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Energy Storage, Transmission, and Distribution

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18.1 Energy Storage Technologies

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18.1.1 Overview of Storage Technologies

Energy storage will play a critical role in an efficient and renewable energy future; much more so than it does in today's fossil-based energy economy. There are two principal reasons that energy storage will grow in importance with increased development of renewable energy:

- Many important renewable energy sources are intermittent, and generate when weather dictates, rather than when energy demand dictates.
- Many transportation systems require energy to be carried with the vehicle.¹

Energy can be stored in many forms: as mechanical energy in rotating, compressed, or elevated substances; as thermal or electrical energy waiting to be released from chemical bonds; or as electrical charge ready to travel from positive to negative poles on demand.

¹This is almost always true for private transportation systems, and usually untrue for public transportation systems, which can rely on rails or overhead wires to transmit electric energy. However, some public transportation systems such as buses do not have fixed routes and also require portable energy storage.

TABLE 18.1 Overview of Energy Storage Technologies and Their Applications

	Utility Shaping	Power Quality	Distributed Grid	Automotive
		Direct electric		
Ultracapacitors		✓		✓
SMES		✓		
		Electrochemical		
Batteries				
Lead–acid	✓	✓	✓	
Lithium-ion	✓	✓	✓	✓
Nickel–cadmium	✓	✓		
Nickel–metal hydride				✓
Zebra				✓
Sodium–sulfur	✓	✓		
Flow Batteries				
Vanadium redox	✓			
Polysulfide bromide	✓			
Zinc bromide	✓			
Electrolytic hydrogen				✓
		Mechanical		
Pumped hydro	✓			
Compressed air	✓			
Flywheels		✓		✓
		Direct Thermal		
Sensible Heat				
Liquids			✓	
Solids			✓	
Latent Heat				
Phase change	✓		✓	
Hydration–dehydration	✓			
Chemical reaction	✓		✓	
		Thermochemical		
Biomass solids	✓		✓	
Ethanol	✓			✓
Biodiesel				✓
Syngas	✓			✓

All technologies are discussed in this chapter except hydrogen-based solutions, which are treated in [chapter 27](#) and [chapter 28](#).

Storage media that can take and release energy in the form of electricity have the most universal value, because electricity can efficiently be converted either to mechanical or heat energy, whereas other energy conversion processes are less efficient. Electricity is also the output of three of the most promising renewable energy technologies: wind turbines, solar thermal, and photovoltaics. Storing this electricity in a medium that naturally accepts electricity is favored, because converting the energy to another type usually has a substantial efficiency penalty.

Still, some applications can benefit from mechanical or thermal technologies. Examples are when the application already includes mechanical devices or heat engines that can take advantage of the compatible energy form; lower environmental impacts that are associated with mechanical and thermal technologies; or low cost resulting from simpler technologies or efficiencies of scale.

In this chapter, the technologies are grouped into five categories: direct electric, electrochemical, mechanical, direct thermal, and thermochemical. Table 18.1 is a summary of all of the technologies covered. Each is listed with indicators of appropriate applications that are further explained in [Section 18.1.3](#).

18.1.2 Principal Forms of Stored Energy

The storage media discussed in this chapter can accept and deliver energy in three fundamental forms: electrical, mechanical, and thermal. Electrical and mechanical energy are both considered high-quality

energy because they can be converted to either of the other two forms with fairly little energy loss (e.g., electricity can drive a motor with only about 5% energy loss, or a resistive heater with no energy loss).

The quality of thermal energy storage depends on its temperature. Usually, thermal energy is considered low quality because it cannot be easily converted to the other two forms. The theoretical maximum quantity of useful work W_{\max} (mechanical energy) extractable from a given quantity of heat Q is

$$W_{\max} = \frac{T_1 - T_2}{T_1} \times Q,$$

where T_1 is the absolute temperature of the heat and T_2 is the surrounding, ambient absolute temperature.

Any energy storage facility must be carefully chosen to accept and produce a form of energy consistent with either the energy source or the final application. Storage technologies that accept and/or produce heat should, as a rule, only be used with heat energy sources or with heat applications. Mechanical and electric technologies are more versatile, but in most cases electric technologies are favored over mechanical because electricity is more easily transmitted, because there is a larger array of useful applications, and because the construction cost is typically lower.

18.1.3 Applications of Energy Storage

In Table 18.1 above, each technology is classified by its relevance in one to four different, principal applications:

- *Utility shaping* is the use of very large capacity storage devices to answer electric demand, when a renewable resource is not producing sufficient generation. An example would be nighttime delivery of energy generated by a solar thermal plant during the prior day.
- *Power quality* is the use of very responsive storage devices (capable of large changes in output over very short timescales) to smooth power delivery during switching events, short outages, or plant run-up. Power-quality applications can be implemented at central generators, at switchgear locations, and at commercial and industrial customers' facilities. Uninterruptible power supplies (UPS) are an example of this category.
- *Distributed grid technologies* enable energy generation and storage at customer locations, rather than at a central (utility) facility. The distributed grid is an important, enabling concept for photovoltaic technologies that are effective at a small scale and can be installed on private homes and commercial buildings. When considered in the context of photovoltaics, the energy storage for the distributed grid is similar to the utility shaping application in that both are solutions to an intermittent, renewable resource, but distributed photovoltaic generation requires small capacities in the neighborhood of a few tens of MJ, while utility shaping requires capacities in the TJ range.² Renewable thermal resources (solar, geothermal) can also be implemented on a distributed scale, and require household-scale thermal storage tanks. For the purposes of this chapter, district-heating systems are also considered a distributed technology.
- *Automotive applications* include battery-electric vehicles (EVs), hybrid gasoline–electric vehicles, plug-in hybrid electric vehicles (PHEVs), and other applications that require mobile batteries larger than those used in today's internal combustion engine cars. A deep penetration of automotive batteries also could become important in a distributed grid. Large fleets of EVs or PHEVs that are grid connected when parked would help enable renewable technologies, fulfilling utility shaping and distributed grid functions as well as their basic automotive function.

²Storage capacities in this chapter are given in units of MJ, GJ, and TJ: 1 MJ = 0.28 kWh, 1 GJ = 280 kWh, and 1 TJ = 280 MWh.

Additional energy storage applications exist, most notably portable electronics and industrial applications. However, the four applications described here make up the principal components that will interact in a significant way with the global energy grid.

18.1.4 Specifying Energy Storage Devices

Every energy storage technology, regardless of category, can be roughly characterized by a fairly small number of parameters. Self-discharge time, unit size, and efficiency serve to differentiate the various categories. Within a category, finer selections of storage technology can be made by paying attention to cycle life, specific energy, specific power, energy density, and power density.

Self-discharge time is the time required for a fully charged, noninterconnected storage device to reach a certain depth of discharge (DOD). DOD is typically described as a percentage of the storage device's useful capacity, so that, for instance, 90% DOD means 10% of the device's energy capacity remains. The relationship between self-discharge time and DOD is rarely linear, so self-discharge times must be measured and compared at a uniform DOD. Acceptable self-discharge times vary greatly, from a few minutes for some power-quality applications, to years for devices designed to shape annual power production.

Unit size describes the intrinsic scale of the technology, and is the least well-defined of the parameters listed here. If the unit size is small compared to the total required capacity of a project, complexity and supply shortages can increase the cost relative to technologies with a larger unit size. Some technologies have a fairly large unit size that prohibits small-scale energy storage.

Figure 18.1 maps all of the technologies discussed in this chapter, according to their unit size and 10% self-discharge time. The gamut of technologies available covers many orders of magnitude on each axis, illustrating the broad choice available. Utility shaping applications require a moderate self-discharge time

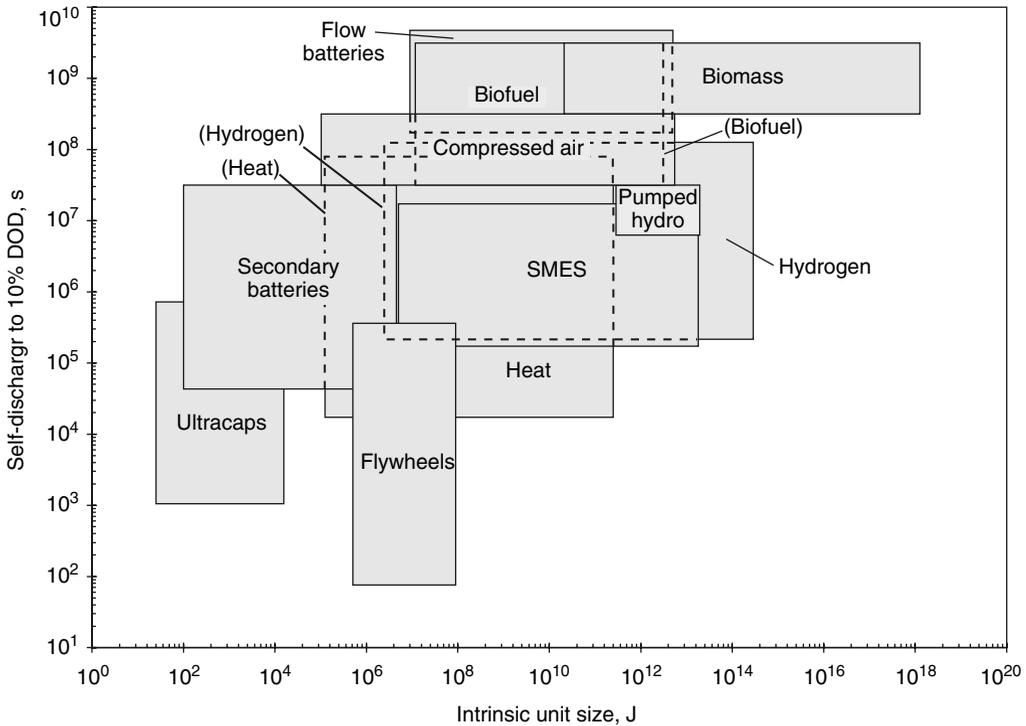


FIGURE 18.1 All storage technologies, mapped by self-discharge time and unit size. Not all hidden lines are shown. Larger self-discharge times are always more desirable, but more or less important depending on the application. Intrinsic unit size does not have a desirability proportional to its value, but rather must be matched to the application.

and a large unit size; power-quality applications are much less sensitive to self-discharge time but require a moderate unit size. Distributed grid and automotive applications both require a moderate self-discharge time and a moderate unit size.

Efficiency is the ratio of energy output from the device, to the energy input. Like energy density and specific energy, the system boundary must be carefully considered when measuring efficiency. It is particularly important to pay attention to the form of energy required at the input and output interconnections, and to include the entire system necessary to attach to those interconnections. For instance, if the system is to be used for shaping a constant-velocity, utility wind farm, then presumably both the input and output will be AC electricity. When comparing a battery with a fuel cell in this scenario, it is necessary to include the efficiencies of an AC-to-DC rectifier for the battery, an AC-powered hydrogen generation system for the fuel cell system, and DC-to-AC converters associated with both systems.

Efficiency is related to self-discharge time. Technologies with a short self-discharge time will require constant charging to maintain a full charge; if discharge occurs much later than charge in a certain application, the apparent efficiency will be lower because a significant amount of energy is lost in maintaining the initial, full charge.

Cycle life is the number of consecutive charge–discharge cycles a storage installation can undergo while maintaining the installation's other specifications within certain, limited ranges. Cycle-life specifications are made against a chosen DOD depending on the application of the storage device. In some cases, for example pressurized hydrogen storage in automobiles, each cycle will significantly discharge the hydrogen canister and the appropriate DOD reference might be 80% or 90%. In other cases, for example a battery used in a hybrid electric vehicle, most discharge cycles may consume only 10% or 20% of the energy stored in the battery. For most storage technologies, cycle life is significantly larger for shallow discharges than deep discharges, and it is critical that cycle-life data be compared across a uniform DOD assumption.

Specific energy is a measure of how heavy the technology is. It is measured in units of energy per mass, and in this chapter this quantity will always be reported in MJ/kg. The higher the specific energy, the lighter the device. Automotive applications require high specific energies; for utility applications, specific energy is relatively unimportant, except where it impacts construction costs.

Energy density is a measure of how much space the technology occupies. It is measured in units of energy per volume, and in this chapter we will always report this quantity in MJ/L. The higher the energy density, the smaller the device. Again, this is most important for automotive applications, and rarely important in utility applications. Typical values for energy density associated with a few automotive-scale energy technologies are listed in Table 18.2, together with cycle-life and efficiency data.

Energy-density and specific-energy estimates are dependent on the system definition. For example, it might be tempting to calculate the specific energy of a flow battery technology by dividing its capacity by the mass of the two electrolytes. But it is important to also include the mass of the electrolyte storage

TABLE 18.2 Nominal Energy Density, Cycle Life and Efficiency of Automotive Storage Technologies

	Energy Density MJ/L	Cycle Life at 80% DOD ^a	Electric Efficiency %
Supercapacitors	0.2	50,000	95
Li-ion batteries	1.8	2,000	85
NiMH batteries	0.6	1,000	80
H ₂ at 350 bar	3.0	n/a ^b	47
H ₂ at 700 bar	5.0	n/a	45
Air at 300 bar	<0.1	n/a	37
Flywheels	<0.1	20,000	80
Ethanol	23.4	n/a	n/a

Electric efficiencies are calculated for electric-to-electric conversion and momentary storage.

^aDepth of discharge.

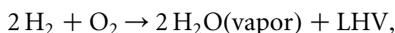
^bNot applicable.

containers, and of the battery cell for a fair and comparable estimate of its specific energy. Therefore, the energy density and specific energy are dependent on the size of the specific device; large devices benefit from efficiency of scale with a higher energy density and specific energy. *Specific power* and *power density* are the power correlates to specific energy and energy density.

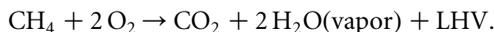
18.1.5 Specifying Fuels

A fuel is any (relatively) homogenous substance that can be combusted to produce heat. Though the energy contained in a fuel can always be extracted through combustion, other processes may be used to extract the energy (e.g., reaction in a fuel cell). A fuel may be gaseous, liquid, or solid. All energy storage technologies in the thermochemical category store energy in a fuel. In the electrochemical category, electrolytic hydrogen is a fuel.

A fuel's lower heating value (LHV) is the total quantity of sensible heat released during combustion of a designated quantity of fuel. For example, in the simplest combustion process, that of hydrogen,



or for the slightly more complex combustion of methane,

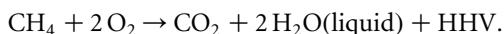


In this chapter, the quantity of fuel is always expressed as a mass, so that LHV is a special case of specific energy. Like specific energy, LHV is expressed in units of MJ/kg in this chapter.

Higher heating value (HHV) is the LHV, plus the latent heat contained in the water vapor resulting from combustion.³ For the examples of hydrogen and methane, this means



and



The latent heat in the water vapor can be substantial, especially for the hydrogen-rich fuels typical in renewable energy applications. [Table 18.3](#) lists LHV and HHV values of fuels discussed in this chapter; in the most extreme case of molecular hydrogen, the HHV is some 18% higher than the LHV. Recovery of the latent heat requires controlled condensation of the water vapor; technologies for doing so are described in [Chapter 13](#).

In this chapter, all heating values are reported as HHV rather than LHV. HHV is favored for two reasons: (1) its values allow easier checking of energy calculations with the principle of energy conservation, and (2) when examining technologies for future implementation, it is wise to keep an intention of developing methods for extracting as much of each energy source's value as possible.

18.1.6 Direct Electric Storage

18.1.6.1 Ultracapacitors

A capacitor stores energy in the electric field between two oppositely charged conductors. Typically, thin conducting plates are rolled or stacked into a compact configuration with a dielectric between them. The dielectric prevents arcing between the plates and allows the plates to hold more charge, increasing the maximum energy storage. The ultracapacitor—also known as supercapacitor, electrochemical capacitor, or electric double layer capacitor (EDLC)—differs from a traditional capacitor in that it employs a thin

³The concepts of sensible and latent heat are explained further in [Section 18.1.9](#).

TABLE 18.3 Properties of Fuels

	Chemical Formula	Density g/L	LHV MJ/kg	HHV MJ/kg
Methanol	CH ₃ OH	794	19.9	22.7
Ethanol	C ₂ H ₅ OH	792	26.7	29.7
Methane	CH ₄	0.68	49.5	54.8
Hydrogen	H ₂	0.085	120	142
Dry syngas, airless process ^a	40H ₂ + 21CO + 10CH ₄ + 29CO ₂	0.89	11.2	12.6
Dry syngas, air process ^a	25H ₂ + 16CO + 5CH ₄ + 15CO ₂ + 39N ₂	0.99	6.23	7.01

^aChemical formulae and associated properties of syngas are representative; actual composition of syngas will vary widely according to manufacturing process.

Source: From All except syngas from U.S. Department of Energy, *Properties of Fuels*, Alternative Fuels Data Center 2004.

electrolyte, on the order of only a few angstroms, instead of a dielectric. This increases the energy density of the device. The electrolyte can be made of either an organic or an aqueous material. The aqueous design operates over a larger temperature range, but has a smaller energy density than the organic design. The electrodes are made of a porous carbon that increases the surface area of the electrodes and further increases energy density over a traditional capacitor.

Ultracapacitors' ability to effectively equalize voltage variations with quick discharges make them useful for power-quality management and for regulating voltage in automotive systems during regular driving conditions. Ultracapacitors can also work in tandem with batteries and fuel cells to relieve peak power needs (e.g., hard acceleration) for which batteries and fuel cells are not ideal. This could help extend the overall life and reduce lifetime cost of the batteries and fuel cells used in hybrid and electric vehicles. This storage technology also has the advantage of very high cycle life of greater than 500,000 cycles and a 10- to 12-year life span.¹ The limitations lie in the inability of ultracapacitors to maintain charge voltage over any significant time, losing up to 10% of their charge per day.

18.1.6.2 Superconducting Magnetic Energy Storage

An superconducting magnetic energy storage (SMES) system is well suited to storing and discharging energy at high rates (high power.) It stores energy in the magnetic field created by direct current in a coil of cryogenically cooled, superconducting material. If the coil were wound using a conventional wire such as copper, the magnetic energy would be dissipated as heat due to the wire's resistance to the flow of current. The advantage of a cryogenically cooled, superconducting material is that it reduces electrical resistance to almost zero. The SMES recharges quickly and can repeat the charge/discharge sequence thousands of times without any degradation of the magnet. A SMES system can achieve full power within 100 ms.² Theoretically, a coil of around 150–500 m radius would be able to support a load of 18,000 GJ at 1000 MW, depending on the peak field and ratio of the coil's height and diameter.³ Recharge time can be accelerated to meet specific requirements, depending on system capacity.

Because no conversion of energy to other forms is involved (e.g., mechanical or chemical), the energy is stored directly and round-trip efficiency can be very high.² SMES systems can store energy with a loss of only 0.1%; this loss is due principally to energy required by the cooling system.³ Mature, commercialized SMES is likely to operate at 97%–98% round-trip efficiency and is an excellent technology for providing reactive power on demand.

18.1.7 Electrochemical Energy Storage

18.1.7.1 Secondary Batteries

A secondary battery allows electrical energy to be converted into chemical energy, stored, and converted back to electrical energy. Batteries are made up of three basic parts: a negative electrode, positive

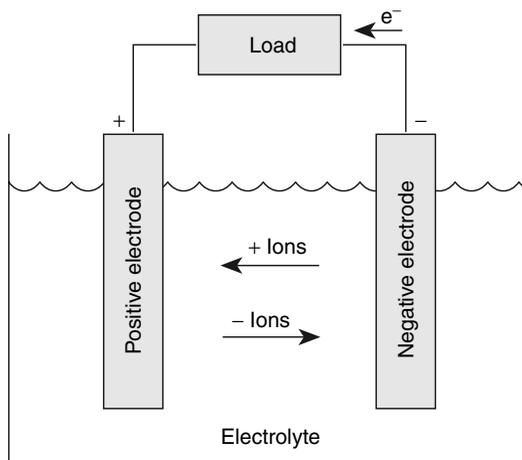


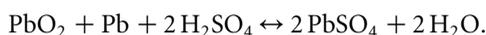
FIGURE 18.2 Schematic of a generalized secondary battery. Directions of electron and ion migration shown are for discharge, so that the positive electrode is the cathode and the negative electrode is the anode. During charge, electrons and ions move in the opposite directions and the positive electrode becomes the anode while the negative electrode becomes the cathode.

electrode, and an electrolyte (Figure 18.2). The negative electrode gives up electrons to an external load, and the positive electrode accepts electrons from the load. The electrolyte provides the pathway for charge to transfer between the two electrodes. Chemical reactions between each electrode and the electrolyte remove electrons from the positive electrode and deposit them on the negative electrode. This can be written as an overall chemical reaction that represents the states of charging and discharging of a battery. The speed at which this chemical reaction takes place is related to the internal resistance that dictates the maximum power at which the batteries can be charged and discharged.

Some batteries suffer from the “memory effect” in which a battery exhibits a lower discharge voltage under a given load than is expected. This gives the appearance of lowered capacity but is actually a voltage depression. Such a voltage depression occurs when a battery is repeatedly discharged to a partial depth and recharged again. This builds an increased internal resistance at this partial depth of discharge and the battery appears as a result to only be dischargeable to the partial depth. The problem, if and when it occurs, can be remedied by deep discharging the cell a few times. Most batteries considered for modern renewable applications are free from this effect, however.

18.1.7.2 Lead–Acid

Lead–acid is one of the oldest and most mature battery technologies. In its basic form, the lead–acid battery consists of a lead (Pb) negative electrode, a lead dioxide (PbO₂) positive electrode and a separator to electrically isolate them. The electrolyte is dilute sulfuric acid (H₂SO₄), which provides the sulfate ions for the discharge reactions. The chemistry is represented by:



(In all battery chemistries listed in this chapter, left-to-right indicates battery discharge and right-to-left indicates charging.)

There are three main types of lead–acid batteries: the flooded cell, the sealed gel cell, and the sealed absorbed glass mat (AGM) lead–acid battery. The wet cell has a liquid electrolyte that must be replaced occasionally to replenish the hydrogen and oxygen that escape during the charge cycle. The sealed gel cell has a silica component added to the electrolyte to stiffen it. The AGM design uses a fiberglass-like separator to hold electrolyte in close proximity to the electrodes, thereby increasing efficiency. For both the gel and AGM configurations, there is a greatly reduced risk of hydrogen explosion and corrosion from

disuse. These two types do require a lower charging rate, however. Both the gel cells and the AGM batteries are sealed and pressurized so that oxygen and hydrogen produced during the charge cycle are recombined into water.

The lead–acid battery is a low-cost and popular storage choice for power-quality applications. Its application for utility shaping, however, has been very limited due to its short cycle life. A typical installation survives a maximum of 1500 deep cycles.⁴ Yet, lead–acid batteries have been used in a few commercial and large-scale energy management applications. The largest one is a 140-GJ system in Chino, California, built in 1988. Lead–acid batteries have a specific energy of only 0.18 MJ/kg and would therefore not be a viable automobile option apart from providing the small amount of energy needed to start an engine. It also has a poor energy density at around 0.25 MJ/L. The advantages of the lead–acid battery technology are low cost and high power density.

18.1.7.3 Lithium-Ion

Lithium-ion and lithium polymer batteries, although primarily used in the portable electronics market, are likely to have future use in many other applications. The cathode in these batteries is a lithiated metal oxide (LiCoO_2 , LiMO_2 , etc.) and the anode is made of graphitic carbon with a layer structure. The electrolyte consists of lithium salts (such as LiPF_6) dissolved in organic carbonates; an example of Li-ion battery chemistry is

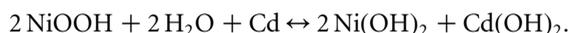


When the battery is charged, lithium atoms in the cathode become ions and migrate through the electrolyte toward the carbon anode where they combine with external electrons and are deposited between carbon layers as lithium atoms. This process is reversed during discharge. The lithium polymer variation replaces the electrolyte with a plastic film that does not conduct electricity but allows ions to pass through it. The 60°C operating temperature requires a heater, reducing overall efficiency slightly.

Lithium-ion batteries have a high energy density of about 0.72 MJ/L and have low internal resistance; they will achieve efficiencies in the 90% range and above. They have an energy density of around 0.72 MJ/kg. Their high energy efficiency and energy density make lithium-ion batteries excellent candidates for storage in all four applications considered here: utility shaping, power quality, distributed generation, and automotive.

18.1.7.4 Nickel–Cadmium

Nickel–cadmium (NiCd) batteries operate according to the chemistry:

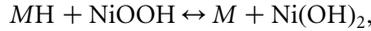


NiCd batteries are not common for large stationary applications. They have a specific energy of about 0.27 MJ/kg, an energy density of 0.41 MJ/L and an efficiency of about 75%. Alaska’s Golden Valley Electric Association commissioned a 40-MW/290-GJ nickel–cadmium battery in 2003 to improve reliability and to supply power for essentials during outages.⁵ Resistance to cold and relatively low cost were among the deciding factors for choosing the NiCd chemistry.

Cadmium is a toxic heavy metal and there are concerns relating to the possible environmental hazards associated with the disposal of NiCd batteries. In November 2003, the European Commission adopted a proposal for a new battery directive that includes recycling targets of 75% for NiCd batteries. However, the possibility of a ban on rechargeable batteries made from nickel–cadmium still remains and hence the long-term viability and availability of NiCd batteries continues to be uncertain. NiCd batteries can also suffer from “memory effect,” where the batteries will only take full charge after a series of full discharges. Proper battery management procedures can help to mitigate this effect.

18.1.7.5 Nickel–Metal Hydride

The nickel–metal hydride (NiMH) battery operates according to the chemistry:



where *M* represents one of a large variety of metal alloys that serve to take up and release hydrogen. NiMH batteries were introduced as a higher energy density and more environmentally friendly version of the nickel–cadmium cell. Modern nickel–metal hydride batteries offer up to 40% higher energy density than nickel–cadmium. There is potential for yet higher energy density, but other battery technologies (lithium-ion, in particular) may fill the same market sooner.

Nickel–metal hydride is less durable than nickel–cadmium. Cycling under heavy load and storage at high temperature reduces the service life. Nickel–metal hydride suffers from a higher self-discharge rate than the nickel–cadmium chemistry. Nickel–metal hydride batteries have a specific energy of 0.29 MJ/kg, an energy density of about 0.54 MJ/L and an energy efficiency of about 70%. These batteries have been an important bridging technology in the portable electronics and hybrid automobile markets. Their future is uncertain because other battery chemistries promise higher energy storage potential and cycle life.

18.1.7.6 Sodium–Sulfur

A sodium–sulfur (NaS) battery consists of a liquid (molten) sulfur positive electrode and liquid (molten) sodium negative electrode, separated by a solid beta-alumina ceramic electrolyte (Figure 18.3). The chemistry is as follows:



When discharging, positive sodium ions pass through the electrolyte and combine with the sulfur to form sodium polysulfides. The variable *x* in the equation is equal to 5 during early discharging, but after free sulfur has been exhausted a more sodium-rich mixture of polysulfides with lower average values of *x* develops. This process is reversible as charging causes sodium polysulfides in the positive electrode to

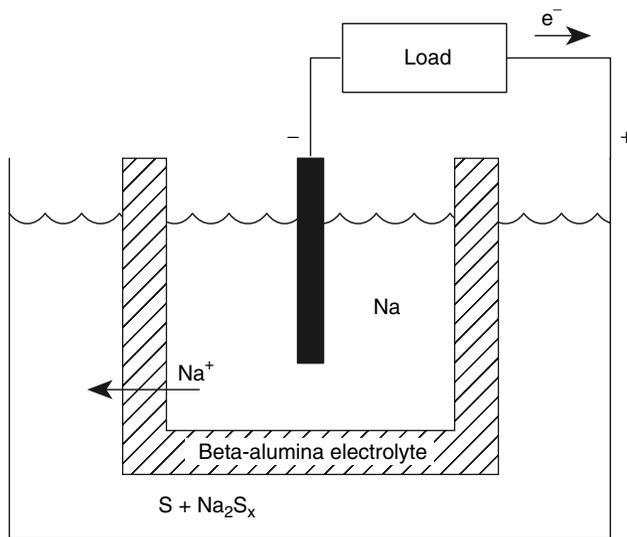
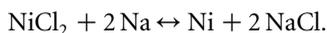


FIGURE 18.3 Sodium–sulfur battery showing discharge chemistry. The sodium (Na) and sulfur (S) electrodes are both in a liquid state and are separated by a solid, beta-alumina ceramic electrolyte that allows only sodium ions to pass. Charge is extracted from the electrolytes with metal contacts; the positive contact is the battery wall.

release sodium ions that migrate back through the electrolyte and recombine as elemental sodium. The battery operates at about 300°C. NaS batteries have a high energy density of around 0.65 MJ/L and a specific energy of up to 0.86 MJ/kg. These numbers would indicate an application in the automotive sector, but warm-up time and heat-related accident risk make its use there unlikely. The efficiency of this battery chemistry can be as high as 90% and would be suitable for bulk storage applications while simultaneously allowing effective power smoothing operations.⁶

18.1.7.7 Zebra

Zebra is the popular name for the sodium–nickel–chloride battery chemistry:



Zebra batteries are configured similarly to sodium–sulfur batteries (see [Figure 18.3](#)), and also operate at about 300°C. Zebra batteries boast a greater than 90% energy efficiency, a specific energy of up to 0.32 MJ/kg and an energy density of 0.49 MJ/L.⁷ Its tolerance for a wide range of operating temperature and high efficiency, coupled with a good energy density and specific energy, make its most probable application the automobile sector, and as of 2003 Switzerland’s MES-DEA is pursuing this application aggressively.⁸ Its high energy efficiency also makes it a good candidate for the utility sector.

18.1.7.8 Flow Batteries

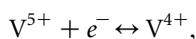
Most secondary batteries use electrodes both as an interface for gathering or depositing electrons, and as a storage site for the products or reactants associated with the battery’s chemistry. Consequently, both energy and power density are tied to the size and shape of the electrodes. Flow batteries store and release electrical energy by means of reversible electrochemical reactions in two liquid electrolytes. An electrochemical cell has two compartments—one for each electrolyte—physically separated by an ion exchange membrane. Electrolytes flow into and out of the cell through separate manifolds and undergo chemical reaction inside the cell, with ion or proton exchange through the membrane and electron exchange through the external electric circuit. The chemical energy in the electrolytes is turned into electrical energy and vice versa for charging. They all work in the same general way but vary in chemistry of electrolytes.⁹

There are some advantages to using the flow battery over a conventional secondary battery. The capacity of the system is scaleable by simply increasing the amount of solution. This leads to cheaper installation costs as the systems get larger. The battery can be fully discharged with no ill effects and has little loss of electrolyte over time. Because the electrolytes are stored separately and in large containers (with a low surface area to volume ratio), flow batteries show promise to have some of the lowest self-discharge rates of any energy storage technology available.

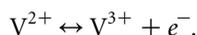
Poor energy densities and specific energies remand these battery types to utility-scale power shaping and smoothing, although they might be adaptable for distributed-generation use. There are three types of flow batteries that are closing in on commercialization: vanadium redox, polysulfide bromide, and zinc bromide.

18.1.7.8.1 Vanadium Redox

The vanadium redox flow battery (VRB) was pioneered at the University of New South Wales, Australia, and has shown potentials for long cycle life and energy efficiencies of over 80% in large installations.¹⁰ The VRB uses compounds of the element vanadium in both electrolyte tanks. The reaction chemistry at the positive electrode is:



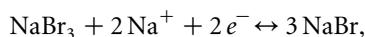
and at the negative electrode,



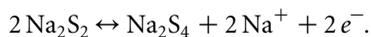
Using vanadium compounds on both sides of the ion-exchange membrane eliminates the possible problem of cross-contamination of the electrolytes and makes recycling easier.¹¹ As of 2005, two small, utility-scale VRB installations are operating, one 2.9-GJ unit on King Island, Australia and one 7.2-GJ unit in Castle Valley, Utah.

18.1.7.8.2 Polysulfide Bromide

The polysulfide bromide battery (PSB) utilizes two salt solution electrolytes, sodium bromide (NaBr) and sodium polysulfide (Na₂S_x). PSB electrolytes are separated in the battery cell by a polymer membrane that only passes positive sodium ions. The chemistry at the positive electrode is



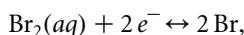
and at the negative electrode,



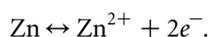
The PSB battery is being developed by Canada's VRB Power Systems, Inc.¹² This technology is expected to attain energy efficiencies of approximately 75%.¹³ Although the salt solutions themselves are only mildly toxic, a catastrophic failure by one of the tanks could release highly toxic bromine gas. Nevertheless, the Tennessee Valley Authority released a finding of no significant impact for a proposed 430-GJ facility and deemed it safe.¹⁴

18.1.7.8.3 Zinc Bromide

In each cell of a zinc bromide (ZnBr) battery, two different electrolytes flow past carbon-plastic composite electrodes in two compartments separated by a microporous membrane. Chemistry at the positive electrode follows the equation:



and at the negative electrode:



During discharge, Zn and Br combine into zinc bromide. During charge, metallic zinc is deposited as a thin-film on the negative electrode. Meanwhile, bromine evolves as a dilute solution on the other side of the membrane, reacting with other agents to make thick bromine oil that sinks to the bottom of the electrolytic tank. During discharge, a pump mixes the bromine oil with the rest of the electrolyte. The zinc bromide battery has an energy efficiency of nearly 80%.¹⁵

Exxon developed the ZnBr battery in the early 1970 s. Over the years, many GJ-scale ZnBr batteries have been built and tested. Meidisha demonstrated a 1-MW/14-GJ ZnBr battery in 1991 at Kyushu Electric Power Company. Some GJ-scale units are now available preassembled, complete with plumbing and power electronics.

18.1.7.9 Electrolytic Hydrogen

Diatomic, gaseous hydrogen (H₂) can be manufactured with the process of electrolysis; an electric current applied to water separates it into components O₂ and H₂. The oxygen has no inherent energy value, but the HHV of the resulting hydrogen can contain up to 90% of the applied electric energy, depending on the technology.¹⁶ This hydrogen can then be stored and later combusted to provide heat or work, or to power a fuel cell (see [Chapter 26](#)).

The gaseous hydrogen is low density and must be compressed to provide useful storage. Compression to a storage pressure of 350 bar, the value usually assumed for automotive technologies, consumes up to

12% of the hydrogen's HHV if performed adiabatically, although the loss approaches a lower limit of 5% as the compression approaches an isothermal ideal.¹⁷ Alternatively, the hydrogen can be stored in liquid form, a process that costs about 40% of HHV using current technology, and that at best would consume about 25%. Liquid storage is not possible for automotive applications, because mandatory boil-off from the storage container cannot be safely released in closed spaces (i.e., garages).

Hydrogen can also be bonded into metal hydrides using an absorption process. The energy penalty of storage may be lower for this process, which requires pressurization to only 30 bar. However, the density of the metal hydride can be between 20 and 100 times the density of the hydrogen stored. Carbon nanotubes have also received attention as a potential hydrogen storage medium.¹⁸ Hydrogen storage technologies are covered in more detail in [Chapter 25](#).

18.1.8 Mechanical Energy Storage

18.1.8.1 Pumped Hydro

Pumped hydro is the oldest and largest of all of the commercially available energy storage technologies, with existing facilities up to 1000 MW in size. Conventional pumped hydro uses two water reservoirs, separated vertically. Energy is stored by moving water from the lower to the higher reservoir, and extracted by allowing the water to flow back to the lower reservoir. Energy is stored according to the fundamental physical principle of potential energy. To calculate the stored energy, E_s , in joules, use the formula:

$$E_s = Vdgh,$$

where V is the volume of water raised (m^3), d is the density of water (1000 kg/m^3), g is the acceleration of gravity (9.8 m/s^2), and h is the elevation difference between the reservoirs (m) often referred to as the *head*.

Though pumped hydro is by nature a mechanical energy storage technology, it is most commonly used for electric utility shaping. During off-peak hours electric pumps move water from the lower reservoir to the upper reservoir. When required, the water flow is reversed to generate electricity. Some high dam hydro plants have a storage capability and can be dispatched as pumped hydro storage. Underground pumped storage, using flooded mine shafts or other cavities, is also technically possible but probably prohibitively expensive. The open sea can also be used as the lower reservoir if a suitable upper reservoir can be built at close proximity. A 30-MW seawater pumped hydro plant was first built in Yanbaru, Japan in 1999.

Pumped hydro is most practical at a large scale with discharge times ranging from several hours to a few days. There is over 90 GW of pumped storage in operation worldwide, which is about 3% of global electric generation capacity.¹⁹ Pumped storage plants are characterized by long construction times and high capital expenditure. Its main application is for utility shaping. Pumped hydro storage has the limitation of needing to be a very large capacity to be cost-effective, but can also be used as storage for a number of different generation sites.

Efficiency of these plants has greatly increased in the last 40 years. Pumped storage in the 1960s had efficiencies of 60% compared with 80% for new facilities. Innovations in variable speed motors have helped these plants operate at partial capacity, and greatly reduced equipment vibrations, increasing plant life.

18.1.8.2 Compressed Air

A relatively new energy storage concept that is implemented with otherwise mature technologies is compressed air energy storage (CAES). CAES facilities must be coupled with a combustion turbine, so are actually a hybrid storage/generation technology.

A conventional gas turbine consists of three basic components: a compressor, combustion chamber, and an expander. Power is generated when compressed air and fuel burned in the combustion chamber

drive turbine blades in the expander. Approximately 60% of the mechanical power generated by the expander is consumed by the compressor supplying air to the combustion chamber.

A CAES facility performs the work of the compressor separately, stores the compressed air, and at a later time injects it into a simplified combustion turbine. The simplified turbine includes only the combustion chamber and the expansion turbine. Such a simplified turbine produces far more energy than a conventional turbine from the same fuel, because there is potential energy stored in the compressed air. The fraction of output energy beyond what would have been produced in a conventional turbine is attributable to the energy stored in compression.

The net efficiency of storage for a CAES plant is limited by the heat energy loss occurring at compression. The overall efficiency of energy storage is about 75%.²⁰

CAES compressors operate on grid electricity during off-peak times, and use the expansion turbine to supply peak electricity when needed. CAES facilities cannot operate without combustion because the exhaust air would exit at extremely low temperatures causing trouble with brittle materials and icing. If 100% renewable energy generation is sought, biofuel could be used to fuel the gas turbines. There might still be other emissions issues but the system could be fully carbon neutral.

The compressed air is stored in appropriate underground mines, caverns created inside salt rocks or possibly in aquifers. The first commercial CAES facility was a 290-MW unit built in Hundorf, Germany in 1978. The second commercial installation was a 110-MW unit built in McIntosh, Alabama in 1991. The third commercial CAES is a 2,700-MW plant under construction in Norton, Ohio. This nine-unit plant will compress air to about 100 bar in an existing limestone mine 2200 ft. (766 m) underground.²¹ The natural synergy with geological caverns and turbine prime movers dictate that these be on the utility scale.

18.1.8.3 Flywheels

Most modern flywheel energy storage systems consist of a massive rotating cylinder (comprised of a rim attached to a shaft) that is supported on a stator by magnetically levitated bearings that eliminate bearing wear and increase system life. To maintain efficiency, the flywheel system is operated in a low vacuum environment to reduce drag. The flywheel is connected to a motor/generator mounted onto the stator that, through some power electronics, interact with the utility grid.

The energy stored in a rotating flywheel, in joules, is given by

$$E = \frac{1}{2} I \omega^2$$

where I is the flywheel's moment of inertia (kg m^2), and ω is its angular velocity (s^{-2}). I is proportional to the flywheel's mass, so energy is proportional to mass and the square of speed. In order to maximize energy capacity, flywheel designers gravitate toward increasing the flywheel's maximum speed rather than increasing its moment of inertia. This approach also produces flywheels with the higher specific energy.

Some of the key features of flywheels are low maintenance, a cycle life of better than 10,000 cycles, a 20-year lifetime and environmentally friendly materials. Low-speed, high-mass flywheels (relying on I for energy storage) are typically made from steel, aluminum, or titanium; high-speed, low-mass flywheels (relying on ω for energy storage) are constructed from composites such as carbon fiber.

Flywheels can serve as a short-term ride-through before long-term storage comes online. Their low energy density and specific energy limit them to voltage regulation and UPS capabilities. Flywheels can have energy efficiencies in the upper 90% range depending on frictional losses.

18.1.9 Direct Thermal Storage

Direct thermal technologies, although they are storing a lower grade of energy (heat, rather than electrical or mechanical energy) can be useful for storing energy from systems that provide heat as a native output (e.g., solar thermal, geothermal), or for applications where the energy's commodity value is heat (e.g., space heating, drying).

Although thermal storage technologies can be characterized by specific energy and energy density like any other storage technology, they can also be characterized by an important, additional parameter: the delivery temperature range. Different end uses have more or less allowance for wide swings of the delivery temperature. Also, some applications require a high operating temperature that only some thermal storage media are capable of storing.

Thermal storage can be classified into two fundamental categories: sensible heat storage and latent heat storage. Applications that have less tolerance for temperature swings should utilize a latent heat technology.

Input to and output from heat energy storage is accomplished with heat exchangers. The discussion below focuses on the choice of heat storage materials; the methods of heat exchange will vary widely depending on properties of the storage material, especially its thermal conductivity. Materials with higher thermal conductivity will require a smaller surface area for heat exchange. For liquids, convection or pumping can reduce the need for a large heat exchanger. In some applications, the heat exchanger is simply the physical interface of the storage material with the application space (e.g., phase-change drywall, see below).

18.1.9.1 Sensible Heat

Sensible heat is the heat that is customarily and intuitively associated with a change in temperature of a massive substance. The heat energy, E_s , stored in such a substance is given by:

$$E_s = (T_2 - T_1)cM,$$

where c is the specific heat of the substance (J/kg °C) and M is the mass of the substance (kg); T_1 and T_2 are the initial and final temperatures, respectively (°C). The specific heat c is a physical parameter measured in units of heat per temperature per mass: substances with the ability to absorb heat energy with a relatively small increase in temperature (e.g., water) have a high specific heat, whereas those that get hot with only a little heat input (e.g., lead) have a low specific heat. Sensible heat storage is best accomplished with materials having a high specific heat.

18.1.9.1.1 Liquids

Sensible heat storage in a liquid is, with very few exceptions, accomplished with water. Water is unique among chemicals in having an abnormally high specific heat of 4,186 J/kg K, and furthermore has a reasonably high density. Water is also cheap and safe. It is the preferred choice for most nonconcentrating solar thermal collectors.

Liquids other than water may need to be chosen if the delivery temperature must be higher than 100°C, or if the system temperature can fall below 0°C. Water can be raised to temperatures higher than 100°C, but the costs of storage systems capable of containing the associated high pressures are usually prohibitive. Water can be mixed with ethylene glycol or propylene glycol to increase the useful temperature range and prevent freezing.

When a larger temperature range than that afforded by water is required, mineral, synthetic, or silicone oils can be used instead. The tradeoffs for the increased temperature range are higher cost, lower specific heat, higher viscosity (making pumping more difficult), flammability, and, in some cases, toxicity.

For very high temperature ranges, salts are usually preferred that balance a low specific heat with a high density and relatively low cost. Sodium nitrate has received the most prominent testing for this purpose in the U.S. Department of Energy's Solar Two Project located in Barstow, California.

Liquid sensible heat storage systems are strongly characterized not just by the choice of heat-transfer fluid, but also by the system architecture. Two-tank systems store the cold and hot liquids in separate tanks (Figure 18.4). Thermocline systems use a single tank with cold fluid entering or leaving the bottom of the tank and hot fluid entering or leaving the top (Figure 18.5). Thermocline systems can be particularly low cost because they minimize the required tank volume, but require careful design to prevent mixing of the hot and cold fluid.

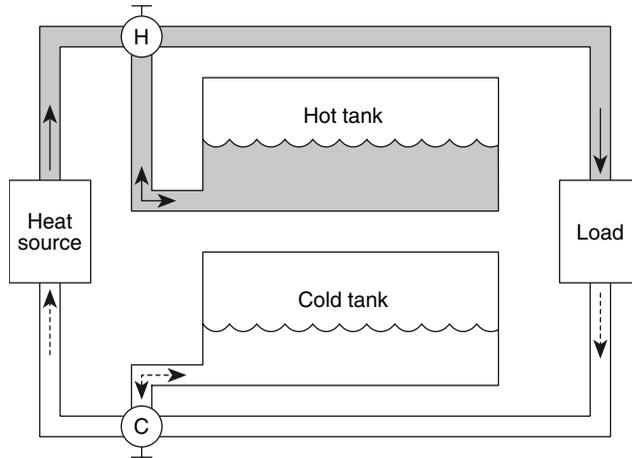


FIGURE 18.4 Two-tank thermal storage system; hot water is shown in gray and cold water is shown in white. When the heat source is producing more output than required for the load, valve H is turned to deposit hot liquid in the tank. When it is producing less than required for the load, the valve is turned to provide supplemental heat from the storage tank. Note that each tank must be large enough to hold the entire fluid capacity of the system.

One particularly interesting application of the thermocline concept is nonconvecting, salinity-gradient solar ponds that employ the concept in reverse. Solar ponds are both an energy collection and energy storage technology. Salts are dissolved in the water to introduce a density gradient, with the densest (saltiest) water on the bottom and lightest (freshest) on top. Solar radiation striking the dark bottom of the pond heats the densest water, but convection of the heated water to the top cannot occur because the density gradient prevents it. Salinity-gradient ponds can generate and store hot water at temperatures approaching 95°C.²²

18.1.9.1.2 Solids

Storage of sensible heat in solids is usually most effective when the solid is in the form of a bed of small units, rather than a single mass. The reason is that the surface-to-volume ratio increases with the number

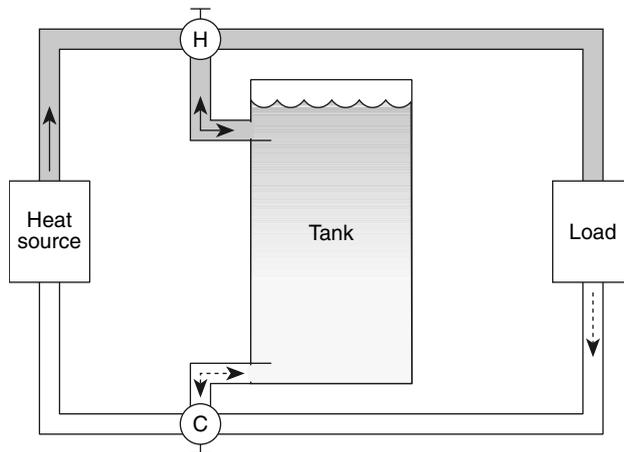


FIGURE 18.5 Thermocline storage tank. Thermocline storage tanks are tall and narrow to encourage the gravity-assisted separation of hot and cold fluid, and include design features (especially at the input/output connectors) to prevent mixing in the stored fluid.

of units, so that heat transfer to and from the storage device is faster for a greater number of units. Energy can be stored or extracted from a thermal storage bed by passing a gas (such as air) through the bed. Thermal storage beds can be used to extract and store the latent heat of vaporization from water contained in flue gases.

Although less effective for heat transfer, monolithic solid storage has been successfully used in architectural applications and solar cookers.

18.1.9.2 Latent Heat

Latent heat is absorbed or liberated by a phase change or a chemical reaction and occurs at a constant temperature. A phase change means the conversion of a homogenous substance among its various solid, liquid, or gaseous phases. One very common example is boiling water on the stovetop: though a substantial amount of heat is absorbed by the water in the pot, the boiling water maintains a constant temperature of 100°C. The latent heat, E_s , stored through a phase change is:

$$E_s = lM,$$

where M is the mass of material undergoing a phase change (kg), and l is the latent heat of vaporization (for liquid–gas phase changes) or the latent heat of fusion (for solid–liquid phase changes), in J/kg; l is measured in units of energy per mass. Conservation of energy dictates that the amount of heat absorbed in a given phase change is equal to the amount of heat liberated in the reverse phase change.

Although the term *phase change* is used here to refer only to straightforward freezing and melting, many sources use the term *phase-change materials* or *PCMs* to refer to any substance storing latent heat (including those described in Section 18.1.9.6 and Section 18.1.9.7, as well.)

18.1.9.2.1 Phase Change

Practical energy storage systems based on a material phase change are limited to solid–solid and solid–liquid phase changes. Changes involving gaseous phases are of little interest due to the expense associated with containing a pressurized gas, and difficulty of transferring heat to and from a gas.

Solid–solid phase changes occur when a solid material reorganizes into a different molecular structure in response to temperature. One particularly interesting example is lithium sulfate (Li_2SO_4) which undergoes a change from a monoclinic structure to a face-centered cubic structure at 578°C, absorbing 214 J/g in the process, more than most solid–liquid phase changes.²³

Some common chemicals, their melting points and heats of fusion are listed in Table 18.4. Fatty acids and paraffins received particular attention in the 1990s as candidate materials for the heat storage component of phase-change drywall, a building material designed to absorb and release heat energy near room temperature for the purpose of indoor temperature stabilization.²⁴ In this application, solids in the drywall maintain the material's structural integrity even though the phase-change materials are transitioning between solid and liquid states.

18.1.9.2.2 Hydration–Dehydration

In this process, a salt or similar compound forms a crystalline lattice with water below a “melting-point” temperature, and at the melting point the crystal dissolves in its own water of hydration. Sodium sulfate (Na_2SO_4) is a good example, forming a lattice with ten molecules of water per molecule of sulfate ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) and absorbing 241 J/g at 32°C.²⁵

Hydration–dehydration reactions have not found significant application in renewable energy systems, although they, too, have been a candidate for phase-change drywall.

18.1.9.2.3 Chemical Reaction

A wide variety of reversible chemical reactions are available that release and absorb heat (see, for example, Hanneman, Vakil, and Wentorf²⁶). The principal feature of this category of latent heat storage technologies is the ability to operate at extremely high temperatures, in some cases over 900°C.

TABLE 18.4 Melting Points and Heats of Fusion for Solid–Liquid Phase Changes

	Melting Point°C	Heat of Fusion J/g
Aluminum bromide	97	42
Aluminum iodide	191	81
Ammonium bisulfate	144	125
Ammonium nitrate	169	77
Ammonium thiocyanate	146	260
Anthracene	96	105
Arsenic tribromide	32	37
Beeswax	62	177
Boron hydride	99	267
Metaphosphoric acid	43	107
Naphthalene	80	149
Naphthol	95	163
Paraffin	74	230
Phosphoric acid	70	156
Potassium	63	63
Potassium thiocyanate	179	98
Sodium	98	114
Sodium hydroxide	318	167
Sulfur	110	56
Tallow	76	198
Water	0	335

Source: From Kreith, F. and Kreider J.F., *Principles of Solar Engineering*, Taylor & Francis, 1978. With permission

Extremely high temperature applications have focused primarily on fossil and advanced nuclear applications; to date, none of these chemical methods of heat storage have been deployed in commercial renewable energy applications.

18.1.10 Thermochemical Energy Storage

This section provides an overview of biomass storage technologies from an energetic perspective only. Additional details on biomass fuels are presented in [Chapter 25](#).

18.1.10.1 Biomass Solids

Plant matter is a storage medium for solar energy. The input mechanism is photosynthesis conversion of solar radiation into biomass. The output mechanism is combustion of the biomass to generate heat energy.

Biologists measure the efficiency of photosynthetic energy capture with the metric net primary productivity (NPP), which is usually reported as a yield in units similar to dry Mg/ha-yr (dry metric tons per hectare per year). However, to enable comparisons of biomass with other solar energy storage technologies, it is instructive to estimate a solar efficiency by multiplying the NPP by the biomass heating value (e.g., MJ/dry Mg) and then dividing the result by the average insolation at the crop's location (e.g., MJ/ha-yr). The solar efficiency is a unitless value describing the fraction of incident solar energy ultimately available as biomass heating value. Most energy crops capture between 0.2 and 2% of the incident solar energy in heating value of the biomass; [Table 18.5](#) shows examples of solar efficiencies estimated for a number of test crops.

The principal method for extracting useful work or electricity from biomass solids is combustion. Therefore, the solar efficiencies listed in [Table 18.5](#) need to be multiplied by the efficiency of any associated combustion process to yield a net solar efficiency. For example, if a boiler-based electric generator extracts 35% of the feedstock energy as electricity, and the generator is sited at a switchgrass plantation achieving 0.30% solar capture efficiency on a mass basis, the electric plant has a net solar

TABLE 18.5 Primary Productivity and Solar Efficiency of Biomass Crops

Location	Crop	Yield (dry Mg/ha-yr)	Average Insolation (W/m ²)	Solar Efficiency(%)
Alabama	Johnsongrass	5.9	186	0.19
Alabama	Switchgrass	8.2	186	0.26
Minnesota	Willow and hybrid poplar	8–11	159	0.30–0.41
Denmark	Phytoplankton	8.6	133	0.36
Sweden	Enthropic lake angiosperm	7.2	106	0.38
Texas	Switchgrass	8–20	212	0.22–0.56
California	<i>Euphorbia lathyris</i>	16.3–19.3	212	0.45–0.54
Mississippi	Water hyacinth	11.0–33.0	194	0.31–0.94
Texas	Sweet sorghum	22.2–40.0	239	0.55–0.99
Minnesota	Maize	24.0	169	0.79
West Indies	Tropical marine angiosperm	30.3	212	0.79
Israel	Maize	34.1	239	0.79
Georgia	Subtropical saltmarsh	32.1	194	0.92
Congo	Tree plantation	36.1	212	0.95
New Zealand	Temperate grassland	29.1	159	1.02
Marshall Islands	Green algae	39.0	212	1.02
New South Wales	Rice	35.0	186	1.04
Puerto Rico	<i>Panicum maximum</i>	48.9	212	1.28
Nova Scotia	Sublittoral seaweed	32.1	133	1.34
Colombia	Pangola grass	50.2	186	1.50
West Indies	Tropical forest, mixed ages	59.0	212	1.55
California	Algae, sewage pond	49.3–74.2	218	1.26–1.89
England	Coniferous forest, 0–21 years	34.1	106	1.79
Germany	Temperate reedswamp	46.0	133	1.92
Holland	Maize, rye, two harvests	37.0	106	1.94
Puerto Rico	<i>Pennisetum purpurcum</i>	84.5	212	2.21
Hawaii	Sugarcane	74.9	186	2.24
Java	Sugarcane	86.8	186	2.59
Puerto Rico	Napier grass	106	212	2.78
Thailand	Green algae	164	186	4.90

Source: From Klass, D. L., *Biomass for Renewable Energy, Fuels, and Chemicals*, Academic Press, San Diego, CA, 1998. With permission.

efficiency of $0.30\% \times 35\% = 0.11\%$. Because biomass is a low-efficiency collector of solar energy, it is very land intensive compared to photovoltaic or solar thermal collectors that deliver energy at solar efficiencies over 20% (see [Chapter 19](#) and [Chapter 21](#) for a full discussion). However, the capacity of land to store standing biomass over time is extremely high, with densities up to several hundred Mg/ha (and therefore several thousand GJ/ha), depending on the forest type. Standing biomass can serve as long-term storage, although multiple stores need to be used to accommodate fire risk. For short-term storage, woody biomass may be dried, and is frequently chipped or otherwise mechanically treated to create a fine and homogenous fuel suitable for burning in a wider variety of combustors.

18.1.10.2 Ethanol

Biomass is a more practical solar energy storage medium if it can be converted to liquid form. Liquids allow for more convenient transportation and combustion, and enable extraction on demand (through reciprocating engines) rather than through a less dispatchable, boiler- or turbine-based process. This latter property also enables its use in automobiles.

Biomass grown in crops or collected as residue from agricultural processes consists principally of cellulose, hemicellulose, and lignin. The sugary or starchy by-products of some crops such as sugarcane, sugar beet, sorghum, molasses, corn, and potatoes can be converted to ethanol through fermentation processes,

and these processes are the principal source of ethanol today. Starch-based ethanol production is low efficiency, but does succeed in transferring about 16% of the biomass heating value to the ethanol fuel.²⁷

When viewed as a developing energy storage technology, ethanol derived from cellulose shows much more promise than the currently prevalent starch-based ethanol.²⁸ Cellulosic ethanol can be manufactured with two fundamentally different methods: either the biomass is broken down to sugars using a hydrolysis process, and then the sugars are subjected to fermentation; or the biomass is gasified (see below), and the ethanol is subsequently synthesized from this gas with a thermochemical process. Both processes show promise to be far cheaper than traditional ethanol manufacture via fermentation of starch crops, and will also improve energy balances. For example, it is estimated that dry sawdust can yield up to 224 L/Mg of ethanol, thus recovering about 26% of the higher heating value of the sawdust.²⁹ Because the ethanol will still need to be combusted in a heat engine, the gross, biomass-to-useful-work efficiency will be well below this. In comparison, direct combustion of the biomass to generate electricity makes much more effective use of the biomass as an energy storage medium. Therefore, the value of ethanol as an energy storage medium lies mostly in the convenience of its liquid (rather than solid) state.

18.1.10.3 Biodiesel

As starch-based ethanol is made from starchy by-products, most biodiesel is generated from oily by-products. Some of the most common sources are rapeseed oil, sunflower oil, and soybean oil. Biodiesel yields from crops like these range from about 300 to 1000 kg/ha-yr, but the crop as a whole produces about 20 Mg/ha-yr, meaning that the gross solar capture efficiency for biodiesel from crops ranges between 1/20 and 1/60 the solar capture efficiency of the crop itself. Because of this low solar-capture efficiency, biomass cannot be the principal energy storage medium for transportation needs.³⁰

Biodiesel can also be manufactured from waste vegetable or animal oils; however, in this case, the biodiesel is not functioning per se as a solar energy storage medium, so is not further treated in this work.

18.1.10.4 Syngas

Biomass can be converted to a gaseous state for storage, transportation, and combustion (or other chemical conversion).³¹ Gasification processes are grouped into three different classes: *pyrolysis* is the application of heat in anoxic conditions; *partial oxidation* is combustion occurring in an oxygen-starved environment; *reforming* is the application of heat in the presence of a catalyst. All three processes form syngas, a combination of methane, carbon monoxide, carbon dioxide and hydrogen. The relative abundances of the gaseous products can be controlled by adjusting heat, pressure, and feed rates. The HHV of the resulting gas can contain up to 78% of the original HHV of the feedstock, if the feedstock is dry.²⁹ Compositions and heating values of two example syngases are listed in Table 18.3.

The equivalent of up to 10% of the gas HHV will be lost when the gas is pressurized for transportation and storage. Even with this loss, gasification is a considerably more efficient method than ethanol manufacture for transferring stored solar energy to a nonsolid medium.

18.2 Advanced Concepts in Transmission and Distribution

Robert Pratt, Christopher P. Schaber, and Steve Widergren

18.2.1 Introduction

Global prosperity depends upon efficient and affordable energy. Without a major shift in the way energy systems are planned, built, and operated, the world will invest trillions of dollars in conventional electric infrastructure over the next 20 years to meet expected growth.^{32,33}

The future electric system will incorporate information technology in revolutionary ways, much as information technology has transformed other aspects of business because, fundamentally, “bits are cheaper than iron.” The impact of the information age on the electric system will allow nations to realize

the benefits already achieved by leading-edge industries that use real-time information, distributed e-business systems and market efficiencies to minimize the need for inventory and infrastructure and to maximize productivity, efficiency, and reliability.

With the help of information technologies, the creation of a distributed, yet integrated, system will empower consumers to participate in energy markets—the key to stabilizing prices. Market participants from utilities to new third parties to consumers will create value by developing and deploying solutions that cross enterprise and regulatory boundaries. At the same time, this transformation of the energy system addresses the urgent need to enhance national security. A distributed, network-based electric system will reduce single-point vulnerabilities and allow the grid to become “self-healing” by incorporating autonomic system reconfiguration in response to human-caused or natural disruptions.

Deploying information technology in a highly connected world will maximize the use of existing assets and minimize the need for new assets. To do this, the future electric system will:

- Provide the incentive for customer and third-party assets to collaborate with existing grid assets to control costs and improve reliability by revealing the true time- and location-dependent value of electricity
- Provide the basis for collaboration by allowing the revealed values to be shared in real time by leveraging broadband communications that are rapidly becoming ubiquitous
- Provide the means to take advantage of the opportunities for collaboration and capture value in return through rapid advances in distributed controls and e-business applications

Much of the challenge and opportunity presented by these solutions is that their value proposition often involves crossing enterprise and regulatory boundaries. This means that nontechnical challenges must be addressed to support policy changes and business models that allow new technology and operational practices to flourish.

Information technology will profoundly transform the planning and operation of the power grid, just as it has changed business, education, and entertainment. It will form the “nervous system” that integrates new distributed technologies—demand response, distributed generation, and storage—with traditional grid generation, transmission, and distribution assets to share responsibility for managing the grid as a collaborative “society” of devices.^{35–38}

18.2.2 Technology Advancements for Electricity Delivery

The following sections describe new technologies, or concepts that are becoming more economically feasible, for application to improved operation of the electric system. These are summarized in three general categories: distributed resources, transmission and distribution resources, information and communications technology, and control, applications, and operational paradigms.

18.2.2.1 Distributed Resources

Distributed resources are physical, capital assets that generate, store, or consume electric power at the fringes of the electric delivery system. Traditionally, these resources have not been broadly considered or deployed as transmission and distribution assets; however, significant efforts are underway to take advantage of such existing resources, and to provide motivation for future installations that can further benefit the system.³⁴ This section describes several of the resources that fall into this category:

End Use Control. Manual or automated control of end use systems to reduce or defer electric power use is an important element in active measures for enhancing delivery operations. Automatic load shedding (under-frequency, under-voltage), operator-initiated interruptible load, demand-side management programs, voltage reduction, and other load curtailment strategies have long been an integral part of coping with unforeseen contingencies as a last resort, and/or as a means of assisting the system during high-stress, overloaded conditions. Advances in load control technology will allow end use systems to play a more active role in the day-to-day operations of the electric system as well as create a more graceful response to emergency conditions.

Intelligent Building Systems. Intelligent building systems are emerging in factories, commercial buildings, and now residential facilities. These systems save energy by increasing efficient operations. Coordinated utilization of cooling, heating, and electricity in these establishments can significantly reduce energy consumption. Operated in a system that supports price-responsive demand programs, intelligent building systems can locally optimize operations to the benefit of larger system concerns.

System-Sensitive Appliances. System-sensitive appliances are emerging with the ability to measure and respond to frequency or voltage conditions or to react to simple signals, such as energy prices or emergency conditions. Washers, dryers, HVAC units, and other devices now come equipped with onboard intelligent systems that have the potential to respond to energy signals (see Control, Applications, and Operational Paradigms section below).

Distributed Generation (DG). Fuel cells, microturbines, reciprocating engines, and small renewable generation such as wind and solar power, are increasingly being deployed across the system. DG can supply local load or sell into the system and offers owners self-determination. As these distributed resources increase in number, they can become a significant resource for reliable system operations. Their vast numbers teamed with end use systems adds a further dimension to the advantages of controllable load discussed above.

Combined-Heating Power (CHP). Combined-heating-power and buildings-cooling-heating-power (BCHP) are systems that combine distributed fuel-fired generation with equipment that recovers waste heat for heating or cooling at the for a building, facility, or district, maximizing the utilization of fuel.

Renewable Generation. Renewable generation includes small wind-power, photovoltaic solar, and other renewable generation systems connected at the distribution level. Note that large wind farms are similar to central generation in that they do not displace the need for transmission and distribution assets. Unlike distributed fuel-fired generation, renewable generation is difficult to dispatch coincident with the needs of the grid, unless a storage system is involved.

Local Energy Storage. Systems that store energy locally for the benefit of end use systems can also be aggregated to the benefit of larger system operation concerns.

Electric Storage. Systems that store electricity for later discharge include traditional batteries, flow batteries, supercapacitors, flywheels, and extend to uninterruptible power supplies modified to support local system operations.

Thermal Storage. These systems store energy used for heat or cooling, usually in the form of hot or chilled water or ice, for later use in a building or an industrial process. The ability to “charge” to or “draw” from these resources provides flexibility to the timing of electricity use.

Direct DC End Use. Returning to the days of Edison, equipment within customer premises are emerging that distribute and use DC power directly (instead of converting it from AC with attendant cost and inefficiencies) such as computers and electronic equipment, fans, pumps and other equipment with variable speed drives, battery chargers, and uninterruptible power supplies. DC distribution is especially useful if onsite generation inherently involves DC power directly or at an intermediate stage, such as from photovoltaics, microturbines, and fuel cells.

Local Voltage Regulation. Transformers, capacitors, or power electronics equipment that maintains voltage at the customer meter at a specified nominal level, can reduce wasted consumption from over-voltage while allowing higher-than-nominal distribution voltages to increase system throughput during times of peak demand.

Advanced Energy Efficiency. Investments in improved equipment, building structure, or industrial processes can reduce the quantity of electricity consumed yet provide equivalent service. Efficiency benefits occur with sensitivity to the end use being served, but are indifferent to the needs of the grid.

18.2.2.2 Transmission and Distribution Resources

The transmission and distribution (T & D) system of the future must not only have increased capacity to support the market demand for energy transactions, it must also be flexible to adapt to alterations in energy delivery patterns. These patterns change at various timescales: hourly, daily, weekly, and seasonally. The delivery system must also adapt to operation patterns dictated by the evolving

geographical distribution of load and generation. As generation siting and dispatch decision making become less predictable and demand-side resources play a larger role in system operations, new technologies that afford transmission and distribution planners a wider range of alternatives for deployment of power become more attractive. This section discusses some of the newer hardware technologies that are being researched and deployed to reinforce grid operations. The list presented is not exhaustive.^{39–41}

Conductors. The siting of the new transmission will continue to be a major challenge. Getting the most out of existing rights of way minimizes the need for new lines and rights of way and can minimize the societal concerns associated with visual pollution and high-energy EMFs.

Advanced Composite Conductors. Usually, transmission lines contain steel-core cables that support strands of aluminum wires that are the primary conductors of electricity. New cores developed from composite materials are proposed to replace the steel core. A new core consisting of composite glass-fiber materials shows promise as stronger than steel-core aluminum conductors while being 50% lighter in weight with up to 2.5 times less sag. The reduced weight and higher strength equate to greater current-carrying capability. This technology can be integrated in the field by most existing reconductoring equipment.

High-Temperature Superconducting (HTSC) Technology. The conductors in HTSC devices operate at extremely low resistances. They require refrigeration (generally liquid nitrogen) to supercool ceramic superconducting materials. The technology is applicable to transmission lines, transformers, reactors, capacitors, and current limiters. HTSC cable occupies less space (AC transmission lines bundle three phase together; transformers and other equipment occupy smaller footprint for same level of capacity). Exposure to EMFs can be reduced with buried cables and this also counteracts visual pollution issues. Transformers can reduce or eliminate cooling oils that, if spilled, can damage the environment. For now, the maintenance costs remain high.

Below-Surface Cables. The underground cable advancements are employing fluid-filled polypropylene paper laminate (PPL) and extruded dielectric polyethylene (XLPE) cable technologies. Other approaches, such as gas-insulated transmission lines (GIL), are being researched and hold promise for future applications. Although there have been significant improvements in the technology, manufacturing costs remain high.

T & D Configurations. Advances are being made in the configuration of transmission lines. New design processes coupled with powerful computer programs can optimize the height, strength, and positioning of transmission towers, insulators, and associated equipment in order to meet engineering standards appropriate for the conductor (e.g., distance from ground and tension for a given set of weather parameters).

Tower and Pole Design Tools. A set of tools is emerging to analyze upgrades to existing transmission facilities or the installation of new facilities to increase their power-transfer capacity and reduce maintenance. Unused potential can be discovered in existing facilities to enhance upgrades, whereas new facilities can be engineered to closer design tolerances. Visualization techniques are adding the regulatory and public review cycles.

Modular Equipment. One way to gain flexibility for changing market and operational situations is to develop standards for the manufacture and integration of modular equipment. This can reduce overall the time and expense for transmission systems to adapt to the changing economic and reliability landscape.

T & F System Devices. Implemented throughout the system, these devices include capacitors, phase shifters, static VAR compensators (SVCs), thyristor-controlled series capacitors (TCSC), thyristor-controlled dynamic brakes, and other similar devices. Used to adjust system impedance, these devices can increase the delivery system's transfer capacity, support bus voltages by providing reactive power, or enhance dynamic or transient stability.

HVDC. With active control of real and reactive power transfer, HVDC can be modulated to damp oscillations or provide power-flow dispatch independent of voltage magnitudes or angles (unlike conventional AC transmission). HVDC runs independent of system frequency and can control the

amount of power sent through the line. This latter benefit is the same as for FACTS devices discussed below. The high cost of converter equipment and its maintenance limits the application; however, as these costs continue to drop, the number of implementations will rise. Proposals have been made for DC application at the distribution level. The military continues to advance the technology in shipboard systems and mobile land-based facilities.

Flexible AC Transmission System (FACTS). FACTS devices use power electronics to adjust the apparent impedance of the system. Capacitor banks are applied at loads and substations to provide capacitive reactive power to offset the inductive reactive power typical of most power system loads and transmission lines. With long inter-tie transmission lines, series capacitors are used to reduce the effective impedance of the line. By adding thyristors to both of these types of capacitors, actively controlled reactive power is available using static VAR compensators and thyristor-controlled series compensators, which are shunt- and series-controlled capacitors, respectively. The thyristors are used to adjust the total impedance of the device by switching individual modules. Unified power-flow controllers (UPFCs) also fall into this category. Phase shifters are transformers configured to change the phase angle between buses; they are particularly useful for controlling the power flow on the transmission network. Adding thyristor control to the various tap settings of the phase-shifting transformer, permits continuous control of the effective phase angle (and thus control of power flow). As with HVDC, the power electronics used in these devices are expensive in price and maintenance, but costs are dropping.

T & D Energy Storage. The traditional function of an energy storage device is to save production costs by holding cheaply generated off-peak energy that can be dispatched during peak consumption periods. By virtue of its attributes, energy storage can also provide effective power system control with modest incremental investment. Different dispatch modes can be superimposed on the daily cycle of energy storage, with additional capacity reserved for the express purpose of providing these control functions. Storage at the bulk system level also benefits the integration of intermittent renewable resources such as wind and solar power. The loss of efficiency between converting electricity into and out of storage is an important consideration in deploying these resources.

Batteries. Large battery systems use converters to transform the DC in the storage device to the AC of the power grid. Converters also operate in the opposite direction to recharge the batteries. Battery converters use power electronics that, by the virtue of their ability to change the power exchange rapidly, can be utilized for a variety of real-time control applications ranging from enhancing transient stability to preconditioning the area control error for automatic generator control enhancement. The expense of manufacturing and maintaining batteries has limited their impact in the industry.

Superconducting Magnetic Energy Storage (SMES). SMES uses cryogenic technology to store energy by circulating current in a superconducting coil. SMES devices are efficient and compact because of their superconductive properties. As with the superconducting equipment mentioned above, SMES entails costs for the cooling system, special protection, and the specialized skills required to maintain the device.

Pumped Hydro and Compressed Air Storage. Pumped hydro consists of large ponds with turbines that can be run in either pump or generation modes. During periods of light load (e.g., night) excess, inexpensive capacity drives the pumps to fill the upper pond. During heavy-load periods, the water generates electricity into the grid. Compressed air storage uses the same principle except that large, natural underground vaults are used to store air under pressure during light-load periods. Pumped hydro, like any hydro generation project, requires significant space and has corresponding ecological impact. Compressed air storage systems require special geological formations.

Flywheels. Flywheels spin at high velocity to store energy. As with pumped hydro or compressed air storage, the flywheel is connected to a motor that either accelerates the flywheel to store energy or draws energy to generate electricity. Superconductivity technology can also be deployed to increase efficiency.

18.2.2.3 Information and Communications Technology

Automation and the ability to coordinate intelligent systems across wide areas are transforming all areas of our economy. The electric system is leveraging advances in generally available information and

communication resources to enhance its operational effectiveness and incorporate new participants at the fringes of the system in operations.

Communication Media. Wireless, power line carrier, cable, fiber, and other forms of broadband communication to delivery system components and end use premises is beginning to carry the information needed to implement new applications such as, consumption data, sensor data on grid conditions, and e-commerce information including service offerings, prices, contract terms, and incentives.

Information Security. Technology that provides secure and reliable communications is essential to prevent intrusion by unauthorized parties or those without a need or right to know specific information.

Privacy and Authentication. Grid operators, consumers and businesses all demand technology that ensures the privacy of information is maintained and the identity of participants is unambiguous.

E-commerce Transactions. Technology that manages a multitude of small financial transactions in an auditable and traceable way will provide the financial incentive for day-to-day, moment-by-moment collaboration of end users with the grid (e.g., micropayments).

Real-Time Monitoring. The capability of the electricity grid is restricted through a combination of the limitations on individual devices and the composite capacity of the system. Improving monitoring to determine these limits in real time and to measure the system state directly can increase grid capability.

Power-System Device Sensors. Advancement in sensor technology is enabling dynamic ratings on the use of T&D resources. This includes the measurement of conductor sag, transformer coil temperature, and underground cable monitoring and diagnostics.

System-State Sensors. Technology advancements are improving the operational view of large regions of the power network. Power-system monitors collect essential signals (key power flows, bus voltages, alarms, etc.) from local monitors and make them available to site operation functions. This provides regional surveillance over important parts of the control system to verify system performance in real time. Sample rates and data quality is increasing as costs decrease. For example, phasor measurement units (PMUs) are synchronized digital transducers that stream data, in real time, to phasor data concentrators (PDC). The general functions and topology for this network resemble those for dynamic monitor networks. Data quality for phasor technology is trustworthy, and secondary processing of the acquired phasor information can provide a broad range of signal types.

Advanced Meters. Electric usage meters at customer premises are being replaced with technology that not only measures the energy usage, but also provides flexible interval energy monitoring and real-time power measurement to address needs such as peak usage, and power quality.

18.2.3 Control, Applications, and Operational Paradigms

The technologies summarized in the previous sections can be integrated into the electric system in a cooperative manner to address many applications: existing, proposed, and yet to be invented. There are many potential applications; some emerging ones are listed below and organized by end use, distribution, transmission, electricity service provider, and market operations.

18.2.3.1 End Use Operations and Planning

The management of end use resources in factories, commercial buildings, and residential facilities offer arguably the greatest area for advancement and contribution to system operations. Some important applications include the following:

- Customer information gateways: information portals that support two-way communications, including real-time price signals and long-term contracts, across the customer enterprise boundary to suppliers, grid operators, and other third parties.
- Demand response and energy management systems: controls that optimize the scheduling of energy use by appliances, equipment, and processes to minimize overall costs for electricity and respond to incentives from the service providers to curtail loads at times of peak demand or grid distress.
- System-sensitive appliances, equipment, and processes: controls that autonomously sense

disturbances in grid frequency and voltage, directing end use devices to immediately curtail their demand for periods of up to a few minutes (or, conversely, turning things like heating elements on to soak up momentary fluctuations of excess power) to prevent or arrest cascading blackouts. They also delay device restart after a voltage collapse or a blackout, easing service restoration by preventing the surge in demand from devices that have been without power for a while.

- Autonomous agents for power purchases: software serving as the trading agent on behalf of customers, searching market opportunities and arranging for the lowest cost suppliers, including subsequently auditing power bills to ensure fair play.

18.2.3.2 Distribution Operations and Planning

- Automated meter reading: a smart meter allows the customer and their suppliers to access the electric meter to enable automated meter reading for billing and other purposes as well as access to consumption data by end use energy management systems.
- Distribution automation: advanced distribution grid management systems that optimize supply voltage, manage peak demands by reconfiguring feeders to switch customers from one supply point to another, minimize the number of customers affected by outages, and accelerate outage restoration. This includes advanced protection schemes that adapt protection device settings based on operating conditions.
- Fault location and isolation: use advanced sensing and communications to better identify the location of faults, then invoke distribution automation capabilities to reconfigure feeders, safely reenergize as much of the affected region as possible, and inform work crews to repair the problem. Diagnostics and fault location tools for underground cables represent an important aspect of this area.
- Distribution capacity marketplaces: software that projects the need for new distribution capacity, posting the cost of required upgrades and allowing customers and third parties to offer distributed resource projects (such as distributed generation, efficiency, and demand response) to defer or avoid construction; then operating those resources through local market signals or incentives to manage net demand at the capacity constraint.
- Distributed generation for reactive power support and other ancillary services: software that manages customer-owned distributed generators to support the power grid by supplying reactive power in addition to real power and other ancillary services like spinning and nonspinning reserves, via direct dispatch based on prearranged contracts or indirect dispatch through markets or incentives.

18.2.3.3 Transmission Operations and Planning

- Transactive control for transmission grids: systems for trading real-time transmission rights, analogous to automated stock market trading systems, that allow market signals to cause suppliers and load serving entities to shift or curtail wheeling of power from one region to another, effectively reconfiguring the power grid in real time in response to a potential or pending crisis.
- Substation automation: device-level intelligence combines with high-speed, reliable communications to improve operations effectiveness. For example, transformer tap changes will coordinate with capacitor banks to perform voltage or reactive power control functions. More and better quality information is used locally for adaptive relay protection schemes that change their settings based on present system configuration information. Information exchanged between neighboring substations can be used to further coordinate system protection schemes and economic operation.

- **Regional control:** on a regional level, remedial action schemes can adaptively arm themselves based on updated information from several points in the system. Regional control centers can also coordinate the transmission operating configuration based on gathering better information from the field. For example, the results from system studies, such as contingency analysis and optimal power flow can make use of dynamic line ratings that are regularly updated based on weather forecasts and sag measurements from the field.

18.2.3.4 Electricity Service Provider Operations and Planning

- **Differentiating customer service levels:** systems that integrate demand response, distribution automation, and local distributed generation to supply premium reliability service to customers that require it, providing digital quality power to those willing to pay a premium without “gold-plating” the system for other customers satisfied with current service.
- **Emergency end use curtailment:** communications and control software that broadcasts emergency status information and leverages demand response capabilities to ration power to customers on a prearranged basis, providing power for critical customers and end uses while curtailing less critical demand to match the available supply; the intent is for everyone to have some power in a crisis rather than using rolling blackouts, for instance.

18.2.3.5 Market Operations and Forecasting

- **Market operations:** software that operates markets and incentives that engage distributed resources and demand response to manage peak demands and ancillary services in supply, transmission, and local distribution systems.
- **Load forecasters:** algorithms that provide continually updated, adaptive predictions of the demand for electricity at various levels in the system ranging from end use to distribution and transmission, as it responds to changes in conditions such as weather and price; based on techniques ranging from statistical methods and neural networks to engineering model parameter estimation.

18.2.4 System-Sensitive Appliances

The abundance of information, including price signals and grid conditions, will allow demand-response technologies to play a significant role in a virtual energy infrastructure. Consider that regardless of time of day or even time of year, about 20% of the load on the electric system is from consumer appliances that cycle on and off, such as heating, air conditioning, water heaters, and refrigerators. At the same time, generators also maintain steady operating reserves on “hot standby” that are equivalent to about 13% of the total load on the system in case problems suddenly arise. Why not find a way to reduce the demand of these appliances in times when operators would typically be dipping into the expensive cushion?

The (Grid Friendly™ controller) low-cost sensors embedded in appliances can sense grid conditions by monitoring the frequency of the system and provides automatic demand response in times of disruption. Within each interconnected operating region, a disturbance reflected in the system frequency is a universal indicator of serious imbalance between supply and demand that, if not relieved, can lead to a blackout. A simple computer chip installed in end use appliances can reduce the appliance’s electricity demand for a few minutes or even a few seconds to allow the grid to stabilize. The controllers can be programmed to autonomously react in fractions of a second when a disturbance is detected whereas power plants can take minutes to come up to speed.⁴²

As these controllers penetrate the appliance marketplace, important control issues must be addressed. For example, the control approach must deactivate appliances in a graduated manner so as not to “shock” the grid by dropping more load than necessary to rebalance supply and demand.⁴³ They must

also be reactivated after the crisis in a similarly smooth fashion. It may be highly desirable to organize this response as a hierarchy ordered from the least to the highest priority end uses—from the least critical functions, such as air conditioning, to the most critical functions, such as communications, traffic control, water, sewage, and fuel pumps. Then, if a crisis persists, grid operators can allocate power to end uses simply by maintaining grid frequency at small increments below the normal range. Managing demand in the power grid in an “all-or-nothing” fashion will no longer be necessary.

By integrating the controllers with appliances at the factory, costs can be reduced to a few dollars per appliance. Done properly, consumers will not even notice the short interruption (by turning off the compressor in a refrigerator, but leaving the light on, for example). In the process, consumers become an integral part of power-grid operations and could even be rewarded for their participation in helping prevent a widespread outage. Therefore, without the need for any formal communications capability, appliances are transformed from being part of the problem to part of the solution. They now act as assets that form a much quicker and better safety net under the power grid, freeing up power plants from standby duty to increase competition, lower prices and meet future load growth. Moreover, because they act autonomously, no communication system is required beyond the power grid itself. However, when a communication system becomes available, the “smarts” are already on board the appliances to do much more sophisticated negotiation and control, such as reducing peak loads.

18.2.5 Markets + Control = The Transactive Network

Transactive (e.g., contract) networks and agent-based systems present an opportunity to implement process controls in which highly optimized control (both local and global) is an inherent attribute of the strategy rather than an explicitly programmed feature. The premise of transaction-based control is that interactions between various components in a complex energy system can be controlled by negotiating immediate and contingent contracts on a regular basis in lieu of standard on/off command and control. Each device is given the ability to negotiate deals with its peers, suppliers and customers in order to maximize revenues while minimizing costs. This is best illustrated by an example.

18.2.5.1 The End Use Facilities Marketplace

A typical building might have several chillers that supply a number of air handlers with chilled water on demand. If several air handlers require the full output of one chiller, and another air handler suddenly also requires cooling, traditional building control algorithms simply startup a second chiller to meet the demand and the building's electrical load ratchets upward accordingly.

A transaction-based building control system behaves differently. Instead of honoring an absolute demand for more chilled water, the air handler requests such service in the form of a bid (expressed in dollars), increasing its bid in proportion to its “need” (divergence of the zone temperature from its setpoint). The chiller controls, with knowledge of the electric rate structure, can easily express the cost of service as the cost of the kWh to run the additional chiller plus the incremental kW demand charge. If the zone served by this air handler just began to require cooling, its “need” is not very great at first, and so it places a low value on its bid for service and the additional chiller stays off until the level of need increases. Meanwhile, if another air handler satisfies its need for cooling, the cost of chilled water immediately drops below the bid price because a second chiller is no longer required, and the air handler awaiting service receives chilled water.

This is analogous to air traffic control where a limited resource is managed by scheduling demand into time slots. Alternatively, a peer-to-peer transaction can take place in which an air handler with greater need for service displaces (literally outbids) another whose thermostat is nearly satisfied.

In this way, the contract-based control system accomplishes several things. First, it inherently limits demand by providing the most “cost-effective” service. In doing this, it inherently prioritizes service to the most important needs before serving less important ones. Second, it decreases energy consumption by preventing the operation of an entire chiller to meet a small load, where it operates inefficiently.

Third, contract-based controls inherently propagate cost impacts up and down through successive hierarchical levels of the system being controlled (in this example, a heating/cooling system). The impacts on the utility bill, which are easily estimated for the chiller operation, are used as the basis for expressing the costs of air handler and zone services. Using cost as a common denominator for control makes expression of what is effectively a multilevel optimization much simpler to express than an engineered solution would be. It allows controls to be expressed in local, modular terms while accounting for their global impact on the entire system.

In effect, the engineering decision-making process is subsumed by a market value-based decision-making process that injects global information conveyed by market activity (i.e., asks, bids, immediate and contingent contracts, closings, and defaults) into the local engineering parameters that govern the behavior of individual systems over multiple timescales.

18.2.5.2 The Distribution Marketplace

One of the most critical, yet difficult, parts of the value chain to reveal is the value of new or expanded distribution capacity. When distribution utilities determine a need to add or increase the capacity of a substation, it is typical for the costs to range from \$100/kW to \$200/kW, or even higher in less common cases such as urban centers.⁴⁴ Although this is generally not enough value to fund a distributed-generation project that may cost \$800/kW, for example, it nevertheless is a substantial fraction of the needed investment. When added to other values seen by the customer, such as backup power and reduced demand and energy charges, plus values for grid support and displaced central generation at the transmission and wholesale levels, the project may be attractive to the customer, the utility, or a third party if all these values can be accumulated or shared.

This suggests a role for a new distribution-level marketplace. The distribution utility that traditionally deals with operations and planning now has an additional function—operating a local marketplace or incentive structure where these values are revealed. By posting long-term upgrade costs as an opportunity notice to customers and third parties to bid alternative investments, such opportunities will reveal themselves.

For example, if a single distributed generator is located at a substation or feeder to displace an upgrade, then sooner or later it will go down just when the load is peaking on a hot summer day. To maintain the initial level of reliability, multiple, smaller units must be installed, or load management contracts must be signed with enough customers to back up the resource occasionally. Direct load curtailment contracts are one way to do this, using technology such as transactive control to make it seamless, automatic, and minimally disruptive. A market-like economic dispatch based on a local congestion surcharge is another way to let these resources compete for the right to serve peak loads at minimal cost. In either case, the distribution marketplace becomes a focal point for the transformation.

18.2.5.3 The Transmission Marketplace

The transmission power grid and wholesale markets can potentially be operated in an analogous, transactive fashion that provides a mechanism for the “self-healing” features that are the key to increasing the reliability of the grid while minimizing the infrastructure cost involved. A scenario best illustrates this concept. In today’s wholesale market, a large customer shopping for a long-term contract for power finds an energy service provider offering the minimal cost contract guaranteeing generation and transmission of power to the local distribution utility on its behalf. When a crisis occurs that suddenly disrupts the grid and severely constricts the transmission capacity of the corridor being used, the frequency disruption immediately triggers frequency-sensitive appliances throughout the entire region to temporarily rebalance supply and demand. This allows time for an automated power-trading system, analogous to an automated stock market trading scheme, to reconfigure the system in response to the crisis.

To do this, the energy management system immediately posts an emergency congestion surcharge on the constrained pathway. This surcharge triggers the energy service provider to issue a short-term subcontract to a generator in another location to use a different transmission pathway to deliver power

on behalf of the customer. In effect, this is what grid operators do today, reconfiguring the grid and voiding power wheeling contracts with a telephone and paperwork. However, the fact that the August 14, 2003 blackout in the Eastern Interconnection, once begun,⁴⁵ rolled from Ohio to New York in nine seconds serves as a reminder that information technology is essential for reacting with the speed necessary to arrest such events.

The key is tapping into the remarkable property of markets to reorganize themselves efficiently and the speed of high technology to effect that reorganization. Although engineers speak of “control” and economists speak of “markets,” in the future power grid, these concepts will merge and blend to form a transactive network that effectively forms the central nervous system of an adaptive, evolving system.

18.2.6 Renewable Energy Sources Integration

Broadly defined, renewable energy sources include wind, solar (solar photovoltaic (PV) and solar thermal), biomass, hydroelectric, ocean and river currents, waves, and tides. However, only wind, solar, and biomass sources are largely unconstrained by resource location. Thus, these renewable energy sources are ideally suited as distributed sources within the future electric system. Biomass-derived fuels can power conventional and emerging external and internal combustion engines. Thus, this renewable source brings the additional value of regulated/controllable power output and benefits in the form of voltage and reactive power support, spinning reserve, and improved power quality. In short, biomass-derived fuels can simply replace conventional fossil-based fuels in powering conventional power generator units such as diesel generator sets. However, both solar and wind energy sources can also bring many of these additional values.

Both solar and wind energy have, to date, been considered to be intermittent sources (when energy storage is absent). However, as these power sources become accepted as conventional components of the power generation mix and are used more effectively, there has come the recognition that these resources are best described as “variable” and that furthermore the outputs are relatively highly predictable. In addition, the parallel development of reliable, intelligent, low-cost, electronic-based voltage-source power converters has brought the ability of solar and wind generators to supply both high-quality power and reactive power support. Therefore, wind and solar power generators should now be included in the distributed power generator resource category.

The integration of ubiquitous communications and integrated distributed control now allows distributed generation, and particularly renewable power sources to utilize loads (especially thermostatic loads) to “firm up” intermittent sources making them collectively a more reliable resource. Additionally, opportunities for distributed renewables to participate in real-time emission management and provide grid support such as reactive power, cold load pickup during restoration, and backup for nearby critical loads provide benefits that can be realized economically.

Renewable power generators can be assigned effective load-carrying capability (ELCC) (or capacity credit) values. These values can be established when the deployment configuration, integration, and dispatch of these resources, along with other distributed resources, is optimized within a specific distribution or transmission system. For example, it has been shown that had a dependable capacity of 5000 MW of PV been installed in the California ISO region in 2000, the peak load on June 15, 2000 could have been reduced by 3000 MW. This would have cut by one-half the number of equivalently sized natural-gas-driven combustion gas turbines needed to ensure system reserve capacity.⁴⁶ Although PV power is only available during daylight hours, the annual average ELCC estimated for PV power plants distributed throughout California has nonetheless been calculated to be 64% of the PV plant rating. Furthermore, when the California system electric load is driven by the sun, the ELCC exceeds 80%. Thus a 5-MW PV system would be considered a summer peaking power source of 4 MW.

Wind-power output in many locations also has a definite diurnal pattern. However, analyses of real operating data currently underway in both the United States and Europe show that the very favorable geographic diversity effect (due to many wind turbines scattered throughout a relatively large geographical area), along with the significant advances in short-term wind forecasting, can permit

electric power system planners and operators to assign high values of ELCC and capacity factor to wind-power systems.⁴⁷

In short, the intelligent deployment, integration, and operation of wind and solar energy sources within the future electric system enable renewable power resources to be categorized as distributed power generation assets without qualification, bringing with them many of the values of the traditional distributed power generation sources (such as diesel generators and gas turbine generators) that can be exploited within the system, renewable power to provide ancillary benefits such as grid reactive support, and additional societal benefits to be realized such as real-time emissions management.

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