Greenway College

How you can help build the school that engineers OUR SUSTAINABLE FUTURE

Troy McBride

3

Storing Energy

> There must surely come a time when heat and power will be stored in unlimited quantities in every community, all gathered by natural forces. . . . When we learn how to store electricity, we will cease being apes ourselves; until then we are tailless orangutans. You see, we should utilize natural forces and thus get all of our power.
>
> —Thomas A. Edison, 1910

> Cellular phones are great for businesspeople on the go in the city, traveling salesmen, people like that, but coverage will never be cost-effective in rural areas and they'll never be able to compete against the huge infrastructure for landline phones. Do you know how much money has been put into running phone lines to every house in the United States? Sure, cellular phones will get smaller, better, and cheaper, but they'll never compete directly against landlines. Maybe in a few hundred years . . .
>
> —Telecom engineer, to a
> colleague in the early 1990s

Introduction

Energy is only useful if we can access it when, where, and how we want it. Chemical energy stored in combustible fuels like gasoline can't directly do many of the jobs that electrical energy can—you can't easily run a cell phone with a lump of coal. Electrical energy, on the other hand, is of the highest quality and can be harnessed to do almost any job, but it is expensive and bulky to bottle and carry around. We exclusively use large wires to bring electrical power to our buildings and homes; our technologies to carry around electrical energy with us and to move it into the future, to *when* and exactly *where* we want it, are more diverse—with huge amounts of energy stored for later use by pumping water uphill and tiny amounts of energy made portable in hearing aid batteries. Batteries and other methods of storing and carrying around energy tend to be more expensive than direct usage, but the need for portability in space and time often outweighs its costs: for instance, billions of batteries are sold each year in the US alone.

Combining zero-emissions sustainable energy generation (chapter 2) with technologies to bottle up useful energy and move it around space and time allows us to provide for all the energy uses of our society in a totally green, zero-sacrifice manner. The technologies that store some of the energy generated at Greenway, thus enabling the college to meet all its stationary and mobile energy needs—even when the wind falters or the sun goes behind a cloud—are the subject of this chapter.

Terms of Engagement

We utilize electrical, mechanical, thermal, and other forms of energy to run everything from hearing aids to delivery trucks to skyscrapers. No single technology can meet all these needs, so over the last century engineers have developed many sources of useful energy. From the point of view of portability, these energy sources can be divided into *stationary* and *mobile* types. Coal, nuclear, and hydroelectric power plants are stationary (except for a few antique steam trains and the occasional nuclear submarine). Some sources of energy can wear either hat: chemical fuels like diesel, methane, and hydrogen can be (and are) used to power both stationary and mobile machines. Finally, most chemical batteries, such as car batteries, flashlight batteries, or the rechargeable batteries found in personal electronics, are used in mobile devices. Some recent installations of chemical batteries paired with wind and solar chemical batteries—as big as trailer homes and many times heavier—are stationary.

Batteries and fluid fuels are the dominant mobile energy sources. To clearly understand their roles, we must bring in a second distinction—*primary versus secondary* energy sources. Petroleum, uranium, sunlight, and rivers running downhill are primary sources because they provide us with useful energy that we would not have otherwise. On the other hand, a charged NiCad battery, a wound-up spring, or a cylinder of compressed air must get its energy from somewhere else: it is secondary. Primary sources charge secondary sources. Some fluid fuels, like biodiesel, natural gas, or kerosene, are primary sources, while others, like hydrogen derived from water, are secondary, holding a “charge” of energy originally harvested somewhere else.

Mobile versus stationary is a way of thinking about storing and using energy, while *primary versus secondary* is a way of thinking about where energy ultimately comes from. A third consideration is energy *density*. Each pound or gallon of any mobile energy source, whether primary or secondary, must deliver sufficient energy (and deliver it quickly enough) to justify the hassle and cost of hauling it around. A car battery the size of a house would be useless no matter how cheap it was. Stationary energy sources, on the other hand, can often get away with low energy density: they may collect energy from diffuse primary sources, like the wind, and store it in comparatively bulky forms of storage, like elevated artificial lakes.

In general, secondary costs more than primary and mobile costs more than stationary. Electrical energy from a watch battery—which is mobile, secondary, and miniaturized to boot—costs about one hundred thousand times as much as energy from a wall socket.[1] Yet there is still a market for watch batteries because their mobility and tiny size justify their high cost per unit of energy. Moral: when shopping for an energy supply for a specific application, raw cost per kilowatt-hour is seldom the whole story.

Liquid fossil fuels, for example, are cheap, stable, high-density primary energy sources—in some ways, a great buy. That's why we buy them. Yet they are also polluting to extract and burn, geopolitically invidious, and finite in supply. Someday, perhaps soon, crude oil production will fall behind swelling global demand and stay there. Synthetic fluids refined from tar sands and coal may patch the supply-demand gap for a while, but their extraction destroys or disturbs vast landscapes and their lifecycle greenhouse emissions are even greater than those of coal and oil. Wouldn't it be nice if dense, mobile energy could be derived from inexhaustible sources like sun, wind, and sewage?

Fortunately, they can. Electric cars can be charged by windmills and solar cells, and biodiesel or ethanol can be manufactured from renewable feedstocks. Hydrogen can be produced by electrolysis, the electrical splitting of H_2O into H_2 and O_2, while methane (a.k.a. natural gas) can be made in biodigesters from plant or animal waste. There are other options, too. The bottom line is that fluid fuels and batteries can provide mobile, high-density energy from clean, affordable primary energy sources.

Which means that by judiciously using batteries and manufactured fuels, Greenway College can meet all its mobile-power needs without fossil fuels. And by storing large

---

[1] The factor of 100,000 is based on \$0.14/kWh for grid power versus \$14,000/kWh for a watch battery. The former figure is from http://www.eia.doe.gov/electricity/epm/table5_6_b.html, the latter from A. B. Lovins et al., *Small Is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size*, Rocky Mountain Institute, Snowmass CO, 2002 (p. 96).

amounts of energy in stationary devices, it can assure itself an uninterruptible, 24-7 supply of high-quality electrical power even while getting its energy mostly from intermittent sources like sun and wind.

Let's look more closely at how this can be accomplished.

Storage Basics

Rule Number One of energy storage is that you never get as much energy back out as you put in. Storage therefore costs you twice, once for the hardware and once for all the energy that is lost in the storage-retrieval cycle. On these terms, storage sounds crazy—an elaborate scheme for wasting energy—yet it is in fact often economic or even essential. This is obvious for mobile devices like laptops and cars, but the virtues of large-scale, stationary energy storage are also being increasingly sung by engineers the world round. Storage devices big enough to power a college campus can justify their cost in money and energy.

There are several methods for storing energy in bulk: the most common is to pump a few billion gallons of water uphill and stash them behind a dam. Electricity drives the pumps that raise the water and is recovered later when the water runs downhill through turbines. From the grid's point of view, a pumped-storage reservoir is just a huge rechargeable battery. High-pressure air can be saved in caverns or tanks. Large conventional chemical batteries can be charged and discharged. Methane generated by bacteria from sewage, cornstalks, or other organic junk can be stored in tanks, or hydrogen produced by cracking H_2O can be saved as a super-cold liquid or gas under high pressure or in metallic sponges.

The most commonly mentioned role for stationary storage these days is supporting renewable energy. Solar cells and wind turbines are famous for generating power intermittently; that is, only when the sun shines or the wind blows. This intermittency is important—but not as important, on the national scale, as is often claimed.[2] Solar output matches pretty well the daily peak demand for power, which occurs around midday and a bit later. Wind generation is intermittent at different times in different parts of the country—the wind is always blowing somewhere—so power transmission from one area to another balances some of the effects of intermittency.

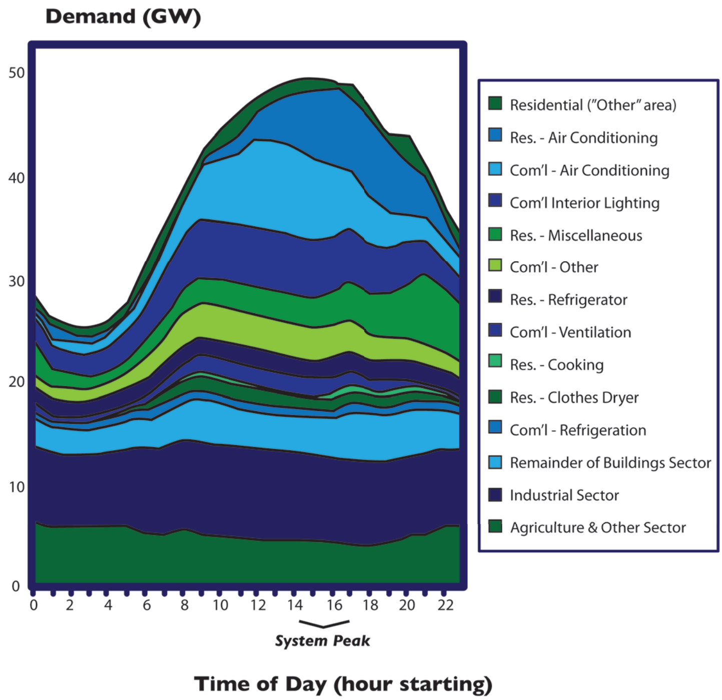

Fig. 3.1. California electric demand versus time of day for a hot summer day. Demand approximately doubled from its lowest point at 3 AM to its peak from 2 PM to 4 PM.[3]

---

[2] Yih-huei Wan and Brian K. Parsons, "Factors Relevant to Utility Integration of Intermittent Renewable Technologies," NREL/TP-463-4953, August 1993, accessed July 23, 2012, http://www.nrel.gov/docs/legosti/old/4953.pdf.

[3] Richard E. Brown and Jonathan G. Koomey, "Electricity Use in California: Past Trends and Present Usage Patterns," Ernest Orlando Lawrence Berkeley National Laboratory, May 2002, accessed June 6, 2012, http://en-

Another motive for purchasing storage is the fact that electrical *usage* is also not constant like wind or solar *supply*. As shown in figure 3.1, electrical demand is much higher during the daytime from about 8 AM to 9 PM. The top-of-the-curve "system peak" is highest during heat waves, when many air conditioners get turned on at once—or, in the South, during cold snaps, when many electric heaters get turned on. Peak demand can be met by turning on generators that burn fuels like natural gas, or by tapping other stored energy, or by some combination of the two.

Greenway Needs Storage

As explained in the previous chapter, Greenway won't need the grid and will be capable of operating independently from it. If grid connection is the usual method of getting reliable electrical power, how will Greenway ride out the dips and peaks of its solar and wind systems without it? The answer, of course, is storage. When the sun isn't shining or the wind dies down, Greenway's energy system will draw as much energy as it needs out of storage. This will happen automatically, without a hiccup: users will never notice the difference. Indeed, Greenway's stand-alone energy system will likely be *more* reliable than the grid, which fails often enough in the US to cause $57 billion of economic losses per year.[4] Also, Greenway must pack some of its renewable energy into secondary, mobile forms, namely batteries and fluid fuels, to run its portable equipment and vehicles.

The inherent trade-off of all energy storage—hardware costs and energy losses versus increased reliability and mobility—must be faced realistically by anyone seeking

---

duse.lbl.gov/info/LBNL-47992.pdf.

[4] K. H. LaCommare and J. H. Eto, "Understanding the Cost of Power Interruptions to U.S. Electricity Consumers," Ernest Orlando Lawrence Berkeley National Laboratory, September 2004, accessed May 21, 2012, http://certs.lbl.gov/pdf/55718.pdf.

renewables-based energy independence. (Some alternative energy generation systems, such as geothermal or biomass, are not intermittent, but these are unlikely to supply as much electricity to Greenway as inherently intermittent solar and wind.) This investment of dollars and additional energy for the functionality gained by energy storage is not dissimilar to the investment in dollars and energy for petroleum extraction, processing to gasoline, shipping, and distribution. Factors in evaluating the practicality and affordability of any system for storing energy include storage efficiency and energy losses, expected lifespan, start-up costs, and maintenance costs. Others are the speed at which the energy can be recovered upon demand, the duration of time that the energy can be efficiently stored, and, especially for mobile applications, weight and volume considerations. Against all these costs stand the valuable services that storage can provide.

Several effective energy-storage technologies are considered mature, while other technologies continue to be improved. The latter include ultracapacitors, superconductors, compressed-air systems, and hydrogen fuel cells. All have start-up costs and are ultimately energy consumers but can help transform intermittent renewable power into reliable power. Below, we take a closer look at some technologies that might play a role at Greenway College, both for stationary and mobile energy supply.

Meet the Candidates

Pumped hydro storage presently accounts for 99 percent of existing grid-scale storage worldwide.[5] But the times they are a-changing. Storage reservoirs can be built only in certain places, are economic only if gigantic, take minutes (not seconds) to respond to demand, and have other drawbacks.

---

[5] "Energy Storage: Packing Some Power," *The Economist*, May 3, 2012, accessed May 22, 2012, http://www.economist.com/node/21548495.

Table 3.1

Levelized cost of energy, lifecycle duration, and round-trip efficiency for a range of storage technologies

Storage Technology	**Levelized Cost of Energy ($/kWh)**	**Lifecycle**	**Round-Trip Efficiency**
Hydro storage	$$	75 years	70%
Classical compressed air (combusted with natural gas)	$$	40 years	35–65%*
Advanced compressed air (advanced adiabatic or isothermal)	$$	40 years	50–70%†
Hydrogen (electrolysis & combustion engine)	$$$	10 years	25%
Hydrogen (electrolysis & fuel cell)	$$$$	5 years	35%
Sodium sulfur batteries	$$$	10 years	60–70%
Flow batteries (e.g. vanadium redox, zinc bromide)	$$$$	8 years	60–70%
Lead acid batteries	$$$	3 years	75%
Li-ion batteries	$$$$	5 years	95%
Flywheel	$$$$$	25 years	95% (1% parasitic)
Ultracapacitor	$$$$$	25 years	97%

Sources for data include author estimates, the book EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, and World Energy Council Report, "Energy Storage Monitor: Latest Trends in energy storage | 2019," https://www.worldenergy.org/assets/downloads/ESM_Final_Report_05-Nov-2019.pdf.

Technologies are ordered from multiple-hour to short-term storage. Levelized cost of energy (LCOE) is the total lifetime cost of a storage system divided by the total amount of energy delivered by the system. Values are approximate, case dependent, and may change with technology advancement. No solid independent study of LCOE for storage is yet available, and thus relative values have been used where $$ implies < $0.20/kWh, $$$ <$0.50/kWh, $$$$ < $1.00/kWh, and $$$$$ > $1.00/kWh, with cost of fuel based on average nighttime U.S. electricity costs.

Notes: *There are various ways to calculate efficiency for compressed-air energy storage hybridized with natural gas combustion. (Samir Succar and R. H. Williams, "Compressed Air Energy Storage: Theory, Resources, and Applications for Wind Power," Energy System Analysis Group, Princeton University, April 8, 2008.) † No commercial systems exist to date for this technology.

Engineers have therefore struggled to develop more nimble alternatives, some of which are listed in the first column of table 3.1. The number of times a storage system can be charged and discharged before wearing out ("Lifecycle") and the fraction of energy stored that can be retrieved ("Round-Trip Efficiency") are also listed. (Round-trip efficiency can be interpreted as follows: If it takes 3 watt-hours of energy to charge a rechargeable AA battery that can supply only 2.5 watt-hours once charged, then the battery's round-trip efficiency is 2.5 divided by 3, namely 83 percent.)

The array of choices in table 3.1 may be at first sight bewildering. Should Greenway College buy pumped hydro storage or Li-ion batteries? Or advanced compressed air? Or maybe some kind of combo platter? Juggling all the factors and technological trade-offs to design Greenway's energy system is indeed a nontrivial job. However, if building a sustainable energy economy were as simple as plugging in a coffeemaker, we wouldn't need a Greenway College at all.

Below, we discuss and compare a few of the leading contenders for Greenway College's stationary (non-vehicular) storage needs, beginning with the most traditional: pumped hydro.

Pumped Hydro

As already noted, pumped hydro is presently the global champ among stationary energy-storage options. It stands out for its long lifetime (about seventy-five years), good round-trip efficiency (approximately 70 percent), and low cost per unit of energy stored and retrieved. That is why pumped hydro accounts for over 97 percent of grid energy storage in the US, with 23 GW.[6] The idea is simple: Electrical

---

[6] National HydroPower Assocation. *2018 Pumped Storage Report*. Washington, DC. https://www.hydro.org/wp-content/uploads/2018/04/2018-NHA-Pumped-Storage-Report.pdf.

energy is used to pump water to an elevated reservoir (figure 3.2). The energy can be retrieved (mostly) when the water is run downhill through turbines. Pumped-hydro storage uses proven machine designs that have high efficiency, long lifetime, and low maintenance, but its high- and low-level reservoirs can require radical modification of the landscape.

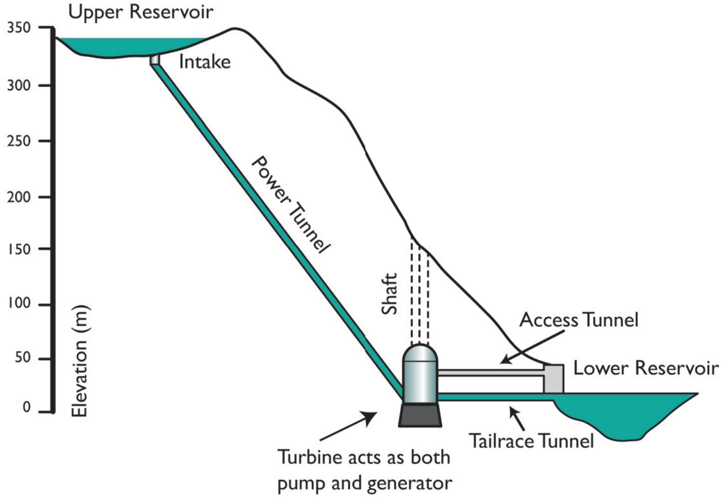

Fig. 3.2. Schematic of pumped-hydro energy storage. Electric power is used to pump water to the upper reservoir, usually at night, and is then generated by running water downhill again, usually during the day.

A key factor in the effectiveness of any pumped-hydro storage installation is its "head," the elevation difference between the upper and lower reservoirs. The higher the altitude to which a gallon of water is pumped, the more energy it can deliver when run downhill: doubling the head doubles the amount of energy stored by each gallon of water in the upper reservoir. Therefore, most pumped-hydro reservoirs are built on land at least a hundred meters above the lower reservoir.

Suitable sites for constructing large, high-head storage reservoirs are not to be found just anywhere. Fortunately, Greenway would require a reservoir much smaller than those built to service the grid, and consequently would find it easier to site its system. A fairly small upper reservoir—about 8,000 square meters area (2 acres), average depth 10 meters—would provide ample storage for the college's needs. For a reservoir of this size, sites with suitable elevation are not hard to find in the Northeast United States: at a closed-down Vermont college that appeared on the market, suitable for a Greenway campus, an upper reservoir could have been constructed with an appropriate 150 meters of head.

In sum, if Greenway College is built on a rural site with appropriate topography, pumped storage will be a strong contender for its primary energy-storage technology.

Compressed Air

Compressed-air energy storage (CAES) stores energy using the springlike compressibility of air. First, electricity turns a compressor to force high-pressure air into a cylinder or cavern. To recover this energy, the stored air is used to drive a generator. In existing utility-scale CAES systems, the pressurized air does not push a turbine by itself but is used to boost a natural-gas turbine that combines gas with compressed air before burning it. By using low-cost, off-peak electrical energy to generate and store compressed air, the amount of natural gas consumed to generate a unit of electrical energy is reduced the next day.

It's a good trick, but Greenway College won't be building a compressed-air-assisted natural gas plant. Even if we were willing to burn fossil fuels, which we're not—or able to generate enough renewable methane to run such a turbine—a Greenway-sized gas turbine would not be efficient: below about 2,000 kW, cost doubles and efficiency drops by about a third.[7] Greenway College, even during peak demand, will

---

[7] Meherwan P. Boyce, *Gas Turbine Engineering Handbook*, (Burlington, MA: Gulf Professional Publishing, 2006).

need less than 1,000 kW of power (which is about as much as it takes to run a Super Wal-Mart).[8]

However, other forms of CAES may work for Greenway. Technologies that use compressed air alone as an energy-storage medium, with no need for the natural gas, may be scaled to campus size at good efficiency.

The biggest barrier to making CAES efficient and affordable is the drastic temperature change that can occur when air is compressed and expanded. Whenever air (or any gas) is compressed, it tends to become hotter. If compressed rapidly to many times atmospheric pressure, it can become hotter than any household oven—700 °C (1,300 °F) for air compressed from atmospheric pressure to 70 atmospheres, more than hot enough to melt aluminum. In a CAES system, all this heat—which represents much of the energy invested in the compression process—must either be kept from leaking away while the air is stored, which entails an insulated, more costly storage system, or it must be allowed to leak away. But if the inconvenient heat is simply discarded, that is a loss of energy and thus of storage efficiency. On the other hand, if the compressed gas is stored at room temperature, a new difficulty appears during recovery of energy—*frigid* temperatures. Gas tends to cool when it expands, so rapid expansion from high pressure can produce super-cold air (e.g., negative 200 °C (–330 °F) for air expanded from 70 atmospheres to atmospheric pressure, almost cold enough to liquefy the expanded air). Such extreme cold would force the use of expensive, cold-resistant materials, cause frost and ice buildup, and so forth.

Several CAES methods have been proposed that will deal with this issue. All involve moving thermal energy around to

---

[8] Matthew L. Wald, "A Wind Farm Would Link Northeastern Grids," *New York Times*, December 9, 2010, accessed May 24, 2012, http://green.blogs.nytimes.com/2010/12/09/wind-farm-would-link-northeastern-grids/.

avoid inconvenient extremes of hot and cold. One can, for example, remove heat from the air during compression, store it (in a tank of hot water or some other heat reservoir), and restore it to the air during expansion.

In any form, CAES is pumped hydro's closest competitor for convenience, safety, and cost. Although midscale, aboveground, air-only CAES technologies are not yet established in the market, they may be soon. They will offer several advantages: first, their air tanks and other components can be located most anywhere, while a pumped-hydro storage reservoir cannot. Second, CAES with aboveground air storage will not impact the local ecology and hydrology as much as reservoir construction does. Third, such technologies are likely to become commonplace in the grid in coming years, and it is precisely such technologies that Greenway College students and faculty must investigate, understand, challenge, and improve.

Thermal Energy Storage

Thermal energy is the random motion of atoms and molecules jiggling in place or flying about. Because thermal energy is disorganized, it is more difficult to harness in the form of useful work than is the highly ordered energy of a charged battery, an elevated body of water, or a spinning flywheel. Nevertheless, because thermal energy is easy to produce from sunlight or fire, we use thermal systems for most electrical energy generation (making steam in power plants) as well as for direct heating and cooling.[9]

Out-of-place, excess thermal energy is actually a burden rather than a resource. When fuel burns in the cylinder of a car engine, it is generating thermal energy, which causes the

---

[9] Though in colloquial speech "heat" and "thermal energy" are used interchangeably, in physics "heat" strictly means energy transferred between one system and another by a thermal process.

gas trapped in the cylinder to expand, pushing on the piston and ultimately turning the wheels. Some of the thermal energy from combustion is thus converted to mechanical work, but most cannot be put to use and must be thrown away by the radiator. In stationary settings, we can be more clever and efficient: “combined heat and power” systems harness otherwise wasted heat from electric generation (in, say, a wood or gas-fired plant) to heat buildings, water, or the like. Another option is to *store* thermal energy for later use: heating, cooling, or energy generation.

Changing phase, for example from solid to liquid (as in freezing water), or liquid to gas, is also a form of thermal energy storage, because a phase change is accompanied by a change in the energy content of substance with little or no change in temperature. Water actually releases thermal energy as it freezes—0.1 kWh per kilogram—which is why orange growers spray water on their trees to save their fruit during a frost.[10] Some thermal-energy storage systems rely on a substance that undergoes a phase change.

Solar thermal-energy storage systems heat substances during the day, when solar energy is available, and then use the stored energy as needed, day or night. The simplest and most widespread form of thermal storage is residential hot water. Seasonal hot-water storage has also been implemented, as in the central hot-water heating system that has served several hundred apartments in Friedrichshafen, Germany, since 1996.[11]

At large scale and high temperatures—high enough to

---

[10] Arlie Powell, “Methods of Freeze Protection for Fruit Crops,” Alabama Cooperative Extension System, October 2000, accessed May 22, 2012, http://www.aces.edu/pubs/docs/A/ANR-1057-B/index2.tmpl.

[11] Thomas Schmidt and Janet Nußbicker, “Monitoring Results from German Central Solar Heating Plants with Seasonal Storage,” ISES 2005 Solar World Congress, Orlando, Florida, August 6–12, 2005, accessed May 22, 2012 At http://www.solites.de/download/literatur/05-03.pdf.

melt salt—thermal storage allows some solar electric-generating installations, such as the Gemasolar thermal-solar plant in Andalucía, Spain, to supply electricity long after the sun has set. The Gemasolar plant (operational since 2011) stores enough solar-heated molten salt to provide power during fifteen hours of darkness.[12]

At Greenway College, thermal energy storage will at first be used mainly to supply hot water—an important role, as hot water constitutes about 15 percent of all energy use in residential buildings.[13] Self-heating, self-cooling buildings, such as are described in the next chapter, may also use internal thermal storage to help keep themselves at a steady, comfortable temperature.

A thermal-solar electric generating station, with or without thermal storage, is currently not proposed for Greenway. Other storage technologies that will probably not be considered for reasons of scale and safety include large stationary batteries based on flowing chemicals ("flow batteries") or batteries based on high-temperature sodium and sulfur, although these may see increasing application in the grid.

Hydrogen

Hydrogen is a promising secondary energy carrier, especially for transportation and portable devices. It is one of the densest fuels in terms of energy stored per unit weight, and when it is combusted or reacted with oxygen the result is chiefly water. Although most hydrogen is manufactured by combining natural gas with steam, hydrogen (H_2) can also be

---

[12] "Gemasolar Thermosolar Plant," National Renewable Energy Laboratory, 2011, accessed May 22, 2012, http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=40.

[13] "High Efficiency Water Heaters," US Environmental Protection Agency, 2006, accessed July 24, 2012, http://www.energystar.gov/ia/new_homes/features/WaterHtrs_062906.pdf.

produced by cracking water molecules (H_2O). This cracking process consumes energy: when the hydrogen recombines with oxygen, the energy is released. Recombination of hydrogen with oxygen may occur with high efficiency in a fuel cell, a device that produces electricity directly from chemical reactions. Hydrogen can also be burned in internal combustion engines or turbines. Its advantages include its ability to double as a vehicular fuel or stationary storage medium; even cell phones and laptops can be powered by hydrogen reacted in miniature fuel cells.[14]

A clean, elegant cycle thus beckons: water plus electricity makes hydrogen, hydrogen plus oxygen makes water and electricity. One can imagine an all-electric campus or entire society where electricity from solar cells and windmills makes hydrogen from water, and the hydrogen runs vehicles or produces electricity in fuel cells.

There are obstacles, however. Although a kilogram of hydrogen holds a lot of energy, it also takes up a lot of space: at any given temperature and pressure it is the least dense of all materials. High pressures, low temperatures, or sophisticated metallic sponges are required to store large quantities of it in confined spaces. This raises costs, especially for vehicular uses. Also, round-trip efficiency for a water-hydrogen-water cycle is relatively low: presently less than 35 percent, versus about 70 percent for pumped hydro or chemical batteries or 50 to 60 percent for compressed air.

A study by the US National Renewable Energy Laboratory found that a fuel-cell system deriving its hydrogen from water could probably compete economically with batteries

---

[14] Lisa Zyga, "Hydrogen-Powered Cell Phone Doubles Battery Lifetime," PhysOrg, January 14, 2008, accessed May 24, 2012, http://www.physorg.com/news119544735.html. Also, Carol Potera, "Beyond Batteries," *Environmental Health Perspectives* 115:1 (2007): A38–A41, accessed May 24, 2012, http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1797861/pdf/ehp0115-a00038.pdf.

for energy storage in installations of middling size.[15] And despite a popular belief that hydrogen is uniquely dangerous, it is not: leaked hydrogen disperses rapidly, unlike gasoline, and burns with a pale flame that radiates little heat and so does not readily ignite nearby objects.[16] Safety studies have shown that hydrogen-powered vehicles can be at least as safe as conventionally fueled vehicles.[17] Hydrogen-powered cars exist today only in very limited market offerings, but modification of four-cycle internal combustion engines to run on hydrogen is straightforward (although in such engines, proper fuel-to-air ratio is key to minimizing production of nitrous oxide, a pollutant).

All things considered, it is highly likely that Greenway will use hydrogen for both long-term stationary energy storage and for some of its maintenance equipment and vehicles. Such technologies are already on the market: for example, Hydrogenics Corporation (www.hydrogenics.com) offers a complete lineup of components for hydrogen power backup, including electrolysis, compression, storage, and generation. For approximately $1 million, a system can be purchased that generates 4 kg/hour of hydrogen from water and stores it at 400 atmospheres, including a dispenser for mobile uses and a 125 kW stationary backup generator. This system can

---

[15] Darlene M. Steward, "Analysis of Hydrogen and Competing Technologies for Utility-Scale Energy Storage," NREL/PR-560-47547, US National Renewable Energy Laboratory, February 11, 2010, accessed May 23, 2012, http://www.nrel.gov/docs/fy10osti/47547.pdf.

[16] "Fuel Cells Technologies Program," US Department of Energy, February 2011, accessed May 22, 2012, http://www.hydrogen.energy.gov/pdfs/doe_h2_safety.pdf.

[17] "Analysis of Published Hydrogen Vehicle Safety Research," DOT HS 811 267, US Department of Transportation, National Highway Traffic Safety Administration, February 2010, accessed May 22, 2012, http://www.nhtsa.gov/DOT/NHTSA/NVS/Crashworthiness/Alternative%20Energy%20Vehicle%20Systems%20Safety%20Research/811267.pdf.

generate power from its stored hydrogen for approximately twenty-four hours.

Fast Responders

So far we have been speaking of bulk energy storage—devices that can meet the energy needs of a whole campus for many hours on end, if need be. The technologies that supply such storage tend to be slow to respond, however, compared to the speed at which a computer screen goes blank when the power flickers. To produce truly uninterruptible power, to fully smooth the continually twitching mismatch between supply and demand, faster-acting forms of storage are needed: batteries, flywheels, ultracapacitors, and superconductors. These tend to be expensive for storing bulk energy, but such technologies have fast response times and good power density.

Batteries. Electrochemical batteries, which include such well-known products as alkaline AA batteries and lead-acid car batteries, are the most mature technology for meeting short-term energy demand. They have disadvantages, however. Lead-acid batteries offer low cost, but moderate energy density and reduced lifetimes. Lithium-based technologies offer higher energy density and longer lifetime, but traditionally at high cost. Lithium-based batteries have been coming down rapidly in price with widespread usage in electric vehicles and stationary storage. A host of other battery chemistries have been developed, each filling some market niche and having its own advantages and disadvantages. Greenway College will study all these technologies and work with many of them, especially for transportation and short-term storage, but will also rely on some of the long lifetime alternatives described above for bulk storage.

Flywheels. Flywheels can be used to store electrical energy as kinetic energy—the energy of moving matter—in a heavy, rotating disk (a “flywheel.”) With very low-friction bearings, such as floating the disk in a vacuum with magnets, energy can be stored with little loss for long periods of time.

The amount of energy stored is determined by a flywheel's mass, shape, and speed. To store more energy in a flywheel, one can either build a bigger flywheel or a denser flywheel, or spin the flywheel at higher speeds.

Flywheel storage is commercially available today for uninterruptable power supplies and, incipiently, for maintaining the quality of power supplied by the grid. For example, Active Power of Austin, Texas, offers an energy-storage system using a notched steel flywheel that is capable of storing 1.8 kWh of energy and delivering it at rates of up to 500 kW. That is enough energy for a cluster of computers to ride out a brief interruption in grid power. In 2011, an installation of two hundred much bigger flywheels built by Beacon Power began operation in Stephentown, New York. The flywheels are charged (spun up) during off-peak hours, then tapped for power whenever spiking loads threaten to drag down the frequency of the AC power on the grid. Each Beacon unit is about 10 feet tall, spins a magnetically levitated flywheel at 16,000 revolutions per minute in vacuum, and stores up to 25 kWh.

For Greenway College, units like the Active Power system might provide a long-lifetime, low-impact system for rapid response.

Ultracapacitors. Electric charges can be held apart from each other in devices called capacitors, storing energy. Tiny capacitors are found in most all electronic devices, and large ones are contemplated for fast-response energy storage.

Since capacitors store their energy directly as separated electrons, they can start delivering that energy in thousandths or even millionths of a second. They can be reused thousands or millions of times, while electrochemical batteries can be charged and discharged a few thousand times at most. They can also be charged more quickly than any other storage device and have no moving parts—always a plus.

Capacitors' biggest drawback is that they do not store much energy for their size (low energy density). Efforts to fix this problem have led to the development of "ultracapacitors" or "supercapacitors," which can store hundreds of times more electrical energy than similarly sized traditional capacitors,[18] which is a third to a half as much as a similarly sized lead-acid batteries. Ultracapacitors cannot deliver their energy quite as quickly as traditional capacitors, but are still about ten times faster than a chemical battery with similar capacity. Plenty fast.

Cost remains high, about ten to one hundred times higher than for an equivalent amount of lead-acid battery storage. Nevertheless, because an ultracapacitor lasts so long, the *lifetime* cost of storing a unit of energy can be as much as ten times less for an ultracapacitor than for a chemical battery.

Large ultracapacitors have been used in some buses, trains, and submarines, but are not yet at widespread work in the grid due to their high up-front cost. Greenway will keep a close eye on this technology as it evolves.

Superconducting Magnetic Energy Storage. Energy can be stored in a superconductor, which is any substance that presents zero resistance to the flow of electric current. Like capacitors, superconducting storage devices can yield their energy at electronic speeds. However, they currently only work if very cold: for superconductors, liquid nitrogen at about 200 °C below zero (–330 °F) is considered shockingly warm. Superconductors with their zero resistive losses are attractive to the zero-waste ethos of Greenway College, but

---

[18] Jason Lee, "Ultracapacitor Applications for Uninterruptible Power Supplies (UPS)." White paper, Maxwell Technologies, undated, accessed May 23, 2012, http://www.maxwell.com/products/ultracapacitors/docs/201202_whitepaper_application_for_ups.pdf.

due to cost and availability, superconductor energy storage will likely be limited to laboratory study at the outset.

Taking Storage on the Road

Greenway will maintain a fleet of vehicles—its own vehicles, that is, not the hodgepodge of student-owned cars generally found in any college's most remote parking lots. (Perhaps a campus-run car-sharing system modeled on Zipcar can induce green-minded students to leave their personal automobiles, if any, at home.) Fueling vehicles can seriously dent a college budget: in 2010, Ohio State burned over two million liters (over half a million gallons) of vehicular fuel at a cost of almost $800,000.[19]

As mentioned earlier, energy density is crucial for mobile energy sources. Figure 3.3 shows that the energy density of all fluid and gaseous fuels is considerably higher than current battery technology. Yet batteries can be charged directly from solar panels and wind turbines, without the bother and inefficiency of manufacturing fluids. Should Greenway use fluid fuels, batteries, or some blend?

Of course, the status quo method of running our plows, staff cars, pickup trucks, lawn mowers, and other vehicles would be to use old-fashioned gasoline and diesel, like any normal college. Instead, we strive to make that status quo seem as strange and wasteful as wood-fired locomotives and gas lighting. There are clean and efficient ways to run vehicles, maintenance equipment, and portable electronics—ways that involve no sacrifice in performance, enhance energy independence, and are clean and affordable.

---

[19] Gordon Gantt, "Ohio State Must Fuel Fleet at All Costs," *The Lantern*, May 18, 2011, accessed May 23, 2012, http://www.thelantern.com/campus/ohio-state-must-fuel-fleet-at-all-costs-1.2229787.

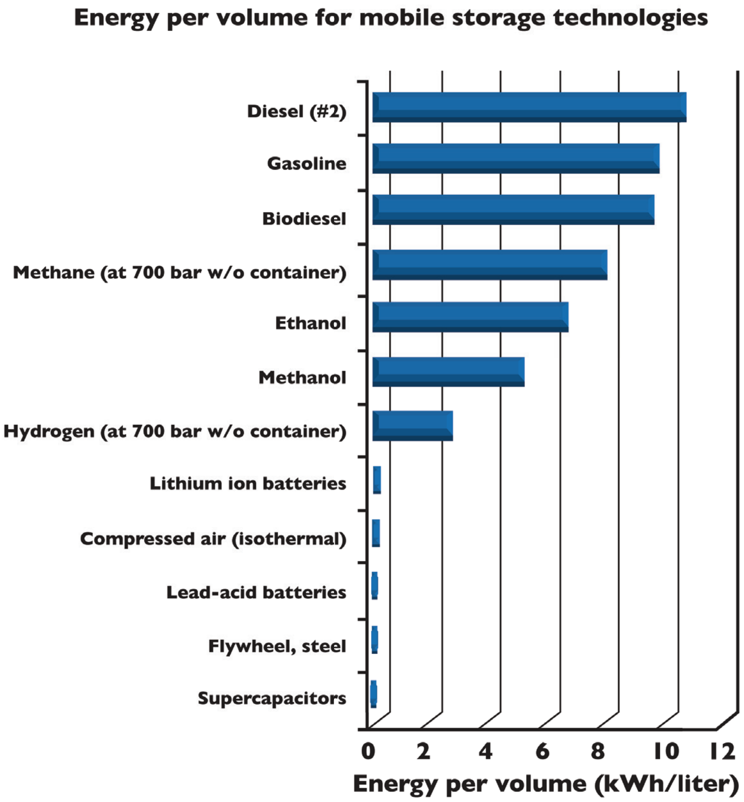

Fig. 3.3. Approximate energy densities of various storage materials, defined here as the amount of energy stored in one liter (about a quart) of the given medium.[20]

---

[20] The numbers in this table have been assembled from a variety of sources, including author estimates, the website of the Electricity Storage Association (http://energystorage.org/tech/technologies_comparisons.htm), the US DOE's "Properties of Fuels Table" (http://www.afdc.energy.gov/afdc/pdfs/fueltable.pdf), and the following articles: A. Rufer, "Solutions for Storage of Electrical Energy, " EPFL, proceedings of ANAE in 2003, and Richard F. Post, T. Kenneth Fowler, and Stephen F. Post, "A High-Efficiency Electromechanical Battery," *Proceedings of the IEEE* 81:3 (1993): 462–474.

All-Electric Vehicles

Greenway will produce all its own electricity and charge electric vehicles primarily during times of excess generation. Electric vehicles have been intensively researched for decades. They are quiet, reliable, and as clean as the electric generators that charge them. The lithium ion batteries (and to a lesser extent nickel-metal hydride) used in today's electric and hybrid cars are a technologically mature form of energy storage that will certainly see use on Greenway campus.

A longstanding drawback of electric vehicles has been their limited range, which until recently was a fraction of gasoline-powered vehicles'. For all but the longest distance driving, electric vehicles and equipment now perform superior to internal combustion engine vehicles and equipment. Electric vehicles and equipment have truly reached the age of zero sacrifice.

A remaining drawback of electric vehicles is recharge time: a conventional car can gas up in a minute or two, but an electric vehicle can take hours to recharge. This is not much of a disadvantage for Greenway, however. Because the college will own enough vehicles and equipment, charging can happen when convenient and balance electricity usage.

Ethanol, Methanol, and Biodiesel

Other options for mobile energy storage include carbon-based secondary (synthetic) fuels such as methanol, ethanol, biodiesel, and methane, all of which have decent energy density. They can be made from biomass feedstocks such as wood, corn, soy, and organic waste and burned in conventional engines. In some cases they can be reacted in fuel cells.

The environmental impacts of these fuels vary widely, depending on how they are made: corn-based ethanol, found in gasoline across the US, has been said by some analysts to consume nearly as much (or even more) energy in its manufacture than it yields when burned.[21] Even optimistic analyses indicate that for each unit of energy released by combusting corn ethanol, three-quarters of a unit of energy must be invested to grow and process the corn. Nor does an energy-in, energy-out analysis take into account soil loss from conventional corn growing, nutrient pollution from fertilizer, and higher food prices worldwide due to the diversion of arable land to ethanol production.[22] The "greenness" of corn ethanol is therefore questionable.

At the other extreme, methane gas is spontaneously emitted by bacteria digesting sewage or landfill waste. If this methane is not collected or burned, but dispersed directly to the atmosphere, it causes about twenty times as much greenhouse warming, molecule for molecule, as carbon dioxide. For this reason, landfill methane is sometimes flamed off (in effect turning it into carbon dioxide) as a greenhouse mitigation measure. Using it as a fuel is therefore a double win: useful energy plus greenhouse mitigation. New York City already captures half the methane emitted from its sewage plants and burns it to meet 20 percent of the energy needs of its wastewater treatment system.[23]

Greenway may use biomethane from digesters on a small scale and will undertake research projects on biofuels.

---

[21] D. Pimentel and T. Patzek, "Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower," *Natural Resources Research* 14:1 (2005): 65–76. But see also http://www.transportation.anl.gov/pdfs/AF/265.pdf (and criticisms of the latter at http://www.consumerenergyreport.com/2006/03/30/how-reliable-are-those-usda-ethanol-studies/).

[22] Elizabeth Rosenthal, "U.N. Says Biofuel Subsidies Raise Food Bill and Hunger," *New York Times*, October 7, 2008, accessed May 22, 2012, http://www.nytimes.com/2008/10/08/world/europe/08italy.html.

[23] Mireya Navarro, "City Is Looking at Sewage Treatment As a Source of Energy," *New York Times*, February 8, 2011, accessed May 23, 2012, http://www.nytimes.com/2011/02/09/science/09sewage.html?_r=1.

Energizing Greenway

Greenway will provide amenities equal to or better than those of a conventionally powered campus, all while having neutral or positive impact on the environment and using no fossil fuels. Thus, in our first implementations of energy generation and energy storage, we will rely on tried and true technologies that entail no sacrifice of reliability and thus of comfort. More experimental systems will not be implemented until after the successful establishment of the initial college buildings and their supporting technology.

Depending on the pace of technology development, this may make small-scale pumped-hydro storage our on-campus bulk storage technology of choice. Small-scale pumped hydro would not involve jumping any large technological hurdles, since its piece parts—pipes, turbines, pumps, and generators—are highly reliable. However, a campus having fairly high relief, with sites suitable for the construction of upper and lower reservoirs, would be needed.

Relatively well-established, long-term storage options that do *not* depend on site topography include chemical batteries, compressed air, and hydrogen. We will create hydrogen as fuel for vehicles and also perhaps for stationary backup power. The low round-trip efficiency of hydrogen makes it less attractive as our sole bulk-storage solution. Biofuels may supplement our stored energy supply at reasonable cost: for instance, methane from biodigestion is a portable, storable source of primary energy. Finally, high-speed, low-capacity energy storage will also probably be installed, based on flywheels, ultracapacitors, or batteries, to render small glitches in the on-campus power supply invisible to users.

There is, if anything, an embarrassing wealth of options. Technologies are developing fast, and all options must be weighed at the time of initial campus design. The best buys must be installed in such a way as to not foreclose future evolution of Greenway's energy system. The goal is not to supply Greenway with a perfect, finished energy system on day one, even if that were possible, but to supply it with an *evolvable* energy system that serves the campus's needs with high reliability while allowing students and staff to tinker, test, research, improve, reform. But the time to act is now.