appear to offer some attractive characteristics, and their development is being pursued.

Individual $Na/FeCl_2$ cells have demonstrated more than 130 Wh/kg and more than 1000 cycles, although their specific power is typically below 100 W/kg, particularly when at low state of charge. Large electric vehicle batteries (about 25 kWh) have been constructed and tested.

Lithium/iron sulfide batteries The LiAl/LiCl-KCl/FeS cell operates at about 450°C; at this temperature the electrodes remain solid, but the electrolyte is a molten salt. This battery displays a number of attractive features compared to the Na/S battery, including prismatic flat-plate construction, ability to withstand numerous freeze-thaw cycles, cell failures in short-circuit conditions, ability

to withstand overcharge, and low-cost materials and construction techniques. The major disadvantage is somewhat lower performance. Although this battery is suitable for both electric-vehicle and load-leveling applications, recent attention has focused on battery designs suitable for electric vehicle propulsion (4). Batteries have been constructed that deliver more than 100 Wh/kg and more than 100 W/kg, and a number of modules have been tested for more than 1000 cycles.

Lithium/iron disulfide batteries The $LiAl/LiCl-LiBr-KBr/FeS_2$ cell is closely related to the LiAl/FeS cell, and variations of it have been studied for a number of years. Prior versions exhibited poor capacity retention, which could be traced to instability of the FeS_2 electrode at the 450°C cell operating temperature. The present version of this cell (6, 25) employs a dense FeS_2 electrode that is only discharged to a stoichiometry corresponding to FeS (rather than to elemental Fe, which was the case in prior versions of this technology). It also uses a LiCl-LiBr-KBr molten salt electrolyte (m.p. 310°C) that permits cell operation at about 400°C. Both of these innovations have resulted in greatly improved capacity retention: cells have been cycled for more than 1000 cycles. Cell performance is comparable to that of Na/S, and the attractive features listed above for LiAl/FeS cells apply as well to $LiAl/FeS_2$ cells. All of these considerations make this a very attractive technology for advanced, high-performance energy storage applications.

An important R&D issue for Li/FeS_2 cells is the identification of practical current-collector materials that are stable in the corrosive environment at the positive FeS_2 electrode.

Thermal Energy Storage

The combustion of fossil fuels to produce thermal energy for transportation, space heating, and manufacturing applications, and the combustion of fossil fuels to produce electricity, dominate the U.S. energy economy (Figure 1). The inherent inefficiency of heat engines (by the Carnot cycle) results in large amounts of waste heat that are difficult to utilize. For example, about 19 quads per year are lost due to thermal inefficiencies in electricity generation. If this thermal energy could be efficiently stored, transported, and utilized, it would represent major energy savings to the U.S.

Imbalances between the rates of solar gain, waste heat production, and heat losses complicate strategies for maintaining comfortable temperature ranges in buildings. Thermal energy storage systems can play important roles in the design and implementation of energy-efficient buildings by balancing thermal loads.

Thermal energy storage (TES) systems can be classified in a number of ways. One way is by the thermochemical process involved: sensible heat changes in a single-phase material, latent heat changes due to a material phase change, reversible heat of chemical reaction, reversible heat of gas physisorption onto a solid surface, etc. Another way to classify TES systems is by temperature of operation (26): industrial cooling at -46 to -18°C, building cooling at 0 to 12°C, building heating at 25 to 50°C, and industrial waste heat storage at 175 to 1100°C. This section discusses sensible-heat and latent-heat TES systems; thermochemical systems based on the storage of heat produced by chemical reactions and sorption processes are considered in a later section.

Performance, durability, and cost goals for TES systems vary with the intended duty cycles (diurnal vs seasonal), temperature range, and application (building vs industrial). These goals are listed in Table 4.

Table 4. Requirements for thermal energy storage systems

Requirement	Building heating and cooling	Industrial process heat	Seasonal storage
Efficiency (%)	>90	>85	>70
Cost ($/kWh)	<22	<26	<10[a]
Temperature (°C)			
- heating	32-50	>175	32-50
- cooling	4-12	-46 to -18	4-12

[a] Cost expressed as $/kW

SENSIBLE-HEAT STORAGE SYSTEMS Storage of thermal energy in common materials (water, rock, adobe) has been used for many years. The low cost of such materials tends to be offset by their low specific heat, which translates into the need for wide temperature changes and large TES system mass and volume. Where local geological conditions are appropriate, the use of aquifers as a TES system can be attractive.

Aquifers A geological structure at the University of Minnesota St. Paul campus has been identified as a suitable aquifer for seasonal TES (27). The sandstone aquifer lies about 180 m below the earth's surface, and it is well separated from nearby aquifers. Tests have shown that the aquifer is capable of storing water heated to 100-150°C, and energy recovery averaged 60% over short-term (8-16 days) and long-term (60 days) experiments with a 5-MW test facility. A significant issue is the chemistry of the groundwater. In this case the groundwater was hard, and ion-exchange softening was necessary to avoid scaling problems. Other problems include thermal stratification, which can degrade the system performance, and long-term effects on local groundwater quality (mineral and microbial content).

LATENT-HEAT STORAGE SYSTEMS The use of phase-change materials to store heat (or cool) can offer an order-of-magnitude increase in specific heat, compared to using sensible-heat TES. Phase-change materials with a wide range of transition temperatures have been identified, and their suitability for various applications is being investigated. Typical R&D issues that must be addressed for each of these materials include containment, chemical stability, cost, uniformity of freezing/melting, and material redistribution during heating/cooling cycles.

Aqueous systems Perhaps the earliest use of a phase-change material for large-scale TES was the so-called Ruth accumulator, which stores pressurized saturated water that is later released as steam. Plants as large as 67 MWh were operated in Germany during the 1920s, and some are still in use today. Another early use of latent-heat storage was ice for cool storage. Peak power demand charges by electric utilities have renewed interest in this old technology, and a number of large buildings have

recently been constructed with provision for ice storage systems to reduce peak air-conditioning needs. Latent-heat TES systems that employ water, ice, or steam, however, tend to be too large for cost-effective use. Also, the 0°C water/ice transition temperature is not optimal for cool-storage applications.

Salt hydrates Eutectic salt hydrates have been evaluated for cool-storage and heat-storage applications; a major goal is to identify eutectic salt hydrates (with transition temperatures near room temperature) that could be incorporated in passive solar structures. This development would greatly reduce the bulk of passive solar building walls. Problems such as containment, stratification, swelling, nonuniform melting and freezing, and differences between melting and freezing temperatures have impeded development of these materials. There is a need, therefore, to investigate other phase-change materials with high specific heats, more optimal transition temperatures, and improved physical properties.

Clathrates A number of gas clathrates (crystalline compounds made with refrigerant gas and water) have been evaluated (28). Their advantages include a range of transition temperatures (0-20°C) that are near-optimal for cool-storage applications, the availability of clathrates with two transition temperatures (permitting both cool storage and heat storage), and the possibility of direct-contact heat exchange with refrigerants. However, there are significant environmental issues associated with the chlorofluorocarbon refrigerants that have been proposed for use with clathrate systems, and complete systems tend to be costly. Similar problems confront the use of ammonia as a refrigerant and cool-storage medium.

Molten salts Latent-heat storage systems based on congruently melting molten salts are being developed for industrial TES (29). The molten salt is retained inside a porous ceramic by capillary forces, which results in a nearly form-stable material that can be fabricated as pellets. A Na_2CO_3-$BaCO_3$/MgO TES system (m.p. 710°C) has been operated for several thousand thermal cycles. This system is being evaluated in a brick factory, which should give valuable feedback for system efficiency and lifetime under practical operating conditions. Success with this system has encouraged

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the investigation of medium-temperature (260-510°C) encapsulated molten salt TES systems. Other elevated-temperature latent-heat storage materials under evaluation include Si-encapsulated Al-Si alloy eutectics, which can be prepared as metal shot. Provided that the TES system temperature can be controlled below 600°C to minimize Si migration rates, this system offers high specific heat, high thermal conductivity, corrosion resistance, and the possibility of direct-contact heat exchange.

A 30-kWh NaOH-NaNO$_3$ molten salt TES system has been developed for pressurized-water nuclear reactor load-following applications (30), and it has also been proposed for use with molten carbonate fuel cell systems. Tests of more than 1000 heating/cooling cycles have shown that structural materials such as carbon steels are acceptable, however, thermal stratification tends to affect system performance. The melting point of this molten salt is about 259°C, its latent heat is about 66 cal/g, and an oil is used as a heat-transfer medium.

Advanced systems An advanced TES material under development is cross-linked high-density polyethylene (X-HDPE), which undergoes a solid-solid phase transition at about 132°C with a latent heat of 40 cal/g (31). The porous nature of this material permits the use of direct-contact heat exchange, and studies are under way to determine the feasibility of pumping this material as a slurry. Other advanced TES concepts that permit TES systems to operate at lower temperatures (15-80°C) are under investigation (26). Some examples include crystalline alkyl hydrocarbon phase-change materials and limited-miscibility liquid-liquid systems.

Mechanical Energy Storage

Mechanical energy storage systems are generally the most mature of the technologies discussed in this chapter. They are based on familiar equipment, such as pumps, turbines, and compressors, that is mass produced and relatively inexpensive.

The most suitable application for mechanical energy storage systems is electric utility load leveling. Their rapid response time to load changes (about 1 minute) offers operating benefits to utilities that are comparable to those discussed earlier for secondary batteries. Three technologies are

considered viable candidates for future energy storage applications: pumped hydroelectric, compressed air, and flywheels.

PUMPED HYDROELECTRIC ENERGY STORAGE   Electric utilities recognize the need for advanced systems to store less expensive baseload power to meet peak power demand, which would otherwise be provided by turbines fueled by gas or oil. It is pumped hydroelectric, however, that accounts for nearly all of the electric utility storage capacity in place today. Domestic utilities rely on pumped hydroelectric for about 3% of total generating capacity; other industrial countries have 3-4 times this fraction (32).

Pumped hydroelectric storage is a mature technology, accepted and used by utilities for more than 50 years. Sizes range from a few MW to 2 GW, with storage capacities up to 24 GWh. The development of the reversible pump-turbine represents a major advance that encouraged the construction of large pumped hydroelectric plants in the U.S. during the 1950s and 1960s.

Conventional pumped hydroelectric energy storage systems rely upon above-groundwater storage reservoirs, so energy-related capital costs tend to be small, about $10/kWh. Power-related capital costs were about $600/kW in 1987, and the total installed system cost (designed for a 10-hr discharge) was approximately $700/kW (33). Major drawbacks to pumped hydroelectric systems are the relative scarcity of available sites, environmental issues, and the long (typically 10 years) lead time for construction. Other drawbacks are not unlike those of conventional hydroelectric facilities, which are shared by most major civil engineering and construction projects. Typical operational problems include pump-turbine component failures (related to vibration and cavitation), water leakage from reservoirs and conduits, conduit failures, and long-term geological changes.

Siting restrictions for conventional pumped hydroelectric installations have led to the consideration of underground systems. Economic considerations favor large systems (more than 1 GW) that can support a hydraulic head twice as high as the 750 m that conventional reversible pump-turbines can accept. The General Electric Co. and Hitachi, Ltd., in a joint venture supported by EPRI, have developed a two-stage reversible pump-turbine that can support a 1500-m head, and 650-MW units

are now commercially available (32). The energy-related costs associated with constructing an underground pumped hydroelectric system are higher than those of conventional pumped hydroelectric systems; these costs have been estimated at $30/kWh, bringing the total capital cost to at least $900/kW for an underground facility (33).

Major R&D goals are aimed at shortening the construction time and improving the operating reliability of pumped hydroelectric facilities, whether conventional or underground. Improved methods for tunnel excavation and stabilization are needed, so that they can withstand repeated pressure load fluctuations.

COMPRESSED AIR ENERGY STORAGE Baseload power can be used to compress air and inject it into underground caverns. The stored energy can then be recovered during peak demand periods by heating and expanding the stored air through a turbine-generator. Compressed air energy storage (CAES) therefore represents a hybrid technology, *i.e.*, a combination storage/peaking unit. A schematic diagram of a CAES system is shown in Figure 6.
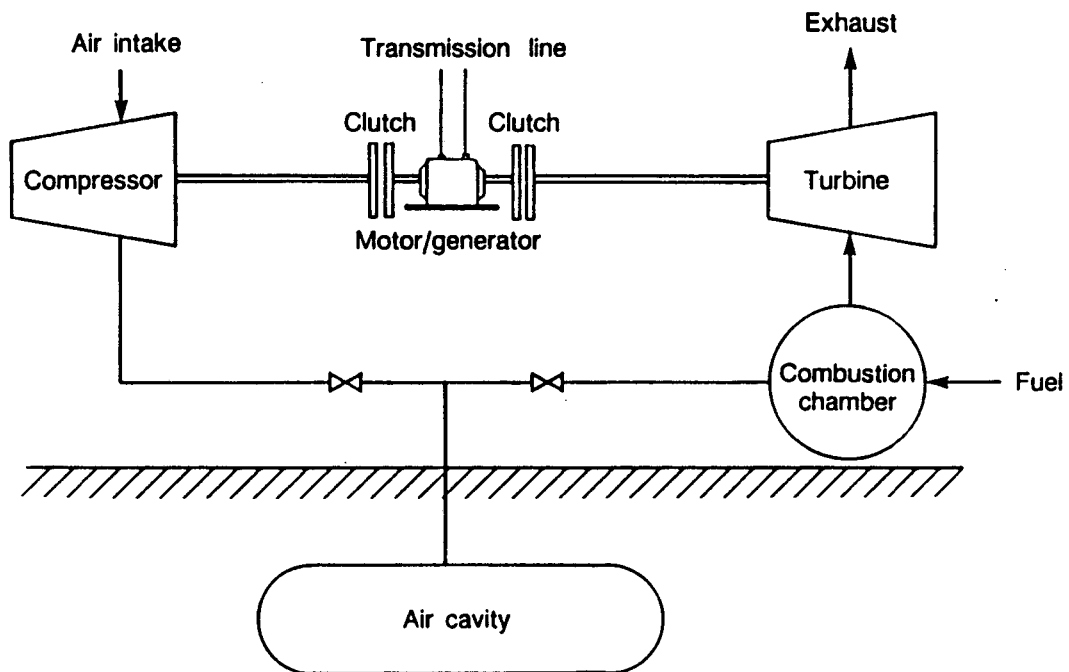

Figure 6.   Schematic diagram of a compressed air energy storage plant. (XBL 8811-9802)

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Compressed air can be stored, in principle, in caverns formed in either salt, rock, or aquifer formations. Well-established procedures, such as solution mining of salt formations, can be used to excavate caverns that are sufficiently airtight. The only commercial operating CAES unit, designed by Brown, Boveri Co. and constructed by the electric utility Nordwestdeutsche Kraftwerke A.G. in the Federal Republic of Germany, has been operating since 1978. The motor-generator, compressor, and other equipment are of standard design, and no attempt is made to recover wasted compression heat. However, intercoolers are used to cool the air between the low-pressure and high-pressure sections of the compressor, in order to minimize the power output required from the motor-generator during the charging cycle. This unit uses two salt caverns for air storage, which provide a 3.5-h discharge period. It is a 290-MW unit, and it requires 0.83 kWh of electricity and 5500 Btu of natural gas for each kWh of power output.

Because CAES units accept both baseload-generated electricity and fossil fuels with various heating values, there is some ambiguity about the definition of CAES efficiency. For different CAES configurations, each kWh of output typically requires 0.75-0.83 kWh of electric energy to drive the air compressor, and 4000-5500 Btu to heat the pressurized air before it reaches the turbine-generator. These values correspond to 41-52% energy storage efficiencies, based on the intrinsic heat content of the fuel (3412 Btu/kWh). Energy storage efficiencies range from 72 to 87%, based on the electric-energy-equivalent content of the fuel (10,000 Btu/kWh).

Recent work on CAES systems has focused on methods to better utilize the waste heat generated (minimizing the use of premium fuel during the discharge cycle), evaluation of underground structures suitable for compressed-air storage, and the development of CAES module sizes that are more cost effective and have shorter construction times than larger units.

An experimental 20-MW CAES test facility has been built at Sesta, Italy, and studies are under way to evaluate advanced plant configurations (34). The test facility was built in a geothermal area, where a natural aquifer was available. Calculations were performed to compare various schemes that have been proposed to improve the efficiency of CAES: (*a*) heat exchangers ("recuperators") to recover turbine exhaust heat, (*b*) thermal energy storage devices to utilize the heat rejected by the

intercoolers, and (c) steam injection into the combustor, to reduce the use of fossil fuels. It was found that a CAES plant configuration that makes use of all three schemes gave the best thermodynamic efficiency and required the smallest amount of premium fuel. However, the levelized operating costs, which are strong functions of assumptions made about fuel costs and load profile, were rather similar for different CAES configurations.

The Alabama Electric Cooperative is constructing a 110-MW CAES plant, developed by Gibbs & Hill, Inc., which is planned to be in operation late in 1990 (35). CAES was chosen after a comparative technical and economic analysis of alternative technologies that are available. A significant difference between this plant and the 290-MW German plant described previously is the use of an advanced recuperator to recover turbine exhaust heat. Performance characteristics include an electric energy requirement of 0.78 kWh per kWh of output, and a fuel heat rate of 4500 Btu per kWh of output. The unit efficiency should be significantly higher than that of the 290-MW German plant (see above discussion on CAES efficiency).

Smaller (25-50 MW) CAES plants are recognized for their shorter times of construction, about 2.5 years compared to about 4.5 years for larger units (33). Comparative trade-off analyses of 25-MW and 50-MW CAES designs have been made (36). These studies assumed underground air storage in an aquifer, and included the following design features: (a) use of TES to heat stored air before it enters the turboexpander, (b) consideration of both high-pressure and low-pressure TES systems, and (c) air-cooled intercoolers. Fifteen combinations of turbomachinery, TES system pressure, storage intervals, and storage depth were evaluated. It was found that the addition of TES increases CAES plant capital costs by 20-30%, but offers a significant reduction in premium fuel consumption (as well as NO_x, SO_x and CO emissions). An adiabatic TES system (which recovers air compression heat) could eliminate premium fuel consumption, but the CAES efficiency would drop from about 75% to about 58% (based on the electric-energy-equivalent content of the fuel).

Other recent studies have considered the suitability of aquifer formations for CAES, as these tend to be less expensive to develop, compared to salt or rock formations. A study of an aquifer formation in Pittsfield, Illinois was carried out to evaluate basic air-storage design principles and

evaluate models of aquifers. Analyses of air bubble development, volume changes, and air bubble delivery were carried out. It was found that the Pittsfield air storage reservoir is not suitable for CAES applications, primarily due to the system's limited air flow deliverability, due to the fact that the reservoir is underpressurized and exhibits low air permeability.

Continuing efforts to improve CAES efficiency, limit the quantity of premium fuels required, and develop suitable underground sites will result in greater utility acceptance of this promising technology.

FLYWHEELS   Another attractive form of mechanical energy storage has been used for thousands of years. Today virtually all combustion engines rely on the energy stored in flywheels to sustain shaft rotation between piston thrusts. Traditional flywheels lack the necessary specific energy to be seriously considered for large-scale energy storage applications, but recent advances in material technology have changed this picture. The development of low-density fiber composite materials that exhibit very high strength has encouraged the design and construction of flywheel energy storage systems with much higher specific energies than could be obtained with metal rotors. New mechanical designs have recognized the unique physical properties of these fiber composites, and permitted much higher rotation speeds.

Recent reviews (38, 39) have considered the merits of flywheels for various applications, including electric vehicles and load leveling. A number of advanced fibers, including polyamides (Kevlar), silica, and graphite, are now available. Strengths as high as 3400 MPa can be obtained (*e.g.*, with graphite composites), which corresponds to an intrinsic maximum rotor specific energy of 630 Wh/kg. A practical value of flywheel system specific energy, taking into account variable rotation rates (that are necessarily less than the maximum permissible) and packaging weight, is about 20% of the theoretical value. Achieved maximum rotor specific-energy values have ranged from 18 to 78 Wh/kg, and practical flywheel system specific-energy values would project to less than 20 Wh/kg. These considerations suggest that flywheels would not be a good choice as a primary power source for an electric vehicle, although they may find applications in so-called hybrid vehicles, where

the flywheel would satisfy peak power demands, and the primary energy storage device would provide steady power. An assessment of flywheels has shown that they are not cost effective for either utility or CSOM load-leveling applications (39).

Flywheel R&D has focused on (*a*) rotor designs that account for the anisotropic nature of fiber strength, (*b*) magnetic bearings and evacuated enclosures to minimize frictional losses, (*c*) integrated motor generators (40-42), and (*d*) the development of flywheel housings to accommodate the debris from rotor failure.

Although a number of rotor shapes have been investigated (38, 39), a constant-thickness multi-ring disk with a hole at its center appears to be a useful configuration (40). Graphite/epoxy composites (40) and glass-fiber composites (41) are attractive rotor materials. Most tests of these materials have been performed with small (less than 1 kWh) units. Failure typically occurs (the rotor bursts) at rotation speeds above 40,000 rpm.

An advanced "pancake" magnetic bearing has been successfully developed (40, 42). Permanent magnets are sandwiched between ferromagnetic plates, and the bearing is positioned so that the flux lines support the rotor. Electromagnetic coils are strategically located to keep the rotor centered.

A 2.75-kWh, 160-kW flywheel storage system has been installed in a diesel-powered bus and tested for many cycles (41). The unit delivers about 6 Wh/kg and 350 W/kg, and it has shown a 20% reduction in fuel consumption by leveling the diesel engine output and accepting regenerative braking energy. The electrical efficiency of this system was about 90%, but costs were not reported.

The performance results for flywheel energy storage systems suggest that they are well suited for applications where high specific power and many cycles are important, and a low to moderate specific energy is acceptable. Hybrid (spark-ignition/electric) vehicle applications would appear to be very suitable if a cost-effective system can be developed. Continued advancements to fully realize the capability of lightweight fiber composite materials should lead to improved flywheel specific energies.

Chemical Energy Storage

HYDROGEN GENERATION, STORAGE, TRANSMISSION AND UTILIZATION   Hydrogen has long been recognized as an ideal medium for a variety of energy conversion and utilization systems. A hydrogen economy has been proposed, in which H_2 is derived from renewable (*e.g.*, solar) or abundant (*e.g.*, fusion) primary energy sources, distributed through pipelines, and utilized for transportation, heating, and electricity-generation applications. This is indeed an attractive scenario, because H_2 is virtually inexhaustible, clean burning, convenient, and versatile. However, realizing a true hydrogen economy depends on the development of cost-effective means for generating, storaging, transmitting, and using hydrogen.

Hydrogen Generation   More than 5 million tons of H_2 are produced in the U.S. each year; most is generated and used in petroleum and chemical production processes. Most H_2 for commercial use is generated by reforming natural gas, although some is recovered as a by-product from chlorine-caustic cells, or derived by electrolysis. The development of a cost-effective electrolysis process, or another method for water splitting, is a major goal for the use of renewable resources in a hydrogen economy, otherwise methane will be the preferred source of H_2.

Considerable effort has been expended on the development of water electrolysis processes, and a recent review has been published (43). Most work has centered on bipolar alkaline water electrolyzers, which are now in commercial use. Typical operating conditions are 0.1-0.3 A/cm^2, 70-90°C, 1-3 atm, and cell voltage 1.85-2.20 V. Sintered nickel, impregnated with a high-surface-area nickel structure, is used as the electrocatalyst for the H_2-evolution electrode. The O_2-evolution electrocatalyst is typically a mixture of oxides (spinel or perovskite structures are preferred) that include cobalt oxide. Asbestos or polymer-reinforced asbestos materials are often used as diaphragm separators. The energy consumption of a modern electrolyzer is about 4.5 kWh per standard m^3 of H_2. While electrolyzers such as these represent major advances compared to prior technology, the H_2 produced is perhaps twice as expensive as that derived from methane. Electrolysis is used special circumstances, *e.g.*, where electricity is very inexpensive or there is a need for very pure H_2. There is a

strong incentive to reduce cell voltage and increase cell current density to lower the cost of electrolytic H_2.

Increasing the temperature and pressure of an alkaline water electrolysis cell will improve its performance, and cell designs that minimize the anode-cathode gap are used: the electrodes are pressed against a porous diaphragm separator, and most of the gas is evolved from the back sides of the electrodes. Composite diaphragms, typically plastic-bonded zirconia or polysulfone-impregnated polyantimonic acid, have shown better stability than polymer-reinforced asbestos diaphragms, which are stable only at temperatures under 100°C. Advanced cells such as these can operate at more than 110°C and require about 1.65 V at 0.5 A/cm^2, which represents a significant improvement over results for alkaline electrolyzers operating at lower temperatures. The energy consumption of such an electrolyzer should be less than 4 kWh per m^3 of H_2. However, at the higher temperatures Ni corrosion becomes a problem, as does the chemical stability of gasket and other cell construction materials.

Other advanced water electrolyzers are being developed. These include electrolyzers based on solid polymer electrolyte (SPE) membrane separators (44). Improvements in SPE electrolyzers have yielded performance approaching that of alkaline electrolyzers; however, there is no apparent cost advantage in using SPE electrolyzers (43). High-temperature water electrolysis, based on the use of stabilized zirconia ceramic electrolytes, is projected to use significantly less energy for the production of H_2 (less than 3 kWh per m^3 of H_2), compared to either alkaline or SPE technologies (45). Data are not available, however, to make meaningful cost projections for H_2 generated by high-temperature water electrolysis.

Hydrogen storage Hydrogen can be stored as a compressed gas, cryogenic liquid, or solid hydride. Storage as a compressed gas requires the use of heavy cylinders, and storage as a cryogenic liquid would double the cost of producing the H_2. A number of hydrides have been investigated, and a recent review is available (46). Although hydrides can store significant amounts of H_2 on a volume basis, they can typically store only about 1% H_2 on a mass basis. Alloys such as ZrMn, Mg_2Ni, $LaNi_5$ and FeTi have shown favorable properties, but lighter-weight materials are needed. A novel

LaNi$_5$ and FeTi have shown favorable properties, but lighter-weight materials are needed. A novel means of H$_2$ storage under investigation is cryoadsorption onto surface-modified carbon at 77°K at 1-60 atm (45). Up to 4 wt% H$_2$ has been adsorbed in this manner, but cost-effectiveness has not been demonstrated.

Storage of H$_2$ in the form of a H$_2$-rich compound, such as CH$_3$OH or NH$_3$, would be a reasonable alternative to hydride storage. Use of these compounds is significantly more difficult than direct H$_2$ use.

Hydrogen transmission Hydrogen can be transported through pipes as a gas or liquid, although pumping liquid H$_2$ over long distances would be prohibitively expensive due to the need for adequate pipe insulation. Hydrogen embrittlement of pipeline materials is a major problem, and it is unlikely that existing pipelines could be used.

Hydrogen utilization Hydrogen is a very versatile fuel, which can be easily used in any combustion process. There are significant safety issues associated with its use, particularly for widespread applications such as transportation. The most efficient way to use H$_2$, for either electricity generation or transportation, is in fuel cells. A recent review of fuel cell technology is available (47).

REVERSIBLE CHEMICAL REACTIONS A number of reversible chemical reactions exhibit the same features that make electrochemical reactions so attractive for energy storage. Reversible reactions that have been investigated include (*a*) steam reforming CH$_4$ to form CO and H$_2$, (*b*) splitting NH$_3$ into N$_2$ and H$_2$, (*c*) reducing SO$_3$ into SO$_2$ and O$_2$, (*d*) adsorbing NH$_3$ onto salt compounds, and (*e*) adsorbing gases onto materials such as silica gel, charcoal, zeolites, salts, etc. Configurations for these chemical energy storage systems have been reviewed (48). A fundamental problem shared by all of these systems is their small heat of reaction (or heat of adsorption). The result is chemical energy storage systems in which large quantities of materials have to be handled, per unit of energy stored. Some liquid and solid reactants have higher specific heats, but the required separation processes complicate implementation of a practical energy storage system.

Magnetic Energy Storage

Superconducting magnetic energy storage (SMES) is the only known method for the bulk storage of energy directly as electricity. SMES stores electric energy as dc electric current passing through an inductor. The inductor, made from a superconducting material, is circular, so that current can circulate indefinitely with almost no losses. A diagram of a SMES system is shown in Figure 7. SMES exhibits very high energy storage efficiencies: round-trip ac-dc-ac efficiencies of about 90% are typical. The system responds to a load change more rapidly (less than 1 sec) than any other energy storage system. SMES is, in principle, nearly ideally suited for electric utility load-leveling applications.
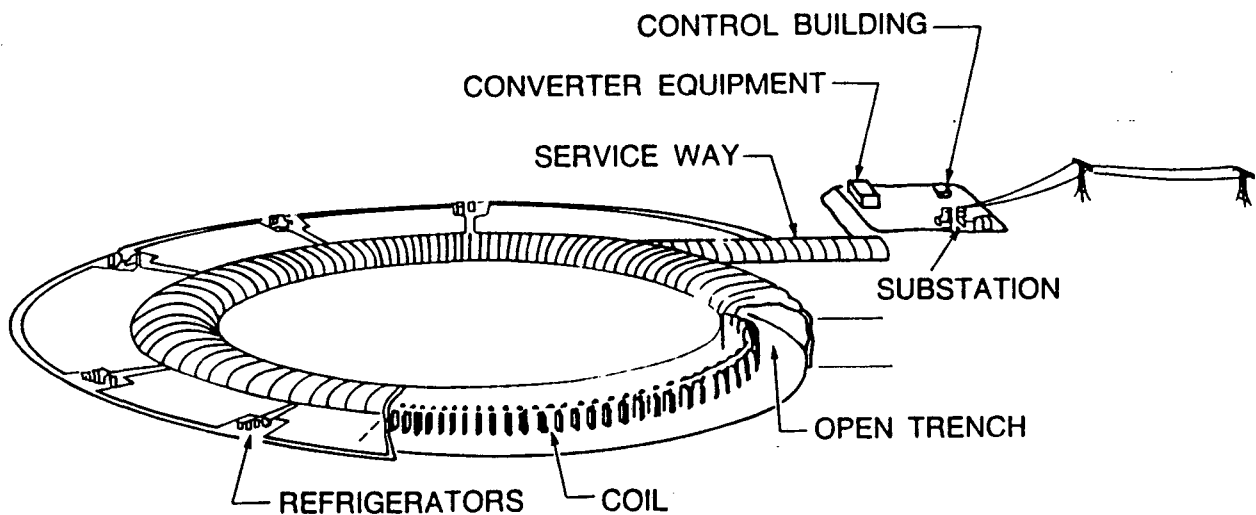
Figure 7.   Schematic diagram of a superconducting magnetic energy storage facility. (XBL 8811-9803)

A 8.3-kWh SMES unit was installed and tested at the Bonneville Power Administration Tacoma substation (49), and energy was interchanged between the SMES unit and the Pacific Intertie grid. The SMES unit was found to damp effectively oscillations typically observed on the grid.

Two major problems confront the implementation of SMES units: the high cost, and the environmental issues associated with the strong magnetic field. Projected costs of a 1-GW SMES unit are more than $1300/kW, in 1982 dollars (50). The recent discovery of high-temperature super-conductors (51) could have a major impact on SMES costs, provided that they can be made into appropriate shapes and withstand high current fluxes.

CONCLUDING REMARKS

The 1970s saw a renewed interest in energy conservation, conversion, storage, and utilization. Research and development on promising technologies was begun at that time, and continuing efforts have resulted in dramatic improvements in numerous energy systems. In particular, energy storage systems have made great strides, and some advanced storage technologies are now poised to enter the marketplace.

We can expect continuing improvements in energy storage systems, so that by the turn of the century advanced systems will permit technologies like electric vehicles and load leveling devices to compete.

ACKNOWLEDGMENTS

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