Greenway College

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

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2 Making and Using Energy

> It is in our vital interest to diversify America's energy supply—and the way forward is through technology.
>
> —President George W. Bush, State of the Union address, January 23, 2007

> Energy will be the immediate test of our ability to unite this nation, and it can also be the standard around which we rally. On the battlefield of energy we can win for our nation a new confidence, and we can seize control again of our common destiny.
>
> —President Jimmy Carter, July 15, 1979

> We are like tenant farmers chopping down the fence around our house for fuel when we should be using Nature's inexhaustible sources of energy—sun, wind and tide. . . . I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that.
>
> —Thomas A. Edison, 1931

The Universal Ingredient

Without energy nothing is harvested, mined, refined, manufactured, packaged, or shipped. Energy cools and lights our buildings, processes our data, powers our tools, lights our streets, propels our vehicles, and runs our farms and factories. Consequently, when energy prices go up, the price of everything goes up, from toothpaste to trans-Pacific container shipping. Even modestly higher-than-normal prices for just one source of energy, crude oil, can be a drag on the entire economy.[1]

All the improvements in physical well-being achieved by industrialized society over the last 150 years—like greater longevity, leisure, and comfort—have been made possible by abundant, concentrated energy supplies. All our food, housing, transport, communication, and military might is built and animated by energy. At first that energy came primarily from wood, then coal, then coal and oil, and now coal, oil, natural gas, and a potpourri of nuclear, hydro, wind, solar, and other sources. The oil embargo of 1973–74 highlighted how tightly national security depends on energy security, while rubbing our noses in the fact that our "addiction" to oil, as President George W. Bush called it,[2] leads inexorably to energy *in*security. The Department of Defense says that energy sustainability is an "organizing paradigm that applies to all DoD mission and program areas" and that the US military's "heavy reliance on fossil fuels creates significant risks and costs at a tactical, as well as a strategic level."[3] The main remedy, the DoD says, "will be to reduce reliance on fossil fuels through energy efficiency and renewable energy." Nevertheless, the US military is still the world's largest single user of petroleum.[4] It is easier to see the need to change than to change.

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1 R. E. Earley and K. Smith, "What Has Happened to the Share of Energy in the U.S. Economy Since the Early 1970s?" US Energy Information Agency, updated April 10, 2001, accessed May 21, 2012, http://www.eia.doe.gov/oiaf/economy/energy_price.html.

2 "Bush: U.S. Must Break Oil 'Addiction,'" *CNN*, February 11, 2009, accessed May 21, 2012 http://www.cbsnews.com/2100-250_162-1260701.html.

3 *Strategic Sustainability Performance Plan* (FY 2010), US Department of Defense Office of Installations & Environment, accessed May 21, 2012, http://www.denix.osd.mil/sustainability/upload/DoD-SSPP-PUBLIC-26Aug10.pdf.

4 S. Karbuz, "Can the US Military Move to Renewable Fuels?" *Bulletin of the Atomic Scientists*, October 31, 2008, accessed May 21, 2012, http://

The litany of environmental harms caused by extracting and applying energy is all too familiar. Obtaining fossil fuels entails destructive mining practices (e.g., mountaintop removal), drilling both onshore and off, hydraulic fracturing, and strip mining (fully exploiting Alberta's tar sands would entail disturbing a wilderness area bigger than Florida).[5] Nuclear power suffers from unique waste-disposal problems and is tied to nuclear weapons proliferation because refined uranium and plutonium are the stuff of ultimate weapons.

Over a trillion dollars is spent on energy per year in the US.[6] Despite that awesome sum, we are in the era of cheap, abundant energy and have been since the dawn of the industrial revolution. Experts debate how long the cheap fossil fuel portion of this party will last, but most agree that the current system is unsustainable: we cannot go on like this forever. At projected worldwide resource consumption rates, the Earth's known conventional fuel reserves amount roughly to about forty years of oil, fifty-four years of natural gas, over one hundred years of coal, and over two hundred years of uranium 235 (at present consumption rates, not proposed nuclear-renaissance rates).[7] The exact dates are debatable,

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www.thebulletin.org/web-edition/features/can-the-us-military-move-to-renewable-fuels.

5 "Strip Mining for Oil in Endangered Forests," Natural Resources Defense Council, June 2006, accessed May 21, 2012, http://www.nrdc.org/media/docs/060607a.pdf. See also "Alberta Tar Sands: It's Not Just About Mining," Skytruth, accessed May 21, 2012, http://blog.skytruth.org/2011/11/and-t-only-gets-larger-from-here-on-out.html.

6 "Consumer Expenditure Estimates for Energy by Source, 1970–2009," US Energy Information Administration, accessed March 16, 2012, http://www.eia.gov/totalenergy/data/annual/pdf/sec3_11.pdf.

7 "2010 Survey of Energy Resources," World Energy Council, accessed May 21, 2012, http://www.worldenergy.org/documents/ser_2010_report_1.pdf. Also: Steve Fetter, "How Long Will the World's Uranium Supplies Last?" *Scientific American*, accessed May 21, 2012, http://www.scientificamerican.com/article.cfm?id=how-long-will-global-uranium-deposits-last.

but do not really matter: some are less than a generation away and none are extremely remote.

Alternative or "renewable" energy generation, in contrast, relies on energy flows powered by the sun and the Earth's inner heat, all of which are inexhaustible on any timescale relevant to human history. Sunlight is the main source of renewable energy, whether directly (in heat collection or electricity generation), the winds (via differential heating of the Earth's surface), the water cycle (hydroelectricity), or plant life (wood and other biomass). The sun showers the Earth with as much energy every hour as human civilization uses every year.[8] The motions of the Earth, sun, and moon drive ocean tides, which can also be harnessed for power generation, while heat left over from the formation of the solar system, supplemented by the slow breakdown of uranium 238 in the Earth's deep interior, drives geothermal power. Renewable energy sources are therefore "sustainable": they last. As a major side benefit, they tend to free their users from far-flung supply lines, divorcing energy supply from geopolitics.

Most energy experts agree with the majority of the American people: we need to abandon today's dirty, fragile, expensive, and ultimately doomed energy system in favor of a clean, secure, affordable, sustainable one. To move toward this goal we need to both use energy as efficiently as possible and produce what we do use in a sustainable manner. Greenway College will walk both paths at once. Without sacrificing any of the comforts and conveniences of a modern college campus, it will be both a *super-efficient user* and a *self-sufficient supplier* of energy.

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8 Oliver Morton, "Solar Energy: A New Day Dawning?" *Nature* 443 (2006), 19–22, accessed May 24, 2012, http://www.nature.com/nature/journal/v443/n7107/pdf/443019a.pdf.

Money vs. Mission?

In terms of up-front cost, simply hooking up to the electrical grid in the usual way would be cheaper than attaining energy self-sufficiency. The latter requires efficient energy use coupled with on-site generation and energy storage. But a college is not a factory: it does not exist to make a given amount of profit per widget sold or student graduated. Although a college must survive financially, it has a goal, a reason for existing, that transcends its budget: namely, to foster learning. The unique educational mission of Greenway College is to *produce graduates that will engineer our sustainable future and contribute to our graceful transformation to a sustainable society*. It will equip its students to be first-rate users, innovators, and entrepreneurs of the whole range of sustainable technologies by involving them in the exploration, refinement, and demonstration of exactly those technologies in the fabric of the campus itself.

Greenway's energy system will, then, be not only a supplier of energy services but an on-campus teaching resource, and must be planned, budgeted, and evaluated accordingly. On these terms, it does not make sense to ask which energy technologies will cost the least merely to install, or which technologies will pay for themselves in a given time window, and then build Greenway around the answers to such questions. The question for Greenway is, *what affordable mix of energy technologies will most fully and flexibly serve the college's reasons for existing?* This mix will likely include diverse renewable energy sources, storage technologies, and a wide array of efficiency and sustainability solutions.

What's more, room for change will be built into Greenway's energy system. The college's mission implies that it must reinvent itself over time, as students and faculty learn, experiment, and build. It may begin, for example, by relying heavily on photovoltaics and biomass, then add wind, small-scale hydropower, geothermal energy, or other technologies as time goes on. It may begin by being self-sufficient in energy, then become capable, over a decade or two, of exporting energy to surrounding communities or the grid.

Energy wisdom boils down to using energy efficiently and making it well. Below, we outline how Greenway can economically do both.

Using Less Without Doing Less

Energy efficiency is based on the traditional values of thrift and common sense. No sensible person opens all their windows in midwinter and burns extra fuel to heat the great outdoors. If one can achieve equal or greater comfort with less energy at lower cost, one always chooses the more efficient path.

Energy efficiency reduces energy demand. Demand can also be reduced by changing lifestyles (taking shorter showers, say), but most people would rather keep getting all the energy services they are accustomed to, only more efficiently (by getting their domestic hot water from a heat pump, for example). As explained in chapter 1, we tend to agree: efficiency is a less controversial path than lifestyle change. It appeals to enlightened self-interest rather than asking people to make what they perceive as sacrifices. Therefore, Greenway will not be austere. If anything, it will be a paragon of normality and comfort. This can be done because most people care not about kilowatts and kilowatt-hours, but energy *services*. They don't want amps, volts, watts, and joules but comfortable rooms, pleasant lighting, hot coffee, cold milk, and computers that work. If these demands can be met affordably with less energy—and they can—it makes every kind of sense to do so.

We cannot overemphasize that Greenway will provide a normal array of comforts and energy services. Our mantra is "totally green with *zero sacrifice*."

It might be objected, with some justification, that "sacrifice" is subjective: to live like a millionaire might involve "sacrifice" for a billionaire. But we use "zero sacrifice" to mean simply a standard of living that the vast majority of Americans would recognize as comfortable. We will assure a stable, reliable energy supply sufficient for all the activities of any college campus—reading, lab work, homework, computing, eating, socializing, showering, and so on. One or two scions of privilege might grumble, but we think it reasonable to describe such a campus as "zero sacrifice."

Totally green zero sacrifice requires high efficiency. The opportunity is huge: our society's usual methods of using energy are grossly wasteful, bleeding billions of dollars per year from homes and corporations. A report by McKinsey & Company found that technological adjustments alone—no lifestyle change—could cut US non-transportation energy use by 23 percent while saving half a trillion dollars, net.[9] And this is a *conservative* estimate, based on minor adjustments like using more efficient light bulbs, turning off unused appliances, weather-stripping windows and doors, and so forth. A campus designed from the ground up to provide lighting, heating, cooling, computing, and other energy services with the least possible energy might cost-effectively cut energy use by half, or even more. With demand sufficiently low, and with careful and deliberate planning, such a campus can readily produce all of its own energy without relying on the grid or deliveries of fuel.

Making Energy

It is, using traditional practices, much simpler to build a conventionally powered building than one that produces its

9 H. C. Granade et al., "Unlocking Energy Efficiency in the U.S. Economy: McKinsey Global Energy and Materials, 2009," accessed May 21, 2012, http://www.mckinsey.com/Client_Service/Electric_Power_and_Natural_Gas/Latest_thinking/Unlocking_energy_efficiency_in_the_US_economy.

own energy. In the usual course of affairs, one subcontractor digs and pours a standard foundation, another frames the building to comply (minimally) with code, another trucks in out-of-the-box coolers, heaters, windows, insulation, circulators, and other components, and another installs gas lines or oil tanks. An electrician runs the on-site wiring and utility workers hook it up to the grid. Finally, like wedding guests at the end of the reception, they all walk away and leave you with your new life.

Simple, maybe, but expensive, despite the fact that everything is done by lowest bidders. None of these contractors are motivated to reduce your energy costs, because they aren't going to be paying your electric, gas, and oil bills for all the years that your new building will need constant infusions of energy to remain livable. You are roped to those bills—bills that are tied to the vagaries of OPEC policy, peak oil, carbon pricing, regulation, Middle East crises, Enron-style debacles, and a dozen other factors out of your control. Short of major retrofits to your building and its gear, you *must* pay those bills, no matter how high energy prices go, because without a nonstop flow of ample energy from outside sources, your asset is a cold, dark shell.

At Greenway we will make our own energy, completely separating ourselves from the mainly fossil-fuel-powered grid and transportation network, from fuel-price fluctuations, and from a host of related environmental and geopolitical liabilities. Among other benefits, this will buffer Greenway against the vicissitudes of the larger economy, making us fiscally nimbler, better equipped to thrive in hard times, slower to sink, quicker to rise.

What would you do if you could start with a blank sheet of paper and design your own campus from scratch, using all the best technologies available today? Even if you are not an expert, your approach will probably improve greatly over today's out-of-the-box construction practices. We invite you to put your bookmark in for a few minutes and sketch out the elements of a design, and then consider our approach, outlined below. You will probably think of many of the same basic principles that we intend to apply.

Most basically, "energy" is not just one thing: different forms of energy tend to fulfill different needs, heating and cooling buildings, powering lighting and electrical devices, and moving machinery and vehicles.

Buildings. About 40 percent of present US energy use occurs in buildings—heating and cooling them and powering all the activities that go on inside.[10] When it comes to cutting this use, radical is the only realistic. US energy secretary and Nobel Prize winner Stephen Chu has said that for new construction, "extremely cost-effective buildings with energy savings of 60–80 percent are possible" without sacrifice of comfort.[11] The US National Renewable Energy Laboratory recently built three large commercial-class office spaces in Colorado that generate as much energy as they use—"zero net energy" buildings.[12] Inside such structures, a wide array of technically mature, field-tested, affordable tricks trims energy demand without sacrificing services: daylighting, LED lighting, timers, motion detectors, heat pumps, and much more. For heating and cooling of new buildings, the job can often be done for a tenth or less of current energy use, according to the InterAcademy Council—not speculatively, but as already demonstrated in numerous structures.[13] Over twenty-five thousand build-

10 "Buildings and Their Impact on the Environment: A Statistical Summary," US Environmental Protection Agency, April 22, 2009, accessed March 16, 2012, http://www.epa.gov/greenbuilding/pubs/gbstats.pdf.

11 "Secretary Chu Op-Ed on Energy Efficiency from the World Economic Forum," March 16, 2010, accessed March 16, 2012, http://energy.gov/articles/secretary-chu-op-ed-energy-efficiency-world-economic-forum.

12 "Research Support Facility: Leadership in Energy Performance," NREL, accessed March 16, 2012, http://www.nrel.gov/sustainable_nrel/pdfs/51742.pdf.

13 "Lighting the Way: Toward a Sustainable Energy Future," InterAcademy

ings requiring almost no heating or cooling, even in northern-European and Mediterranean climates, have been built to the European "Passivhaus" standard.[14]

But if such big savings are so easily realized, why are only a select few companies and individuals reaping the benefits of aggressive efficiency programs? The causes of this strange, almost anticompetitive, wastefulness include irrational regulations, institutional inertia, split incentives, and technical ignorance. The efficiency resource is intrinsically fragmented, meaning that to exploit it requires thoughtful action at many points: it is *simpler* to pay a few fat energy bills than to use less energy. (But then, it is always simpler to lose money than to earn it.) Another chronic stumbling block is that efficiency investments pay back only over time, not in one bright flash by throwing a giant green switch at a ceremony. Also, we have had a tendency in recent decades to focus on short-term financial motivators, but efficiency takes time to pay.

Electricity. Electricity is the most broadly useful form of energy, though expensive to produce and store. Average US electric power usage per adult is about 30 kilowatt-hours (kWh) per day—enough to keep about fifty laptop computers or two hair dryers running nonstop.[15]

Most of us don't generate our own electricity but buy it from the national grid, which is that network of power plants,

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Council, October 2007, accessed May 21, 2012, http://www.interacademy-council.net/File.aspx?id=24548.

14 Tom Zeller Jr., "Can We Build in a Brighter Shade of Green?" *New York Times*, September 25, 2010, accessed May 21, 2012, http://www.nytimes.com/2010/09/26/business/energy-environment/26smart.html?pagewanted=all.

15 A kilowatt (kW) is a unit of energy *rate* or *flow*, similar to gallons per minute for a liquid. A kilowatt-hour (kWh) is a unit of energy *quantity*, like gallons. A single thousand-watt hair dryer uses 1 kW of power; left on for one hour, it uses 1 kWh of energy. As of 2008, the average US residential customer used 11,040 kWh of electricity per year (http://tonto.eia.doe.gov/ask/electricity_faqs.asp).

Energy, Power, and Units

Writers often use the words "energy," "power," and "electricity" interchangeably. This causes much confusion in discussions of energy policy, efficiency, and related topics.

In science, **energy** is the ability to do a certain amount of work. A charged battery, for example, contains a fixed amount of potential energy. (It remains "potential" until it actually does something.)

Power is the rate at which energy is used to perform some task, like lighting a light bulb. Consider using a battery to run a light bulb. A brighter light bulb uses up the energy in the battery faster than a dimmer bulb, turning it into light and heat, so we say that it uses more power.

Electricity is a vague word, therefore not often used by engineers or scientists, but in everyday speech it refers simply to that invisible, amazingly useful stuff that comes from wall sockets. A decent nontechnical definition of electricity, in this everyday sense, would be **electrons doing useful work**. One can speak of both electrical **energy** (some amount of energy made available in the form of electricity, typically measured in kilowatt-hours) and electrical **power** (the rate at which electrical energy is used, typically measured in kilowatts).

Electrical energy is only one form of energy. One can also have chemical potential energy (e.g., in coal or gasoline), thermal energy (e.g., for heating), kinetic energy (e.g., the energy of running water), and others. Different forms of energy tend to be used for different tasks—gasoline in cars, or electrical energy for computers, say.

Electricity is unique because it can be used to accomplish almost any task. It can heat soup or power a laser beam, cool a house or run a car. Electrical energy can even be stored (in effect) by charging a battery, compressing air, making hydrogen from water, or other methods.

Electricity is the direct, natural product of solar panels and wind turbines. At Greenway, we will make full use of electricity's versatility to provide energy services and expand our technology options.

long-distance power lines, local poles and lines, and other gear that produces and distributes electricity across the continent. Most electricity delivered through the grid comes from heavy-duty power plants: coal (around 31 percent), natural gas (around 29 percent), nuclear (around 22 percent), and hydroelectric (around 7 percent).[16] We shouldn't take our electricity for granted just because these large power plants are typically out of sight and out of mind. When the author was a professor, he led tours to visit many power plants: they are both engineering marvels and, with their immense hunger for resources and wastefulness of primary energy, clear examples of why sustainable technology and engineering are so important.

It is increasingly common (though still the source of a small percentage of US electricity) for customers to own grid-connected generators of their own such as solar panels, often set up to feed power to the grid whenever their output is not needed by the customer. Connecting one's home, business, or campus to both the grid and a small-scale generator is straightforward in the forty-seven states that now require power companies to accept interconnection with such installations and to buy surplus power from them.[17]

Grid connection has two major advantages for small-scale users and generators of power: First, any surplus on-site generation earns income. Second, if one's on-site power source fails, the grid can supply one's electricity needs. At the same time, on-site generation can keep one's lights on during a grid outage (though this is not standard practice for grid-connected systems). Grid outages, most of them lasting just

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16 U.S. Energy Information Administration, "Electric Power Sector Energy Consumption," *Monthly Energy Review*, July 2019, accessed August 17, 2019, https://www.eia.gov/totalenergy/data/monthly/pdf/sec2_13.pdf.

17 "State Net Metering Policies," National Conference of State Legislators, accessed Aug 7, 2019, http://www.ncsl.org/research/energy/net-metering-policy-overview-and-state-legislative-updates.aspx.

long enough to crash every computer in the building, cost US commercial-class electricity customers about $57 billion every year.[18]

But if one is connected to the grid, one is implicated in how the grid is powered, and that is a problem. As mentioned, over 30 percent of US electricity is coal-generated (less in some regions, more in others). The rest comes mostly from natural gas, nuclear power, hydroelectricity, and wind (the latter still only about 7 percent as of 2018, though growing). If Greenway College wants to lead the way to a sustainable clean-energy future, it should *create* that future by disconnecting from the polluting grid while still providing itself with a full range of energy services. To maximize its impact, Greenway must walk the walk as well as talk the talk. When people see a modern campus powered entirely and reliably by renewable, locally generated energy, they will understand that renewable energy can work on a national scale.

In the past, off-grid systems have tended to be underpowered, one-of-a-kind designs, but when a stand-alone community like Greenway College is built from scratch with modern know-how, its energy system can be designed to supply power that is just as ample, reliable, and high quality as power from the grid. Connection to the grid might be considered as a way to sell surplus energy and for research purposes in the future—but not as a backup or lifeline. That would be too timid, too par for the course. It would not prove that renewables can stand on their own.

The arguments for being able to operate separately from the grid seem to us compelling. We therefore propose to produce all of Greenway's power on-site using a diverse portfolio of clean energy sources whose joint reliability will be

18 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.

higher than that of any one component. What distinguishes such sources is that they are *local and sustainable*, that is, harvest power from energy flows occurring naturally around and within the infrastructure of the community. Later in this chapter, we lay out exactly what Greenway's portfolio of clean energy sources will look like, including numbers on size and cost.

At this point you may be tempted to express skepticism. "Sure, 100 percent renewable electricity generation is possible when the wind is blowing and the sun is shining, but what about the rest of the time? What happens on a calm night?"

Good question. Here are quick, partial answers:

1. *Complementary sources.* Not all renewable power generators are intermittent. In addition to wind and solar, one may include around-the-clock generators in the power mix, such as a small hydropower turbine or a biogas-fired generator.

2. *Demand response.* During dips in power supply, one can arrange corresponding dips in demand by postponing power delivery to large loads that can wait a little while (e.g., freezers). At large scale, this technique is increasingly applied by US utilities across the grid.[19] Greenway College's intelligent, computerized power-management system will match select loads tolerant to postponement with power availability in a manner that is invisible to residents.

3. *Storage.* Energy can be put into storage when it is abundant and retrieved when production sags. This is already done by utilities, who most often use high-elevation hydroelectric water reservoirs for the

19 "2010 Long-Term Reliability Assessment," North American Electric Reliability Corporation, 2010, accessed May 21, 2012, http://www.nerc.com/files/2010_LTRA_v2-.pdf.

purpose. Smaller-scale storage may use batteries, reservoirs, compressed air, flywheels, synthetic liquid and gas fuels (e.g., hydrogen), and other means. With adequate storage, an off-grid installation powered entirely by erratic sources can have steady, around-the-clock power.

Greenway College will have to store energy in various forms to run on-campus vehicles, lawnmowers, portable devices, and the like. Storage will smooth the flow of renewable energy to these applications and enable Greenway to be off the grid, killing two birds with one stone. Storage is so important, in fact, that we devote the next chapter of this book to it.

4. *Transport.* Most vehicles run on gasoline and petroleum-derived diesel fuel, but one can readily purchase electric, methane-powered, hybrid biodiesel, and hydrogen vehicles and equipment for transportation and (with some relatively simple modifications) maintenance. Greenway's vehicular fleet will contain a mix of such technologies and evolve over time as such technologies evolve.

    - Electric vehicles are an obvious option because Greenway will be producing its own electricity. These are efficient users of energy, with battery-based versions transferring about 50 to 60 percent of the electric energy used to the job of moving the car itself.[20] (This compares favorably with gasoline and diesel vehicles, which have tank-to-wheel efficiencies of around 20 percent.[21])

20 Battery storage and retrieval is around 80 percent efficient (90 percent charging, 90 percent discharging), the electric motor is about 85 percent efficient, and drivetrain efficiency is about 75 percent. This gives about a 50 percent overall efficiency. See http://www.electroauto.com/info/pollmyth.shtml.
21 "Electric Vehicles," US Department of Energy, 2012, accessed May 21,

- Methane burns cleanly, and methane-powered buses, forklifts, and other vehicles are commonplace today, so this is not an exotic technology either. Methane is produced naturally by anaerobic bacteria digesting organic matter, so methane from on-campus biodigesters will likely be available for vehicular and other purposes (e.g., cooking). Methane may also be synthesized by various means. Similar to the production of methane from biodigestion, biodiesel to fuel hybrid-diesel vehicles may be fermented from organic sources such as soy, canola seed, and algae.

- Hydrogen can be easily synthesized using electricity to separate the hydrogen and oxygen atoms in ordinary water (H_2O). Hydrogen can power vehicles either in fuel cells or in internal combustion engines. Hydrogen-powered vehicles, like biodiesel and biomethane vehicles, offer the convenience of rapid fill-up (seconds or minutes, versus hours to fully charge an electric car). However, if one's original energy form is electricity (e.g., from solar panels or wind turbines), hydrogen-powered vehicles are less efficient energy users than electric vehicles, having only 20 percent overall efficiency from outlet to wheel.[22] This is because hydrogen must first be *manufactured* using electricity, then reacted in a fuel cell or burned in an engine, with energy losses at every step, whereas an electric vehicle can

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2012, http://www.fueleconomy.gov/feg/evtech.shtml.

22 Joe Romm, "Climate and Hydrogen Car Advocate Gets Almost Everything Wrong About Plug-in Cars," October 6, 2009, accessed May 21, 2012, http://thinkprogress.org/climate/2009/10/06/204758/climate-and-hydrogen-car-advocate-gets-almost-everything-wrong-about-plug-in-cars/.

charge from the electric source directly. Fueling a Greenway College on-campus fleet of twenty electric vehicles would require average electric generation of about 480 kWh/day; for hydrogen vehicles, about twice as much.

Costs

Alternative-energy installations often have higher up-front capital costs than conventional fossil fuel plants of equivalent power output, but also have the world-changing advantage of zero fuel costs (or, for biomass, fuel costs remain but are localized). Once all costs are factored in, the price per unit of energy produced by alternative generation, even with today's technology, becomes competitive.

As shown in table 2.1, wind installations are similar in price (per unit energy produced) to new gas turbines, and less expensive than a new coal plant, primarily because of wind's zero fuel costs. Biomass technologies can compete with conventional generation, depending on biomass fuel costs; biomass fuel costs can be near zero for on-site waste-mass usage or may include substantial farming costs.

The costs of solar electric installations have been declining exponentially for many years, and are likely to continue doing so.[23] New solar installations can be not only significantly less expensive than coal plants but competitive with new natural gas and wind installations.[24] Once installed, solar photovoltaic systems have minimal operational costs, making them an excellent investment. (Solar hot water units,

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23 Dylan McGrath, "Study: U.S. Photovoltaic Costs Declining," *EE Times*, February 19, 2009, accessed May 21, 2012, http://www.eetimes.com/electronics-news/4081427/Study-U-S-photovoltaic-costs-declining.

24 "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2020," U.S. Energy Information Administration, accessed June 11, 2020, https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

Table 2.1

Approximate cost data for new energy generation installations

Technology	Levelized Capital Cost (₵/kWh)	Operational Costs including Fuel (₵/kWh)	Capacity Factor	Total Levelized Cost of Energy (₵/kWh)
Natural Gas	0.8	3.0	87%	3.8
Coal	4.8	2.9	85%	7.6
Nuclear	5.6	2.6	90%	8.2
Hydroelectric	3.7	1.6	75%	5.3
Geothermal	2.0	1.7	90%	3.8
Biomass	4.0	5.6	83%	9.5
Solar CSP	11.8	1.2	57%	13.0
Solar Photovoltaic	2.6	1.0	29%	3.6
Wind	3.0	1.0	41%	4.0

Source: U.S. Energy Information Administration, "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2020."

as opposed to photovoltaic—direct solar to electricity-generating solar panels—are also competitive for their purpose.[25]) Both solar and wind costs per unit energy for new installations have dropped steeply over the last thirty years, as shown in figure 2.1.

What about nuclear power? We take no ideological stance on nuclear power, but new nuclear construction is currently more expensive than the major renewables. As shown in table 2.1, the DOE EIA 2020 reports a projected new-construction nuclear cost of 8.2¢/kWh as compared to 4.0 ¢/kWh and under for new wind and solar construction.

25 "Solar Hot Water Resources and Technologies," US Department of Energy, 2012, accessed May 21, 2012, http://www1.eere.energy.gov/femp/technologies/renewable_shw.html.

For Greenway, nuclear power is not an on-site option in any case: tiny nuclear reactors have been proposed, but are not commercially available.

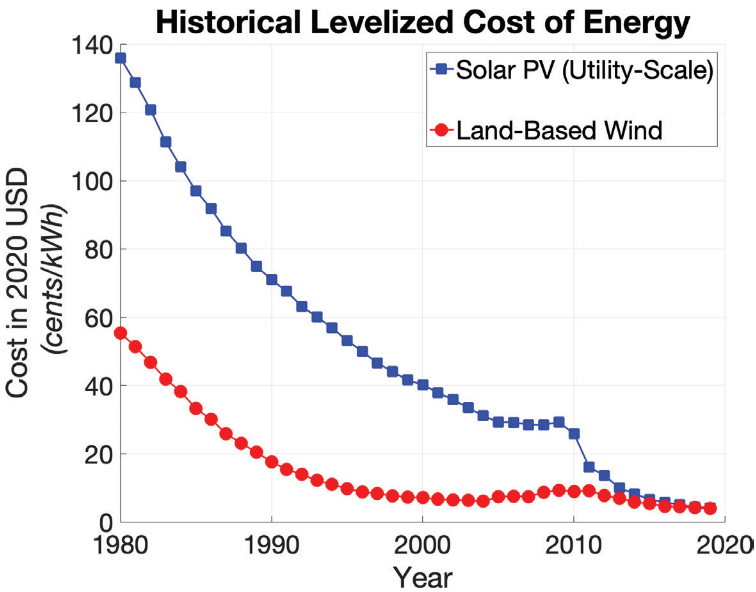

Fig. 2.1. Over the last thirty years, costs per kilowatt-hour for solar and wind power have fallen drastically.[26]

Making Energy at Greenway

As the previous section shows, cost is not an obstacle. The only question is exactly how to design a right-sized, afford-

26 Data to 2005 is from Melissa A. Schilling and Melissa Esmundo, "Technology S-curves in Renewable Energy Alternatives: Analysis and Implications for Industry and Government," *Energy Policy* 37:5(2009), 1767–1781, accessed May 21, 2012, doi.org/10.1016/j.enpol.2009.01.004.

Wind and solar data after 2005 are from *Lazard's Levelized Cost of Energy Analysis—Version 13.0*, November 2019, https://www.lazard.com/media/451086/lazards-levelized-cost-of-energy-version-130-vf.pdf.

able system that meets Greenway's needs—but that is a big question. In this section, we outline such a system.

With zero sacrifice, we conservatively project a 75 percent reduction in heating and cooling energy for buildings (compared to an otherwise comparable, conventionally powered college) as well as 50 percent reduction in all other forms of energy use. Eventually, additional savings may be realized, but this is a technically reasonable starting point.

For a residential college, typical energy requirements are around 25 to 50 kWh/day per person (lumping all power types together—electricity and fuels—and using the standardized kilowatt-hour unit, though this is often reserved for electricity). With efficiency improvements, energy requirements may be initially predicted at 10 to 25 kWh/day per person plus a margin for transportation and maintenance equipment. For a two hundred-person college, we conservatively estimate an around-the calendar average of about 4,000 kWh/day.

However, that is a lowball estimate. We require a system with ample supply (including storage—see chapter 3) to ride out periods of low generation and high demand. Electricity surpluses will not be a problem, but electricity shortages would most definitely be a problem. We therefore propose to build a 15,000 kWh/day electrical system, over three times the minimum electric generating capacity for our target campus population, that will provide 100 percent reliability, cover energy-storage losses, and accommodate future growth of the college. In routine campus operations, surplus power from generators will be used to build up long-term storage (e.g., hydroelectric, battery, or hydrogen). The choice of technologies for this generously-sized system will be matched to the geographic and topographic location of the college, although solar photovoltaic will almost surely be the dominant electrical source, with wind turbines used as appropriate.

Nonelectric sources of energy will also be utilized. The primary space heating and hot water system will most likely be a ground-source heat pump powered using electricity from wind, solar, and stored energy. A direct solar collector could be also be used for hot water and water preheating to reduce energy usage by the ground-source heat pump. A combined heat and power generation system (biomass or hydrogen) could be used to further reduce heating and hot water load, as well as to reduce energy-storage requirements. Initially, fuel for the biomass plant will be wood and organic waste.

Wind and solar are presently the least expensive renewable energy sources per kilowatt-hour. We propose an installation of two to four turbines, moderately sized to reduce visual impact. Wind generators typically operate at a capacity factor of 20 percent to 40 percent, depending on local wind conditions, so a well-sited 1,000 kW wind setup would generate an average of about 300 kW (sometimes more, sometimes less) or 7,200 kWh/day.

Solar photovoltaics are now the least expensive new electricity source at many locations. Photovoltaic costs have been declining at about 3.2 percent per year since 1998, and are likely to continue this trend.[27] Solar generation typically operates at an annual capacity factor of 15 to 30 percent in the continental USA. A 1,000 kW solar array[28] might generate on average about 5,000 kWh/day. Thus 1,000 kW wind and 1,500 kW solar would generate the proposed annual average goal of about 15,000 kWh/day.

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27 Galen Barbose, Naïm Darghouth, and Ryan Wiser, "Tracking the Sun III: The Installed Cost of Photovoltaics in the U.S. from 1998–2009," Lawrence Berkeley National Laboratory, December 2010, accessed May 21, 2012, http://eetd.lbl.gov/ea/emp/reports/lbnl-4121e.pdf.

28 For example, 1,000 kW-AC; 1,500 kW-DC; south-facing array, mostly unshaded, in the Northeast United States.

Solar's potential is gigantic: according to the US National Renewable Energy Laboratory,

> In the United States, cities and residences cover about 140 million acres of land. We could supply every kilowatt-hour of our nation's current electricity requirements simply by applying PV to 7 percent of this area—on roofs, on parking lots, along highway walls, on the sides of buildings, and in other dual-use scenarios.[29]

Shy rooftops nationwide are pleading to be covered by solar panels!

The sun will not only generate a chunk of our electricity, but it will also help heat our showers: a midsized active solar collector installation could be used to fully heat water in the summer and preheat it in the winter. A collector area of about 300 m^2 would be appropriate for Greenway. This technology is extremely mature: in 2010, solar hot water collectors worldwide were capable of producing 185 *million* kilowatts of thermal power.[30]

Biomass is sustainable, almost net zero as regards global-warming potential, and available locally. Small-scale burning of biomass, as in a woodstove, raises substantial concerns about emissions and byproducts (ash, smoke, and the like). However, if biomass is used to manufacture relatively clean-burning fuels at mid or large scale, substantial reductions in emissions and waste can be achieved. Sulfur dioxide emissions per unit energy for a high-temperature biomass gasification installation can be less than a tenth those of a home-based

29 "PV FAQs," National Renewable Energy Laboratory (US), February 2004, accessed May 21, 2012, http://www.nrel.gov/docs/fy04osti/35097.pdf.

30 "Renewables 2011, Global Status Report," Renewable Energy Policy Network for the 21st Century, August 2011, accessed May 21, 2012, http://www.ren21.net/Portals/97/documents/GSR/REN21_GSR2011.pdf.

woodstove or furnace; particulates, only 3 percent as much; carbon dioxide, one-sixth.[31]

A significant advantage of a biomass energy system is that it can run at any time—it is not reliant at any moment on whether the wind is blowing or sun shining—and can therefore be used to reduce reliance on energy storage. Biogas can produce electricity, heat, or both: in Europe, where hundreds of biogas systems are installed annually, it was already producing 4.9 percent of all electricity by 2019.[32]

By adjusting the mix of solar and wind, as well as possibly including hydro, geothermal, biomass, solar thermal, and other site-dependent alternative energy generation technologies, a totally green energy generation system can be designed for any geographic location in the United States.

Not Invited to the Party

Some alternative energy sources are in early stages of development or very site specific. Wave, tidal, and ocean-thermal power are relatively early in development, can be expensive, and require locating on coastal property. True geothermal heat would require favorable geology and deep drilling, neither of them likely options for Greenway. Nuclear fusion, satellite-based microwave power, and other speculative alternatives must find fulfillment elsewhere, as well.

Such omissions are OK because Greenway does not aim to do everything, to be everything: it aims to implement a richly diverse mixture of practical technologies that work for a particular real-world site. Since all actual sites have con-

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31 Barbara Klingler, "Environmental Aspects of Biogas Technology," German Biogas Association, 1999, accessed May 21, 2012, http://homepage2.nifty.com/biogas/cnt/refdoc/whrefdoc/d7env.pdf.

32 Marc Schaller, "Biogas Electricity Production Hits 17 272 GWh a Year in Europe." Engineer Live, September 2008, accessed May 21, 2012, http://www.engineerlive.com/Energy-Solutions/Waste-to-Energy/Biogas_electricity_production_hits_17_272GWh_a_year_in_Europe_/20788/.

straints, Greenway, by working within site-specific and scale-specific limitations, will actually be producing knowledge of universal value.

Conclusion

In this chapter, we have estimated the energy requirements of Greenway College and laid out the elements of a system that will meet the college's needs while also serving its teaching mission. Solar and wind electricity, ground-source heat pump, solar hot water—all these are in the picture, framed by the smart, efficient *use* of energy that defines Greenway's demand profile.

The technologies we favor are not only intrinsically sustainable but eminently practical: solar photovoltaics, wind, and solar hot water are well established, low maintenance, and reliable. Both solar and wind have recently become cost competitive with new fossil-fuel. These technologies produce intermittent output, but by combining these sources with other technologies, including energy storage—as reviewed in the next chapter—we can build a highly reliable, zero-sacrifice, sustainably powered stand-alone facility. At Greenway, we will engineer a beautiful energy machine that works 24–7–365.